UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE GEOCIÊNCIAS

**GEOCRONOLOGIA E EVOLUÇÃO TECTÔNICA
PALEO-MESOPROTEROZOICA DO ORIENTE
BOLIVIANO - REGIÃO SUDOESTE DO
CRATON AMAZÔNICO**

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TESE DE DOUTORAMENTO

Programa de Pós-Graduação em Geoquímica e Geotectônica

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DOUTRINA E CONVENIOS 130:18

RESUMO

Este trabalho caracteriza a evolução tectônica, identificando a cronologia dos principais eventos tectono-magmáticos do Pré-Cambriano Boliviano. A complexa evolução geológica do Oriente da Bolívia se estende desde o Paleozoico a Mesoproterozoico compreendendo as províncias Rio Negro, Juruena, Rondoniana, San Ignacio e Sunsás na região conhecida como Bloco Paraguai. Diversos métodos de estudo foram adotados na pesquisa tendo em vista tratar-se de um terreno com evolução policíclica e incluíram, além do mapeamento geológico e petrografia dos principais tipos de rocha, a metodologia U-Pb para determinação da idade de corpos graníticos e a metodologia Sm-Nd na estimativa de idade das fontes destes corpos plutônicos e inferências de ordem petrogenética, bem como dados geoquímicos obtidos para detalhamento das interpretações petrogenéticas. Nas interpretações houve ainda a avaliação crítica da literatura recente, a integração de dados de campo, aeromagnéticos e aero-radiométricos, inclusive embasadas na experiência profissional do autor. Os dados obtidos na última década modificaram substancialmente a concepção do Pré-Cambriano Boliviano, tendo sido caracterizados três conjuntos litológicos temporalmente distintos antecedendo a orogênia San Ignacio. O *granito Correroca* na parte meridional da área possui idade ^{207}Pb - ^{206}Pb de 1,92 – 1,89 Ga, com modelo de idades T_{DM} de 2,8 a 2,9 Ga e valores de $\epsilon_{\text{Nd}(t)}$ de -8,5 e -9,4. A *Suíte Yarituses* composta pelos granitos La Cruz, Refugio e San Pablo possui quimismo calcio-alcálico. Os dados U-Pb SHRIMP, TIMS e abrasão por laser-ICPMS indicam a formação desta suíte no lapso temporal entre 1673 a 1621 Ma. A idade de cristalização U-Pb SHRIMP do granito La Cruz é de 1673 ± 21 Ma, idade modelo T_{DM} de 1,83 Ga e valor de $\epsilon_{\text{Nd}(t)}$ de + 2,1 indicativo de derivação mantélica. O granito Refugio tem idade U-Pb TIMS de 1673 ± 25 Ma e o pluton San Pablo idade ICPMS por laser abrasão de 1621 ± 80 Ma (idade T_{DM} de 1,7 Ga e valor de $\epsilon_{\text{Nd}(t)}$ de + 3,5). Este conjunto de dados sugere uma derivação mantélica principal para a suíte Yarituses. O *granodiorito San Ramón* possui uma idade de cristalização de 1429 ± 4 Ma (SHRIMP), T_{DM} de 1,7 Ga, e $\epsilon_{\text{Hf}(t)}$ entre + 3,49 e +5,47 e representa um evento de geração da crosta, a partir de material juvenil. O magmatismo, deformação e metamorfismo da orogênia San Ignacio constitui o principal evento representado na área de estudo, cujo maior representante é o Complexo Granitoide Pensamiento com seus plutons sin a tardi-cinmáticos e tardi a

pos-cinemáticos. Os granitos San Martín, La Junta e Diamantina possuem idades de cristalização de 1373- 1340 Ma, idades modelo T_{DM} de 1,6 a 2,0 Ga, com valores de $\epsilon_{Nd(t)}$ de + 2,0 até -4,0. Os granitos Las Maras, Talcoso, Limonal e San Andrés produziram idades de cristalização de 1347 a 1275 Ma. As idades T_{DM} dos granitos Limonal e San Andrés correspondem a 1,9 e 1,8 e $\epsilon_{Nd(t)}$ de -1,4 e 1,6 respectivamente. A geoquímica em rocha total indica uma composição compatível com arco magmático, corroborando a assinatura acima dos parâmetros petrogenéticos. Em suma, a orogênese San Ignacio representa um arco acrecionário de natureza continental que construiu a arquitetura final da província Rondoniana-San Ignacio pela colisão entre o Bloco Paraguá e a província Rio Negro-Juruena. A evolução mesoproterozoica finaliza com a formação da faixa colisional Sunsás. Esta orogênese produziu plutonismo sin a tardi cinemático e tardi a cinemático marcando o limite com o bloco Paragua. A natureza alóctone e colisional do orógeno Sunsás como o evento mais jovem do Cráton Amazônico é marcada por frentes tectônicas, bem definidos de sentido sinistral, convergentes para o Bloco Paragua.

ABSTRACT

This work characterizes the tectonic and magmatic evolution of the Precambrian shield of Bolivia. The complex geological evolution of the eastern Bolivia extends from the Paleo- to Mesoproterozoic, and can be related with the magmatic and metamorphic events that are ascribed to the Rio Negro - Juruena (1.78-1.60 Ga), Rondonian - San Ignacio (1.56-1.30 Ga) and Sunsás – Aguapei (1.25-1.00 Ga) provinces, known in Bolivia as the Paragua block. Several methods of study were adopted in the research with the scope that this is a land with polycyclic evolution. As such our study included, besides the geological mapping and petrography of major rock types, the U-Pb age determinations of granitoid rocks, Sm-Nd and Rb-Sr isotopic analyses, as well as geochemical data. At the interpretation there was the critical evaluation of recent papers, the integration of field data, aeromagnetic and aero-radiometric, including the field experience of the author. The data obtained in the last decade have substantially changed the geology of the Bolivian Precambrian shield. It has been characterized three temporally distinct granite suites preceding the San Ignacio orogeny (1.37-1.30 Ga): the *Correreca granite* in the southern part of the area has $^{207}\text{Pb}/^{206}\text{Pb}$ age from 1.92 to 1.89 Ga, with T_{DM} model ages of 2.8 to 2.9 Ga and values of $\epsilon_{\text{Nd}(t)}$ of -8.5 and -9.4; the *Yarituses suite* (La Cruz, Refugio and San Pablo granites) shows calc-alkaline signature. Data U-Pb SHRIMP, TIMS and ICP-MS laser ablation indicate the formation of this suite between 1673 to 1621 Ma. The U-Pb SHRIMP crystallization age of La Cruz granite is 1673 ± 21 Ma, T_{DM} model age of 1.83 Ga and $\epsilon_{\text{Nd}(t)}$ of +2.1 indicative of a predominantly mantle source. The Refugio granite has U-Pb TIMS age of 1673 ± 25 Ma and the San Pablo pluton yields a ICP-MS Laser ablation age of 1621 ± 80 Ma (T_{DM} age of 1.7 Ga and $\epsilon_{\text{Nd}(t)}$ +3.5). These data suggest again a mantle source for the Yarituses suite. The *San Ramon granodiorite* event has a crystallization age of 1429 ± 4 Ma (SHRIMP), T_{DM} of 1.7 Ga, and $\epsilon_{\text{Hf}(t)}$ between +3.49 and +5.47 and represents a juvenile accreted episode. The magmatism, deformation and metamorphism of San Ignacio orogeny is the main event of the study area, represented by the Pensamiento Granitoid Complex with sin to late-kinematic and late to post-kinematic plutons. The San Martín, La Junta and Diamantina granites have crystallization ages of 1373 - 1340 Ma, T_{DM} model ages from 1.6 to 2.0 Ga, with values of $\epsilon_{\text{Nd}(t)}$ from 2.0 up to -4.0. The Las Maras, Talcoso, Limonal and San Andrés granites yielded crystallization ages of 1347-1275 Ma. The

T_{DM} ages of Limonal and San Andrés granites are between 1.9 and 1.8 Ga and the $\epsilon_{Nd(t)}$ values of -1.4 and +1.6 respectively. The whole rock geochemistry of these granites indicates a composition consistent with the magmatic arc. Thus the San Ignacio orogeny represents a continental accretionary arc that built the final architecture of the Rondonian-San Ignacio province (1.56-1.30 Ga) by the collision between the Paragua block and the Rio Negro -Juruena province (1.78-1.60 Ga). The Mesoproterozoic evolution of the SW margin of the Amazonian craton ends with the formation of the Sunsás collisional belt that produced sin to-late and late to-post-kinematic plutonism. The allochthonous and collisional nature of the Sunsás orogeny is marked by tectonic fronts, with well-defined sinistral sense, converging towards the Paragua block.

1. INTRODUÇÃO

1.1 Apresentação

Esta tese aborda a evolução crustal da porção SW do Cráton Amazônico, com base em investigações geológicas, apoiadas por dados petrográficos, geoquímicos e geocronológicos. Os estudos abrangem áreas-chave do Pré-Cambriano boliviano com vistas às correlações tectônicas com terrenos policíclicos proterozoicos na contraparte brasileira, nos estados de Rondônia e Mato Grosso. O tema também é relevante para reconstruções paleotectônicas, uma vez que o SW da Amazônia é correlacionável com partes da Laurentia e Báltica, conforme simbolizado pelo Supercontinente Rodínia, edificado entre 1,2 - 1,0 Ga.

Para cumprimento dos estudos, este projeto de doutoramento beneficiou-se da colaboração de pesquisadores de universidades brasileiras (USP, UERJ, UFMT, UFPa), sob os auspícios do Conselho Nacional de Desenvolvimento Científico e Tecnológico-CNPq (processos 304300/2003-9; 470373/2004-0 coordenados pelo orientador da Tese), bem como do Centro de Pesquisas Geocronológicas (CPGeo) do Instituto de Geociências da USP (IGc/USP Brasil). Vale destacar que as atividades do projeto incluíram a formação de recursos humanos em diferentes níveis (Dr., Ms., IC), valorizando ainda mais o esforço da cooperação científica no fomento ao conhecimento da geologia e geotectônica do Pré-Cambriano boliviano.

As atividades conjuntas realizadas na última década propiciaram avanços científicos de impacto no conhecimento geológico do Pré-Cambriano boliviano, divulgado em congressos e em periódicos indexados, cujos principais resultados serão aqui sintetizados, com destaque para a produção científica pessoal decorrente desta presente pesquisa. O autor desta tese, docente da Universidade Mayor de San Andrés (Bolívia), usufruiu de bolsa de Doutorado da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - CAPES, por meio do projeto “Evolução tectônica dos terrenos pré-cambrianos do oriente de Bolívia durante o Mesoproterozoico - na região sudoeste do Craton Amazônico”. O autor também contou com recursos eventuais do Programa de Pós-Graduação de Geoquímica e Geotectônica do IGc-USP e do CPGeo para sua participação em Congressos (regionais, nacionais e internacionais), que

tiveram por intuito a divulgação e discussão dos resultados parciais da Pesquisa. Sem estes apoios financeiros e a integração científica com os pesquisadores brasileiros, os estudos no Pré-Cambriano boliviano teriam sido inviabilizados, face à complexa logística para acesso à região de selva para os perfis geológicos e coleta de amostras, bem como para fazer frente ao apoio de análises para a pesquisa, especialmente isotópicos e geoquímicos.

Algumas décadas se passaram antes que o tema do Pré-Cambriano boliviano fosse incluído entre as prioridades de cooperação científica entre o Brasil e Bolívia. Como consequência novas visões foram alcançadas acerca do conhecimento crono-stratigráfico de uma região remota e de difícil acesso, em função da realização de estudos sistemáticos geocronológicos, isotópicos e geoquímicos, havendo ênfase nas rochas granitóides regionais. Com isso interrompeu-se o baixo interesse sobre o conhecimento geológico Pré-cambriano desde a finalização do clássico projeto anglo-boliviano por meio de um convênio de cooperação entre o Serviço Geológico da Bolívia (GEOBOL) e o Serviço Geológico Britânico (IGS- BGS) desenvolvido na Bolívia (e.g., Litherland, 1981; Report on geological discussions in São Paulo. Rep. East. Bolivia Miner. Expl. Project, Santa Cruz, ML 33; Litherland et al., 1986).

A colaboração profícua de pesquisadores interessados na evolução primitiva permitiu a divulgação dos primeiros avanços dos trabalhos conjuntos em congressos no Brasil e Bolívia (nos anos 2004, 2006), e no International Geological Congress, ocorrido no Rio de Janeiro (ano 2000) e Oslo (2008). O interesse do autor em desenvolver este projeto de doutoramento decorre do fato de ter atuado na década de 1990 no mapeamento do Pré-cambriano boliviano continuando o trabalho do “Proyecto Precámbrico” GEOBOL – projeto Anglo-Boliviano pioneiro que produziu o primeiro mapa geológico na escala 1:1.000.000 do Oriente boliviano. A oportunidade de retomar este tipo de estudo, surgiu a partir de uma viagem dos professores da Universidade Federal de Mato Grosso, às universidades regionais da Bolívia, do Chile e do Peru, com o propósito de promover um primeiro relacionamento entre as instituições de ensino superior do Centro Oeste Sul-Americano. Deu-se início uma cooperação científica informal, visando realizar trabalhos conjuntos, de cunho técnico/científico, estágios de professores e estudantes, como suporte da Cooperação Internacional e à Integração

Regional. Em consequência desta iniciativa, este autor foi convidado a proferir palestra sobre a geologia pré-cambriana da fronteira Brasil-Bolívia no IX Simpósio de Geologia do Centro Oeste realizado em Cuiabá em julho de 2003, no qual coordenou, a convite, uma pioneira excursão científica ao Pré-Cambriano Boliviano. Naquela oportunidade veio conhecer o então Diretor do Instituto de Geociências (IGc) - USP, Prof. Dr Wilson Teixeira, contato este que conduziu posteriormente à decisão pessoal de se matricular no Programa de Pós-Graduação da USP, em 2005 – devidamente referendada pela Universidade Mayor de San Andres.

O presente documento está estruturado sob a forma de 5 artigos científicos o que requer uma estruturação e comentários distintos do modelo tradicional. O *primeiro capítulo*, introdutório da Tese, apresenta o tema estudado com ênfase na importância desta pesquisa para a compreensão da evolução geológica do Pré-cambriano boliviano e a sua relação ao Craton Amazônico, bem como o porquê da iniciativa pessoal de realizá-lo. O *segundo capítulo* propõe o objetivo principal desta pesquisa e os objetivos específicos em razão da área eleita para os estudos acadêmicos, ao passo que o *terceiro capítulo* apresenta a localização da área onde se concentraram os trabalhos propostos. O *quarto capítulo* apresenta um histórico do avanço do conhecimento geológico (e bibliografia pertinente), além de uma reflexão do estado da arte do Pré-Cambriano do oriente boliviano, a partir das descobertas fundamentadas principalmente nos dados geocronológicos mais recentemente obtidos por terceiros. O *quinto capítulo* sintetiza os métodos de trabalho e estratégias aplicadas na Tese, as quais incluíram: a compilação de dados e publicações, com base no acesso a acervos de acesso restrito da GEOBOL (agora SERGEOTECMIN; em La Paz e Santa Cruz) em cadernetas, relatórios internos, mapas do “Proyecto Precámbrico”; mapas geofísicos digitalizados a partir da base de GEOBOL na década dos 90, imagens Google Earth de acesso franco na internet, assim como dos trabalhos de campo e de gabinete realizados na elaboração de mapas digitalizados, na escala 1:250.000 e 1:1.000.000.

O *capítulo sexto*, está representado pelos comentários e críticas pertinentes aos cinco artigos científicos publicados em periódicos nacionais (01 artigo em Brasil e 01 em Bolívia) e internacionais (03 artigos), devidamente anexados, havendo ênfase nos

comentários integrados em relação ao bloco Paraguá e suas implicações para o SW do Craton Amazônico. O capítulo final (*sétimo*) apresenta as referências bibliográficas

2. OBJETIVOS

Como objetivo principal pretende-se obter uma visão mais abrangente possível acerca da natureza e cronologia dos principais eventos tectono-magmáticos que afetaram a região SW do Craton Amazônico, com ênfase nos terrenos da Bolívia, e realce nas rochas que edificaram a chamada província Rondoniana-San Ignacio (1.56-1.30 Ga; e.g, Cordani and Teixeira, 2007).

Os objetivos específicos são:

- i) A aplicação da metodologia U-Pb para determinação da idade de corpos graníticos (métodos SHRIMP, ICP-MS, TIMS) e de eventos metamórficos, fazendo uso de populações de zircão previamente analisadas por catodoluminescência, sempre que possível;
- ii) A aplicação da metodologia Sm-Nd na estimativa de idade das fontes destes corpos plutônicos e inferências de ordem petrogenética e tectônica. Esta ferramenta é complementada com a metodologia Rb-Sr através de diagramas Nd-Sr.
- iii) A obtenção de dados geoquímicos de elementos maiores, traços e terras raras obtidos para detalhamento das interpretações petrogenéticas em rochas granitídes especialmente.
- iv) A execução de perfis geológicos em áreas chave para fins de amostragem e análises geoquímicas, petrográficas e geocronológicas.
- v) Integração de dados de campo, aeromagnéticos e aero-radiométricos de GEOBOL, imagens satelitais, para refinamento da cartografia para determinadas unidades.

3. LOCALIZAÇÃO DA ÁREA DE ESTUDO

A região de estudo está localizada no oriente de Bolívia compreendendo parte leste do departamento Santa Cruz e o sul do departamento Beni, abrangendo parte das folhas 1: 250.000 de Concepción, Monte Verde, Perseverancia, Puerto Villazón, Huanchaca, Manomó, San Ignacio de Velasco, San José de Chiquitos, Roboré-Santo Corazón y Las Petas (Figura 3.1). Estas áreas em sua maior parte são desconhecidas geologicamente. O principal acesso por rodovia compreende Santa Cruz- San Ramón, San Javier, Concepción e San Ignacio de Velasco na Chiquitania. Outra via por sua vez está situada na porção meridional a partir de Santa Cruz até San José e Robore paralela á ferrovia. Partindo-se dos referidos pontos os acessos vicinais são estradas de terra, de difícil acesso em época de chuvas.

O Pré-Cambriano boliviano é uma área remota com estradas precárias e de acesso difícil. Em épocas secas o acesso aos afloramentos não apresenta dificuldades. Em época de chuvas as estradas ficam fechadas ao tráfego de veículos. A logística usual de campo no Pré-Cambriano boliviano necessita de aluguel do carro (4x4 tracionado) disponíveis em Santa Cruz, a cidade com melhor estrutura logística para os trabalhos de campo. Cada campanha demanda um percurso de 1500 ate 2000 km, inclusive com uso de tanques reserva de combustível e contratação de “materos” para corte de eventuais troncos de árvore que vez por outra interrompem as trilhas de acesso aos afloramentos. Uma viagem de campo foi realizada junto a candidata Gabriela Vargas, então doutoranda na Universidade Estadual do Rio de Janeiro. Para executar o trabalho foram alugadas duas motos com os seus respectivos motoristas, o que dá idéia das dificuldades de acesso por caminhos muitas vezes pouco usuais.

Figura 3.1 Mapa de localização da área de estudo.

3. REVISÃO HISTÓRICA DA GEOLOGIA DO ORIENTE DE BOLÍVIA

Em termos históricos, cabe ao cientista Alcides d'Orbigny a fama de ser o pai de pesquisa geológica na Bolívia. Este naturalista francês em sua viagem pela América do Sul entre 1826 e 1832, visitou uma grande parte do território da Bolívia. Em sua grande obra apresentada em onze volumes “Voyage dans l'Amérique Meridionale” que apareceu em Paris, em 1835-1847, a mais importante para o presente tema são os três volumes que descrevem suas viagens. O volume Geologia que traz observações precisas sobre as planícies de Moxos (departamento Beni) em particular, é digno de ser lido ainda hoje, acima de tudo pela apresentação cuidadosa dos seus desenhos. Seus méritos, dedicados à pesquisa geológica pioneira na Bolívia, devem ser sempre reconhecidos (Ahlfeld, 1946).

F. Ahlfeld chegou à Bolívia em 1923 e até 1928 dedicou-se a investigações técnicas de mineração e depósitos minerais. Em 1935, assumiu a Divisão Geológica da Dirección Geral de Minas e Petróleo de La Paz. Nesta função viajou por boa parte do território boliviano a fim de coletar dados para um mapa geológico do país. Sua pesquisa geológica foi publicada pela primeira vez no ano de 1954, juntamente com o primeiro mapa geológico da região andina da Bolívia. Contudo, desde as viagens de d'Orbigny na Bolívia oriental, as investigações geológicas no Pré-cambriano foram totalmente negligenciadas. Em 1908 a área das serranias de Huanchaca foi visitada pelo explorador inglês Col. P. H. Fawcett, cujas descrições foram base para o livro de Arthur Conan Doyle “El mundo perdido”.

Com relação ao potencial metalogenético das rochas intrusivas precambrianas da Bolívia F. Peiser, um geólogo de campo na Dirección General de Minas de La Paz, realizou estudos geológicos nos anos de 1939-1944 em grande parte do Distrito San Ramón. Este autor publicou um mapa e comentários sobre os pegmatitos micáceos da região de San Javier Concepcion e San Antonio de Lomerío (Peiser, 1944a); em um artigo subsequente Peiser (1944b), destacou os veios de quartzo-aurífero relacionados que ocorrem no Distrito San Ramón.

Já Kempff e Peiser (1945) descreveram os depósitos minerais pegmatíticos de Santa Ana, perto de San Ignacio. Já a Serrania San Simón, localizada ao sul do departamento Beni tem sido explorada de forma intermitente desde que o ouro foi descoberto pelos jesuítas na segunda metade do século 17. Rochas pegmatíticas também foram descritas na Bolívia em San Agustín, lado sudeste de San Ramón. Estes pegmatitos foram examinados em maior detalhe por tanto por Peiser (1944a) como Ahlfeld (1954), uma vez que neles foram observados veios de quartzo auríferos. Cabe também citar os estudos geológicos de F. Ahlfeld ao longo da ferrovia de Corumbá a Santa Cruz, publicados pela primeira vez no livro Geologia de Bolívia (Ahlfeld, 1954) que reporta também as observações de Peiser.

Quanto ao estado da investigação geológica na Bolívia para a época (sendo que até agora houve pouca mudança) são poucos os trabalhos publicados. Em função disso, a Bolívia é um país geologicamente muito pouco conhecido. Todos os esforços concentravam-se na parte andina, por exemplo no Cerro Rico de Potosí, as minas de Siglo XX e Huanuni, com jazidas ricas em Ag, Sn, W, Pb e Zn de classe mundial em veios de 0,1 até 5 m chamados “tipo boliviano. O Cerro Rico de Potosí foi descoberto em 1545 e em 1611 já tinha a volta de 150.000 habitantes, a maior depois de Paris (Arce- Burgoa, 2007).

Até os anos da década dos 50 a área de San Ignacio de Velasco tinha sido pouco pesquisada geologicamente desde os estudos iniciais de d'Orbigny. Devido a essa lacuna de conhecimento as colinas que fazem fronteira com a região das cabeceiras do Itenez (Guaporé), Rio Verde e Rio Tarbo são geologicamente terras ainda virgens, também na zona fronteira entre Bolívia e Brasil, ao longo do Rio Itenez (Figura 3.1).

Segundo Ahlfeld (1946), o leste da Bolívia fazia parte do Escudo Brasileiro, que era considerado um maciço antigo representado principalmente pelo embasamento cristalino. Numa divisão geológica tentativa regional, Ahlfeld propôs a presença de rochas primitivas (arcaicas) e rochas algonquianas (Proterozoico), além de rochas magmáticas pré-paleozoicas. Com respeito às rochas primitivas foram distinguidas duas áreas principais: A primeira é uma faixa no departamento de Beni, perto de Guayaramerín onde o embasamento cristalino aflora nas cachoeiras do Rio Madera. As

rochas descritas originalmente em 1906 por Evans (apud Ahlfeld, 1946) são as seguintes, envolvendo domínios geográficos contíguos no Brasil e Bolívia: gnaiss granulítico com microclínio e micropertita no salto Teotônio no Brasil, gnaiss granitóide (Villa Bella), gnaisses e anfibolitos. A segunda área compreende o bloco Chiquitano (Bolívia) que se estende desde Guarayos e San Miguel até Santo Corazón (Figura 3.1). Os tipos de rocha principais são os ortognaisses, paragnaisses, migmatitos, leptinitos, arteritos, micaxistos ou folhelhos, quartzitos e anfibolitos. Essas rochas primitivas apresentam-se altamente metamorfizadas, correspondendo à catazona.

A série Algonquiana, segundo Ahlfeld (1946), está representada no leste da Bolívia, nas colinas a leste das montanhas de Sunsás. Quanto à província Ñuflo de Chavez, presume-se que determinados folhelhos que afloram na parte ocidental do vale do rio Quiser, norte de Santa Rosa de la Mina e San Javier sul, alternando com filito piritoso, também interpretado como pertencente ao Algonquiano.

As rochas magmáticas pré-paleozoicas descritas originalmente por Ahlfeld compreendiam intrusões graníticas que, segundo o conhecimento da época, não tinham um posicionamento cronológico definitivo. De acordo com Evans (citado em Ahlfeld, 1946), que estudou a geologia das corredeiras do rio Madera no extremo noroeste da Bolívia, no limite com o estado de Rondônia (Brasil), a geologia local era complexa, pois ocorriam rochas ígneas intrusivas como granitos com 74% de sílica (e.g., Cachoeira San Antonio), adamelitos (granitos com piroxênio, granitos porfiríticos com 69,6% SiO₂), sienitos biotíticos (Salto Teotônio), granitos anfibólicos (Porto Velho e Três Irmãos) granitos porfiríticos atravessados por diques de pegmatitos, aplitos, e ainda granitos a duas micas. Assim, Ahlfeld (1946) descreveu uma faixa de veios de quartzo praticamente contínua, limitada regionalmente em ambos os lados por intrusões pegmatíticas, que continua para o norte de San Javier. Na província de Velasco para oeste de Santa Ana d'Orbigny descreve veios de quartzo, com ametista e cristal de rocha. Já no ano de 1944, também embasados nas observações de Peiser, houve vários pedidos relativos à exploração de mineração de cristal de rocha no Santo Corazón. Geólogos da Comibol (Corporación Minera de Bolívia) fizeram em 1970 uma visita de reconhecimento a San Simon, ao sul do departamento Beni (Figura 3.1) para fazer uma primeira avaliação integrada das ocorrências mineralizadas. Em 1973,

geólogos da COBOEN (Comissão Boliviana de Energia Nuclear) realizaram uma avaliação das reservas de ouro ali existente.

De outra parte, devido ao interesse da Bolívia Gulf Oil Company (posteriormente YPFB - Yacimientos Petrolíferos Fiscales Bolivianos) foram iniciados os estudos em rochas sedimentares que recobrem o Pré-cambriano e que ocorrem entre Santiago e Santo Corazón (Hess, 1960). Também com foco na prospecção de petróleo, rochas sedimentares precambrianas de grau metamórfico incipiente foram agrupadas na Série Sunsás por Oviedo e Justiniano (1968), em uma seção tipo ao longo do Rio Santo Corazón, que drena a Serranía Sunsás perto de Santo Corazón. Coube a estes dois geólogos estimar pela primeira vez a espessura de mais de 5000 m desta unidade clássica da Bolívia, com uma divisão tripartite em arenito quartzítico micáceo de cor branco na base, seguido por semi-pelitos e arenitos quartzíticos de cor rosa. Mais tarde, Castillo e outros (1971) reconheceram a existência de um conglomerado basal na Série Sunsás.

Entre os anos 1976 e 1983 a Bolívia foi palco de um dos maiores projetos de mapeamento sistemático da América do Sul, realizado por meio de um convênio de cooperação entre GEOBOL (Serviço Geológico da Bolívia) e o Serviço Geológico Britânico (IGS- BGS), cujos resultados principais estão sintetizados em Berrangé e Litherland (1982) e Litherland et al (1986).

Este trabalho envolveu duas fases:

Fase I. Compreendeu a coleção dos principais tipos de rocha para ser estudados em laboratório, e identificar as características estruturais nas imagens de satélite LANDSAT. Isso ajudou a identificar as condições de campo e fornecer informações úteis para a logística. Para algumas áreas inacessíveis um helicóptero foi utilizado.

Foram mapeadas duas folhas 1:100.000 em 1976 como parte do treinamento para o pessoal boliviano. As brigadas foram formadas por um geólogo do IGS, um ou dois geólogos de GEOBOL e pessoal de apoio. O mapeamento foi realizado usando folhas topográficas 1:50.000 do Instituto Geográfico Militar, fotografias aéreas convencionais e imagens Landsat para o controle regional. Coletaram-se sedimentos de corrente e solo para a prospecção geoquímica de reconhecimento. Foi ainda realizado

mapeamento e amostragem geoquímica na escala 1:100.000 de algumas áreas de interesse econômico como a Província Alcalina de Velasco por elementos de terras raras e o Complexo Ígneo Rincón del Tigre por Cu, Ni, Mn, Cr, Co.

Fase II. A região norte do Projeto na época não tinha mapa topográfico, então foi preparado um mapa base 1:500.000 baseado em um mosaico de imagem LANDSAT, contendo todas as informações geológicas e geográficas disponíveis. Esta Fase II foi planejada e dividida em duas subfases. A primeira delas envolveu um acompanhamento detalhado acima de anomalias geoquímicas e mineralizações descobertas de terras raras durante a Fase I, tais como as do Cerro Manomó, San José de Chiquitos pelo Cu, o Complexo Ígneo Rincón del Tigre, os pegmatitos de Concepción e San Ignacio, a Serranía San Simon pelo ouro e Ascensión de Guarayos pelo Sn (Litherland et al., 1986). A segunda subfase foi dedicada ao mapeamento e a geoquímica da zona norte do Pré-cambriano boliviano .

O período de mapeamento das folhas 1:250.000 demandou 3 anos com a participação de um ou dois geólogos para cada uma delas. O mapeamento e amostragem geoquímica foram orientados por meio de fotografias aéreas convencionais e imagens Landsat (bandas 6 e 7, escala 1:250.000 e 1:100.000) com plotagem em mapas topográficos 1:250.000. Devido às especificidades da região, com densa floresta, utilizaram-se várias formas de transporte, incluindo-se bois e cavalos, canoas de alumínio e troncos da árvore impulsionados por remos ou botes com motor, aeronaves de asa fixa, incluindo aviões mono-motores, um DC-3 e helicópteros. A base do Projeto em Santa Cruz tinha rádio-transmissores em contato permanente com as brigadas.

Como resultado deste esforço governamental importante avanço no conhecimento geológico do Pré-cambriano foi atingido, propiciando novos rumos para o progresso científico da Bolívia. Foram elaborados aproximadamente 280 relatórios internos, acompanhados de mapas para uso exclusivo da GEOBOL (situação permanece atualmente). Para uso público, foram elaborados 57 mapas geológicos em escala 1:100.000 com relatórios bilíngües que cobrem quadrículas de 20'x 30' na Zona Sul. Estes mapas cobrem uma área maior sobre a fronteira com o Brasil, como Las

Petas-San Matías e incluem a localização das amostras geoquímicas e de rochas coletadas. Em adição foram elaborados 14 mapas geológicos e relatórios na escala 1:250.000, cobrindo uma folha topográfica de 1° 00" x 1° 30 ', incluindo uma extensão até a borda da fronteira com o Brasil. Cada folha-mapa contém um relatório sobre sua geologia e o potencial mineral, exceto casos em que um único relatório abrange duas folhas. As folhas individuais são mostradas na Figura 3.1. Estas folhas contém um relatório de acompanhamento.

O Proyecto Precámbrico contou ainda com um programa de determinação de idade realizadas na unidade de isótopos da BGS (British Geological Survey), tendo sido produzidas 89 determinações pelo método K-Ar e 81 pelo método Rb-Sr. Darbyshire (1979) elaborou um relatório especial com a interpretação das determinações de idade, juntamente com um mapa 1:1.000.000 que indica locais amostrados. Por exemplo, o artigo de Litherland & Bloomfield (1981) sintetizou os resultados do mapeamento de cerca de 100.000 km² do setor oriental da Bolívia. Os dados geocronológicos permitiram delinear o arcabouço evolutivo regional, com os Granulitos Lomas Manechis e o Complexo Gnáissico Chiquitania representando as unidades basais formadas durante o Ciclo Orogênico Transamazônico ($\pm$ 2.000 Ma), ao passo que dois ciclos orogênicos posteriores foram identificados: San Ignacio ($\pm$ 2000-1300 Ma) e Sunsás (<1300-950 Ma). O Ciclo San Ignacio incluiu a deposição dos Xistos San Ignacio (com soleiras básicas / ultrabásicas) e sua posterior mobilização junto com o substrato primitivo dentro de uma faixa de rumo norte acompanhada de fases graníticas. Segundo estes autores o Ciclo Sunsás iniciou-se com a deposição do Grupo Sunsás seguido da formação de um cinturão orogênico marginal ao antepaís. Este Ciclo foi acompanhado por fases graníticas e uma atividade principal de rochas básicas-ultrabásicas. O encerramento da orogenia Sunsás marcou a cratonização do escudo boliviano em torno de 950 Ma

A integração dos resultados gerais do projeto está sintetizada na obra clássica de Litherland et al. (1986) que até hoje é referência para os que têm interesse em conhecer a geologia boliviana e suas correlações com unidades geológicas do SW do Craton Amazônico. Entre outras publicações importantes destacam-se as primeiras teorias evolutivas propostas para a geologia regional e modelagem tectônica (e.g.,

Klinck e Litherland, 1982; Litherland et al., 1985; Litherland et al., 1989). Estes dois últimos trabalhos, um deles publicado na Nature, apresentam pela primeira vez as modelos paleotectônicos para os cinturões móveis mesoproterozóicos então identificados na Bolívia. O artigo de Litherland et al. (1985) defende o modelo de faixas móveis paralelas pré-cambrianas do Craton Amazônico que exibem a mesma orientação andina, ressaltando que esta cadeia inclui restos de embasamento pré-cambriano, que em alguns casos é mais antigo que 2000 Ma como é o caso do cerro Uyarani, na Cordilheira Ocidental (Worner et al 2000), muito embora a relação entre estas rochas e o Cráton Amazônico sejam desconhecidas, devido à grande extensão da cobertura sedimentar cenozóica. Na interpretação dos autores os dois domínios estão ligados na forma de cinco faixas móveis com uma largura combinada de 1.000 km, progressivamente mais jovens, com idades variando de 1300 Ma até o presente. Neste trabalho, como protólito dos granulitos é considerada uma seqüência sedimentar e uma série plutônica calcioalcalina. Ressalta-se também neste artigo o caráter litoestratigráfico do Grupo Sunsás que como tal representa um nível estratigráfico guia, bem como indica-se o sentido sinistral das zonas de cisalhamento Sunsás e que o metamorfismo atinge a zona de granada nas rochas desta seqüência supracrustal.

Outros produtos importantes foram gerados na oportunidade do projeto, a exemplo dos mapas do subprojeto GEOBOL-SGAB (Serviço Geológico Sueco) "Avaliação dos recursos minerais do Precámbrico", como parte de um projeto estratégico, visando reabilitar o setor de mineração boliviano, com apoio financeiro do Banco Mundial, da Agência Sueca de Cooperação para o Desenvolvimento Internacional (SIDA) e do próprio Governo de Bolívia (representado pelo Serviço Geológico de Bolívia, GEOBOL). Nesse particular, o doutorando foi co-autor de dois boletins produzidos neste subprojeto. O primeiro deles, baseado em sensoriamento remoto com apoio geofísico, descreveu a seqüência vulcano-sedimentar que forma o Grupo Naranjal na área de San Ramón (Witschard et al., 1993). O segundo é um trabalho de mapeamento geológico no Distrito San Ramon e sua principal contribuição é a descrição pormenorizada da seqüência vulcano-sedimentar do Grupo Naranjal que forma um cinturão de rochas verdes ao qual associa-se mineralização de ouro. Produziu-se um mapa temático para a área de San Ramon, com a combinação de

dados radiométricos e magnéticos, dando um importante subsídio à interpretação das estruturas mapeadas no terreno (Adamek et al., 1996). O doutorando foi também responsável por uma das brigadas que atuaram no mapeamento da região de San Diablo e Cerro El Encanto (escalas 1:250.000 e 1:100.000) em 1991-1995; projeto este apoiado por levantamento aerogeofísico com suporte financeiro do Banco Mundial SERGEOMIN (ex GEOBOL) com a publicação dos respectivos mapas. Este levantamento aerogeofísico, utilizando pela primeira vez os métodos magnetômetria, radiometria e VLF (Witschard et al., 1993), incluiu uma região mais extensa desde San Ramon até a região de San Javier, Concepción e Ascensión de Guarayos. Posteriormente, a Sanders Geophysics Limited em 1994 continuou o levantamento geofísico em seis setores Huachi, Las Petas-San Matias, Santo Corazón, San Ignacio e San Simon (Figura 3.2).

Mais recentemente, no âmbito do Programa de Promoção do Investimento em Mineração, realizado pelo Departamento de Cooperação Técnica para o Desenvolvimento (DCTD), do PNUD (Nações Unidas) e o Serviço geológico da Bolívia (GEOBOL), foram elaborados modelos geológicos sobre áreas com potencial mineral de metais preciosos para fins de promoção de projetos de exploração mineral. Nesse sentido Lopez e Bernasconi (1988) reconheceram a faixa de "xistos verdes" (Grupo San Ignacio), no Distrito San Ramón como potencialmente favorável para concentrações econômicas de ouro. Esta faixa de baixo grau metamórfico tem um comprimento superior a 150 km e uma largura de 50-60 km, e uma orientação NNW.

Por fim, posteriormente ao Projeto Precámbrico, alguns trabalhos de exploração em San Simon incluíram mapeamento geológico, com apoio de dados geofísicos (VLF-EM e IP), para melhor definir as zonas de cisalhamento mapeadas regionalmente. Na oportunidade destes trabalhos foram realizadas amostragem geoquímica de solo, rocha e laterita, bem como escavado um túnel de 700 metros cortando as estruturas de mineralização de ouro e ainda perfurados cerca de 39.000 metros para interpretação das estruturas (Ticlla-Colque, 2000; Moisy e Ticlla-Colque, 2002, Arce Burgoa, 2007).

Figura 3.2 Mapa da geofísica aerotransportada

Na década de 2000 foram retomados os trabalhos científicos na Bolívia, agora contando com as primeiras determinações de idade U-Pb SHRIMP (Boger et al, 2005), de modo a melhor definir os eventos acrescionários anteriormente delineados com base nos Rb/Sr e K/Ar. Neste trabalho são apresentadas implicações tectônicas em relação ao chamado Craton Paraguá e aos eventos San Ignacio e Sunsás tendo por base comparações com a Laurentia. Boger et al, (2005) estabelecem claramente que o Complexo de Gnaiss Chiquitania e o Grupo de Xistos San Ignacio são derivados de fontes de 1765 Ma e que não foram depositados antes de 1690 Ma. Consideram a colocação da Suíte Lomas Manechis entre 1690 - 1660 Ma e fizeram um giro na cronoestratigrafia considerando a Suíte Lomas Manechis mais jovem do que as duas unidades anteriores. Com os dados U-Pb em zircão magmático e metamórfico restringem a orogenia San Ignacio no período 1340 - 1320 Ma. Interpretam as dobras na área de San Ignacio formadas durante a idade Sunsás, no entanto Litherland et al. (1986) estabeleceram este tipo de estruturas dentro do Complexo de Gnaiss Chiquitania.

O embasamento do Bloco Paragua não tem equivalentes em tempo em Rondônia e Mato Grosso. Para estes autores o Bloco Paraguá e o Bloco Arequipa - Antofalla acrecionaram-se ao Cráton Amazônico durante a orogenia Sunsás. No entanto são propostos modelos distintos, por exemplo, Cordani e Teixeira (2007) como apresentado por Boger et al. (2005, cf. Figura 6), consideram que a colisão do bloco Paraguá (nosso terreno intra-oceânico de acreção Pensamiento-Rio Alegre), com a parte sul da província RNJ já cratonizada originou a orogenia Rondoniana-San Ignacio. Para estes autores o rifting dos grupos Aguapeí e Nova Brasilândia correspondem ao colapso orogênico final dentro da província RSI. A ativação posterior deles poderia ser um reflexo das colisões sucessivas, que produziu a faixa Sunsás. A sutura final seria, mais propriamente, entre a Amazônia e Laurentia, com o Sunsás como parte da faixa Grenville. Nos últimos 4 anos novas contribuições científicas foram publicadas, refinando o conhecimento geológico dos terrenos pré-cambrianos do Oriente Boliviano [Santos et al. (2008), Matos et al. (2009), Bettencourt et al. (2010), Teixeira et al. (2010)]. Estes quatro trabalhos são decorrência direta do

desenvolvimento do projeto de Doutorado do presente autor e, como tal, serão objeto de comentários pertinentes no Capítulo 6.

5. METODOLOGIA

Para esta etapa foram consultados os relatórios acompanhados de mapas do projeto GEOBOL-BGS (British Geological Survey) "Proyecto Precámbrico" que foram apenas para uso interno do pessoal de GEOBOL e não para publicação. Foram compilados os 21 relatórios e mapas de levantamento geológico em escala 1: 250.000 e o relatório das determinações de idade (Darbyshire, 1979). Também foram estudados os artigos produzidos pela contraparte britânica sobre vários aspectos da geologia da região (Berrangé, 1982; Litherland e Bloomfield, 1981). Entre os relatórios internos mais importantes foram consultados os trabalhos acerca das complexas teorias e principais modelos tectônicos estabelecidos durante o levantamento cartográfico (Klinck e Litherland, 1982) e Litherland e Klinck (1982). Foram consultados as cadernetas e os dois trabalhos do Projeto "Avaliação de Recursos Minerais do Pré-Cambriano" que fazia parte do Projecto de Reabilitação do Setor de Mineração, apoiados pelo Banco Mundial e a assistência técnica do Serviço Geológico da Bolívia, GEOBOL e o SGAB (Sweden Geological Survey). Também foram revistos os trabalhos do Programa de Promoção de Investimentos e Mineração realizado pelo Departamento de Cooperação Técnica para o Desenvolvimento (DCTD), do PNUD e do Serviço Geológico da Bolívia (GEOBOL), que prepararam informações de modelos geológicos de áreas potenciais para a mineração de metais preciosos para ser promovido como possíveis alvos para investimento em projetos exploração mineral (Lopez e Bernasconi 1988). Finalmente foi feita a interpretação de imagens de satélite de livre disponibilidade na internet. Neste caso, o Google Earth foi de grande importância para o estudo das feições estruturais e a compreensão da geologia da área estudada, uma vez que as técnicas de interpretação foram baseadas na experiência do autor da tese em áreas de pouca floresta como são os Andes bolivianos.

5.1 Trabalhos de campo

A partir dos perfis geológicos realizados e amostragens, os trabalhos experimentais enfatizaram os diferentes sistemas granitóides (unidades

litoestratigráficas regionais) previamente estabelecidos na literatura (Fletcher, 1979; Litherland et al., 1986; adamek et al., 1996), com o intuito de definir suas respectivas idades e estudar as características geoquímicas e isotópicas. Em paralelo, foram realizadas comparações com dados publicados em unidades paleo- e mesoproterozoicas em Mato Grosso e Rondônia para subsidiar as interpretações sobre a evolução geológica regional. Em adição, a aplicação de aspectos estruturais, com ênfase no entendimento da cinemática regional do Pré-Cambriano Boliviano, foi útil na interpretação de mapas aeromagnéticos e aero-radiométricos.

Várias foram as visitas efetuadas à ex-GEOBOL, Santa Cruz com o intuito de pesquisar as amostras do Proyecto Precámbrico. Contudo, infelizmente esta Instituição pioneira da geologia na Bolívia não tem recursos e apoio do governo para realizar trabalhos de cartografia geológica.

A respeito dos trabalhos de campo, as amostras do Complexo Granitóide Pensamiento (21 amostras) foram enviadas a São Paulo desde a fronteira San Matias (Bolívia) - Curicha (Brasil). O veículo usado nesta campanha foi de SERGEOMIN, Santa Cruz (ex GEBOL). A quilometragem total atingiu 2.362 desde Santa Cruz, Santa Rosa de Roca, Piso Firme, San Ignacio de Velasco, San Matias e Santa Cruz. O transporte desde Curicha (Brasil) até no IGc da USP foi em ônibus comercial. Com uma carta do Diretor do IGc-USP dirigida às autoridades aduaneras de Bolívia e Brasil que indicava o objetivo de pesquisa destas rochas o despacho desde este sítio foi muito simples. Um dos objetivos de uma das campanhas foi amostrar os granitos Sunsás na região entre San Javier e Casa de Piedra feito numa época de chuvas. O aluguel de duas motocicletas conduzidas por pessoal de San Javier permitiu a amostragem; o percurso foi de 80 km por dia.

A logística de campo no Pré-Cambriano Boliviano precisou de aluguel do carro em Santa Cruz. Cada campanha demanda um percurso de 1500 ate 2000 km. As amostras da campanha de dezembro de 2005, totalizando 500 quilos de 44 amostras aproximadamente ficaram em aguardo no SERGEOMIN, Santa Cruz para ser despachadas a São Paulo. Foi necessária a participação pessoal do doutorante para fazer o envio por trem Santa Cruz até Quijarro no extremo este de Bolívia, fronteira com Corumbá no estado de Mato Grosso do Sul. O expediente de passar a fronteira na

Aduana foi complicado pelo intenso tráfego. O envio desde Corumbá até a Terminal de Tiete foi em ônibus. Nesta terminal contratou-se um táxi e levou-se as amostras até o IGc, na USP.

O trabalho de campo constou do mapeamento dos terrenos do Pré-Cambriano do oriente da Bolívia baseadas nos trabalhos anteriores do autor da tese na cartografia realizada com GEOBOL e as empresas de exploração por minérios na década dos anos 90. A maior atenção foi dedicada às folhas Huanchaca, Monte Verde, Puerto Villazón, Perseverancia (Figura 3.1) onde afloram as unidades do Complexo Granitóide Pensamiento. Nesta área remota, a logística viu-se dificultada pela cobertura de vegetação e o acesso difícil. Os trabalhos de campo ao sul do Complexo Granitóide Pensamiento foram concentrados nas folhas geológicas 1: 250.000 Concepción, San José de Chiquitos, Santo Corazón-Roboré tendo sido obtidos exemplares representativos das suítes granitóides, fazendo particular ênfase à orogenia San Ignacio.

As amostras de rocha estão localizadas em Coordenadas com GPS utilizando-se o Sistema Geodésico de Referencia South American Datum- SAD 56 (ver Apêndice A). Os afloramentos descritos contém um registro fotográfico centrado na composição mineral, estrutura, magmatismo, metamorfismo e deformação. Em adição, foi percorrida a sequência mais pesquisada no Pré-Cambriano boliviano, o Grupo Naranjal (rochas metavulcano-sedimentares), na região de San Ramón-Guarayos (Biste e Gourley, 2000). Ali ocorrem mineralizações auríferas associadas a BIF e cherts de origem exhalativo, posteriormente afetadas por zonas de cisalhamento e cujo depósito é Puquio Norte que produzia ao fim da década de 90 aproximadamente 250.000 onças de ouro (R. Saenz Paz, comunicação verbal). A amostragem desta sequência volcano-sedimentar será direcionada para geocronologia em zircão detrítico pelo método ICPMS-LA.

Finalmente, foram também amostrados granitos intrusivos (e.g., San Pablo, Tauca e Santo Corazón) associados à Zona de Cisalhamento San Diablo (área de San José de Chiquitos). Ali também ocorrem mineralizações auríferas associadas como o depósito de Cu-Au de Don Mario, originado a partir de soluções hidrotermais provenientes de

uma fonte granítica, depositadas sob controle litológico-estrutural e posteriormente afetadas por zonas de cisalhamento.

Tabela 1. Etapas de campo realizadas no Pré-Cambriano Boliviano.

Nº	Data	Folha	Dias	Am.	Percorso	Unidades amostradas	Part.
1	De 31/07/04 até 11/08/04	Concepción, San Ignacio	12	20	Santa Cruz, San Ignacio	San Ramón, San Javier, Refugio, San Rafael	RM
2	De 20/07/05 até 30/07/05	Concepción	11	15	Santa Cruz, San Ignacio, Piso Firme	CGP: La Junta, San Martín, Porvenir, Diamantina	RM
3	De 10/12/05 até 17/12/05	Concepción Monte Verde	8	44	Santa Cruz, San Javier, Comunidad Turunapé, Lomerío, Guarayos	Lomas Manechis, Chiquitanía, Limonal, La Cruz, Guarayos	WT, MCG, RM, GVM
4	De 10/10/06 até 17/10/06	Huanchaca, San José de Chiquitos	8	10	Santa Cruz, San Javier, Santa Rosa de Roca Florida, San Pablo	S. Diablo, S. Pablo, El Carmen, Chiquitania	JSB, MCG, BLP, RM, GVM, VM, TR
5	De 12/10/07 até 21/10/07	Huanchaca San Ignacio	10	5	Santa Cruz, San Javier, Santa Rosa de Roca Florida, Campamento	Granito Discordancia, Sill Huanchaca, Campamento	RM, VM, PB
6	De 08/02/08 até 14/02/08	Concepción Monte Verde	7	10	Santa Cruz, San Javier, Rio Blanco	Las Maras, Santa Rosa, Cachuela Suarez, Turunapé e Atadijo	RM, GVM
7	De 11/10/08 até 20/10/08	San José de Chiquitos e Santo Corazón	10	36	Santa Cruz, San José, Roboré, Santo Corazón	Taseoro, S. Diablo, S. Pablo, S. Juan, Tauca, Chaquipoc, Bocamina, Murciélagos, Boquí, Correrica, Sto. Corazón, Rincon Del Tigre e Don Mario	RM, MCG, GVM, RF
8	De 27/01/10 até 30/01/10	Concepción, San Ignacio	4	11	Santa Cruz, San Javier, Moscu, San Ignacio, Lomas Maneches	Moscu, Cachuela, Chiquitanía, Lomas Maneches	CCGT, JM, AM, RM

Participantes (Part.)

Brasil: WT= Wilson Teixeira; MCG= Mauro Cesar Gerales; JSB= Jorge S. Bettencourt; BLP= Bruno L. Payolla
 Bolivia RM=Ramiro Matos; GVM= Gabriela Vargas Mattos

Estudantes UMSA VM=Vladimir Machaca, TR= Tatiana Rojas; PB= Patricia Bravo; RF= Rodrigo Fernandez.

No total, mais de sete mil quilômetros foram percorridos no projeto de Tese, abrangendo praticamente todas as unidades do Pré-cambriano Boliviano, inclusive em áreas remotas de acesso restrito (parques nacionais tombados). Trata-se, portanto, de uma amostragem única e valiosa que deverá continuar a subsidiar inúmeros trabalhos

acadêmicos nos próximos anos, e servirão de base duradoura para colaborações acadêmicas em benefício do progresso geológico da Amazônia.

5.2 Trabalhos experimentais

O desenvolvimento desta tese trouxe importantes benefícios para a comunidade científica interessada no conhecimento geológico do SW do Craton Amazônico pois permitiu a formação de um grupo de pesquisadores desenvolvendo atividades de campo e laboratoriais. Com isso foi possível caracterizar as principais unidades geológicas e boa parte dos plútons granitóides relacionados às orogêneses San Ignacio e Sunsás. Uma volumosa coleção de rochas foi amostrada, visando os estudos laboratoriais (geoquímicos e isotópicos) os quais são apresentados no Apêndice -A.

A par das apresentações dos resultados preliminares obtidos em congressos e eventos, uma tese de Doutorado, (Gabriela Vargas-Mattos) foi defendida no mês de março de 2010 no Instituto de Geociências da UERJ. Do mesmo modo dois bolsistas IC (IGC-USP) foram incorporados no projeto notadamente na geocronologia de corpos granitóides (e.g., granitos Casa de Piedra, Refugio, Las Maras, Limonal, etc.) do Pré-cambriano boliviano.

A aplicação das modernas metodologias e a obtenção de dados geoquímicos foram paralelos a trabalhos complementares duma equipe de pesquisa que definiram a estratégia abrangendo uma enorme área em branco de datações, a qual a través do tempo permitiu um refinamento da área com as mais modernas metodologias (U-Pb, Sm-Nd) que derivou na elaboração do mapa geológicos mais precisos.

Petrografia

As amostras coletadas nas diferentes etapas de campo representam as unidades do Complexo Lomas Manechis, Complexo Gnáissico da Chiquitania, Grupo de Esquistos San Ignacio, os granitóides da Suíte Granítica San Ignacio que formam o Complexo Granítico Pensamiento na zona setentrional e os granitos dispersos ao sul deste complexo. As amostras foram analisadas ao microscópio óptico com a

finalidade de observar texturas, estruturas e associações minerais diagnósticas dos eventos ígneos e metamórficos regionais que permitiram a interpretação da geoquímica e geocronologia. As amostras de gnaisses e granitos (38 lâminas) foram cortadas em fatias de 1-2 cm de espessura e submetidas à coloração para distinção dos feldspatos sódicos e cálcicos. Posteriormente, realizou-se as estimativas modais que permitiram a classificação no diagrama QAP de Streckeisen.

Geoquímica (Elementos maiores, menores e terras raras)

As amostras representativas das unidades granitóides coletadas nas etapas de campo foram separadas em dois grupos: as rochas do Complexo Granitóide Pensamiento e as rochas granitóides aflorantes ao sul deste Complexo. Foram obtidas análises de elementos maiores, traços e terras raras; os elementos maiores analisados (em óxidos) foram: SiO₂, Al₂O₃, MnO, MgO, CaO, Na₂O, K₂O, TiO₂, P₂O₅, e Fe₂O₃; os elementos traços analisados foram Ba, Ce, Ga, Nb, Nd, Pb, Rb, Sr, Th, U, V, Zr. As técnicas analíticas empregadas incluíram fluorescência de raios X no Laboratório de Química do IGc-USP. Os elementos terras raras foram analisados com espectrômetro de plasma ARL 3410 sequencial, os elementos analisados foram La, Ce, Nd, Sm, Eu, Gd, Dy, Ho, Er, Yb, Lu. Os dados de química mineral foram tratados com o auxílio do programa para processamento de dados petrológicos Microsoft Excel e no programa Minpet (Richard 1995), e apresentados em diagramas classificatórios e discriminantes e de ambiência tectônica binários.

Geocronologia

Foram empregados três métodos geocronológicos para os estudos das rochas do Pré-cambriano boliviano: U-Pb, Sm-Nd e Rb-Sr. Para a sistemática U-Pb em cristais de zircão foram utilizadas diferentes técnicas: SHRIMP, TIMS e LA-MC-ICP-MS, sendo que os grãos de zircão foram separados usando técnicas convencionais.

Os granitos La Junta (amostra LJ20512), San Martín (CA0509), Diamantina (CP30507), La Cruz (LC0558) e San Andrés (SA0404) foram datadas por U-Pb SHRIMP. Os zircões foram documentados com imagens de luz transmitida e refletida, bem como catodoluminescência (CL) com o intuito de revelar as suas estruturas internas e externas. Os granitos Refugio (amostra SR83) e Las Maras (amostra LM81) foram analisados pelo método U-Pb TIMS, ao passo que os granitos San Pablo (amostra SP0601), Talcoso (amostra BO418) e Limonal (amostra MT544) foram analisadas por U-Pb LA-MC-ICP-MS. A Tabela 2 a seguir é um resumo das análises do projeto no IGc da USP, como parte de doutorado do aluno Ramiro Matos.

Tabela 5.2 Resumo das análises e metodologias utilizadas na área de estudo.

Afloramentos descritos	Amostras	Petrografia	Coloração de feldspatos	Análises químicas	U-Pb SHRIMP zircão	U-Pb TIMS	U-Pb ICP-MS-LA	Rb-Sr RTO	Sm-Nd RTO
120	89	43	38	42	7			32	40
		401, 403, 404, 406, 407, 408, 412	401, 403, 404, 406, 408, 412 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 518, 524, 531, 532, 533, 534, 535, 538, 545, 546, 549, 550, 551 552, 553A, 553B 558,	401, 403, 404, 406, 407, 408, 412 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516 518, 524, 531, 532, 533, 535, 537, 538, 546, 549, 550, 551 552, 553A, 553B, 554, 556, 558, PNK71, PNK72	507, 509, 512, 558, 404, 534, 518	413, 418 LM81, SR83	544, 418 601	403, 404, 406, 408, 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516 531, 532, 533, 534, 535, 546, 547, 550, 552, 553A, 553B, 558	401, 403, 404, 406, 408, 412 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516 518, 528, 531, 532, 533, 534, 535, 538, 546, 547, 549, 550, 551 552, 553A, 553B, 554, 558

PRODUÇÃO CIENTÍFICA COMENTADA

Neste capítulo faremos uma breve reflexão acerca do conteúdo de 5 artigos publicados em periódicos nos quais houve a participação do doutorando como autor e co-autor. Também apresentamos uma proposta do cenário evolutivo com base no avanço do conhecimento e na caracterização de novas unidades geológicas pré-cambrianas no Oriente Boliviano. Também são anexados outros produtos gerados (resumos apresentados) bem um manuscrito em preparação a ser submetido a um periódico internacional, este último apresentando a visão atual do autor sobre a evolução mesoproterozoica da área de estudo e implicações paleocontinentais.

Com o início do projeto de doutorado do autor, no ano de 2005, foi possível articular uma série de cooperações com pesquisadores e instituições brasileiros, possibilitando avançar no conhecimento geológico do Pré-Cambriano da Bolívia Oriental. Estas atividades, em parte apoiadas financeiramente pelo Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), culminaram com novos e importantes dados geológicos, geocronológicos e geoquímicos que foram examinados nesta Tese. Ressalte-se que parte desta nova etapa de conhecimento resultou do esforço pessoal do autor por meio da divulgação sistemática do conhecimento geológico e geocronológico da Bolívia em Simpósios Regionais no Brasil e no exterior, a partir de 2003, através de conferências convidadas, trabalhos orais e painéis: 5SSAGI; 7º Simpósio da Geologia da Amazônia; 33º IGC; Congreso Geológico da Bolivia; 45 Anos de Geocronologia (Matos et al., 2006; Matos et al., 2008; Matos et al., 2009; Matos et al., 2010).

Em várias oportunidades, associadas aos eventos científicos, foram organizadas e lideradas pelo autor excursões para reconhecimento das unidades geológicas regionais aos participantes destes eventos. Em adição foram incrementadas pesquisas conjuntas em diferentes segmentos do território boliviano, atividades que permanecem até hoje com colegas da UFMT, UERJ e USP. Esta estratégia de ação conduziu a uma efetiva integração da geologia do Pré-Cambriano nos projetos de pesquisadores brasileiros, resultando no incremento de dados analíticos essenciais para o avanço do conhecimento da área de estudo objeto do Doutorado.

A seguir, são apresentados comentários e críticas pertinentes aos trabalhos completos publicados, a partir de 2008.

6.1 Santos, J. O. S., Rizzotto, G.J., McNaughton, N. J., Matos, R., Hartmann, L. A., Chemale Jr., F., Potter, P. E., Quadros, M.L.E.S, 2008. *Age and autochthonous evolution of the Sunsás Orogen in West Amazon Craton based on mapping and U-Pb geochronology. Precambrian Research, 165, 120-152.* (Apêndice D)

A amostragem das rochas do Pré-Cambriano da Bolívia reportada neste trabalho foi realizada por João Orestes Santos durante a primeira excursão à área, organizada pelo doutorando, na ocasião do Simpósio Geologia do Centro-Oeste ocorrido em Cuiabá de 2003. Nesta publicação os primeiros dados U-Pb e Sm/Nd obtidos na Austrália (Perth) foram compartimentados em duas províncias: províncias Rondônia-Juruena (1,84-1,54 Ga) e Sunsás (1,46-1,11 Ga).

Para a província Sunsás, em um cenário integrado com a contraparte brasileira do SW do Craton Amazônico, foram propostas quatro orogenias, com base nas idades U-Pb SHRIMP e correlações geológicas: Santa Helena (1,46-1,42 Ga), Candeias (1,37-1,32 Ga), San Andrés (c. 1,27 Ga) (pelo povoado San Andrés, a oeste de Concepción) e Nova Brasilândia (1,18-1,11 Ga). No entanto, este modelo proposto não concorda com o cenário clássico das províncias Rio Negro Juruena, Rondoniana-San Ignacio e Sunsás Aguapeí (e.g., Cordani e Teixeira, 2007), cada um delas caracterizada por uma etapa de crescimento crustal e cratonização subsequente. Cabe também notar que Litherland et al. (1986) postulou um período estável de ~ 300 Ma separando as orogenias San Ignacio e Sunsás descritas na Bolívia, fato também registrado claramente pela ocorrência de rochas sedimentares não deformadas de idade Sunsás (serrania Huanchaca), depositadas discordantemente sobre o embasamento, como descrito por Litherland e Power (1989). Estas considerações sugerem que a proposta de uma orogênese alóctone “Sunsas” com duração de 400 milhões de anos, conforme a defendida, não se sustenta com base nos dados disponíveis no caso do território boliviano.

De outra parte, o granodiorito San Ramón, datado originalmente por Santos et al (2008) representa um novo evento acrescionário identificado pela primeira vez no

escudo Pré-Cambriano da Bolívia. Trata-se de um corpo intrusivo de c. 35 km², mesocrático, inequigranular, pertencente à série de alto potássio, com caráter peraluminoso. A rocha está levemente foliada e hospeda zonas de cisalhamento na direção NNW. Para o plúton San Ramon foram obtidas idades SHRIMP U- Pb similares em zircão e titanita de 1429 ± 4 Ma, com idade T_{DM} de 1,7 Ga, estabelecendo, portanto, um episódio distinto e anterior ao Complexo Granitóide Pensamiento (a ser comentado adiante) que tem grande extensão territorial no chamado Craton Paraguá. Os parâmetros petrogenéticos ($\epsilon_{Hf(t)}$ entre + 3,49 e +5,47) do plúton San Ramon implicam num evento magmático juvenil, porém sua dimensão geográfica ainda depende de estudos adicionais embasados em geocronologia U-Pb.

6.2 Matos, R., Teixeira, W., Geraldés, M. C., 2008. *El granito diamantina: evidencia isotópica y química de magmatismo de arco en el Complejo Pensamiento, Provincia Rondoniana-San Ignacio, Precámbrico de Bolivia oriental. Revista del institutode Investigaciones Geológicas y del Medio Ambiente. Año 2, Diciembre de 2008, p. 5-11.*

Neste trabalho foi enfatizado o Granito Diamantina como exemplo de uma intrusão pos-cinemática do Complexo Granitóide Pensamiento. Quatro amostras do granito apresentam conteúdo de SiO₂ de 72 a 75wt%, indicando caráter calcioalcalino, e composição peraluminosa. No diagrama de multielementos as amostras apresentam anomalias negativas de Sr, P e Ti e interpretam-se devido á fracionamento da mica, feldspato, apatita e titanita. Uma datação U-Pb SHRIMP do granito Diamantina produz uma idade de 1340 ± 20 Ma. O Granito Diamantina apresenta 4 idades modelo T_{DM} variáveis entre 1.6 e 1.9 Ga (três razões $f_{Sm/Nd}$ entre -0.50 e -0.42 e uma razão de -0,25), e $\epsilon_{Nd(1.33Ga)}$ de +0.4 a -1.2, que indicam mistura de material derivado do manto e material crustal.

6.3 Matos, R., Teixeira, W., Geraldés, M. C., Bettencourt, J. S., 2009. *Geochemistry and Nd-Sr Isotopic Signatures of the Pensamiento Granitoid Complex, Rondonian-San Ignacio Province, Eastern Precambrian Shield of Bolivia: Petrogenetic Constraints for a Mesoproterozoic Magmatic Arc Setting. Geologia USP, Série Científica 9, 2, 89-117.*

Este trabalho sintetiza os estudos realizados durante uma etapa intermediária da Tese no Complexo Granitoide Pensamiento. Este ocorre na porção norte do Pré-Cambriano Boliviano, estando tectonicamente associado à evolução da província Rondoniana San Ignacio (1,56-1,30 Ga) (Bettencourt et al. 2010). Suas rochas são classificadas em dois conjuntos: plutons sin- a tardi-cinemáticos e tardi- a pós-cinemáticos, com base nas inferências geológica, geocronológicas e características geoquímicas. Os plutons considerados sin- a tardi-cinemáticos representam uma maior área no complexo e mostram idades entre 1373-1347 Ma, os valores de $\epsilon_{Nd(t)}$ de +1,8 e -4,3 mostra mistura de material juvenil com crustal. No entanto os tardi- a pós-cinemáticos com valores de $\epsilon_{Nd(t)}$ em geral positivos mostram uma maior participação mantélica. Estes granitos foram estudados devido a que eles são os mais representativos do Complexo. Os resultados obtidos interpretados em conjunto com os dados geológicos de unidades contemporâneas na contraparte brasileira reforçam a existência de um arco magmático de idade mesoproterozoica que finalizou a evolução acrescionária da província Rondoniana-San Ignacio.

6.4 Bettencourt, J.S., Leite Jr., W.B., Ruiz, A. S., Matos, R., Payola, B.L., Tosdal, R.M., 2010. The Rondonian- San Ignacio Province in the SW Amazonian Craton: An overview. *Journal of South American Earth Sciences*, 29, 28-46.

Esta síntese reúne, pela primeira vez, as concepções tectônicas consensuais de pesquisadores brasileiros e do doutorando, embasados na correlação detalhada dos dados geológicos e geocronológicos do SW do Craton Amazônico, incluindo a ambiência tectônica. A revisão da evolução tectônica é apoiada pela definição de limites entre os terrenos, considerando que o terreno Paraguá separou-se da província Rio Negro-Juruena no lapso temporal 1,50-1,40 Ga. Fica implícito que o embasamento metamórfico consiste do Complexo Granulítico Lomas Manechis, o Complexo de Gnaiss Chiquitania e o Grupo de Xistos San Ignacio. Divide-se a evolução da província Rondoniana- San Ignacio em dois períodos: 1560 - 1370 e 1370 - 1300 Ma. O primeiro intervalo temporal está caracterizado por eventos diacrônicos no tempo e espaço; o segundo período corresponde à subducção de litosfera oceânica (orógeno San Ignacio) devido à colisão de um microcontinente, o terreno Paraguá contra um continente

(Craton proto-Amazônico). A colisão entre o Bloco Paragua e o Cráton Amazônico construiu a província Rondoniana-São Ignácio, resultando na formação do orógeno Rondoniano San Ignacio (1,56-1,30 Ga). Particularmente a duração temporal proposta por Bettencourt et al. (2010) para o orógeno San Ignácio (1370-1320 Ma) desenvolveu-se até 1275 Ma uma vez que o granito San Andrés tem esta idade, apresentando-se porém obliterado pela deformação Sunsás. Por outro lado, defendemos que o termo Complexo Pensamiento seja restrito à parte setentrional do terreno Paragua, uma vez que se trata de um domínio preservado da deformação Sunsás, ao contrário do conjunto que aflora mais ao sul, apesar da toponímia local San Ignacio.

Em relação ao terreno Paraguá, o autor prefere empregar o termo “bloco Paragua” (cf. Boger et al. 2005) devido ao fato que este termo é mais apropriado para simbolizar o seu comportamento alóctone durante o Paleo e Mesoproterozoico, quando atuou como substrato dos granitóides da suíte San Ignacio. A cratonização deste bloco (e da província Rondoniana-San Ignácio) ocorreu entre 1,30-1,25 Ga, conforme sugerem os dados Rb/Sr e K/Ar regionais e evidências geológicas.

6.5 Teixeira, W., Geraldes, M. C., Matos R., Ruiz, A. S., Saes, G., Vargas-Mattos, G., 2010. A review of the tectonic evolution of the sunsás belt. SW Amazonian Craton. *Journal of South American Earth Sciences*, 29, 47-60.

Este trabalho, tratando da evolução terminal do Craton Amazônico, enfatiza a natureza alóctone e colisional do orógeno Sunsás (1100-900 Ma) (concepção clássica). A faixa dobrada Sunsás com base nos dados geocronológicos mais recentes produziu plutonismo importante no período entre 1100 e 910 Ma. No território boliviano está marcada por frentes tectônicas bem definidas (sentido sinistral) demonstradas em três escalas de observação (micro, meso e macroescala) com idade aproximada de 1080 - 1050 Ma. As intrusivas plutônicas associadas ao evento Sunsás são agrupadas tentativamente em magmatismo sin- a tardi tectônico. Os primeiros estão relacionados com as zonas de cisalhamento e os segundos cortam a foliação típica de idade Sunsás.

No entanto os valores K-Ar em uma muscovita nos xistos Cristal do frente San Diablo, uma muscovita de um pegmatito que corta o granito El Carmen (972 ± 21) e uma biotita no granito San Pedro com 968 ± 21 Ma (Litherland et al. 1986) sugerem a

época de resfriamento para a orogenia Sunsás. O modelo de deformação regional de Teixeira e colaboradores propõe que a colisão Sunsás deu-se de WSW para ENE contra o Bloco Paraguá, com a estabilidade tectônica final ocorrendo em torno de 950 Ma. Neste artigo os autores não destacaram o significado tectônico das intrusões básicas-ultrabásicas, como o complexo Rincón del Tigre que, em nossa opinião representa um magmatismo associado a etapa final da evolução Sunsás. Na verdade a idade reportada para este complexo (cerca 992 Ma), portanto mais jovem que os pulso felsico (1100-1070 Ma) e uma idade mínima referencial.

Em termos paleotectônicos, a faixa dobrada Sunsás representa eventos extensivos e compressivos que constituem excelentes testemunhas dos estágios mais jovens da evolução geológica entre a Amazônia e a Laurentia (ver comentários adicionais adiante).

6.6 COMENTÁRIOS SOBRE O ESTADO DE ARTE DO PRÉ-CAMBRIANO BOLIVIANO

A crosta pré-cambriana na possui evolução tectônica perfeitamente comparável com os terrenos policíclicos pertencentes às províncias Rio Negro-Juruena e Rondoniana-San Ignacio, nos estados de Rondônia (Bettencourt et al., 1999; Payolla et al., 2002; Rizzotto & Quadros, 2007) e Mato Grosso (Geraldes et al., 2001), embora o nível de conhecimento geológico e geocronológico regional seja muito heterogêneo e algumas vezes incipiente. Em função disso, ainda persistem muitas lacunas no tocante ao quadro litoestratigráfico, em especial em relação às seqüências supracrustais e suítes intrusivas. Do mesmo modo há dúvidas no tocante à caracterização espaço-temporal dos diferentes eventos tectonomagmáticos, o que dificulta o estabelecimento de modelos evolutivos. Nesse sentido o mapa geológico integrado (Apêndice C) apresenta modificações na cartografia dos corpos graníticos das orogêneses San Ignacio e Sunsás, em especial na região de San Ramon. Em adição foram realizadas modificações na cartografia na região sul do front tectônico San Diablo, com destaque para as estruturas que refletem a tectônica transcorrente geral. Estas questões encontram-se ilustradas na Figura 6.3 (no caso da cartografia dos granitos), no mapa

do Apêndice C e no texto adiante quando se comenta a tectônica dúctil da orogenese Sunsas no front San Diablo.

Isto posto, os estudos desenvolvidos nesta Tese permitiram importantes avanços em termos do conhecimento evolutivo, ilustrados pela caracterização de novas unidades geológicas, conforme sintetizado abaixo e no mapa do Apêndice C.

6.6.1. Granito Correreca

Recentemente no 7º SSAGI em Brasília foram apresentados os dados isotópicos deste plúton, que ocorre na área oeste de Rincón del Tigre e Santo Corazón. A imagem de satélite apresenta um terreno baixo com uma tênue foliação NNW, extensamente coberto por floresta. Segundo Mitchell (1979) o corpo está sobreposto ao norte pelos sedimentos do Grupo Sunsás, a oeste pelo Grupo Boquí e ao sul pelo Grupo Murciélagos. A leste o plúton faz contato de falha com o Complexo Granitóide Santo Corazón. A geoquímica mostra uma afinidade peraluminosa, de médio potássio, compatível com ambiente tectônico de arco.

Duas amostras do granito Correreca forneceram idades ^{207}Pb - ^{206}Pb (evaporação) de 1925 ± 32 Ma e 1894 ± 13 Ma que são comparáveis dentro do erro (Vargas Mattos, 2010), sendo que as idades T_{DM} correspondem a 2,81 e 2,90 Ga (valores de ϵ_{Nd} de -8,5 e -9,4). A idade de cristalização é significativamente mais antiga que o valor U-Pb de 1818 Ma para o protólito (núcleo de zircão) do Complexo Granulítico Lomas Manechis (Santos et al., 2008), e revelam a presença pela primeira vez de crosta paleoproterozoica em um trato territorial da Bolívia (região de Santo Corazon). Esta idade paleoproterozoica indicaria que a área sul da Zona de Cisalhamento San Diablo, denominada terreno San Pablo por Saes et al. (1992), seria um terreno alóctone com uma história geológica distinta.

6.6.2. Suíte Yarituses

Os dados geocronológicos U-Pb SHRIMP, TIMS e ablação por laser-ICPMS obtidos indicam a formação desta suíte granítica (segundo a tribo Yarituses que ocupa

a área de San Javier, onde estes corpos afloram) no lapso temporal entre 1673 a 1621 Ma, portanto comparáveis as idades U-Pb reportadas para a suíte granítica Lomas Maneches de Boger et al. (2005). Os dados de campo e imagem de satélite mostram que os granitos desta suíte não são apenas sills, como mencionado por Boger et al. (2005), (ver mapa do Apêndice C). Este fato induziu o presente autor a introduzir o termo Suite Yarituses como uma nova unidade regional, distinguindo-a da clássica suíte Lomas Manechis. Ao mesmo tempo, mantém-se aqui a denominação Complexo Granulítico Lomas Manechis de Litherland et al. (1986), como uma unidade distinta mais antiga com base na idade magmática U/Pb para um gnaiss granulítico de 1818 ± 13 Ma na área de San Matias (Santos et al., 2008). Ressalta-se, porém, que o granito Correraca (idades Pb-Pb em zircão de 1925-1894) é a rocha mais antiga dentro do Pré-cambriano Boliviano(ver acima).

Em resumo, a suite Yarituses compreenderia, com base no conhecimento atual, os granitos La Cruz, Refugio e San Pablo que foram identificados geocronologicamente nesta tese.

Granito La Cruz

Este corpo aflora 15 km ao nordeste de San Ramón, e constitui dois corpos de forma aproximadamente sigmoidal devido à deformação Sunsás, estando intrudidos no Grupo de Xistos San Ignacio. O granito La Cruz (amostra LC0558) é um sienogranito leucocrático, de cor rosa pálido, com escassa biotita como o mineral máfico. A textura dominante é alotriomórfica granular com o feldspato potássico pertítico caracterizado pelo padrão trançado. Geoquimicamente, a rocha é peraluminosa, calcioalcalina de alto potássio e de caráter intraplaca. Da análise U-Pb SHRIMP de oito grãos de zircão, cinco núcleos plotam sobre o diagrama Concórdia com idade $^{207}\text{Pb}/^{206}\text{Pb}$ de 1673 ± 21 Ma (MSWD = 1,6) (Figura 6.1a), considerada como a idade de cristalização. Esta idade compara-se dentro do erro com duas idades obtidas por Boger et al.(2005) e uma por Santos et al.(2008) para as rochas no intervalo de 1689 to 1663 Ma. A idade modelo T_{DM} é de 1,83 Ga (razão $f_{\text{Sm/Nd}}$ de -0.42), com o ϵ_{Nd} de + 2.1 que indica derivação mantélica.

Granito Refugio

O plúton Refugio distribui-se no lado norte da estrada de San Javier - Concepción (Apêndice C). Santos et al. (2008) reportaram as primeiras idades SHRIMP U-Pb em zircão, monazita e titanita do granito Refugio. Os núcleos de zircões produziram uma idade de $^{207}\text{Pb}/^{206}\text{Pb}$ de 1641 ± 4 Ma; a idade modelo T_{DM} de 1.66 Ga, e $\epsilon_{\text{Nd}(t)}$ +4.06 assinalando sua derivação mantélica e portanto a cristalização da rocha. Para esta Tese, este corpo foi amostrado em dois lugares. A primeira amostra SR83 localiza-se a 8 km leste de San Javier. A rocha é um leucogranito, cor esbranquiçada, sendo que o mineral máfico é a biotita. Os dados isotópicos U-Pb TIMS da amostra SR83 de quatro frações produz três pontos concordantes e um discordante, com uma idade $^{207}\text{Pb}/^{206}\text{Pb}$ de 1673 ± 25 Ma, um MSWD = 36, idade esta comparável à obtida anteriormente para a cristalização do pluton (Figura 6.1b). A segunda amostra RF0408 foi coletada 17 km ao leste de San Javier, na estrada para Concepción. Trata-se de um sienogranito, fracamente foliado, com textura granular hipidiomórfica, cor rosa pálido, afinidade peraluminosa, de alto potássio, e ambiência tectônica de arco vulcânico. A idade modelo T_{DM} é de 1.9 Ga (razão $f_{\text{Sm}/\text{Nd}}$ de -0.49), com valor de $\epsilon_{\text{Nd}t}$ de +0,18. Comparativamente ao dado de Santos et al. (2008), isto indica a presença de diferentes componentes na petrogênese deste plutonismo, neste ultimo caso.

Granito San Pablo

Este granito forma um corpo de 11 km de comprimento por 4 km de largura, exposto 25 km sul de San Antonio de Lomerío (Apêndice C). O pluton é paralelo à Frente San Diablo de orientação WNW, conseqüentemente, o granito está afetado pelo cisalhamento. A rocha é um quartzo monzonito a biotita de cor rosa, e de granulação fina a média. O índice de saturação de alumina mostra uma afinidade peraluminosa, de médio K e ambiente de intraplaca (Vargas Mattos, 2010). Em lâmina delgada apresenta uma textura granular anedral.

a

b

c

Figura 6.1. (a). Diagrama Concórdia: análises U-Pb SHRIMP do granito La Cruz. (b). Diagrama Concórdia: análises U-Pb TIMS do granito Refugio. (c). Diagrama Concórdia: análises U-Pb LA ICP MS do granito San Pablo.

Os zircões do quartzo monzonito San Pablo (amostra SP0601) são prismáticos e na imagem MEV apresentam forma subarredondada. Os resultados U-Pb plotados em diagrama concórdia fornecem uma idade de cristalização de 1621 ± 80 Ma (2σ) (Figura 6.1c). A idade modelo T_{DM} corresponde a 1,7 Ga (razão $f_{Sm/Nd}$ de -0.38), com valor de ϵ_{Ndt} de +3,5 indicando significativa contribuição mantélica na origem da rocha.

6.6.3 Suite Orogênica San Ignacio

Representa a própria orogênese San Ignacio, cujos processos magmáticos, deformacionais e metamórficos estão amplamente representados no Pré-Cambriano da Bolívia, tanto no Complexo Granitóide Pensamiento como ao sul dele, embora parcialmente obliterados pela orogênese Sunsás (e.g., Boger et al., 2005; Bettencourt et al., 2010; Teixeira et al., 2010).

O termo Complexo Granitóide Pensamiento (Litherland et al., 1986) compreende um conjunto de rochas granitóides no setor norte do Pré-Cambriano boliviano (ou Bloco Paraguá) que não foi afetado pela orogenia Sunsás. Com base em evidências geológicas e isotópicas (ver abaixo), as rochas deste Complexo devem ser separadas dos granitóides do setor sul que ocorrem de modo disperso dentro do embasamento. O plutonismo orogenético é composto de volumosas massas graníticas, que acompanharam processos metamórficos com fusões localizadas de rochas do Complexo Lomas Manechis e gnaisses Chiquitania. A geoquímica em rocha total indica uma composição em geral peraluminosa, subalcalina de alto K, compatível com ambiente de arco magmático.

Datações SHRIMP em zircão dos plútons San Martín e La Junta considerados sin a tardi-cinemáticos, situados na parte setentrional do bloco Paragua, produziram 1373 ± 20 Ma e 1347 ± 21 Ma respectivamente, com idades modelo T_{DM} entre 1,7 e 2,0 Ga, (La Junta quatro razões $f_{Sm/Nd}$ entre -0.50 e -0.42 e San Martín uma razão de -0,28) e valores de ϵ_{Ndt} entre +1,8 e -4,3. Assim também os plutons Porvenir, San Cristobal e Piso Firme, que são considerados tardi a pos-cinemáticos, têm idades T_{DM} entre 1,6 e 1,7 Ga (razões $f_{Sm/Nd}$ entre -0,31 e -0,25) e valores de ϵ_{Ndt} entre +2,7 e +1,5, o que corrobora uma origem em arco magmático. O pluton Diamantina, de natureza tardi- a

pos-cinemático, possui uma datação SHRIMP em zircão de 1340 ± 20 Ma, tem idades T_{DM} entre 1,6 e 1,9 Ga e valores de ϵ_{Nd} entre +0,4 e -1,2. Isto ratifica a existência de um arco magmático juvenil mesoproterozoico durante a sua gênese, conforme reportado recentemente por Matos et al. (2009).

A respeito dos granitoides do setor sul (plútons Las Maras, San Rafael, Talcoso Limonal, Cachuela e San Andrés), nove datações SHRIMP, TIMS e de abrasão por laser (Boger et al., 2005; Santos et al., 2008; Vargas-Mattos, 2010 e Matos et al, em preparação), em zircões produziram idades entre 1347 e 1275 Ma (Figura 6.2), idades modelo T_{DM} entre 1,7 e 2,0 Ga, e valores de ϵ_{Nd} entre +4 e -4. Essa composição isotópica de Nd indica que o magma é derivado de uma mistura de fusão de um manto empobrecido com fusão de fonte crustal mais antiga. Por extrapolação as idades T_{DM} mais antigas corroboram com a idéia de uma crosta pretérita com idade assemelhada ao evento Correraca. Por outro lado, as análises geoquímicas deste conjunto de rochas granitoides indicam uma composição predominantemente peraluminosa a metaluminosa, subalcalina de alto K e natureza tectônica de intraplaca e arco volcânico.

As informações disponíveis sugerem que a orogênese San Ignacio representa um arco acrescionário que construiu a arquitetura final da província homônima, pela colisão entre o Craton Paraguá e o antepaís ao norte – evolução essa que foi precedida pelo desenvolvimento de arcos magmáticos juvenis e continentais (Bettencourt et al., 2010; Teixeira et al., 2010).

Os representantes coevos da evolução do arco San Ignacio, expostos na contraparte brasileira, são os Complexos Colorado e Mamoré (Rizzotto e Quadros, 2007; Teixeira et al., 2006; Bettencourt et al., 2009). Na Bolívia este evento acrescionário afetou heterogeneamente todas as unidades pré-existentes, incluindo fusões localizadas dos paragneisses Chiquitania e granulitos Lomas Manechis, conforme apontam muitas idades U/Pb SHRIMP obtidas em bordas recrystalizadas de zircões (Santos et al., 2008; Matos et al., em preparação).

(a)

(b)

(c)

(d)

(e)

(f)

(g)

Figura 6.2 Diagrama Concordia Suite San Ignacio (a) Granito San Martín; (b) Granito La Junta; (c) Granito Diamantina, (d) Granito San Andrés, (e) Granito Las Maras; (f) Granito Talcoso; (g) Granito Limonal.

Finalmente, uma avaliação integrada dos dados disponíveis para as suítes Yarituses e San Ramon no contexto evolutivo mesoproterozoico estão sendo interpretados em um manuscrito em preparação (Matos et al; em preparação – Apêndice D), o qual apresenta também correlações com o SW do craton Amazônico .

6.6.4. Evolução crustal Paleo a Mesoproterozoica

A avaliação integrada dos dados geocronológicos, geoquímicos e geológicos, obtidos nesta tese ou compilados em publicações recentes, devidamente embasada na revisão da geologia regional permite estabelecer algumas considerações quanto ao arcabouço tectônico do Pré-Cambriano do Oriente Boliviano. Não obstante, embora o quadro evolutivo mesoproterozoico esteja delineado, diversas das intrusivas granitóides previamente interpretadas como de idade San Ignacio e/ou Sunsás, com base em relações geológicas e dados estruturais (e.g., Litherland et al., 1986; Boger et al., 2005), não foram confirmadas pelas datações U/Pb realizadas no projeto de doutorado (ou publicações recentes), exigindo com isso o respectivo re-enquadramento crono-estratigráfico. Esta situação também se extrapola para as rochas encaixantes, exemplificadas pelo Complexo Lomas Manechis e, especialmente, pelas unidades para-derivadas como o Complexo Chiquitania e o Grupo San Ignacio.

Em síntese, o embasamento Pré-Cambriano na Bolívia Oriental é composto pelos complexos Lomas Manechis e Chiquitania, e o Grupo de Xistos San Ignacio, e ainda pelo granito Correraca recentemente caracterizado (ver acima). O complexo Lomas Manechis, considerada a unidade de mais alto grau metamórfico do Precambriano, ocorre na Serrania Lomas Maneches, Carmen de Ruiz e Espíritu- Las Rengas (Mapa geológico - Apêndice C). O conjunto está composto de granulitos charnockíticos, enderbíticos, básicos e gnaisses bandados quartzo-feldspáticos segundo Litherland et al. (1986), além dos sills de rochas granitóides (de acordo com Boger et al., 2005) com idade SHRIMP U-Pb de 1690-1630 Ma. Esta unidade metamórfica está caracterizada pela heterogeneidade litológica, estrutural e provavelmente geocronológica, foi datada por Santos et al., 2008 em Las Rengas, na proximidade do Posto Fortuna. Possui núcleos de zircões com idades U-Pb SHRIMP $^{207}\text{Pb}/^{206}\text{Pb}$ de 1818 ± 13 Ma, ao passo que as bordas recrystalizadas de monazita

indicam idades 1339 ± 4 Ma, indicando a remobilização por conta da orogênese San Ignacio. A idade T_{DM} (2.07 Ga) e valor de ϵ_{Ndt} (+0.53) admitem um protólito com curta residência crustal.

O Complexo Chiquitania é constituído principalmente por paragneisses que exibem cor variando de cinza claro a escuro, granulação fina a média e textura granolepidoblástica. Apresentam marcante bandamento composicional metamórfico, definido pela alternância de bandas félsicas de constituição quartzo-feldespática e níveis máficos em geral de constituição biotítica, parcialmente migmatizados que é o litotipo predominante. Estas rochas possuem muita representatividade na zona central e sul da área de estudo, definem uma foliação S_1 orientada segundo direção NW-SE e estão afetadas pelo metamorfismo da fácies anfibolito. Análises U-Pb (SHRIMP) em zircões detríticos desta unidade 20 km a leste de San Rafael indicam idades entre 1830 Ma e 1690 Ma para seus protólitos (e.g., Boger et al., 2005). No entanto grãos de zircão levemente discordantes acusaram uma idade $^{207}\text{Pb}/^{206}\text{Pb}$ de 1333 ± 6 Ma interpretado como relativo a época da fusão parcial associada à orogênese San Ignacio. Portanto o Complexo Chiquitania depositou-se após 1690 Ma, conforme proposto por Boger et al. (2005). Idades semelhantes foram reportadas por Santos et al. (2005) para um paragneisse a granada, localizado a 25 km a leste de Concepción. A principal população de zircões detríticos apresenta idades $^{207}\text{Pb}/^{206}\text{Pb}$ entre 1690-1630 Ma.

Santos et al. (2008) apresentam análises U-Pb SHRIMP do ortogneisse Rio Fortuna localizado 28 km a oeste de Ascensión. Ocorrem duas populações, uma delas assinalada pela presença de núcleos e herança em zircões, com idade entre 1772 e 1734 Ma. A segunda população de zircões magmáticos e bordas recristalizadas agrupam-se na concórdia com idade $^{207}\text{Pb}/^{206}\text{Pb}$ de 1333 ± 3 Ma. Com base nesta idade e no caráter ígneo da rocha datada há duas possibilidades: 1) Complexo Chiquitania agrega unidades orto e para-derivadas; 2) o ortogneisse Rio Fortuna é uma unidade precedente ao complexo Chiquitania. Na verdade preferimos a segunda opção correlacionando esta rocha as do Complexo Lomas Maneches.

O Grupo de Xistos San Ignacio caracteriza-se pela distribuição em faixas estreitas, contendo rochas metavulcano-sedimentares que incluem vulcânicas bimodais (basaltos toleíticos e vulcânicas cálcio-alcalinas), rochas metassedimentares clásticas e

químicas (arenitos, xistos, BIF, chert). O grupo está circundado por gnaisses e granitos e está superposto em discordância pelos conglomerados e arenitos do Grupo Sunsás. Os estudos feitos pelo autor neste Grupo abrangem a sequência metavulcano-sedimentar Naranjal (em fase de datação) que forma uma extensa faixa NS na porção sudoeste da área de estudo. Boger et al. (2005) coletaram grãos de zircão detrítico de uma amostra entre San Ignacio e San Rafael; que forneceram: uma idade $^{207}\text{Pb}/^{206}\text{Pb}$ de 1764 ± 6 Ma; 3 grãos entre 1840-1910 Ma; 14 grãos produziram aproximadamente 1690 Ma e 4 grãos entre 1690-1760 Ma. Com base nestes dados, os Xistos San Ignacio não foram depositados antes de 1690 Ma.

Este embasamento Pré-cambriano heterogeneo foi afetado por eventos magmáticos associados a orogêneses mesoproterozoicas, que geraram a suíte juvenil Yarituses, o plúton San Ramon) e o Complexo Granitoide Pensamiento (já sumarizados nesta Tese) e o magmatismo Sunsás (orogênese homônima).

Orogênese Sunsas

Este evento orogenético desenvolveu-se ao sul do Craton Paraguá, e representa o evento tectonomagmático mais jovem do Mesoproterozóico Boliviano, sendo contemporâneo à evolução do cinturão Nova Brasilândia em Rondônia (e.g, Tohver et al, 2006; Cordani e Teixeira, 2007; Rizzotto e Quadros, 2007). Conforme concebido por Litherland et al. (1986), a orogênese Sunsás originou-se a partir da deposição dos sedimentos do Grupo Sunsás e Vibosi em uma margem passiva, enquanto que evento contemporâneo no antepaís deu origem à bacia intracratônica Huanchaca-Aguapeí, conforme correlações geológicas apoiadas por idades U/Pb em zircão detrítico (Santos et al., 2005; Saes et al., 2006; Teixeira et al., 2010). A inversão desta margem passiva em ativa provocou a deformação dos sedimentos Sunsás e Vibosi no âmbito do domínio orogênico. Ao mesmo tempo o espessamento crustal decorrente com geração de importante plutonismo intrusivo nos estratos sedimentares dobrados, como resultado da evolução de um cinturão colisional no período de 1,20 a 0,95 Ga (Teixeira et al., 2010). As rochas granitóides da Orogenia Sunsás como os plutons Naranjito, El Carmen, Casa

de Piedra Taperas, e Primavera foram estudados em detalhe na tese de Doutorado de Vargas-Mattos (2010).

A geofísica aérea realizada na área de San Diablo (Landivar e Gonzalez, 1997) e os trabalhos de pesquisa mineira (Billiton, RTZ) definiram diversas frentes tectônicas ou zonas de cisalhamento, vinculadas à dinâmica colisional da faixa Sunsás, a saber: San Diablo, El Encanto, Don Mario, Surutú e Bahia Las Tojas. A característica principal destas frentes é o padrão anastomosado, envolvendo núcleos lenticulares de rocha pouco milonitizada (Apêndice C). O grau de metamorfismo das rochas corresponde às fácies anfibolito inferior a médio dentro de uma zona de deformação dúctil. Como rochas do embasamento reconheceram-se gnaiss migmatito, augen gnaiss, paragneiss granoblástico e gnaiss leucocrático relacionados ao Complexo Chiquitania. Uma banda estreita de orientação este-oeste é constituída por xisto a muscovita, meta-arenito e rocha calco-silicática. Dentro da seqüência de xistos, existem afloramentos de um metaconglomerado oligomítico com clastos de quartzo cor cinza, branco e translúcido, de 9 x 2 cm em tamanho, formando tectonitos L ou prolatos dentro de uma matriz rica em muscovita e quartzo. Em outros afloramentos, os clastos do metaconglomerado são achatados ou oblatos, ou tectonitos S. Ao sudoeste do Cerro El Encanto o metaconglomerado Sunsás recobre o Complexo Chiquitania em discordância; os clastos de quartzo mostram forte achatamento característico dos tectonitos S (Mitchell, 1979).

O Distrito San Ramon (Figura 6.3) é caracterizado por um estilo de tectônica oblíqua com estruturas S-C, sub-grãos gerados por fraturas de cisalhamento e deslocados e rotação de porfiroblastos ocorrida durante a orogenia Sunsás. Estas estruturas afetaram o embasamento e as rochas da suíte Yarituses, o granito San Ramón, a suíte granitóide San Ignacio e os granitóides Sunsás, sendo semelhantes à dinâmica deformacional sinistral da faixa metavulcano-sedimentar de Nova Brasilândia e a Zona de Cisalhamento Ji-Paraná (Tohver et al., 2005).

Na Bolívia o sentido sinistral de cisalhamento é observado no campo e na geofísica aerotransportada (Adamek et al. 1996, Matos 2009), estando possivelmente relacionadas em sua maior ordem, com a colisão entre a Amazonia e Laurentia durante a orogenia Grenville. Isto implica em uma continuidade das estruturas de Rondônia até

a Bolívia. A maioria dos milonitos nos frentes de cisalhamento mostra uma foliação milonítica (denominada S), que está geralmente com um ângulo inferior a 45° nos limites da zona de cisalhamento. A foliação paralela à borda da zona de cisalhamento é denominada C. As estruturas S-C podem ser identificadas como exemplos de escalas regionais nas imagens de satélite, constituindo indicadores cinemáticos para determinar o sentido de cisalhamento, neste caso exibindo movimento lateral sinistral como é o caso do Distrito San Ramón.

6.6.5 Considerações finais

Com a integração de dados de campo obtidos da bibliografia e a vivência do autor no oriente boliviano, agregado a os perfis geológicos em áreas chave, os dados litoquímicos, a aplicação da metodologia U-Pb, Sm-Nd, Rb-Sr permitiu obter uma visão atual da natureza e cronologia dos principais eventos tectono-magmáticos que afetaram a região SW do Craton Amazônico em particular para o Pré- cambriano da Bolívia.

Estos datos permiten destacar alguns pontos de grande importância relacionado á evolução geológica.

1. Um evento magmático representado pelo granito Correraca 1925 a 1894 Ma revela a presença pela primeira vez de crosta paleoproterozoica no Pré-Cambriano de Bolívia, na região meridional da faixa Sunsás, que indicaria que a área sul da Zona de Cisalhamento San Diablo, denominada terreno San Pablo por Saes et al. (1992), seria um terreno alóctone com uma história geológica distinta.

2. No bloco Paraguá o embasamento está constituído pelo Complexo Granulítico Lomas Manechis, o Complexo Gnáissico Chiquitania e o Grupo de Xistos San Ignacio representando as unidades basais com idades de 1810-1690 Ma.

3. As datações geocronológicas U-Pb SHRIMP, TIMS e ablação por laser-ICPMS obtidos indicam a formação da Suíte Granítica Yarituses no lapso de tempo entre 1673 a 1621 Ma, as idades modelo T_{DM} de 1,7-1,9 Ga ($f_{Sm/Nd}$ de 0.38 a 0,42), com o $\epsilon_{Nd(t)}$ de +0,2 a +2.1 que indica derivação mantélica.

4. O granodiorito San Ramón constitui um novo evento magmático no escudo Pré-Cambriano da Bolívia. Este plúton produziu uma idade SHRIMP U- Pb de 1429 Ma, com idade T_{DM} de 1,7 Ga, com parâmetros petrogenéticos ($\epsilon_{Hf(t)}$ entre + 3,49 e +5,47)

que implicam um evento juvenil. Este pluton seria o coevo com as suítes Santa Helena e Agua Clara (1,48-1,42 Ga), Pindaituba (1,46-1,42 Ga) e a suíte Rio Branco de natureza anorogênica (1,42 Ga) (Bettencourt, et al., 2010).

5. Já os a suite orogênica San Ignacio está representada no Pré-Cambriano da Bolívia, tanto pelo Complexo Granitóide Pensamiento como ao sul dele, neste último caso parcialmente obliterados pela orogênese Sunsás. Datações SHRIMP em zircão dos plútons sin a tardi-cinemáticos San Martín e La Junta produziram idades de 1373 a 1347, idades modelo T_{DM} entre 1,7 e 2,0 Ga. O pluton Diamantina, de natureza tardi- a pos-cinemática, possui uma datação SHRIMP em zircão de 1340, tem idades T_{DM} entre 1,6 e 1,9 Ga e valores de ϵ_{Ndt} entre +0,4 e -1,2. A respeito dos granitoides do setor sul, nove datações SHRIMP, TIMS e de abrasão por laser em zircões produziram idades entre 1347 e 1275 Ma, idades modelo T_{DM} entre 1,7 e 2,0 Ga, e valores de ϵ_{Ndt} entre +4 e -4, indicando que o magma derivou de uma mistura de fusão de manto com fusão de fonte crustal mais antiga. A orogênese San Ignacio representa um arco acrecionário que construiu a arquitetura pela colisão entre o Craton Paraguá e a Província Rio Negro-Juruena. As evidencias da colisão poderiam se explicar pela ocorrência de rochas sedimentares não deformadas de idade Sunsás (serrania Huanchaca), depositadas discordantemente sobre o embasamento na area de San Simon e a Serrania Dalriada, como descrito por Litherland e Power (1989).

Os representantes coevos da evolução do arco San Ignacio, expostos em Rondônia são os Complexos Colorado e Mamoré.

6. O Distrito San Ramon na parte meridional da faixa Sunsás é caracterizado por um estilo de tectônica oblíqua com estruturas S-C, afetando o embasamento e as rochas das suíte Yarituses, o granito San Ramón, a suíte orogênica San Ignacio e os granitoides Sunsás, sendo a dinâmica deformacional sinistral semelhante a Nova Brasilândia e a Zona de Cisalhamento Ji-Paraná (Tohver et al., 2005).

7. O mapeamento realizado na área sul de San Diablo definiram diversas frentes tectônicas ou zonas de cisalhamento, vinculadas à dinâmica colisional da faixa Sunsás. A característica principal destas frentes é o padrão anastomosado, envolvendo núcleos lenticulares de rocha pouco milonitizada.

Figura 6.3 Distribuição geográfica dos plútons mesoproterozoicos e das principais estruturas da área de estudo.

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Age and autochthonous evolution of the Sunsás Orogen in West Amazon Craton based on mapping and U–Pb geochronology

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ABSTRACT

The West Amazon Craton consists of rocks of the Sunsás Orogen and the Rondônia-Juruena Province. The Sunsás Orogen comprises the western part of the Amazon Craton in South America and is best exposed in eastern Bolivia and western Rondônia and Mato Grosso states of Brazil. The integration of available maps and isotopic data together with new U–Pb and Sm–Nd analyses from 20 samples (plus 55 earlier dates), establish the timing of geologic events in the West Amazon Craton from 1840 to 1110 Ma. To unravel the complex geologic history of the study area, we primarily sampled granitoids and gneisses to develop a better stratigraphy and secondarily to narrow the age gaps between known discordances. Four periods of orogenic activity are identified within the Sunsás Orogen: 1465–1427 Ma (Santa Helena orogeny), 1371–1319 Ma (Candeias orogeny), ca. 1275 Ma (San Andrés orogeny), and 1180–1110 Ma (Nova Brasilândia orogeny). Notable is the absence of an Ottawan orogeny (1080–1020 Ma) equivalent. In the Rondônia-Juruena Province three main orogenies are recognized: the Juruena (1840–1780 Ma), the Jamari (1760–1740 Ma) and the Quatro Cachoeiras (1670–1630 Ma). Post-Sunsás rocks include Rondônia tin granites, Palmeiral sandstones, Nova Floresta basalt, and alkalic pipes.

All inherited U–Pb ages of zircon and all exposed pre-Sunsás rocks in Bolivia have ages that correlate well to the neighbouring Rondônia-Juruena Province. This fact, together with the absence of fragments of older, Archean and Trans-Amazonian crust, suggests that the Sunsás Orogen is autochthonous and evolved over a continental margin formed dominantly by rocks of the Jamari (1760–1740 Ma) and Quatro Cachoeiras (1670–1630 Ma) orogenies plus rocks of the post-tectonic Serra Providência Suite (1560–1540 Ma). Almost all granulites known in Eastern Bolivia and in neighbouring area in Brazil are not basement rocks, but were formed during the Mesoproterozoic and are mainly associated with the Candeias orogeny (1371–1319 Ma). Dated samples of the Chiquitania and Lomas Manechi Complexes in Bolivia revealed a variety of ages and types of ages (metamorphic, magmatic, and inherited) indicating that those two units require more study. There is no evidence for the existence of a Paraguá Craton or Paraguá Block, which is almost totally composed of arc-related granites also formed during the Candeias orogeny.

The main difference between the Sunsás Orogen and the Grenville Orogen of Laurentia is the absence in Amazonia of an Ottawan-equivalent orogeny (1080–1020 Ma). The existence of age-equivalents of the Candeias and Santa Helena orogenies in Laurentia (Pinwarian orogeny and rocks of the Eastern Granite-Rhyolite Province and the Composite Arc Belt) indicates that the connection of the two continents may have started from about 1450 Ma. In addition, the two belts may not have been directly juxtaposed, but instead, that one may have been the extension of the other during the Mesoproterozoic. The possibility that Amazonia joined the southwestern part of Laurentia also provides a good fit for the Hudson-Tapajós and

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Mazatzal-Yapavai-Rondônia-Juruena Provinces. This possible link to Laurentia may have started during the formation of the Trans-Hudson Orogen and its correlative Rondônia-Juruena and Tapajós provinces from about 1900 Ma.

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1. Introduction

This study has multiple objectives: to improve the Proterozoic stratigraphic correlations between western Brazil and eastern Bolivia; to develop better constraints about the duration of the Sunsás Orogenic cycle and the ages of its main orogenies; to test the relationship of the Sunsás Province to its neighbour, the Rondônia-Juruena Province; to assess the evidence for the existence of the Paraguá Craton (Boger et al., 2005; Tohver et al., 2004); to update comparison to the Grenville Orogen of Laurentia; and to provide new clues about Mesoproterozoic paleogeography of the region. This lead to an integrated chronological table (see Section 5).

The Sunsás Orogen was formed along the western margin of the Amazon Craton during the Mesoproterozoic (1450–1100 Ma). It was partially consumed by the Andes Orogen to the west and locally by the Brasiliano Orogen (Neoproterozoic) to the southeast (Fig. 1). Much later, it was largely buried by Phanerozoic deposits derived from the erosion of the Andes Orogen to the west (Schenk et al., 2000; Roddaz et al., 2006). The original belt may have been 6000 km long, extending from northeast Argentina and Paraguay into eastern Venezuela, but today the Sunsás Belt is best exposed along the Brazil–Bolivia border, in an area of about 350,000 km², where only regional geological maps are available.

The presence of tin granites dated at about 980 ± 21 Ma by Rb–Sr whole-rock isochron led Priem et al. (1966, 1971) to first pro-

pose correlation to the Grenville Orogen of Laurentia. Only three decades later did Sadowski and Bettencourt (1996) and Bettencourt et al. (1999) confirm the Late Mesoproterozoic–Early Neoproterozoic age of the post-orogenic (post-Sunsás) Rondônia tin granites using U–Pb TIMS geochronology. However, the first Grenvillian U–Pb age of orogenic rocks within the Sunsás Belt came only in 1999, when Rizzotto et al. (1999) dated S-type granite derived from the partial melt of metapelites of the Nova Brasilândia Group at 1100 ± 10 Ma.

The Sunsás Orogen is interpreted as part of the Mesoproterozoic Supercontinent named Rodinia (Dalziel, 1991; Hoffman, 1991; Karlstrom et al., 2001; Li et al., 2008). The connection of the West Amazon Craton to Laurentia within the Rodinia supercontinent is now a broadly accepted idea (Dalziel, 1991; Hoffman, 1991; Santos et al., 2002; Tohver et al., 2002; Boger et al., 2005; Fuck et al., 2008). The Sunsás Belt has been correlated to different areas of Laurentia: the southwestern Llanos segment (Tohver et al., 2002); the Grenville Province of Ontario (Sadowski and Bettencourt, 1996; Santos et al., 2002); and the southern and central Appalachians (Loewy et al., 2003; Tohver et al., 2004). The paleo-reconstruction of the Amazonia-Laurentia connection at the end of the Mesoproterozoic (at ca. 1.0 Ga) is, however, uncertain for two main reasons: only a limited zone of the Sunsás Belt of about 1100 km is exposed within one that potentially was longer than 6000 km. In addition, large areas remain unmapped, poorly known or buried.

Fig. 1. The distribution of the Sunsás Belt in South America in relation to the Amazon and La Plata Cratons (this work), and Atlantic Shield (from Schobbenhaus and Neves, 2003). Also shown are other Mesoproterozoic remnants within the Andes Belt, and location of Figs. 3 and 4.

The time interval of the Sunsás Orogen and the main orogenies within the orogen started to be defined in 1999, when U–Pb geochronology became available (Rizzotto et al., 1999; Bettencourt et al., 1999; Santos et al., 2000). Santos et al. (2002) proposed a duration of about 350 m.y. to build the orogen (1450–1100 Ma); they recognized three main orogenies or peaks of orogenic activity at 1465–1420 Ma (Santa Helena), 1370–1320 Ma (Candeias), and 1180–1100 Ma (Nova Brasilândia).

According to Santos et al. (2002), the first orogeny (Santa Helena, Geraldes et al., 2001) corresponds in age to the Pinwarian orogeny of the Grenville Orogen (Wasteneys et al., 1997) and to part of the Eastern Granite-Rhyolite Province of Laurentia (McBride et al., 2001). The rocks of the Candeias orogeny (Santos et al., 2000; 1350–1320 Ma) are equivalent in age to the Mount Holly Complex of Vermont (Ratcliffe et al., 1991). The Nova Brasilândia orogeny (Rizzotto et al., 1999; 1180–1100 Ma) is chronologically comparable to the Shawinigan Pulse (1190–1140 Ma) post-dating the Elzevirian orogeny of the Grenville Orogen (Rivers, 1997; Streepey, 2003; Davidson, 2008).

The main difference between the Grenville and Sunsás Orogens is that the Sunsás Orogen is lacking an equivalent to the youngest orogeny of Laurentia, the Ottawan orogeny (Santos et al., 2002, 2004a,b). During Ottawan time (1080–980 Ma; including the Rigolet Pulse, Rivers, 1997; Davidson, 2008), the West Amazon Craton was stabilized as shown by A-type tin granites (Rondônia Suite, 980 Ma; Bettencourt et al., 1999; Sparremberger et al., 2002), the presence of little deformed foreland basins (Caiabis, Palmeiral, <1030 Ma), rift-related basalts (Nova Floresta Formation, 1062 ± 3 Ma; Tohver et al., 2002), and alkalic pipes (Teotônio and Guariba; Teixeira, 1978).

Recent studies (Boger et al., 2005; Tohver et al., 2004, 2005) consider an allocthonous evolution of the Sunsás Belt and that its evolution is associated with the existence of a craton between the orogenic belt and the Amazon Craton: the Paraguá Craton in eastern Bolivia (Litherland et al., 1986, 1989). Because the relationship of the Sunsás Orogen to the craton margin (the Jurueña Orogen, 1810–1550 Ma; Santos, 2003) since approximately 1460 Ma is poorly known, there is no strong evidence for an allocthonous evolution. Further, the Paraguá Craton has not been defined and its presence is yet to be confirmed.

The present stratigraphy of the Precambrian rocks of Bolivia is based on Rb–Sr geochronology and on a scheme associated to the metamorphic grade (strato-metamorphism; Litherland et al., 1986). By this stratigraphy, the higher the metamorphic grade the older the rock. This methodology is tested and compared to the neighbouring stratigraphy in Rondônia and Mato Grosso States of Brazil.

The present study combines a large dataset of 20 new U–Pb and Sm–Nd data with previous U–Pb data, and integrates both with the new geological maps of Brazil (Schobbenhaus et al., 2004).

2. Regional geology

2.1. Overview of Amazon Craton provinces

Until 1974, the architecture of the Amazon Craton was interpreted as composed of two shields or blocks limited by E–W contact coincident to the axis of the Phanerozoic Amazon Basin. The northern part was named the Guyana Shield and the southern part the Brasil-Central or Guaporé Shield. Based on K–Ar and secondarily on Rb–Sr data, Amaral (1974) demonstrated that the major internal limits of the craton are not E–W but NNW–SSE and that the western part (Western Province) of the craton is younger (Mesoproterozoic) than the central and eastern provinces, which are older (Archean and Paleoproterozoic). The model proposed by Amaral (1974) for

the Amazon Craton evolution was followed by a model based on Rb–Sr isotopes (Cordani et al., 1979; Teixeira et al., 1989; Tassinari et al., 1996; Tassinari and Macambira, 1999). The present study uses a model based on U–Pb data of Santos et al. (2000) and Santos (2003) also includes two recent updates based on the work of Vasquez et al. (2008) on the Bacajá Domain plus that of Ruiz (2006) and Cordani et al. (2008) on the Rio Apa Domain (Fig. 1). According to Santos et al. (2003) the Sunsás Province (1450–1100 Ma) evolved against the Rondônia-Juruena Province (1820–1550 Ma) and the Rio Negro Province (1830–1480 Ma) – Fig. 2. During the evolution of the Sunsás Orogen extensive sinistral shear zones were produced inside the craton resulting from oblique compression from the north-northwest (σ_1 of Fig. 1) against the Amazon Craton (Santos et al., 2006). These shear zones are concentrated in a 1200 km long and ±120 km wide belt, which affects all pré-Sunsás provinces in north and northwest parts of the craton: the Rio Negro, the Trans-Amazon and the Tapajós-Parima. This shearing event has been known since 1966 and is named the K'Mudku Mylonite episode (Barron, 1966).

2.2. Previous work

Only regional geological maps are available within the Sunsás Belt area. In Bolivia there is no significant geological work since the “Proyecto Precámbrico”, a British-Bolivian bilateral program starting in 1976 and concluded in 1986 (Litherland et al., 1986, British Geological Survey, Overseas Memoir 9). A summary of the results of the project was published in Precambrian Research (Litherland et al., 1989). On the Brazilian side of the belt the most recent maps are the collection of digital maps at 1:1,000,000 scale published in 2004 (Schobbenhaus et al., 2004), which incorporate results of local maps at 1:250,000 and 1:100,000 scales. The lithostratigraphic names used in this work follow the nomenclature used by the geological surveys of Brazil (Santos, 2003; Rizzotto et al., 2004) and Bolivia (Litherland et al., 1986). Altogether over 80 stratigraphic units are recognized in the study area.

The geographic extension and the temporal evolution of the Sunsás Province were addressed using U–Pb SHRIMP (Santos et al., 2000, 2001, 2005, 2006; Boger et al., 2005; Bettencourt et al., 2006), U–Pb TIMS (Geraldes et al., 2000, 2001; Tohver et al., 2004; Ruiz, 2006), and Ar–Ar (Fernandes et al., 2005; Tohver et al., 2002, 2004, 2005) geochronology.

2.3. Geology of the Rondônia-Juruena Province

The geology of the western Rondônia-Juruena Province is summarized in Fig. 3, which is based on Santos (2003) and Rizzotto et al. (2004) and includes sample locations. The province was formed during approximately 300 m.y. (1840–1540 Ma) and has three main domains: Juruena (eastern), Jamari (western), and Alto Jauru (extreme south). The basement of the Juruena Domain (1848–1793 Ma) is about 80–40 m.y. older than the western basement, the Jamari Complex (1760–1740 Ma). The Juruena basement is composed of the Juruena Granodiorite (1848–1823 Ma), the Paranaíta Suite (1819–1793 Ma), the Cristalino Syenite (1806 Ma), the undated São Marcelo Group, and the undated Bacaeri Complex (JICA, 2000; Lacerda Filho et al., 2001; Santos, 2003). Volcano-plutonic continental arcs (Andean-type) formed between 1790 and 1770 Ma in the Juruena Domain; these include the Colíder Group (1786–1781 Ma), Vitória Suite (1785–1775 Ma), São Romão Granite (1770 Ma), Monte Verde Complex (1774 Ma), and São Pedro Granite (1784 Ma). The Jamari Domain started at 1760 Ma (oldest rocks of the Jamari Complex, this paper) with the formation of an island arc association of metatonalites and metabasalts in central-north Rondônia. These metatonalites and metabasalts are

Fig. 2. The Sunsás Province in relation to other provinces of the Amazon Craton (adapted from Santos, 2003). The three main domains of the Rondônia-Juruena Province are marked by red numbers: 1 (Jamari Domain), 2 (Juruena Domain), and 3 (Alto Jauru Domain). The location of several basins covering the Sunsás Province also is indicated.

contemporaneous to the volcano-plutonic association of the Aripuanã River region (northeast of Fig. 3); for example the Maçaranduba Dacite (1762 ± 6 Ma) and the Paraibão Granite (1755 ± 5 Ma; Neder et al., 2002). During the formation of the Jamari Complex in the western part of the Rondônia-Juruena Province and in the Maçaranduba-Paraibão association in the centre of the province, extensive A-type granite generation occurred in the eastern domain (Juruena) forming the Teles Pires Suite (1757 ± 16 Ma;

Santos, 2003). Study by Pinho et al. (2001) revealed that the widespread volcanic rocks underlying the Beneficente Group in northwestern Mato Grosso are equivalent in age to those of the Colíder Group (ca. 1780 Ma); they also demonstrated the existence of a regional metamorphic event at ca. 1669 Ma.

Volcano-sedimentary (Roosevelt Group, 1740 Ma; Santos et al., 2000) and sedimentary (Beneficente Group, <1730 Ma; Leite and Saes, 2003) units occur throughout the two main domains of the

Fig. 3. Simplified geological map of Rondônia region (based on Santos, 2003 and Schobbenhaus et al., 2004) showing the location of dated samples (white labels). Dating from Santos et al. (2000) are cream labels. The regional location of this map is indicated also in Fig. 1.

province (1 and 2 in Fig. 2). Continental collision occurred during 1670–1630 Ma with movement from the south. This produced an E–W overprint in the older rocks, as is clearly seen in the Beneficente and Roosevelt Groups. Most of the paragneisses of Rondônia-Juruena Province were formed during this collisional orogeny, named Quatro Cachoeiras (Rizzotto et al., 2004) in reference to the paragneiss belt of the Jamari Domain (Schobbenhaus et al., 2004). This orogeny also metamorphosed the Monte Verde Group of the Juruena Domain (1654 Ma; Lacerda Filho et al., 2001) and the Colniza Granodiorite of the Aripuanã River region (1669 ± 13 Ma; Pinho et al., 2003). After a period of about 80 m.y., apparently without any important geological activity, the Serra Providência Suite (1560–1530 Ma; Bettencourt et al., 1999; Santos, 2003) was formed in the Jamari Domain. This suite comprises an assemblage of A-type rapakivi granites and charnockitic rocks. The

Aripuanã Granite (1542 ± 2 Ma; Silva et al., 2002) to the east is contemporaneous with the Serra Providência Suite.

The Rondônia-Juruena Province extends to the south under the Parecis Basin (Fig. 2), where the Alto Jauru Domain (also termed the Cachoeirinha Domain by Ruiz et al., 2005a) is exposed (Pinho et al., 1997; Geraldès et al., 2001). The basement under the Parecis Basin is composed of volcano-sedimentary rocks (Cabaçal and Quatro Meninas Groups) and orthogneisses (Cabaçal, Santa Fé, and Aliança), dated by U–Pb ID-TIMS at 1790–1745 Ma (Geraldès et al., 2000). Here there is also an intrusive suite of granitoids, named the Cachoeirinha (Geraldès et al., 2000) or Santa Cruz Suite (Ruiz et al., 2005a) that has ages of 1562 ± 36, 1549 ± 10, and 1546 ± 15 Ma (Ruiz, 2006) equivalent to that of the Serra Providência Suite of the Jamari Domain. The Cachoeirinha Suite is interpreted as an orogenic arc (Geraldès et al., 2000; Ruiz, 2006), contrasting with

Fig. 4. Location of investigated samples and previously dated samples on simplified geological map of eastern Bolivia based on Litherland et al. (1986). Samples studied in this work have rectangular white labels whereas samples dated by Boger et al. (2005) have elliptical labels and italicized letters. The regional location of this map is indicated in Fig. 1.

the intracratonic rifting of the Serra Providência to the north (Bettencourt et al., 1999).

2.4. Geology of the Sunsás Province

The Sunsás Orogenic cycle was proposed by Litherland et al. (1986, 1989) to encompass orogenic rocks formed between 1280 and 980 Ma and is represented by the meta-sedimentary Sunsás and Vibosi Groups, granite bodies, and mafic intrusions. As known today, the Sunsás Province covers an exposed area of about 350,000 km² in adjacent Brazil and Bolivia between latitudes 8–18° south and longitudes 58–67° west. Santos et al. (2000, 2003) used the range of 1450–1100 Ma for the Sunsás Orogenic Cycle to include three main orogenies separated by intervals of less orogenic activity: Santa Helena (1450–1420 Ma), Candeias (1350–1320 Ma) and Nova Brasilândia (1200–1100 Ma). The older rocks of the Sunsás Orogen (Santa Helena Batholith) are located in the southeastern part of the belt in Mato Grosso and described by Geraldes et al. (2001) as representing a primitive magmatic arc. The second orogeny (Candeias) has two main components: an Andean-type magmatic arc (Candeias granitoids in Rondônia and Pensamiento Complex in Bolivia; Santos et al., 2003; Matos et al., 2006) and also some high-grade collisional metamorphic rocks (Colorado and Rio Crespo metamorphic suites; Payolla et al., 2001; Rizzotto et al., 2002; Bettencourt et al., 2006). Meta-sedimentary rocks and small bodies of S-type granite (Rizzotto et al., 1999) mainly compose the Nova Brasilândia orogeny. The meta-sedimentary rocks are more pelitic to the north (Nova Brasilândia Group) and more psammitic to the south (Aguapeí and Sunsás Groups). Quartz-arenites and subordinated arkose, subarkose, siltite and conglomerate are the main rocks within the Sunsás and Vibosi Groups. These rocks have undergone very low or low-grade metamorphism (Litherland et al., 1986, p. 60).

The age of the Sunsás orogeny was restricted by Litherland et al. (1986) to 1000–950 Ma and included rocks dated in the

1143–730 Ma range (Rb–Sr and K–Ar). The Sunsás Group is called the Aguapeí Group (Saes and Leite, 1993) in Mato Grosso and the correlation of the two units is made since Litherland et al. (1986) because some meta-sedimentary belts (Huanchaca, Aguapeí, and Ascención) occur continuously on both sides of Brazil–Bolivia border as, for example, in the Ascención region (Fig. 4). The Sunsás orogenic front was restricted to the western part of the Bolivian Precambrian (Litherland et al., 1986, 1989; Tassinari et al., 1996, 1999). However, Santos et al. (2000) demonstrated that the Sunsás orogenic front is located about 400 km to the east in central Rondônia (Figs. 2 and 3) and that most of the granites previously interpreted as formed by the Sunsás orogeny in Bolivia may not be orogenic, but are in fact post-orogenic and correlative to the Rondônia Suite of Brazil (980 Ma; Bettencourt et al., 1999). Rizzotto et al. (1999), using U–Pb geochronology, found that the orogenic paroxysm occurred at 1110 Ma and that the metamorphic grade reached the upper amphibolite facies (sillimanite zone) or even locally the granulite facies (Tohver et al., 2004). Another metamorphic event is detected by Tohver et al. (2005) in the age range of 1155–1187 Ma using Ar–Ar in hornblende. This metamorphism (lower amphibolite facies?) reached temperatures of 450–550 °C (Tohver et al., 2005), which are not enough to recrystallize zircon (undetected by U–Pb geochronology). The U–Pb data of Rizzotto et al. (1999) have also shown that the latest orogeny within the Sunsás Orogen is about 130 m.y. older (paroxysm at 1110 Ma instead of 980 Ma) than previously established by Rb–Sr and K–Ar dating (Litherland et al., 1986).

The poorly known basement in western Rondônia (Fig. 3) is represented by the Mamoré Complex. This complex is thought to have been formed during 1450–1320 Ma and includes rocks formed during the Candeias and Santa Helena orogenies of Santos et al. (2002).

Santos et al. (2002) recognized three main orogenies within the Sunsás Orogen (Santa Helena, Candeias, and Nova Brasilândia) and established a preliminary correlation with the Grenville Orogen of Laurentia. The Santa Helena orogeny (1465–1420 Ma; Geraldes et

al., 2001; Ruiz, 2006) is comparable in age to the Pinwarian orogeny and the Eastern Granite-Rhyolite Province of Laurentia (McBride et al., 2001); the Candeias orogeny (1370–1320 Ma) to the Composite Arc Belt (Carr et al., 2000) or Mount Holly Complex (Ratcliffe et al., 1991); and the Nova Brasilândia orogeny (1180–1110 Ma) is contemporaneous to the late Elzevirian orogeny of Grenville Orogen (Rivers, 1997). The most important distinction between the Sunsás and Grenville Orogens is that the Amazon Craton apparently lacks orogenic rocks younger than 1100 Ma: there is no exposed equivalent to the Ottawan orogeny (Carr et al., 2000).

3. Sample strategy and analytical methods

The 20 rocks for isotopic investigation were selected from many rock samples collected by the authors (J.O.S. Santos, G.J. Rizzotto, P.E. Potter, and M.L.E.S. Quadros) during the field seasons of 2000 and 2003 and from the rock library of CPRM (Brazilian Geological Survey) in its Porto Velho office. Our sampling covers most stratigraphic units present in the Precambrian of Bolivia and Rondônia. Locations of sampling sites are shown in Figs. 3 and 4. General data for each sample (coordinates, rock name, stratigraphic unit, mineral dated by U–Pb, number of analyses per sample, references for names) are summarized in Table 1 and ordered from older to younger. All rocks were investigated in thin section and most of them have chemical analyses plus Sm–Nd data. The principal mineral used for U–Pb geochronology is zircon, although titanite and monazite are also used in two samples. During the analysis of zircon both cores and rims were dated. The rims provided either the ages of younger metamorphic or magmatic crystallization.

3.1. U–Pb SHRIMP methodology

Rock samples were crushed, milled and sieved at 60 mesh and the heavy minerals were separated using heavy liquid (TBE-tetra-bromo-ethane) and magnetic separation techniques. The final separation of the minerals was by hand picking the grains. These were mounted on epoxy discs with fragments of standards, ground and polished until nearly half of each grain was

removed, photomicrographed in transmitted and reflected light, and imaged (backscattered electrons) for their internal morphology, using a scanning electron microscope at the Centre for Microscopy and Microanalysis at the University of Western Australia. The epoxy mounts were then cleaned and gold-coated to have a uniform electrical conductivity during the SHRIMP analyses. The zircon standards used were Sri Lanka CZ3 zircon (564 Ma; $^{206}\text{Pb}/^{238}\text{U}$ ratio = 0.0914; 551 ppm U) and BR266 zircon (559 Ma, 903 ppm U). Titanite standard is Namibia Khan (518 Ma; $^{206}\text{Pb}/^{238}\text{U}$ ratio = 0.083671; 700 ppm U), and monazite standards are French, QMa and PD95 (Rasmussen et al., 2007). The isotopic composition of the minerals was determined using SHRIMP II (De Laeter and Kennedy, 1998), using methods based on those of Compston et al. (1992). For zircon and titanite, a primary ion beam of ~ 4 nA, 10 kV O_2^{2-} with a diameter of $\sim 25\text{ }\mu\text{m}$ was focused onto the mineral. Monazite was analysed using a reduced spot size ($10\text{--}15\text{ }\mu\text{m}$) and weaker primary beam (~ 1.2 nA) to prevent the ThO^{2+} signal exceeding that tolerated by the ion counter. Corrections for common Pb were made using the measured ^{204}Pb and the Pb isotopic composition of Broken Hill galena. For each spot analysis, initial 60–90 s were used for pre-sputtering to remove the gold, avoiding the analysis of common Pb from the coatings. Results with more than 0.50% common lead correction are presented but not used in age calculations. Zircons and titanite data are reduced using SQUID (Ludwig, 2002), and Krill (P.D. Kinny, Curtin University) was used for monazite. Data were plotted on concordia diagrams using ISO-PLOT/Ex software (Ludwig, 1999), which error ellipses on concordia plots are shown at the 95% confidence level (2σ). All ages given in text are weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ ages. Details of U–Pb data are presented in Table 2, where samples follow the same order of Table 1 and the descriptions of Section 4.1.

3.2. Sm–Nd methodology

Whole-rock powders were spiked with mixed ^{149}Sm – ^{150}Nd tracer and dissolved in a Teflon vial using an HF–HNO₃ mixture and 6N HCl until complete material dissolution. Column procedures used cationic AG-50W-X8 (200–400 mesh) resin in order

Table 1
Summary of the rock samples dated in this work^a

Sample	Rock	Unit	Easting ^b	Northing ^b	Mineral	n	Sm–Nd ^c	References ^d
JO3M	Granulitic gneiss	Lomas Manechi Complex	–59.478924	–16.341479	z-m	12–6	x	Litherland et al. (1986)
GR35	Quartz-diorite	Jamari Complex	–61.897222	–11.205527	z	10	x	Isotta et al. (1978)
GR59	Tonalite	Jamari Complex	–62.903889	–9.7956110	z	13	x	Isotta et al. (1978)
JL78	Tonalite	Jamari Complex	–62.833889	–10.160944	z	16	x	Isotta et al. (1978)
JO12	Orthogneiss	Refugio Orthogneiss	–62.330851	–16.274368	z	12	x	This work
GR333	Meta-granite	Serra Providência Suite	–62.069333	–10.779444	z	12	x	Leal et al. (1978)
JO14	Tonalite	San Ramón	–62.507128	–16.615514	z-t	9–4	x	This work
JS39	Monzogranite	Alto Candeias Granite	–63.521555	–10.506500	z	7		Souza et al. (1975)
JL6	S-type granite	Unnamed	–62.973472	–10.078778	z	6		This work
JO9	Gneiss	Las Madres Gneiss	–61.969680	–16.004839			x	Litherland et al. (1986)
JO16	Gneiss	Rio Branco Gneiss	–62.505284	–16.381691			x	Litherland et al. (1986)
JO6	Orthogneiss	Rio Fortuna Gneiss	–59.733488	–16.314850	z	17	x	Litherland et al. (1986)
JO5	Gneiss	Lomas Manechi Complex	–59.520732	–16.495433	z	6	x	Litherland et al. (1986)
JO18	Orthogneiss	Santa Rita Gneiss	–60.652397	–16.265587	z	10	x	Litherland et al. (1986)
JO10	Granite	San Andrés Granite	–62.210490	–16.215077	z	10	x	Litherland et al. (1986)
MQ23	S-type granite	Laje Granite	–64.766948	–10.397774	z	21		Rizzotto et al. (2004)
JP3	Sillimanite gneiss	Nova Brasilândia Group	–65.322834	–10.538490	z	7		Rizzotto et al. (1999)
JO13	Rhyolite	Puquio Rhyolite	–62.431190	–16.578660	z		x	This work
JO8	Garnet gneiss	Sunsás Group	–61.928064	–15.964474	z	16	x	Litherland et al. (1986)
JO11	Mica schist	Dolorida (Sunsás Group)	–62.271984	–16.249407	mu			This work
JO7	Alkali granite	Velasco Alkaline Complex	–61.083286	–15.981384	z	6	x	Litherland et al. (1986)

^a Ordered from the older (JO3) to the younger (JO7) rock.

^b Coordinates are geographic decimal using SAD69 datum. Minerals are z: zircon; t: titanite, and m: monazite (dated by U–Pb SHRIMP); mu: muscovite dated by Ar–Ar. n, number of U–Pb analyses per sample.

^c Sm–Nd analyses are whole rock.

^d References are exclusive for stratigraphic names.

Table 2
U–Pb SHRIMP isotopic data ordered from the older to the younger rock

Grain spot	U (ppm)	Th (ppm)	Th U	4f206 (%)	Isotopic ratios					Ages		Disc. %
					²⁰⁷ Pb/ ²⁰⁶ Pb	²⁰⁸ Pb/ ²⁰⁶ Pb	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	²⁰⁸ Pb/ ²³² Th	²⁰⁷ Pb/ ²⁰⁶ Pb	²⁰⁶ Pb/ ²³⁸ U	
JO3, Lomas Manechi granulitic gneiss, zircon (UWA mount 04-76)												
i.1-1	99	103	1.07	0.30	0.11466 ± 0.97	0.3090 ± 0.96	0.3441 ± 0.91	5.4426 ± 1.33	0.0978 ± 1.35	1876 ± 17	1906 ± 15	−1.6
i.1-2	645	10	0.02	0.50	0.08493 ± 0.92	0.0112 ± 7.60	0.3441 ± 0.91	2.7456 ± 0.70	− ± −	1359 ± 11	1330 ± 5	0.2
i.2-1	234	95	0.42	0.00	0.11459 ± 0.63	0.1205 ± 0.98	0.3418 ± 0.71	5.4007 ± 0.95	0.0989 ± 1.21	1873 ± 11	1895 ± 12	−1.2
i.3-1	105	94	0.93	0.02	0.11060 ± 0.92	0.2676 ± 1.00	0.3258 ± 1.21	4.9682 ± 1.51	0.0941 ± 1.64	1809 ± 17	1818 ± 19	−0.5
i.4-1	492	12	0.03	0.26	0.08753 ± 0.76	0.0138 ± 2.04	0.2304 ± 0.41	2.7829 ± 0.68	− ± −	1374 ± 10	1334 ± 5	2.7
i.5-1	288	172	0.62	0.34	0.11015 ± 0.77	0.1827 ± 0.67	0.3283 ± 0.51	4.9863 ± 0.93	0.0935 ± 1.27	1802 ± 14	1830 ± 8	−1.6
i.8-1	179	112	0.65	0.10	0.11188 ± 0.76	0.1842 ± 0.87	0.3308 ± 0.67	5.1031 ± 1.01	0.0929 ± 1.20	1830 ± 14	1842 ± 11	−0.7
i.9-1	702	7	0.01	0.50	0.08560 ± 0.82	0.0139 ± 4.29	0.2360 ± 0.41	2.8109 ± 0.61	− ± −	1346 ± 9	1363 ± 5	−1.2
i.11-1	342	255	0.77	0.24	0.11107 ± 0.76	0.2212 ± 0.97	0.3315 ± 0.58	5.0791 ± 0.94	0.0932 ± 1.35	1818 ± 14	1846 ± 9	−1.5
i.12-1	330	275	0.86	0.02	0.11144 ± 0.53	0.2464 ± 0.57	0.3279 ± 0.92	5.0381 ± 1.06	0.0937 ± 1.10	1823 ± 10	1828 ± 15	−0.3
i.13-1	700	21	0.03	0.31	0.08563 ± 0.74	0.0130 ± 2.37	0.2402 ± 0.43	2.8781 ± 0.66	− ± −	1358 ± 9	1387 ± 5	−2.0
i.14-1	659	6	0.01	0.27	0.08914 ± 0.92	0.0086 ± 19.1	0.2364 ± 0.44	2.9116 ± 0.78	− ± −	1411 ± 12	1368 ± 5	2.9
JO3, Lomas Manechi granulitic gneiss, monazite (UWA mount 04-76)												
b.15-1	7631	52813	6.92	0.015	0.08597 ± 0.16	1.8585 ± 0.14	0.2310 ± 1.48	2.7383 ± 1.52	0.0670 ± 2.61	1338 ± 3	1330 ± 18	0.1
b.16-1	3105	49200	15.85	0.038	0.08600 ± 0.25	4.1633 ± 0.17	0.2355 ± 1.50	2.7922 ± 1.55	0.0699 ± 1.86	1338 ± 5	1348 ± 18	−1.9
b.16-2	6090	41577	6.83	0.000	0.08628 ± 0.22	1.8419 ± 0.16	0.2371 ± 1.50	2.8204 ± 1.52	0.0690 ± 1.59	1344 ± 4	1352 ± 18	−2.0
b.17-1	5291	66607	12.59	0.007	0.08589 ± 0.20	3.3957 ± 0.10	0.2330 ± 1.46	2.7594 ± 1.51	0.0772 ± 6.99	1336 ± 4	1350 ± 18	−1.0
b.19-1	4189	56442	13.47	0.015	0.08615 ± 0.21	3.4972 ± 0.13	0.2373 ± 1.47	2.8187 ± 1.53	0.1605 ± 5.68	1341 ± 4	1373 ± 18	−2.0
b.20-1	8611	47438	5.51	0.007	0.08620 ± 0.15	1.4803 ± 0.28	0.2317 ± 1.47	2.7534 ± 1.50	0.1684 ± 0.93	1343 ± 3	1343 ± 18	0.0
GR35, Jamari Complex quartz-diorite, zircon (UWA mount B51)												
d.1-1	155	50	0.33	0.05	0.10800 ± 0.61	0.1077 ± 0.95	0.3221 ± 0.92	4.7963 ± 1.10	0.0936 ± 1.41	1766 ± 11	1800 ± 14	−1.9
d.2-1	1079	12	0.01	0.16	0.10135 ± 0.25	0.0978 ± 0.98	0.2982 ± 0.98	4.1683 ± 1.01	− ± −	1649 ± 5	1682 ± 14	−2.0
d.2-2	233	82	0.36	0.09	0.10845 ± 0.55	0.0047 ± 1.78	0.3136 ± 0.86	4.6889 ± 1.02	0.0917 ± 1.47	1773 ± 10	1758 ± 13	0.9
d.5-1	176	68	0.40	0.02	0.10686 ± 0.59	0.0282 ± 1.32	0.3121 ± 0.90	4.5987 ± 1.07	0.0891 ± 1.32	1747 ± 11	1751 ± 14	−0.3
d.8-1	142	50	0.36	0.05	0.10763 ± 0.69	0.0629 ± 1.20	0.3186 ± 0.94	4.7282 ± 1.17	0.0942 ± 1.54	1760 ± 13	1783 ± 15	−1.3
d.9-1	160	46	0.30	0.04	0.10845 ± 0.77	0.0847 ± 1.29	0.3135 ± 0.92	4.6875 ± 1.20	0.0889 ± 1.87	1774 ± 14	1758 ± 14	0.9
d.11-1	325	147	0.47	0.09	0.10708 ± 0.45	0.1357 ± 0.59	0.3125 ± 0.82	4.6132 ± 0.94	0.0894 ± 1.08	1750 ± 8	1753 ± 13	−0.1
d.12-1	145	52	0.37	0.10	0.10633 ± 0.75	0.1064 ± 1.01	0.3097 ± 0.94	4.5401 ± 1.20	0.0875 ± 1.73	1737 ± 14	1739 ± 14	−0.1
d.17-1	157	33	0.22	0.06	0.10820 ± 0.66	0.1137 ± 0.86	0.3156 ± 0.92	4.7079 ± 1.13	0.0900 ± 2.00	1769 ± 12	1768 ± 14	0.1
d.17-2	382	33	0.09	0.02	0.10610 ± 0.49	0.1089 ± 1.00	0.3010 ± 0.81	4.4037 ± 0.95	0.0936 ± 2.68	1733 ± 9	1696 ± 12	2.1
GR59, Jamari Complex tonalite, zircon (UWA mount B75)												
k.1-1	84	32	0.40	0.00	0.10760 ± 1.20	0.1208 ± 1.81	0.3135 ± 1.24	4.6513 ± 1.73	0.0957 ± 2.19	1759 ± 22	1758 ± 19	0.1
k.2-1	202	108	0.55	0.07	0.10705 ± 0.86	0.1651 ± 1.05	0.3115 ± 0.82	4.5973 ± 1.19	0.0922 ± 1.43	1750 ± 16	1748 ± 13	0.1
k.3-1	199	82	0.43	0.20	0.10309 ± 1.19	0.1297 ± 1.36	0.3052 ± 0.95	4.3380 ± 1.52	0.0895 ± 2.24	1680 ± 22	1717 ± 14	−2.2
k.4-1	242	109	0.46	0.01	0.10513 ± 0.76	0.1403 ± 1.16	0.3005 ± 0.74	4.3618 ± 1.06	0.0908 ± 1.40	1719 ± 14	1694 ± 11	1.5
k.5-1	205	131	0.66	0.13	0.10704 ± 0.69	0.1999 ± 3.80	0.2866 ± 0.64	4.2306 ± 0.94	0.0857 ± 3.89	1750 ± 13	1625 ± 9	7.1
k.5-2	138	50	0.38	0.10	0.10284 ± 0.95	0.1133 ± 1.19	0.2982 ± 0.66	4.2287 ± 1.15	0.0881 ± 1.86	1676 ± 17	1682 ± 10	−0.4
k.5-3	213	69	0.34	0.09	0.10208 ± 0.82	0.1010 ± 1.18	0.2987 ± 0.73	4.2033 ± 1.10	0.0883 ± 1.66	1662 ± 15	1685 ± 11	−1.3
k.7-1	174	61	0.36	0.17	0.10668 ± 0.85	0.1316 ± 1.06	0.2926 ± 0.60	4.1560 ± 1.04	0.0850 ± 1.71	1679 ± 16	1655 ± 9	1.4
k.8-1	165	73	0.45	0.06	0.10344 ± 0.88	0.1215 ± 1.00	0.3095 ± 0.85	4.4939 ± 1.22	0.0881 ± 1.57	1720 ± 16	1738 ± 13	−1.1
k.9-1	214	85	0.41	0.06	0.10300 ± 0.62	0.1091 ± 1.10	0.2935 ± 0.57	4.2343 ± 0.84	0.0856 ± 1.13	1708 ± 11	1659 ± 8	2.9
k.10-1	168	67	0.41	0.01	0.10762 ± 0.70	0.1186 ± 1.29	0.3072 ± 0.57	4.5592 ± 0.90	0.0880 ± 1.44	1760 ± 13	1727 ± 9	1.8
k.11-1	197	84	0.44	0.19	0.10354 ± 1.15	0.1305 ± 1.32	0.3149 ± 0.95	4.3021 ± 1.48	0.0870 ± 2.16	1688 ± 21	1698 ± 14	−0.6
k.12-1	140	53	0.39	0.00	0.10710 ± 0.91	0.1210 ± 1.37	0.3132 ± 1.24	4.6508 ± 1.32	0.0966 ± 1.67	1751 ± 17	1765 ± 15	−0.8
JL78, Jamari Complex tonalite, zircon (UWA mount B76)												
h.1-1	560	199	0.37	0.03	0.08622 ± 0.75	0.1837 ± 0.99	0.1838 ± 0.99	2.1851 ± 1.24	0.0502 ± 1.53	1343 ± 14	1088 ± 10	19.0
h.2-1	157	70	0.46	0.03	0.10659 ± 0.79	0.1270 ± 1.13	0.2375 ± 2.34	3.4906 ± 2.47	0.0662 ± 2.63	1742 ± 14	1374 ± 29	21.1
h.3-1	137	52	0.40	0.00	0.10617 ± 0.62	0.1150 ± 2.30	0.2903 ± 0.87	4.2497 ± 1.05	0.0858 ± 2.53	1735 ± 11	1643 ± 13	2.5
h.3-2	573	52	0.09	0.03	0.08579 ± 0.30	0.0297 ± 0.84	0.2322 ± 1.14	2.7472 ± 1.17	− ± −	1334 ± 5	1346 ± 14	−1.5
h.4-1	1123	183	0.17	0.01	0.08589 ± 0.19	0.0499 ± 0.62	0.2291 ± 0.64	2.7170 ± 0.67	0.0641 ± 1.15	1338 ± 4	1330 ± 8	0.6
h.4-2	984	156	0.16	0.02	0.08609 ± 0.20	0.2279 ± 0.96	0.2277 ± 0.65	2.7037 ± 0.68	0.0641 ± 1.15	1341 ± 4	1322 ± 8	1.4

Table 2 (Continued)

Grain spot	U (ppm)	Th (ppm)	Th U	4f206 (%)	Isotopic ratios					Ages		Disc. %
					²⁰⁷ Pb/ ²⁰⁶ Pb	²⁰⁸ Pb/ ²⁰⁶ Pb	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	²⁰⁸ Pb/ ²³² Th	²⁰⁷ Pb/ ²⁰⁶ Pb	²⁰⁶ Pb/ ²³⁸ U	
h.4-3	1165	106	0.09	0.01	0.08616 ± 0.33	0.0279 ± 0.94	0.2261 ± 0.34	2.6861 ± 0.48	0.0662 ± 1.05	1342 ± 6	1314 ± 4	2.1
h.5-1	151	78	0.54	0.12	0.10604 ± 0.82	0.1550 ± 1.21	0.3041 ± 1.16	4.4465 ± 1.41	0.0866 ± 1.80	1732 ± 15	1712 ± 17	1.2
h.6-1	160	55	0.36	0.10	0.10704 ± 1.32	0.2559 ± 2.01	0.2557 ± 2.01	3.7736 ± 2.41	0.0744 ± 3.50	1750 ± 24	1468 ± 26	16.1
h.7-1	373	153	0.42	0.11	0.08538 ± 0.46	0.0854 ± 0.64	0.2278 ± 0.91	2.6820 ± 1.11	0.0654 ± 1.35	1324 ± 12	1323 ± 11	0.1
h.8-1	149	67	0.46	0.01	0.10662 ± 0.46	0.1242 ± 0.79	0.3036 ± 0.74	4.4622 ± 0.88	0.0889 ± 1.35	1742 ± 8	1709 ± 11	2.2
h.9-1	910	171	0.20	0.02	0.08613 ± 0.46	0.0588 ± 1.61	0.2252 ± 0.82	2.6746 ± 0.93	0.0663 ± 1.54	1341 ± 9	1309 ± 10	2.4
h.10-1	97	45	0.48	0.04	0.10769 ± 0.61	0.1385 ± 0.86	0.3127 ± 1.15	4.6563 ± 1.30	0.0902 ± 1.60	1766 ± 11	1754 ± 18	0.7
h.11-1	450	169	0.39	0.00	0.08572 ± 0.62	0.1140 ± 0.92	0.2203 ± 1.45	2.6039 ± 1.46	0.0651 ± 1.58	1332 ± 12	1284 ± 15	3.6
h.15-1	120	65	0.56	0.12	0.10688 ± 0.82	0.1620 ± 1.22	0.3136 ± 1.32	4.6216 ± 1.72	0.0901 ± 2.12	1747 ± 20	1758 ± 20	3.6
h.17-1	96	42	0.45	0.00	0.10577 ± 1.02	0.1270 ± 1.52	0.3041 ± 1.15	4.4325 ± 1.41	0.0861 ± 2.11	1732 ± 15	1711 ± 17	−0.7
JO12, Refugio Orthogneiss, zircon (UWA mount 04-118)												
c.1-2	106	65	0.63	0.13	0.10100 ± 1.95	0.1809 ± 1.10	0.2923 ± 0.86	4.0698 ± 2.13	0.0828 ± 2.61	1643 ± 36	1653 ± 13	−0.6
c.1-5	142	70	0.51	0.00	0.10110 ± 0.89	0.1339 ± 1.25	0.2915 ± 2.14	4.0652 ± 2.32	0.0765 ± 2.47	1645 ± 17	1649 ± 31	0.0
c.2-1	344	226	0.68	0.02	0.10096 ± 0.55	0.1995 ± 0.66	0.2965 ± 0.54	4.1281 ± 0.77	0.0871 ± 0.85	1642 ± 10	1674 ± 8	−2.0
c.2-2	493	268	0.56	0.05	0.10246 ± 0.44	0.1627 ± 0.53	0.3011 ± 0.36	4.2544 ± 0.57	0.0867 ± 0.70	1669 ± 8	1697 ± 5	−1.7
c.2-3	215	152	0.73	0.04	0.10098 ± 0.60	0.2084 ± 0.69	0.2992 ± 0.52	4.1663 ± 0.79	0.0853 ± 0.87	1642 ± 11	1688 ± 8	−2.8
c.2-5	463	255	0.57	0.00	0.10059 ± 0.43	0.1546 ± 0.87	0.2891 ± 0.50	4.0092 ± 0.66	0.0786 ± 0.76	1635 ± 8	1637 ± 7	−0.1
c.2-6	158	100	0.65	0.01	0.10079 ± 0.71	0.1803 ± 0.85	0.2799 ± 0.64	3.8892 ± 0.95	0.0774 ± 1.07	1639 ± 13	1591 ± 9	2.9
c.4-1	378	203	0.55	0.10	0.10198 ± 0.59	0.1607 ± 0.59	0.3054 ± 0.41	4.2947 ± 0.72	0.0876 ± 1.00	1660 ± 11	1718 ± 6	−3.5
c.4-2	350	178	0.53	0.03	0.10114 ± 0.42	0.1433 ± 0.54	0.2948 ± 0.38	4.1117 ± 0.56	0.0800 ± 0.70	1645 ± 8	1666 ± 6	−1.2
c.7-1	278	186	0.69	0.07	0.10224 ± 0.82	0.1869 ± 0.65	0.3044 ± 0.52	4.2914 ± 0.97	0.0828 ± 1.20	1665 ± 15	1713 ± 8	−2.9
c.8-1	107	59	0.57	0.02	0.10260 ± 0.99	0.1546 ± 1.32	0.2774 ± 1.13	3.9238 ± 1.50	0.0749 ± 1.74	1672 ± 18	1578 ± 16	5.6
c.13-1	119	97	0.84	0.09	0.10123 ± 0.88	0.2313 ± 0.91	0.2812 ± 0.76	3.9254 ± 1.16	0.0769 ± 1.24	1647 ± 16	1598 ± 11	3.0
GR333, Serra Providência Meta-granite, zircon (UWA mount B76)												
b.4-2	73	47	0.66	0.38	0.09451 ± 1.57	0.1931 ± 1.32	0.2717 ± 1.75	3.4190 ± 2.35	0.0763 ± 2.59	1452 ± 30	1524 ± 24	−6.7
b.8-1	395	2	0.01	0.12	0.08591 ± 0.42	0.0019 ± 5.93	0.2173 ± 1.06	2.5789 ± 1.15	− ± −	1339 ± 8	1268 ± 12	5.3
b.9-1	111	82	0.77	0.01	0.09437 ± 0.57	0.2254 ± 0.57	0.2640 ± 0.84	3.4348 ± 1.02	0.0769 ± 1.37	1516 ± 11	1510 ± 14	0.4
b.9-2	386	163	0.44	0.00	0.09420 ± 0.30	0.1296 ± 0.40	0.2658 ± 1.07	3.4492 ± 1.11	0.0787 ± 1.14	1510 ± 6	1519 ± 14	−0.6
b.9-3	415	6	0.01	0.13	0.08605 ± 0.42	0.0071 ± 1.73	0.2154 ± 0.70	2.5615 ± 0.77	− ± −	1344 ± 6	1258 ± 8	5.4
b.12-1	540	174	0.33	0.00	0.09334 ± 1.07	0.0982 ± 2.17	0.2317 ± 0.78	2.9814 ± 1.33	0.0678 ± 2.43	1495 ± 20	1343 ± 10	10.1
b.14-1	256	166	0.67	0.00	0.09543 ± 0.65	0.1954 ± 0.72	0.2654 ± 1.35	3.4922 ± 1.50	0.0779 ± 1.56	1537 ± 12	1517 ± 18	1.3
b.15-1	406	194	0.49	0.00	0.09382 ± 0.70	0.1389 ± 1.68	0.2118 ± 0.83	2.7398 ± 1.09	0.0605 ± 2.04	1504 ± 13	1238 ± 9	18.0
b.19-1	45	30	0.70	0.00	0.09601 ± 1.23	0.2099 ± 0.99	0.2671 ± 1.07	3.5355 ± 1.63	0.0813 ± 1.94	1548 ± 23	1526 ± 15	1.0
b.19-2	559	5	0.01	0.08	0.08697 ± 0.27	0.0070 ± 1.75	0.2136 ± 0.68	2.5500 ± 0.73	− ± −	1351 ± 5	1248 ± 8	7.6
b.20-1	290	164	0.59	0.00	0.09438 ± 0.34	0.1713 ± 0.41	0.2668 ± 1.07	3.4561 ± 0.84	0.0776 ± 0.94	1516 ± 6	1518 ± 11	−0.1
b.20-2	99	95	0.99	0.04	0.09588 ± 0.65	0.2932 ± 0.61	0.2662 ± 0.85	3.5198 ± 1.08	0.0786 ± 1.16	1546 ± 12	1528 ± 16	1.1
JO14, San Ramón Tonalite, zircon (UWA mount 04-72)												
b.1-1	242	16	0.07	0.05	0.09084 ± 0.89	0.0200 ± 2.40	0.2453 ± 0.58	3.0728 ± 1.06	0.0762 ± 4.70	1443 ± 17	1414 ± 7	2.0
b.2-1	271	35	0.13	0.00	0.08967 ± 0.71	0.0398 ± 1.67	0.2460 ± 0.48	3.0417 ± 0.86	0.0744 ± 1.74	1418 ± 14	1418 ± 6	0.0
b.3-1	645	179	0.29	0.11	0.09051 ± 0.74	0.0853 ± 0.85	0.2474 ± 0.47	3.0877 ± 0.87	0.0718 ± 1.88	1436 ± 14	1425 ± 6	0.8
b.6-1	504	97	0.20	0.01	0.09026 ± 0.50	0.0580 ± 1.33	0.2455 ± 0.76	3.0550 ± 0.91	0.0716 ± 1.55	1431 ± 10	1415 ± 10	1.1
b.8-1	449	61	0.14	0.03	0.09040 ± 0.55	0.0412 ± 1.31	0.2437 ± 0.62	3.0381 ± 0.83	0.0711 ± 1.72	1434 ± 11	1406 ± 8	1.9
b.9-1	420	204	0.50	0.03	0.09045 ± 0.57	0.1460 ± 0.75	0.2505 ± 0.40	3.1240 ± 0.69	0.0725 ± 0.86	1435 ± 11	1441 ± 5	−0.4
b.10-1	186	16	0.09	0.09	0.09060 ± 0.97	0.0278 ± 2.26	0.2504 ± 0.66	3.1286 ± 1.17	0.0723 ± 5.40	1438 ± 18	1441 ± 8	−0.2
b.12-1	397	52	0.14	0.06	0.08985 ± 0.74	0.0408 ± 1.53	0.2517 ± 0.66	3.1182 ± 1.00	0.0732 ± 2.60	1422 ± 14	1447 ± 9	−1.7
b.13-1	425	102	0.25	0.00	0.08996 ± 0.64	0.0726 ± 1.11	0.2501 ± 0.55	3.1027 ± 0.85	0.0735 ± 1.32	1425 ± 12	1439 ± 7	−1.0
JO14, San Ramón Tonalite, titanite (UWA mount 04-72)												
a.1-1	248	219	0.91	1.23	0.08973 ± 1.39	0.9512 ± 0.38	0.2470 ± 0.35	3.0563 ± 1.43	0.1214 ± 3.72	1420 ± 26	1423 ± 4	−0.2
a.1-2	280	252	0.93	1.05	0.08996 ± 1.28	0.8863 ± 0.57	0.2486 ± 0.34	3.0831 ± 1.33	0.1466 ± 3.70	1425 ± 24	1431 ± 4	−0.4
a.1-3	251	233	0.96	1.17	0.08913 ± 1.53	0.8170 ± 4.38	0.2394 ± 0.45	2.9415 ± 1.59	0.1346 ± 3.67	1407 ± 29	1383 ± 6	1.7
a.1-4	264	246	0.96	1.07	0.08992 ± 1.36	0.7734 ± 1.66	0.2409 ± 0.42	2.9868 ± 1.43	0.0930 ± 3.59	1424 ± 26	1391 ± 5	2.3
JS39, Alto Candeias Monzogranite, zircon (UWA mount B63)												
e.1-1	131	41	0.32	0.03	0.08598 ± 0.66	0.0985 ± 0.98	0.2345 ± 0.51	2.7762 ± 0.85	0.0724 ± 1.17	1359 ± 13	1358 ± 6	0.1
e.2-1	263	87	0.34	0.01	0.08532 ± 0.47	0.1022 ± 0.69	0.2256 ± 0.56	2.6537 ± 0.73	0.0673 ± 0.90	1320 ± 10	1311 ± 7	0.7
e.4-1	113	38	0.35	0.03	0.08618 ± 0.71	0.1065 ± 2.08	0.2200 ± 1.02	2.6145 ± 1.24	0.0668 ± 2.35	1344 ± 17	1282 ± 12	4.6
e.5-1	536	135	0.26	0.02	0.08599 ± 0.32	0.0784 ± 0.54	0.2331 ± 0.35	2.7637 ± 0.47	0.0698 ± 0.70	1342 ± 7	1351 ± 4	−0.7
e.7-1	374	102	0.28	0.03	0.08656 ± 0.38	0.0829 ± 0.83	0.2263 ± 0.32	2.7012 ± 0.50	0.0662 ± 1.00	1336 ± 9	1314 ± 4	1.6

e.8-1	105	30	0.29	0.18	0.08590 ± 0.73	0.0892 ± 1.15	0.2254 ± 0.58	2.6696 ± 0.93	0.0655 ± 1.75	1303 ± 19	1308 ± 7	−0.4
e.9-1	398	122	0.32	0.03	0.08610 ± 0.38	0.0960 ± 0.58	0.2264 ± 0.71	2.6872 ± 0.80	0.0678 ± 0.99	1343 ± 9	1316 ± 8	2.0
JL6, Unnamed S-type granite, zircon (UWA mount B76)												
f.2-1	1278	27	0.02	0.03	0.08569 ± 0.32	0.0985 ± 0.98	0.2254 ± 0.80	2.6637 ± 0.86	0.0606 ± 3.23	1331 ± 6	1311 ± 9	1.6
f.3-1	953	18	0.02	0.03	0.08560 ± 0.40	0.1022 ± 0.69	0.2255 ± 0.81	2.6620 ± 0.91	0.0587 ± 8.27	1329 ± 8	1311 ± 10	1.4
f.5-1	1449	36	0.03	0.02	0.08594 ± 0.31	0.1065 ± 2.08	0.2283 ± 0.79	2.7052 ± 0.85	0.0640 ± 4.52	1337 ± 6	1326 ± 10	0.8
f.5-2	830	17	0.02	0.04	0.08582 ± 0.40	0.0784 ± 0.54	0.2252 ± 0.82	2.6652 ± 0.92	0.0571 ± 3.98	1334 ± 8	1309 ± 10	1.9
f.6-1	980	18	0.02	0.03	0.08589 ± 0.40	0.0829 ± 0.83	0.2268 ± 0.83	2.6864 ± 0.92	0.0609 ± 8.08	1336 ± 8	1318 ± 10	1.3
f.8-1	1013	18	0.02	0.04	0.08557 ± 0.39	0.0892 ± 1.15	0.2267 ± 0.81	2.6743 ± 0.90	0.0541 ± 9.72	1329 ± 8	1317 ± 10	0.9
JO6, Rio Fortuna Orthogneiss, zircon (UWA mount 04-76)												
b.1-1	1391	227	0.17	0.03	0.10646 ± 0.36	0.0482 ± 0.91	0.3152 ± 0.31	4.6273 ± 0.47	0.0890 ± 1.12	1740 ± 7	1766 ± 5	−1.5
b.2-1	357	68	0.20	0.00	0.0851 ± 0.60	0.0578 ± 1.16	0.2312 ± 0.47	2.7140 ± 0.77	0.0681 ± 1.26	1319 ± 12	1341 ± 6	−1.7
b.3-1	554	48	0.09	0.00	0.08614 ± 0.52	0.0267 ± 1.35	0.2289 ± 0.43	2.7187 ± 0.67	0.0658 ± 2.26	1341 ± 10	1329 ± 5	0.9
b.4-1	179	49	0.28	0.03	0.10689 ± 0.97	0.0823 ± 1.45	0.3090 ± 0.62	4.5546 ± 1.16	0.0893 ± 2.74	1747 ± 18	1736 ± 10	0.6
b.5-1	266	54	0.21	0.22	0.08195 ± 2.38	0.0520 ± 1.63	0.2231 ± 0.98	2.5222 ± 2.56	0.0499 ± 4.84	1245 ± 46	1298 ± 12	−4.2
b.5-1b	286	51	0.18	0.04	0.08638 ± 0.81	0.0544 ± 1.42	0.2273 ± 0.55	2.7076 ± 0.98	0.0659 ± 2.20	1347 ± 16	1320 ± 7	2.0
b.5-2	238	83	0.36	0.21	0.10274 ± 0.91	0.1038 ± 1.02	0.2953 ± 0.67	4.1848 ± 1.12	0.0818 ± 1.94	1675 ± 17	1668 ± 10	0.4
b.5-3	293	53	0.19	0.22	0.10642 ± 1.16	0.0519 ± 1.26	0.2908 ± 0.55	4.2678 ± 1.26	0.0739 ± 6.11	1740 ± 21	1645 ± 8	5.4
b.7-1	310	75	0.25	0.16	0.10650 ± 0.70	0.0569 ± 1.87	0.3086 ± 0.53	4.5323 ± 0.88	0.0664 ± 2.89	1741 ± 13	1734 ± 8	0.4
b.8-1	734	58	0.08	0.02	0.09154 ± 0.48	0.0243 ± 1.21	0.2493 ± 0.34	3.1463 ± 0.59	0.0711 ± 2.86	1458 ± 9	1435 ± 4	1.6
b.8-2	470	77	0.17	0.00	0.10842 ± 1.13	0.0486 ± 1.26	0.3276 ± 0.56	4.8967 ± 1.26	0.0926 ± 2.02	1773 ± 21	1827 ± 9	−3.0
b.8-3	621	69	0.11	0.00	0.08854 ± 0.53	0.0288 ± 1.48	0.2417 ± 0.37	2.9508 ± 0.64	0.0576 ± 2.73	1394 ± 10	1396 ± 5	−0.1
b.11-1	315	88	0.29	0.07	0.10748 ± 0.67	0.0830 ± 1.00	0.3086 ± 0.53	4.5745 ± 0.85	0.0870 ± 1.60	1757 ± 12	1734 ± 8	1.3
b.11-2	610	70	0.12	0.01	0.08602 ± 0.57	0.0345 ± 1.24	0.2338 ± 0.40	2.7734 ± 0.69	0.0675 ± 2.18	1339 ± 11	1354 ± 5	−1.2
b.13-1	218	60	0.29	0.05	0.10777 ± 0.83	0.0800 ± 1.19	0.3126 ± 0.62	4.6463 ± 1.03	0.0863 ± 2.26	1762 ± 15	1754 ± 9	0.5
b.14-1	236	49	0.21	0.18	0.10722 ± 0.86	0.0617 ± 1.29	0.3123 ± 0.67	4.6189 ± 1.08	0.0847 ± 3.16	1753 ± 16	1752 ± 10	0.1
b.15-1	249	64	0.26	0.00	0.10791 ± 0.84	0.0759 ± 1.06	0.3163 ± 0.55	4.7067 ± 1.00	0.0890 ± 1.62	1764 ± 15	1772 ± 8	−0.4
JO5, Lomas Manechi gneiss, zircon (UWA mount 04-78)												
f.1-1	1489	164	0.11	0.04	0.08566 ± 0.32	0.0336 ± 0.75	0.2274 ± 0.28	2.6858 ± 0.42	0.0656 ± 1.07	1331 ± 6	1321 ± 3	0.7
f.1-2	1370	136	0.10	0.04	0.08561 ± 0.34	0.0300 ± 0.81	0.2285 ± 0.29	2.6970 ± 0.44	0.0647 ± 1.36	1330 ± 6	1326 ± 3	0.2
f.1-3	1353	148	0.11	0.02	0.08613 ± 0.37	0.0330 ± 0.90	0.2278 ± 0.34	2.7050 ± 0.50	0.0658 ± 1.16	1341 ± 7	1323 ± 4	1.4
f.2-1	3963	217	0.06	0.00	0.08581 ± 0.20	0.0170 ± 0.66	0.2299 ± 0.20	2.7202 ± 0.28	0.0686 ± 0.99	1334 ± 4	1334 ± 2	0.0
f.2-2	166	67	0.42	0.06	0.08505 ± 1.03	0.1213 ± 1.18	0.2249 ± 0.63	2.6521 ± 1.05	0.0644 ± 1.73	1317 ± 20	1310 ± 8	0.5
f.4-1	1569	91	0.06	0.01	0.08588 ± 0.30	0.0179 ± 0.99	0.2266 ± 0.25	2.6838 ± 0.39	0.0665 ± 1.25	1336 ± 6	1317 ± 3	1.4
JO18, Santa Rita Orthogneiss, zircon (UWA mount 04-78)												
h.1-1	95	258	2.80	0.15	0.08453 ± 1.62	0.8139 ± 0.80	0.2306 ± 0.91	2.6877 ± 1.86	0.0668 ± 1.24	1305 ± 31	1338 ± 11	−2.5
h.1-2	49	70	1.49	0.12	0.08759 ± 1.73	0.4397 ± 1.44	0.2246 ± 1.31	2.7118 ± 2.17	0.0658 ± 2.43	1320 ± 65	1302 ± 16	1.4
h.2-1	325	360	1.15	0.04	0.08512 ± 0.73	0.3381 ± 0.59	0.2246 ± 0.50	2.6364 ± 0.88	0.0662 ± 0.80	1318 ± 14	1306 ± 6	0.9
h.3-1	448	187	0.43	0.00	0.08530 ± 0.54	0.1256 ± 0.73	0.2287 ± 0.48	2.6895 ± 0.72	0.0666 ± 0.88	1322 ± 11	1328 ± 6	−0.4
h.3-2	410	182	0.46	0.06	0.08434 ± 0.85	0.1331 ± 0.77	0.2263 ± 0.45	2.6321 ± 0.96	0.0651 ± 1.01	1300 ± 17	1315 ± 5	−1.2
h.3-3	299	110	0.38	0.09	0.08626 ± 0.71	0.1130 ± 1.01	0.2300 ± 0.54	2.7350 ± 0.89	0.0673 ± 1.59	1330 ± 17	1333 ± 7	−0.2
h.4-1	131	108	0.86	0.13	0.08486 ± 1.49	0.2583 ± 1.02	0.2244 ± 1.07	2.6269 ± 1.82	0.0671 ± 1.69	1313 ± 29	1305 ± 13	0.6
h.5-1	394	59	0.15	0.06	0.10536 ± 0.53	0.0433 ± 1.58	0.3033 ± 0.44	4.4060 ± 0.68	0.0828 ± 2.28	1746 ± 21	1708 ± 7	0.8
h.6-1	129	132	1.06	0.76	0.08958 ± 1.06	0.3138 ± 1.22	0.2241 ± 0.82	2.7685 ± 1.34	0.0627 ± 2.22	1261 ± 49	1293 ± 10	−2.5
h.8-1	148	218	1.53	0.13	0.08567 ± 1.25	0.4476 ± 0.78	0.2196 ± 0.82	2.5949 ± 1.48	0.0641 ± 1.19	1331 ± 24	1280 ± 9	3.9
JO10, San Andrés Granite, zircon (UWA mount 04-118)												
g.2-1	241	97	0.42	0.06	0.08360 ± 0.74	0.1225 ± 0.97	0.2275 ± 0.51	2.6886 ± 0.90	0.0674 ± 1.19	1332 ± 14	1321 ± 6	0.8
g.3-1	259	210	0.84	0.24	0.08543 ± 1.56	0.2467 ± 0.70	0.2254 ± 0.52	2.6549 ± 1.64	0.0675 ± 1.59	1325 ± 30	1310 ± 6	1.1
g.5-1	372	205	0.57	0.01	0.08285 ± 0.78	0.1703 ± 0.72	0.2253 ± 0.62	2.5738 ± 0.99	0.0671 ± 1.15	1266 ± 15	1310 ± 7	−3.5
g.5-2	324	133	0.42	0.05	0.08333 ± 0.69	0.1210 ± 0.91	0.2240 ± 0.49	2.5734 ± 0.84	0.0647 ± 1.09	1277 ± 13	1303 ± 6	−2.0
g.6-1	139	126	0.94	0.02	0.08368 ± 1.01	0.2796 ± 1.07	0.2231 ± 0.80	2.5744 ± 1.29	0.0665 ± 1.34	1285 ± 20	1298 ± 9	−1.0

Table 2 (Continued)

Grain spot	U (ppm)	Th (ppm)	Th U	4f206 (%)	Isotopic ratios					Ages		Disc. %
					²⁰⁷ Pb/ ²⁰⁶ Pb	²⁰⁸ Pb/ ²⁰⁶ Pb	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	²⁰⁸ Pb/ ²³² Th	²⁰⁷ Pb/ ²⁰⁶ Pb	²⁰⁶ Pb/ ²³⁸ U	
g.7-1	95	61	0.66	0.03	0.08380 ± 1.24	0.1944 ± 1.35	0.2200 ± 0.86	2.5420 ± 1.51	0.0646 ± 1.63	1288 ± 24	1282 ± 10	0.5
g.10-1	116	81	0.73	0.09	0.08349 ± 1.84	0.2120 ± 1.15	0.2343 ± 0.89	2.6978 ± 2.04	0.0679 ± 1.85	1281 ± 36	1357 ± 11	−6.0
g.11-1	352	139	0.41	0.02	0.08274 ± 0.87	0.1227 ± 0.79	0.2218 ± 0.43	2.5299 ± 0.97	0.0672 ± 0.96	1263 ± 17	1291 ± 5	−2.2
g.12-1	309	144	0.48	0.12	0.08366 ± 1.15	0.1418 ± 0.80	0.2270 ± 0.47	2.6182 ± 1.24	0.0656 ± 1.85	1285 ± 22	1319 ± 6	−2.6
g.16-1	121	81	0.69	0.20	0.08395 ± 2.70	0.2062 ± 1.14	0.2194 ± 0.90	2.5415 ± 2.85	0.0640 ± 3.20	1293 ± 53	1279 ± 10	1.1
MQ23, Laje S-type granite, zircon (UWA mount 05-60)												
d.1-1	138	86	0.65	0.00	0.09523 ± 0.91	0.1926 ± 1.04	0.2658 ± 0.97	3.4896 ± 1.33	0.0794 ± 1.45	1533 ± 17	1519 ± 13	0.9
d.2-1	303	118	0.40	0.00	0.08614 ± 0.67	0.1169 ± 0.94	0.2299 ± 0.78	2.7311 ± 1.03	0.0670 ± 1.22	1341 ± 13	1334 ± 9	0.5
d.2-2	147	59	0.42	0.00	0.09731 ± 1.08	0.1249 ± 1.35	0.2716 ± 0.88	3.6438 ± 1.39	0.0815 ± 1.72	1573 ± 20	1549 ± 12	1.6
d.3-1	521	207	0.41	0.02	0.09710 ± 0.45	0.1189 ± 0.64	0.2744 ± 0.68	3.6739 ± 0.82	0.0795 ± 0.96	1569 ± 8	1563 ± 9	0.4
d.4-1	181	91	0.52	0.03	0.09589 ± 0.80	0.1517 ± 1.00	0.2764 ± 0.89	3.6546 ± 1.19	0.0805 ± 1.38	1546 ± 15	1573 ± 12	−1.8
d.4-2	100	65	0.68	0.07	0.09624 ± 1.19	0.2027 ± 1.27	0.2629 ± 1.13	3.4892 ± 1.64	0.0782 ± 1.78	1552 ± 22	1505 ± 15	3.1
d.5-1	84	39	0.48	0.00	0.09433 ± 1.11	0.1459 ± 1.47	0.2729 ± 1.16	3.5497 ± 1.61	0.0839 ± 1.87	1515 ± 21	1556 ± 16	−2.7
d.5-1	86	40	0.48	0.00	0.09572 ± 1.56	0.1450 ± 1.70	0.2715 ± 1.30	3.5836 ± 2.03	0.0846 ± 2.63	1542 ± 29	1549 ± 18	−0.4
d.5-2	860	282	0.34	0.01	0.09512 ± 0.39	0.1031 ± 0.59	0.2809 ± 0.37	3.6834 ± 0.53	0.0855 ± 0.70	1530 ± 7	1596 ± 5	−4.3
d.7-1	163	63	0.40	0.15	0.09513 ± 1.13	0.1235 ± 1.30	0.2723 ± 0.84	3.5716 ± 1.41	0.0819 ± 1.99	1531 ± 21	1552 ± 12	−1.4
d.10-1	1168	14	0.01	0.02	0.08680 ± 0.36	0.0039 ± 2.63	0.2268 ± 0.62	2.7140 ± 0.71	− ± −	1354 ± 7	1317 ± 7	2.7
d.11-1	1674	59	0.04	0.00	0.08635 ± 0.28	0.0107 ± 1.23	0.2280 ± 0.61	2.7151 ± 0.67	− ± −	1345 ± 5	1324 ± 7	1.6
d.11-2	182	72	0.41	0.00	0.09584 ± 0.83	0.1223 ± 1.09	0.2658 ± 0.88	3.5121 ± 1.21	0.0800 ± 1.55	1545 ± 16	1519 ± 12	1.6
d.12-1	1862	39	0.02	0.03	0.08629 ± 0.29	0.0068 ± 1.60	0.2441 ± 0.25	2.9045 ± 0.38	− ± −	1342 ± 6	1408 ± 3	−4.9
d.14-1	134	42	0.32	0.00	0.08585 ± 1.00	0.0946 ± 1.54	0.2328 ± 1.00	2.7554 ± 1.41	0.0685 ± 1.83	1335 ± 19	1349 ± 12	0.1
d.15-1	322	155	0.50	0.02	0.13806 ± 0.43	0.1450 ± 0.64	0.3952 ± 0.75	7.5229 ± 0.86	0.1152 ± 1.01	2203 ± 7	2147 ± 14	0.7
d.16-1	1069	6	0.01	0.25	0.08729 ± 0.37	0.0066 ± 2.49	0.2212 ± 0.62	2.6621 ± 0.73	− ± −	1356 ± 10	1288 ± 7	5.0
d.17-1	655	254	0.40	0.03	0.11165 ± 0.36	0.1146 ± 0.54	0.3263 ± 0.65	5.0239 ± 0.74	0.0928 ± 0.87	1826 ± 6	1821 ± 10	0.3
d.19-1	187	78	0.43	0.08	0.10406 ± 0.71	0.1269 ± 1.05	0.3066 ± 0.87	4.3985 ± 1.12	0.0896 ± 1.41	1698 ± 13	1724 ± 13	−1.5
d.19-2	263	174	0.68	0.15	0.10662 ± 0.75	0.2044 ± 0.77	0.3149 ± 0.66	4.6288 ± 1.00	0.0929 ± 1.14	1742 ± 14	1765 ± 10	−1.3
d.21-1	607	117	0.20	0.15	0.08586 ± 0.78	0.0763 ± 0.95	0.2020 ± 0.53	2.3918 ± 0.94	0.0743 ± 1.97	1335 ± 15	1186 ± 6	11.1
JP3, Iata sillimanite gneiss, zircon (UWA mounts B68 and B75)												
a.1-1	100	123	1.27	0.00	0.09041 ± 1.55	0.0036 ± 26.1	0.2210 ± 2.53	2.7529 ± 2.96	0.0020 ± 36.4	1433 ± 29	1287 ± 29	10.2
a.2-1	79	34	0.44	0.05	0.08541 ± 0.94	0.1350 ± 1.5	0.2220 ± 0.65	2.6150 ± 1.14	0.0673 ± 1.8	1325 ± 18	1293 ± 8	2.5
a.4-1	125	147	1.21	0.00	0.09527 ± 2.38	0.0132 ± 7.1	0.4316 ± 3.38	5.6624 ± 4.11	0.0105 ± 19.5	1531 ± 44	2313 ± 66	−51.1
a.7-2	137	62	0.47	0.10	0.09550 ± 1.09	0.1337 ± 1.48	0.2591 ± 0.99	3.4111 ± 1.47	0.0729 ± 1.71	1537 ± 21	1485 ± 13	3.4
j.2-1	379	21	0.06	0.01	0.08494 ± 0.64	0.0164 ± 2.0	0.2315 ± 0.46	2.7121 ± 0.79	0.0662 ± 2.3	1314 ± 12	1343 ± 6	−2.1
j.3-1	34	14	0.43	0.41	0.08051 ± 3.70	0.1272 ± 2.7	0.2225 ± 1.49	2.4734 ± 3.92	0.0613 ± 6.1	1212 ± 71	1295 ± 17	−6.8
j.8-1	209	74	0.36	0.17	0.09585 ± 0.89	0.1077 ± 1.4	0.2703 ± 0.67	3.5736 ± 1.11	0.0774 ± 2.0	1546 ± 17	1542 ± 9	0.2
JO8, Las Madres garnet gneiss, Chiquitania Complex, zircon (UWA mount 04-78)												
g.1-1	330	157	0.49	0.00	0.10339 ± 0.59	0.1399 ± 0.73	0.2997 ± 0.49	4.2726 ± 0.77	0.0852 ± 0.90	1686 ± 11	1690 ± 7	−0.2
g.2-1	887	254	0.30	0.02	0.10081 ± 0.33	0.0869 ± 0.55	0.2898 ± 0.27	4.0287 ± 0.43	0.0849 ± 0.66	1639 ± 6	1641 ± 4	−0.1
g.3-1	377	167	0.46	0.01	0.10325 ± 0.49	0.1324 ± 0.65	0.3061 ± 0.49	4.3578 ± 0.69	0.0889 ± 0.90	1683 ± 9	1721 ± 7	−2.3
g.4-1	231	95	0.42	0.03	0.10379 ± 0.76	0.1217 ± 1.00	0.2915 ± 0.60	4.1720 ± 0.96	0.0835 ± 1.39	1693 ± 14	1649 ± 9	2.6
g.4-2	842	418	0.51	0.00	0.10271 ± 0.34	0.1460 ± 0.46	0.2980 ± 0.33	4.2208 ± 0.47	0.0848 ± 0.57	1674 ± 6	1682 ± 5	−0.5
g.5-1	372	11	0.03	0.04	0.07689 ± 0.72	0.0100 ± 3.60	0.1921 ± 0.58	2.0347 ± 0.93	− ± −	1118 ± 15	1133 ± 6	−1.3
g.5-2	86	37	0.45	0.42	0.09980 ± 1.53	0.1283 ± 1.57	0.3002 ± 1.16	4.1313 ± 1.91	0.0803 ± 2.99	1620 ± 28	1692 ± 17	−4.5
g.6-1	902	466	0.53	0.02	0.10347 ± 0.37	0.1578 ± 0.48	0.2974 ± 0.30	4.2422 ± 0.47	0.0875 ± 0.57	1687 ± 7	1678 ± 4	0.5
g.7-1	683	150	0.23	0.00	0.09612 ± 0.43	0.0695 ± 0.80	0.2774 ± 0.37	3.6759 ± 0.57	0.0846 ± 0.99	1550 ± 8	1578 ± 5	−1.8
g.8-1	456	41	0.09	0.08	0.08654 ± 0.56	0.0295 ± 1.49	0.2316 ± 0.49	2.7631 ± 0.74	− ± −	1350 ± 11	1343 ± 6	0.6
g.8-2	113	47	0.43	0.09	0.10317 ± 1.11	0.1287 ± 1.43	0.2884 ± 0.85	4.1037 ± 1.39	0.0848 ± 2.04	1682 ± 20	1634 ± 12	2.9
g.9-1	46	26	0.59	0.31	0.10471 ± 2.28	0.1689 ± 2.22	0.3163 ± 1.41	4.5667 ± 2.68	0.0945 ± 3.93	1709 ± 42	1772 ± 22	−3.6
g.10-1	183	94	0.53	0.14	0.10215 ± 0.69	0.1529 ± 0.89	0.3048 ± 0.69	4.2925 ± 0.98	0.0863 ± 1.20	1664 ± 13	1715 ± 10	−3.1
g.11-1	181	115	0.65	0.15	0.10192 ± 0.88	0.1931 ± 0.92	0.2926 ± 0.93	4.1119 ± 1.29	0.0850 ± 1.45	1659 ± 16	1655 ± 14	0.3
g.12-1	560	42	0.08	0.01	0.08502 ± 0.51	0.0229 ± 1.55	0.2187 ± 0.44	2.5642 ± 0.68	− ± −	1317 ± 10	1275 ± 5	3.1
g.12-2	301	116	0.40	0.07	0.10156 ± 0.68	0.1147 ± 0.85	0.2924 ± 0.52	4.0947 ± 0.85	0.0829 ± 1.33	1653 ± 13	1653 ± 8	0.0

JO7, Velasco alkali granite, zircon (UWA mount 04-78)												
d.2-1	1202	484	0.42	0.49	0.04788 ± 3.72	0.1344 ± 2.37	0.0211 ± 0.82	0.1396 ± 3.81	0.0063 ± 4.20	93 ± 88	134.9 ± 1.1	-45
d.3-1	2438	2091	0.89	0.14	0.04810 ± 1.64	0.2747 ± 0.95	0.0210 ± 0.72	0.1393 ± 1.79	0.0065 ± 1.31	104 ± 39	134.0 ± 1.0	-29
d.5-1	1354	486	0.37	0.36	0.04758 ± 3.25	0.1201 ± 1.97	0.0211 ± 1.38	0.1387 ± 3.53	0.0064 ± 4.09	78 ± 77	134.9 ± 1.8	-72
d.9-1	3361	2795	0.86	0.32	0.04758 ± 1.62	0.2674 ± 0.57	0.0219 ± 1.34	0.1440 ± 2.10	0.0067 ± 1.62	78 ± 38	140.0 ± 1.9	-78
d.11-1	3762	3014	0.83	0.36	0.04942 ± 1.46	0.2581 ± 0.78	0.0216 ± 0.76	0.1475 ± 1.65	0.0066 ± 1.26	168 ± 34	138.0 ± 1.0	18

Notes: Uncertainties are 1σ. Isotopic ratios errors in %. All Pb in ratios are radiogenic component. Most are corrected from ²⁰⁴Pb and some for ²⁰⁸Pb (metamorphic, Th-poor grains or rims). Analyses lacking ²⁰⁸Pb/²³²Th ratio were corrected using ²⁰⁸Pb, disc.; discordance, as 100 - 100[(²⁰⁶Pb/²³⁸U)/(²⁰⁷Pb/²⁰⁶Pb)]/206 = (common ²⁰⁶Pb)/(total measured ²⁰⁶Pb) based on measured ²⁰⁴Pb.

Notes: Uncertainties are 1σ . Isotopic ratios errors in %. All Pb in ratios are radiogenic component. Most are corrected from ^{204}Pb and some for ^{208}Pb (metamorphic, Th-poor grains or rims). Analyses lacking $^{208}\text{Pb}/^{232}\text{Th}$ ratio were corrected using ^{208}Pb , disc.: discordance, as $100 - 100 \cdot (t^{206}\text{Pb}/t^{238}\text{U}) / (t^{207}\text{Pb}/t^{206}\text{Pb})$ (total measured ^{206}Pb) based on measured ^{204}Pb .

to separate REE, followed by Sm and Nd separation using anionic poly-Teflon HDEHP LN-B50-A (100–200 mesh) resin according to Patchett and Ruiz (1987). Each sample was dried to a solid and then loaded with 0.25N H_3PO_4 on an appropriated filament (single Ta for Sm and triple Ta–Re–Ta for Nd). Isotopic ratios were measured in static mode with a VG Sector 54 multi-collector mass spectrometer at the Laboratório de Geologia Isotópica of the Universidade Federal do Rio Grande do Sul (Brazil). We normally collected 100–120 ratios with a 1-V 88Sr beam and a 0.5–1-V ^{144}Nd beam. Nd ratios were normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. All analyses were adjusted for instrumental bias due to periodic adjustment of collector positions as monitored by measurements of our internal standards. Measurements for the Nd Spex $^{143}\text{Nd}/^{144}\text{Nd} = 0.511130$ (± 0.000010). Total blanks average were <100 pg for Sm and <500 pg for Nd. Correction for blank was insignificant for Nd isotopic compositions and generally insignificant for Sm/Nd ratios. Neodymium crustal residence ages (T_{DM}) were calculated following the depleted mantle model of De Paolo (1981). Nd_t values were calculated using the U–Pb SHRIMP or U–Pb TIMS ages from this work and from the literature. For three samples lacking U–Pb data the assumed ages are based on stratigraphic correlation (Table 3).

4. Geochronological results and discussion

4.1. U–Pb SHRIMP

Analytical results are grouped into two provinces (Rondônia-Juruena and Sunsás) and described in chronological order, from the oldest to the youngest samples, following the order of Table 1. This table also shows the geographic coordinates and the dated minerals for each sample. The U–Pb data are presented in Table 2 and a summary of the results in Table 3.

4.1.1. Rondônia-Juruena Province

4.1.1.1. Lomas Manechi granulitic gneiss (JO3). The outcrop is located 7 km west of Ascención in eastern Bolivia, Santa Cruz Department (Fig. 4). The rock is dark grey displaying an irregular foliation (nebulitic) and has pyroxene. Zircon grains (120–250 μm in diameter) are short prisms and rounded grains; all have metamorphic rims, some large enough to be analysed by SHRIMP. The cores are euhedrally zoned and truncated by the metamorphic rims. The zoned magmatic population of zircon has a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1818 ± 13 Ma (MSWD = 2.6; $n = 6$) whereas the metamorphic rims have the weighted mean age of 1338 ± 21 Ma (Table 2; Fig. 5). Because this rim age has low precision, monazite from the same sample was also dated (Fig. 5) providing a more precise age of 1339 ± 4 Ma (MSWD = 1.15; $n = 6$), which is taken as a better estimate of the metamorphic peak. Monazite grains (100–200 μm) are yellowish, clear, rounded, with irregular internal zoning. Because both zircon (partially) and monazite (fully) recrystallized or overgrew existing grains, the metamorphic grade is high and is interpreted as formed during the Candeias collisional orogeny. Its magmatic age of 1818 Ma is the oldest age in Bolivia and is comparable to the basement ages within the Juruena region in northern Mato Grosso, particularly the Juruena Granodiorite (1817–1848 Ma; JICA-MMAJ, 2000). The rock also has two inherited grains with ages at ca. 1874 Ma. These ages are equivalent to the ages of late-Tapajós volcano-plutonism (Irirí Group and Maloquinha Suite; Santos et al., 2004a,b). Sample JO3 could be a fragment of Juruena-type crust within the Sunsás Orogen in Bolivia.

4.1.1.2. Jamari Complex quartz-diorite (GR35). This sample comes from an outcrop located 5 km to the south of Presidente Médici (Fig. 3) along BR364 highway in Rondônia. The rock is fine to medium-grained, foliated, with plagioclase porphyroclasts in a

Table 3

Summary of the U–Pb ages and Sm–Nd model ages discussed in text

Sample	Rock	Unit	Ages			$T_{DM(t)}$	ϵ_{Nd}	Ref.
			Metamorphic	Magmatic	Detrital/inherited			
J03	Granulitic gneiss	Lomas Manechi	1339 ± 4	1818 ± 13		2.07	+0.53	1
GR35	Quartz-diorite	Jamari	1649 ± 5	1758 ± 7		2.00	+1.57	1
GR59	Tonalite	Jamari	1677 ± 6	1753 ± 9		1.90	+1.95	1
JL78	Tonalite	Jamari	1334 ± 7	1738 ± 6		1.95	+1.04	1
MQ96	Dacite	Roosevelt		1740 ± 8		1.72	+3.81	2
PT12	Paragneiss	Ouro Preto	1657 ± 12					2
JO12	Orthogneiss	Refugio		1641 ± 4		1.66	+4.06	1
GR333	Meta-granite	S. Providência	1348 ± 4	1515 ± 8		2.00	−0.95	1
JO14	Tonalite	San Ramón		1429 ± 4		1.57	+2.32	1
JS39	Monzogranite	Alto Candeias		1339 ± 7				1
JL6	S-type granite	Unnamed	1339 ± 3					1
JO9	Gneiss	Las Madres		1330		1.74	−0.61	1
JO16	Gneiss	Rio Branco		1330		1.58	+0.94	1
JO6	Orthogneiss	Rio Fortuna	1336 ± 3	1349 ± 6	1674, 1772–1734	2.06	−3.83	1
JO5	Gneiss	Lomas Manechi	1334 ± 3	1334 ± 3		2.06	−3.97	1
JO18	Orthogneiss	Santa Rita		1319 ± 6	1746	1.96	−2.57	1
JO10	Granite	San Andrés		1275 ± 7	1331 ± 13	1.68	−0.15	1
GR66	Paragneiss	N. Brasilândia			< 1160 ± 14, 1210, 1290, 1427, 1753			2
MQ23	S-type granite	Laje		1110 (?)	1334 ± 9, 1356 ± 10, 1545, 1826, 2203			1
JP3	Sillimanite gneiss	Iata			1210, 1325, 1433, 1531, 1546			1
MT1	Quartzite	Aguapeí			< 1171, 1278, 1447, 1617, 1660			3
JO13	Rhyolite	Puquio		< 1110		1.54	< −1.46	1
JO8	Garnet gneiss	Las Madres	1118 ± 15		1678, 1640, 1551, 1351, 1318	1.86	−4.88	1
JO7	Alkali granite	Velasco		136 ± 2		0.74	−2.37	1

Notes: All ages are U–Pb SHRIMP ages (Ma), except sample PT12 (U–Pb TIMS). Ref.—references for ages: 1, this work; 2, Santos et al. (2000); 3, Santos et al. (2001); 4, Santos (2003). The ages in italic on “magmatic” column are ages estimated by correlation (see text). $T_{DM(t)}$ model ages in Ga.

granoblastic matrix composed of quartz, plagioclase, epidote and amphibole. Mylonitic foliation averages N15°E, dipping is 60°SE, and lineation plunges 55°; S70°E. Local partial melting produced thin (2–10 cm thick) quartz-K-feldspar veins with garnet. The quartz-diorite has a single population of zircon with crystals that are 50–200 μ m long, prismatic (aspect ratio 1:3), finely zoned, with no evidence of older cores. Two grains have metamorphic rims or metamorphic zones. The age of the magmatic population is 1758 ± 7 Ma (MSWD = 1.9; n = 8; Fig. 6), a typical age of the Jamari Complex (Santos, 2003; Schobbenhaus et al., 2004). The metamorphic rims are younger: 1724 ± 8 Ma (rim d.17-2) and 1649 ± 5 Ma (rim d.2-1) and display very low Th/U ratios of 0.09 and 0.01

(Table 2) typical of metamorphic growth. The age of 1649 Ma is identified as coeval with the Quatro Cachoeiras collision. Because no regional event is recognized at 1724 Ma this U–Pb SHRIMP age is likely to be the result of spot analyses overlapping both the rim and the magmatic core.

4.1.1.3. Jamari Complex tonalite (GR59). This tonalite was collected about 21 km NW of Ariquemes (Fig. 3) in the Madalena River Basin in Rondônia. It is a medium-grained tonalitic orthogneiss with regular, centimetric banding and folded quartz-K-feldspar veins. Texture is porphyroclastic and plagioclase porphyroclasts are enveloped by biotite-hornblende concentrates. The mylonitic

Fig. 5. U–Pb concordia plot of sample JO3, Lomas Manechi granulitic gneiss, showing a magmatic age at 1818 ± 13 Ma, a metamorphic age at 1339 ± 4 Ma, and an inherited age at 1874 ± 9 Ma.

Fig. 6. Concordant $^{207}\text{Pb}/^{206}\text{Pb}$ age of GR35 quartz-diorite at 1758 ± 7 Ma, an example of Jamari Complex. The age of metamorphic rim at 1649 ± 5 Ma (rim d.2-1) is also shown (see Table 2). Blank ellipse corresponds to a mixed age of 1724 ± 8 Ma.

foliation is sigmoidal trending $\text{N}30^\circ\text{E}$; 80°NW . The tonalite has metric lenses of calc-silicate gneiss. Finely zoned zircon grains are prismatic (1:2–1:5) and 50–350 μm long. They have rounded edges and euhedral apatite inclusions are common. The Th/U ratios are between 0.34 and 0.66. The rock has two ages – one at 1753 ± 8 Ma and the other at 1677 ± 6 Ma, 2σ (Figs. 7 and 8). The younger and magmatic age occurs both in single crystals and in recrystallized rims developed over older cores. Grain k.5 has a core with 1750 ± 13 Ma and magmatic rim with 1676 ± 17 Ma (Table 2 and Fig. 8). The older inherited age of 1753 ± 8 Ma (MSWD = 0.43; $n=6$) is correlated with the Jamari Complex. The tonalite GR59 is interpreted to have been deformed and re-melted about 74 m.y. later during the Quatro Cachoeiras orogeny.

4.1.1.4. Jamari Complex tonalite (JL78). This tonalite was sampled about 1.5 km to the south of BR364 highway between Ariquemes and Jaru in Rondônia. The gneiss is medium-grained and has centimetric bands of mafic (biotite and rare amphibole) and felsic (quartz and plagioclase, with minor biotite and magnetite) zones.

Fig. 7. Concordia plot of sample GR59, Jamari Complex tonalite displaying two ages at 1753 ± 8 and 1677 ± 6 Ma.

Fig. 8. BSE image of grain k.5 of sample GR59 (Jamari Complex tonalite) displaying two magmatic ages at 1750 ± 13 Ma and 1676 ± 16 Ma (Table 2). The younger age reflects the partial melting of the rock during the Quatro Cachoeiras orogeny.

Orthoamphibolite lenses are common and their mylonitic foliation trends $\text{N}5^\circ\text{W}$. Lineations are marked by ribbon quartz striking $\text{N}70^\circ$; $\text{N}55^\circ\text{E}$. About two thirds of the zircon grains from JL78 are equidimensional, elliptical to circular in plane section, due to metamorphic re-crystallization and the other third are prismatic (about 180–250 μm long). All grains show bright rims in BSE (black in CL) over magmatic zoned cores (Fig. 9). The age of the cores is 1738 ± 6 Ma (MSWD = 2.6; $n=7$ out of 8; Fig. 10) slightly younger than the other ages of the Jamari Complex (i.e. 1761 and 1753 Ma, GR59 and GR35). Metamorphic rims have an age of 1334 ± 7 Ma (MSWD = 4.9; $n=7$; Fig. 10), and are interpreted as high-grade metamorphic zircon formed during the Candeias collision.

4.1.1.5. Refugio Orthogneiss (JO12). This gneiss crops out 12 km to the east of San Javier along the San Javier-Concepción road in Eastern Bolivia, Department of Santa Cruz (Fig. 4). The gneiss is leucocratic, well banded ($\text{N}30^\circ\text{W}$) and has the composition of syeno- to monzogranite granite with biotite as its main mafic mineral. Banding is sinuous and probably of magmatic origin. On the 1:250,000 Concepción sheet of Bolivia (Litherland et al., 1986) this rock is

Fig. 9. BSE image of zircon h.3 of sample JL78. Most zircons of this sample have metamorphic rims and magmatic cores such as grain h.3. This grain has a zoned magmatic core with normal Th/U ratios at 0.40 and a BSE bright metamorphic rim with very low Th/U ratio of 0.09 (Table 2). The rock was formed during the Jamari orogeny (1743 ± 9 Ma) and metamorphosed about 400 m.y. later during the Candeias orogeny (1334 ± 6 Ma) – see Fig. 10.

Fig. 10. Concordia plot of sample JL78 (Jamari Complex tonalite) displaying magmatic population of zircon (cores) at 1738 ± 6 Ma and metamorphic population (rims) at 1334 ± 6 Ma.

mapped as the Refugio Granite. This gneiss has two populations of zircon none with visible metamorphic rims and older cores. Zircon is zoned and prismatic (aspect ratio 1:1.5 to 1:3), 100–240 μm long, with Th/U ratios from 0.53 to 0.73 (Table 2). The magmatic population has the pooled $^{207}\text{Pb}/^{206}\text{Pb}$ age ($n=8$) of 1641 ± 4 Ma (MSWD=0.66) and correlates to the Quatro Cachoeiras orogeny (Fig. 11). The inherited grains are slightly older and apparently represent only one inherited population formed at 1668 ± 8 Ma (MSWD=0.64; $n=4$). The Refugio orthogneiss is much older than the San Andrés Granite (sample JO10, 1275 Ma) and may represent a fragment of the Rondônia-Juruena Province which survived within the Sunsás Orogen in Bolivia. Additional support for this hypothesis comes from the similar inherited ages of 1663 ± 13 Ma and 1686 ± 16 Ma detected by Boger et al. (2005) in zircon from the Lomas Manechi charnockite (sample 240) and San Rafael Granite (228). The Sm–Nd model age (depleted mantle) is 1.66 Ga (Table 1) and the ϵ_{Nd} (at 1641 Ma) is +4.06. This suggests that the melt which generated the Refugio Orthogneiss was derived from a source which was dominantly juvenile with little or no crustal contamination.

Fig. 11. U–Pb concordia plot of sample JO12, Refugio Orthogneiss showing magmatic age at 1641 ± 4 Ma ($n=8$) and an inherited population at 1668 ± 8 Ma ($n=4$).

Fig. 12. U–Pb concordia plot of sample GR333, Serra Providência Meta-granite. The rock crystallized at 1515 ± 8 Ma and was metamorphosed at 1348 ± 4 Ma (ages of metamorphic rims). Most discordant analyses (10% and 16%; white ellipses) are not used.

The inherited zircon (1668 ± 8 Ma) may be derived from such a juvenile source of ca. 1665 Ma.

4.1.1.6. Serra Providência Meta-granite (GR333). This meta-granite comes from 15 km to the NW of Ji-Paraná town near the western border of Serra Providência Batholith (type-locality) in Rondônia (Fig. 3). It is a pinkish to greyish, coarse-grained monzogranite with mylonitic structure and irregular banding. Rapakivi texture is partially preserved and its mafic bands are mainly composed of biotite, plagioclase and hornblende, and felsic bands of quartz and K-feldspar. Banding strikes $N60^\circ W$; $65^\circ SW$ with lineation trending $N20^\circ$; $N55^\circ W$. Where deformation is more intense the gneiss is finer grained and the banding is more regular. Average composition is oligoclase (33%), microcline (28%), quartz (26%), biotite (8%), hornblende (4%), titanite (1%), allanite, zircon, apatite and fluorite (<1%). Metamorphic re-crystallization occurred at middle amphibolite facies temperatures. Zircon crystals are prismatic, with aspect ratios 1:2 to 1:4, poorly zoned, and Th/U ratios vary from 0.43 to 0.99 (Table 2). Metamorphic areas are present, particularly at the pyramidal terminations, but do not form complete rims as in sample JL78. Metamorphic areas are extremely low in Th/U ratios (as low as 0.004, as in grain b.8-1), bright in BSE and dull in CL images. The magmatic age is 1515 ± 8 Ma (MSWD = 1.4; $n=5$; Fig. 12), which was obtained from the most concordant data (i.e. >98%), excluding grains b.12-1 and b.15-1 (Table 2). This age is in agreement with previous dating of the Serra Providência Batholith (Bettencourt et al., 1999). The metamorphic age of the Serra Providência Granite is additional evidence of mylonitization associated with the Candeias collision at 1348 ± 4 Ma (MSWD = 1.4; $n=4$; Fig. 12). This age is slightly older than the age of the metamorphism of the Rio Crespo Suite in Rondônia (1331 ± 9 Ma; Bettencourt et al., 2006).

4.1.2. Sunsás Province

4.1.2.1. San Ramón Tonalite (JO14). This sample was collected 2 km south of San Ramón on the road to Santa Cruz de La Sierra in Bolivia (Fig. 4). It is composed of plagioclase, hornblende and quartz with minor biotite and is cut by trondhjemitic veins, 2–8 cm thick. No foliation is visible nor is there evidence of metamorphism. Zircon grains are clear and relatively large (200–600 μm). Only two grains show re-crystallization zones of metamorphic zircon (b.1-1 and b.2-1). Titanite is abundant as brown-reddish chips of 500 μm to 1 mm

Fig. 13. Concordia diagram of the San Ramón Tonalite where U–Pb ratios of titanite (hatched) and zircon group at the age of 1429 ± 4 Ma.

in diameter. Titanite has darker and lighter zones in BSE and analyses were concentrated in the brighter zones, which have higher U content (240–280 ppm; Table 2). All $^{207}\text{Pb}/^{206}\text{Pb}$ ages of zircon and titanite form a pooled age of 1429 ± 4 Ma (MSWD = 1.15; $n = 13$; Fig. 13). The age of the titanite is undistinguishable from the zircon age (within error). The Sm–Nd model age (Table 1) is 1.57 Ga and the ϵ_{Nd} (at 1429 Ma) is +2.3, which demonstrates the dominantly juvenile origin of the rock. The age of the San Ramón tonalite is similar to the age of the juvenile Santa Helena Tonalite (Geraldes et al., 2001) and of the Pindaituba Suite (Ruiz, 2006) in western Mato Grosso in the southern part of the Sunsás Belt. All units are interpreted as juvenile and derived from the upper mantle (Geraldes et al., 2001; Santos et al., 2002; Ruiz, 2006) and as remnants of the first magmatic arc accreted to the craton during the beginning of the Sunsás Orogen evolution. The orogeny is named Santa Helena (Geraldes et al., 2001; Santos et al., 2002; Santos, 2003; Ruiz, 2006) and is best known in Mato Grosso (Geraldes et al., 2001; Ruiz, 2006). The apparent scarcity of preserved granulites formed during the Santa Helena orogeny within the Sunsás Belt in Bolivia and Rondônia may result from lack of both mapping and robust geochronology. Intense magmatic activity during 1450–1420 Ma is suggested by the strong presence of detrital zircons with this age within the late and post-Sunsás sedimentary rocks (Santos et al., 2002).

4.1.2.2. Alto Candeias Granite (JS39). This rock is a monzogranite cropping out 6 km to the northeast of Campo Novo in Rondônia (Fig. 3) at the centre of the Candeias Batholith. There are two facies, one equigranular and the other porphyritic. The porphyritic facies has a medium to coarse-grained matrix containing elliptic and tabular crystals of perthitic orthoclase (2–6 mm) mantled by plagioclase. The phaneritic matrix is composed of quartz, albite, amphibole, biotite and opaques. Mesoperthites (albite in orthoclase) are common. The equigranular facies is a biotite monzogranite with magmatic flux foliation and common angular xenoliths, which are mainly paragneisses. Discrete ductile shears are present in the core of the batholith. The rock has only one population of magmatic zircon and metamorphic rims or zones were not detected. Zircon is prismatic (aspect ratio 4:1), zoned with U contents ranging from 105 to 503 ppm (Table 2). The age is 1339 ± 7 Ma (MSWD = 1.7; $n = 6$; Fig. 14), which represents the age of the Candeias Batholith in its type-locality and is comparable to the U–Pb ages of the components in the Pensamiento Granite Com-

Fig. 14. U–Pb concordia plot of zircon of sample JS39, a monzogranite of Alto Candeias Batholith in its central region. The magmatic $^{207}\text{Pb}/^{206}\text{Pb}$ age is 1339 ± 7 Ma. The gray ellipse is from an outlier not used in age calculation.

plex in Bolivia: the San Rafael (1334 ± 12 Ma, Boger et al., 2005), La Junta (1347 ± 21 Ma) and Diamantina (1340 ± 20 Ma) granites (ages recalculated from Matos et al., 2006).

4.1.2.3. Un-named S-type granite (JL6). This rock comes from an outcrop of paragneiss southwest of Ariquemes in Rondônia (Fig. 3). The gneiss has dark bands composed mainly of biotite and garnet layered with felsic quartz-feldspathic bands. Biotite is iron-rich and partially altered to chlorite and epidote. Veins and pods of garnet leucogranite derived of partial melt are common and one of these was sampled (JL6). Most of these veins are parallel to the banding (N10°E; 80°SE and mineral lineation at 35°; S10°E). The asymmetry of pressure shadows on garnet crystals indicates sinistral movement. Zircon tends to be equidimensional (120–200 μm), multifaceted, appearing rounded. No zoning is visible and all crystals are bright in BSE. All grains are metamorphic, U-rich (830–1449 ppm) and Th-poor (17–36 ppm). Small nuclei (10–20 μm) are present in most of grains but impossible to be dated because they are small, fractured and metamict. Th/U ratios are very low (0.018–0.022), indicative of a metamorphic origin. The age is 1339 ± 3 Ma (MSWD = 0.61; $n = 6$ – Fig. 15) and suggests that the rock was metamorphosed during the Candeias collision. Most rocks of Jamari Complex and Serra Providência Suite of central-north Rondônia were strongly and variably metamorphosed during 1350–1320 Ma. It is uncertain whether the S-type melt derives from paragneiss associated with the Quatro Cachoeiras metamorphic suite (ca. 1650 Ma; Rizzotto et al., 2004) or with the Rio Crespo metamorphic suite (1331 ± 9 Ma; Bettencourt et al., 2006).

4.1.2.4. Rio Fortuna Orthogneiss (JO6). This rock was sampled 28 km to the west of Ascensão and 2 km south of Brazil–Bolivia border in Santa Cruz Department (Fig. 4) in the area of the Rio Fortuna Gneiss (Litherland et al., 1986). It is a dark grey orthogneiss with granodioritic to tonalitic composition and has conspicuous and coarse metamorphic banding (layers of 2–12 cm thick trending N40°W). Zircon (200–400 μm) is dominantly prismatic and most grains have well-defined core and rim structures (grains b.5, b.8, and b.11). There are two main populations of zircon: zoned magmatic zircon and rims both formed at 1336 ± 3 Ma (MSWD = 0.07; $n = 4$; Fig. 16) and inherited grains and cores in the age range of 1772–1734 Ma. One core (b.5-2) has the age of 1674 Ma, which correlates to the

Fig. 15. U–Pb concordia plot of zircons from sample JL6, an unnamed S-type granite. The 1339 ± 3 Ma age is remarkably similar to the age of granulite metamorphism in Bolivia (sample JO5, Fig. 17).

Fig. 17. U–Pb concordia plot of zircons from sample JO5, a gneiss from the Lomas Manechi Complex. The age of 1334 ± 2 Ma is from magmatic and metamorphic zircons. This is an example of granulite facies metamorphism associated to the Candeias orogeny in Bolivia.

Quatro Cachoeiras orogeny. The two contrasting populations of zircon – magmatic and young (1336 Ma) versus inherited and old (1772 – 1734 Ma and 1674 Ma) – indicate that the rock was formed during the Candeias collisional orogeny and that the rock is derived from the older Jamari Complex and the Quatro Cachoeiras metamorphic suite.

4.1.2.5. Lomas Manechi gneiss (JO5). This is a well foliated ($N50^\circ W$) gneiss of granodioritic composition (plagioclase, quartz, biotite, and microcline) collected about 30 km to the south of Ascención and 35 km to the south of Brazil–Bolivia border in an area mapped as Lomas Manechi Complex (Litherland et al., 1986) – Fig. 4. The foliation shows mylonitic stretching of quartz and plagioclase. Most zircon grains are large (200 – 500 μm) and rounded and some are short prisms with rounded edges. Zircons are U-rich (up to 3950 ppm; Table 2) and have a consistent concordant $^{207}Pb/^{206}Pb$ age at 1334 ± 2 Ma (MSWD = 1.6; $n = 6$; Fig. 17). Five analyses are on

metamorphic zircon grains (unzoned and very low Th/U ratios of 0.06–0.11) or rims and one analysis is from a magmatic area (zoned and Th/U ratio of 0.46). Both magmatic and metamorphic ages are within error. The age correlates with the Candeias orogeny and not with the basement. In fact most of high-grade metamorphism in Eastern Bolivia and Western Brazil was produced during the Candeias orogeny and even some during the Nova Brasilândia orogeny (JO8). Within the whole exposed Sunsás Orogen, granulitic metamorphism is typical of the Mesoproterozoic but not of basement rocks.

4.1.2.6. Santa Rita Orthogneiss (JO18). This rock was collected from 34 km to the east of San Ignacio town in Bolivia, Santa Cruz Department (Fig. 4). It is an orthogneiss of granodiorite composition, with flat and parallel banding. Individual gneissic bands range from 2 to 30 cm in thickness and are cut by a few, irregular and thin quartz–K-feldspar veins. Zircon is prismatic (1:1.5 to 1:4), zoned and unzoned, with irregular edges and no evidence of either metamorphic rims or zones and older cores. Most of the zircon grains have the same age at 1319 ± 6 Ma (MSWD = 1.3; $n = 8$; Fig. 18) and only one grain is inherited (1729 ± 9 Ma). This indicates that the Santa Rita Gneiss is younger than the Chiquitania Complex (older than 1400 Ma; Litherland et al., 1986) and that it was formed during the late stages of Candeias orogeny. The inherited zircon has an age comparable to the age of felsic volcanic rocks of Rondônia-Juruena Province such as the Roosevelt Group dacite (MQ96, 1740 ± 8 Ma; Santos et al., 2000) and to the rocks of Jamari Complex (1760–1740 Ma, this work).

4.1.2.7. San Andrés Granite (JO10). This sample was collected 24 km SW of Concepción along the road between San Javier and Concepción in Santa Cruz Province, Bolivia (Fig. 4). It is a coarse-grained leucocratic, biotite granite with discrete foliation trending $N20^\circ W$. Zircon grains are clear, prismatic (aspect ratio 1:1.5 to 1:3), weakly zoned, 80–150 μm long, and contain intermediate amounts of U (95–372 ppm); Th/U ratios range between 0.41 and 0.94 (Table 2). Some crystals (g.5-2 and g.10-1) have areas interpreted as metamorphic, which are too small to be dated (<10 μm). All $^{207}Pb/^{206}Pb$ ages form one population at 1275 ± 7 Ma (MSWD = 1.16; $n = 7$, Fig. 19). Two grains (g.2-1 and g.3-1) are inherited and correlated to the rocks of the Candeias orogeny. The age of 1275 Ma is younger than

Fig. 16. U–Pb concordia plot of zircon of the Rio Fortuna Gneiss (JO6). The rock has two main ages: the age of 1336 ± 3 Ma groups ages of magmatic zircon and metamorphic rims and the 1772 – 1734 Ma range represents inherited zircon cores, possibly derived from Jamari-type crust.

Fig. 18. Concordia plot of Santa Rita Orthogneiss of Chiquitania Complex (JO18). The age at 1319 ± 6 Ma demonstrates that the rock is younger than the Chiquitania Complex (supposed to be older than 1400 Ma; Litherland et al., 1986) and that it was formed during the Candeias orogeny. The inherited age of 1729 ± 9 Ma may represent participation of Jamari-type crust in the melt which generated rock JO18.

the rocks generated during the Candeias orogeny, but older than the age of the Nova Brasilândia orogeny. The age of 1275 ± 7 Ma may represent granite formation during another, perhaps discrete, magmatic arc here named the San Andrés. Litherland et al. (1986) mention several plutons formed at about this time, such as Orobayaya Granite (1283 ± 33 Ma), El Tigre Nordmarkite (1286 ± 96 Ma), and San Javier Granite (1291 ± 49 Ma). However, the nature of the dating (Rb–Sr whole-rock isochrons) and their large uncertainties (33–6 m.y.) make the correlation of those three intrusions with the San Andrés orogeny uncertain. The San Rafael Granite may be another intrusion produced during the San Andrés orogeny because sample 228 of Boger et al. (2005) has grain 12.1 formed at 1259 ± 13 Ma (U–Pb). The Candelária Granite is other granite formed during the San Andrés orogeny according to the U–Pb age of 1285 ± 16 Ma (Ramiro Matos, unpublished).

Fig. 19. Concordia plot of zircon U–Pb ages of the San Andrés Granite, sample JO10. The age at 1275 ± 7 Ma may represent the existence of an orogeny between the Candeias and Nova Brasilândia herein named the San Andrés. The age of 1331 ± 13 Ma represents inheritance from the Candeias orogeny.

Fig. 20. Concordia plot showing the two main populations of zircon in sample MQ23 (Laje S-type Granite). The interpretation is that the cluster at 1573–1515 Ma is derived from Serra Providência-like rocks, whereas the population at 1356–1334 Ma is derived from felsic rocks and paragneisses generated during the Candeias orogeny. The Laje Granite is interpreted as post-Candeias and is tentatively correlated to the Nova Brasilândia orogeny.

4.1.2.8. Laje S-type Granite (MQ23). This sample was collected in the west Candeias Batholith region (Fig. 3). It is a fine-grained equigranular granite, slightly foliated (magmatic flux), pink to grey, containing discontinuous and irregular quartz veins usually parallel to the foliation of the host rock (paragneiss). Garnet porphyroblasts (± 1 cm) are abundant in quartz-rich aggregates. Essential mineralogy is K-feldspar, oligoclase, quartz, biotite and garnet. These granites are small bodies, intrusive into paragneisses (metapelites) and are believed to have been derived from them. Magmatic foliation is concordant to the paragneiss banding ($N45^\circ E$; $30^\circ SE$ with mineral lineation at 20° ; $N90^\circ E$). As expected in S-type granites, this rock has a complex population of zircon including several shapes and ages. Twenty-one dated grains have ages from 2203 to 1334 Ma (Table 2). Older grains may be inherited from the Jurueña basement (1826 ± 6 Ma, grain d.17-1) and the Jamari Complex (1742 ± 14 Ma, grain d.19-2). The two main populations of zircon have the ages of 1573–1515 Ma and 1356–1334 Ma – Fig. 20. The ages of the first cluster are similar to the ages of samples of the Serra Providência Suite (Bettencourt et al., 1999; Payolla et al., 2002; Santos, 2003). This suggests that there was a strong component of the Serra Providência Suite in the source from which the Laje Granite (MQ23) originated. The ages of 1356–1334 Ma include metamorphic and magmatic zircon based on Th/U ratios and BSE images and the maximum possible age of the granite is 1334 Ma. This suggests that the sedimentary rocks which were melted to form the Laje Granite have at least two main components: one derived from rocks of the Candeias orogeny and the other from the Serra Providência Suite. Granites of this suite are common to the northwest, north, northeast and east of the sampling site. The existence of several intrusions of Candeias-age to the west-southwest of MQ23 outcrop is a potential source of the magmatic-detrital zircon found in the sample. The widespread metamorphic rocks (paragneisses) to the west of the MQ23 outcrop (Rio Mamoré Complex, Fig. 3), seems to be the most likely source for the metamorphic-detrital grains. Because the metamorphic grains are detrital, it seems that the Laje S-type granite postdates the Candeias orogeny. Because the generation of S-type melts is common at ± 1110 Ma during the paroxysm of the Nova Brasilândia orogeny (Rio Pardo Granite; Rizzotto et al., 1999; Santos, 2003) the more probable correlation for sample MQ23 is with the Nova Brasilândia orogeny.

4.1.2.9. *Iata sillimanite gneiss (JP3)*. The outcrop of this sample is known in Rondônia as the “Iata outcrop”, located 30 km to the north of Guajará-Mirim in Brazil (Fig. 3). The rock is steeply folded and isofolds trend E–W and extend to the Bolivia territory. The sample is very poor in zircon and rich in quartz, sillimanite and pyrite. Processing three samples yielded only 14 grains of zircon all of which are highly fractured and, in addition, four are metamict. Thus only seven reliable U–Pb SHRIMP analyses could be made (Table 2). Three of the seven grains (mean average of 1541 ± 12 Ma) may be derived from the Serra Providência Suite; one grain (1433 Ma) has an age within the range of the Santa Helena orogeny; two grains (1325 and 1314 Ma) are possibly derived from the Candeias-type granites; the youngest grain of 1212 Ma establishes the maximum age of the sillimanite gneiss (post-San Andrés orogeny), which is tentatively correlated to the Nova Brasilândia Group. This interpretation extends the distribution of the rocks formed during the youngest Nova Brasilândia orogeny to the west probably reaching the Bolivian territory to the west of the Mamoré River (Fig. 3).

4.1.2.10. *Las Madres paragneiss (JO8)*. This sample is a garnet-rich leucocratic paragneiss cropping out 25 km northeast of Concepción in the area mapped as Las Madres Gneiss of Chiquitania Complex by Litherland et al. (1986) in Bolivia (Fig. 4). Its zircons are relatively large (200–400 μm), have rounded edges and variable shapes and colour and are all detrital. The main population ($n=12$) has ages in the 1690–1630 Ma range (Fig. 21) and is interpreted as derived from rocks of the Quatro Cachoeiras orogeny, such as the Refugio Orthogneiss (JO12) to the west of Concepción. One grain has an age of 1550 ± 8 Ma and possibly is derived from rocks correlated to the Serra Providência Suite. Three grains (g.12, g.8, and g.5) have younger, low Th/U (0.03–0.09), metamorphic cores (1317 ± 10 , 1350 ± 11 , and 1118 ± 15 Ma) inside older rims having ages of 1653 ± 8 , 1682 ± 20 , and 1620 ± 28 Ma (Fig. 22). The formation of metamorphic nucleus and patches results from metamorphic fluids migrating along fractures within the zircon (Hartmann et al., 1997). One scenario is that the high-grade Candeias-type metamorphism of source-rock (1317 and 1350 Ma) preceded the erosion and sedimentation of the pelitic rock, which subsequently was metamorphosed into a paragneiss. The latest metamorphic recrystallization of zircon g.5 at 1118 Ma reflects the age of the paragneiss formation during the Nova Brasilândia orogeny; the age

Fig. 22. BSE image showing unusual inverse relation between rim and core in zircon. Grain g.12 of sample JO8 (Las Madres paragneiss) has a younger metamorphic core (1317 ± 10 Ma) inside an older magmatic grain (1653 ± 8 Ma).

of 1110 ± 10 Ma is considered the age of the metamorphic climax of the Nova Brasilândia orogeny (Rizzotto et al., 1999; Santos, 2003; Tohver et al., 2004).

4.1.2.11. *Puquio Norte Rhyolite (JO13)*. The Puquio Norte gold deposit is hosted by undated low-grade, foliated meta-sedimentary rocks, which are cut by a sub-vertical felsic dike or sill parallel to foliation. The meta-sedimentary unit is part of the San Ignacio Group, whose age was estimated in the 2000–1400 Ma range by Litherland et al. (1986). Most of the rocks of this group have many analogies to the younger meta-sedimentary Aguapeí and Sunsás Groups, including the Ar–Ar age at 990 Ma and the style of its gold mineralization. The dike would provide the minimum age for the unit, but the dike is very poor in zircon and of the five zircon grains extracted from the sample, all are inherited, as indicated by the variable shape and colour and the corroded edges of the crystals. Each grain has different $^{207}\text{Pb}/^{206}\text{Pb}$ ratios in the 0.1050–0.950 range corresponding to ages of 1700–1500 Ma. The ratios are from analyses with only one scan. The Sm–Nd model age is 1.54 Ga, which is a lower limit for the rhyolite age. The rhyolite age may be anything younger than 1.54 Ga. However, because of the interpreted correlation of the Puquio meta-sedimentary rocks to the Sunsás Group based on mapping and Ar–Ar dating of 990 ± 3 Ma (sample JO11; Santos, unpublished) the rhyolite dike is probably younger than 1100 Ma.

4.1.3. Andes Province

4.1.3.1. *Tanomonia Granite (JO7)*. Mesozoic intrusions related to the Andes evolution are present within the Sunsás Province where Litherland et al. (1986) identified three complexes of alkaline affinities: the Cerro Manomó Carbonatite, the Candelária Complex (nordmarkite, trachyte, foyaite, pulaskite), and the Velasco Complex (biotite granite, pulaskite, nordmarkite, quartz-syenite). Two samples of Velasco Complex were dated by Rb–Sr isochrons at 144 ± 4 Ma (Bambá pluton) and 141 ± 5 Ma (Cabeza de Toro pluton), Litherland et al. (1986). We investigated the southernmost intrusion, the Tanomonia pluton by U–Pb and Sm–Nd to compare its age to the Rb–Sr age and to investigate the contamination of the magma with rocks of the Sunsás Orogen. Sample JO7 is orthoclase granite with large, U-rich (up to 3700 ppm) and Th-rich (up to 3000 ppm) zircon crystals. The U–Pb age is 135.9 ± 1.8 Ma (MSWD = 1.03; $n=5$; Fig. 23) or Early Cretaceous (Valanginian–Hauterivian according to the time scale of Gradstein et al., 2005), which is about 5% younger than the Rb–Sr ages. The Nd model age is 0.74 Ga (Table 4) and may

Fig. 21. Relative probability plot of zircon ages from sample JO8, the Las Madres garnet gneiss. The main detrital population has its main age peak at 1690–1630 Ma, which is evidence for a dominant derivation from Quatro Cachoeiras-type rocks. A metamorphic rim at 1118 Ma shows, however, that the rock was metamorphosed during the Nova Brasilândia orogeny.

Fig. 23. Concordia plot of zircon from the Tanomonia Granite (135.9 ± 1.8 Ma) corresponding to an Early Cretaceous age (Valanginian-Hauterivian; Gradstein et al., 2005).

indicate derivation from the Neoproterozoic rocks of the Brasiliano Orogen, whose front is present about 150 km to the south and southwest of the Velasco Complex. Another interpretation is that the model age may result from a mixture of Mesozoic juvenile material with Sunsás-age crust. At least three magmatic events took place at the craton margin during the Mesozoic: the formation of the Anari basalt (Marzulli et al., 1999); the Early Cretaceous Velasco alkali-granites; and the Upper Cretaceous Juína and Pimenta Bueno kimberlites (Rizzotto et al., 2004).

4.2. Sm–Nd results

Santos et al. (2000) integrated the available Sm–Nd data for the SW Amazon Craton and demonstrated that the Nd model ages (depleted mantle model) of the Sunsás Province are in the range of 1.06–1.93 Ga. This fact precludes significant participation of old continental crust in the evolution of the Sunsás Province, i.e. Archean and Trans-Amazonian rocks were not incorporated in reasonable amounts during magma generation along the orogen. Some

of the Nd model ages of 1.50–1.20 Ga suggest generation of juvenile crust and little or no participation of older crust. The other group of model ages are in the 1.50–1.90 Ga range, and is interpreted as evidence of the recycling of Rondônia-Juruena crust. The Sm–Nd data of Tables 1 and 3 show only one sample (JO14, San Ramon tonalite) with a short crustal residence time: the rock was formed at 1431 Ma and its model age is 1.56 Ga ($\epsilon_{\text{Nd}} = +2.32$). The other analysed samples reveal model ages from 2.06 to 1.68 Ga, suggesting again the participation of the nearby Rondônia-Juruena crust in some of the melts produced during the Sunsás evolution and perhaps some contribution of rocks from the Tapajós-Parima Province (model ages older than 1.90 Ga).

The Sm–Nd data of Santos et al. (2000) for the Rondônia-Juruena Province correspond to model ages in the 2.19–1.68 Ga range. These values combine rocks with a strong juvenile source-component (model ages between 1.90 and 1.60 Ga) and rocks with evidence of participation of rocks from the neighbouring province: the Tapajós-Parima (values older than 1.90 Ga). The Sm–Nd data (Table 4) show similarity to the Santos et al. (2000) data. The model ages are 1.99–1.67 Ga and some of the rocks represent new crust formed during the orogen, such as the Lomas Manechi granulite, JO3 (crystallization at 1818 Ma, model age at 1.86 Ga; $\epsilon_{\text{Nd}} = +3.36$) and the Refugio Orthogneiss, JO12 (crystallization at 1641 Ma, model age at 1.66 Ga; $\epsilon_{\text{Nd}} = +4.06$).

5. Discussion

5.1. Synthesis of Sunsás Belt evolution, age and nomenclature

The integration of both previous and new U–Pb and Sm–Nd data makes possible a synthesis (Table 5) of the main events of the Rondônia-Juruena and Sunsás Provinces (see discussion below for full details).

A compilation of the 71 available U–Pb ages for the West Amazon Craton is shown in Table 6. There are four clusters of ages each representing periods of continuous magmatic and tectonic activity (orogeny) separated by periods of much lesser activity or orogenic interval. These four main orogenies are summarised below:

- (a) The Santa Helena orogeny, 1465–1427 Ma, is exposed in two separate areas: a southern area (Mato Grosso: Santa Helena Batholith, Pindaituba Suite, Vila Oeste Gneiss; Ruiz, 2006) and

Table 4
Sm–Nd data (whole-rock) for studied samples of West Amazon Craton

Sample	Rock	Unit	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	Error 1 σ	$\epsilon_{\text{Nd}(0)}$	Age ^a (Ma)	$\epsilon_{\text{Nd}(t)}$	T_{DM}^b (Ga)
JO3	Granulitic gneiss	Lomas Manechi	3.94	21.94	0.108572	0.511625	21	–20.09	1818	+0.53	2.07
GR35	Quartz-diorite	Jamari	2.05	8.80	0.13455	0.512016	45	–12.46	1761	+1.57	2.00
GR59	Tonalite	Jamari	8.41	45.38	0.10736	0.511725	10	–18.14	1753	+1.95	1.90
JL78	Tonalite	Jamari	8.51	48.15	0.10690	0.511669	23	–18.90	1738	+1.04	1.95
MQ96	Dacite	Roosevelt	6.31	39.10	0.111464	0.511902	10	–14.69	1740	+4.35	1.72
JO12	Orthogneiss	Refugio	3.4	23.5	0.087878	0.511678	13	–19.06	1641	+4.06	1.67
GR333	Meta-granite	Providência	7.48	35.21	0.12800	0.511916	25	–14.42	1515	–0.95	2.00
JO14	Tonalite	San Ramón	7.66	57.86	0.080035	0.511677	12	–19.08	1429	+2.32	1.57
JO9	Gneiss	Las Madres	10.4	57.2	0.110000	0.511867	12	–15.37	1330	–0.61	1.74
JO16	Gneiss	Rio Branco	2.1	14.7	0.087557	0.511747	15	–17.71	1330	+0.94	1.58
JO6	Gneiss	Rio Fortuna	8.78	45.03	0.117849	0.511761	20	–17.44	1349	–3.83	2.06
JO5	Gneiss	Lomas Manechi	9.73	49.78	0.118118	0.511764	12	–17.38	1334	–3.97	2.06
JO18	Orthogneiss	Santa Rita	28.90	142.38	0.122721	0.511883	24	–15.06	1319	–2.57	1.96
JO10	Granite	San Andrés	14.8	77.9	0.114947	0.511963	24	–13.50	1275	–0.15	1.68
JO13	Rhyodacite	Puquio	3.84	25.79	0.090071	0.511804	15	–16.60	1110	–1.46	1.54
JO8	Garnet gneiss	Las Madres	16.02	91.03	0.106375	0.511743	13	–17.79	1118	–4.88	1.86
JO7	Alkali granite	Velasco	47.5	343.2	0.083756	0.512434	13	–4.31	135	–2.37	0.74

Notes: Samples ordered from the older (JO3) to the younger (JO7). All data recalculated using CHUR isotopic ratios: $^{147}\text{Sm}/^{144}\text{Nd} = 0.19665$; $^{144}\text{Nd}/^{143}\text{Nd} = 0.512655$; MORB isotopic ratios: $^{147}\text{Sm}/^{144}\text{Nd} = 0.21353$; $^{144}\text{Nd}/^{143}\text{Nd} = 0.513168$.

^a U–Pb ages. Ages in italic are assumed by correlation.

^b Depleted mantle model (DePaolo, 1981). $T_{\text{DM}(t)}$ model ages in Ga.

Table 5
Chronology and correlation of main events/units of Sunsás and Rondônia-Juruena Provinces

	Province						Age (Ma)
	Rondônia-Juruena	Jamari ^a	Alto Jauru ^a	Sunsás	Rondônia ^b	W Mato Grosso ^b	
Post-Sunsás							
Foreland basins	Apiacás, Dardanelos	Palmeiral, Prainha		Huanchaca	Palmeiral, Pacaás		<980
A-type granites		Rondônia Suite			Rondônia Suite	Rio Branco Suite	1060–980
Sunsás							
Nova Brasilândia orogeny				Sunsás, Vibosi, and Aguapeí Groups; Sunsás paragneiss	Nova Brasilândia Group, S-type granites	Aguapeí Group	1180–1100
San Andrés orogeny				San Andrés, San Rafael, Orobayaya Granites	Detrital zircon in Nova Brasilândia samples		1275
Candeias orogeny		Jamari Complex metamorphism, Serra Providência metamorphism		Pensamiento Complex, Lomas Manechi metamorphism, Rio Fortuna Gneiss (JO6), Santa Rita Gneiss (JO18)	Candeias Granite, Rio Crespo Group	Indiavaí Granite	1371–1319
Santa Helena orogeny				San Ramón Tonalite	Mamoré Complex (?), detrital zircon in Nova Brasilândia samples	Santa Helena Tonalite, Pindaituba Suite	1465–1427
Pre-Sunsás							
Post-tectonic granites	Aripuanã Granite	Serra Providência Suite	Cachoeirinha and Santa Cruz suites				1560–1530
Quatro Cachoeiras orogeny	Monte Verde metamorphism, Colniza Granodiorite	Quatro Cachoeiras Group, Jamari Complex metamorphism	Vila Oeste Gneiss	Refugio Orthogneiss, detrital zircon in Las Madres Paragneiss (JO8)			1670–1630
Beneficente Basin	Beneficente Group	Beneficente Group					1740–1700
Magmatic Arc 4	Roosevelt Group, Paraíba Granite, Maçaranduba Dacite, Teles Pires Suite	Jamari Complex	Cabaçal and Quatro Meninas Groups; Santa Fé and Aliança Gneisses	Detrital zircon in sample JO6, Rio Fortuna Gneiss			1760–1740
Magmatic Arc 3	Colider Group, Vitória Suite, Monte Verde Complex, São Pedro Granite, São Romão Granite		Santa Fé orogeny				1786–1770
Magmatic Arc 2	Paranaíta Suite, Cristalino Syenite,			Lomas Manechi protolith (JO3)			1819–1793
Magmatic Arc 1	Juruena Granodiorite						1848–1823

Notes: Details of ages and references are in Tables 6 and 7. The dashed lines are marking periods (30–60 m.y.) of much less magmatic and tectonic activity (hiatus).

^aDomain; ^bRegion.

a southwestern area (San Ramon Tonalite) of the Sunsás Orogen and consists mostly of island-arc-type rocks (Geraldes et al., 2001; Santos et al., 2002; Ruiz, 2006). Other occurrences not yet identified are anticipated, because detrital zircons with ages in the 1465–1417 Ma range are present in sandstones and quartzites from a broad geographic distribution, such as in Nova Brasilândia: JP8 ($n=1$), JP3 ($n=1$), GR66 ($n=2$); Aguapeí: JO1 ($n=1$), JP10 ($n=3$), MT1 ($n=10$); Palmeiral: JP2 ($n=1$), JP6 ($n=4$); Pacaás-Novos: pac ($n=2$); Prosperança: VP2 ($n=1$), studied by Santos et al. (2008).

(b) The Candeias orogeny, 1371–1319 Ma, has two main components: (1) An Andean-type magmatic arc with I-type (eastern Candeias Batholith), high-K (A_2 -type; central Candeias Batholith and Ariqueles Granite) and some S-type granites (sample JL6); and (2) metamorphic rocks reaching to the granulite facies (Rio Crespo and Colorado suites; Bettencourt et al., 2006; Rizzotto et al., 2002). More than 60% of the exposed Sunsás Orogen is formed by rocks of this orogeny. The name San Ignacio is not used to avoid confusion: the San Ignacio Supergroup was deposited between 2000 and 1400 Ma (Litherland et al., 1986), but the same name was also used for a younger orogeny (1400–1280 Ma).

(c) The San Andrés orogeny, upper and lower age limits unknown, is represented by the San Andrés Granite formed at 1275 Ma. Detrital zircons in late-Sunsás and post-Sunsás basins (Santos et al., 2002) indicate important felsic magmatic activity at 1220–1280 Ma that may be associated with the San Andrés orogeny. Santos et al. (2008), studying the ages of detrital zircon in five samples of post-Sunsás sandstones detected two important peaks of magmatic activity at 1285 and 1240 Ma. This orogeny may include the following granites: San Andrés, San Rafael, Orobayaya, El Tigre, San Javier, and Candelaria.

(d) The Nova Brasilândia orogeny, 1180–1110 Ma, is dominated by meta-sedimentary belts such as Nova Brasilândia, Aguapeí, and Sunsás. The most common metamorphic grades are medium to high (upper amphibolite) in the northern part of the belt in Rondônia (Iata, Colorado, and Nova Brasilândia units) and low to medium grade (green schist to lower amphibolite facies) in the southern zone in Bolivia and Mato Grosso (Aguapeí and Sunsás Groups). Granulite facies is locally present as described by Tohver et al. (2004) and as identified in sample JO8 (Las Madres garnet gneiss). The meta-sedimentary basins are more pelitic to the north (Rondônia) and more psammitic to the south (Bolivia and Mato Grosso). Small bodies of S-type granites represent another characteristic rock produced during the Nova Brasilândia orogeny.

These orogenies are not necessarily manifested throughout the entire Sunsás Orogen, they may also be diachronous. They were formed during Mid- to Late Mesoproterozoic resulting of northeast-directed crustal contraction.

The Candeias Batholith was originally mapped as orogenic and heterogeneous (Souza et al., 1975). Some following models proposed an anorogenic or intraplate tectonic setting focusing in the A-type composition and lack of deformation in some facies (Isotta et al., 1978). Bettencourt et al. (1999) proposed an extensional regime related to the orogenic cycle or to the opening of Grenvillian Ocean. However, the K-rich facies predominates only in the central zone, whereas the western zone is composed by dominant S-type facies (sample MQ23, this work) and the eastern part is composed by I-type monzogranite and granodiorite (mapping by the senior author during 1970, unpublished data; Souza et al., 1975). The A-type composition is not direct evidence for anorogenic or intraplate setting because part of the A-type granites – the A_2 -type – forms in

Table 6

U–Pb ages of orogenic rocks in the Sunsás and Rondônia-Juruena Provinces

Sample	Rock	Unit	Tectonic unit	U–Pb age	m ¹	Type	T _{DM(t)} ^a	ε _{Nd}	Reference
134	Paragneiss	Nova Brasilândia	4th orogeny Nova Brasilândia	1097 ± 5	m	Metamorphic			Tohver et al. (2004)
GR20	Leucogranite	Rio Pardo		1110 ± 8	z	Magmatic			Rizzotto et al. (1999)
JO2	Conglomerate	Aguapeí		1165–1149	z–x	Detrital			Santos et al. (2005)
JO13	Rhyodacite	Puquio Norte		1700–1500	z	Inherited			This work
JO8	Garnet gneiss	Las Madres		1118 ± 15	z	Metamorphic			This work
MT1	Quartzite	Aguapeí	3rd orogeny San Andrés	<1171	z	Detrital			Santos et al. (2001)
JP3	Sillimanite gneiss	Iata		<1210	z	Detrital			This work
GR66	Quartzite	N. Brasilândia		1160 ± 14	z	Detrital			Santos et al. (2000)
GR66	Quartzite	N. Brasilândia		1226 ± 13	z	Detrital			Santos et al. (2000)
228	2 mica granite	San Rafael		1259 ± 13	z	Magmatic			Boger et al. (2005)*
JO10	Granite	San Andrés	2nd orogeny Candeias	1275 ± 7	z	Magmatic	1.68	–0.15	This work
GR66	Quartzite	N. Brasilândia		1289 ± 16	z	Detrital			Santos et al. (2000)
JO18	Orthogneiss	Santa Rita		1319 ± 6		Magmatic			This work
240	Charnockite	Lomas Manechi		1320 ± 10	z	Magmatic			Boger et al. (2005)
WB44A	Augen gneiss	Jaru		1326 ± 2	z	Metamorphic			Payolla et al. (2002)
RO8	Kinzigit	Rio Crespo		1331 ± 8	z	Metamorphic	1.84	+0.50	Tassinari et al. (1999)
WB51	Orthogneiss	Rio Crespo		1331 ± 9	z	Metamorphic			Bettencourt et al. (2006)
JO10	Granite	San Andrés		1331 ± 13	z	Inherited			This work
JO5	Gneiss	Lomas Manechi		1334 ± 3	z	Metamorphic			This work
228	2 mica granite	San Rafael		1339 ± 6	z	Inherited			Boger et al. (2005)*
APQ11	Monzogranite	Indiavaí		1334 ± 14	z	Magmatic	1.95	+1.04	Ruiz (2006)
JL78	Tonalite	Jamari		1334 ± 7	z	Metamorphic			This work
JO6	Orthogneiss	Rio Fortuna		1336 ± 3	z	Magmatic			This work
235A1	Paragneiss	Chiquitania		1336 ± 6	z	Metamorphic			Boger et al. (2005)
JL6	S-type granite	Unnamed		1339 ± 3	z	Metamorphic			This work
JO3M	Granulitic gneiss	Lomas Manechi		1339 ± 4	m	Metamorphic	2.06	–3.83	This work
JS39	Monzogranite	Alto Candeias		1339 ± 7	z	Magmatic			This work
MQ23	S-type Granite	Laje		1334 ± 9	z	Magmatic			This work
JO9	Gneiss	Las Madres							This work
JO16	Gneiss	Rio Branco							This work
GR333	Meta-granite	S. Providência		1348 ± 4	z	Metamorphic	2.00	–0.95	This work
RO10	Leucogabbro	Colorado		1352 ± 6	z	Magmatic			Rizzotto et al. (2002)
WO52	Granite	Ariquemes		1352 ± 8	z	Magmatic			Santos et al. (2000)
235A	Paragneiss	Chiquitania		1371 ± 14	z	Metamorphic			Boger et al. (2005)
LR42	Monzogranite	Santa Clara		1426 ± 27	z	Magmatic			Ruiz (2006)
GR66	Quartzite	N. Brasilândia	1st orogeny Santa Helena	1427 ± 11	z	Detrital			Santos et al. (2000)
JO14	Tonalite	San Ramón		1429 ± 4	z–t	Magmatic			This work
LR20	Monzogranite	Anhangüera		1437 ± 28	z	Magmatic			Ruiz (2006)
RP24	Monzogranite	Pindaituba		1437 ± 45	z	Magmatic			Ruiz (2006)
MT1	Quartzite	Aguapeí		1447 ± 7	z	Detrital			Santos et al. (2001)
RN23	Orthogneiss	Vila Oeste		1447 ± 18	z	Magmatic	1.70	+1.92	Ruiz (2006)
RN22	Granodiorite	Mineiros		1455 ± 12	z	Magmatic			Ruiz (2006)
CARD	Granite	Cardoso		1455 ± 20	z	Magmatic			Condie et al. (2005)
RP15	Monzogranite	Sapé		1462 ± 9	z	Magmatic			Ruiz (2006)
RN151	Tonalite	Nova Lacerda		1464 ± 12	z	Magmatic			Ruiz (2006)
JWB3a	Garnet gneiss	Ouro Preto	Quatro Cachoeiras	1634 ± 8	z	Metamorphic			Bettencourt et al. (2001)
JO12	Orthogneiss	Refugio		1641 ± 4	z	Magmatic			This work
GR35	Quartz-diorite	Jamari		1649 ± 5	z	Metamorphic			This work
PS171	Amphibolite	Monte Verde		1653 ± 42	z	Metamorphic			M. Pimentel (personal communication)
JWB10	Granulitic gneiss	Ouro Preto		1655 ± 11	z	Metamorphic			Bettencourt et al. (2001)
PT12	Paragneiss	Ouro Preto		1657 ± 12	z	Metamorphic	2.16	–0.30	Santos et al. (2000)
RN23	Orthogneiss	Vila Oeste		1657 ± 31	z	Inherited			Ruiz (2006)
JS15	Gneiss	Quatro Cachoeiras		1661 ± 11	z	Magmatic			Silva et al. (2002)
240	Charnockite	Lomas Manechi		1663 ± 13	z	Inherited			Boger et al. (2005)
P18	Meta-granodiorite	Colniza		1669 ± 13	z	Metamorphic			Pinho et al. (2003)
GR59	Tonalite	Jamari		1677 ± 6	z	Magmatic	1.90	+1.95	This work
WB152	Paragneiss	Machadinho		1677 ± 5	z	Metamorphic			Payolla et al. (2002)
JO8	Garnet gneiss	Concepción		1678 ± 11	z	Detrital			This work
228	2 mica granite	San Rafael		1686 ± 16	z	Inherited			Boger et al. (2005)
261	Orthogneiss	Lomas Manechi		1689 ± 5	z	Magmatic			Boger et al. (2005)

Table 6 (Continued)

Sample	Rock	Unit	Tectonic unit	U–Pb age	m ¹	Type	T _{DM(t)} ^a	ε _{Nd}	Reference
JL78	Tonalitic gneiss	Jamari	Jamari	1738 ± 6	z	Magmatic	1.95	+1.04	This work
JO18	Orthogneiss	Santa Rita		1746 ± 21	z	Inherited	1.96	–2.57	This work
B335	Tonalite	Jamari		1750 ± 24	z	Magmatic	2.22	–1.84	Tassinari et al. (1996)
JO6	Foliated granite	Rio Fortuna		1753 ± 10	z	Inherited	2.06	–3.83	This work
A338a	Tonalitic gneiss	Jamari		1756 ± 38	z	Magmatic	2.20	–1.50	Tassinari et al. (1996)
GR66	Quartzite	N. Brasilândia		1753 ± 18	z	Detrital			Santos et al. (2000)
GR59	Tonalite	Jamari		1753 ± 8	z	Magmatic	1.90	+1.95	This work
GR35	Quartz-diorite	Jamari		1758 ± 7	z	Magmatic	1.99	+1.57	This work
WB152	Paragneiss	Machadinho		1762 ± 4	z	Inherited	2.13	–1.19	Payolla et al. (2002)
221d	Paragneiss	San Ignacio Gr.		1764 ± 6	z	Detrital			Boger et al. (2005)
235a	Gneiss	Chiquitania		1764 ± 12	z	Inherited			Boger et al. (2005)
JO3	Granulitic gneiss	Lomas Manechi	Juruena	1818 ± 13	z	Magmatic	2.07	+0.53	This work

Notes: Samples of this work located in Figs. 3 and 4. m1—mineral: z, zircon; x, xenotime; t, titanite; m, monazite.

^a Ages recalculated from Boger et al. (2005).

^a Nd model ages from whole-rock (Ga), except sample CARD, where the model age is from Hf isotopes in zircon.

orogenic environment. According to Eby (1992), the A₂-type granites are generated from magmas derived from continental crust or underplated crust that has been through a cycle of continent-continent collision. More recent models for the Candeias Batholith (Santos et al., 2000; Schobbenhaus et al., 2004; Rizzotto et al., 2004) suggest derivation from continental crust in orogenic environment, which agrees with the paleogeography of the western margin of the Amazon Craton at 1370–1320 Ma. Such paleogeography suggests that intraplate magmatism is unlikely and there is no evidence for a mantle plume underneath the Sunsás Orogen at 1370–1320 Ma to generate intraplate-like granites.

5.2. Distribution of Sunsás Orogen

The distribution of the Sunsás Orogen in South America is not well defined and all available information is derived from less than 15% of the belt. At least 85% of the belt is covered by Phanerozoic deposits, mostly modern molasse deposited in foreland basins derived from the erosion of the Andes. These basins are named Apure and East Venezuela (Venezuela), Llanos and Putumayo (Colombia), Marañón (Ecuador and Peru), Acre and Solimões (Brazil), Madre de Diós (Peru), Beni and Santa Cruz (Bolivia), and Chaco (Paraguay and Argentina) basins (Fig. 2).

There is strong evidence to extend the Sunsás Orogen from the Brazil–Bolivia (type-area) to the north and to the south forming a belt about 6000 km long from northern Argentina–Paraguay to East Venezuela. Because these northern and southern extensions are largely covered by Phanerozoic foreland deposits, evidence for such a belt is indirect.

To the north of parallel 36°S, there are several crustal fragments of Sunsás-age preserved within the Andean Belt. These are known as the Arequipa Complex (Quilca and Mollendo) in Peru (Wasteneys et al., 1995; Martignole and Martelat, 2003; Casquet et al., 2006), the Las Matras Trondhjemite in northwest Argentina (Sato et al., 2004), Garzon, Santander, and Santa Marta Complexes in Colombia (Priem et al., 1982; Pace et al., 1997), and the Merida Complex in Venezuela (Pace et al., 1997; Lopez et al., 2001).

The presence of large crustal fragments of age correlate to the Sunsás Orogen combined with the absence of older, Archean to Paleoproterozoic crust within the Andes Orogen (to the north of parallel 36°S) is direct evidence that the central and northern Andes was built on a continental margin formed by the Sunsás Province (Litherland et al., 1985). Although these fragments have been suggested as independent and isolated microcratons (Casquet et al., 2006), allochthonous (Suarez, 1990), or interpreted as exotic terranes (Wasteneys et al., 1995), we argue that they were all part of the

larger and continuous Sunsás Orogen during the Mesoproterozoic (Santos et al., 2000; Li et al., 2008; Fuck et al., 2008).

5.2.1. Extension to the north

The Iquitos High in Peru–Brazil border is a buried topographic high (paleo-arch) in the West Amazon that is parallel to the Sunsás front as mapped in Rondônia (Fig. 1). The Iquitos ridge is evident as a NNW elongate gravity high (Fig. 6 of Roddaz et al., 2005) and that may have been produced during one of the two major Sunsás collisions – either the Candeias, 1350–1320 Ma or the Nova Brasilândia, 1180–1100 Ma. In Colombia, there are three main exposed areas of age comparable to the age of the Sunsás Orogen: the Santa Marta Complex in the northern Andes (Priem et al., 1982), the Garzon Complex (Kroonenberg, 1982; Pace et al., 1997) at the Amazon Craton–Andes boundary and the Piraparaná and Yaca-yaca formations (Priem et al., 1989) near the Brazilian border (Fig. 1). In Venezuela, the presence of the Sunsás Orogen is interpreted in a region totally covered by the Llanos or Eastern Venezuela Basin to the north of the Imatoca Complex and north of the Orinoco River. Here the existence of the K'Mudku event has been reported since Bellizzia (1974) and named the Orinoquensis event. Onstott et al. (1989), investigating the Paleoproterozoic Imatoca Complex (Santos et al., 2005, 2006) and using Ar–Ar dating, published 11 Mesoproterozoic plateau ages in the 1439–1112 Ma range. This strong metamorphic overprint is an indication that the northern craton margin in Venezuela is not far from the Sunsás orogenic front. Other evidence derives from the study by Goldstein et al. (1997) using detrital zircon. The main population ($n = 17$) of detrital zircon in a sample of modern sand collected from the lower Orinoco River near Ciudad Bolívar has ages correlating to the Sunsás Orogen (1449–1016 Ma). Those zircons may come from the Mesoproterozoic Merida fragment at the headwaters of the Apure River in the Andes (Western Venezuela, Fig. 1). However, this potential source is about 1200 km to the west and represents less than 1% of the area of the Orinoco River Basin. Further, the presence of only six Paleozoic–Mesozoic zircon grains in that sample suggests that the contribution of detritus from the Andes (recycled or not) to the Orinoco system is small. The suggested and more probable source of those zircons are actually hidden Sunsás rocks to the north and west of Orinoco River, which eroded mainly before the deposition of the Llanos, Apure and East Venezuela basins (Schenk et al., 2000).

5.2.2. Extension to the south

Recent work by Ruiz et al. (2005b) and Ruiz (2006) recorded the Mesoproterozoic age of the Rio Apa “terrane” along the Brazil–Paraguay border. The Rio Apa Belt appears to be structurally

concordant with the Sunsás Orogen and is now interpreted as an extension of the Amazon Craton to about 240 km to the south. Recent U–Pb data from Cordani et al. (2008) on Rio Apa samples revealed an orthogneiss formed at ca. 1350 Ma (sample 95) and Cordani and Teixeira (2007) detected a strong metamorphic imprint at about 1300 Ma. The basement rocks have ages of 1829 Ma (similar to the age of Jurueña Granodiorite, Table 5), and within 1763–1720 Ma (mainly comparable to the ages of the Jamari Complex). All these are evidences that the Rio Apa region is related to the Amazon Craton.

The prolongation of the Rio Apa Belt farther to the south is unknown, because it lies under the Paraná Basin. In central-north Argentina, the Sierras Pampeanas show a provenance from Sunsás-age lithosphere as indicated by Hf isotopes (Chernicoff et al., 2008). The Sunsás connection is present in Sierras de Córdoba where Schwartz and Gromet (2004) proposed a link to the Amazon Craton and to the Sunsás Belt. Steenken et al. (2004) proposed that the basement rocks of the Sierras San Luis in Argentina have age comparable to the Grenvillian Orogen. Another fragment comparable in age to the Sunsás Orogen occurs to the south in Argentina: there where the Las Matras tonalite-trondhjemite forms the basement of the Cuyania terrane (Chernicoff et al., 2008), which according to Sato et al. (2000, 2004), was formed at 1244 ± 42 Ma.

5.3. Age of the Lomas Manechi Complex

The age of the Lomas Manechi¹ Complex is considered older than 1961 Ma based on a Rb–Sr isochron plot of Litherland et al. (1986, 1989). This isochron combines isotopic ratios from six different groups of rocks (charnockites, gneisses of Chiquitania Complex, Ascención Schists of San Ignacio Group, granulites, leptytes, and mafic rocks). The heterogeneity of the plot reflects the very high MSWD value of 286, evidence for a mixture of several populations of ages. The Lomas Manechi Complex was defined as a granulite complex and all its granulites dated by U–Pb were formed during the Candeias orogeny. There is no evidence for older, pre-Candeias, granulite metamorphism within the Sunsás and Rondônia-Jurueña Provinces. We recommend keeping the Lomas Manechi name for the granulitic rocks in Bolivia as these represent the high-grade metamorphic component of the Candeias orogeny as detected previously in the Rondônia region of Brazil (Santos et al., 2002). The youngest age for metamorphic zircons is 1319 ± 6 Ma (JO18) and the oldest metamorphic zircon population has an age of 1353 ± 11 Ma (JO3); this constrains the high-grade metamorphic event to the 1319–1353 Ma period. Another problem is that charnockitic igneous rocks are associated with the Lomas Manechi Complex (supposed basement) together with granulites. Charnockitic rocks are regionally known as post-tectonic (in relation to the orogenies of Rondônia-Jurueña Province) intrusions contemporaneous to the Serra Providência Suite and formed during 1570–1530 Ma (Payolla et al., 2002; Santos et al., 2000). Unfortunately, the charnockites of Eastern Bolivia remain undated by U–Pb so we cannot test properly their correlation to the Serra Providência Suite. The only possible test was made using Rb–Sr data. Combining the charnockites of Litherland et al. (1989) Rb–Sr plot to the charnockites of Rondônia (Santos et al., 2000) in a single isochron plot (Fig. 24) shows that they all plot on the same regression line at 1587 ± 86 Ma (MSWD = 2.9; $n = 10$). This is the first indication of the existence of charnockitic rocks equivalent in age to the Serra Providência Suite (including the Ouro Preto charnockites) in eastern Bolivia.

Fig. 24. Integration of Rb–Sr isotopic data (whole-rock analyses) of Ouro Preto charnockites from Rondônia (samples PT1, PT1a, PT15, and PT15a; Santos et al., 2000) with mafic granulites and charnockitic granulites of the Lomas Manechi Complex in Bolivia (samples 4, 67, 69, 89, 106, and 148; Litherland et al., 1986, appendix 5). All data are shown on the same regression line at 1587 ± 86 Ma.

5.4. The problem of the Paragvá Craton

Litherland et al. (1986) were the first to publish the existence of a craton of about 124,000 km² in northern Bolivian Precambrian and named it the Paragvá Craton following the unpublished report of Klink and Litherland (1982). Since then, this craton is recognized on most maps and tectonic models proposed for the evolution of the southwestern part of the Amazon Craton (Tassinari and Macambira, 1999; Galdames et al., 2001; Boger et al., 2005; Tohver et al., 2002, 2005; Fernandes et al., 2005). One problem is that such a craton is essentially composed (at least about 72%) of the rocks of the “Orogenic Pensamiento Granitoid Complex” (Litherland et al., 1986, 1989) and the ages of this complex are too young (in relation to the ages of the basement) to be a Precambrian craton. Litherland et al. (1989) recognized two main groups of granitoids within the Pensamiento Complex: syn- to late-kinematic (1350 Ma) and late- to post-kinematic granitoids (1300 Ma). These ages are much younger than the ages of several units in the Bolivian Precambrian, such as the San Ignacio Supergroup, Chiquitania Complex, and Lomas Manechi Complex, both of which formed between 2000 and 1400 Ma according to Litherland et al. (1986, 1989). The Paragvá Craton would be only older than the Sunsás and Aguapeí Belts (Fig. 51 of Litherland et al., 1986), which establishes its minimum age at >1180–1100 Ma according to the U–Pb ages available for both units (Santos et al., 2005; D’Agrella-Filho et al., 2008). The ages of 1350 and 1300 Ma are Rb–Sr whole-rock isochrons and may reflect reset ages in older rocks (i.e. the effect of the Candeias orogeny on older basement). The Pensamiento Complex is composed of an expanded series, including monzogranites, granodiorites, tonalites, trondhjemites and diorites. Litherland et al. (1986) also described hornblende-biotite gneiss and Matos et al. (2006) show that part of the complex has the geochemistry of a magmatic arc and syn-collisional environment. Recently Matos et al. (2006) demonstrated that some granitoids and gneisses of the Pensamiento Complex were formed (and not recycled) during the Candeias orogeny. Three granite and gneiss bodies are dated using U–Pb SHRIMP (Matos et al., 2006): Diamantina Monzogranite, La Junta biotite-(hornblende) Orthogneiss, and San Martín hornblende Monzogranite. The ages of these granitoids are (recalculated here at 2σ): 1340 ± 20 Ma, 1347 ± 21 Ma, and 1373 ± 20 Ma. These ages demonstrate that most,

¹ Lomas Manechi, instead of Lomas Maneches. Manechi is the Bolivian name for several species of monkeys of the genus *Alouatta* as for example *Alouatta seniculus*. Manechi is equivalent to guariba in Brazil.

Fig. 25. The relationship of the “Paraguá Craton” to the Sunsás Belt and the Pensamiento Granite Complex (crosses). Because the Pensamiento Complex is not basement (see the labelled ages of the Diamantina, La Junta, and San Martín Granites, all recalculated from Matos et al., 2006), the maximum potential area for the craton is the hatched zone to the southeast. Location of Paraguá Craton, Pensamiento Complex, Sunsás Belt, and Aguapeí Belt following Litherland et al. (1986, 1989).

if not all of Pensamiento Complex was formed during the Candeias orogeny. There are many analogies (stratigraphic, petrological, and geochronological) between the Pensamiento granitoids and the Candeias Batholith in Rondônia. In light of the above evidence, we argue that the “Paraguá Craton” does not exist and that the Pensamiento Granitoid Complex is mainly composed of intrusions generated in a continental, Andean-type, orogenic arc produced during the Candeias orogeny.

Removing the area of the Pensamiento Complex from the area of the supposed craton (Figs. 25 and 46 of Litherland et al., 1986), the remaining area is only 34,600 km². Boger et al. (2005) dated one sample (240) of the Lomas Manechi Complex in this area and reported an age of 1320 ± 11 Ma. They also dated five samples of the Bolivian Precambrian and found only one rock formed before the Sunsás Orogen at 1689 ± 11 Ma (sample 261). This sample is located within the Sunsás Belt of Figure 51 in Litherland et al. (1986) and occurs outside the area of the supposed craton (Fig. 25).

Four samples from the Lomas Manechi and Chiquitania Complexes (JO3, JO5, JO6, and JO18) were dated and three of them were formed during the Candeias orogeny. Only sample JO3 is older (1818 Ma), but was metamorphosed by the Candeias orogeny at 1339 Ma (see Section 4.1.2). Another pre-Candeias rock among the seventeen dated by U–Pb is the Refugio Orthogneiss (JO12, 1641 ± 4 Ma), which is also outside the limits of the “Paraguá Cra-

ton” (Fig. 25). The relatively young Sm–Nd model ages (1.58 and 1.74 Ga) of two undated gneisses from the Chiquitania Complex, the Las Madres (JO9) and Rio Branco (JO16) gneisses (Tables 1 and 5) are additional evidence that most of the complex was not formed from basement rocks.

None of the granulite rocks (type-rock of the Lomas Manechi unit) in eastern Bolivia and western Rondônia (Tassinari et al., 1999; this work) are basement rocks (pre-Sunsás Orogen), but orogenic rocks formed during the Candeias and Nova Brasilândia orogenies. The amount of older rocks (1818 and 1641 Ma, this work; 1686–1663 Ma, Boger et al., 2005) in the Bolivian Precambrian is very minor (one sample) and is restricted to the southern area of the supposed craton and beyond it (three samples). The size of these occurrences is unknown, but because they are surrounded by rocks formed during the Candeias orogeny, they are interpreted as small and discontinuous fragments which do not represent a craton or even a tectonic block. Because the evident temporal correlation, these fragments probably derive from the neighbouring Rondônia-Juruena Province. They represent small areas of the continental margin which survived the Candeias orogeny. Excluding the Pensamiento Complex and the younger part of the Lomas Manechi and Chiquitania Complexes of the proposed area for the “Paraguá Craton” (i.e. about 70–80% of the area of the “craton”), its area would be reduced to only about less than 10,000 km².

This small crustal fragment that formed at about 1818–1630 Ma probably is not a craton and is interpreted as a discontinuous fragment of the Rondônia-Juruena Province, which survived the Sunsás evolution, particularly the collisional Candeias orogeny.

5.5. Proterozoic stratigraphy of Eastern Bolivia

The inferred stratigraphic succession of the Bolivian Precambrian is based on the metamorphic grade, where the older rocks or units that have the higher metamorphic grade (Litherland et al., 1986). Granulites (Lomas Manechi Complex) were considered the basement and the less-metamorphosed rocks were grouped as the youngest units (Sunsás and Vibosi Groups). Because the region evolved from several successive orogenies from ca. 1820 to 1110 Ma, the use of metamorphic grade to establish stratigraphy is not reliable. Each orogeny may have produced a variety of rocks under variable sedimentary, magmatic, and metamorphic environments. Almost all granulites known in Eastern Bolivia and in neighbouring areas in Brazil are not basement rocks, but were formed during the Mesoproterozoic and are related to the Candeias orogeny. However, the Nova Brasilândia orogeny – including the Sunsás and Aguapeí Groups – contrary consisting of only low metamorphic grade (Litherland et al., 1986), also produced anatectic, upper amphibolite metamorphism and re-crystallization of zircon. Dated samples of the Chiquitania and Lomas Manechi Complexes revealed a variety of ages and types of ages (metamorphic, magmatic, and inherited) indicating that those two units should be further subdivided. All are evidence that a broad reinterpretation of these two units is required as well as a review of available regional geological maps.

5.6. U–Pb ages of the Rondônia-Juruena Province

The available U–Pb data including data from this work and from the literature are listed in Table 5 (orogenic rocks) and Table 6 (post-orogenic rocks). The U–Pb ages are listed chronologically independently of their origin, be they magmatic, metamorphic,

inherited or detrital. Twenty-six ages from the Rondônia-Juruena Province are organized into three groups of ages, at 1764–1746 Ma (10 samples), 1689–1632 (12 samples), and 1818 Ma (1 sample). The first group corresponds to ages of the Jamari Domain and the second to the collisional Quatro Cachoeiras orogeny. The older age at 1818 Ma is comparable to ages of the Juruena Granodiorite of the Juruena Domain (Lacerda Filho et al., 2001; Santos, 2003). Most of the ages of Quatro Cachoeiras orogeny are metamorphic, reflecting the re-crystallization of zircon under high-grade conditions that resulted from an orogen with a strong collisional component. This type of component has not yet been detected within the Jamari orogeny as shown by the apparent absence of metamorphic zircons in the period of 1760–1740 Ma.

The Serra Providência Suite was formed during the Early Mesoproterozoic about 60–90 m.y. after the cessation of the Quatro Cachoeiras orogeny. There are 16 U–Pb ages of rapakivi granites, granites and charnockites formed during 1573–1532 Ma (Table 5). The Serra Providência Suite was restricted to the Jamari Domain (Santos et al., 2002), but there is an equivalent in the Juruena Domain, namely the Aripuanã Granite (MQ33, 1542 ± 2 Ma; Rizzotto et al., 2002). The apparent scarcity of Serra Providência magmatism within the Juruena Domain possibly results from the paucity of mapping and dating. Part of the numerous granites interpreted as related to the Teles Pires Suite (1780–1760 Ma; Rizzotto et al., 2004) may be younger and equivalent to the Aripuanã Granite.

5.7. Autochthonous evolution of the Sunsás Orogen

All of our new U–Pb data indicate that the exposed area of the Sunsás Orogen developed largely in situ. This is supported by two lines of evidence. First, on both sides of the border Sunsás rocks contain scattered fragments – from centimetres to kilometres – of Paleoproterozoic rocks with ages equivalent to those of the Rondônia-Juruena Province. Secondly, potentially exotic allochthonous rocks (either Archean or Trans-Amazonian in age) have yet to be found.

Table 7

U–Pb and Ar–Ar ages of post-orogenic rocks (post-Andean, post-Sunsás, and post-Quatro Cachoeiras)

	Sample	Rock	Unit	U–Pb	Method	$T_{DM(t)}$	ϵ_{Nd}	Reference
Post-Andean	J07	Alkali granite	Velasco	136 ± 2	S	749	–2.31	This work
Post-Sunsás	MGJB194	Syenogranite	Maçangana	991 ± 14	C			Bettencourt et al. (1999)
	AM52b	Syenogranite	Santa Bárbara	993 ± 5	Cm	1.73	–3.21	Sparrenberger et al. (2002)
	O2678	Alkali granite	Pedra Branca	998 ± 5	C			Bettencourt et al. (1999)
	301	Rapakivi granite	Taperas	$1061 \pm 6^*$	S			Boger et al. (2005)
	NF14e	Basalt	Nova Floresta	1062 ± 3	Aw			Tohver et al. (2002)
Post-Quatro Cachoeiras	GR333	Meta-granite	Providência	1515 ± 8	S	1.99	–0.69	This work
	WB36	Quartz-syenite	União	1532 ± 5	C	1.88	+0.20	Bettencourt et al. (1999)
	JS1	Gneiss	Providência	1535 ± 27	S			Silva et al. (2002)
	MQ33	Granite	Aripuanã	1537 ± 8	S			Silva et al. (2002)
	MQ33	Granite	Aripuanã	1542 ± 2	C			Rizzotto et al. (2002)
	AR3-1	Monzogranite	Samuel	1544 ± 5	C	2.07	–0.20	Payolla et al. (2002)
	JS19	Leucogranite	Providência	1545 ± 8	S			Silva et al. (2002)
	MQ23	S-type granite	Laje	1573–1515	S			This work
	J08	Garnet gneiss	Las Madres	1550 ± 8	S	1.86	–4.88	This work
		Granite	Samuel	1550–1540	C			Payolla et al. (2002)
	JS16	Gneiss	Providência	1555 ± 19	S			Silva et al. (2002)
	WB46c	Monzogranite dyke	Japonês	1560	C	1.86	–0.70	Payolla et al. (2002)
	WB46a	Charnockite	Japonês	1560	C	1.86	+0.80	Payolla et al. (2002)
	SPGR36	Syenogranite	Providência	1565 ± 4	C			Bettencourt et al. (1999)
	SPGR39	Monzogranite	Providência	1566 ± 3	C	1.52	–0.86	Bettencourt et al. (1999)
	WO63	Mylonitic granite	Providência	1569 ± 16	S	2.22	–4.58	Santos et al. (2000)
	MS6030	Orthogneiss	Providência	1570 ± 30	C	1.89	+0.79	Tassinari et al. (1996)
	SPGR21	Monzogranite	Providência	1573 ± 13	C			Bettencourt et al. (1999)

Notes: S, SHRIMP; C, conventional (TIMS); A, Ar–Ar. All data from zircon except AM52b (m: monazite) and NF14e (w: whole-rock).

*Recalculated age.

All inherited U–Pb ages of zircon from granitoids and gneisses and all exposed pre-Sunsás rocks in Bolivia have ages well correlated to the neighbouring province, the Rondônia-Juruena Province. The pre-Sunsás U–Pb ages obtained in Bolivia are undistinguishable from the ages of rocks from the Brazilian side (Table 6), strongly suggesting that the Sunsás Belt in both Bolivia and Brazil evolved over a continental margin formed dominantly of rocks of the Jamari and Quatro Cachoeiras orogenies and only secondarily of rocks of the Juruena Domain and Serra Providência Suite (1560–1540 Ma). The same conclusion was reached by Santos et al. (2002, 2005), using detrital zircon. These observations and the absence of any craton to the west (see Section 5.4) indicate that the Sunsás Orogen evolved as a direct (autochthonous) accretion to the western Amazon Craton margin in four periods of more intense orogenic activity as discussed above (Section 5.1). We infer the existence of a continent to the west and moving eastward as a driving force closing the Santa Helena Basin/Ocean and causing the Candeias collision. Direct evidence for such a continent has not yet been found (it may have been removed during Rodinia supercontinent breakup) but certainly should be looked for in future studies.

The fragments of pre-Sunsás rocks present within the Sunsás Province, despite been deformed or redeformed and metamorphosed during the latest orogeny (Nova Brasilândia), correlate with the rocks of the older province (Rondônia-Juruena) to the east and northeast of the Sunsás front. Such fragments may be almost in situ or may have been displaced short distances towards the Sunsás Front allowing terming the orogenic evolution as parautochthonous. A similar evolution is interpreted by Davidson (2008) for that part of the Grenville Province lying between the Grenville front and the Allochthonous Boundary Thrust (Rivers, 1997).

5.8. Connection to Laurentia

The inferred collision of Amazonia to Laurentia to form part of the Rodinia supercontinent has been considered to occurred at ± 1200 Ma (Tohver et al., 2002), 1100 Ma (metamorphism of Brasilândia and Aguapeí Groups; Fuck et al., 2008), or 1080–970 Ma (Li et al., 2008). However, there is no evidence in Amazonia for a continental collision of such magnitude at 1200 Ma, 1100 Ma or later. There is no record of magmatism, tectonism, and high-grade metamorphism at ca. 1200 Ma in the West Amazon Craton, a period of orogenic quiescence. The metamorphism of Nova Brasilândia and Aguapeí meta-sedimentary belts is mainly greenschist facies and locally reached upper amphibolite conditions (Rizzotto et al., 1999). The volume of felsic magmatic activity during the Nova Brasilândia orogeny (1180–1110 Ma) is minor. The most feasible timing for the Amazonia-Laurentia amalgamation would be during the Candeias orogeny (1370–1320 Ma), when large volume of felsic magma was generated, and when widespread granulite metamorphism was produced not only within the Sunsás Orogen, but up to thousand of km inside the craton, such as the K'Mudku shear belt.

Amazonia-Laurentia correlations are mainly based on the comparison of orogenic rocks (Sunsás and Grenville Orogens) possibly because Neoproterozoic Post-Grenvillian magmatism (ca. 1000–800 Ma) is little reported in Laurentia. Volkert et al. (2005) described widespread small felsic intrusions within the Grenville terrane in the north-central Appalachians of New Jersey and New York. These intrusions are dated from 1020 ± 4 Ma to 965 ± 10 Ma providing a strong temporal correlation to the post-orogenic Rondônia Suite of Brazil and Bolivia (Table 8).

5.8.1. Definition of units

Some authors (Gower and Krogh, 2002) use the name “Grenville orogeny” for the latest orogeny at 1090–980 Ma, for which most

authors in North America (Rivers, 1997; Carr et al., 2000; McLelland et al., 1996) prefer the name “Ottawan”. The absence of orogenic rocks in the Sunsás Orogen that are equivalent in age to the Ottawan orogeny (1110–950 Ma; Carr et al., 2000) indicates that cratonization started earlier in the Amazon Craton than in Laurentia. The age limits of the Ottawan orogeny are controversial and may vary along the Grenville Belt: e.g. 1110–950 Ma (Carr et al., 2000), 1090–1030 (Volkert et al., 2005), or 1080–1020 Ma (Rivers, 1997). All these lower age-limits of the Ottawan orogeny (1080, 1090, 1100 Ma) indicate that this orogeny only started at or after 1100 Ma, during post-Nova Brasilândia time (Table 8). The rocks in the western Amazon Craton with ages comparable to the Ottawan orogeny are not orogenic, but instead are cratogenic (rapakivi tin granites, continental rift deposits, alkali basalt, alkaline pipes, etc.) and extend into the interior of the craton, particularly inside the Rondônia-Juruena Province. The Nova Floresta basaltic flows (1062 Ma; Tohver et al., 2002) and associated dike swarms and sills (such as the Rincón Del Tigre in Bolivia) are related to an important period of crustal extension and mantle plume activity. These extensional intracratonic processes may be associated with continental break-up and suggest that separation of Amazonia from the Rodinia supercontinent may have started before 1000 Ma during the Late Mesoproterozoic and not during the Neoproterozoic.

The duration of the Elzevirian orogeny is also controversial: 1350–1185 Ma (McLelland et al., 1996); 1250–1190 Ma (Rivers, 1997); and 1230–1180 Ma (Gower and Krogh, 2002). The equivalent to the Elzevirian orogeny in Amazonia would be the discrete San Andrés orogeny (1275 Ma) and perhaps the early rocks formed during the Nova Brasilândia orogeny (1180–1110 Ma). During this orogeny, represented by the formation of inter-arc basins, upper amphibolite facies metamorphism, and generation of S-type granites, the Grenville Province was affected by intense magmatism (Adirondian magmatism, referred to by McLelland et al., 1996 as AMCG magmatism) at 1180–1080 Ma (McLelland et al., 1996; Kusky and Loring, 2001) – Table 8.

The Eastern Granite-Rhyolite Province (EGRP) is defined in United States by Bickford et al. (1986) as buried basement composed by granite-rhyolite rocks formed during 1500–1300 Ma. These rocks are cropping out in two areas: the Southern Granite Rhyolite Province (SGRP) and the Eastern Granite Rhyolite Province (Van Schmus et al., 1996). These were formed along the southern margin of Laurentia respectively at 1400–1340 Ma and 1500–1440 Ma, according to Slagstad et al. (2004a) based on Van Schmus et al. (1996) and Bickford (1988). More recently, Renee (2005) indicated that the age of the older eastern province is ca. 1470 Ma, whereas the age of the younger southern province is ca. 1370 Ma. Most Canadian workers do not use the term EGRP and correlate similar age rocks in the Grenville Province to the Eastern Granite-Rhyolite Province of the United States. Tollo et al. (2004; Fig. 1) presented a map of Laurentia where both the eastern and southern provinces are shown undivided and parallel to the Grenville Orogen. The two Granite-Rhyolite Provinces usually are not included in the evolution of the Grenville Province, probably because their rocks are not much deformed. Typical rocks and ages of this arc are the Britt pluton in Ontario (1456 ± 7 Ma; Van Breemen et al., 1986), the Shawanaga pluton (ca. 1460 Ma; Culshaw et al., 1994), and the basement of the Muskoka and Shawanaga Domains (1450 Ma; Slagstad et al., 2004b). The Eastern Granite-Rhyolite Province includes some rocks that may be younger than 1400 Ma, but most available younger ages have low precision ($1346 \pm 69/-39$ Ma; Van Breemen et al., 1986). The crystallization ages of granites and rhyolites of the SGRP are in the 1400–1340 Ma range (Renee, 2005). The above dates suggest a temporal correlation of the EGRP to the Santa Helena orogeny (1465–1427 Ma) and of the SGRP to the Candeias orogeny (1371–1319 Ma) – see

Table 8

Chronological comparison between Amazonia and Laurentia evolution from ca. 1840 to ca. 965 Ma

Age	Amazonia		Laurentia	
	Province	Sunsás	Rondônia-Juruena	Grenville and pre-Grenville
	Domain		Jamari	Juruena
960				
980				
1000				
1020		Tin granites		
1040				
1060				Ottawan 1080–1020
1080				
1100				
1120				
1140				
1160				
1180				
1200				
1220				
1240				
1260				
1280				
1300				
1320				
1340				
1360				
1380				
1400				
1420				
1440				
1460				
1480				
1500				
1520				
1540				
1560				
1580				
1600				
1620				
1640				
1660				
1680				
1700				
1720				
1740				
1760				
1780				
1800				
1820				
1840				
1860				

Ages of the Amazonia continent are from the text and Tables 1, 2 and 4. Ages of Laurentia are taken from Rivers (1997), Schneider et al. (2001), Gower and Krogh (2002), Tollo et al. (2004), Schwerdtner et al. (2004), Cannon et al. (2005), Amato et al. (2006), Schneider et al. (2007), Gonzales and Van Schmus (2007).

Tables 5 and 8. According to Slagstad et al. (2004a), early models (Hoffman, 1989; Windley, 1993) suggested an anorogenic setting for both the ERGP and SGRP based on A-type composition of the granites and relative lack of deformation. Later models suggested orogenic setting and derivation from juvenile continental crust (Van Schmus et al., 1996). Could it be that the Eastern Granite-Rhyolite Province may represent the early stages of the Grenville

Orogen in Laurentia? Another regional unit of Laurentia not considered to be part of the Grenville Orogen by several authors is the Composite Arc Belt (1320–1220 Ma, Schwerdtner et al., 2004), an assemblage of metamorphosed volcanic, sedimentary, and plutonic rocks. The oldest rocks of the Composite Arc Belt have an age equivalent to the youngest rocks of the Candeias orogeny of Amazonia (Table 8).

The West Amazon Craton seems to be much richer in intraplate plutons formed between 1580–1520 Ma (Serra Providência Suite, rapakivi granites and charnockites) when compared to Laurentia. Magmatism of that age is detected by Van Breemen and Corriveau (2005) in inherited zircon of Wakeham Group and nearby plutons (1610–1550 Ma).

The two main components of the Sunsás basement compare well in age to pre-Grenville units of Laurentia. The Quatro Cachoeiras orogeny (1689–1632 Ma) is broadly comparable to the Mazatzal Orogen of central-north United States (Van Schmus et al., 2007) both in timing and nature: both are essentially collisional orogenies which deformed neighbour orogen formed during geon 17 (Jamari in Amazonia and Yavapai in Laurentia). It is comparable in timing to the Labradorian rocks of Canada (1710–1600 Ma; Gower and Krogh, 2002) including the Labradorian Batholith (1650 Ma; Schärer and Gower, 1988) and plutonic rocks of AMCG affinity (1650–1630 Ma). The Jamari orogeny (1764–1746 Ma) is coeval to pre-Labradorian rocks (>1710 Ma; Gower and Krogh, 2002) in Canada and to the Yavapai accretion in central-north USA (ca. 1760 Ma; Holm et al., 2007). The older Juruena Domain (1840–1780 Ma) is partially contemporaneous to the Trans-Hudson Orogen in Canada (1820–1790 Ma; Schneider et al., 2007) and in Colorado (1800–1750 Ma; Gonzales and Van Schmus, 2007). The Yavapai Orogen in Iowa, Wisconsin and Minnesota was formed between 1760 and 1650 Ma (Cannon et al., 2005; Holm et al., 2007), a period partially contemporaneous to the timing of Jamari Complex and Quatro Cachoeiras Group (Table 8). The Yavapai (geon 17) and Mazatzal (geon 16) terranes of Laurentia in the USA “probably also continue eastward into Ontario, Canada and farther east into protolith of the Grenville Province” (Van Schmus et al., 2007). This is analogous to the Amazonia evolution, where the Jamari (geon 17) and Quatro Cachoeiras (geon 16) terranes are the main protoliths of the Sunsás Orogen.

5.8.2. Alternative hypothesis

How were the Amazonia and Laurentia continents connected, if at all, during the interval of 1465–1110 Ma?

The role of the Amazonia continent in the Rodinia supercontinent has been much debated since 1991 (Dalziel, 1991), and the timing of its amalgamation to Laurentia has been proposed as 1200 Ma by Tohver et al. (2004). The late separation of Amazonia from Rodinia is yet to be chronologically established, but the general breakup of Rodinia is considered Neoproterozoic at about 780 Ma (Harlan et al., 2003) or 800 Ma (Weil et al., 1998). The fragmentation may have started earlier, before about 1000 Ma, as suggested by the absence of Ottawan rocks in Amazonia. The existence of age-equivalents of the Candeias and Santa Helena orogenies in Laurentia (Pinwarian orogeny and rocks of Eastern Granite-Rhyolite Province and of the Composite Arc Belt, Table 8) is an indication that the connection of the two continents may be older than 1200 Ma. It may have started as early as ca. 1450 Ma as suggested by Santos et al. (2002) or even earlier (ca. 1820 Ma?), should the correlation of the Trans-Hudson Orogen to the Jamari and Juruena Domains be correct (Table 8).

The palaeogeography of the large combined Sunsás-Grenville Orogen in the Rodinia supercontinent at the end of the Mesoproterozoic is largely unresolved. Most paleo-reconstructions have interpreted the juxtaposition of Amazonia and Laurentia side-by-

Fig. 26. The positions of the Amazonia and Laurentia continents at the end of the Mesoproterozoic considering orthogonal link. The figure shows the Phanerozoic Belts (pink) for visualization of the actual shape of continents. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Fig. 27. Proposed paleo-reconstruction of Amazonia (left) and Laurentia (right) continents at ca. 1000 Ma. Map integrated from Tollo et al. (2004) and Santos (2003). Ages for Amazonia according to this work and for Laurentia following Magnani et al. (2004), Cannon et al. (2005), Amato et al. (2006), Mueller and Frost (2006), Schneider et al. (2007), Holm et al. (2007).

side (Weil et al., 1998; Keppie et al., 2001; Tohver et al., 2004; Cawood et al., 2007; Li et al., 2008) in the eastern part of Laurentia (the eastern connection). However, there is another possibility to consider in light of the new U–Pb ages. This new possibility utilizes the polarity of subduction in both the Sunsás and Grenville Orogens and the broader geochronology of both Laurentia and Amazonia continents during the Mesoproterozoic. First, we note that the Grenville Orogen broadly developed from southeast to northwest, whereas the Sunsás Orogen evolved in the opposite sense from southwest to northeast. Because of the good correlations between most of Mesoproterozoic (Sunsás and Grenville) and Late Paleoproterozoic units, it seems likely that the two continents were once closely adjacent or even connected. If so, one was subsequently rotated in relation to the other to ensure the same polarity for the two orogens (Fig. 26).

The proposed western connection model also works well for the other pre-Grenville provinces on both continents. The Trans-Hudson (Schneider et al., 2007) and Yavapai (Holm et al., 2007) orogens in Laurentia fit well with the Rio Negro, Rondônia-Juruena, and Tapajós-Parima provinces (Santos, 2003) in Amazonia (Fig. 27). The collision of the Mazatzal Province to the Yavapai Province in southwestern Laurentia (1680–1650 Ma, Magnani et al., 2004; 1650–1630 Ma, Holm et al., 2007) is remarkably contemporaneous to the Quatro Cachoeiras collisional orogeny in Amazonia. The main lineaments present in the Mazatzal-Yavapai (presently N60E Jemez lineament; Magnani et al., 2004) and in the Rondônia-Juruena (actually E–W Quatro Cachoeiras lineament) provinces become parallel after reconstruction of Fig. 27. This fit supports the Amazonia-Laurentia connection as being pre-Grenvillian and part of the 1.9–1.8 Ga Paleoproterozoic Columbia supercontinent (Rogers and Santosh, 2003). A western connection also suggests that the amalgamation of the Archean Wyoming Province to the western Laurentia margin at 1.90–1.80 Ga (Mueller and Frost, 2006) was pushed from the west by Amazonia (see position of Wyoming Province in Fig. 27). Hopefully, future paleomagnetic studies can test this idea.

The crustal block or continent which drove the evolution of the combined Grenville-Sunsás into Amazonia-Laurentia continent to form the Rodinia supercontinent would have been positioned to the south, southeast and southwest of Amazonia-Laurentia continent as shown in Fig. 26. It seems likely that such a block was removed, probably during the Rodinia breakup.

6. Conclusions

Despite some advances achieved by this work, there is a gap on knowledge of the West Amazon Craton. Several problems remain unresolved and ongoing U–Pb SHRIMP and Hf isotopes studies can contribute for their solution. The main improvements in the regional geology are listed below:

- (1) New U–Pb and Sm–Nd data, together with the integration of previous geochronology, establish the chronological evolution of the Sunsás and Rondônia-Juruena Provinces; these new data also improve correlations between tectonic domains and geographic regions (Table 5).
- (2) The Sunsás Orogen evolved in situ in the western margin of the Amazon Craton during about 360 m.y. (from 1465 to 1110 Ma). Four orogenies are defined: Santa Helena, Candeias, San Andrés, and Nova Brasilândia, each separated by long periods of quiescence.
- (3) Use of metamorphic grade-based stratigraphy is not appropriate for a region with several successive orogenies. Some examples of stratigraphic reinterpretations based on new U–Pb dating include the following:

- The granulitic rocks in Bolivia (Lomas Manechi Complex) and Rondônia are not the basement (the older regional rocks), but were formed by the Candeias orogeny at 1370–1320 Ma.
 - The rocks generated by the youngest orogeny (the Nova Brasilândia; 1180–1110 Ma) are not restricted to the low metamorphic grade, but also include rocks of upper amphibolite facies and anatectic rocks.
 - All the four Sunsás Orogenies and the basement rocks include orhogneisses, which are not restricted to the Chiquitania Complex.
- (4) The predominance of detrital zircons with ages comparable to the age of the Sunsás Orogen in the lower Orinoco River sand is evidence for the extension of the Sunsás Belt into eastern Venezuela. The Mesoproterozoic age of part of the Rio Apa Complex in Paraguay and the Hf model ages in northeast Argentina are evidence for the presence of the Sunsás Orogen to the southeast of the type locality (Brazil-Bolivia border). These two extensions to northeast and southeast are mostly covered by Phanerozoic basins and together form a 6000 km long belt.
 - (5) There is no evidence for the existence of a microcraton – the Paraguá – between the Sunsás Orogen and the Amazon Craton.
 - (6) The apparent absence of the Ottawan orogeny in Amazonia shows that cratonization began earlier there than in Laurentia and also that the break-up of the Rodinia supercontinent may have started before 1.0 Ga.
 - (7) The polarity of subduction in Laurentia and Amazonia during the Mesoproterozoic suggests that the paleo-juxtaposition of the two continents along the Atlantic margin of Laurentia (the eastern connection) is unlikely. Instead, the docking of Amazonia seems to fit much with the west-southwest parts of Laurentia (the western connection).

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EL GRANITO DIAMANTINA: EVIDENCIA ISOTÓPICA Y QUÍMICA DE MAGMATISMO DE ARCO EN EL COMPLEJO PENSAMIENTO, PROVINCIA RONDONIA- SAN IGNACIO, PRECAMBRICO DE BOLIVIA ORIENTAL

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Palabras claves: Bolivia, Complejo Granítico Pensamiento, Granito Diamantina, Orogenia San Ignacio, sistemática Sm-Nd, Cratón Amazónico.

RESUMEN

El Granito Diamantina es un plutón comprendido en el Complejo Granitoide Pensamiento (CGP), en el Precámbrico de Bolivia. El CGP está asignado a la evolución de la Provincia Rondoniana- San Ignacio (1.50-1.30 Ga) del sudoeste del Cratón Amazónico. La evolución del Cratón en el Proterozoico resulta del desarrollo de fajas móviles de dirección NO-SE, que se tornan más jóvenes al sudoeste como es el caso de las orogenias Rondoniana-San Ignacio (1.36-1.30 Ga) y Sunsás (1.20-1.00 Ga) en Bolivia y Brasil. El CGP aflora enteramente dentro del Cratón Paraguá y está parcialmente sobreimpreso por la orogenia Sunsás. El CGP comprende granitos y términos subvolcánicos y subordinadamente sienitas, granodioritas, tonalitas, trondhjemitas y dioritas, tectónicamente caracterizadas como sin a tardi-cinemáticas y tardi a post cinemáticas. El granito Diamantina es un plutón tardi a post cinemática.

Cuatro muestras del Granito Diamantina analizadas en roca total por elementos mayores, traza y ETR indican carácter subalcalino, en el diagrama AFM caen en el campo calcoalcalino. El granito despliega contenido de SiO₂ de 72 a 75wt% y es peraluminoso en composición. Esta roca muestra dos características diferentes en el diagrama REE: i) las muestras CP0505, CP20506 y CP30507 exhiben un comportamiento empinado. Esto se relacionaría con los altos contenidos de LREE y bajo contenido en HREE, probablemente reflejando la fraccionación de anfíbol y/o allanita. ii) la muestra ME0508 presenta forma de "ala de gaviota" con moderada anomalía negativa de Eu, típica de granitos diferenciados. En el diagrama de multielementos, los picos negativos de Sr, P y Ti se interpretan como debido a la fraccionación de mica, feldespato, apatita, y fases de Ti. Una datación U-Pb SHRIMP produjo una edad de 1340 ± 20 Ma. El Granito Diamantina despliega edades modelo T_{DM} variables entre 1.6 y 1.9 Ga (razones $f_{Sm/Nd}$ entre -0.50 y -0.25), y $\epsilon_{Nd(1.33Ga)}$ de +0.4 a -1.2. que indican una mezcla de material derivado del manto y material cortical. Estos datos son consistentes con un ambiente de arco magmático.

INTRODUCCIÓN

El Cratón Amazónico (Figura 1), de amplio desarrollo en Sudamérica, comprende las provincias geocronológicas Maroni-Itacaiunas (2.25-1.95 Ga), Ventuari-Tapajós (2.0-1.8 Ga), Río Negro-Juruena (1.78-1.55 Ga), Rondoniana-San Ignacio (1.50-1.30 Ga), y Sunsás (1.25-1.0 Ga), Teixeira et al., (1989); Tassinari et al., (2000). Los estudios de Sm-Nd (Cordani y Sato, 1999) confirmaron esta arquitectura cortical, respaldada por numerosos trabajos geocronológicos en isótopos de U-Pb y Rb-Sr en rocas granitoides. La Provincia Rondoniana-San Ignacio (PRSI) de amplia distribución en la región sudoeste del Cratón Amazónico (Brasil y Bolivia) fue estudiada por varios autores (Litherland et al., 1986; Sato y Tassinari, 1997; Van Schmus et al., 1998; Bettencourt et al., 1999; Gerales et al., 2000, 2001, 2004; Leite y Saes, 2000; Payolla et al. 2002, Santos et al., 2000; Santos et al., 2005, 2006), sin embargo la edad, estructura, composición de las unidades rocosas y eventos orogénicos dentro del territorio boliviano aun son poco conocidos.

El Granito Diamantina, un plutón del CGP, constituye una elevación de orientación norte, de forma elíptica, de 53 km de largo (Klinck y O'Connor, 1982). Aflora como una "isla" en medio de la vegetación sobre el camino que une las localidades de Santa Rosa de la Roca y Piso Firme, departamentos de Santa Cruz y Beni (Figura 2). El tipo de roca dominante es un monzogranito biotítico, de color rosado pálido, sin foliación y considerado como tardío a postcinemático. Las rocas hospedantes del Granito

Diamantina son los granitos San Martín y La Junta, considerados sincinemáticos a tardicinemáticos en edad, moderadamente foliados de acuerdo a la estructura regional del Complejo Granitoide Pensamiento.

Este trabajo, efectuado en el Instituto de Investigaciones Geológicas y del Medio Ambiente (IGEMA) de la UMSA y el Centro de Pesquisas Geocronológicas del Instituto de Geociencias de la Universidad de Sao Paulo, Brasil, presenta resultados de geoquímica y de isótopos de Sm-Nd y U-Pb del Granito Diamantina y emplaza importantes definiciones isotópicas en los protolitos rocosos de la PRSI en territorio boliviano. Este estudio es parte de un proyecto de doctorado que el autor, docente e investigador de la UMSA realiza en la USP de Sao Paulo, Brasil. El propósito de la tesis es determinar la evolución tectónica del Precámbrico del oriente de Bolivia y su relación a la evolución de la región sudoeste del Cratón Amazónico en el Mesoproterozoico.

GEOLOGÍA REGIONAL

El Granito Diamantina, pertenece al Complejo Granitoide Pensamiento dentro del Cratón Paraguá y forma parte de la Provincia Rondoniana-San Ignacio en el Precámbrico de Bolivia (Litherland et al., 1986). Esta provincia es el resultado de la geodinámica durante el Mesoproterozoico (1600 a 1000 Ma) que produjo una serie de fajas acrecionadas culminando con una colisión continental contra la provincia Río Negro-Juruena (1.78-1.55 Ga) (Cordani y Teixeira, 2007), El evento colisional está marcado por el metamorfismo de facies granulita (1.35-1.32 Ga) que produjo una sobreimpresión en la roca hospedante. Se debe resaltar que el conocimiento detallado del escenario tectónico de la Provincia Rondoniana-San Ignacio es una tarea difícil debido a la evolución cortical policíclica. La sobreimpresión más joven está asociada a la orogenia colisional Sunsás (1.2-1.0 Ga).

GRANITO DIAMANTINA, GEOLOGÍA Y PETROGRAFÍA

Las rocas del basamento metamórfico del Precámbrico boliviano están constituidas por el Complejo Granulítico Lomas Maneches, el Complejo Gnéisico de la Chiquitania y por el Grupo de Esquistos San Ignacio. Estas tres unidades fueron intruídas por los granitos del Complejo Pensamiento y por los granitos de la Zona Sur. El Complejo Granitoide Pensamiento es una unidad plutónica extensa con granitoides subvolcánicos subordinados. Este mar de gneisses y granitos consiste de sienitas, granodioritas, tonalitas, trondhjemitas y dioritas. Se reconocen dos eventos magmáticos intrusivos dentro del CGP, los granitos sin a tardi cinemáticos y los granitos tardi a post cinemáticos. El granito Diamantina es parte de ese segundo grupo.

El granito Diamantina está expuesto sobre el camino de Santa Rosa de Roca a Piso Firme. Es de grano fino y a veces de grano medio a grueso, con biotita como mineral máfico principal. Contiene xenolitos de litologías variadas (gneisses biotíticos, gneisses de granate-biotita y gneiss hornbléndico). Contiene venas y lentes de pegmatita (Klinck y O'Connor, 1982). El granito Diamantina en el presente trabajo fue muestreado en cuatro lugares (Figura 2). El tipo de roca dominante es un sienogranito biotítico rosado pálido, no foliado. Una muestra (ME0508; un cuarzo monzonito moderadamente foliado), se colectó en la estancia La Mechita y se asemeja a un gneiss del Complejo Chiquitania.

Tabla1. Descripción petrográfica de cuatro muestras del Granito Diamantina.

Muestra	Plutón	Características principales
CP0505	Diamantina	Sienogranito masivo a ligeramente porfirítico, de grano medio, de color blanco rosado. La textura es equigranular anhedral a subhedral. Esporádicos parches de intercrecimiento de plagioclasa con cuarzo vermicular. Algunos cristales de plagioclasa (An26), contienen pajuelas de muscovita. El feldespato potásico es microperítico y muestra maclado en rejilla propio de la microclina. La biotita es el principal mineral ferromagnesiano y está escasamente cloritizado y es de color amarillo pajizo a verde olivo oscuro. La roca contiene masas irregulares de minerales opacos, zircón euhedral, escasa apatita, a veces incluida en la biotita.
CP20506	Diamantina	Sienogranito de grano medio, blanquecino, masivo a ligeramente porfirítico. Textura equigranular subhedral a anhedral. Los cristales de plagioclasa (An28), contienen una densa masa de muscovita de grano fino y minerales de arcilla, de color pardo pálido procedentes de la alteración. El feldespato potásico muestra maclado en enrejado característico de la microclina. La biotita está escasamente cloritizada y es de color amarillo pajizo a verde olivo oscuro. El epidoto es de origen secundario y aparece en pequeños cristales. Masas esqueléticas de minerales opacos conteniendo apatita y epidoto. La apatita aparece también como inclusión en la biotita. El zircón y el apatito se presentan en cristales euhedrales.
CP30507	Diamantina	Sienogranito de grano medio, blanquecino, masivo a ligeramente porfirítico.. Textura inequigranular anhedral. El feldespato potásico contiene un intercrecimiento tipo microperitita. Parches de plagioclasa intercrecida con cuarzo vermicular. La biotita es de color amarillo pajizo a verde olivo oscuro. Pajuelas de muscovita en plagioclasa. Masas irregulares de minerales opacos asociados a la biotita. Apatita euhedral.
ME0508	Diamantina	Cuarzo monzonita de color rosado blanquecino. Grano medio a grueso. Textura equigranular subhedral a anhedral. Algunos fenocristales de feldespato potásico, con maclado tipo microclina. La plagioclasa contiene cristales de grano muy fino de muscovita y arcillas de color pardo pálido. Abundante plagioclasa intercrecida con cuarzo vermicular. Biotita de color amarillo pajizo a verde olivo oscuro. Muy poco epidoto diminuto secundario. Zircón como inclusiones en la biotita. Apatita euhedral.

TÉCNICAS ANALÍTICAS

Se seleccionaron cuatro muestras para el análisis químico de roca total para elementos mayores y menores (SiO_2 , TiO_2 , Al_2O_3 , $\text{Fe}_2\text{O}_{3\text{Tot}}$, MnO , MgO , CaO , K_2O , Na_2O and P_2O_5) y elementos traza en el Laboratorio Químico del Instituto de Geociencias de la Universidad de São Paulo (IGc-USP), Brasil, siguiendo las técnicas formuladas por Navarro (2004). Asimismo, se analizaron cuatro muestras por Sm-Nd en roca total en el Centro de Pesquisas Geocronológicas (CPGeo) del Instituto de Geociencias de la Universidad de Sao Paulo siguiendo la rutina descrita por Sato et al. (1995).

RESULTADOS Y DISCUSIÓN

El granito Diamantina muestra contenido de SiO_2 de 72 a 75wt%, y pertenece al campo de alto K en el diagrama SiO_2 versus K_2O de Peccerillo y Taylor (1976), e indica una composición peraluminosa en el diagrama de Maniar y Piccoli (1989); la razón $\text{K}_2\text{O}/\text{Na}_2\text{O}$ varía de 1.5 a 1.8. Cuatro muestras del Granito Diamantina analizadas en roca total por elementos mayores, trazas y ETR indican carácter subalcalino; en el diagrama AFM de Irvine y Baragar se encuentran en el campo calcoalcalino. Este plutón muestra dos características diferentes en el diagrama REE (Figura 3): i) las muestras CP0505, CP20506 y CP30507 exhiben un comportamiento empinado. Esto se relacionaría con los altos contenidos de LREE y bajo contenido en HREE, probablemente reflejando la fraccionación de anfíbol y/o allanita. ii) la muestra ME0508 en el diagrama de ETR presenta forma de “ala de gaviota” con moderada anomalía negativa de Eu debido a la fraccionación de la plagioclasa, típica de granitos diferenciados; los valores más elevados en los ETRP indica fuente cortical para esta muestra. En el diagrama de multielementos (Figura 4), los picos negativos de Sr, P y Ti se interpreta como debido a la fraccionación de mica, plagioclasa, apatita, y fases de Ti en la magnetita.

Los parámetros isotópicos de Nd de las rocas investigadas se calcularon de acuerdo a la referencia proporcionada por la edad U/Pb SHRIMP en los bordes de zircones (1.33 Ga) del Granito San Rafael

(Boger et al., 2005), interpretado como la edad de emplazamiento del plutón durante la orogenia San Ignacio. Adicionalmente edades zircón U-Pb SHRIMP se efectuaron (Matos, en preparación) en la muestra CP30507 del Granito Diamantina, permitiendo la interpretación de los procesos petrogenéticos del CGP.

El Granito Diamantina despliega edades modelo T_{DM} variables entre 1.6 y 1.9 Ga (razones $f_{Sm/Nd}$ entre -0.50 y -0.25), y $\epsilon_{Nd(1.33Ga)}$ de +0.4 a -1.2. A partir de los datos anteriores el Granito Diamantina muestra valores de Nd compatibles con una mezcla de material derivado del manto con corta residencia cortical en el proceso petrogenético. El nuevo análisis U-Pb SHRIMP efectuado en el Granito Diamantina produjo una edad de 1340 ± 20 Ma (Matos, en preparación, 2008). El Granito Diamantina consiguientemente es contemporáneo con el Granito San Rafael (1.33 Ga), un plutón representativo de la Orogenia San Ignacio en Bolivia (Boger et al., 2005). Los datos adicionales de edad U-Pb SHRIMP en zircón en el rango de 1.34 – 1.32 Ga para las unidades Lomas Maneches y Chiquitania (Boger et al., 2005; Santos et al., 2006; 2007), revela una sobreimpresión metamórfica asociada con esta orogenia que afectó no solo al escudo del Precámbrico Boliviano sino también la contraparte Brasileña.

CONCLUSIONES

Varios eventos orogénicos se reportaron en el SW del Cratón Amazónico, en el Estado de Mato Grosso, como ser Alto Jauru (1.79- 1.74 Ga), Cachoeirinha (1.58-1.52 Ga) y Santa Helena (1.45-1.40 Ga), Geraldés et al., (2004); asimismo, se determinaron series graníticas rapakivi en el Estado de Rondonia como Serra da Providencia (1.66- 1.64 Ga), Santo Antonio y Teotonio (1406 Ma y 1387 Ma respectivamente), Alto Candeais (1338-1346 Ma) y San Lorenzo-Caripunas (1314-1309 Ma) estudiadas por Bettencourt et al., (1999). Las características isotópicas y geoquímicas presentadas en este trabajo concuerdan bien con un escenario de arcos magmáticos culminando con una colisión continental a los 1.33 Ga contra la provincia Rio Negro-Juruena, como recientemente fue propuesto para la evolución de la provincia Rondoniana-San Ignacio por Cordani y Teixeira (2007). Adicionalmente, las rocas granitoides del Precámbrico Boliviano presentan valores negativos de Nb, Sr and Ti, mientras que muestran valores de Rb, Ba y Th enriquecidos respecto al Nb (Litherland et al., 1986). Este es un rasgo típico de magmas evolucionados en arcos magmáticos.

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FIGURA 1. Provincias geotectónicas de Sudamérica (según Cordani et al., 2000).

Figura 3. Diagrama REE, normalizado al condrito del Granito Diamantina.

Figura 4. Diagrama de elementos traza normalizado al condrito del Granito Diamantina.

Geochemistry and Nd-Sr Isotopic Signatures of the Pensamiento Granitoid Complex, Rondonian-San Ignacio Province, Eastern Precambrian Shield of Bolivia: Petrogenetic Constraints for a Mesoproterozoic Magmatic Arc Setting

Geoquímica e Assinaturas Nd-Sr do Complexo Granitoide Pensamiento, Província Rondoniana-San Ignacio, Pré-Cambriano de Bolívia Oriental: Caracterização Petrogenética de um Arco Magmático no Mesoproterozoico

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ABSTRACT

The Pensamiento Granitoid Complex (PGC), located in the northern part of the eastern Precambrian shield of Bolivia, is tectonically assigned to the Rondonian-San Ignacio Province (1.55 - 1.30 Ga) of the Amazonian Craton that is made up by Archean and Proterozoic provinces. The Proterozoic ones result from accretionary orogens that become successively younger southwestwards, such as the Rondonian/San Ignacio (1.37 - 1.32 Ga) and the Sunsás orogenies (1.20 - 1.00 Ga). The PGC crops out mainly on the "Paragua craton" bounded to the south by the Sunsás belt, and composed of granites and subvolcanic terms, and subordinately of syenites, granodiorites, tonalites, trondhjemitic and diorites as orogenic representatives of the Rondonian/San Ignacio Orogeny, intrusive into the Lomas Maneches (ca. 1.68 Ga) and Chiquitania (ca. 1.7 Ga) complexes. Thirteen whole rock chemical analyses for major, trace and REE elements were performed for the La Junta, San Martín, Diamantina, Porvenir, San Cristóbal, Piso Firme plutons of the PGC. The negative trends of MgO, Al₂O₃ and CaO contents with increasing SiO₂ suggest that fractional crystallization played an important role in the petrogenesis of the investigated rocks. The data also indicate a mainly peraluminous, sub-alkaline to high-K calc-alkaline composition, and fractionated LREE/HREE patterns are consistent with a magmatic arc character for these plutons. SHRIMP U-Pb zircon ages of the La Junta and San Martín syn- to late-kinematic plutons are 1347 ± 21 Ma and 1373 ± 20 Ma respectively, and the Sm-Nd T_{DM} model ages are between 1.9 to 2.0 Ga, while ε_{Nd(1330)} values range from +1.8 to -4.3, respectively. In addition, the late- to post-kinematic Diamantina pluton yields SHRIMP U-Pb zircon age of 1340 ± 20 Ma, and variable Sm-Nd T_{DM} model ages (1.6 to 1.9 Ga) and ε_{Nd(1330)} values (+0.4 to -1.2) that are comparable with previous results found for other coeval plutons. The Porvenir, San Cristóbal and Piso Firme plutons show ε_{Nd(1330)} signatures varying from +1.5 to +2.7, in agreement with a plutonic arc setting as is suggested for the Diamantina pluton. Integrated interpretation of the geochemical and isotopic data coupled with new geologic correlations of the PGC with contemporary units in the Brazilian counterpart establishes one Mesoproterozoic magmatic arc in the evolution of the Rondonian-San Ignacio province.

Keywords: Bolivia; Pensamiento Granitoid Complex; Geochemistry; Nd-Sr isotopes; Rondonian-San Ignacio province; Amazonian Craton.

RESUMO

O Complexo Granitoide Pensamiento (CGP) ocorre na porção norte do Pré-Cambriano Boliviano, estando tectonicamente associado à evolução da província Rondoniana-San Ignacio (1.55 - 1.30 Ga) do Craton Amazônico, constituído por uma província central de idade arqueana e províncias proterozoicas marginais. A evolução proterozoica resulta do desen-

volvimento de cinturões acrescionários sucessivamente mais jovens para sudoeste, a exemplo das orogenias Rondoniana-San Ignacio (1.37 - 1.32 Ga) e Sunsás (1.20 - 1.00 Ga). O CGP ocorre na parte setentrional do Pré-Cambriano Boliviano, ao norte do cinturão Sunsás, sendo constituído por granitos e termos subvulcânicos. Subordinadamente ocorrem sienitos, granodioritos, tonalitos, trondjemitos e dioritos. Em termos tectônicos, essas rochas são classificadas em dois conjuntos: plutons sin a tardicinemáticos e tardi a pós-cinemáticos. Treze análises químicas em rocha total para elementos maiores, traços e ETR foram realizadas em rochas granitoides orogênicas do CGP. Diagramas de correlação geoquímica indicam tendência negativa entre os conteúdos de MgO , Al_2O_3 and CaO em função do aumento de SiO_2 , sugerindo processos de cristalização fracionada na petrogênese das rochas investigadas. Em adição os dados indicam uma composição principalmente peraluminosa, subalcalina de alto K, compatível com ambiente de arco magmático, para a geração dos plútons estudados, corroborado pelo padrão de fracionamento dos ETRL/ETRP. Datações SHRIMP em zircão dos plútons La Junta e San Martin (sin a tardicinemáticos; 1347 ± 21 e 1373 ± 20 Ma, respectivamente) em conjunto com idades modelo T_{DM} entre 1,9 e 2,0 Ga e valores de $\epsilon_{Nd(1330)}$ entre +1,8 e -4,3 são semelhantes a resultados publicados em outros corpos coevos. Em adição, os plútons Porvenir, San Cristobal e Piso Firme (tardi a pós-cinemáticos) têm idades T_{DM} modelo entre 1,6 e 1,7 Ga e valores de $\epsilon_{Nd(1330)}$ positivos entre +2,7 e +1,5, o que sugere uma origem em arco magmático intraoceânico. O plúton Diamantina (tardi a pós-cinemático; idade SHRIMP em zircão de 1340 ± 20 Ma) tem idades T_{DM} modelo entre 1,6 e 1,9 Ga com valores de $\epsilon_{Nd(1330)}$ entre +0,4 e -1,2. Isto corrobora a hipótese de significativa contribuição de material juvenil mesoproterozoico durante a sua gênese. Os resultados aqui obtidos interpretados em conjunto com os dados geológicos de unidades contemporâneas na contraparte brasileira reforçam a existência de um arco magmático juvenil mesoproterozoico que finalizou a evolução acrescionária da província Rondoniana-San Ignacio.

Palavras-chave: Bolívia; Complexo Granitoide Pensamiento; Província Rondoniana-San Ignacio; Geoquímica; Isótopos Nd-Sr.

INTRODUCTION

The Pensamiento Granitoid Complex (PGC) constitutes a large volume of Mesoproterozoic gneisses and granitoid rocks that occur in the Bolivian departments of Santa Cruz and Beni. The PGC rocks are one of the major components that built up the Rondonian-San Ignacio Province (1.55 to 1.30 Ga; e.g., Cordani and Teixeira, 2007) of widespread extension along the SW part of the Amazonian Craton, Brazil (Rondônia and Mato Grosso states besides Bolivia). Tectonically the PGC (Figures 1 and 2) is attributed to the onset of the San Ignacio orogeny in Bolivia (1400 - 1280 Ga; Litherland et al., 1986), as part of the "Paraguá Craton" which bounds are subjected to Sunsás-age low grade metamorphic and shearing overprints (e.g., Litherland et al., 1989; Boger et al., 2005). The San Ignacio orogeny produced three fold generations overprinting Paraguá crystalline basement rocks, whereas the earliest stages of deformation established the observed metamorphic sequence at regional scale (Litherland et al., 1986, 1989; Boger et al., 2005). Field mapping of the PGC revealed that the plutonic rocks are syn- to late-kinematic with reference to Do3 deformational event (Litherland and Bloomfield, 1981) whilst the late- to post-kinematic ones crosscut Do3.

We have carried out a reconnaissance geologic investigation along the road that connects Santa Rosa de la Roca and Piso Firme localities (Figure 2), covering a 330 km transverse along the PGC. From south to north, the studied units are: the syn- to late-kinematic La Junta and San Martin granites, and the late- to post-kinematic Diamantina, Porvenir and San Cristobal granites and the Piso Firme granophyre. However, further detailed geological studies

are needed to better define the relationships among the granitoid rocks and with the crystalline basement. The present work is part of an ongoing PhD project (R. Matos) at the Institute of Geosciences of University of São Paulo, Brazil, aiming to delineate the petrogenetic evolution of the PGC and its tectonic significance. We present petrographic and geochemical data coupled with systematic Sr-Nd isotopic work of PGC rocks, supported by SHRIMP published and unpublished data. The integrated interpretation provides new insights on the nature the Granitoid Complex with implications for the Mesoproterozoic history of the SW part of the Amazonian Craton.

GEOLOGIC FRAMEWORK

The Rondonian-San Ignacio Province - RSIP (Figure 1) was formed by Mesoproterozoic accretionary belts whose dynamics included stacking of intra-oceanic and continental arcs, as well as intervening microcontinents. The accretionary/ agglutination processes culminated with collision against the already cratonized Rio Negro-Juruena Province (1.78 - 1.55 Ga), in the southwest part of the Amazonian Craton. Lithologically the RSIP consists predominantly of granite-gneiss and granitoid rocks, some of them with rapakivi structures, as well as tonalites and granulites. Isotopic studies on these rocks indicate positive to slightly negative $\epsilon_{Nd(t)}$ signatures, roughly between +4.0 and -2.0, reinforcing the idea that juvenile events combined with reworking of the pre-existent crust played a major role during the long-lived plate convergence and collision against the tectonically stable foreland (see for review Tassinari et al., 2000; Cordani and Teixeira, 2007).

Figure 1. Geologic outline of the SW portion of the Amazonian Craton showing the main orogenic belts, the tectonically related intrusive magmatic suites and sedimentary covers and volcano-sedimentary sequences. The inferred boundaries between the Proterozoic provinces are also shown (adapted from Cordani and Teixeira, 2007). Keys: **SP** = Serra da Providência batholith, **CMS** = Colorado Metamorphic Sequence; **NBS** = Nova Brasilândia Sequence. *Inset:* geochronological provinces of the Amazonian Craton = Central Amazonian - CA (> 2.6 Ga); Maroni-Itacaiúnas - MI (2.25 - 2.05 Ga); Ventuari-Tapajós - VT (1.98 - 1.81 Ga); Rio Negro-Juruena - RNJ (1.78 - 1.55 Ga); Rondonian-San Ignacio - RSI (1.55 - 1.30 Ga) and Sunsás - SU (1.25 - 0.97 Ga). See text for details.

Figure 2. Geologic sketch of the studied area showing the regional occurrence of the Pensamiento Granitoid Complex (PGC) and the country rocks (modified from Litherland et al., 1986).

The collision features between the Rio Negro-Juruena and Rondonian-San Ignacio provinces are mirrored by faults, shear zones and fold-and-thrust belts (e.g., Tassinari et al., 2000), and associated to granulitic facies metamorphism (1.35 - 1.32 Ga) that overprint the country rocks in some places of the state of Rondônia, Brazil (SHRIMP U/Pb ages of zircon overgrowths; Bettencourt et al., 1999; Payolla et al., 2002; Santos et al., 2005) - see Table 1 and Figure 1. Contemporarily, the Colorado Complex (1.35 Ga), a “mafic” to “chemical”-clastic assemblage of passive-margin setting of the RSIP, in Rondônia (e.g., Teixeira et al., 2006), was deformed and overprinted by recognized medium- to high grade metamorphism. During this phase syn- to late tectonic, high-K, calc-alkaline granitoid rocks (e.g., Igarapé Enganado and Alto Escondido suites; 1345 - 1336 Ma) were emplaced into the Colorado Complex (Rizzotto and Quadros, 2007), whereas coeval granitoid rocks intruded into the already cratonized Rio Negro-Juruena crust (e.g., Alto Candeias Intrusive Suite; 1.34 Ga) - see Figure 1. On the whole all of these

magmatic and metamorphic events are representative of the Rondonian-San Ignacio orogeny of widespread occurrence in the SW corner of the Amazonian Craton (Cordani and Teixeira, 2007; Teixeira and Cordani, 2009).

The RSIP exhibits a polycyclic evolution, giving rise to several rock units (e.g., Rio Crespo, Santa Helena, Rio Alegre, Colorado, PCG; see Table 2) that show chemical and isotopic affinities of island arc and continental arc settings. These rock units were variably overprinted by the Sunsás orogeny (1.2 - 1.0 Ga) at the same time that several coeval geologic features were formed in Rondônia and Bolivia, such as rift basins (e.g., Nova Brasilândia, Pacaás Novos, Palmeiral), platform covers (e.g., Huanchaca/Aguapeí; see Figure 2), shear zones and basic and felsic magmatism (Rizzotto et al., 2002; Litherland et al., 1986; Tohver et al., 2006). The emplacement of the Santa Bárbara and Santa Clara Intrusive Suites between 1.08 and 0.98 Ga and of the Younger Granites of Rondônia (0.99 - 0.97 Ga) reveals the important role of extensional regimes over the cratonized crust during post-tectonic or anorogenic stages of the Sun-

Table 1. Main characteristics of the Rondonian-San Ignacio and Sunsás provinces, SW Amazonian Craton. Keys: **RSI** = Rondonian-San Ignacio orogeny; **SU** = Sunsás orogeny.

Characteristics of the Province	Major events	Main regional units and crustal structures	Main intrusive complexes
<i>Rondonian-San Ignacio (RSI)</i> (1.55 - 1.30 Ga). Collisional orogeny combined with accretionary domains. Voluminous orogenic plutonism. Regional cooling (1.31 - 1.30 Ga). Foreland for the Sunsás orogeny with contemporary tectonic reactivations and magmatism.	<ul style="list-style-type: none"> • Rio Crespo Intrusive Suite (1.49 Ga). • Rio Alegre orogen: island arc affinity rocks (1.51 - 1.48 Ga; ϵ_{Nd} from +2.5 to +4.7). • Santa Helena arc (calc-alkaline granitoid rocks). (1.44 - 1.42 Ga; ϵ_{Nd} from +2.6 to +4.0). • RSI orogeny: a) Colorado Complex metamafic and chemical-clastic assemblage metamorphosed to medium- to high-grade facies (1.36 - 1.32 Ga; ϵ_{Nd} from +0 to +5.2); b) Pensamiento Granitoid Complex, San Ignacio orogeny (PGC; 1.32 - 1.37 Ga). 	<p>Ocean floor mafic-ultramafic rocks. Calc-alkaline rocks. MCG associations: bimodal magmatism (1.36 - 1.35 Ga).</p> <p>San Ignacio orogenic granitoids (1.34 - 1.32 Ga). Rift basins tectonically linked with the Sunsás orogeny (see below): Pacaas Novos, Uopione, Palmeiral, Aguapeí/Huanchaca, Sunsás/Vibosi, sedimentary deposits.</p>	<p>Late to post-tectonic intrusions: e.g., Alto Candeias (1.34 Ga), Santa Clara (1.08 - 1.07 Ga) and Santa Bárbara (1.08 - 0.98 Ga) granitoid Suites.</p> <p>Anorogenic plutonism: e.g., Younger Granites of Rondônia (0.99 - 0.97 Ga).</p>
<i>Sunsás (SU)</i> (1.20 - 1.00 Ga). Collisional orogeny with thrust and fold belts. Cratonization and regional exhumation of the SW Amazonian Craton (1.00-0.92 Ga).	<ul style="list-style-type: none"> • Deformation and metamorphism: thrust and shear belts (1.10 Ga). • Local thermal overprint due to granite emplacement. 	<p>Passive margin assemblages overprinted by regional deformation and metamorphism. Syn- to late orogenic plutonism.</p> <p>Nova Brasilândia Sequence (1.21 - 1.05 Ga): bimodal magmatism and sediments.</p>	<p>Post-tectonic plutonism: (0.97 - 0.92 Ga). Rincón del Tigre mafic-ultramafic complex (~1.0 Ga).</p>

sás orogeny (e.g., Bettencourt et al., 1999; Payolla et al., 2002; Sparrenberger et al., 2002).

Litherland and Bloomfield (1981) originally defined the Sunsás orogeny as a cycle of sedimentation that took place in an extensional environment (e.g., Sunsás and Vibosi groups; Litherland et al., 1989). This was followed by erosion, deformation and metamorphism of the passive-margin sedimentary sequences, as well as of the PGC and the crystalline basement rocks named Paraguá Craton. Due to the Sunsás orogeny, brittle cataclastic deformation and mylonitization largely overprinted the country rocks giving rise to Rio Negro Front, the Santa Catalina Zone (Litherland et al., 1986; Klinck and O'Connor, 1983; Litherland and Klinck, 1982), the Blanco-Ibaimini Line Shear Zone and the curvilinear San Diablo Front, in Bolivia (Figure 1). In addition, coeval reactivated structures over the RSIP developed northward (e.g., Aguapeí fold and thrust belt, Nova Brasilândia belt, in Brazil - Figure 2). As such, the boundary between the Rio Negro-Juruena and Sunsás provinces with the RSIP is a very complex one.

The RSIP has been studied by several authors by means of geologic mapping, structure, geochemistry, geochronology (e.g., Litherland et al., 1986; Teixeira et al., 1989; Sato and Tassinari, 1997; Bettencourt et al., 1999; Cordani et al., 2000; Tassinari et al., 2000; Geraldies et al., 2001; Payolla et al., 2002; Boger et al., 2005; Santos et al., 2006, 2008). These efforts have also led to paleotectonic reconstructions mainly using geologic correlations, paleomagnetism and age data from the granitoid systems and mafic magmatism (Sadowski and Bettencourt, 1996; Tassinari et al., 2000; Tohver et al., 2002, 2004a, 2004b, 2005a, 2005b). Table 2 presents SHRIMP U-Pb, Rb-Sr and K-Ar ages of selected geologic units of the Bolivian Precambrian shield, including the data available for the PGC rocks to be discussed afterward.

The geologic framework of Bolivian Precambrian Shield (Litherland et al., 1986, 1989) comprises mainly four lithostratigraphic units based on the geologic work performed by the British Geologic Survey - GEOBOL, supported by Rb/Sr and K/Ar ages: 1. the Lomas Maneches Granulitic Complex; 2. the Chiquitania Gneissic Complex; 3. the San Ig-

nacio Schist Group; 4. the PGC - see Table 2 and Figure 2. The Lomas Maneches Complex was originally considered as the oldest lithostratigraphic unit of the shield, as suggested by Rb/Sr regional model age, but this assumption have been discarded on the basis of more precise SHRIMP work recently reported (see below). It comprises bands of charnockitic, enderbitic, and basic hypersthene granulites, and gneisses that contain metamorphic hypersthene or cordierite. The Chiquitania Gneiss Complex, considered to be structurally over the Granulite Complex, consists of banded micaceous quartz-feldspathic gneisses, without hypersthene and/ or cordierite. These rocks in the "Paraguá craton" show K-Ar mineral ages in the range 1.34 - 1.32 Ga

that compare well with the age pattern of the granitoid rocks of the PGC (assigned as the San Ignacio orogeny). The San Ignacio Schist Group crops out as discrete NW belts that are surrounded by distinct gneisses and granitoid rocks of the Lomas Maneches and Chiquitania units. It is composed of quartzites, metapsamites, schists, phyllites and metavolcanics. This unit is overlaid by the flat-lying sediments of the Sunsás Group (e.g., Huanchaca Formation) in the "Paraguá craton" (Figures 1 and 2).

Subsequently Boger et al. (2005) performed additional geologic work with the add of SHRIMP U-Pb zircon geochronology in distinct rock units that crop out southward from the PGC (see Figure 2), thereby providing new

Table 2. Summary of SHRIMP U-Pb, Rb-Sr and K-Ar ages of selected rocks of Bolivian Precambrian shield. Keys: **zr** = zircon; **hb** = hornblende; **bi** = biotite; **wr** = whole rock isochron; **Met. age** = metamorphic age; **Inh. age** = inherited age; * K-Ar cooling age; ** Isochron model age (spurious); ^P Pensamiento Granitoid Complex. References: **a.** Boger et al. (2005); **b.** Santos et al. (2006; 2008); **c.** Litherland et al. (1986).

Unit	Rock	Sample	Age (Ma)	Met. age (Ma)	Inh. age (Ma)	Method	Mat.	Ref.
Chiquitania	gneiss	235A1		1333 ± 6		U-Pb	zr	a
Chiquitania	gneiss	235A	1764 ± 12			U-Pb	zr	a
Chiquitania	gneiss	23	1336 ± 33*			K-Ar	hb	c
Chiquitania	gneiss	24	1323 ± 33*			K-Ar	hb	c
Lomas Maneches	gneiss	240	1663 ± 13	1320 ± 11		U-Pb	zr	b
Lomas Maneches	granulite	-	~1960**			Rb-Sr	wr	c
Lomas Maneches	gneiss	JO5		1334 ± 2		U-Pb	zr	b
Lomas Maneches	granulite	JO3	1818 ± 13	1339 ± 4**		U-Pb	zr; **mo	b
Lomas Maneches	gneiss	261	1689 ± 5			U-Pb	zr	a
Refugio	granite	JO12	1641 ± 4		1668 ± 8	U-Pb	zr	b
San Ramón	granite	JO14	1429 ± 4			U-Pb	zr-ti	b
San Rafael	granite	228	1334 ± 12		1686 ± 16	U-Pb	zr	a
Santa Rita	orthogneiss	JO18	1319 ± 6		1746 ± 21	U-Pb	zr	b
Rio Fortuna	orthogneiss	JO6	1336 ± 3		1753 ± 10	U-Pb	zr	b
San Ignacio	paragneiss	221D	< 1764 ± 6			U-Pb	zr	a
San Ignacio	schist	-	1340			Rb-Sr	wr	c
Florida ^P	granite	151	1244 ± 27*			K-Ar	bi	c
Florida ^P	granite	189	1380 ± 19			K-Ar	bi	c
Padre Eterno ^P	granite	178	1326 ± 19*			K-Ar	bi	c
Piso Firme ^P	granophyre	-	1325 ± 45			Rb-Sr	wr	c
La Junta ^P	granite	-	1375 ± 80			Rb-Sr	wr	c
Diamantina ^P	granite	-	1391 ± 70			Rb-Sr	wr	c
San Andrés	granite	JO10	1275 ± 7			U-Pb	zr	b
Orobayaya	granite	-	1283 ± 33			Rb-Sr	wr	c
El Tigre	alkaline	-	1286 ± 46			Rb-Sr	wr	c
San Javier	granite	-	1291 ± 49			Rb-Sr	wr	c
San Cristobal	granite	153	1296* ± 18			K-Ar	bi	c
Cerro Grande	granophyre	-	1176 ± 100			Rb-Sr	wr	c

insights on the chronostratigraphy of Bolivian Precambrian shield. They interpreted the Lomas Maneches as a magmatic suite consisting of granitic sills that were emplaced after the deposition of the Chiquitania Complex, but previously to the deposition of the San Ignacio Group. The main results (Table 2) are summarized as follow:

1. one sample from the Lomas Maneches suite contains zircon core that yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1663 ± 13 Ma, inferred as the rock's emplacement age. Additional analyses of the zircon rims yielded an age of 1320 ± 11 Ma, interpreted as the time of partial melting;
2. another Lomas Maneches sample yielded a concordant $^{207}\text{Pb}/^{206}\text{Pb}$ zircon age of 1689 ± 5 Ma;
3. two samples of the Chiquitania Complex showed zircon cores with inherited ages of 1788 ± 16 Ma, 1757 ± 14 Ma and 1764 ± 12 Ma, whilst the zircon rims were interpreted as metamorphic (1333 ± 6 Ma);
4. one San Ignacio paragneiss yielded (29 detrital zircons) a concordant $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1764 ± 6 Ma;
5. five zircon cores from the syn-kinematic San Rafael Granite yielded an upper intercept age of 1686 ± 16 Ma, suggesting its derivation from a Paleo- to Mesoproterozoic protolith - an idea that was already envisaged by the limited Nd isotopic evidence reported for selected PGC rocks (Darbyshire, 2000). Finally, the San Rafael pluton has zircon rim analyses that yielded an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1334 ± 12 Ma, indicating the tectonic relationship with the San Ignacio orogeny.

Santos et al. (2006, 2008) reported additional SHRIMP U-Pb ages in zircon, monazite and titanite from granitoid rocks to the south of PGC. One sample of the Lomas Maneches granulitic gneiss has magmatic zircons with $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1818 ± 13 Ma, which is the oldest age identified in Bolivia up to present. The monazite from this rock gives a metamorphic age of 1342 ± 3 Ma, in agreement with the age of another Lomas Maneches sample that has metamorphic zircons with 1334 ± 2.4 Ma (concordant $^{207}\text{Pb}/^{206}\text{Pb}$ age). On the other hand the Refugio granite has zircons with no metamorphic rim, and yields a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1641 ± 4 Ma and T_{DM} model age of 1.7 Ga ($\epsilon_{\text{Nd}(t)} = +4.06$). The San Ramon granite yields similar zircon and titanite $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1429 ± 4 Ma. Its Sm-Nd T_{DM} model age is 1.6 Ga ($\epsilon_{\text{Nd}(t)} = +2.3$). Therefore both granites were mainly derived from Mesoproterozoic juvenile sources. The San Andrés granite yields a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1275 ± 7 Ma, and may represent one of the syn-kinematic granites associated to Sunsás orogeny. On the other hand, the Rio Fortuna orthogneiss has two zircon populations: the first population (inherited core grains) between 1772 - 1734 Ma whereas the second one (magmatic zircon

and rims) formed at 1336 ± 3 Ma. Finally, the Santa Rita orthogneiss has magmatic zircons with $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1319 ± 6 Ma, although a single grain yields an inherited U-Pb age of 1729 ± 9 Ma (see Table 2).

In summary, the U-Pb SHRIMP ages and Sm-Nd data, coupled with the more recent field information of the Precambrian rocks of Eastern Bolivia established the age and igneous nature of the Lomas Maneches suite (1.69 - 1.66 Ga). Furthermore the U-Pb data evidenced some significantly older protholiths (up to 1.82 Ga) may have participated in the Proterozoic evolution. On the other hand, the San Ignacio orogeny, marked by syn- to late- kinematic plutonic pulses (PGC) and coeval metamorphism, took place in Bolivian territory between 1.37 - 1.32 Ga. This time interval correlates well with the ultimate tectonic and magmatic episodes assigned to the Rondonian-San Ignacio orogeny in the Brazilian counterpart, as proposed by Cordani and Teixeira (2007) and Teixeira and Cordani (2009).

The Pensamiento Granitoid Complex

The PGC consists of voluminous intrusive plutonic and subvolcanic granitic rocks, with subordinate syenites, granodiorites, tonalites, trondhjemitic and diorites, which have been dated firstly by Rb/Sr and K/Ar methods that indicate ages between 1.39 to 1.24 Ga (Litherland et al., 1986) (see Table 2). According to these authors the youngest K-Ar ages refer to the uplift and regional cooling of the Paraguá craton. In addition, they distinguished two intrusive magmatic events within the PGC, on the basis of the structural work: the syn- to late-kinematic and the late- to post-kinematic granitoid rocks such as the San Martin and La Junta granites, and the Diamantina pluton, respectively. Moreover, they recognized two regional metamorphic episodes (Mo1 and Mo2) in association with the San Ignacio Orogeny, attributed to the Do1/Do2 and Do3 deformational phases, respectively, whereas the metamorphism varies from low grade to granulite facies. A high grade hypersthene zone was recognized to the west of the San Martin river, and decreases to medium grade on the both sides of it (Klinck and O'Connor, 1983). The Do3, the major penetrative event in the area, accompanies generation of the bulk syn-kinematic granitoid plutons. Some of the late to post-kinematic granitoid plutons postdate Do3 phase and were emplaced following a markedly NNW trend (Litherland et al., 1986).

Recent geologic mapping (R. Mattos, pers. information) has revealed that the La Junta pluton has sharp intrusive contacts with the 1.69 - 1.66 Ga Lomas Maneches suite. Moreover, the field information has indicated that the San Cristóbal, Porvenir, and Diamantina granites, besides the Piso Firme granophyre (Figure 2), are late- to

post-kinematic, although Litherland et al. (1986) classified this granophyre as a syn- to late- tectonic intrusion. Furthermore, in the Brazilian counterpart (southeastern of Rondônia), contemporary orogenic and post-orogenic granites are intrusive into the 1.36 - 1.30 Ga Colorado Complex (Rizzotto and Quadros, 2007), that is tectonically linked with the Rondonian-San Ignacio Orogeny, as proposed by Teixeira and Cordani (2009).

The syn- to late- kinematic Puerto Alegre/La Junta granites of PGC display comparable T_{DM} model ages (2.0 and 2.1 Ga) and $\epsilon_{Nd(T)}$ values of -1.5 and -2.8, respectively (Darbyshire, 2000; Darbyshire, pers. comm., 2007). In contrast, the ~1.35 Ga Piso Firme granophyre (Litherland et al., 1986) yields significant younger but comparable T_{DM} model ages (1.5 and 1.6 Ga) and positive $\epsilon_{Nd(T)}$ values (+3.3 to +3.9). In a similar way the contemporary Diamantina and Orobayaya granites yield positive $\epsilon_{Nd(T)}$ values (+1.0 to +1.4) and T_{DM} model ages of 1.7 Ga (see Table 1).

ANALYTICAL TECHNIQUES

Thirteen samples were selected for major and minor elements (SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_{3Tot} , MnO , MgO , CaO , K_2O , Na_2O and P_2O_5) and trace elements chemistry at Chemical Laboratory of Institute of Geosciences of the University of São Paulo (IGc/USP), Brazil (Table 3), and following the technical procedures for REE separation as reported by Navarro (2004). The samples were first powered to < 200 mesh in an agate mill. The analytical routine for major elements and some trace elements comprises fusion using a mixture of 0.25g of rock powder and 0.75 g flux (lithium tetra and metaborate). HNO_3 0.2N solutions diluted to 1:1000 were analyzed in an ARL-3410 sequential spectrometer. The routine of the laboratory comprises: fluorescence X-ray spectrometry (Philips PW2400) for the analysis of the major and minor elements (SiO_2 , TiO_2 , Al_2O_3 , Fe_{Tot} , MnO , MgO , CaO , K_2O , P_2O_5); atomic absorption spectrometry, after dissolution with $HF + HClO_4$ for Na_2O ; decomposition with $HF + H_2SO_4$ in platinum crucible buffered for FeO , and FeO titulation with $KMnO_4$; loss of ignition by calcination at 1000°C under constant weight; X-ray fluorescence spectrometry using pressed powder pellets for Ba, Rb, Sr, Y, Cu, Pb and Zn.

The same thirteen samples were analyzed by Sm-Nd whole-rock technique at the Geochronological Research Center (CPGeo) of the IGc-USP (Table 4). Approximately 0.1 mg of powdered rock sample was dissolved in concentrated HNO_3 , HF and HCl . The Sm and Nd concentrations were determined by isotope dilution with a combined spike tracer, using the two-column technique, as described by Sato et al. (1995). The isotope ratios were measured on VG-354 multi-collector mass spectrometer.

Laboratory blanks for the chemical procedure, during the period of analyses, yielded maximum values of 0.4 ng for Nd and 0.7 ng for Sm. The average $^{143}Nd/^{144}Nd$ for La Jolla standard was 0.511857 (46), with 2 σ standard deviations reported in parentheses. The Sm-Nd T_{DM} model ages, were calculated using DePaolo (1981) model parameters: $a = 0.25$, $b = 3$, $c = 8.5$ as well as $^{143}Nd/^{144}Nd = 0.7219$ to normalize the isotope ratios [$^{143}Nd/^{144}Nd (CHUR)_0 = 0.512638$ and $^{147}Sm/^{144}Nd (CHUR)_0 = 0.1967$]. The ϵ_{Nd} values were calculated using the simplified equation $\epsilon_{Nd(T)} = \epsilon_{Nd(0)} - Q_{Nd} \cdot f_{Sm/Nd} \cdot T$, with the $(CHUR)_0$ values above and $Q_{Nd} = 25.09$. The ϵ_{Nd} values for the PGC samples were recalculated for the 1.33 Ga reference age (SHRIMP U-Pb, as reported by Boger et al., 2005).

In addition to the Sm-Nd work, thirteen samples were analyzed by Rb-Sr using isotope dilution technique at the CPGeo (Table 5). The $^{87}Sr/^{86}Sr$ ratios are listed with absolute errors (2 σ), and have been corrected to the mean value of the NBS-987 standard [0.710254 ± 0.000022 (2 σ)]. The overall blank for the chemical procedure was 4 ng for Sr. Isotope ratios were measured on VG-354 multicollector and single collector mass spectrometers, and the $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$.

RESULTS

The investigated samples were previously studied by petrography (see Appendix A). The new isotopic and geochemical data were interpreted together with the published characteristics of PGC rocks (e.g., Litherland et al., 1986; Darbyshire, 2000), and taking into account the geochronologic background of the Bolivian Precambrian shield, particularly SHRIMP U-Pb zircon ages of distinct rock-units of Paraguá craton (Boger et al., 2005; Santos et al., 2006, 2008), including the unpublished ones (data from R. Matos).

Field aspects and petrography

Appendix A presents hand sample and petrographic descriptions with modal composition, textures and structures of the investigated PCG rocks (see Figure 2) whereas Appendix B summarizes the megascopic and microscopic petrography of this PGC after Klinck and O'Connor (1983); Hawkins (1982); Pitfield (1983) and Litherland (1982).

Modal composition for selected rocks of the PGC was determined using macro point counting method as described by Fitch (1959). Staining of rock slabs was necessary to distinguish between K-feldspar and plagioclase and to determine their proportions (Table 6). The investigated syn- to late-kinematic rocks can be classified mostly as syenogranites, monzogranites and quartz monzonites whe-

Table 3. Major and trace elements of the PGC. Keys: **Porv.** = Porvenir; **Diam.** = Diamantina.

Sample	PF 0501	SC 10502	SC 20503	PRV 0504	CP 0505	CP 20506	CP 30507	ME 0508	CA 0509	FLT 0510	LJ 10511	LJ 20512	LJ 30513
Unit	Piso Firme	San Cristobal	San Cristobal	Porv.	Diam.	Diam.	Diam.	Diam.	San Martin	La Junta	La Junta	La Junta	La Junta
Rock	QSy	MzGrBi	MzGrBi	SyGrHb	SyGrBi	SyGrBi	SyGrBi	QMzBi	SyGrHb	SyGr	QMzBi	MzGrBi	MzGrHb
SiO ₂	76.07	76.08	74.12	74.26	72.33	72.14	73.53	74.84	76.76	69.27	71.26	74.19	68.63
Al ₂ O ₃	12.44	12.46	13.02	13.75	14.39	14.47	13.49	13.43	11.51	14.83	14.48	14.16	15.46
MnO	0.025	0.030	0.054	0.043	0.035	0.034	0.034	0.033	0.044	0.034	0.032	0.022	0.030
MgO	0.06	0.08	0.22	0.22	0.30	0.29	0.28	0.19	0.09	0.75	0.43	0.24	0.59
CaO	0.56	0.56	1.07	1.27	1.33	1.28	1.15	1.00	0.62	1.24	1.33	2.04	1.80
Na ₂ O	4.47	3.73	3.49	3.74	3.19	3.21	2.96	3.36	2.41	2.55	2.80	3.63	3.49
K ₂ O	4.07	4.88	4.86	4.53	5.52	5.94	5.44	5.07	5.63	6.52	6.30	3.96	4.98
TiO ₂	0.123	0.117	0.242	0.173	0.255	0.243	0.241	0.140	0.188	0.477	0.330	0.106	0.442
P ₂ O ₅	0.017	0.017	0.048	0.047	0.068	0.062	0.067	0.051	0.025	0.148	0.120	0.044	0.156
Fe ₂ O ₃	1.50	1.42	2.24	1.31	1.68	1.65	2.03	1.35	2.20	2.79	2.05	1.33	3.24
Loi	0.67	0.38	0.21	0.39	0.38	0.20	0.34	0.40	< 0.01	0.82	0.40	0.19	0.67
Total	100.01	99.75	99.57	99.73	99.48	99.52	99.56	99.86	99.48	99.43	99.53	99.91	99.49
ACNK	0.97	1.00	1.00	1.03	1.05	1.03	1.05	1.05	1.03	1.10	1.04	1.01	1.07
K ₂ O/Na ₂ O	0.91	1.31	1.39	1.21	1.73	1.85	1.84	1.51	2.34	2.56	2.25	1.09	1.43
Ba	811	336	614	822	902	776	690	429	721	1515	776	805	525
Nb	11	10	8	22	9	7	12	8	7	13	12	4	20
Pb	6	13	12	21	44	39	44	55	22	26	40	20	36
Rb	100	157	158	179	245	212	249	251	144	165	224	141	223
Sr	24	24	59	21	215	201	153	176	69	287	168	296	109
Th	8	7	6	14	20	39	55	32	17	20	33	5	67
U	3	3	2	5	5	7	8	16	1	2	3	2	5
V	< 9	< 9	< 9	< 9	< 9	18	14	< 9	< 9	26	14	16	37
Y	45	66	54	148	23	18	18	122	95	54	23	7	43
Zr	215	142	197	360	178	197	185	118	292	206	216	110	314
La	31.4	33.0	34.8	65.1	69.7	99.5	70.0	24.2	91.6	64.0	70.5	17.2	110
Ce	60.1	61.7	55.9	179	128	128	182	56.9	212	130	148	31.8	220
Pr	7.83	8.97	9.45	19.3	15.2	21.3	17.8	6.49	26.8	20.2	17.3	3.55	25.9
Nd	29.2	35.1	36.4	76.0	52.4	71.1	61.2	23.5	106	76.1	60.5	11.6	91.0
Sm	6.44	8.13	8.33	17.9	8.55	11.0	11.2	5.95	24.1	14.0	10.8	1.77	16.3
Eu	0.64	0.44	1.12	1.88	1.20	1.27	1.24	0.79	2.70	1.95	1.10	0.59	1.15
Gd	6.61	8.59	8.30	20.1	7.34	9.21	9.28	7.96	24.3	12.5	9.81	1.75	15.6
Tb	1.13	1.52	1.48	3.57	0.77	0.90	1.00	1.92	3.88	1.71	1.08	0.21	1.86
Dy	7.10	9.36	8.98	22.3	3.75	4.06	4.45	14.1	21.0	9.39	4.99	1.15	9.11
Ho	1.69	2.23	2.07	5.26	0.72	0.66	0.72	3.82	4.16	1.90	0.85	0.25	1.56
Er	4.80	6.24	5.86	14.9	2.00	1.65	1.72	11.3	10.1	5.00	1.99	0.75	3.39
Tm	0.77	0.98	0.94	2.30	0.29	0.20	0.22	1.75	1.24	0.68	0.24	0.12	0.34
Yb	5.33	6.67	6.41	15.4	1.92	1.21	1.33	11.3	7.03	3.98	1.31	0.89	1.69
Lu	0.80	0.99	0.94	2.27	0.29	0.19	0.21	1.65	0.85	0.51	0.20	0.14	0.25
Hf	7.00	6.13	6.15	12.6	5.51	6.43	6.45	4.93	11.0	5.86	7.33	4.45	10.0
Ta	0.77	0.75	0.76	1.38	0.68	0.28	0.25	0.49	0.53	1.22	0.26	0.46	0.96
(La/Yb) _n	3.99	3.34	3.66	2.85	24.60	55.33	35.30	1.44	8.79	10.90	36.40	13.97	44.26
(Eu) _n /Eu	0.30	0.16	0.41	0.30	0.46	0.38	0.37	0.35	0.34	0.45	0.32	0.16	0.22

Table 4. Sm-Nd isotopic data for rocks of the PGC. Keys: **SyGr** = Syenogranite; **MzGr** = Monzogranite; **QMz** = Quartz monzonite; **QSy** = Quartz syenite.

Sample	Unit	Rock	Sm (ppm)	Nd (ppm)	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd	ε _(t)	f _{Sm/Nd}	T _{DM} (Ga)	ε _(Ti)
PF0501	Piso Firme	QSy	6.830	30.375	0.1360	0.51223	-7.99	-0.31	1.59	2.32
SC10502	San Cristobal	MzGrBi	7.826	32.431	0.1459	0.51234	-5.87	-0.26	1.58	2.75
SC20503	San Cristobal	MzGrBi	9.647	40.460	0.1442	0.51232	-6.28	-0.27	1.59	2.63
PRV0504	Porvenir	SyGrHb	19.278	79.089	0.1474	0.51229	-6.89	-0.25	1.74	1.48
CP0505	Diamantina	SyGrBi	10.664	63.260	0.1019	0.51183	-15.7	-0.48	1.65	0.39
CP20506	Diamantina	SyGrBi	12.872	78.696	0.0989	0.51179	-16.6	-0.50	1.66	0.03
CP30507	Diamantina	SyGrBi	13.279	70.132	0.1145	0.51186	-15.2	-0.42	1.82	-1.25
ME0508	Diamantina	QMzBi	5.738	23.615	0.1469	0.51220	-8.51	-0.25	1.92	-0.06
CA0509	San Martín	SyGrHb	25.353	107.634	0.1424	0.51226	-7.43	-0.28	1.68	1.78
FLT0510	La Junta	SyGr	18.727	99.733	0.1135	0.51173	-17.8	-0.42	2.01	-3.66
LJ10511	La Junta	QMzBi	14.692	80.734	0.1100	0.51172	-17.9	-0.44	1.95	-3.21
LJ20512	La Junta	MzGrBi	3.599	22.018	0.0988	0.51164	-19.6	-0.50	1.87	-2.94
LJ30513	La Junta	MzGrHb	18.697	100.573	0.1124	0.51169	-18.6	-0.43	2.04	-4.29

Table 5. Sr isotopic data for rocks of the PGC. Keys: **SyGr** = Syenogranite; **MzGr** = Monzogranite; **QMz** = Quartz monzonite; **QSy** = Quartz syenite. **T(Ma)** = 1.33 Ga calculated according as a SHRIMP U/Pb age (Boger et al., 2005).

Unit	Sample	Rock	Rb (ppm)	Sr (ppm)	1/Sr	⁸⁷ Sr/ ⁸⁶ Sr (Y)	⁸⁷ Rb/ ⁸⁶ Sr (X)	(⁸⁷ Sr/ ⁸⁶ Sr) _t p/T(Ma)
Piso Firme	PF0501	QSy	111.59	27.68	0.0361	0.72473	11.687	
San Cristobal	SC10502	MzGrBi	157.45	27.69	0.0361	1.03027	16.979	0.70656
San Cristobal	SC20503	MzGrBi	170.66	71.97	0.0139	0.83417	6.949	0.70169
Porvenir	PRV0504	SyGrHb	183.36	21.98	0.0455	1.18192	25.278	
Diamantina	CP0505	SyGrBi	271.15	224.81	0.0044	0.76889	3.512	0.70194
Diamantina	CP20506	SyGrBi	228.71	207.95	0.0048	0.76477	3.201	0.70370
Diamantina	CP30507	SyGrBi	301.01	167.87	0.0060	0.79670	5.235	
Diamantina	ME0508	QMzBi	232.91	166.14	0.0060	0.78021	4.086	0.70230
San Martín	CA0509	SyGrHb	158.81	72.92	0.0137	0.82563	6.376	0.70407
La Junta	FLT0510	SyGr	169.30	287.44	0.0035	0.73645	1.710	0.70386
La Junta	LJ10511	QMzBi	242.15	187.28	0.0053	0.77713	3.768	0.70530
La Junta	LJ20512	MzGrBi	140.09	323.02	0.0031	0.73007	1.258	0.70609
La Junta	LJ30513	MzGrHb	245.65	119.90	0.0083	0.81792	5.994	

rears the late- to post-kinematic ones plot mainly in the syenogranite, monzogranite, quartz monzonite and quartz syenite fields in the Streckeisen QAP diagram (see Figure 3).

Syn- to late- kinematic granitoid rocks

La Junta granite

This moderately to weakly foliated body occurs in the southern part of PGC. The colour composite satellite im-

agery and the surface cover of the La Junta granite do not allow defining its size because the field relations with the other rock units are not exposed. In some places the granite becomes distinctly gneissic with a well developed planar fabric. The observed anatexis is syn- to late- Do3, but an early prograde metamorphism (pre- Do3) reached high-grade metamorphism in the country rocks located close to the pluton, as evidenced by prismatic sillimanite.

According to Hawkins (1982) the La Junta granite includes numerous xenoliths of hornblende-biotite gneiss

Table 6. Modal analysis for rocks of the PGC. All samples have Nd and Sr analyses (this work). See text for details. Keys: **SyGr** = Syenogranite; **MzGr** = Monzogranite; **QMz** = Quartz monzonite; **QSy** = Quartz syenite; **Qz** = Quartz; **K-feld** = K-feldspar; **Plag** = Plagioclase; **Biot** = Biotite; **Horn** = Hornblende; **Zr** = Zircon; **Sph** = Sphene; **Magn** = Magnetite; **Apat** = Apatite; **Allan** = Allanite; **Epid** = Epidote; **Chlor** = Chlorite; **PF** = Piso Firme; **SC** = San Cristobal; **P** = Porvenir; **D** = Diamantina; **LJ** = La Junta; **SM** = San Martín. * Magnetite was determined using a pocket magnet.

Sample	Unit	Lithology	X (utm)	Y (utm)	Primary minerals					Accessory minerals					Secondary	
					Qz.	K-feld.	Plag.	Biot.	Horn.	Zr.	Sph.	Magn.*	Apat.	Allan.	Epid.	Chlor.
PF0501	PF	QSy	635376	8493848	15	65	20			x		x			x	
SC10502	SC	MzGrBi	623763	8479614	34	41	23	2		x		x	x		x	
SC20503	SC	MzGrBi	625302	8474694	29	42	25	4		x	x					
PRV0504	P	SyGrHbBi	653060	8445505	32	50	15	x	3	x		x			x	
CP0505	D	SyGrBi	661618	8392877	27	54	14	5		x		x	x			x
CP20506	D	SyGrBi	662459	8385600	35	42	21	2		x		x	x		x	x
CP30507	D	SyGrBi	660835	8376150	23	49	26	2		x		x	x			
ME0508	D	QMzBi	659335	8367510	19	41	38	2				x	x		x	
CA0509	SM	SyGrHb	642653	8367578	28	60	10		2	x	x	x	x	x	x	x
FLT0510	LJ	SyGrBi	662154	8342436	25	46	21				x	x	x		x	8
LJ10511	LJ	QMzBi	662601	8324646	8	49	37	6		x		x	x			x
LJ20512	LJ	MzGrBi	681788	8313212	19	42	36	3		x	x	x	x		x	x
LJ30513	LJ	MzGrHbBi	662293	8309407	30	30	35	1	4			x	x		x	

partly migmatitic, calc-silicate gneiss, quartzite and amphibolite. This author classified the La Junta granite as a porphyritic rock, medium-to coarse-grained with biotite and hornblende. In addition to our analyses (FLT0510, LJ10511, LJ20512, LJ30513), the QAP diagram includes data from Hawkins (1982) (dark gray field in Figure 3). The resulting feature indicates that the La Junta pluton is constituted by gneisses of monzogranitic to syenogranitic composition. Sample FLT0510 is a pinkish, coarse-grained syenogranite gneiss, and consists of K-feldspar and plagioclase surrounded by a irregularly streaky chlorite accompanied by epidote, also strongly replaced by sericite shreds that are pale gray in color and cloudy. Sample LJ10511, one biotite, quartz monzonitic gneiss, has apatite, whereas sample LJ20512, one medium leucocratic biotitic monzogranitic gneiss, has sphene as the principal accessory mineral. Sample LJ30513 is a hornblende monzogranite, white pinkish in color, medium to coarse grained, isotropic to moderately foliated and porphyritic.

San Martin granite

This pluton crops out extensively in the western side of PGC (Figure 2). It is a heterogeneous batholith, partly migmatitic, granitic gneiss of autochthonous character (Klinck and O'Connor, 1983). The investigated sample (CA0509) has a syenogranite composition in the QAP diagram (Figure 3). In the central part of the batholith banded

Figure 3. Streckeisen QAP diagram for selected samples of the PGC. **T** = Tonalite; **Grdi** = Granodiorite; **MzGr** = Monzogranite; **SyGr** = Syenogranite; **AGr** = Alkali-feldspar granite; **QMz** = Quartz monzonite; **QSy** = Quartz syenite. + = Late-to post-kinematic granites; ○ = Diamantina granite; △ = Syn-to late kinematic granites. All samples have Nd and Sr isotopic data (this work); see text for details. Keys: ● - La Junta granite (modified from Hawkins, 1982); ○ - Diamantina Granite (modified from Litherland, 1982); △ - Diamantina Granite (modified from Klink and O'Connor, 1982); ● - Piso Firme Granophyre (modified from Pitfield, 1983); ○ - San Cristobal Metagranite (modified from Pitfield, 1983).

enclaves of migmatitic biotite gneiss show both concordant and discordant contacts with the granite injections. The biotite defines a weak foliation, but lens- or augen-texture are observed in places. Along the western side of the batholith the distribution of the isogrades indicates medium grade metamorphic conditions. The most representative rock exhibits a granular texture and biotite flakes and prismatic hornblende. The K-feldspar form scattered phenocrysts from 1.5 to 3 cm long. In the southern part the San Martin pluton becomes melanocratic.

Late- to post -kinematic granitoid rocks

Piso Firme granophyres

This rock crops out nearby Piso Firme village in Beni department, in the vicinity of Paraguá river (PF samples; Figure 2) The colour composite satellite imagery shows this pluton as wooded hills with the principal fractures following E-W direction and subordinately NNW trend. The east-west long axis of the intrusion is 6 km vs. 3 km wide along the NS direction.

The Piso Firme granophyre (Pitfield, 1983) comprises three distinctive lithologic facies from north to south: a) coarse to medium-grained potassic granophyre (sample PF0501 in the present work); b) medium to coarse-grained microespherulitic granophyre; c) spherulitic plagiophyric microgranophyre. One aegirine-riebeckite-bearing sodic-potassic granophyre crops out as a small hillrock that was previously described in the eastern side of Cerro Piso Firme (Pitfield, 1983). The QAP diagram includes the new data and those from Pitfield (1983) (light gray field; Figure 3). The investigated samples fall between the syenogranite and the alkali-feldspar granite fields.

Porvenir granite

This body, first characterized near the homonymous village, crops out as positive topographic feature, such as the Pica Pica hill (sample PRV0504; Table 6) located to the eastern side from the road to Piso Firme and Cerro Porvenir (Figure 2). On the color composite satellite imagery this intrusion forms a forested hill raising no more than 60 - 100 m above the plain. It shows a roughly shape with fractures of joints following NW direction, sometimes gently curved (Klinck and O'Connor, 1983). Following its long NW oriented axis the outcrop is 10 - 12 km long, and the width of the intrusion in the NW direction is 2 to 5 km. The investigated outcrop is an isotropic, medium-fine grained, massive hornblende syenogranite to weakly foliated monzogranite. These compositions are displayed by the samples plotted in the QAP diagram (Figure 3). The quartz

appears as polygonal grained aggregates, and K-feldspar is partly replaced by sericite. Plagioclase is very subordinate. Hornblende forms irregular shaped grains commonly in aggregates. The observed granoblastic textures suggest a post-tectonic metamorphism, in agreement with the low grade metamorphism (actinolite+epidote+chlorite) reported by Klinck and O'Connor (1983) in rocks located 7.5 km to the SW of the Porvenir granite.

San Cristobal granite

This granite makes up the Leyton hill (samples SC10502 and SC20503; Figures 2, 3 and Table 6), among many other hills named Serranía San Cristobal - a NW oriented ridge which is clearly seen in the colour composite satellite imagery. In general, the rock in Leyton hill is a homogeneous, biotitic monzogranite that locally grades or is emplaced into concordant zones of the gneisses of the crystalline basement. Banded porphyroblastic gneiss and pegmatite are also present. From the above the San Cristobal granite can be classified as a moderately to smooth streaky granitic gneiss. Its N-NW foliation (Do3) is assigned to be tectonically related with the San Ignacio orogeny (e.g., Litherland et al., 1986). The rock is pinkish in hand sample, and in the thin section quartz is anhedral with undulose extinction, K-feldspar consists of irregular microcline twinning and plagioclase occurs as tabular crystals with fine and coarse twinning. In the QAP diagram (Figure 3) our data in conjunction with those from Pitfield (1983) plot in the monzogranite field.

Diamantina granite

This intrusion makes up a north trending hill, forming a large elliptical body about 53 km long (Klinck and O'Connor, 1983), that crops out as an "island" in the forest, close to the road to Piso Firme village (Figure 2). The northern and central parts of the Diamantina granite are made up by several outcrops that exhibit two clear systems of joints (80° and 170°). In the southern part the outcrops appear as small sprinkled mottled aspect.

According to Klinck and O'Connor (1983) the Diamantina pluton was formed by distinct intrusive phases: first magmatic phase produced granodiorite and/or tonalite. After cooling of these rocks, a second phase (monzogranite) intruded the earlier granodiorite-tonalite, as shown by the typical xenoliths with spherical to tabular forms (50 cm to 43 m long). They are also fine-grained and sometimes medium and coarse grained and may contain biotite as the principal mafic mineral. Other xenoliths comprise exotic lithologies (biotite gneisses, garnet-biotite gneiss and hornblende gneisses) with irregular distri-

bution. The northern side of the Diamantina granite is xenoliths free compared to the southern side. Some lenses and veins of pegmatites are present. The Diamantina granite represents either the last magmatic post-tectonic phase of the PGC (Klinck and O'Connor, 1983) or shortly succeeded Do3 episode (Litherland, 1982).

The Diamantina granite was sampled in four places (Figure 2). The dominant rock type is a pale pink and non foliated biotitic syenogranite. One sample (ME0508; moderately foliated biotitic quartz monzonite), collected at La Mechita farm was previously considered as belong to the Chiquitania Complex by Litherland 1:1.000.000 map. However, it was herein considered as representative of the Diamantina intrusion based in the field relationships of our work.

The QAP diagram (Figure 3; Table 6) shows our analyses and the published ones (Klinck and O'Connor, 1983) that were sampled in the western side of the Diamantine granite (medium gray field). The previous data indicate a transition from tonalite to syenogranite in composition, but the new analyses fall mainly within the monzogranite field. In addition, Figure 3 shows the data from Litherland (1982) (dark- medium gray field) referring to the samples from the eastern side of the body. This distinct samples show a transition from intermediate rocks of quartz monzonite to syeno-granite.

Major and trace elements

Table 3 presents the major and trace elements data of thirteen samples of PGC.

Syn- to late-kinematic granitoid rocks

Four samples of the La Junta granite (FLT0510, LJ10511, LJ20512, LJ30513) and one of the San Martin granite (CA0509) show SiO_2 contents from 69 to 77 wt%. Major oxides display regular trends of decreasing Al_2O_3 , MgO , CaO and $\text{Fe}_2\text{O}_{3\text{Tot}}$ with increasing SiO_2 contents suggesting that fractional crystallization played an important role in the petrogenetic process (Figure 4). Figures 5A to 5C present variation diagrams of Zr, Ba and Sr against SiO_2 showing roughly decreasing of the trace elements with increasing SiO_2 . This behavior is probably due to zircon, feldspar and plagioclase separation from the evolving melts. Figure 5D (Rb/Sr vs. Sr/Ba) shows linear trends for the samples, which suggests again the hypothesis of fractional crystallization. All the investigated samples, including those from syn- to late-kinematic plutons reported in the literature (Litherland et al., 1986), are sub-alkaline (Figures 6A and 6B), as indicated by the characteristic $\text{Na}_2\text{O}+\text{K}_2\text{O}$ values < 8.5 wt% (Table 3) (see, e.g., Nardi and Bonin, 1991). In addition the La Junta and San

Martin samples show mainly a high-K and calc-alkaline affinity with SiO_2 content higher than 69 wt% (see Figures 7 and 8) suggesting they have an arc-related geochemical signature. The highest-K tendency of FLT0510 and LJ10511 samples is probably due to the feldspar and plagioclase alterations ($\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio of 2.56 and 2.25 respectively; see Table 3), that originate sericite as cloudy masses and minute shreds. Therefore the whole rock compositions of these particular samples were modified toward apparent peraluminosity (Figure 8).

The REE patterns of the La Junta and San Martin granite samples (Figure 9) are moderately fractionated in terms of LREE/HREE with a slightly negative Eu anomaly. In the spider diagram the samples present steep patterns due to their high LILE contents which compare well with the typical pattern of Andean-type igneous rocks (segmented line in Figure 10). The observed negative peaks of Sr, P, and Ti suggest fractionation of feldspars, apatite, and titanomagnetite and sphene, respectively. Sample LJ20512 presents a contrasting signature with no negative Eu anomaly (Figure 9), suggesting either one depleted REE source, or fractionation with amphibole and/or allanite in the residue. The lower values of Ta and Nb in the sample LJ20512 may be ascribed to crustal contamination.

Late- to post -kinematic granitoid rocks

Major and trace elements data of four samples from Porvenir and San Cristobal granites and Piso Firme granophyre are given in Table 3. In the Harker's diagram (Figure 4), the samples display negative correlations for Al_2O_3 , MgO , CaO and $\text{Fe}_2\text{O}_{3\text{Tot}}$ with increasing SiO_2 contents and a positive correlation to the Na_2O , suggesting the role of fractional crystallization process. The plots of Zr, Ba and Sr against SiO_2 show decreasing of the trace elements with the increasing contents of SiO_2 (Figure 5) which is probably due to zircon, feldspar and plagioclase separation from the evolving melts. On the Rb/Sr vs. Sr/Ba diagram (Figure 5D), the studied samples show a linear trend, which is consistent again with fractional crystallization. All the samples are sub-alkaline (Figure 6), in agreement with their characteristic $\text{Na}_2\text{O}+\text{K}_2\text{O}$ values (Table 3).

The investigated late- to post -kinematic rocks have narrow range in the SiO_2 contents (from 74 to 76 wt%) and plot in the high-K field likewise most of the syn- to late-kinematic rocks (Figures 8A and 8B). The Piso Firme granophyre and San Cristobal granite have metaluminous composition and the Porvenir granite (Figure 9), show a tendency to peraluminous character ($\text{ACNK} = 1.03$). These three plutons have $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios that range from 0.9 to 1.4 (see Table 2). Regarding the REE patterns, all the samples show low LREE fractionation, and subhorizontal tendency of HREE

Figure 4. Variation diagrams of major elements for the PGC. Symbols as shown in Figure 3.

Figure 5. Variation diagrams of trace elements vs. SiO_2 for PGC rocks. **5A.** Zr vs. SiO_2 , **5b.** Ba vs. SiO_2 , **5C.** Sr vs. SiO_2 , **5D.** Rb/Sr vs. Sr/Ba. Symbols as shown in Figure 3.

Figure 6. A. Plot of the PGC rocks (this work) in the total alkalis vs. silica diagram; modified from Middlemost (1985). Symbols as shown in Figure 3. **B.** Plot of PGC rocks from Litherland et al. (1986) in the total alkalis vs. silica diagram; modified from Middlemost (1985).

with negative Eu anomaly. This probably reflects plagioclase and/or feldspar fractionation process (Figure 9B). They are slightly less enriched in LILE compared to the syn- to late-kinematic granitoid rocks, and also have deeper negative peaks of Sr, P and Ti reflecting once more the role of fractional crystallization (see Figure 11).

Four samples of the Diamantina granite show SiO_2 content from 72 to 75 wt%, and plot within the high-K field (Figure 7), with a peraluminous composition (Figure 8). The $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio of the Diamantina samples varies from 1.5 to 1.8, suggesting their pristine character. They show two different REE signatures (Figure 9): 1. samples CP0505, CP20506 and CP30507 exhibit steep patterns compared with the Piso Firme, San Cristobal and Porvenir granitoid rocks. This is related with the LREE high contents and depletion in HREE, probably reflecting amphibole fractionation and/or allanite; 2. sample ME0508 shows “gull wing-shaped” REE pattern with moderate negative Eu anomaly, typical of differentiated granites (Figure 9C). In the multi-element diagrams, the samples show a pattern similar to the syn- to late-kinematic plutons (see Figure 10) with the negative peaks of Sr, P, and Ti which are interpreted as due to fractionation of mica, feldspar, apatite, and Ti phases (Figure 11C).

Nd-Sr isotopes

The Nd and Sr isotopic parameters of the investigated PGC rocks were recalculated according as reference SHRIMP U/Pb age of 1.33 Ga (zircon rims) reported for the San Rafael granite, and interpreted as the emplacement age (Boger et al., 2005).

The Sm-Nd whole rock analyses for the syn- to late-kinematic granitoid rocks yielded “normal” crustal (plutonic rocks) $f_{\text{Sm}/\text{Nd}}$ ratios of -0.28 (San Martin) and -0.42 to -0.50 (La Junta). Their T_{DM} model ages are 1.67 Ga and in the range 1.87 to 2.04 Ga, respectively (Table 4). The $\epsilon_{\text{Nd}(1.33\text{Ga})}$ value for the San Martin granite is +1.8 whereas the La Junta samples show contrasting negative values between -2.9 to -4.3 (Table 4). The late- to post kinematic San Cristobal, Porvenir and Piso Firme plutons show roughly comparable $f_{\text{Sm}/\text{Nd}}$ ratios (-0.31 and -0.25), similar T_{DM} model ages (1.6 to 1.7 Ga) and positive $\epsilon_{\text{Nd}(1.33\text{Ga})}$ values of +2.7 to +1.5 (Table 4). In contrast, the Diamantina granite displays variable T_{DM} model ages between 1.6 and 1.9 Ga ($f_{\text{Sm}/\text{Nd}}$ ratios between -0.50 and -0.25), and $\epsilon_{\text{Nd}(1.33\text{Ga})}$ values from +0.4 to -1.2. As such, the $\epsilon_{\text{Nd}(1.33\text{Ga})}$ signatures are consistent with mixing of mantle derived and short crustal residence components (e.g., Paleoproterozoic) in the petrogenetic process. This idea agrees well with the variable Nd contents (22 to 100 ppm) of the studied samples (see Table 4).

Figure 7. A. Plot of PGC rocks in the K₂O wt% vs. SiO₂ wt% diagram of Le Maitre (2002). Symbols as shown in Figure 3. **B.** Plot of PGC rocks reported by Litherland et al. (1986) in the K₂O wt% vs. SiO₂ wt% diagram of Le Maitre (2002).

Figure 8. A. Alumina saturation diagram of Maniar and Piccoli (1989) for rocks of PGC. Symbols as shown in Figure 3. **B.** Alumina saturation diagram, after Maniar and Piccoli (1989) for PGC rocks (gray field), as reported by Litherland et al. (1986).

Figure 9. Chondrite-normalized REE patterns of the PGC. **A.** Syn- to late-kinematic granitoids (La Junta and San Martín). **B.** Late- to post-kinematic granitoids (San Cristobal and Porvenir and Diamantina granites and Piso Firme Granophyre). **C.** Diamantina Granite 10c. Normalized values are from Taylor and McLennan (1985).

Figure 10. Trace element concentrations normalized to the ORG composition. **A.** Syn- to late-kinematic granitoids (La Junta and San Martín). **B.** Late- to post-kinematic granitoids (San Cristobal and Porvenir granites and Piso Firme granophyre). **C.** Late- to post-kinematic Diamantina granite. Normalizing values are from Pearce et al. (1984).

Figure 11. Trace element concentrations normalized to the composition of chondritic meteorites. The data are plotted from left to right according with the increasing compatibility to PGC samples. **A.** Syn- to late-kinematic granitoids (La Junta and San Martín). **B.** Late- to post-kinematic granitoids (San Cristóbal and Porvenir granites and Piso Firme Granophyre). **C.** Diamantina Granite. Normalized values are from Taylor and McLennan (1985).

Figure 12 provides additional clues for the petrogenetic inferences of the PGC samples by recalculating the $\epsilon_{\text{Nd}(t)}$ value and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the 1.33 Ga reference age (see Table 5). However, some samples of the late- to post-tectonic plutons (PF0501, PRV0504, CP30507) indicated spurious $^{87}\text{Sr}/^{86}\text{Sr}_t$ reference values (< 0.701) and were not further considered herein because the clear disturbance of their isotopic systems.

The correlation diagram discriminates different isotopic fields for the PCG rocks. The syn- to late-kinematic La Junta and San Martín samples yield $^{87}\text{Sr}/^{86}\text{Sr}_t$ ratios from 0.704 to 0.706, show predominantly negative $\epsilon_{\text{Nd}(t)}$ values (up to -4.3), and plot close to Bulk Earth. This reinforces the role of heterogeneous sources in their origin in an arc setting. The late- to post-kinematic plutons show two distinct signatures, combined a larger variation in $^{87}\text{Sr}/^{86}\text{Sr}_t$ ratios (from 0.702 to 0.707). The first group exhibits $^{87}\text{Sr}/^{86}\text{Sr}_t$ ratios from 0.702 to 0.707 and $\epsilon_{\text{Nd}(1.33\text{Ga})}$ values from +1.48 to +2.75. The second group (Diamantina) shows $^{87}\text{Sr}/^{86}\text{Sr}_t$ values from 0.702 to 0.704, and $\epsilon_{\text{Nd}(1.33\text{Ga})}$ values from +0.39 to -1.25 (Figure 12, Tables 4 and 5). The San Cristóbal and Diamantina (CP0505) samples preserve the most juvenile signatures among the investigated PGC rocks. The signature implies again to the important role of Mesoproterozoic mantle sources in the petrogenesis, in agreement with an intra-oceanic arc setting.

The fact that these late- to post-kinematic intrusions are sharply discordant in relation with the regional foliation of the country rocks, in conjunction with their distinct positive $\epsilon_{\text{Nd}(t)}$ values and youngest T_{DM} model ages suggest that they are products from a juvenile magmatic arc. In contrast, the syn- to late-kinematic granitoid rocks (e.g., La Junta granite) have Nd isotopic signatures that are coherent with mixing sources, except for the San Martín pluton.

Figure 12. $(^{87}\text{Sr}/^{86}\text{Sr})_{(1.33\text{Ga})}$ vs. $\epsilon_{\text{Nd}(1.33\text{Ga})}$ correlation diagram for PGC samples. Symbols as shown in Figure 3.

DISCUSSION AND TECTONIC CORRELATION

The PGC is formed by voluminous Mesoproterozoic syn- to late-kinematic and late- to post-kinematic granitoid events, dated between 1373 and 1340 Ma, as the SHRIMP U-Pb evidence. Additional SHRIMP U-Pb zircon datings [Matos, in preparation (2009)] carried out in the La Junta and the Diamantina granites yielded comparable ages (1347 ± 21 Ma and 1340 ± 20 Ma, respectively), in agreement with a previous Rb/Sr isochron age for the Diamantina pluton (Litherland et al., 1986) - whereas the San Martín Granite yielded a significantly older SHRIMP zircon age (1373 ± 20 Ma). As such the geochronologic work provides new insights for the timing of the syn- to late tectonic phases of the San Ignacio Orogeny, in Bolivia. It is noteworthy that additional SHRIMP U-Pb zircon ages (Boger et al., 2005; Santos et al., 2006, 2008) for the basement rocks (Lomas Maneches and Chiquitania units) in the range 1.34 - 1.32 Ga revealed metamorphic overprints associated with the San Ignacio Orogeny and also with coeval magmatic and deformational events in the Brazilian counterpart.

The PGC rocks display Nd-Sr_(t) signatures that suggest that different sources contributed to the magma genesis of the plutonic pulses, in coherence with the trace element compositions that reflect magmatic differentiation processes combined with crustal contamination (see above). This scenario is consistent with the onset of successive magmatic arcs culminating with continental collision of the PGC (at ca. 1.33 Ga) against the Rio Negro-Juruena Province, as proposed for the Mesoproterozoic evolution of the SW Amazonian craton (e.g., Boger et al., 2005; Cordani and Teixeira, 2007).

The syn- to late-kinematic La Junta granite has $^{87}\text{Sr}/^{86}\text{Sr}_t$ ratios of 0.704 to 0.706, the oldest T_{DM} ages (1.9 - 2.0 Ga) and negative ϵ_{Ndt} values (-2.9 to -4.3), as previously delineated by Darbyshire (2000). Such isotopic features favor again the hypothesis of significant contribution of crustal material in the petrogenetic process, supported by the recognized negative Nb and Ta anomalies in the studied samples, as well as by the plot of the samples near the boundary "within plate-volcanic arc granite fields" in the Pearce' Diagram (Figure 13). Furthermore, the syn- to late-kinematic plutons are associated with gneisses and migmatites, but do not contain basic xenoliths (Hawkins, 1982; Litherland, 1981; this work). This suggests that they are products from partial melting of the lower crust, as discussed by Nardi and Bonin (1991) on the basis of petrogenetic inferences from Proterozoic granites in southern Brazil.

The late- to post-kinematic Porvenir, San Cristobal, Piso Firme intrusions displayed ϵ_{Ndt} values from +2.7 to +1.5; T_{DM} ages from 1.6 to 1.7 Ga, and $^{87}\text{Sr}/^{86}\text{Sr}_t$ ratios between 0.702 and 0.706. In addition, Darbyshire (2000) reported signifi-

cant positive ϵ_{Ndt} values of +3.3 and +3.9 for the Piso Firme granophyre with T_{DM} ages of 1.5 and 1.6 Ga. The isotopic signatures agree well with the observed Sr, P and Ti negative peaks that are characteristics of fractional crystallization. This process is similarly envisaged from the presence of intermediate compositions of the late- to post-kinematic rocks (quartz monzonites to quartz syenites and syenogranites). The lower alkaline contents ($\text{Na}_2\text{O} + \text{K}_2\text{O} < 8.5$) are otherwise commonly seen in mantle derived rocks of arc settings. In the Pearce' diagram (Figure 13) the late- to post-kinematic samples fall in the within plate field (Porvenir, San Cristobal, Piso Firme). In contrast the Diamantina samples plot mainly within the "volcanic arc field" whereas they show $^{87}\text{Sr}/^{86}\text{Sr}_t$ (0.702 to 0.704) and ϵ_{Ndt} values (+0.4 to -1.2) close to Bulk Earth (Figure 12). From the above signatures these plutons probably derived from mixtures among MORB-like magmas and isotopically homogeneous protholiths.

Petrogenetic models to explain the generation of felsic magmas, as the case of PGC, may be considered into two broad categories (Riley et al., 2001). The first assumption advocates that felsic magmas are derived from mafic parent magma by fractional crystallization or assimilation combined with fractional crystallization (AFC). This process is often suggested for small magma batches for generating large volumes of felsic magma, when unreasonably large amounts of basalt must be crystallized. Nevertheless, an alternative model, in which mafic magmas provide heat for the partial melting of crustal rocks, is considered more appropriate for large volume felsic magma bodies, likewise the case of the PGC.

Figure 13. The Rb vs. (Y + Nb) discrimination diagram for PGC granites (after Pearce et al., 1984) showing the fields of syn-collisional granites (syn-COLG), within-plate granites (WPG), volcanic-arc granites (VAG) and ocean-ridge granites (ORG). Symbols as shown in Figure 3.

From the above, the integrated geological, geochemical and isotopic data suggest that the La Junta plutons (syn- to late-kinematic) resemble I-Caledonian type granites (e.g., Pitcher, 1993; Cobbing, 1996; Barbarin, 1999; Roberts and Clemens, 1993), which are represented by batholiths related to infracrustal melts linked with subduction of oceanic lithosphere beneath the more stable foreland. In contrast, most of the investigated late- to post-kinematic rocks originated predominantly from juvenile sources as suggested by the Nd/Sr_(t) signatures, geochemistry and the observed primary hornblende. According to Chappell and White (2001) I-type suites range from metaluminous, hornblende-bearing granites to very weakly peraluminous rocks that contain biotite as the only ferromagnesian mineral.

The rocks of the PGC display roughly similar geochemistry to the Colorado Complex that occurs in the Brazilian counterpart. Major and trace elements data in PGC samples (Litherland et al., 1986) display regular trends of decreasing Al₂O₃, MgO, CaO and Fe₂O_{3Tot} with increasing SiO₂ contents. They are similarly sub-alkaline to high-K calc-alkaline, and metaluminous to peraluminous in composition. A similar chemical tendency is displayed by the contemporary syn-kinematic Igarapé Enganado Intrusive Suite, and the post-kinematic Alto Escondido Intrusive Suite of the Colorado Complex, in Rondônia, Brazil (Rizzotto and Quadros, 2007). On the other hand, the Diamantina granite shows high LREE fractionation pattern, and subhorizontal tendency of HREE with negative Eu anomalies which is similarly seen again by the granitoid suites of the Colorado Complex.

The Nd isotopic features of the Colorado felsic-mafic intrusions (Teixeira et al., 2006; Rizzotto and Quadros, 2007) - T_{DM} model ages between 1.5 to 1.6 Ga and ε_{Nd(t)} = +2.3 - compares well with that of the San Martin and Piso Firme plutons; they are distinct from the La Junta isotopic features (see above). However, such a petrogenetic complexity may be expected in accretionary belts, in agreement with the tectonic framework of SW Amazonian Craton. In this respect, the late- to post-kinematic granitoids, including the Diamantina granite indicate juvenile- and crustal-like Nd signatures and show chemical features that are suggestive of differentiation from tonalites to alkali-feldspar granites. This strongly supports once more a plutonic arc setting for the origin of the Diamantina pluton in which a “fertilized” mantle source would be envisaged. If this is correct, the Porvenir, San Cristobal, Diamantina and Piso Firme granitoid rocks would display the most “primitive” signatures of such plutonic episodes among the PGC rocks investigated here. Furthermore, these late- to post-kinematic granitoid are comparable in age with the Alto Candeias Intrusive Suite (U-Pb ages of 1346 Ma and 1338 Ma) in Rondônia (Bettencourt et al., 1999; Payolla et al., 2002). Moreover, the PGC granitoid

rocks present negative values of Nb, Sr and Ti whereas they show Rb, Ba and Th enriched relative to Nb (Litherland et al., 1986). This is again a typical feature of magmas evolved in magmatic arcs.

Finally, according with the scenario for collisional orogenies envisaged by Condie (1997) we suggest that the PGC resulted from island arc evolution with the intervening Paraguá Craton, and further collision with the Rio Negro-Juruena Province. If this is true, the PGC rocks together with coeval igneous suites (e.g., Colorado Complex, Alto Candeias Intrusive Suite) represents the onset of the ultimate stage of the Rondonian-San Ignacio orogeny (Cordani and Teixeira, 2007), considered here as the major magmatic and metamorphic event that gave rise to the Rondonian-San Ignacio province.

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Appendix A. Petrographic description of the Pensamiento Granitoids Complex rocks.

Sample	Pluton	Main characteristics
PF0501	Piso Firme	Medium-fine grained, pinkish brown, massive porphyry quartz syenite. The thin section shows intergrowth of quartz and alkali feldspar of micrographic type and radiate fabric. Subordinate anhedral quartz occurs as clusters together with isolated laths of plagioclase or aggregates. Muscovite appears as scarce secondary mineral. Ferromagnesian minerals were not observed.
SC10502	San Cristobal	Pink medium-grained, slightly foliated monzogranite gneiss. It shows inequigranular anhedral texture. It contains clusters of anhedral quartz. The K-feldspar and plagioclase show variable sizes. The plagioclase (An26) and feldspar crystals form cloudy sericitised surfaces.
SC20503	San Cristobal	Medium-fine grained, pinkish white, banded monzogranite gneiss with small and discontinuous streaky biotite. It is common an anhedral inequigranular texture. Clusters of quartz are of different sizes. The microcline appears in subhedral crystal tablets. Plagioclase (An27) in small crystals appears between quartz and feldspar. The biotite is pale straw-yellow to dark olive-green. The sphene is principal accessory mineral.
PRV0504	Porvenir	Medium-fine grained, pinkish massive syenogranite. It has an inequigranular anhedral seriate texture. A granular mixture of quartz and feldspar appears with few crystals of hornblende and biotite. The K-feldspar shows microcline-type twinning and forms anhedral K-microperthite. Plagioclase (An29) shows albite twins, and some clusters of anhedral quartz are also present. The biotite is straw yellow to pale redish brown. The hornblende is green and appears as clusters associated with biotite and irregular masses of opaque minerals.
CP0505	Diamantina	Coarse to medium- grained, pinkish white, massive to slightly porphyritic syenogranite. It shows equigranular anhedral to subhedral texture. The K-feldspar is microperthite and shows microcline-type twinning. Some orthoclase crystals show Carlsbad twinning. Scarce patches of plagioclase are intergrowth with vermicular quartz. Some plagioclase crystals (An26) contain shreds of muscovite. The biotite is pale straw-yellow to dark olive-green, and scarcely chloritized. Irregular mass of opaque minerals are also present. Euhedral zircon and scarce apatite may form biotite inclusions.
CP20506	Diamantina	Medium grained, white, massive to slightly porphyritic syenogranite. It has a consistently equigranular subhedral to anhedral texture. The plagioclase crystals (An28) contain a dense mass of very fine grained muscovite and clay minerals of brown pale color ascribed to alteration. The K-feldspar, a well developed microperthite, shows microcline-type twinning. The biotite is a pale straw-yellow to dark olive-green, sometimes chloritized. Secondary epidote occurs in small crystals. Squeletal masses of opaque minerals contain apatite and epidote. Zircon and apatite in euhedral crystals are the common accessory minerals.
CP30507	Diamantina	Medium grained, white, massive to slightly porphyritic syenogranite. The thin section shows an inequigranular anhedral texture. The K-feldspar is a usually a microcline-microperthite, and the scarce orthoclase-microperthite shows Carlsbad-type twinning. Patches of plagioclase are seen as intergrowth with vermicular quartz. The biotite is pale straw-yellow to dark olive-green. Shred muscovite is seen in plagioclase. Irregular masses of opaque minerals are associated to biotite. The principal accessory mineral is euhedral apatite.

(cont.)

Appendix A. (continued)

Sample	Pluton	Main characteristics
ME0508	Diamantina	Pinkish white, medium-coarse grained quartz monzonite with an equigranular subhedral to anhedral texture. It contains some phenocrysts of K-feldspar microperthite that show microcline-type twinning. The plagioclase crystals contain very fine grained muscovite and clay minerals of brown pale color. Abundant patches of plagioclase are intergrown with vermicular quartz. Biotite is pale straw-yellow to dark olive-green. Few minute secondary epidote is also present. Euhedral apatite and zircon inclusions occur as inclusions in the biotite.
CA0509	San Martín	Medium-fine grained, banded and foliated pink syenogranite gneiss with euhedral hornblende with inequigranular anhedral texture. Broad sinuous, albite lamellae traverses the tartan twinning of a microcline crystal. Small plagioclase crystals contain very fine muscovite and clay minerals. Common clusters of anhedral quartz with wavy extinction are also present, and secondary quartz in fine aggregates form some mosaics. Irregular mass of opaque minerals and minute crystals of secondary epidote are also present. Pale to dark brown allanite appears in aggregates of few crystals.
FLT0510	La Junta	Coarse-grained syenogranite gneiss, pink in color with inequigranular anhedral texture. Microperthitic intergrowth shows narrow albite lamellae forming a braided pattern in an orthoclase host. Small plagioclase crystals contain very fine muscovite and clay minerals of brown pale color in parallel polarized light. Plagioclase occurs as deformed twins. Streaky banded chloritized biotite is associated with epidote aggregates, sphene and irregular redish opaque minerals occurs as intergrowths with vermicular quartz. Sphene shows a micrographic intergrowth. Euhedral apatite is also present.
LJ10511	La Junta	Coarse grained, pinkish white, massive to slightly foliated and porphyritic quartz monzonite with an inequigranular anhedral texture. Microcline microperthitic intergrowth is common as well as some clusters of anhedral quartz. Abundant patches of plagioclase occurs as intergrowths with vermicular quartz. The plagioclase contains very fine muscovite and brown pale clay minerals in parallel polarized light. The biotite is a pale straw-yellow to greenish brown mineral and is chloritized.
LJ20512	La Junta	Medium grained, pinkish white, porphyritic monzogranite with an inequigranular subhedral to anhedral texture. It contains granular cluster of quartz of different size, with sutured contacts. The K-feldspar shows microcline-type twinning. The anhedral plagioclase contains very fine muscovite and clay minerals of brown pale color in parallel polarized light. The plagioclase (An29) shows a pericline twinning, and the biotite is a pale straw-yellow to dark olive-green poorly chloritized. Irregular masses of opaque minerals are also present. The principal accessory mineral is the euhedral sphene.
LJ30513	La Junta	Medium grained, gray pinkish monzogranite with an inequigranular anhedral to subhedral texture. The K-feldspar is microperthite and shows microcline-type twinning. The plagioclase contains a fine shred of muscovite, and contains patches of vermicular quartz. The hornblende is pleochroic, and in shades of green. Biotite is pale straw-yellow to dark olive-green, sometimes with relict aspect between the crystals of quartz and feldspars. Secondary epidote is rare. Apatite appears as euhedral crystal.

Appendix B. Summary of megascopic and microscopic petrography for the Pensamiento Granitoids Complex rocks (after Klinck and O'Connor, 1983; Hawkins, 1982; Pitfield, 1983; Litherland, 1982).

Pluton	Main characteristics
San Martin Granite (Klinck and O'Connor, 1982).	<p>In the undeformed granite a xenomorphic interlobate equigranular texture is present; the color ranges from greyish-orange-pink, greyish-pink, yellow-brown to light-olive brown. Modal analysis plot in the monzogranite field. Equigranular more rarely inequigranular, locally hypidiomorphic texture is observed with plagioclase forming equant grains. Quartz forms ameiboid crystals and sutured interlobate mosaics. The K-feldspar is usually microcline-microperthite. Tabular plagioclase (An26) insets with a clear rim and sericitised core are common along with blob-like quartz inclusions. Biotite forms straw or olive brown colored flakes and is associated with accessory opaque ore, zircon and apatite. Accessory epidote appears in some samples in association with the biotite.</p> <p>In the deformed granite three increments of deformation-intensity from quartz textures are seen. The first comprises intergranular milonitisation between quartz grains with a precursor development of mortar texture. The biotite fabric is still random. The second increment in intensity of deformation generated xenoblastic, interlobate elongate textures. The biotite defines a tectonic fabric of variable intensity. The quartz occurs as elongate lenses and is parallel to the biotite fabric. The quartz ribbon texture appears and plagioclase twin planes are deformed as intensity of deformation increases. The ribbons define a preferred orientation. Subsequent metamorphism caused partial polygonisation.</p> <p>Xenoliths: banded migmatites (e.g., Chiquitania Complex).</p>
La Junta Granite (Hawkins, 1982).	<p>Pinkish-grey in color, medium-to coarse-grained, gneissic monzogranite to syenogranite which grades into a paler pink variety with a lower biotite content. The rock consists of porphyroblastic alkali feldspar and string perthitic microcline, aligned parallel to the biotite and associated to quartz and plagioclase with myrmekitic intergrowth. The biotite appears altered to chlorite. The accessory minerals are: sphene (locally altering to leucoxene), zircon, apatite, allanite and opaque ores. Some secondary calcite and epidote may be present locally.</p> <p>The La Junta Granite exhibits a well-developed migmatitic envelope along its southern margin that suggests an autochthonous origin.</p> <p>Xenoliths: partly absorbed rocks (hornblende-biotite gneiss, calc-silicate gneiss, quartzite, amphibolite).</p>
Piso Firme Granophyre (Pitfield, 1983).	<p>There are three observed types: <i>i</i>) Coarse-grained potassic granophyre; <i>ii</i>) Medium- to coarse-grained microspherulitic. <i>iii</i>) Spherulitic plagiophyric microgranophyre.</p> <p><i>i</i>) micrographic monzogranite characterized by its coarse- to medium grained, pink-red to brown color, holocrystalline with randomly specks of dark ferromagnesian minerals. Subordinate lithologies include micrographic monzogranite, sodipotassic granophyre and quartz porphyry. Thin section is characterized by micrographic intergrowth of K-feldspar-quartz with herringbone, ribbon or wedge shaped hieroglyphic patterns. Quartz inclusions are enlarged. Plagioclase (An6-14) is zoned. Mafics include olive greenish-brown biotite $\pm$ green amphibole ($\pm$ chlorite $\pm$ epidote $\pm$ clinozoisite $\pm$ calcite $\pm$ sericite alteration). The accessory minerals include magnetite, hematite, sphene, allanite and zircon. Drusy cavities, rootless spiracles and veined segregates infilled by milky or smoke quartz $\pm$ calcite $\pm$ fluorite $\pm$ pyrite $\pm$ secondary iron oxides. Selvages of pale green muscovite are also present.</p> <p><i>ii</i>) The medium- to coarse-grained microspherulite granophyre, pale to dark greenish-brown or pinkish to greenish-medium to dark gray in color. Rarely small inclusions of black, glassy microgranophyre. Stellate or radiate arrangement. Cryptographic spherulitic K-feldspar aggregates. The plagioclases (An8-12) are zoned, euhedral crystals locally corroded and altered to epidote-clinozoisite, carbonate and sericite. Rod, bead and string micro to crypto perthites, some antiperthite and myrmekite. Pale to dark olive green biotite variably altered to chlorite. The accessory minerals include sphene, allanite, zircon and opaque ore. Sparse drusies, segregation clots and veinlets of quartz and iron-stained carbonate are also present.</p> <p><i>iii</i>) Medium- to very fine-grained spherulitic plagiophyric microgranophyre, showing vitreous, conchoidal fracture. The rock is dark-bluish or greenish-gray to black and locally pink in color. Spherulites up to 1.5 mm across with radially cryptographic fibrous intergrowths of K-feldspar-quartz are observed. Plagioclase (An7-16) occurs as euhedral tablets and twinned aggregates partly altered to clay and calcite. Sericite shreds are also present. The accessory minerals are sphene and opaque ore.</p> <p>An aegirine-riebeckite-bearing sodi-potassic granophyre crops out at the eastern extremity of Piso Firme hill. The rock is pinkish-to greenish-gray in color, coarse-grained and has scarce piroxenes visible in hand sample.</p>

(cont.)

Appendix B. (continued)

Pluton	Main characteristics
The San Cristobal Metagranite (Pitfield, 1983).	<p>It is a medium-to coarse- or very coarse-grained, pink to pale pinkish-grey in color, variably foliated hornblende-biotite adamellite. The normalised quartz-feldspar modal percentages are consistent with a monzogranite composition. In thin section the metagranite shows a hypidiomorphic to xenomorphic granular texture with more or less equal proportions of quartz, plagioclase and variably perthitic microcline. It rarely forms small augen and lensoid segregates. The quartz is clear to smoky in color and appears streaked or elongated with the foliation. The K-feldspar forms incipient blastic growths enveloping other mineral phases and presents an anastomosing habit. Plagioclase (An14-26) shows corrosion and replacement by K-feldspar with local myrmekitic reaction fronts or globular quartz inclusions. Biotite constitutes up to 5% of the rock, forming pale to dark olive green flakes which define a foliation. Bright green to dark blue-green, somewhat poikilitic hornblende, no more than 2% of the rock, is associated with biotite in composite aggregates. Both biotite and hornblende may be altered to chlorite. The main accessory minerals are sphene, zircon, magnetite and less commonly, metamict allanite. The sphene occurs as scattered grains and lozenge-shaped sections as well as a mantling to some opaque minerals. Zircon is typically zoned with idiomorphic overgrowths on rounded detrital grains.</p> <p>Xenoliths: biotite-hornblende gneisses, biotite amphibolites and epidote calc-silicate rocks.</p>
Porvenir Granite (Klinck and O'Connor, 1982)	<p>It consists of greyish-orange, pink to pale-red, medium-grained equigranular biotite-hornblende monzogranite. A weak linear fabric is defined by the streaking of mafics and the preferred orientation of the quartz-feldspathic groundmass. The texture is xenoblastic-interlobate, inequigranular. K-feldspar microcline perthite occurs as xenoblastic grains with drop-like quartz inclusions. The plagioclase forms cloudy sericitised grains in the groundmass and is also recrystallised into the granoblastic polygonal varieties into the mosaic. The mafics are greenish-straw colored biotite and green hornblende that forms clots with opaque ore. It can be associated with epidote and sphene.</p>
Diamantina Granitoid (Klinck and O'Connor, 1982)	<p>This is a light-grey, weathering greyish-orange-pink in color, medium- to coarse-grained biotite-monzogranite to granodiorite with a hypidiomorphic texture, rarely a xenomorphic texture. Quartz occurs as seriate, interlocking grains with internal strain shadow extinction. Seriate grain boundaries are developed between quartz and plagioclase and quartz and K-feldspar. The latter appears as subidiomorphic crystals of thread or hair perthite or microcline and shows a poikilitic texture with common inclusions of bleb-like quartz and idiomorphic plagioclase. The plagioclase presents a clear rim and sericitised core, showing a narrow compositional range between (An23-24). Sericitisation is common, and contacts with K-feldspar show a narrow clear rim in the plagioclase. In some places the sericite in the plagioclase defines a faint compositional zonation. Myrmekitic intergrowth can be developed as embayments against microcline. Biotite, main mafic mineral (2-7%), occurs as straw-brown and greenish scattered flakes or wispy streaks. Some samples show a pronounced biotite foliation especially near to biotite-rich xenoliths. In places the biotite plus associated opaque ore define a foliation and occur in a hypidiomorphic mosaic of quartz, plagioclase and microcline. The accessory minerals are opaque ore (magnetite), sphene and idiomorphic zircon. It gave rise to pleochroic haloes in the biotite. The allanite crystals attain idiomorphic form ranging up to 3mm long. It is zoned and metamict showing concentric and radiating fractures. This is caused by the alteration of allanite to the metamict state.</p> <p>Xenoliths of tonalite-granodiorite composition: they vary from 50 cm to 43 m long, and are fine grained, to medium- to coarse-grained. Light-grey to grey in colour and with biotite as the principal mafic mineral. The texture is hypidiomorphic with greenish-olive biotite. In thin section the rock has allotriomorphic plagioclase with well defined compositional zoning. Composition ranges from about (An25-33), and alteration to sericite is common. K-feldspar content is low, ranging from zero to about 13% and occurs as microcline-perthite. It has plagioclase insets and drop-like quartz inclusions. Some of the K-feldspar may be metasomatic and account for the diffuse contacts locally developed between the granodiorite and monzogranite. Quartz is xenomorphic, lobate and generally strained with development of sub-grain boundaries. The accessory minerals are sphene, allanite and idiomorphic zircon occurring as irregular clusters.</p> <p>Other xenoliths: Biotite gneisses, garnet-biotite gneiss and hornblende gneisses.</p> <p>Late veins: Pegmatites composed of quartz and microcline or veins of quartz and magnetite.</p>

(cont.)

Appendix B. (continued)

Pluton	Main characteristics
Diamantina Granitoid (Litherland, 1982),	<p>In the eastern sector of the body occurs a pale pink or pale grey, medium-to medium-coarse-grained rock, in places containing scattered K-feldspar megacrysts that ranges from 1 to 3 cm long. The investigated samples were classified as quartz syenite to quartz-monzonite, and syenogranites and monzogranites in composition.</p> <p>Microcline or perthite megacrysts enclose smaller crystals of altered plagioclase and quartz. The plagioclase may be zoned and variable altered to sericite or epidote. The accessory minerals are: apatite, ore, zircon and allanite whose crystals up may be to 3 mm long.</p> <p>The southern part of the body is migmatitic with paleosome (gneiss) and neosome (granitoid) components mixed on all scales. Small pegmatitic veins and segregations of approximately 5 cm thick may be present.</p> <p>Xenoliths: biotite-rich schists or biotite gneisses, that are up to 5 m long.</p>

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The Rondonian-San Ignacio Province in the SW Amazonian Craton: An overview

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ABSTRACT

The Rondonian-San Ignacio Province (1.56–1.30 Ga) is a composite orogen created through successive accretion of arcs, ocean basin closure and final oblique microcontinent–continent collision. The effects of the collision are well preserved mostly in the Paraguá Terrane (Bolivia and Mato Grosso regions) and in the Alto Guaporé Belt and the Rio Negro-Juruena Province (Rondônia region), considering that the province was affected by later collision-related deformation and metamorphism during the Sunsás Orogeny (1.25–1.00 Ga). The Rondonian-San Ignacio Province comprises: (1) the Jauru Terrane (1.78–1.42 Ga) that hosts Paleoproterozoic basement (1.78–1.72 Ga), and the Cachoeirinha (1.56–1.52 Ga) and the Santa Helena (1.48–1.42 Ga) accretionary orogens, both developed in an Andean-type magmatic arc; (2) the Paraguá Terrane (1.74–1.32 Ga) that hosts pre-San Ignacio units (>1640 Ma: Chiquitania Gneiss Complex, San Ignacio Schist Group and Lomas Manechis Granulitic Complex) and the Pensamiento Granitoid Complex (1.37–1.34 Ga) developed in an Andean-type magmatic arc; (3) the Rio Alegre Terrane (1.51–1.38 Ga) that includes units generated in a mid-ocean ridge and an intra-oceanic magmatic arc environments; and (4) the Alto Guaporé Belt (<1.42–1.34 Ga) that hosts units developed in passive marginal basin and intra-oceanic arc settings. The collisional stage (1.34–1.32 Ga) is characterized by deformation, high-grade metamorphism, and partial melting during the metamorphic peak, which affected primarily the Chiquitania Gneiss Complex and Lomas Manechis Granulitic Complex in the Paraguá Terrane, and the Colorado Complex and the Nova Mamoré Metamorphic Suite in the Alto Guaporé Belt. The Paraguá Block is here considered as a crustal fragment probably displaced from its Rio Negro-Juruena crustal counterpart between 1.50 and 1.40 Ga. This period is characterized by extensive A-type and intra-plate granite magmatism represented by the Rio Crespo Intrusive Suite (ca. 1.50 Ga), Santo Antonio Intrusive Suite (1.40–1.36 Ga), and the Teotônio Intrusive Suite (1.38 Ga). Magmatism of these types also occur at the end of the Rondonian-San Ignacio Orogeny, and are represented by the Alto Candeias Intrusive Suite (1.34–1.36 Ga), and the São Lourenço-Caripunas Intrusive Suite (1.31–1.30 Ga). The cratonization of the province occurred between 1.30 and 1.25 Ga.

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1. Introduction

The term Rondonian Province was first introduced by Cordani et al. (1979) for a deformational and metamorphic event in the SW Amazonian Craton, that was constrained by Rb–Sr and K–Ar geochronology to 1.45–1.25 Ga. Teixeira and Tassinari (1984) and Teixeira et al. (1989) interpreted the province to be a mobile belt extending from northern Rondônia (Brazil) to San Ignacio region (Bolivia) including the rocks attributed to the San Ignacio Orogeny

(1.40–1.28 Ga) of Litherland et al. (1986). Tassinari et al. (1996), based on U–Pb TIMS and SHRIMP ages, proposed the term Rondonian-San Ignacio Province (RSIP: 1.45–1.30 Ga). Subsequently, Tassinari et al. (2000), based on U–Pb data and geological data, subdivided rocks of the RSIP (1.50–1.29 Ga) into the Rio Alegre Terrane (1.50 Ga), Santa Helena Orogen (1.47–1.42 Ga), and Rondonian-San Ignacio Orogen (1.40–1.29 Ga).

Overall, according to Cordani and Teixeira (2007), the RSIP (1.50–1.30 Ga) is an amalgamation of intra-oceanic magmatic arcs and accretionary prisms formed during a continental collision along the SW boundary of the Rio Negro-Juruena Province. It is a collage of medium to high-grade accretionary belts, large shear

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zones, and plutonic complexes that reflect the collisional nature of the boundary. Conversely, Santos et al. (2000) and Santos et al. (2008), based on U–Pb and Sm–Nd, separated the rocks of the RSIP into the Rondônia-Juruena Province (1.84–1.54 Ga) and Sunsás Province (1.46–1.11 Ga). They proposed that the Sunsás Orogen is characterized by an autochthonous evolution and was formed by four orogenies: Santa Helena (1.46–1.42 Ga), Candeias (1.37–1.32 Ga), San Andres (ca. 1.27 Ga) and Nova Brasilândia (1.18–1.11 Ga).

Currently, the RSIP in the southwestern border of the Amazonian Craton is limited to the north and east by the Rio Negro-Juruena Province. To the south, the RSIP is bounded by the Sunsás Province along the Sunsás tectonic front (Rio Negro Front and Santa Catalina Straight Zone). The western part of the RSIP is covered by Phanerozoic sedimentary sequences. The total area exposed is at least ~2000 km long and ~800 km wide. It includes large parts of the Precambrian shield of the Brazilian states of Rondônia and Mato Grosso, as well as a large area of the Santa Cruz and Beni departments in Bolivia. Outcrops of the RSIP in the northwestern corner of the Amazonian Craton are obscured by Phanerozoic sedimentary sequences.

Despite the substantial new geological mapping, and the additional collection of geophysical, geochronological and geochemical data, very little is known about several segments of the RSIP in Rondônia, Mato Grosso and eastern Bolivia regions. This lack of data hampers a better correlation of units. Furthermore, definition of tectonic unit boundaries, age limits, lateral continuation, internal organization, subdivision and varied nomenclature all are controversial, nonetheless leading to several competing chronologic frameworks, and terminology for the tectonic events in the RSIP.

We proposed the RSIP is a composite orogen, consisting of an older complex accretionary orogen (1556–1430 Ma) followed by, the terminal microcontinent-continent collision at 1340–1320 Ma. The major tectonic units are: the Paraguá Terrane, Jauru Terrane, Rio Alegre Terrane and the Alto Guaporé Belt (Fig. 1). We furthermore expand the upper age of RSIP to 1.56 Ga in order to include the Cachoeirinha Orogen (1.56–1.52 Ma). The overall time interval for RSIP is thus considered herein to 1.56–1.30 Ga.

We review the presently accepted evolutionary history of the RSIP, including the temporal and spatial distribution, precursors, and tectonic settings. Included are descriptions of the terranes and orogens, and their tectonic limits. These data provide the basis for an overall interpretation and related tectonic model. Post-Rondonian-San Ignacio events (Sunsás Orogeny) that affected the RSIP are described by Teixeira et al. (2010).

2. The RSIP in the context of the SW Amazonian Craton

Several recent reviews of the Amazonian Craton (Tassinari and Macambira, 1999; Santos et al., 2000; Tassinari et al., 2000; Cordani and Teixeira, 2007; Cordani et al., 2009) have focused on the correlation of major geologic units and structures. These reviews are substantially enhanced by regional scale work based on U–Pb TIMS and SHRIMP geochronology, Sm–Nd geochemistry, as well as Pb–Pb evaporation techniques.

The SW portion of the Amazonian Craton is represented by four Proterozoic sub-parallel provinces (Cordani and Teixeira, 2007; Cordani et al., 2009): Ventuari-Tapajós (2.00–1.80 Ga), Rio Negro-Juruena (1.78–1.55 Ga), Rondonian-San Ignacio (1.50–1.30 Ga) and Sunsás-Aguapeí (1.25–1.00 Ga) (Fig. 1). In this context, for Cordani and Teixeira (2007), the RSIP may be interpreted to represent collisional orogeny involving a possible microcontinent combined with domains composed of the Rio Crespo Intrusive Suite (1.50 Ga), Rio Alegre Complex (1.51–1.48 Ga), Santa Helena batholith (1.45–1.42 Ga), Colorado Metamorphic Suite (1.36–1.30 Ga)

and the Pensamiento Granitoid Complex (1.36–1.30 Ga). High-grade metamorphic rocks related to the San Ignacio Orogeny (1.35 Ga) and late- to post-tectonic plutonism: Santo Antônio (1.41 Ga), Teotônio (1.39 Ga), Alto Candeias (1.34 Ga) and São Lourenço-Caripunas intrusive suites are also evident. RSIP cratonization is interpreted to have occurred at 1.30 Ga (Ar–Ar ages) and 1.25 Ga (K–Ar ages).

Cratonization of the RSIP was followed by tectonic reactivation, deformation, thermal overprint, and magmatism related to the Sunsás Orogeny. These effects are manifested by extensive shear zones (e.g. Ji-Paraná Shear Zone, Scandolara et al., 1999; Tohver et al., 2005), mylonitic belts, rifts and sedimentary basins, and post-tectonic and anorogenic intrusions (Cordani and Teixeira, 2007; Cordani et al., 2009; Teixeira et al., 2010).

3. The Rondonian-San Ignacio Province

3.1. The Paraguá Terrane (1.82–1.32 Ga)

The term Paraguá Craton was introduced by Litherland et al. (1986) in eastern Bolivia Precambrian shield to denote a tectonically stable region during the Meso- to Neoproterozoic deformation of the Sunsás and Aguapeí belts. However, Saes and Fragoso Cesar (1996) subdivided the shield into two terranes, the Paraguá Terrane and the San Pablo Terrane, and Tohver et al. (2004) expanded the limits of the craton to include a large area of the Mato Grosso, and proposed that the E–W trending Nova Brasilândia belt (ca. 2000 km in extent) marks the limit between the Amazonian and Paraguá cratons, during the late Mesoproterozoic. In this paper, we adopt the term Paraguá Terrane to denote a composite terrane, which comprises Paleoproterozoic basement rocks (Chiquitania Gneissic Complex, San Ignacio Schist Group, Lomas Manechis Granulitic Complex) and Mesoproterozoic granitoids (Pensamiento Granitoid Complex), amalgamated to the proto-Amazonian Craton during the Rondonian-San Ignacio Orogeny. To the east a ductile shear zone marks the limit with Rio Alegre Terrane. To the north the limit with the Alto Guaporé Belt is hidden by Cenozoic sedimentary sequences. To the south the boundary is hidden by Brasiliano platform sediments (post-Sunsás units), and to the west by Cenozoic sedimentary sequences (Fig. 1).

3.1.1. Pre-San Ignacio basement rocks (>1640 Ma)

The pre-San Ignacio crust, based on Rb–Sr whole-rock ages was considered older than 1961 Ma (Litherland et al., 1986). Boger et al. (2005) refined the understanding of these rocks doing precise U–Pb SHRIMP zircon ages from two high-metamorphic grade rocks of the Lomas Manechis Granulitic Complex (LMGC), predominantly composed of granites, orthopyroxene bearing granitoids and pinkish granitoids that yielded U–Pb SHRIMP zircon crystallization ages of 1689 ± 5 and 1663 ± 4 Ma, and from two high-grade paragneisses from the Chiquitania Gneissic Complex (CGC), represented by biotite-bearing felsic gneisses, and interpreted to be of sedimentary or volcanic origin (detrital zircons). Boger et al. (2005) interpreted the Chiquitania paragneiss protolith to have been derived from a predominantly Paleoproterozoic source formed at about 1765 Ma, whereas the paragneiss protolith was deposited after at ca. 1690 Ma (Fig. 2, Table 1).

Additional U–Pb SHRIMP zircon ages from the Lomas Manechis granulitic gneiss, Rio Fortuna orthogneiss, Santa Rita orthogneiss, and Refugio Granite are reported by Santos et al. (2008). The Lomas Manechis granulitic gneiss contains magmatic zircons with $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1818 ± 13 Ma; these zircons are the oldest yet identified in Bolivia. The Rio Fortuna and Santa Rita orthogneiss show inherited zircon grains formed between 1772 and 1729 Ma. The Refugio Granite has a $^{207}\text{Pb}/^{206}\text{Pb}$ crystallization age of

Fig. 1. (A) Simplified map of the SW Amazonian Craton showing the approximate boundaries of the main provinces, major orogens, terranes and belts, tectonic elements, and lithologic units. (B) Major geochronological provinces of the Amazonian Craton (after Cordani and Teixeira, 2007). MI, Maroni-Itacaiunas Province; VT, Ventuari-Tapajós Province; RNJ, Rio Negro-Juruena Province; RO, Rondonian-San Ignacio Province; SS, Sunsá-Aguapeí Province. Locations of Figs. 2–4 are shown.

Fig. 2. Major orogens, geological units, and tectonic elements of the Paragvá Terrane (eastern Bolivia) (modified from Litherland et al. (1986), Ruiz (2005), Matos et al. (2009)).

1641 ± 4 Ma, and Nd T_{DM} model age of 1.7 Ga and $\epsilon_{Nd(t)} = +4.06$. The La Cruz granite yields $^{207}\text{Pb}/^{206}\text{Pb}$ SHRIMP zircon age of 1673 ± 21 Ma, Nd T_{DM} model age of 1.83 Ga and $\epsilon_{Nd(t)}$ of +2.1.

3.1.2. Granitoid magmatism

The Pensamiento Granitoid Complex (PGC) forms much of the Paragvá Terrane, and is related to the San Ignacio Orogeny (Fig. 2). Herein we divided the PGC into two groups of granitoids (Table 1): (1) the syn- to late-kinematic granitoids (U–Pb SHRIMP zircon ages of 1373–1347 Ma) represented by La Junta, Florida, Puerto Alegre, San Martín and Campamento granites, and (2) late- to post-kinematic granitoids comprising the Diamantina (U–Pb SHRIMP zircon age of 1340 Ma), Porvenir, Padre Eterno, Três Picos, Orobayaya, Discordância, El Tigre, San Cristóbal granites and the Piso Firme Granophyre.

The La Junta and San Martín syn- to late-kinematic granites are characterized by Nd and Sr isotopic compositions ($\epsilon_{Nd(t)}$ values of +1.8 to −3.7; $\text{Sr}_i = 0.7052$) and negative Nb and Ta anomalies indicating that different sources contributed to the granitoid magma genesis in a Mesoproterozoic continental-margin arc system (Matos et al., 2009). Piso Firme and the Diamantina late- to post-kinematic granites exhibit $^{87}\text{Sr}/^{86}\text{Sr}$ ratios close to Bulk Earth and Nd T_{DM} ages (1.92–1.51 Ga), which coupled with the $\epsilon_{Nd(t)}$ values (−1.25 to +3.90) indicate mixtures among MORB-like magmas and isotopic homogeneous protoliths (Darbyshire, 2000; Matos et al., 2009).

In the Brazilian side of the Paragvá Terrane in Santa Bárbara hill, the PGC is characterized by voluminous crustally derived granitic plutons (Tarumã Granite–Gneiss and Lajes Granite) emplaced along a NNW structural pattern. The strongly foliated syn-kinematic Tarumã Granite–Gneiss shows U–Pb zircon age of 1.38 Ga; Nd

Table 1
Summary of the main geological and geochronological features in the Paraguá Terrane (RSIP southern sector).

	Units	Zone	Lithology	Composition	Metamorphism and reformation	U–Pb Shrimp (Zr) age (Ma)	K ³⁹ –Ar ⁴⁰ age (Ma)	Tectonic setting/Sources		
Paraguá Terrane	San Ignacio Orogen (SIO)		Late-to-post-kinematic granitoids	Bt-sienogranite, Bt and Bt-Hbl-syenogranite Nordmarkite $T_{DM} = 1.92$ to 1.65 Ga $\epsilon_{Nd(t)} = +2.75$ to -1.25	Alkaline	Remelting of enriched crustal rocks	1340	1380–1244	Juvenile character related to RSIO	Generated in a continental, Andean-type, orogenic arc related to RSIO continental margin calc-alkaline arc
	Pensamiento Granitoid Complex	Northern	Syn- to late-kinematic granitoids	Granophyre, Qz-syenite Bt and Hbl-syenogranite $T_{DM} = 1.59$ to 1.51 Ga $\epsilon_{Nd(t)} = +3.9$ to $+2.3$	Metaluminous to weakly peraluminous sub-alkaline to high-alkaline I type granites (and scarce S-type)	Deformation and migmatisation of basement rocks are related to RSIO			Different magma sources, Juvenile/crustal sources, Partial melting of lower crust	
	Granitoid rocks	Southern	Bt-augen gneiss, Hbl-Bt - granodiorite Tonalite $T_{DM} = 1.7$ $\epsilon_{Nd(t)} = -0.1$	?			1373–1347			
							1429–1275			
	Pre-San Ignacio basement rocks (>1640 Ms)									
	Lomas Manechis Complex		Charnockitic hypersthene granulites (granite), Enderbitic hypersthene granulites. Mafic hypersthene (norite) granulite leptyte. Granitic sills interleaved with psamitic and calc-silicate metas. rocks. $T_{DM} = 2.07$ to 1.6 Ga. $\epsilon_{Nd(t)} = +4.0$ to -3.97	?	Upper amphibolite to granulite facies (1319–1353 Ma). High $P_{(tot)} > P_{H_2O}$ partial remelting deformation and metamorphism related to RSIO (1319–1380 Ma)	1690–1660	?			
	San Ignacio Schist Group		Pelitic schist with psammitic layers: metavolcanics:metarhyolite, metabasalt, BIF, chert < 1.764 Ma	Bimodal tholeiitic to calc-alkaline	(thickness over 10 km). High-grade gneiss with cordierite and hypersthene	Deposition after 1690 Ma		Oceanic-floor setting. Derived from 1765 Ma source		
	Chiquitania Gneiss Complex		Migmatic semi-pelitic gneiss associated to schist belts; banded micaceous qz.feld. gneiss. $T_{DM} = 1.86$ to 1.74 Ga $\epsilon_{Nd(t)} = -0.61$ to -4.88	?	Upper amphibolite to medium-grade facies. High $P_{(tot)} > P_{H_2O}$. Peak metamorphism at 1333 Ma. Remelting	Detrital zircons 1764–1678	1336–1323	?		

References: Litherland and Bloomfield (1981), Berrangé and Litherland (1982), Litherland et al. (1986), Boger et al. (2005), Ruiz et al. (2007), Santos et al. (2008), Matos et al. (2009). Mineral abbreviations after Kretz (1983).

$T_{DM} = 1.9$ Ga and $\varepsilon_{Nd(t)} = -4.11$ and the weakly foliated late-kyne-matic Lajes Granite exhibits U–Pb zircon age of 1.31 Ga, Nd $T_{DM} = 1.7$ Ga and $\varepsilon_{Nd(t)} = 0.0$ (Geraldes, 2000; Ruiz, 2005).

In the Ricardo Franco or Huanchaca hill the Pensamiento granitoids are not affected by the Sunsás Orogeny, and preserve the San Ignacio metamorphic and deformational characteristics. In the Vila Bela region, the PGC consists of syn-kinematic foliated NNW-trending monzogranite and granodiorite (Guaporé Granite), and weakly foliated granites such as the Passagem Granite (1.29 Ga). Geochemical and isotopic signatures, and negative $\varepsilon_{Nd(t)}$ values of the San Ignacio related granitoids in Brazil indicate that they formed in a continental magmatic arc and/or in a collisional continental setting (Ruiz, 2005).

A reappraisal of the San Ignacio granitoids of the Southern Zone as defined by Litherland et al. (1986) is on course, mainly based on precise U–Pb SHRIMP ages and isotopic geochemistry. For example, the San Rafael granite (1334 ± 12 Ma) was synchronous with the San Ignacio Orogeny, and inherited zircon core age (1686 ± 16 Ma) indicates that the granite interacted or was melted from a Paleoproterozoic protolith (Boger et al., 2005). The San Ramon granite (1429 ± 4 Ma, Nd T_{DM} model age of 1.6 Ga and $\varepsilon_{Nd(t)} = +2.3$) and San Andrés granite (1275 ± 7 Ma) (Santos et al., 2008) indicate the existence of two magmatic events not related to the San Ignacio granitoid magmatism.

Elsewhere, Santos et al. (2008) reported SHRIMP U–Pb zircon ages from Rio Fortuna 1336 ± 3 Ma and Santa Rita 1319 ± 6 Ma, orthogneisses, both previously considered as part of the Chiquitania Gneiss Complex by Litherland et al. (1986), are related to the San Ignacio Orogeny.

3.1.3. Deformation and metamorphism

The San Ignacio Orogeny encompasses three WNW-directed phases of deformation, subscripts Do1, Do2, and Do3 (Litherland et al., 1986). The youngest, Do3, the major penetrative event, was accompanied by voluminous syn-kinematic granite intrusions, and migmatization of the 1690 Ma older sedimentary rocks, but some of the late- to post-kinematic granitoids postdate Do3 phase and were emplaced along a NNW trend (Litherland et al., 1986; Boger et al., 2005). Sunsás-age deformation was confined to Sunsás and Aguapé belts. In the Sunsás Belt the main shear zones and tectonic front are the Rio Negro Front and Santa Catalina Straight Zone, which define the northern limit of the Sunsás Belt, and San Diablo Front (Litherland et al., 1986). In the Aguapé Belt the tectonic effects are represented by transpressive shear zones (e.g. Santa Rita Shear Zone), and transposition of older structures parallel to the N20–40°W/70°–80°SW orogenic trend (Ruiz, 2005) (Fig. 1).

Upper-amphibolite mineral assemblage characterizes the Chiquitania and Lomas Manechis complexes, whereas the San Ignacio Group is characterized by low- to medium-grade metamorphic minerals. U–Pb SHRIMP zircon rim ages from LMGC (orthopyroxene-bearing granitoid) yield a weighted ^{207}Pb – ^{206}Pb age of 1320 ± 11 Ma, and a biotite-bearing felsic gneiss (leucosome) from the CGC has zircon rims with U–Pb ages of 1333 ± 6 Ma (Table 1). These ages are interpreted to reflect the time of partial melting related to the peak metamorphism in the LMGC and CGC during the San Ignacio Orogeny (Boger et al., 2005).

Other U–Pb SHRIMP zircon, monazite and titanite ages from granitoid rocks of the LMGC, Rio Fortuna orthogneiss, Santa Rita orthogneiss suggest that high-grade metamorphism occurred over a long time period between 1353 and 1319 Ma (Santos et al., 2008). Monazite from a Lomas Manechis granulitic rock has a metamorphic age of 1339 ± 4 Ma, which overlaps the $^{207}\text{Pb}/^{206}\text{Pb}$ age of metamorphic zircons at 1338 ± 21 Ma. The Rio Fortuna orthogneiss has magmatic zircons and rims formed at 1336 ± 3 Ma. The Santa Rita orthogneiss has magmatic zircons with $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1319 ± 6 Ma. These authors concluded that all Lomas Manechis

granulite rocks and their counterparts observed in western Rondônia are orogenic rocks formed during the time interval 1353–1319 Ma.

3.2. The Jauru Terrane (1.78–1.42 Ga)

The Jauru Terrane was defined by Saes and Fragoso Cesar (1996) to include Paleoproterozoic metamorphic complexes resulting from accretions of intra-oceanic arcs into the Amazonia Central Province. In this paper, the composite Jauru Terrane consists of Paleoproterozoic basement rocks (Alto Jauru Group, Figueira Branca Intrusive Suite, Alto Guaporé Metamorphic Complex and Cabaçal Tonalite) and the Mesoproterozoic Cachoeirinha and Santa Helena orogens. To the west a ductile shear zone marks the limit with the Rio Alegre Terrane. To the north, east and south the limits are hidden by Phanerozoic sedimentary sequences (Fig. 1).

3.2.1. Paleoproterozoic basement rocks (1.78–1.72 Ga)

The Paleoproterozoic basement rocks consist of four lithostratigraphic units: The Alto Jauru Group, Figueira Branca Intrusive Suite, Alto Guaporé Metamorphic Complex, and Cabaçal Tonalite (Fig. 3, Table 2).

The Alto Jauru Group (Monteiro et al., 1986) consists of gneisses, migmatites and three metavolcano-sedimentary sequences: Cabaçal, Araputanga, and Jauru. Silicic to intermediate volcanic rocks have U–Pb ages of 1.76–1.72 Ga, and $\varepsilon_{Nd(t)}$ values are between +2.6 and +2.2, allowing a dominantly juvenile mantle derivation for these rocks. Geochemical data from the Cabaçal tholeiitic basalts suggest the incorporation of successive intra-oceanic arcs within the Alto Jauru Group, during the evolution of the continental margin of the Rio Negro-Juruena Province (Pinho et al., 1997; Geraldes et al., 2001). Ar–Ar ages between 1.53 and 1.46 Ga record metamorphic cooling related to the Cachoeirinha Orogeny.

The Figueira Branca Intrusive Suite (unknown age) is composed of numerous meta-basic and meta-ultrabasic plutons that intruded the Alto Jauru Group, are polydeformed and are metamorphosed at high-amphibolite to greenschist facies (Saes et al., 1984; Ruiz, 2005). The close association between the mafic-ultramafic intrusions and the Alto Jauru Group supracrustal rocks indicates that the rock association likely represents relicts of Paleoproterozoic oceanic crust (Ruiz, 2005).

The Alto Guaporé Metamorphic Complex as defined by Menezes et al. (1993) consists of granodioritic to tonalitic orthogneiss, which intruded the volcano-sedimentary supracrustal sequences. The gneisses were metamorphosed at greenschist to amphibolite facies. The oldest dated orthogneisses range in U–Pb zircon ages between 1.8 and 1.7 Ga. Positive $\varepsilon_{Nd(t)}$ values varying from +2.4 to –0.8 suggest a crustal contribution to largely mantle derived magma (Pinho, 1996; Geraldes et al., 2001; Ruiz, 2005). Ar–Ar ages indicate that the gneisses were thermally affected during the Cachoeirinha Orogeny at 1.51 Ga or reflect resetting during the Sunsás Orogeny (1.25–1.00 Ma) (Paulo, 2005; Ruiz, 2005).

The Cabaçal Tonalite, first described by Monteiro et al. (1986), is a tonalite batholith metamorphosed at amphibolite facies, which had intruded in the Cabaçal volcanic-sedimentary sequence (Alto Jauru Group). Pb isotopic data suggest a crystallization age of 1.78 Ga (Pinho, 1996). This segment of the Jauru Terrane was successively reworked during the Cachoeirinha (1.56–1.52 Ga) and Santa Helena orogenies (1.48–1.42 Ga) (Ruiz, 2005).

3.2.2. The Cachoeirinha Orogen (1.56–1.52 Ga)

Rocks in the Cachoeirinha Orogen, initially described by Carneiro et al. (1992), evolved during the Cachoeirinha Orogeny (Van Schmus et al., 1998; Geraldes et al., 1999; Geraldes, 2000). The Cachoeirinha Orogen, herein interpreted as an accretionary orogen,

Fig. 3. Simplified geologic–tectonic map of SW Mato Grosso region showing major orogens, terranes and belts, tectonic elements, and lithologic units (modified from Ruiz, 2005).

Table 2

Summary of the main geological and geochronological features of the Jauru and Rio Alegre terranes (RSIP southern sector).

	Units	Lithology	Composition	Metamorphism and deformation	U–Pb shrimp (Zr) age (Ga)	Tectonic setting/sources		
Rio Alegre Terrane	<i>Rio Alegre Orogen (RAO)</i>							
	Santa Rita Intrusive Suite	Syn-to-late-kinematic granitoids Metaperidotite, metagabbro, serpentinite $T_{DM} = 1.67$ Ga $\varepsilon_{Nd(t)} = +4.5$ to $+2.5$	Bt-granite, Hbl-Bt granodiorite, Hbl-Bt tonalite, Diorite. $T_{DM} = 1.53$ to 1.50 Ga $\varepsilon_{Nd(t)} = +4.1$ to $+3.7$	Metaluminous to weakly peraluminous sub-alkaline, calc-alkaline type granites ?	Deformation and greenschist metamorphism related to RAO and reworked Sunsás Orogeny (SO)	1.44–1.38	Juvenile character related to RAO	Generated in volcanic arc type, orogenic arc related to RAO
	Mafic–ultramafic Intrusive Suite				Greenschist to low-amphibolite facies metamorphism. Deformation related to RAO (1.48 - 1.46 Ga) reworked at SO (1.0 - 0.9 Ga)	1.51–1.49	Generated in Middle Ocean Ridge	
	Rio Alegre Volcanic-Sedimentary Unit	Metavolcanics meta-sedimentary rocks $T_{DM} = 1.54$ Ga $\varepsilon_{Nd(t)} = +4.8$ to $+4.3$	?	Greenschist to low-amphibolite facies metamorphism. Deformation related to RAO (1.48 - 1.46 Ga) reworked at SO (1.0 - 0.9 Ga)	1.51	Generated in Middle Ocean Ridge		
Jauru Terrane	<i>Santa Helena Orogen (SHO)</i>							
	Rio Branco Intrusive Suite	Anorogenic	Gabbro, diabase, basalts granites. $T_{DM} = 1.89$ – 1.73 Ga $\varepsilon_{Nd(t)} = +1.9$ to -1.0	A-type syenitic to granitic	Undeformed	1.47–1.42	Intracontinental magmatism. Intra-plate setting, related to the SHO	
	Pindaituba Intrusive Suite	Late to post-kinematic granitoids	Bt – monzogranite. $T_{DM} = \sim 1.8$ to 1.7 Ga $\varepsilon_{Nd(t)} = +8$ to $+0.0$	Peraluminous to weakly metaluminous sub-alkaline, calc-alkaline	Deformation and greenschist-to low-amphibolite facies metamorphism are related to SHO	1.48–1.42	Juvenile character related to SHO	Generated in a continental, Andean-type, orogenic arc related to SHO. Continental margin calc-alkaline arc
	Santa Helena and Água Clara intrusive suites	Syn- to late-kinematic granitoids	Bt-syenogranite Bt-monzogranite, Hbl-Bt granodiorite. $T_{DM} = 1.8$ – 1.5 Ga. $\varepsilon_{Nd(t)} = +4.0$ to $+1.7$				Different magma sources. Juvenile/ crustal sources Partial melting of lower crust	
	<i>Cachoeirinha Orogen (CO)</i>							
	Alvorada Intrusive Suite	Late to post-kinematic granitoids	Bt-monzogranite. $T_{DM} = 1.8$ to 1.7 Ga. $\varepsilon_{Nd(t)} = +2.25$ to -1.3	Peraluminous to weakly meta luminous sub-alkaline, calc-alkaline	Deformation and greenschist-to low-amphibolite facies metamorphism are related to CO	1.56–1.52	Juvenile character related to CO	Generated in a continental, Andean-type, orogenic arc related to CO. Continental margin calc-alkaline arc
	Santa Cruz Intrusive Suite	Syn- to late-kinematic granitoids	Bt-syenogranite, Bt-monzogranite, Hbl-Bt granodiorite. $T_{DM} = 1.8$ – 1.9 Ga. $\varepsilon_{Nd(t)} = +1.0$ to -0.9				Different magma sources. Juvenile/ crustal sources. Partial melting of lower crust	
	<i>Basement rocks (>1720 Ma)</i>							
	Cabaçal Tonalite	Tonalitic gneiss			Amphibolite facies metamorphism	1.78?		
	Alto Guaporé Metamorphic Complex	Tonalitic to monzogranite orthogneiss $T_{DM} = 2.0$ to 1.8 Ga. $\varepsilon_{Nd(t)} = +2.4$ to -0.8	Peraluminous to metaluminous sub-alkaline,calc-alkaline	Upper amphibolite to greenschist facies (1.7 Ga). High P_{TOT} > PH_2O . Partial remelting	1.7 6–1.7 2	Generated in a oceanic, arc island-type orogen.		
Figueira Branca Intrusive Suite	Metagabbros, metapyroxenites, serpentinites. $T_{DM} = 1.78$ Ga. $\varepsilon_{Nd(t)} = +3.68$		Upper amphibolite		?			
Alto Jauru Group	Quartzites, pelitic schist, metavolcanics: metabasalts, metandesites, acid-tuffsm, BIF and chert. $T_{DM} = 1.93$ to 1.85 Ga. $\varepsilon_{Nd(t)} = +2.6$ to $+2.2$	?	Upper amphibolite to greenschist retrogression. Peak- metamorphism at 1.7 Ga. Partial remelting	1.76–1.72	Generated in a oceanic, arc island-type orogen.			

References: Barros et al. (1982), Carneiro (1985), Matos (1994), Matos et al. (2004), Monteiro et al. (1986), Pinho (1996), Saes (1999), Geraldes (2000), Geraldes et al. (2001), Tassinari et al. (2000), Geraldes et al. (2004a), Ruiz (2005), Araújo (2008) and Sousa et al. (2009). Mineral abbreviations after Kretz (1983).

is covered on the north and south by Mesozoic–Cenozoic sedimentary sequences and is bounded to the east and west by the Alto Jauru Group (Ruiz, 2005) (Fig. 3). Included in the orogen are tonalite, granodiorite, granite and gneissic migmatite formed during magmatic and metamorphic events between 1.56 and 1.52 Ga (Geraldes et al., 2001; Paulo, 2005; Ruiz, 2005; Araújo, 2008) (Table 2). These events also overprinted precursor lithotectonic units of the Jauru Terrane. Peak metamorphism during the Cachoeirinha Orogeny reached amphibolite facies, but has largely retrogressed to greenschist facies (Ruiz, 1992; Sousa et al., 2009).

According to Geraldes et al. (2001), Ruiz et al. (2004) and Araújo (2008), the Cachoeirinha Orogen evolved through two magmatic stages. A syn-kinematic stage is represented by the Santa Cruz Intrusive Suite and a late-kinematic stage by the Alvorada Intrusive Suite.

3.2.2.1. The Santa Cruz Intrusive Suite. The Santa Cruz Intrusive Suite is a foliated NNW-trending, multiphased batholith (Ruiz et al., 2004; Ruiz, 2005; Araújo, 2008). The batholith has three distinct facies: (1) pink to red medium- to coarse-grained equigranular syenogranite through monzogranite (2) grayish to pink porphyritic monzogranite, and (3) dark to light-gray inequigranular or medium- to coarse-grained porphyritic granodiorite. The geochemical data suggest that the suite is peraluminous and calc-alkaline in character. U–Pb zircon magmatic ages for these granitoids vary from 1.56 to 1.52 Ga. Nd T_{DM} model ages of 1.9–1.8 Ga, and $\epsilon_{Nd(t)}$ values of +0.9 to +1.0 indicate that the protolith material has both crustal and mantle components (Geraldes et al. 2001; Ruiz, 2005). Ar–Ar and K–Ar isotopic ages for the same suite varying from 1.53 to 1.52 Ga (Carneiro, 1985; Paulo, 2005), suggest that regional cooling is related to the orogenic metamorphism. The orogen might be considered as the roots of a continental-margin arc built upon the Jauru Terrane (Geraldes et al., 2001; Ruiz et al., 2004; Ruiz, 2005; Araújo, 2008; Sousa et al., 2009).

3.2.2.2. The Alvorada Intrusive Suite. This suite, firstly described by Monteiro et al. (1986) and Ruiz (1992) consists of rounded to elliptical shaped granitic plutons composed of light-gray to pink colored medium- to fine-grained isotropic monzogranitic bodies, which are occasionally foliated. Geraldes et al. (2001), Ruiz et al. (2004) and Araújo (2008) reported U–Pb zircon magmatic ages for these granitoids varying from 1.53 to 1.44 Ga, and Nd isotopic data (Nd T_{DM} model ages of 1.8–1.7 Ga and $\epsilon_{Nd(t)}$ between +0.5 and –1.3) suggest a mixing of juvenile mantle derived magmas with recycled older material. The metaluminous to peraluminous, sub-alkaline, calc-alkaline geochemical and isotopic signatures of the suite are typical for volcanic arc granitoids (Ruiz, 2005; Araújo, 2008; Sousa et al., 2009).

3.2.3. The Santa Helena Orogen (1.48–1.42 Ga)

Basement rocks mainly of granitic composition were included in the Santa Helena batholith (Saes et al., 1984). Later on Geraldes et al. (1997) and Van Schmus et al. (1998) proposed the term Santa Helena Suite (1.48–1.42 Ga), comprising igneous and meta-igneous rocks, represented by tonalite, orthogneiss, and granite, forming a calc-alkaline arc-related suite. Tassinari et al. (2000) upgraded the Santa Helena Suite to orogen status. The Santa Helena Orogen is bordered to the west by the Rio Alegre Terrane (Piratininga Shear Zone), to the east by Alto Jauru Group, and to the north and south it is covered by Mesozoic–Cenozoic sedimentary sequences (Fig. 3).

The Santa Helena Orogen is herein interpreted as an accretionary orogen, resulted from the development of a continental magmatic arc during the Santa Helena Orogeny. The orogen encompasses the syn-kinematic intrusions of the Santa Helena and Água Clara intrusive suites (1.48–1.42 Ga) and Pindaiatuba Intrusive Suite (1.46–1.42 Ga), as well as the post-kinematic or

anorogenic rapakivi granites and associated mafic rocks included in the Rio Branco Intrusive Suite (1.42 Ga) (Geraldes et al., 2001, 2004; Ruiz, 2005; Araújo, 2008) (Table 2).

3.2.3.1. The Água Clara Intrusive Suite. The suite is represented by a batholith (Fig. 3), which comprises two petrographic facies: the dominant one is made up of gray-foliated medium- to coarse-grained equigranular granodiorite and the other subordinated facies comprises gray-foliated porphyritic granodiorite and monzogranites (Ruiz, 2005). Geraldes et al. (2001) provide an estimate for the timing of magmatic activity at 1.48 Ga, and Nd T_{DM} model age of 1.8 Ga and $\epsilon_{Nd(t)}$ of +1.7 suggest an important juvenile source for the batholith. The geochemical data show that the granitoids are sub-alkaline, metaluminous to weakly peraluminous, and plot in the calc-alkaline field, reflecting a magmatic arc setting (Ruiz, 2005).

3.2.3.2. The Santa Helena Intrusive Suite. The Santa Helena Intrusive Suite consists of a batholith, which straddles the NNW trend and encompasses four principal strongly foliated petrographic facies associations, which are syenogranite and monzogranite in composition (Ruiz, 2005) (Fig. 3; Table 2). Geraldes et al. (2001) presented U–Pb zircon magmatic ages for the batholith in the range of 1.46–1.42 Ga. The Nd T_{DM} model ages ranging from 1.5 to 1.6 Ga and the $\epsilon_{Nd(t)}$ values between +2.7 and +4.0, indicate a largely juvenile signature (Geraldes et al., 2001). Overall, the magmatism is sub-alkaline and of calc-alkaline chemistry and I-type characteristics. The less evolved Santa Helena granitoid facies is slightly metaluminous and the most fractionated are weakly peraluminous, which indicate crustal contamination (Geraldes et al., 2001). On tectonic classification diagrams, the rocks define distinct fractionation trends and plot from the field of intra-plate granites to the volcanic arc granites (Sousa et al., 2009). Ar–Ar biotite and sericite ages for the Santa Helena granites and schists vary from 0.91 to 0.89 Ga and are interpreted to reflect the regional Sunsás reactivation (Paulo, 2005; Tohver et al., 2006).

3.2.3.3. The Pindaiatuba Intrusive Suite. The suite, consisting of several granitoid batholiths, plutons and stocks, is controlled by first order N30–50°W trending regional fault-zones (Fig. 3). The components of the suite are foliated or occasional mylonitic granitoids and compositionally they range from tonalite to syenogranite. U–Pb zircon yielded crystallization ages varying from 1.46 to 1.42 Ga (Table 2). The Nd T_{DM} model ages are in the range of 1.7 to 1.8 Ga, whereas $\epsilon_{Nd(t)}$ values vary from +0.03 to +2.33, indicating that the original magma was derived largely from juvenile sources. Geochemical results indicate that the Pindaiatuba Intrusive Suite is metaluminous to peraluminous, medium to high-K calc-alkaline tonalite and syenogranite, and the tectono-chemical diagrams show that the granitoids plot within the volcanic arc granites field (Ruiz, 2005).

The Ar–Ar ages by Ruiz (2005) suggest four cooling events: (1) 1.45 Ga biotite age from granodiorite; (2) 1.02 Ga biotite ages in mylonites that crosscut granodiorite; (3) 1.02–1.01 Ga biotite ages from foliated granites; and (4) 0.95–0.94 Ga biotite ages for granite bodies exhibiting tectonic foliation and mylonitization. The 1.45 Ga biotite ages record the timing of cooling of the granodiorite body. The 1.02 Ga from mylonites and foliated granites record the timing of regional deformation and regional metamorphic cooling, respectively. The 0.95–0.94 Ga biotite ages from granite record the age of penetrative foliation related to the Sunsás Orogeny, and perhaps from the thermal effects due to younger Sunsás granite intrusions.

3.2.3.4. The Rio Branco Intrusive Suite. Rock units of the Rio Branco Intrusive Suite intrude volcanic–plutonic rocks of the Alto Jauru

Terrane (Fig. 3) and are considered as part of a bimodal rapakivi igneous association by [Geraldes et al. \(1999, 2004a\)](#). The mafic member comprises gabbro, tholeiitic diabase dykes and porphyritic basalt, which show U–Pb zircon crystallization age of 1471 ± 8 Ma, Nd T_{DM} model ages varying from 1.80 to 1.73 Ga, and $\varepsilon_{Nd(t)}$ ranges from +1.9 to +1.2, suggesting a mantle source and crustal rock contributions ([Geraldes et al., 2004a](#)). The felsic members are mostly composed of red to pink granite rocks of syenitic to granitic composition which yielded U–Pb zircon age of 1427 ± 10 Ma, Nd T_{DM} model ages range of 1.89–1.81 Ga, and $\varepsilon_{Nd(t)}$ values varying from +0.2 to –1.0, indicating an older crustal contribution in their source. The granites exhibit geochemical characteristics of A-type granite and are interpreted to have formed in an intra-plate setting ([Geraldes et al., 2004a](#)).

3.2.3.5. Deformation and Metamorphism. The Paleoproterozoic basement exhibits compressive polyphase deformation pattern. The main structural elements comprise of refolded NEE–NNW trending gneissic compositional banding and NNW striking mylonitic zones, which show mass transport from NE towards SW. The metamorphism reached high-amphibole facies, but has retrogressed to greenschist facies conditions. Granitoid rocks from the Cachoeirinha Orogen show a N30–40°W/60–70°SE trending penetrative foliation associated with shear zones characterized by a transpressive mass transport towards SW. The Santa Helena Orogen is deeply affected by the Sunsás Orogeny (1.25–1.00 Ga) resulting in a N30–40°W trending foliation parallel to the Aguapeí Belt (Indiavaí–Lucialva and Piratininga shear zones), and resetting the Ar–Ar system at 1.0 Ga ([Ruiz, 2005](#)).

3.3. The Rio Alegre Terrane (1.51–1.38 Ga)

The Rio Alegre Terrane was first defined as a suture zone by [Saes and Fragoso Cesar \(1996\)](#), coined as Rio Alegre Terrane by [Saes \(1999\)](#) or Rio Alegre Orogen by [Matos et al. \(2004\)](#). The terrane is bounded to the east by the Jauru Terrane (Piratininga shear zone) and to the west by the Paraguá Terrane (Santa Rita shear zone) and deformed sediments of the Aguapeí Group (1.17–1.15 Ga). The northern and southern extensions are unknown ([Matos et al., 2004](#)), providing that the terrane is covered by Cenozoic sedimentary sequences (Fig. 1). The main geological features and geodynamic significance of the Rio Alegre Terrane are described in detail by [Matos et al. \(2004\)](#) and [Ruiz \(2005\)](#). This accretionary orogen comprises three units: Rio Alegre Volcanic–Sedimentary Unit, Mafic–ultramafic Intrusive Suite, and Santa Rita Intrusive Suite (Fig. 3, Table 2).

3.3.1. Lithologic units

The Rio Alegre Volcanic–Sedimentary Unit comprises mafic and ultramafic volcanic rocks, chemical and clastic sedimentary rocks, metamorphosed at greenschist to low-amphibolite facies. It has been subdivided by [Matos \(1994\)](#) and [Matos et al. \(2004\)](#) into three sub-units, as follows:

- The Basal Minouro Formation* consists of abundant basic to ultrabasic volcanic rocks (basic metavolcanic and subvolcanic rocks, fine-grained metabasalts and diabbases), all associated with fine-grained banded iron formations (with magnetite-bearing layers), chemical sediments, chert and clastic rocks. The geochemical data indicate an ocean floor tectonic setting for these rocks ([Matos et al., 2004](#)).
- The Intermediate Santa Isabel Formation* comprises intermediate and acid lavas and pyroclastic rocks, represented by metadacite, metarhyolite and associated meta-pyroclastic rocks. Two samples of metadacite yield U–Pb zircon ages of 1509 ± 10 Ma and 1503 ± 14 Ma, Nd T_{DM} model ages of ca.

1.54 Ga, $\varepsilon_{Nd(t)}$ values of +4.3 and +4.8, respectively ([Geraldes et al., 2000](#); [Matos et al., 2004](#)).

- The São Fabiano Formation* comprises clastic, chemical and volcanoclastic meta-sedimentary rocks represented by phyllites, quartzites, carbonaceous layers, garnet-kyanite-muscovite-biotite schists, metacherts and banded iron formations.

The Mafic–ultramafic Intrusive Suite crops out for hundreds of kilometers to the NNW, and comprises mesocratic to melanocratic coarse to very coarse-grained cumulate metaperidotite, metaharzburgite, metaleucogabbros, metagabbros and serpentinites, which are derived from metamorphosed dunite, peridotite and harzburgite. In U–Pb zircon data, these rocks yield ages ranging from 1509 ± 10 to 1494 ± 11 Ma, Nd T_{DM} model ages of ca. 1.67 Ga, and $\varepsilon_{Nd(t)}$ values of +4.5 to +2.5 ([Matos et al., 2004](#)).

The Santa Rita Suite Intrusive Suite comprises tonalite and granites, intruded at the Rio Alegre Volcanic–Sedimentary Unit and Mafic–ultramafic Intrusive Suite, and metamorphosed at greenschist to amphibolite facies. U–Pb zircon ages of these rocks vary from 1444 ± 15 to 1384 ± 40 Ma, Nd T_{DM} model ages values are in the range of 1.52–1.49 Ga, and $\varepsilon_{Nd(t)}$ values vary from +3.7 to +3.6 ([Matos et al., 2004](#); [Ruiz, 2005](#)).

The lithologic association, geochemical and isotopic data suggest that the Rio Alegre Volcanic–Sedimentary Unit and Mafic–ultramafic Intrusive Suite (1.51–1.49 Ga) were originated in mid-oceanic ridge setting, and the Santa Rita Intrusive Suite was formed in an oceanic island arc setting (1.44–1.38 Ga) ([Matos et al., 2004](#); [Ruiz, 2005](#)).

3.3.2. Deformation and metamorphism

The NNW-trending Piratininga and Santa Rita mylonitic shear zones constitute the main tectonic features observed in the Rio Alegre Terrane, and are related to the Sunsás Orogeny as demonstrated by Ar–Ar muscovite age (0.9 Ga). However, the Rio Alegre metavolcanic–sedimentary unit shows a polyphase deformation pattern represented by gneissose banding and/or schistosity (S_1) refolding phases related to Rio Alegre Orogeny. The structural elements indicate a tectonic sense of vergence towards N30–50°W, under greenschist facies metamorphic conditions ([Ruiz, 2005](#)).

The São Fabiano Formation consists of a sequence of low-greenschist metamorphic facies compatible with the chlorite zone. The mafic–ultramafic intrusive rocks underwent low-grade metamorphism, expressed by medium-grade greenschist facies conditions (biotite zone); transition to the high-greenschist facies metamorphic conditions (garnet zone) occur in some area ([Matos et al., 2004](#)). The deformation pattern is polyphase and the structural elements indicate a northeastward transport ([Matos et al., 2004](#)).

Metamorphism under greenschist to lower-amphibolite facies and deformation are apparently associated with soft-accretion of an oceanic island arc to the proto-Amazonian Craton during the mesoproterozoic ([Geraldes et al., 2006](#)). The Ar–Ar amphibole ages of 1.41–1.38 Ga and Ar–Ar biotite ages ca. 1.32 Ga ([Paulo, 2005](#); [Tohver et al., 2006](#)) are interpreted by [Geraldes et al. \(2006\)](#) as metamorphic cooling of the Rio Alegre Orogen. However, in our opinion, the Ar–Ar ages of ca 1.32 Ga are related to the Rondonian–San Ignacio collision orogeny (1.34–1.32 Ga).

3.4. The RSIP in Rondônia

The RSIP in the Rondônia region includes geological units with ages varying from 1500 to 1300 Ma. Some of them are grouped into a major tectonic unit, the Alto Guaporé Belt ([Quadros and Rizzotto, 2007](#)). The spatial and temporal distributions of these units are shown in Fig. 4, and the main geological characteristics are summarized in Table 3.

Fig. 4. Simplified geologic–tectonic map of Rondônia region and eastern Bolivia, showing the approximate boundary of the main provinces, major tectonic features, lithologic units, and compiled thermochronologic age data (modified from Litherland et al. (1986), Rizzotto et al. (2004), Quadros and Rizzotto (2007)).

Table 3
Summary of the main geological and geochronological features of the Rondônia region (RSIP northern sector).

Geological unit	Lithological association	U–Pb age (Ma)	⁴⁰ Ar/ ³⁹ Ar age (Ma)	Tectonic setting	Reference
Rondonian-San ignacio Province (1500–1300 Ma)					
<i>Late- to post-tectonic suite</i> São Lourenço-Caripunas Intrusive Suite	Alkali-feldspar granite, syenogranite, quartz-syenite, and rhyolite porphyry. The granites show petrographic and geochemical characteristics of rapakivi granites	1314–1309		Post-tectonic magmatism related to the collisional stage of the Rondonian-San Ignacio orogeny	Bettencourt et al. (1997, 1999)
Alto Candeias Intrusive Suite	Monzogranite, syenogranite, charnockite, and syenite. The granites show petrographic and geochemical characteristics of rapakivi granites	1346–1338		Late-tectonic magmatism related to the collisional stage of the Rondonian-San Ignacio orogeny	Bettencourt et al. (1997, 1999)
<i>Alto Guaporé belt</i> Alto Escondido Intrusive Suite	Monzogranite and syenogranite. The granites show petrographic and geochemical characteristics of calc-alkaline and post-collisional granites. (T) = +2.0	1336	(1312-Hbl)	Magmatism related to the collisional stage of the Rondonian-San Ignacio orogeny.	Quadros and Rizzotto, 2007; Rizzotto and Quadros, 2007
Igarapé Enganado Intrusive Suite	Syenogranite, monzogranite, and granodiorite; rare tonalite, gabbro and hybrid rocks. The granites exhibit petrographic and geochemical characteristics of calc-alkaline granites. $\epsilon_{\text{Nd}(t)}$ = +2.8	1340		Syn- to late-tectonic magmatism related to the collisional stage of the Rondonian-San Ignacio orogeny	Quadros and Rizzotto (2007), Rizzotto and Quadros (2007), Santos et al. (2008), Tassinari et al. (1999)
Serra do Colorado Intrusive Suite	Anorthosite, hornblende, and serpentinite. The rocks show geochemical characteristics of N-MORB and OAB. $\epsilon_{\text{Nd}(t)}$ = +2.7. $\epsilon_{\text{Sr}(t)}$ = –17.1	1352		Intra-oceanic arc	Quadros and Rizzotto (2007), Rizzotto and Quadros (2007), Rizzotto et al. (2002), Teixeira et al. (2006)
Nova Mamoré Metamorphic Suite	Paragneiss, calc-silicate gneiss, pelitic schist, and granofels	<1532 (1330–1345-Zrn)		Deep oceanic basin (passive margin)	Quadros and Rizzotto (2007), Rizzotto and Quadros (2007), Santos et al. (2008), Tassinari et al. (1999)
Colorado Complex	BIF, calc-silicate gneiss, paragneiss, para-amphibolite, and pelitic schist	< 1420 (1340-Zrn)			
Trincheira Mafic-ultramafic Complex	Metagabbro, amphibolitic gneiss, metapyroxenite, metabasalt, and serpentinite. The rocks show geochemical characteristics of N-MORB basalts	(?)	(1319-Hbl)	Oceanic crust	Quadros and Rizzotto (2007), Rizzotto and Quadros (2007), Santos et al. (2008)
<i>Anorogenic Suite</i> Teotônio Intrusive Suite	Alkali-feldspar granite, quartz-alkali-feldspar syenite, and minor syenogranite, quartz-syenite, monzogranite, diorite, monzodiorite, and monzonite. The granites show geochemical characteristics of A-type and intra-plate granites	1387		Anorogenic magmatism in the Rio Negro-Juruena crust temporally related to the early stage of the Rondonian-San Ignacio orogeny	Bettencourt et al. (1999), Payolla (1994)
Santo Antonio Intrusive Suite	Monzonite, syenogranite, quartz monzonite, hybrid rock, and diabase. The granites show geochemical characteristics of A-type and intra-plate granites	1400–1358			
Rio Crespo Intrusive Suite	Fine-grained granitic gneiss and charnockitic granulite. The rocks exhibit geochemical features of A-type and intra-plate granites. $\epsilon_{\text{Nd}(t)}$ = +1.0 to +1.8	1500 (1351–1331-Zrn) (1331-Mnz)		Anorogenic magmatism in the Rio Negro-Juruena crust	Bettencourt et al. (2006), Payolla et al. (2001, 2002), Souza et al. (2006)
Rio Negro-Juruena Province (1780–1550 Ma)					
São Pedro and São Romão intrusive suites, Jamari Complex, Roosevelt Group, Mutum-Parana Formation, Igarapé Lourdes Formation, Quatro Cachoeira Suite, Serra da Providência Intrusive Suite	Monzogranite and granodiorite, tonalitic and dioritic gneiss, volcano-sedimentary sequences, sedimentary sequence, and bimodal plutonism	1780–1550, (1348–1321-Zrn), (1339–1334-Mnz), (1332–1330-Ttn)	(1367–1309-Hbl)	Accretionary belts, volcano-sedimentary and sedimentary covers, anorogenic magmatism	Cordani and Teixeira, 2007, Quadros and Rizzotto (2007), Payolla et al. (2002), Rizzotto and Quadros (2007), Santos et al. (2008), Silva et al. (2002), Scandolara (2006), Tohver et al. (2005)

Note: Mineral abbreviations after Kretz (1983).

The controversial boundary between the RSIP and Rio Negro-Juruena Province was earlier inferred based on Rb–Sr and K–Ar ages (Cordani et al., 1979; Teixeira et al., 1989). This, plus further Tassinari et al. (1996) U–Pb zircon ages, and more recently Ar–Ar ages, led Cordani and Teixeira (2007) to re-evaluate this contact. It is postulated a new inferred boundary, which is not a structural but rather is based on the spatial distribution of the RSIP geological units, K–Ar, Ar–Ar and U–Pb thermal imprints (Figs. 1 and 4).

3.4.1. Anorogenic suites

3.4.1.1. Rio Crespo Intrusive Suite. In the Rondônia region the Rio Crespo Intrusive Suite (ca. 1500 Ma; Bettencourt et al., 2006) is the oldest recognized geologic unit of the RSIP. This unit forms an elongated E–W area across the central Rondônia. The eastern and western extensions of the unit are poorly known (Fig. 4).

The Rio Crespo Intrusive Suite (Payolla et al., 2001) is represented by pink or greenish, fine- to medium-grained, quartz-feldspathic banded gneisses showing medium- to high-grade metamorphic facies. Banding is defined by alternating quartz + plagioclase + K-feldspar layers and hornblende + magnetite + titanite + epidote ± garnet ± orthopyroxene ± clinopyroxene discontinuous layers and enhanced by concordant, locally folded granitic veins. Metacharnockite (ca. 1.56 Ga) and mafic granulite (ca. 1.73 Ga) xenoliths support an intrusive origin for the protolith of the fine-grained gneisses and granulites. Preliminary geochemical data indicate that these rocks are characterized by strong iron enrichment, have metaluminous to marginally peraluminous compositions and exhibit a high- to ultra high-K signature (Payolla et al., 2002). Their trace element contents are comparable to the Phanerozoic A-type and intra-plate granites. The positive $\varepsilon_{\text{Nd}(t)}$ (+1.0 and +1.8) and the narrow range of Nd T_{DM} model ages (1.73–1.75 Ga) of these rocks suggest that they represent juvenile material with minor older crustal source contributions (Bettencourt et al., 2006).

3.4.1.2. Santo Antônio Intrusive Suite. The Santo Antônio Intrusive Suite (1400–1360 Ma; Bettencourt et al. 1999; Quadros and Rizzotto, 2007), along with the Teotônio Intrusive Suite, form the composite Santo Antônio batholith in the northern part of Rondônia (Fig. 4). This batholith covers an area of ca. 2000 km², but its true dimension is unknown because the northern domain is overlain by Phanerozoic continental sediments of the Amazon basin.

The Santo Antônio Intrusive Suite is composed of two main granitic types. These are seriate to locally porphyritic biotite monzogranite and syenogranite, and equigranular biotite monzogranite. Some distinctive rock types of smaller areal extent include fine-grained hornblende-biotite quartz monzonite, dyke-like bodies of hybrid rocks (monzogranite, quartz monzonite, and quartz monzodiorite) and syn-plutonic diabase dykes. The granites are sub-alkaline and slightly peraluminous rocks showing high Fe/Mg, K, F, Rb, Ga, Nb, Zr, and REE, as well as low Ca, Mg, P, and Sr, being similar to Phanerozoic intra-plate and A-type (A2 group) granites (Payolla, 1994; Bettencourt et al., 1997).

3.4.1.3. Teotônio Intrusive Suite. The Teotônio Intrusive Suite (ca. 1387 Ma; Bettencourt et al. 1999) apparently forms a minor part of the Santo Antônio batholith at the present level of erosion (Fig. 4). The rocks of this suite were described by Payolla (1994) in the Teotônio cataract area. Major units are massive coarse-grained alkali-feldspar granite, banded medium-grained alkali-feldspar granite and pink coarse- to medium-grained quartz alkali-feldspar syenite with less common alkali-feldspar granite and syenogranite. Sparse fayalite-clinopyroxene alkali-feldspar syenite dykes and syn-plutonic diorite, monzodiorite and monzonite dykes cut the granites and syenogranites. Fine-grained syenogranite and monzogranite dykes cut the early rocks. The

syenite and granites are metaluminous, and define an alkaline silica-oversaturated series with high Fe/(Fe + Mg). The granites show geochemical characteristics of Phanerozoic intra-plate and A-type (A1 group) granites (Payolla, 1994; Bettencourt et al., 1997).

3.4.2. The Alto Guaporé Belt

The Alto Guaporé Belt is a WNW–ESE trending area (ca. 500 × 100 km), in the southern and southeastern Rondônia region. The northern boundary is the Pacaás Novos basin, Alto Candeias Intrusive Suite, Nova Brasilândia Terrane and Rio Negro-Juruena Province. To the south and east the boundaries are poorly known, providing that the limits are overlain by Phanerozoic sedimentary sequences (Fig. 1). Herein the belt is characterized as an accretionary orogen comprising at least six units (Fig. 4, Table 3): Trinchiera Mafic–ultramafic Complex, Colorado Complex, Nova Mamoré Metamorphic Suite, Serra do Colorado Intrusive Suite, Igarapé Enganado Intrusive Suite and Alto Escondido Intrusive Suite.

3.4.2.1. Trinchiera Mafic–ultramafic Complex. The Trinchiera Mafic–ultramafic Complex (unknown age) consists mostly of banded amphibolite, metagabbro, amphibolitic gneiss, metapyroxenite, metabasalt, and serpentinite. Preliminary geochemical data suggest that the amphibolites and metagabbros show geochemical characteristics of N-MORB (Rizzotto and Quadros, 2007) although some samples exhibit composition ranges of Nd and Sr isotopes ($\varepsilon_{\text{Nd}(t)}$ = +4.1 and +5.2; and $\varepsilon_{\text{Sr}(t)}$ = –5.0 and –30.7), and trace element geochemistry of oceanic arc basalts (Girardi et al., 2008).

3.4.2.2. Colorado Complex. The Colorado Complex is a meta-sedimentary sequence, and is composed of paragneiss, pelitic schist, calc-silicate gneiss, para-amphibolite, and BIF. The protolith of paragneiss and pelitic schist is interpreted as a turbiditic sequence deposited in a passive margin basin (Quadros and Rizzotto, 2007). U–Pb zircon ages of 1420 Ma (detrital zircon) and of 1340 Ma (metamorphic zircon) bracket deposition of the original sedimentary protolith of the paragneiss. The main detrital zircon age group (ca. 1508 ± 13 Ma) shows that the clastic-wedge sediment was predominantly recycled from the Rio Crespo Intrusive Suite (ca. 1.50 Ma), and two other subordinate zircon age groups (ca. 1938 and 1645 Ma) indicate a Paleoproterozoic crust provenance (Rizzotto and Quadros, 2007).

3.4.2.3. Nova Mamoré Metamorphic Suite. The Nova Mamoré Metamorphic Suite was first described in the western side of Rondônia as Nova Mamoré Complex (Quadros and Rizzotto, 2007). However, in our opinion, mainly based on field geological mapping, is that the lithotypes are of restricted occurrence and constitute scattered rock remnants along the Rio Crespo Intrusive Suite. The suite is a meta-sedimentary sequence and shows geological similarities to the Colorado Complex. It is composed of migmatitic paragneiss (pelitic and psamitic gneisses), calc-silicate gneiss and granofels, quartz-feldspathic granofels, and pelitic schist. The protolith of the paragneiss and pelitic schist is interpreted to be a turbiditic sequence deposited on a passive margin basin (Quadros and Rizzotto, 2007). U–Pb detrital zircon ages vary between 2030 and 1532 Ma, and metamorphic zircons yield an age of 1345 Ma. The timing of the deposition of the sedimentary protolith is between 1532 and 1345 Ma (Rizzotto and Quadros, 2007).

3.4.2.4. Serra do Colorado Intrusive Suite. The Serra do Colorado Intrusive Suite comprises layered mafic–ultramafic complexes, which are intrusive in the Trinchiera and Colorado complexes. The suite is made of metagabbro, metagabbro-norite, anorthosite, hornblende, and serpentinite (Quadros and Rizzotto, 2007; Rizzotto and Quadros, 2007). A sample of metagabbro yields a crystallization age of 1352 Ma, and shows geochemical and radiogenic

isotope ($\varepsilon_{\text{Nd}(t)} = +2.1$ and $\varepsilon_{\text{Sr}(t)} = -17.1$) features of N-MORB and OAB (Rizzotto et al., 2002; Teixeira et al., 2006; Girardi et al., 2008).

3.4.2.5. Igarapé Enganado Intrusive Suite. The Igarapé Enganado Intrusive Suite includes mainly syenogranite, monzogranite, and granodiorite, together with rare tonalite, gabbro, and hybrid rock. The suite intrudes the supracrustal rocks of the Colorado complex and normally shows magmatic and/or metamorphic foliation (Quadros and Rizzotto, 2007). Foliated monzogranite and syenogranite provide a similar U–Pb zircon crystallization age of 1340 ± 5 Ma (SHRIMP zircon method) and the samples give positive $\varepsilon_{\text{Nd}(t)}$ values of +2.8 and +2.3, respectively (Rizzotto and Quadros, 2007), suggesting a dominant juvenile character of the magmas. The rocks have metaluminous character with high-K calc-alkaline affinities and the granites show trace elements similarities to collisional granites (Rizzotto and Quadros, 2007).

3.4.2.6. Alto Escondido Intrusive Suite. The Alto Escondido Intrusive Suite is composed of monzogranite and syenogranite and is intrusive in the Trinchera and Colorado Complexes as well as in the Igarapé Enganado Intrusive Suite (Quadros and Rizzotto, 2007). A syenogranite gives a U–Pb zircon crystallization age of 1336 ± 4 Ma (TIMS method), and positive $\varepsilon_{\text{Nd}(t)}$ value of +2.0 (Rizzotto and Quadros, 2007), suggesting a dominant juvenile character of the magmas. The rocks are marginally peraluminous to metaluminous and exhibit high-K calc-alkaline affinities, with trace elements similarities to post-collisional granites (Rizzotto and Quadros, 2007).

3.4.3. Late- to post-tectonic suites

3.4.3.1. Alto Candeias Intrusive Suite. The Alto Candeias Intrusive Suite is largely composed of coarse- to medium-grained porphyritic granites and pyterlites, with lesser amounts of porphyritic charnockites, medium- to fine-grained equigranular granite and syenite (Bettencourt et al., 1997). Three samples of the granites provide intrusion ages between 1346 and 1338 Ma (Bettencourt et al., 1999; Santos et al., 2008). The granites are sub-alkaline, metaluminous, and show geochemical characteristic of Phanerozoic intra-plate and A-type granites (Bettencourt et al., 1997).

3.4.3.2. São Lourenço-Caripunas Intrusive Suite. The São Lourenço-Caripunas Intrusive Suite consists of normal rapakivi granite varieties, such as pyterlite and minor wiborgite, along with associated porphyritic and equigranular granites and subvolcanic and volcanic felsic rocks (Bettencourt et al., 1997). Two granites and one rhyolite porphyry, analysed by Bettencourt et al. (1999), yield intrusion ages between 1314 and 1309 Ma. The rocks are sub-alkaline, metaluminous to marginally peraluminous, and show strong iron enrichment. They have A-type and intra-plate granite trace element signatures (Bettencourt et al., 1997) and are considered to be a late manifestation of the Rondonian-San Ignacio Orogeny.

3.4.4. Deformation and metamorphism

The basement rocks of the RSIP in Rondônia region are marked by a wide network of sinistral strike-slip displacement shear zones called Ji-Paraná and Rio Formoso-Ariquemes shear zones (Fig. 4) (Scandolaria et al., 1999; Tohver et al., 2004, 2005, 2006; Scandolaria, 2006). According to Scandolaria (2006) these shear zones are developed within the time interval 1.20–1.15 Ga at lower-amphibolite facies metamorphism, and all are related either to the late Rondonian-San Ignacio Orogeny stage or to the opening of the Nova Brasilândia basin. Instead Tohver et al. (2006) report that the basement rocks in Rondônia mostly preserve ages older than 1.3 Ga and, localized isotopic Ar–Ar age resetting at 1.18–1.12 Ga is caused by Grenvillian activation of widespread sinistral strike-slip shear zones. Whether the shear zones were generated during

the Rondonian-San Ignacio Orogeny and, subsequently reactivated at 1.18–1.12 Ga or created during the Sunsás Orogeny remains an open question.

The Rondonian-San Ignacio event (1.34–1.32 Ga) is characterized by metamorphic mineral assemblages and anatexis, which are suggestive of upper-amphibolite to granulite facies metamorphism, and are widely developed in the supracrustal rocks of the Colorado Complex and Nova Mamoré Metamorphic Suite (Quadros and Rizzotto, 2007; Rizzotto and Quadros, 2007). A tectono-metamorphic imprint over rocks of the Rio Crespo Intrusive Suite and the Rio Negro-Juruena Province is reported in the Ji-Paraná and Ariquemes region, mainly based on U–Pb zircon, monazite and titanite ages, as well as Ar–Ar in hornblende, biotite and muscovite ages (Fig. 4, Table 3) (Payolla et al., 2002; Silva et al., 2002; Tohver et al., 2005; Bettencourt et al., 2006; Scandolaria, 2006; Santos et al., 2008). Hornblende and biotite Ar–Ar ages are interpreted to mark cooling as granitic magmatism waned, deformation ceased and stability was achieved. Also the syn- to post-Rondonian-San Ignacio magmatism and regional thermal effects are interpreted to be related to crustal thickening associated with the collision occurred between the Paraguá Block and the Rio Negro-Juruena Province.

3.5. Regional correlations

The Rondonian Province (Teixeira and Tassinari, 1984) and San Ignacio Orogen (Litherland et al., 1986, 1989) have been considered to represent coeval segments of Mesoproterozoic crustal growth along the SW margin of the Amazonian Craton (Teixeira et al., 1989; Tassinari et al., 2000; Cordani and Teixeira, 2007). However, this model is controversial (Tohver et al., 2004; Boger et al., 2005). According to Tohver et al. (2004) the E–W trending Nova Brasilândia Belt marks the limit between the Amazonian and Paraguá cratons, and formed during the late Mesoproterozoic. If true, then correlations in the basement province across the belt, including the RISIP, are not possible. On the other hand, Boger et al. (2005) proposed that the Proterozoic rocks of eastern Bolivia (the Paraguá Craton) evolved in four geologic distinct stages not present in the Rondônia and Mato Grosso regions of western Brazil. They conclude that the Paraguá Craton was allochthonous with respect to the southwestern margin of the Amazonia. The time-space chart of events in the Rondonian-San Ignacio Province in SW Amazonian Craton is shown in Fig. 5.

According to Boger et al. (2005) the San Ignacio Schist Group (SISG), Chiquitania Gneissic Complex (CGC) and the Lomas Manechis Granulitic Complex (LMGC) have no equivalents in SW Mato Grosso and Rondônia. However, detrital zircons suggest that the SIG and CGC may be the temporal equivalents to the Quatro Cachoeiras Suite (Quadros and Rizzotto, 2007) or to the Machadinho paragneisses (Payolla et al., 2002), in the Rondônia region. Moreover the 1657–1677 Ma magmatic and metamorphic events observed by Santos et al. (2000, 2008) and Silva et al. (2002), denote the presence of correlatable LMGC units in Rondônia. Zircon core ages from LMGC (1775–1715 Ma, Boger et al., 2005) and Rio Fortuna orthogneiss (1772–1734 Ma, Santos et al., 2008) are comparable with zircon crystallization ages from rocks of the Jamari Complex (1.76–1.73 Ga) in Rondônia. One magmatic zircon from the LMGC yields an age of 1818 Ma, which suggests an older crust in eastern Bolivia, comparable to the basement ages of the Juruena region in northern Mato Grosso (Santos et al., 2008). These facts suggest that the Paraguá Terrane could be a segment of the Rio Negro-Juruena Province detached at ca. 1.50–1.40 Ga time interval, consistent with the model of Sadowski and Bettencourt (1996).

Currently, no correlatable units of the Cachoeirinha accretionary orogen (1.56–1.52 Ga) in the Jauru Terrane are known in

Fig. 5. Tectono-stratigraphic time-space plot showing the timing of major orogenic events, igneous events, depositional packages, and Nd T_{DM} ranges for the Rondonian-San Ignacio Province. RSIO, Rondonian-San Ignacio Orogeny; RCIS, Rio Crespo Intrusive Suite; NMMS, Nova Mamoré Metamorphic Suite; TIS-SAIS, Teotônio and Santo Antônio intrusive suites; ACIS, Alto Candeias Intrusive Suite; SLCIS, São Lourenço–Caripunas Intrusive Suite; TMUC, Trinchira Mafic–ultramafic Complex; CC, Colorado Complex; SCIS, Serra do Colorado Intrusive Suite; IEIS-AEIS, Igarapé Escondido and Alto Enganado intrusive suites; CO, Cachoeirinha Orogeny; RAO, Rio Alegre Orogeny; SHO, Santa Helena Orogeny; SCIS, Santa Cruz Intrusive Suite; AIS, Alvorada Intrusive Suite; RAV, Rio Alegre Volcanic–Sedimentary Unit; SRIS, Santa Rita Intrusive Suite; SHIS, Santa Helena Intrusive Suite; PIS, Pindaituba Intrusive Suite; RBIS, Rio Branco Intrusive Suite; PGC, Pensamiento Granitoid Complex; SR, San Ramón Granitoids; SIO, San Ignacio Orogeny. Data from Litherland et al. (1986), Tassinari et al. (1999), Bettencourt et al. (1999, 2006), Geraldès et al. (2001), Payolla et al. (2001, 2002), Silva et al. (2002), Matos et al. (2004), Boger et al. (2005), Ruiz (2005), Tohver et al. (2005), Tohver et al. (2006), Scandolaro (2006), Quadros and Rizzotto (2007), Rizzotto and Quadros (2007), Santos et al. (2008), Matos et al. (2009).

Rondônia region, although the rapakivi granites and related rocks of the Serra da Providência Intrusive Suite (1.60–1.53 Ga) have been interpreted as a probable inboard expression of the subduction-related magmatism of the Cachoeirinha Orogeny (Bettencourt et al. 1999; Tassinari et al., 2000; Payolla et al., 2002; Geraldès et al., 2004b). Conversely, we suggest that the Serra da Providência Intrusive Suite is part of the Rio Negro-Juruena Province (Table 3) and related to a tectono-metamorphic event dated at 1670–1630 Ma (Santos et al., 2008). Both proposals deserve further investigation.

The A-type and intra-plate granites of the Rio Crespo Intrusive Suite in Rondônia region (ca. 1500 Ma) have no equivalents in the Jauru and Paraguá terranes (Bettencourt et al., 2006). However, these rocks are age-correlative with intermediate volcanic rocks (1510–1500 Ma) of the Rio Alegre Terrane. Based on these observations, we propose that the initial rifting along the flanks of the Rio Negro-Juruena Province was firstly accompanied by the intrusion of the Rio Crespo Intrusive Suite and followed by the Santo Antônio Intrusive Suite (1400–1360 Ma) and Teotônio Intrusive Suite (ca. 1387 Ma).

The Santa Helena accretionary orogen (1.48–1.42 Ga) is largely represented by the syn-kinematic Santa Helena and Água Clara intrusive suites (1.48–1.42 Ga), the Pindaituba Intrusive Suite (1.46–1.42 Ga), and by the post-kinematic and/or anorogenic, bimodal rapakivi Rio Branco Suite (1.42 Ga) (Geraldès et al., 2001; Geraldès et al., 2004; Ruiz, 2005). San Ramón tonalite (1429 Ma) in the Paraguá Terrane may represent correlative magmatic activity (Santos et al., 2008).

The Pensamiento Granitoid Complex (1373–1340 Ma) is time-correlated with the Igarapé Enganado Intrusive Suite (1340 Ma), Alto Escondido Intrusive Suite (1336 Ma) (Alto Guaporé Belt), as well as with the Alto Candeias Intrusive Suite (1346–1338 Ma). These granitoid rocks exhibit distinct petrographic and geochemical characteristics, which suggest involvement of different tectonic settings and magmas sources for their formation, during the same period of time (1373–1336 Ma). In this context the Pensamiento Granitoid Complex was generated in an Andean-type magmatic arc, the Igarapé Enganado and Alto Escondido intrusives suites were formed in an intra-oceanic arc and the Alto Candeias Intrusive Suite shows intra-plate and A-type granite affinities.

Deformation and high-grade metamorphism are recognized along the extent of the RSIP mainly in the Paraguá Terrane and Rondônia region, more frequently between 1340 and 1320 Ma. Peak metamorphism and partial melting are recorded in the Lomas Manechis Granulitic Complex (1339–1320 Ma) and Chiquitania Gneiss Complex (ca. 1333 Ma) (Paraguá Terrane) (Boger et al., 2005; Santos et al., 2008), and in the Colorado Complex and Nova Mamoré Metamorphic Suite (Alto Guaporé Belt) at ca. 1340 Ma (Tassinari et al., 1999; Payolla et al., 2002; Quadros and Rizzotto, 2007; Rizzotto and Quadros, 2007).

3.6. Tectonic framework

The basement rocks (>1560 Ma) which constitute the continental-margin framework to which all the studied Mesoproterozoic orogen where accreted comprise: the Chiquitania Gneiss Complex

and San Ignacio Schist Group (≥ 1.69 Ga) and the Lomas Manechis Granulitic Complex (1.69–1.66 Ga) in the Paraguá Terrane (Boger et al., 2005); the Alto Jauru Group (1.76–1.72 Ga), Figueira Branca Intrusive Suite, Alto Guaporé Metamorphic Complex (1.8–1.7 Ga) and Cabaçal Tonalite (1.78 Ga) in the Jauru Terrane (Ruiz, 2005) and the Jamari Complex (1.76–1.73 Ga), Mutum Paraná Formation (1.75 Ga), Igarapé Lourdes Formation, Quatro Cachoeiras Suite (≥ 1.60 Ga) and Serra da Providência Intrusive Suite (1.60–1.53 Ga) in the Rio Negro-Juruena Province in Rondônia region (Quadros and Rizzotto, 2007) (Tables 1–3).

The following RSIP tectonic evolution and discussion herein proposed is keyed to Fig. 6 and provide a summary of the chronology of events in the time interval 1.56–1.30 Ga, taking into account the currently geological mapping, petrological and geochemical data, U–Pb TIMS and SHRIMP and Ar–Ar dating. For this purpose we have divided the RSIP into two sectors: northern sector

Fig. 6. Hypothetical simplified cartoon version, showing proposed tectonic evolution of the RSIP (see text for explanation). (A) During the time interval 1560–1320 Ma (southern sector). RNJP, Rio Negro-Juruena Province; SCIS, Santa Cruz Intrusive Suite; AIS, Alvorada Intrusive Suite; ACIS, Água Clara Intrusive Suite; SHIS, Santa Helena Intrusive Suite; PIS, Pindaíatuba Intrusive Suite; CAO, Cachoeirinha Orogen; RBIS, Rio Branco Intrusive Suite; SRIS, Santa Rita Intrusive Suite; SHO, Santa Helena Orogen; PB, Paraguá Block; PGC, Pensamiento Granitoid Complex; RAO, Rio Alegre Orogen; PT, Paraguá Terrane. (B) During the time interval 1500–1300 Ma (northern sector). RNJP(R), Rio Negro-Juruena Province (Reworked); RCIS, Rio Crespo Intrusive Suite; RCIS(R), Rio Crespo Intrusive Suite (reworked); SAIS, Santo Antônio Intrusive Suite; TIS, Teotônio Intrusive Suite; TMUC, Trincheira Mafic-ultramafic Complex; CC, Colorado Complex; NMMS, Nova Mamoré Metamorphic Suite; SCIS, Serra do Colorado Intrusive Suite; IEIS, Igarapé Enganado Intrusive Suite; AEIS, Alto Escondido Intrusive Suite; ACIS, Alto Candeias Intrusive Suite; SLCIS, São Lourenço-Caripunas Intrusive Suite; AGB, Alto Guaporé Belt.

(Fig. 4) and southern sector (Figs. 2 and 3). We envisage the evolution of the RSIP into two distinct evolutionary periods: 1560–1370 and 1370–1300 Ma. The older period is marked by diachronous events, leading to the building of the Cachoeirinha, Santa Helena and Rio Alegre accretionary orogens (southern sector), and rifting and oceanic spreading (northern sector), along the flanks of the Rio Negro-Juruena Province. The second period is synchronous along the entire continental margin, and encompasses subduction of oceanic lithosphere and microcontinent (Paraguá Block) – continent (proto-Amazonian Craton) collision. Based on this analysis, the RSIP is interpreted as a composite orogen or an orogenetic system, comprising an older complex accretionary orogen (1556–1340 Ma), and a terminal microcontinent-continent collision orogen at 1340–1320 Ma.

3.6.1. Cachoeirinha Orogeny (1560–1520 Ma)

The Cachoeirinha accretionary orogen was formed in a convergent continental margin, resulting in a juvenile magmatic arc. This arc results from calc-alkaline magmatism, which is represented by the syn- to late-kinematic Santa Cruz Intrusive Suite and late- to post-kinematic Alvorada Intrusive Suite (Fig. 6a).

3.6.2. Santa Helena Orogeny (1480–1420 Ma)

This orogeny was characterized by the development of the Santa Helena accretionary orogen, considered by [Geraldes et al. \(2001\)](#) and [Ruiz \(2005\)](#), as an Andean-type magmatic arc. This orogen is largely represented by syn-kinematic intrusions, the Santa Helena Intrusive Suite and Água Clara Intrusive Suite (1.44–1.42 Ga), and the Pindaíatuba Intrusive Suite (1.46–1.42 Ga). Post-kinematic and/or anorogenic plutons include the 1.42 Ga rapakivi granites and related mafic rocks of the Rio Branco Intrusive Suite ([Geraldes et al., 2001](#); [Geraldes et al., 2004](#); [Ruiz, 2005](#)) (Fig. 6a).

3.6.3. Rio Alegre Orogeny (1440–1380 Ma)

The development of the Rio Alegre accretionary orogen (1510–1380 Ma) comprises oceanic spreading (1510–1490 Ma), subduction and soft-accretion stages (1440–1380 Ma) ([Saes, 1999](#); [Geraldes, 2000](#); [Matos et al., 2004](#); [Ruiz, 2005](#)). The drift stage is characterized by the Rio Alegre Volcano-Sedimentary Unit and the Mafic-ultramafic Intrusive Suite ([Matos, 1994](#); [Matos et al., 2004](#); [Ruiz, 2005](#)). The orogenic stage (1480–1380 Ma) is recorded by oceanic lithosphere consumption during convergence in a probable intra-oceanic arc environment, accompanied by extensive tholeiitic and I-type calc-alkaline plutons and batholiths represented by the Santa Rita Intrusive Suite (Fig. 6a). Subsequent soft-collision was accompanied by N30–50°W tectonic vergence under greenschist facies conditions ([Ruiz, 2005](#)).

3.6.4. Rondonian-San Ignacio Orogeny (1370–1320 Ma)

Mesoproterozoic events at the time interval between 1500 and 1300 Ma are best recognized in Rondônia and eastern Bolivia and the proposed time sequence is shown in Fig. 6b. The rift stage (1500–1387 Ma) was mainly characterized in Rondônia region by the emplacement of A-type and intra-plate granites and associated rocks of the Rio Crespo, Santo Antônio and Teotônio intrusive suites. The drift stage (<1420 Ma) was dominated by the development of an oceanic crust represented by the Trincheira Mafic-ultramafic Complex and passive marginal basin sedimentary sequences comprising the Colorado Complex and the Nova Mamoré Metamorphic Suite. It is suggested that at this time the Paraguá Block became detached from its Rio Negro-Juruena crustal counterpart.

Herein the orogeny is divided into two stages: (1) the subduction stage (1370–1340 Ma) was marked by the formation of the Pensamiento Granitoid Complex in a continental magmatic arc (1373–1340 Ma; $\varepsilon_{\text{Nd}(t)} = +3.9$ to -3.7) within the Paraguá Block,

and by the formation of the Serra do Colorado Intrusive Suite (1352 Ma; $\varepsilon_{\text{Nd}(t)} = +2.7$; $\varepsilon_{\text{Sr}(t)} = -17.1$), Igarapé Enganado Intrusive Suite and Alto Escondido Intrusive Suite (1340–1336 Ma; $\varepsilon_{\text{Nd}(t)} = +2.8$ and $+2.0$), within an intra-oceanic arc, and (2) the collisional stage (1340–1320 Ma) is characterized by deformation, high-grade metamorphism and partial melting (peak metamorphism), which affected primarily the Lomas Manechis Granulitic Complex, Chiquitania Gneiss Complex, Colorado Complex and Nova Mamoré Metamorphic Suite, that represents the culmination stages of the Rondonian-San Ignacio Orogeny. The Alto Candeias Intrusive Suite (1346–1338 Ma) comprises slightly deformed rapakivi granites and associated rocks, closely related to the collisional process. Post-collisional events are represented by extensive bimodal magmatism of the São Lourenço-Caripunas Intrusive Suite (1314–1309 Ma) in Rondônia.

4. Summary and concluding remarks

The Rondonian-San Ignacio Province (RSIP) was created through the oblique collision of the Paraguá Block and the proto-Amazonian Craton (including Jauru and Rio Alegre terranes) resulting in the formation of the Rondonian-San Ignacio Orogen (1.56–1.30 Ga). The record of the collision is preserved mostly in the Paraguá Terrane (Bolivia and Mato Grosso regions), and in the Alto Guaporé Belt and Rio Negro-Juruena Province (Rondônia region), as the orogen has suffered later collision-related deformation and metamorphism during Sunsás Orogeny (1.25–1.00 Ga). The RSIP appears to be a composite orogen, including complex accretionary orogen and collisional orogen developed during the time interval of 1.56–1.34 Ga and 1.34–1.32 Ga, respectively. The Rondonian-San Ignacio Orogen was formed at the onset of the Rondonian-San Ignacio collisional orogeny (1.34–1.32 Ma), and comprises: (1) the Jauru Terrane (1.76–1.72 Ga) hosts of the Cachoeirinha accretionary orogen (1.56–1.52 Ga) and the Santa Helena accretionary orogen (1.48–1.42 Ga), both developed in an Andean-type magmatic arc (2) the Rio Alegre Terrane that comprises the Rio Alegre accretionary orogen (1.51–1.38 Ga), generated in an intra-oceanic environment (3) the Paraguá Terrane (1.82–1.32 Ga) that comprises the San Ignacio accretionary orogen (1.37–1.34 Ga) hosts of the Andean-type Pensamiento Granitoid Complex, and (4) the Alto Guaporé Belt (<1.42–1.34 Ma) that developed in passive marginal basin and intra-oceanic magmatic arc settings. Cratonization of the province is interpreted to have occurred at 1.30 Ga (Ar–Ar ages) and 1.25 Ga (K–Ar ages).

The main orogenies in the tectonic evolution of the RSIP were:

- (1) Cachoeirinha Orogeny (1.56–1.52 Ga): development of Andean-type Cachoeirinha accretionary orogen over the Rio Negro-Juruena Province, represented by the Santa Cruz and Alvorada Intrusive suites.
- (2) Santa Helena Orogeny (1.48–1.42 Ga): development of Andean-type Santa Helena accretionary orogen, comprising the Santa Helena and Água Clara intrusive suites.
- (3) Rio Alegre Orogeny (1.44–1.38 Ga): generation of the Santa Rita Intrusive Suite.
- (4) Rondonian-San Ignacio Orogeny (1.37–1.32 Ga): development of the San Ignacio accretionary orogen, comprising the Pensamiento Granitoid Complex, the intra-oceanic arc comprising the Serra do Colorado, Igarapé Enganado, and Alto Escondido intrusive suites, and collision of the Paraguá Block with the proto-Amazonian Craton.

However, the tectonic framework observed in the RSIP requires a better exercise of understanding, mainly due to the complex geological evolution and overprints related to the Sunsás Orogeny. The

spatial organization of Sunsás age structures in the SW Amazonian Craton is compatible with a transpressional left-lateral component during collision (Sadowski and Bettencourt, 1996; Teixeira et al., 2010), and extension components responsible for the insertion of the Neoproterozoic basins.

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A review of the tectonic evolution of the Sunsás belt, SW Amazonian Craton

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ABSTRACT

The Sunsás–Aguapeí province (1.20–0.95 Ga), SW Amazonian Craton, is a key area to study the heterogeneous effects of collisional events with Laurentia, which shows evidence of the Grenvillian and Sunsás orogens. The Sunsás orogen, characterized by an allochthonous collisional-type belt (1.11–1.00 Ga), is the youngest and southwesternmost of the events recorded along the cratonic fringe. Its evolution occurred after a period of long quiescence and erosion of the already cratonized provinces (>1.30 Ga), that led to sedimentation of the Sunsás and Vibosi groups in a passive margin setting. The passive margin stage was roughly contemporary with intraplate tectonics that produced the Nova Brasilândia proto-oceanic basin (<1.21 Ga), the reactivation of the Ji–Paraná shear zone network (1.18–1.12 Ga) and a system of aborted rifts that evolved to the Huanchaca–Aguapeí basin (1.17–1.15 Ga). The Sunsás belt is comprised by the metamorphosed Sunsás and Vibosi sequences, the Rincón del Tigre mafic–ultramafic sill and granitic intrusive suites. The latter rocks yield $\varepsilon_{\text{Nd}(t)}$ signatures (−0.5 to −4.5) and geochemistry (S, I, A-types) suggesting their origin associated with a continental arc setting. The Sunsás belt evolution is marked by “tectonic fronts” with sinistral offsets that was active from c. 1.08 to 1.05 Ga, along the southern edge of the Paraguá microcontinent where K/Ar ages (1.27–1.34 Ga) and the Huanchaca–Aguapeí flat-lying cover attest to the earliest tectonic stability at the time of the orogen. The Sunsás dynamics is coeval with inboard crustal shortening, transpression and magmatism in the Nova Brasilândia belt (1.13–1.00 Ga). Conversely, the Aguapeí aulacogen (0.96–0.91 Ga) and nearby shear zones (0.93–0.91 Ga) are the late tectonic offshoots over the cratonic margin. The post-tectonic to anorogenic stages took place after ca. 1.00 Ga, evidenced by the occurrences of intra-plate A-type granites, pegmatites, mafic dikes and sills, as well as of graben basins. Integrated interpretation of the available data related to the Sunsás orogen supports the idea that the main nucleus of Rodinia incorporated the terrains forming the SW corner of Amazonia and most of the Grenvillian margin, as a result of two independent collisional events, as indicated in the Amazon region by the Ji–Paraná shear zone event and the Sunsás belt, respectively.

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1. Introduction

The Sunsás–Aguapeí (SA) province at the southwest corner of the Amazonian Craton has been the focus of several geologic works that are part of the reconnaissance mapping of the Bolivian Precambrian shield, first undertaken by the Anglo-Bolivian technical cooperation program known as “Proyecto Precámbrico” – GEOBOL (Litherland *et al.*, 1986, 1989). Further efforts have been made towards the better understanding of the Proterozoic evolution of this cratonic segment, which includes more detailed geologic investiga-

tions not only in Bolivia but also in the neighboring area in Brazil. Nevertheless, the reader must be aware that the geologic knowledge of the Sunsás–Aguapeí age rocks are far from being well-constrained given the limited number of related publications, in particular, over the remote areas of the Bolivian–Brazilian border.

This paper reassesses the tectonic evolution of the Sunsás orogen (1.11–1.00 Ga), the youngest and southwesternmost of the events in the Amazonian Craton by summarizing the up-to-date geologic knowledge, specially its chronological control in order to better characterize the tectonic province bearing the same name. Taking into account the litho–stratigraphic correlations, the Sunsás evolution can be delineated into three steps: (1) the passive margin formation along the southwestern margin of Amazon

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region; (2) the collisional stage and coeval tectonic events manifested in both plate margin and more distally within its Brazilian counterpart; (3) the post-tectonic and anorogenic events.

In a global context the Sunsás orogen is a key-feature among the collisional processes linked with the agglutination of the Rodinia supercontinent, as suggested by the worldwide correlative orogens particularly with the Grenville province (e.g., Hoffman, 1991; Kröner and Cordani, 2003). In this way, intraplate tectonics through the Amazonian Craton are similarly reflective of such a global phenomenon, given by regional metamorphic overprints, shear zones, thrusts, rift basins and anorogenic magmatism dated between 1.2–1.0 Ga (e.g., Cordani et al., 2010).

Most of the Mesoproterozoic reconstructions place Amazonia against the eastern Laurentia (e.g., Sadowski and Bettencourt, 1996; Rivers, 1997; Boger et al., 2005; Tohver et al., 2002, 2005a, 2006; D'Agrella-Filho et al., 2008; Elming et al., 2009; Cordani

et al., 2009). However, alternative positions are envisaged in order to accommodate smaller crustal fragments like the Arequipa-Antofalla (Peru) and Las Matras complexes (Western Sierras Pampeanas in Argentina) that occur in the Andes (e.g., Litherland et al., 1985; Keppie and Ortega-Gutierrez, 1999; Casquet et al., 2006) – see Kröner and Cordani (2003), and Ramos and Aleman (2000) for an outline of Grenvillian-aged reconstructions dealing with Amazonia and the Andes.

2. Overview of the pre-Sunsás evolution

Four Proterozoic provinces make up the tectonic scenario of the SW Amazonian Craton (e.g., Teixeira et al., 1989; Cordani and Teixeira, 2007; Bettencourt et al., 2010), as follow: Ventuari–Tapajós (VT; 2.00–1.81 Ga), Rio Negro–Juruena (RNJ; 1.80–1.60 Ga), Rondonian–San Ignacio (RSI; 1.56–1.30 Ga) and Sunsás–Aguapeí

Fig. 1. Geologic framework of the SW Amazonian Craton showing the tectonic fronts that delineate the southern limit between the Pensamiento Granitoid Complex (PGC) and the Sunsás orogen. The late Mesoproterozoic metasedimentary belts, the Ji-Paraná shear zone (JPSZ) network, platform covers and Sunsás mafic-felsic intrusions are also shown (adapted from Sadowski and Bettencourt, 1996; Boger et al., 2005; Cordani and Teixeira, 2007). Keys: Sunsás platform covers (1 = Palmeiral and Uopione; 2 = Mutum-Paraná). Late Mesoproterozoic granitic suites: scl = Santa Clara (1.08–1.07 Ga); sg = Sunsás granites (1.10–1.00 Ga); rp = Rio Pardo (1.05 Ga); rtp = Rondônia Tin Province (0.99–0.97 Ga). Inset: CA = Central Amazonian province (>2.6 Ga); MI = Maroni-Itacaiunas province (2.25–2.05 Ga); VT = Ventuari–Tapajós (2.00–1.81 Ga); RNJ = Rio Negro–Juruena (1.80–1.60 Ga); RSI = Rondonian–San Ignacio (1.56–1.30 Ga); SA = Sunsás–Aguapeí (1.20–0.95 Ga). Localities: A = Ariqueles, C = Concepcion, GM = Guajará Mirim, J = Jiparaná, NB = Nova Brasilândia, OP = Ouro Preto, PV = Porto Velho, RB = Rio Branco, SC = Santo Corazon, SI = San Ignacio, SJ = San Javier, SR = San Ramon.

(SA; 1.20–0.95 Ga) (Fig. 1). After cratonization of the SA province, the Amazon region acted as a tectonically stable foreland for the Neoproterozoic belts of Western Gondwanaland (e.g., Cordani et al., 2009).

In short, the Proterozoic dynamics involved a long-term soft-accretion/collision regime with concurrent magmatic, sedimentary and metamorphic episodes that resulted into stepwise crustal growth outwards from the core of the proto-craton, as suggested by the tectonic framework and isotopic signatures of the magmatic rocks. As a corollary, the internal cratonic architecture (present position) exhibits linear trending provinces that become relatively young to the SW as reported by Cordani and Teixeira (2007). Noteworthy cratonization of a given province is sustained by the lower age limit of the related basement rocks, shown by regional distribution of the K/Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ ages (e.g., Tassinari et al., 2000; Tohver et al., 2006; Bettencourt et al., 2010).

Other tectonic divisions and boundaries of the Proterozoic provinces have envisaged different configurations on the basis of geologic correlations, U/Pb and Sm/Nd data, regional structures and metamorphic patterns. A few models argue the Sunsás evolution is autochthonous, belonging to an accretionary orogen evolved from 1.45 to 1.10 Ga (Santos et al., 2000, 2006, 2008; Santos, 2003). However, this idea is not sustained by the general concordance of the geochronologic scenarios of the RNJ, RSI and SA provinces, each one characterized by stepwise crustal growth followed by a given cratonization stage, as described in most of the studies dealing with SW Amazon region (e.g., Sadowski and Bettencourt et al., 1996; Geraldes et al., 2001; Tassinari and Macambira, 2004; Boger et al., 2005; Ruiz, 2005; Tohver et al., 2006; Cordani and Teixeira, 2007). In the same way, the Santos' model is apparently not agreeing with the concept and duration of the Sunsás orogen, which was first postulated by Litherland et al. (1986, 1989). According to these authors the Sunsás orogen is allochthonous, as shown by coherent transport of the folded strata against the structurally-defined Paraguá Craton (Litherland and Bloomfield, 1981; Litherland and Klinck, 1982). In this regard, the Paraguá region, where the Paleoproterozoic nature of the crystalline basement is assigned from the available T_{DM} (2.07–1.86 Ga) and SHRIMP U/Pb zircon (1.82–1.66 Ga) ages – e.g., Santos et al. (2008), has been interpreted as a terrane or microcontinent based on the significant mismatch of its tectonic history with the geologic framework of the neighboring RSI province (e.g., Sadowski and Bettencourt, 1996; Boger et al., 2005; Ruiz, 2005).

Although there are no doubts that the Paraguá rocks were allochthonous with respect of the SW Amazon margin [see Bettencourt et al. (2010) for a reappraisal of the RSI evolution], its geodynamic behavior during the late Mesoproterozoic is still under debate. Boger et al. (2005) reported some of the alternative tectonic scenarios, which consider either the final docking of the Paraguá microcontinent and the Amazon region during the Sunsás orogen at c. 1.10 Ga, as similarly suggested by Tohver et al. (2004, 2006). However, these last works also suggested other alternative configurations such as the collision of the Paraguá microcontinent with the southern part of the already cratonized the RNJ province at c. 1.37–1.28 Ga, creating the Rondonian–San Ignacio accretionary belt (see below). We think that the latter hypothesis is more consistent with the available geochronologic background, geologic correlations and regional structure of the SW Amazon region – see Bettencourt et al. (2010).

Table 1 portrays the main geologic units and also the metamorphic and tectonic elements of the RNJ and RSI provinces (e.g., Tassinari et al., 2000; Cordani and Teixeira, 2007). In resume, the RNJ framework is a result of stacking and lateral accretion of successive intra-oceanic arc complexes and granite-greenstone terrains (e.g., Geraldes et al., 2001). On the other hand, the younger adjacent RSI province records the generation and coalescence of intra-oceanic (e.g., Rio Alegre, Colorado/Mamoré) and continental arcs (e.g., Cachoeirinha, Santa Helena, Pensamiento) as well as the intervening microcontinents (e.g., Paraguá), throughout the Mesoproterozoic (1.56–1.30 Ga) – Geraldes et al., 2004a,b; Bettencourt et al. (2010). Thus, it is implied that the interval over which the preceding RNJ evolution is apparently shorter than previously thought (1.78–1.55 Ga; e.g., Cordani and Teixeira, 2007).

The Rondonian–San Ignacio accretionary belt of the RSI province (Fig. 1) is the youngest and most widespread of the related Mesoproterozoic events, comprising the San Ignacio continental arc (Bolivia) and the coeval Colorado and Mamoré complexes in the Brazilian neighborhoods (Cordani and Teixeira, 2007; Bettencourt et al., 2010). The San Ignacio arc (1.37–1.28 Ga) is represented by voluminous sub-alkaline to high-K calc-alkaline meta-igneous suites denominated as Pensamiento Granitoid Complex in the Paraguá region (e.g., Boger et al., 2005; Matos et al., 2009). As a consequence, the Paraguá basement [Lomas Manechis complex (1.68–1.66 Ga), as well as the Chiquitania and San Ignacio metasedimentary units (<1.79 Ga)] were substantially affected by partial melting and metamorphism at c. 1.34–1.32 Ga, which is

Table 1

Main geologic and tectonic characteristics of the Rio Negro-Juruena (RNJ) and Rondonian–San Ignacio (RSI) provinces, southwestern part of the Amazonian Craton (adapted from Bettencourt et al., 2006; Tohver et al., 2006; Cordani and Teixeira, 2007). See text and Figs. 1 and 2 for details.

Characteristics of the Province	Major metamorphic and tectonic events	Main regional units, including orogenic granitoid rocks	Post-tectonic and anorogenic intrusions
<i>Rio Negro-Juruena</i> (1.80–1.60 Ga): Predominant intra-oceanic arcs Regional cooling (1.55–1.50 Ga): cratonic area for the RSI and Sunsás orogens	Juvenile, recurrent plutonic pulses: Rondônia (1.79–1.73 Ga), (1.57–1.53 Ga); Rio Crespo intrusive suite (1.49 Ga) Heterogeneous metamorphic overprint and tectonic reactivations due to the RSI and Sunsás orogens southward	Granite-greenstone assemblages, medium- to high-grade gneissic associations Syn-tectonic calc-alkaline plutonism Volcano-sedimentary sequences and volcanic/plutonic covers Bimodal anorogenic magmatism (AMCG suites)	Intrusive suites: Oriente Novo (1.08 Ga); Rondônia Tin Province – RTP: Santa Bárbara (0.98 Ga), Salto do Céu sills and dikes (1.03– 0.98 Ga)
<i>Rondonian–San Ignacio</i> (RSI; 1.56– 1.30 Ga): passive margin setting. Intra-oceanic and continental arcs. Collision of the Paraguá terrane (c. 1.32 Ga) Regional cooling (1.36–1.28 Ga): cratonic area for the Sunsás belt	Magmatic arcs: Cachoeirinha (1.56– 1.54 Ga), Rio Alegre (1.51–1.48 Ga), Santa Helena (1.44–1.42 Ga). Colorado/Mamoré/ San Ignacio (1.37–1.28 Ga). Medium- to high grade metamorphism. Post-tectonic mafic magmatism (1.40 Ga) Orogenic collapse/oceanic rift (<1.21 Ga). Ji-Paraná shear zone network (1.18– 1.12 Ga) Sunsás inboard effects: intracratonic belts, shear zones (1.08–1.05 Ga), rift structures	Ocean-floor assemblages (Rio Alegre, Colorado, Mamoré complexes) and calc- alkaline rocks (Cachoeirinha, Santa Helena suites). Pensamiento Granitoid Complex (San Ignacio suite). Nova Brasilândia metasedimentary belt Platform covers: Huanchaca/Aguapeí, Pacaás Novos and Uopione grabens (Palmeiral formation) Sunsás inboard effects: Aguapeí fold and thrust belt	Mafic sills (1.2 Ga; Pacaás Novos rift basin). Santa Clara (1.08–1.07 Ga) and Rio Pardo granitic suites (1.05 Ga) Hunchaca dolerite suite (0.98 Ga) RTP: Maçangana (0.99–0.90 Ga). Guapé granitic suite (0.95– 0.92 Ga)

suggested by the SHRIMP U/Pb ages of the zircon overgrowths (e.g., Boger et al., Santos et al., 2008).

In contrast to the San Ignacio arc, the contemporary Colorado and Mamoré rocks have their origin associated with a passive margin to ocean floor setting. These units were produced by subsequent shortening and metamorphism of the sedimentary sequences and magmatic rocks that characterizes the Colorado and Mamoré belts in Rondônia state, also named Alto Guaporé accretionary belt by Bettencourt et al. (2010). To the north, the RNJ rocks record an equivalent age of high-grade metamorphic overprint, given by U/Pb SHRIMP ages (1.30–1.35 Ga) of zircon overgrowths and monazite (Bettencourt et al. 1999a; Payolla et al. 2002, 2003). In addition, slightly foliated intra-plate granitoid intrusions showing a A-type affinity in the RSI province display roughly comparable ages, such as found for the Alto Candeias (1.35–1.34 Ga) and the São Lourenço–Caripunas (1.31 Ga) intrusive suites (Bettencourt et al., 1999a). These magmatic suites can be considered good markers of intraplate activity related with the late tectonic to post-tectonic phases of Rondonian–San Ignacio accretionary belt (Bettencourt et al. 2010).

The timing of cratonization of the RSI province is well recorded over the Paraguá microcontinent, as indicated by preservation of U/Pb monazite and $^{40}\text{Ar}/^{39}\text{Ar}$ (Tohver et al., 2006) and K/Ar mineral ages (Litherland et al., 1986) between 1.34–1.27 Ga. Furthermore, it can also be inferred from the existence of the undeformed Huanchaca Group that unconformably overlies the Paraguá basement rocks. In the same way, the Mamoré and Colorado metamorphic belts, as well as the RSI and RNJ rocks in Mato Grosso preserve $^{40}\text{Ar}/^{39}\text{Ar}$ plateau (1.34–1.31 Ga) and K/Ar ages (1.36–1.31 Ga) – Teixeira et al. (1989, 2006), Bettencourt et al. (1996), Rizzotto et al. (2002), Tohver et al. (2006). Hence, all these ages above indicate that the RSI province and the coalesced Paraguá microcontinent attained tectonic stability by 1.3 Ga ago.

As a result from the Mesoproterozoic polycyclic evolution, the region between the RNJ and the RSI provinces is characterized by the occurrence of a complex juxtaposition of distinct geologic units, such as the Nova Brasilândia belt (1.11–1.00 Ga; Tohver et al., 2004) and a great deal of anorogenic, A-type granitic intrusions like the Santa Clara intrusive suite (1.08–1.07 Ga) and the Rondônia Tin Province plutons (0.99–0.97 Ga) – e.g., Bettencourt et al., 1999a; Santos et al., 2001; Leite Jr. et al., 2003). Complementary late-Mesoproterozoic tectonic reactivations are also recognized in the area (e.g., Pacaás Novos e Uopione rift basins; <1.05 Ga) – see Fig. 1. In a similar way, a major structure – namely Ji-Paraná shear zone network (JPSZ) – extends over hundreds of kilometers (see Fig. 1), crosscutting all the preexisting rock fabrics of the RNJ and RSI provinces (Tohver et al., 2002; Scandolara, 2006). It is marked by NNW, NW and EW transcurrent and transpressive structures developed under low-temperature amphibolite facies conditions at c. 1.34 Ga (Bettencourt et al., 2010) that were further isotopically reset at 1.18–1.12 Ga, as shown by the $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations (e.g., Tohver et al., 2004, 2005a,b).

The JPSZ deformation is probably reflective from an early Grenvillian collision of the SW Amazon against the Llano segment (1.15–1.10 Ga) of southern Laurentia (e.g., Tohver et al., 2005a,b,c, 2006). This event contrasts in timing with the slightly younger Grenvillian episodes (1.05–0.95 Ga) from southern Laurentia, which is one the other hand compatible with the timing of the Sunsás orogen from Amazon region – see below.

Roughly contemporary intraplate manifestations, reflected by shear zones and anorogenic magmatism, have been recognized in many places of the Amazonian Craton (e.g., Teixeira et al., 1989; Cordani et al., 2010), which allow us to make a tectonic link with the Grenvillian-aged events.

3. The Sunsás–Aguapeí province

The chrono-stratigraphic correlations and structural studies of the key-units in Bolivia and Brazil, inferred from reliable radiometric ages, Nd isotopic constraints and chemical data are used to highlight the geologic framework of the SA province, in particular to discuss the Sunsás orogen within its southern bounds (e.g., Gerdal et al., 2001; Rizzotto et al., 2002; Santos et al., 2003; Tassinari and Macambira, 2004; Tohver et al., 2006; Boger et al., 2005; Ruiz, 2005; Teixeira et al., 2006; Vargas-Mattos, 2006; Cordani and Teixeira, 2007; Elming et al., 2009).

The late Mesoproterozoic evolution of the Sunsás belt can be distinguished from the passive margin to the post-tectonic stages in both the foreland margin and more distally within the RNJ and RSI provinces. The Sunsás passive margin sequences (Sunsás and Vibosi groups) and the coeval intraplate features over the stable foreland are reassessed highlighted by the Huanchaca–Aguapeí cratonic sedimentation and the Nova Brasilândia proto-oceanic rift basin. The subsequent orogenic processes associated with the Sunsás and the Nova Brasilândia belts are described and time-genetically correlated. The Sunsás late offshoots over the cratonic margin are also summarized (e.g., Aguapeí aulacogen and the revelant shear zones), as well as the post-orogenic magmatism.

3.1. The Sunsás passive margin stage and coeval pré-orogenic intraplate phenomena

The evolution of the SA province began after a period of long quiescence and erosion of the western cratonic margin (structurally defined by the Paraguá region), early deposition of the Sunsás and Vibosi Groups (alluvial to deltaic lithologies) in a passive margin environment, subsequently affected by the late Mesoproterozoic orogen (Litherland and Bloomfield, 1981) – see Figs. 1 and 2. Both sedimentary sequences overlie the crystalline basement with a striking planar unconformity (e.g., Litherland et al., 1986, 1989; Boger et al., 2005). A minimum age for the deposition of the Sunsás and Vibosi folded strata comes from the geochronology work done in the intrusive Sunsás granitic suite (1100–1000 Ma) and will be presented here later on.

The Sunsás Group comprises a sequence up to 6500 m thick, divided into four lithostratigraphic units with a typical occurrence in the Serrania Sunsás, Bolivia (Litherland and Bloomfield, 1981). It is stratigraphically defined from the base to the top by conglomerates, psammitic units (arkoses, sandstones, quartzites), argillaceous units (mudstones and siltstones), and a combination of arkosic and quartzites lithologies. On other hand, the deposition of the Vibosi Group, a 2000 m thick sequence of mostly sandstones and arkoses that locally overlies unconformably the lithologies of Sunsás Group, took place in the region of maximum subsidence of the basin nowadays located at the southeastern tip of the Sunsás belt.

3.1.1. The Nova Brasilândia proto-oceanic rift

The Sunsás passive margin phase developed synchronously with the origin of the Nova Brasilândia Group in the neighboring Brazilian counterpart (RSI province). This group is subdivided into two distinct sedimentary-igneous units subsequently overprinted by a regional and metamorphic-deformational event that gave rise to the homonymous metasedimentary belt (Fig. 1), as described by Rizzotto (1999), Rizzotto et al. (2001) and Tohver et al. (2004). The belt evolution included two granitic pulses – the Rio Branco and Rio Pardo suites – (e.g., Rizzotto et al., 2001) that are contemporary with the timing of the Sunsás magmatism in the Bolivian shield (Boger et al., 2005) – see afterwards.

Fig. 2. Litho-estratigraphic characteristics of the Huanchaca/Aguapeí (1167–1149 Ma) and the Sunsás/Vibosi groups, related with the Sunsás “cratonic” and “orogenic” settings, respectively. Adapted from Litherland et al. (1986), Saes et al. (1992), Saes et al. (2006) and Ruiz (2005). (1) Huanchaca/Aguapeí type area (undeformed). (2) Ascension/ Santa Bárbara (undeformed). (3) Aguapeí (deformed/thrust). (4) Aguapeí/Rio Branco area (undeformed). (5) and (6) Pacaás Novos and Uopione (undeformed). NBb = Nova Brasilândia belt (1.21–1.05 Ga). F = Fault. See Figs. 1 and 5 (AB section).

The most widespread unit of the Nova Brasilândia Group consisted originally of deep-sea turbidites with siliceous-clastic to carbonatic composition that were metamorphosed to produce calc-silicate gneisses, quartz-feldspar gneisses and mica schists. The metasedimentary package also includes metagabbro sills, amphibolites and minor, metabasalts. The other sedimentary-igneous unit is made up of mafic sills, metadiabases and amphibolites, with subordinate horizons of turbidite.

The Nova Brasilândia Group probably originated in an intracontinental rift setting that was followed by a proto-oceanic opening, further subjected to crustal shortening, deformation and associated magmatism, as suggested by detailed structural studies and metamorphic petrology, coupled with chemical and petrogenetic constraints of the sedimentary and igneous rocks (Rizzotto et al., 2001; Tohver et al., 2004).

The turbidites show compositional and chemical characteristics suggestive of a mixing between distinct continental source materi-

als, whereas the maximum sedimentation age is inferred from the youngest, detrital zircon population with U/Pb SHRIMP ages of 1215 ± 20 Ma (Rizzotto et al., 2001) and 1231 ± 14 Ma (Santos et al., 2000). On the other hand, the basic rocks display low K_2O , TiO_2 and P_2O_5 contents associated with high CaO, Na/K, Zr, Y, REE ones, as well as $La/Sm > 1$, $La/Yb = 1.8$ – 3.3 and $Zr/Nb = 33$ that show a P-MORB tholeiitic affinity (Rizzotto et al., 2001). In addition, the available isotopic data of the basic rocks exhibit a large variation of the ϵ_{Srt} values ($-2.4/+34.2$), with the respective positive ϵ_{Ndt} ones falling on two groups ($+0.1/+1.6$; $+3.0/+5.1$). The highest $\epsilon_{Ndt(t)}$ values reveal the importance of a juvenile component in the magma source during the proto-oceanic rift opening stage (e.g., Rizzotto et al., 2001; Teixeira et al., 2006). However, the original tholeiitic magma underwent significant contamination as inferred from the large range of the ϵ_{Srt} values and lower positive ϵ_{Ndt} values than expected for these magmas, as well as by positive correlation between the Sr values and La/Yb and Rb/Sr ratios (Girardi et al., 2008).

3.1.2. The Huanchaca and Aguapeí cover sequences

These cover sequences are testimony of a complete depositional cycle at the cratonic margin, similarly to the Sunsás and Vibosi sedimentary sequences at their defined orogenic domain (Figs. 1 and 2), (e.g., Saes et al., 1992; Leite and Saes, 2003). Nevertheless, the Huanchaca–Aguapeí cratonic sequence exhibits a significant change in thickness and maturity compared to the sequences in Bolivia, although it can be considered tectonically as platform cover at the time of the Sunsás orogen.

The Huanchaca Group is characteristically flat-lying and non-metamorphic (Figs. 1 and 2), and includes a volcanic–clastic sequence (Litherland et al., 1986; Boger et al., 2005), while in the neighboring side of Brazil, the correlative Aguapeí Group makes up the Ricardo Franco and Serra do Roncador mesas. Moreover, one remnant of the Aguapeí sequence overlies unconformably the eastern extremity of the RNJ province (Rio Branco area; see Figs. 1 and 2) (e.g., Geraldès et al., 2001; Ruiz, 2005).

The Huanchaca Group (Litherland and Power, 1989) comprises basal sandstones and conglomerates (initial transgressive phase), intermediate psammites (the marine progradation phase) and upper fluvial sandstones (the ultimate marine regression phase). Additional stratigraphic studies in the type-area of the Aguapeí Group (Ricardo Franco escarpment) indicate three formations from the base to the top, whilst overlying the basement rocks with a marked unconformity: the Fortuna, Vale da Promissão and Morro Cristalina formations (e.g., Geraldès et al., 1997; Saes, 1999; Tohver et al., 2004; Ruiz, 2005).

The deposition age of the lower Fortuna Formation is well constrained between 1167 ± 27 Ma (the youngest detrital zircon age) and 1149 ± 7 Ma (post-diagenetic event; xenotime age), as determined by SHRIMP U/Pb work in the conglomerates (Santos et al., 2005). Other Aguapeí basal rocks correlative with the Fortuna Formation have complementary SHRIMP U/Pb detrital zircon ages yielding 1231 Ma (e.g., Santos, 2003; Santos et al., 2008; Leite and Saes, 2003) and 1260 Ma (Vargas-Mattos et al., 2007) for the youngest detrital zircon. From the above age data the cratonic sedimentation (Huanchaca–Aguapeí) may be diachronic.

Regional stratigraphic correlations inferred that the Huanchaca–Aguapeí cover sequence evolved through three stages (Saes et al., 1992; Saes, 1999): (i) the initial rift process, marked by conglomerates and accumulation of immature sandstones, with palaeocurrents indicating a longitudinal NW–SE filling pattern; (ii) the flexural subsidence stage that accommodates a thick transgressive section of shallow marine pelites and fine sandstones (tempestites) in the Huanchaca, São Vicente and Rio Branco areas and (iii) a deep marine submarine fan phase located at the central rift zone, which comprises the thickest and most deformed immature sedimentary rocks, whereas (e.g., Huanchaca, Rio Branco areas) the package becomes thinner and non-metamorphic along the outboard zones (see Fig. 2).

The litho–stratigraphic correlation (e.g., facies and palaeocurrents of the Aguapeí Group) coupled with the U/Pb ages of detrital zircons of the basal conglomerates are consistent with the idea that late Mesoproterozoic extensional dynamics produced a system of continental, aborted rifts over the cratonized RNJ and RSI provinces, evolving to a wide sag intracratonic basin (e.g., Leite and Saes, 2003). An intraplate setting is similarly envisaged from the available U/Pb ICP–MS–LA work in detrital zircons of the lower Fortuna Formation that yields $^{207}\text{Pb}/^{206}\text{Pb}$ peak ages of 1800, 1500 and 1350 Ma (Vargas-Mattos et al., 2007). The ages of the most representative zircon populations (1.5 Ga; 1.3 Ga) not only signalize the continental sedimentation source (Leite and Saes, 2003), but also the timing of the adjacent magmatic arcs that built up the RSI province in Mato Grosso state, western Brazil (e.g., Geraldès et al., 2001) (see Table 1 and Fig. 1).

The Pacaás Novos graben (see Figs. 1 and 2), the westernmost of the filled rifts of the Huanchaca–Aguapeí sequence, contains a 500 m thick undeformed pile of coarse siliciclastic deposits, typical of fan braided alluvial system and of dunes, tidalites and proximal storm deposits of coastal–eolian system – namely Palmeiral Formation (Saes et al., 2006). The rift package is floored by gabbroic sills that yield $^{40}\text{Ar}/^{39}\text{Ar}$ plateau crystallization ages of 1198 ± 3 Ma and 1201 ± 3 Ma (e.g., Tohver et al., 2002). They are probably related to the timing of an intraplate extension episode, which is age-equivalent of the Sunsás passive margin stage (see above).

3.2. The Sunsás orogenic phase

The timing of the Sunsás orogen was first estimated by Rb/Sr and K/Ar work carried out in the related granitic rocks and pegmatites (1100–900 Ma) confined within the bounds of Sunsás collisional belt, in Bolivia (e.g., Litherland et al., 1986). This belt is structurally marked by extensive mylonitic shear zones (or straightening “tectonic fronts”; e.g., Santa Catalina, Rio Negro and San Diablo; see Fig. 1) that shows preferential sinistral offsets, active at about ca. 1080–1050 Ma along the southern rim of the Paraguá microcontinent. Despite the Sunsás reworking, the internal (pre-Sunsás) non-penetrative deformation is preserved and little or no metamorphic overprint is described (e.g., Litherland et al., 1986; Sadowski and Bettencourt, 1996; Boger et al., 2005), as well as the older San Ignacio structures in the north of Concepción (Boger et al., 2005).

The network of shears not only dissects the Sunsás units and the older rocks but also allows the emplacement of syn- to late-tectonic granites (e.g., Sunsás granitic suite – Litherland et al., 1989). Furthermore, these structures control occurrences of gold in the state of Mato Grosso (e.g., Fernandes et al., 2006) and in the Don Mario mineral district in Bolivia (Litherland et al., 1986). The latter district hosts important Au–Cu among other metals occurrences produced by hydrothermal mineralization, and is tectonically controlled by shear zones of the San Diablo front (see Fig. 1) and pegmatite injections (U/Pb zircon age of 997 ± 3 Ma). In Don Mario mine, the Au-rich zone is dated by Re/Os in molybdenite at 994 ± 3 Ma (Isla-Moreno, 2009).

The recognized Sunsás and Vibosi metasedimentary sequences of the Sunsás belt (see previous section) exhibit penetrative, up-right NW trending folds and regional low-grade metamorphism (Litherland and Bloomfield, 1981) that differs from the staurolite and sillimanite isograds recorded in the schist sequence that occurs in the vicinity of San Ramon (e.g., Adamek et al., 1996) and from the more intense regional deformation developed in the San Diablo, Rio Negro and Santa Catalina fronts (Fig. 1). The latter structure is left lateral in movement, whereas the Rio Negro front has a dextral shift with a normal (brittle) foliation. Such regime resulted from the near frontal, tangential, SW–NE directed collision of the belt under ductile to ductile–brittle conditions against the Paraguá microcontinent. This regime led to the overall movement of Sunsás orogenic compartments relative to the northward Paraguá stable domain (e.g., Litherland et al., 1986; Boger et al., 2005). As such, the deeper-level rocks of the Paraguá region (e.g., Lomas Manechis and Chiquitania units) are thrust over the higher-level units (San Ignacio and Sunsás rocks), producing the striking open folding and secondary faults and fractures. In this regard, the San Diablo front was tentatively interpreted as a suture zone between the Paraguá and the Sunsás southeast blocks (Saes, 1999). This suggests that the Sunsás and Vibosi metasedimentary rocks may be tectonically related with an arc setting, as envisaged by Litherland et al. (1985).

The Sunsás granitic event encompasses various massives (Litherland et al., 1986; Boger et al., 2005; Vargas-Mattos, 2006; Vargas-Mattos et al., 2009). The older ones (e.g., El Carmen) are

composed of quartz-monzonites, monzonites and syenogranites and minor pyterlites (a kind of rapakivi granites), while the younger bodies (e.g., Primavera, Señoritas) consist of syenite, trachyte and peraluminous and peralkaline granites (Fig. 3). The syn- to late-tectonic intrusions are genetically related to the main Sunsás shear zones, show blurred contacts with the nebulitic sheared migmatites, and show elongated morphology on aerial images. In contrast, the late to post-tectonic plutons are circular or oval bodies (e.g., Taperas granite). They truncate the Sunsás structures, shears or mineral fabrics of the country rocks, and show little or no signs of foliation and deformation (Litherland et al., 1986; Adamek et al., 1996; Boger et al., 2005; Vargas-Mattos, 2006; Vargas-Mattos et al., 2009).

SHRIMP and TIMS U/Pb zircon ages are available for a limited number of intrusive granites but highlight the timing of the Sunsás plutonic event, previously delineated by a Rb/Sr isochron age of 1005 ± 12 Ma for the Casa de Piedra suite (Fig. 3) and by slightly younger K/Ar ages of other intrusions in the range 990–910 Ma (Litherland et al., 1986, 1989). The most reliable U/Pb ages come from the slightly foliated Santa Teresa tonalite that yields 1105 ± 21 Ma (Matos, pers. comm., 2009), the essentially undeformed Taperas granite (1076 ± 18 Ma; Boger et al., 2005) and from an orthogneiss in the Don Mario mineral district (1014 ± 6 Ma; Isla-Moreno, 2009; Table 2 and Fig. 3). In comparison, the Naranjito, Primavera, Taperas and El Carmen plutons yield roughly comparable U/Pb ICP-MS-LA zircon ages (1092–1047 Ma; Vargas-Mattos et al., 2009). Moreover these plutons display variable negative $\epsilon_{\text{Nd}(t)}$ values (−0.5 to −4.5) and T_{DM} ages (1.8–1.6 Ga) (Darbyshire, 2000; Vargas-Mattos et al., 2006). When taken collectively into account, the chemical characteristics of the plutons (S, I, A-types) suggest that the magma sources underwent crustal contamination from protholiths like the Paragvá rocks, given the compatible Nd isotopic constraints (Boger et al., 2005; Santos et al., 2000) – see previous section. From the above, we assume that the Sunsás granites were probably formed in a continental arc environment.

The Rincón del Tigre complex (Prendergast, 2000) was emplaced as a layered, differentiated, mafic/ultramafic sill between the Sunsás and the Vibosi metasedimentary sequences, in the southeast tip of the Sunsás belt (Litherland et al., 1986) – see

Fig. 1. The Rb/Sr (992 ± 86 Ma) and K/Ar (1067 ± 23 Ma) ages (Table 2) obtained from the granophyres (Darbyshire, 1979) are compared within the errors with those reported for the Sunsás granites (see above). Both the Rincón del Tigre Complex and the metasedimentary sequence exhibit gentle NE folds matching well with the lineation trend of the Sunsás shears and with the overprinted deformation in the older rocks (see above). Therefore, the Rincón del Tigre complex was emplaced during the syn to late tectonic phase of the Sunsás orogen.

3.2.1. The Nova Brasilândia belt

The Nova Brasilândia belt (Fig. 1) lies in the ~ 1.36 Ga Colorado and Mamoré complexes (see previous section), covered by late Mesoproterozoic flat-lying sequences of the Pacaás Novos and Uopione rift basins (e.g., <1050 Ma Palmeiral Formation; Santos et al., 2001). The aeromagnetic data interpretation suggests a continuity of the Nova Brasilândia belt to the east over at least 1000 km below the Phanerozoic cover, while the geologic inferences suggests it might be extended to distances up to 2000 km (Tohver et al., 2004; Rizzotto and Quadros, 2007).

Detailed metamorphic petrology and structural data revealed that the Nova Brasilândia belt is characterized by heterogeneous metamorphic grades that increase from north to south (Luft et al., 2000; Tohver et al., 2004). The northern compartment of the belt preserves vestiges of early phases that reached high P–T conditions (medium- to high-T amphibolite facies) whereas the higher metamorphic facies is restricted to the southern portion. The preserved sequence of metamorphism is a result from crustal thickening and collision-related deformation in a transpressional zone, as also supported from observations of deep-seated thrusting and accompanying sinistral strike-slip motion (Tohver et al., 2004). Regional foliations in the Nova Brasilândia belt are defined by the development of both mylonitic shear zones and metamorphic fabrics, generated by mineral growth and transposition of sedimentary fabrics.

Numerous SHRIMP U/Pb, U/Pb TIMS, $^{40}\text{Ar}/^{39}\text{Ar}$ ages are used in conjunction with Nd–Sr isotopic geochemistry to constrain the evolution of the Nova Brasilândia rocks, which includes two episodes of felsic intrusions (Rizzotto, 1999; Rizzotto et al., 2001; Toh-

Fig. 3. Main magmatic and tectonic elements of the Sunsás belt, Bolivia. Adapted from Litherland et al. (1986). See text for details.

Table 2

Summary of age and Nd isotopic data of magmatic rocks tectonically related with the Sunsás–Aguapeí province.

Unit	Tectonics/ intrusions		Rb/Sr isochron (Ma)	⁴⁰ Ar/ ³⁹ Ar K/Ar (Ma)	U/Pb (Ma)	Sm/Nd			
						T _{DM} (Ga)	ε _{Ndt}		
Sunsás belt	Syn- to late-tectonic	Rincón del Tigre	993 ± 139	938 ± 21 907 ± 20	1092 ± 37	1.80	−3.9/−4.5		
		El Carmen							
	Post-tectonic to anorogenic	Santa Teresa	1005 ± 12	958 ± 27 911 ± 20 935 ± 21 991 ± 27	1105 ± 21	1.58	−4.0/−3.1		
		Orthogneiss			1014 ± 6				
		Casa de Piedra			1076 ± 18			1.71/1.66	−3.4/−4.4
		Taperas			1047 ± 24				
		Tasseoro			1070 ± 54 ~1090			1.76 1.66	−2.5 −0.5 −0.8
		Naranjito							
		Primavera							
		Señoritas			1004 ± 1				
Pegmatite	997 ± 3								
Nova Brasilândia belt	Syn-tectonic	Metagabbro			1110 ± 15	1.63	+4.3/+ 2.3 −0.4		
		Monzogabbro			1098 ± 10				
					1113 ± 58				
		Metagabbro			1110 ± 08	1.66 1.91 1.85 1.50	+5.0 +3.1 −1.5 −4.3/ −3.9 +0.5		
		Granite							
		Leucogranite							
		Calc-silicate gneiss							
		Paragneiss							
		Monzogranite							
		Colorado–Mamoré belt			Santa Clara suite (anorogenic)	Manteiga	1052 ± 21	1035 ± 8	1082 ± 5
Santa Clara	1074 ± 21								
^a RTP (anorogenic)	Oriente Novo			950 ± 8	1080 ± 27				
	Rio Pardo				1110 ± 8				
					1005 ± 7				
	Pedra Branca				995 ± 05				
	São Carlos				995 ± 73				
					974 ± 06				
	Massangana				991 ± 14				
	Santa Bárbara				993 ± 5			−2.9/ −4.6	
	989 ± 13								
	978 ± 13								
Aguapeí belt	Guapé suite (anorogenic)	Guapé	950 ± 40			1.29 2.21 2.21	+1.3 −7.1 −7.6 −5.0		
		São Domingos			939 ± 19				
					914 ± 14				
		Sararé			917 ± 18				
				906 ± 1 905 ± 8					

^a Rondônia Tin Province – RTP. See text for details.

ver et al., 2004; Santos et al., 2008). The oldest intrusive phase (Rio Branco suite) constitutes mega-lenses of A-type monzogranites that yield 1113 ± 56 Ma (conventional U/Pb zircon age; Rizzotto, 1999) and 1098 ± 10 Ma (U/Pb SHRIMP zircon age; Santos et al., 2000) pointing out to the rock crystallization age. These plutons were emplaced syntectonically with an early-recognized deformational phase of the belt that accompanies sinistral strike-slip zones, thereby exhibiting gneissic foliation with locally developed mylonitic fabrics (Rizzotto et al., 2001; Tohver et al., 2004). The age of the Rio Branco suite agrees well with U–Pb SHRIMP age of 1110 ± 15 Ma measured for coeval tholeiitic gabbros (see previous section). Additional U/Pb ages in monazite (1096–1082 Ma) and titanite (1070–1020 Ma) evidence the timing of the high-grade metamorphic overprint in the area (Tohver et al., 2004, 2006). The second deformational phase is marked by the Rio Pardo granitic suite (1005 ± 41 Ma; $\varepsilon_{\text{Nd}(t)} = +0.5$; Rizzotto and Quadros, 2007), which exhibits a strong mylonitic foliation with striking E–W trend. In conclusion, both the Nova Brasilândia and the Sunsás belts were involved in an orogenic zone characterized by sinistral strike-slip motion at c. 1.1–1.0 Ga ago.

The regional cooling of the Nova Brasilândia belt took place between 995–910 Ma, as shown by the available $^{40}\text{Ar}/^{39}\text{Ar}$ plateau mineral ages (Fig. 4), therefore ~100–80 Myrs after the timing of

ultimate deformation recorded along the JPSZ located to the north (e.g., Tohver et al., 2006) – see above. Moreover, the geographic distribution of the cooling ages suggests that this part of the Nova Brasilândia belt was exhumed uniformly, because the apparent lack of correlation with its metamorphic-structural compartments (Tohver et al., 2004). However, these $^{40}\text{Ar}/^{39}\text{Ar}$ ages may be somewhat influenced by nearby emplacement of anorogenic granites (990–970 Ga, Bettencourt et al., 1999a,b), as recognized by related hydrothermalism over the Nova Brasilândia basic rocks (Rizzotto et al., 2001; Tohver et al., 2005b; Teixeira et al., 2006). Tohver et al. (2004, 2005a), on the basis of detailed structural data, combined with thermobarometric calculations and geochronological information, interpreted the Nova Brasilândia metamorphic belt as the result of crustal thickening through an imbrication caused by the transpressive suturing of the Amazon region and Paraguá microcontinent at c.1.10 Ga ago.

3.3. Sunsás late to post-orogenic phases

The strain ellipsoid model for the Sunsás collision (Sadowski and Bettencourt, 1996) illustrates the mechanical compatibility among the observed frontal SW–NE directed strain with left-lateral shearing along the northern bounds of the Sunsás belt (e.g., San

Fig. 4. Summary of $^{40}\text{Ar}/^{39}\text{Ar}$ and Rb/Sr mineral ages of the Nova Brasilândia belt (NBb) and the Ji-Paraná shear zone network (JPSZ), RSI province (Rondônia). Keys: PC and U = Pacaás Novos and Uopione rift-type sequences. Pz = Paleozoic. Adapted from [Tohver et al. \(2006\)](#). See text for details.

Diablo front) and the oblique geometry of the Aguapeí fold and thrust belt (see [Fig. 1](#)) and other related extension/transpressive components over the cratonic margin. Examples could be the shear zones in Mato Grosso (RNJ and RSI provinces) and the post-tectonic and anorogenic intrusions in Rondônia, Mato Grosso and Bolivia.

3.3.1. The Sunsás post-tectonic to anorogenic magmatism

Many felsic and mafic intrusions with ages generally 1000 Ma or less represent the youngest manifestations over the cratonic margin (RNJ, RSI, Paraguá microcontinent), given the significant time hiatus between these igneous phases and the cessation of the Sunsás orogenic processes. These intrusions are well illustrated in the Rondônia Tin Province – RTP on basis of voluminous occurrences of A-type AMCG, anorogenic plutons in the RNJ and RSI provinces (see [Fig. 1](#) and [Table 2](#)) (e.g., [Priem et al., 1989](#); [Sadowski and Bettencourt, 1996](#); [Bettencourt et al., 1999a,b](#); [Tassinari et al., 2000](#); [Payolla et al., 2002](#); [Santos, 2003](#)).

The RTP encompasses two distinct suites characterized by the presence of rapakivi varieties (e.g., [Leite Jr. et al., 2003](#)): (i) metaluminous to subordinately peraluminous subsolvus and (ii) sub-alkaline rocks with minor associated quartz-syenite, quartz-monzonite and monzonite. This last suite consists of at least three distinct intrusive phases: early bodies composed of coarse pyterlite to porphyritic biotite syenogranite, late syenogranites that are succeeded by granites, syenites and related varieties. The later two phases are characterized by associated primary metal deposits (e.g., Sn, Mo, W). The ultimate intrusive phase, which is limited in area, shows a hypersolvus nature and alkaline affinity. It is composed of alkali-feldspar granites and peralkaline granites, alkali-feldspar syenites, trachytes, microsyenites, sub-alkaline quartz-feldspar porphyres and hybrid rocks (quartz microsyenite and quartz syenite). These granites are usually derived from crustal sources, such as the Maçangana pluton (990–980 Ma) and the São Carlos massif (974 ± 6 Ma; [Bettencourt et al., 1999b](#)), the Pedra Branca syenogranite (995 ± 5 Ma; [Tosdal and Bettencourt, 1994](#)), and the Santa Bárbara massif (978 ± 13 Ma; [Sparrenberger et al., 2002](#)), as suggested by the field relations, chemical signatures and systematic negative $\epsilon_{\text{Nd}(t)}$ constraints ([Payolla et al., 2002](#)) – see [Table 2](#).

The Rio Pardo granitic suite (905 ± 7 Ma) occurs to the south of the RTP ([Fig. 1](#)) and shows similar anorogenic behavior of the Gua-

pé intrusive suite (Guapé, São Domingos, Sararé plutons), located farther to southeast in the state of Mato Grosso. This latter suite displays U/Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ ages c. 940–905 Ma (e.g., [Geraldes et al., 2001](#); [Ruiz et al., 2005](#)) – [Table 2](#). Chemically, the Guapé plutons are mostly sub-alkaline, metaluminous to peraluminous, and likewise the RTP rocks they show affinity with A-type granites, as inferred from the negative Nd signatures (e.g., São Domingos pluton; $\epsilon_{\text{Nd}(t)} = -7$; [Ruiz, 2005](#)).

Anorogenic igneous rocks are similarly recorded within the southeastern bounds of the Sunsás belt, such as the Señoritas granite (1004 ± 1 Ma) and profuse pegmatites (997 ± 3 Ma) that host metal deposits (Nb, Mo, SW, Sn, Ta, Be), as reported by [Isla-Moreno \(2009\)](#) – see [Table 2](#). Other pegmatites, as well as mafic sills and dikes occur within the belt, showing roughly comparable K/Ar ages ([Litherland et al., 1986](#)).

In the Paraguá region, the Huanchaca dolerite suite ([Litherland et al., 1986](#)), also named Huanchaca intrusive suite ([Ruiz, 2005](#)), comprises unmetamorphosed dikes and sills (not shown) that yield K/Ar apparent ages between 936 and 850 Ma in whole rock. The dikes are massive, up to 20 m thick and crosscut the foliation of the country rocks, whereas the sills generally dip 10–15° to SW, exhibiting sharp contacts with the Huanchaca sedimentary beds. In the neighboring area of Brazil, the sills similarly interlay concordantly the Vale da Promissão middle formation of Aguapeí Group ([Ruiz et al., 2007](#); [Lima et al., 2008](#)), whilst a dike crosscuts a sill at the Ricardo Franco mesa ([Século et al., 2008](#)).

To the east, in Mato Grosso state (RNJ province), the Salto do Céu intrusive suite ([Araújo, 2008](#)) constitutes massive gabbroic and diabase sills of tholeiitic affinity, interlayered with the Vale da Promissão Formation of the Aguapeí Group (see previous section) that yield K/Ar ages in the range 1015–850 Ma ([Barros et al., 1982](#); [Ruiz, 2005](#); [Ruiz et al., 2007](#)). [Elming et al. \(2009\)](#) reported a more precise $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 981 ± 2 Ma for one sill, whereas additional studied samples yielded significantly older ages (1035–1025 Ma). This suggests the Salto do Céu suite may have various igneous pulses. To the west in the Rondônia state the mafic dikes and sills yield roughly comparable $^{40}\text{Ar}/^{39}\text{Ar}$ ages between 1030–950 Ma (e.g., [Santos, 2003](#); [Teixeira et al., 2006](#)).

3.3.2. The Aguapeí fold and thrust belt

The Aguapeí belt or aulacogen (e.g., Souza and Hildred, 1980; Saes et al., 1992) is a narrow NNW–SSE zone of folded sedimentary rocks in Mato Grosso state (Figs. 1 and 2). The belt is structurally confined, lying discontinuously along more than 500 km in between the northeastern/eastern margins of the Paraguá microcontinent and the reactivated basement of the RSI province in east (Brazil).

There is no apparent structural continuity between the northernmost extent of the Aguapeí belt and the E–W trending Nova Brasilândia metasedimentary-metaplutonic belt, located c. 200 km to the NNW in the state of Rondônia (see Fig. 2). In spite of both the Aguapeí and the Nova Brasilândia rocks yield roughly comparable detrital zircon ages (<1230 Ma and <1215 Ma; see previous sections), the continental source of the Aguapeí Group contrasts with the “oceanic” characteristics of the Nova Brasilândia protholiths. Moreover the rocks of Nova Brasilândia belt exhibit a higher metamorphic grade and are more intensity deformed than those of the Aguapeí aulacogen (Tohver et al., 2004).

The Aguapeí weakness tectonic zone is marked by aeromagnetic anomalies that bound to the southwest the 1.51–1.48 Ga Rio Alegre terrane (e.g., Geraldès et al., 2001; Bettencourt et al., 2010). This suggests that the Aguapeí belt may be one gangway across to which the sinistral shearing and thrusts related to the Sunsás collision late offshoots overprinted the cratonic margin (Litherland et al., 1989). As such the Aguapeí belt, in contrast with Sunsás orogenic framework (in Bolivia), exhibits only localized deformation and low-grade metamorphism (e.g., Geraldès et al., 2001), as given by gentle folds (upright to northeast dipping) and shears of NW trending. The deformation related to this event is characterized by recrystallized mylonites that yielded K/Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ mica ages between 960–910 Ma (e.g., Geraldès et al., 1997; Fernandes et al., 2006; Ruiz et al., 2007).

The neighboring country rocks show slightly older, but roughly comparable $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages in the range 1030–920 Ma (Ruiz, 2005). This indicates that regional cooling of the continental crust shortly followed the SW directed thrusting of the reactivated basement over the Aguapeí aulacogen, starting at c. 960 Ma. Whereas the $^{40}\text{Ar}/^{39}\text{Ar}$ and K/Ar pattern allows constraining a time relationship with the regional cooling of the Sunsás orogen (see previous section), based on the isotopic systems that are susceptible to thermal resetting; the associated compressive phase of the Aguapeí belt postdates the Sunsás magmatism (1100–1000 Ga) and related nappe structures in Bolivia (Litherland et al., 1986; Boger et al., 2005). This reinforces the idea that the Aguapeí aulacogen is a late tectonic element of the SA province, reflective from the Sunsás collision.

3.3.3. The late tectonic shear zones

The Piratininga–Corredor and Indavaí–Lucialva zones in the Mato Grosso state (not shown) are major ductile shears that affect both the Aguapeí aulacogen and related country rocks at the south-east part of the RNJ and RSI provinces, as described by Ruiz (2005).

The Piratininga–Corredor shears constitute a highly stress zone that juxtaposes the Rio Alegre terrane and the reactivated basement to the east, while confining the NNW–SSE Aguapeí aulacogen. The protomylonites yield $^{40}\text{Ar}/^{39}\text{Ar}$ plateau muscovite ages between 930 and 920 Ma (Ruiz et al., 2007), which agree well with the age pattern of the Aguapeí belt own (see above). The NW–SE trending Indavaí–Lucialva shears occur along the northeast bounds of the 1.44–1.42 Ga Santa Helena rocks, and exhibit general, upper transport to northeast (see Table 1). The recrystallized mylonites yield $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of c. 915 Ma (Ruiz, 2005) that are comparable to that of the Guapé intrusive suite (see above).

4. Summary and late Mesoproterozoic evolution

Geologic correlations coupled with interpretation of U/Pb ages and petrogenetic constraints provide a clear-cut picture of the Sunsás–Aguapeí evolution (1200–950 Ma), the youngest of the tectonic provinces in SW Amazonian Craton. The early evolution stage (passive margin; <1200 Ma) developed along the southern edge of the already cratonized RNJ and RSI provinces, as given by deposition of the Sunsás and Vibosi groups. This stage was roughly contemporary with extensional and compressional intraplate processes, such as the Nova Brasilândia proto-oceanic opening (<1215 Ma), a wide-sag platform-like sedimentation (Huanchaca–Aguapeí basin; 1167–1149 Ma), as well as deformation and metamorphism along the JPSZ network (1180–1120 Ma). Subsequently, the Sunsás orogen created an allochthonous collisional belt, characterized by mafic–ultramafic and granitic suites (1105–1004 Ma) that truncated both the folded Sunsás/Vibosi strata and the major related tectonic structures. In comparison, the coeval Nova Brasilândia belt (1113–1005 Ma) results from the orogenic shortening and transtension inboard, while the flat-lying Huanchaca–Aguapeí cover represents the associated intracratonic basin. In contrast, the Aguapeí aulacogen (960–910 Ma) and the Indavaí–Lucialva–Piratininga–Corredor mylonitic shear zones (930–910 Ma) may be interpreted as regional late offshoots of Sunsás belt that was developed under transpressive conditions over the plate margin.

So far, the evolution of the SA province can be characterized by two major timing-independent events separated by 100–80 Myrs: (i) the first one overprints the basement rock fabrics (RNJ and RSI provinces) and is highlighted by the Ji–Paraná shearing and deformation features. Its tectonic reactivation allowed the emplacement of the undeformed A-type Santa Clara suite (1082–1074 Ma), which supposedly is associated with the timing of an early cratonization phase in the area. (ii) The second event, namely Sunsás orogen, is the youngest of the orogenic events recorded in the SW cratonic fringe. It is coeval with the Nova Brasilândia belt but they are clearly distinguished whichever because the later exhibits higher metamorphic grade and minor volume of felsic rocks.

The broad distribution of rocks with nearly similar K/Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ ages over the SW Amazon region points out to a timing of the regional uplift and cooling of the Sunsás orogen, and thereby the final tectonic stability of the SA province occurring at about c. 1000–950 Ma (Litherland et al., 1986; Teixeira et al., 1989, 2006; Tohver et al., 2006). In this regard, post-tectonic events of the Sunsás orogen are marked by voluminous A-type granites, pegmatites and mafic dikes and sills (980–940 Ma), as well as by reactivated rift basins (e.g., <1050 Ma; Palmeiral formation). Fig. 5 and Table 3 present a SW–NE tectonic sketch of the Sunsás belt and a tentative time-outline of the late Mesoproterozoic evolution of the SW Amazonian Craton, respectively.

The late Mesoproterozoic orogenic history summarized here prevents the recognition of clear boundaries of the SA province with the RNJ and RSI ones by considering the tectonic juxtaposition of distinct geologic units. For example, the referred JPSZ network, the Nova Brasilândia and Aguapeí belts, the Huanchaca–Aguapeí and other cover sequences described here (see Fig. 1). When taken into account, these features suggest that the SA province overprints much of the RNJ and RSI provinces.

On the other hand, the paleotectonic association of the above geologic units and related structures with the Paraguá microcontinent are still a matter of debate. For example, Boger et al. (2005) argued that the Nova Brasilândia, Aguapeí and Sunsás belts would represent the Sunsás orogen properly on the basis of geologic correlations, in contrast with the model above proposed. Other alter-

Fig. 5. Tectonic sketch across the Sunsás belt and the cratonic margin (SW-NE; present position). SZ = shear zones. Adapted from Sadowski and Bettencourt (1996) and Ruiz (2005). See Fig. 2 (AB section), Table 4 and text for details.

native views (e.g., Tohver et al., 2004) for interpreting the opening phase of the Nova Brasilândia basin, take into consideration a large releasing bend (seaway) formed during a transtensional phase that could mark the relative motion of the proto-Amazonian Craton with Laurentia. According to this, the JPSZ would be associated with an early transpressive suturing that took place between the Amazon plate and the Paraguá microcontinent which resulted in a crustal thickening and metamorphism (at c. 1090 Ma) of the Nova Brasilândia belt. Although the availability of paleomagnetic data is limited, we can not rule out a possible 1.15 Ga Amazonia–Laurentia collision, even thought with a different reconstruction (e.g., D'Agrella-Filho et al., 2008). In any of the above approaches the oceanic nature of the Nova Brasilândia sedimentary-igneous assemblage (see previous sections) allows us to postulate alternative tectonic hypothesis such as the relative rotation from which the Paraguá microcontinent and the RSI province were subjected

during subsequent transtensive and transpressive events that coincides with the suturing episode. In this scenario, either a narrow oceanic opening or an oceanic branch might have important implications for the Amazonia–Laurentia configuration at that time.

Another open question to be further investigated is the relative significance of the Arequipa–Antofalla inlier and others Grenvillian fragments in the Andes for the paleotectonic evolution of the Sunsás belt. They might either represent intervening exotic terranes (or microcontinents) approaching from the west to create the Sunsás belt, or the leading edge of the Laurentia–Amazonia collision.

To conclude, the contemporary events of the Grenvillian system allow an early tectonic link with the Sunsás passive margin stage (<1200 Ma) and the JPSZ strike slip deformation (1180–1120 Ma), through a collision against the Llano segment (1150–1100 Ma) of southern Laurentia, as described by Tohver et al. (2004, 2006). This

Table 3

The Sunsás–Aguapeí province: main geologic units and time constraints of the “orogenic” and “cratonic” domains.

Tectonic evolution (orogenic domain)	Tectonic evolution (cratonic margin)	Estimated age (Ma)
1. Passive margin setting: deposition of the Sunsás (S), Vibosi groups (V)	Intraplate extensional tectonics and concurrent sedimentation: Nova Brasilândia (NB) oceanic rift; Pacaás Novos/Uopione grabens (PU); Huanchaca/Aguapeí (H/A) intracratonic basin; Intraplate (more distal) deformation: Ji-Paraná shear zone network (JPSZ)	<1215 (NB) <1200 (PU) 1167–1149 (H/A) 1190–1120 (JPSZ) 1082–1074 (SCL)
2. Sunsás orogenic units: supracrustal belts (s, v), Sunsás granites (SG) and Rincón del Tigre mafic-ultramafic complex (RT)	Anorogenic Santa Clara intrusive suite (SCL) Sunsás-aged events: crustal shortening, deformation and coeval magmatism, and accompanying medium- to high grade metamorphism – Nova Brasilândia belt	1113–1000 (NB) 1100–1000 (SG) ~1000 (RT)
3. Sunsás collisional dynamics: nappes, San Diablo and Santa Catalina fronts, shear zones, mylonites	Sunsás late tectonic offshoots: Aguapeí belt (Atb), and shear zones	1080–1050* 960–910 (Atb) 930–910** <1050
4. Cratonization and cooling of the Sunsás belt, late tectonic granites, pegmatites	Extensional tectonics: rift basins with continental to shallow marine sediments (e.g., Palmeiral Formation), post-tectonic to anorogenic granites (Rondônia Tin Province; Guapé and Rio Pardo suites), mafic dikes and sills (e.g., Huanchaca, Salto do Céu)	1000–905
5. Final cratonization, exhumation and cooling of the Sunsás province (SW Amazonian Craton)		

event is age-equivalent with the extensional tectonics occurred in the eastern Grenville province, characterized by the presence of marine sedimentary sequences, the AMGC magmatism (1130 ± 50 Ma), the Abitibi dike swarm (1140 Ma), among other features (e.g., Sadowski and Bettencourt, 1996; Windley, 1989; Rivers, 1997). Putting it all together, the extensional and compressive events in the SA province provide good evidence of the early phases of geologic evolution of Amazônia and Laurentia.

The Sunsás belt (1100–1000 Ma) apparently overlaps within age errors with some of the major geologic episodes such as the major Grenvillian deformation in Eastern Laurentia, also known as Ottawa pulse of the Grenville orogen (Rivers, 1997). This episode is known for signaling the terminal continent–continent suturing of the Rodinia supercontinent (e.g., Sadowski and Bettencourt, 1996; Tohver et al., 2006; Cordani et al., 2009).

The tectonic significance and kinematics of the inferred Amazonia–Laurentia collision are largely unresolved, given the differences recognized among the orogenic and post-orogenic rocks in both plates, allowing various Rodinia reconstructions – as discussed by Tohver et al. (2006), Cordani and Teixeira (2007) and Santos et al. (2008). The age limits of the Ottawa pulse may vary along the Grenville province in North America but probably started c. 1100 Ma (e.g., Rivers, 1997; Carr et al., 2000; Gower and Krogh, 2002),

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An overview of the Proterozoic evolution of the Eastern Bolivian shield: SHRIMP, TIMS and LA-MC-ICP-MS U-Pb zircon geochronology and Nd/Sr evidence from the Lomas Manechis and Pensamiento complexes

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Abstract

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Abstract

1. Introduction and tectonic framework

The Precambrian terrains of eastern Bolivia, as part of the Amazonian craton, have been studied during the last 5 years thanks to an international cooperative scientific program, sponsored by the Brazilian Council of Technological and Scientific Research. This effort has

provided a significant set of radiometric ages coupled with Nd/Sr isotopic and geochemical data for the most relevant lithostratigraphic units of the Precambrian shield, therefore allowing a better understanding of the Proterozoic polycyclic evolution. Nevertheless, many geological aspects are still unclear due to the lack of a systematic mapping project with the aid of geochronological and geophysical control, subsequent to the reconnaissance mapping undertaken by the Anglo-Bolivian cooperation program known as “Proyecto Precámbrico”-GEOBOL (Litherland et al., 1986, 1989). In a similar way the extensive rain forest cover with low exposure of outcrops, and particularly the limited access to extreme north of the area, along the border with Brazil are difficult task for any further geologic work.

This paper reports SHRIMP, TIMS U-Pb and Laser Ablation zircon ages for the metamorphic basement and granitoid rocks (Pensamiento Complex), coupled with new Sm-Nd T_{DM} ages. These data are interpreted together with the available geochronological background of Precambrian shield of Bolivia. As such, the age, origin and tectonic significance of these units are addressed, allowing correlations with the recognized igneous and tectonic events in the Brazilian counterpart of the SW Amazonian craton (Fig. 1).

Insert the Fig. 1 here

Further the continental substratum constituting the Paragua block in the extreme NE sector where the SISG is represented by San Simón, Dalriada and El Cielo were deformed during the San Ignacio orogeny (Fig 9). Arguably the anorogenic intrusives Remancito granitoid and Discordancia rapakivi granites (recognized in the Dalriada belt underlying Huanchaca according to Litherland, 1982) could represent the inboard manifestation of the San Ignacio collision of the Paragua Block against the RNJP, implying a within-plate origin for the Sunsás, Nova Brasilândia, and Aguapeí groups (Teixeira et al., 2010). Finally the Suite. Ion microprobe geochronology shows that zircons in granitic gneiss of the Rio Crespo Intrusive Suite are composed of 1,50 Ga igneous cores (Payolla et al., 2002; Bettencourt et al., 2006).

Recent field mapping and geochronological studies carried out on the Paragua block of the Mato Grosso state identified several intrusive bodies. The oldest one is the Agua Branca monzogranite gneiss that was analyzed by LA-ICP-MS in zircon grain yielding 1711 ± 13 Ma (Faria, Ruiz and Matos, 2009). Another pluton is the Turvo orthogneiss reported by Lisboa et al. (2009) where using Pb-Pb systematics in zircon grain obtained an age of 1651 ± 4 Ma. Geraldés et al. (2004) in the Mato Grosso state described the Santa Helena orogen composed by three syn-kinematic intrusions: the Santa Helena Intrusive Suite, Agua Clara Intrusive Suite and Pindaituba Intrusive Suite. These rocks present U-Pb zircon magmatic

ages ranging between 1,48 to 1,42 Ga, the Nd T_{DM} model ages between 1,5-1,8 and the ϵ_{Nd} between 0,03 to +4. Similarly the Rio Branco Intrusive Suite considered as a bimodal rapakivi igneous association yielded U-Pb zircon crystallization age of 1471 ± 8 Ma. In like manner a coeval body has been reported on the Paragua block of Brazilian-Bolivia boundary; the Cascata granite analyzed by Pb-Pb evaporation in zircon grain yielded 1412 ± 5 Ma (Cabrera et al., 2009).

The RSIP in Rondônia (Fig.2) consists predominantly of amphibolite grade granite-gneiss, tonalites and granitoid rocks genetically related to distinct magmatic arcs (e.g., Payolla et al., 2002), partly covered by Late-Mesoproterozoic sedimentary basins. Several AMCG-like intrusive suites are also present. The Sm-Nd studies of the RSIP granitoid rocks yielded positive to slightly negative $\epsilon_{Nd(t)}$ signatures roughly between +5.0 and -2.0 (Payolla et al., 2002; Tassinari et al., 2000), reinforcing the idea that juvenile events combined with reworking of the pre-existent crust played a major role during the plate convergence dynamics and further collision of the Paraguá block with the RNJP (Cordani and Teixeira, 2007). The collision features are envisaged by occurrence of shear zones and fold-and-thrust belts (Tassinari et al., 2000), as well as suggested by the 1.35 - 1.32 Ga granulitic metamorphism (SHRIMP U/Pb ages of zircon overgrowths) that overprints the country rocks of the RNJP.

The basement rock in the western side of Rondonia constitutes several complexes and suites represented by metavolcano-sedimentary sequences and mafic to felsic intrusive rocks. The Trincheira mafic- ultramafic complex comprises subvertical bands of amphibolites and metagabbros of N-MORB signature. The Colorado Complex (Rizzotto et al., 2002; Rizzotto and Quadros, 2007) probably represents the major, ultimate magmatic-metamorphic episode that built up the RSIP. This complex consists of amphibolites, serpentinites, metabasalts, interlayered BIF, para- and orthogneisses, schists and bimodal magmatism originated in a passive margin setting associated to an intra-oceanic arc amalgamated against the already cratonized rocks of the RNJP. In consequence the country rocks were deformed by compression tectonics associated to the collision whilst further intruded by syn and post-tectonic granites. The detailed geochronological data for the Colorado Complex allow the following inferences about the tectonic evolution (Rizzotto et al., 2002; Teixeira et al., 2006; Rizzotto and Quadros, 2007; Bettencourt et al., 2009): *i*) the detrital zircons ages in the paragneisses yield ages from 1938 to 1508; on the other hand the metamorphic zircons yield 1352 ± 4 Ma. The Nova Mamoré Metamorphic Suite is a meta-sedimentary sequence of migmatitic paragneiss, calc-silicate gneiss and granofels metamorphosed to the amphibolite facies. U-Pb detrital zircon age range between 2030 to 1532 Ma and metamorphic zircons yielded 1345 Ma age, this last one coeval with the PGC. Further the

Serra do Colorado Intrusive suite consists of layered mafic to ultramafic complexes; a metagabbro yields an age of 1352 ± 4 Ma considered the crystallization age. These basement rocks above described has been intruded by the Igarapé Enganado Intrusive Suite and the Alto Escondido Intrusive Suite both are composed by syenogranite and monzogranite and are intruded into the Colorado Complex. U-Pb SHRIMP in zircon grains of the Igarapé Enganado Intrusive Suite yield a crystallization age of 1340 ± 5 Ma and $\epsilon_{Nd} + 2.3$. The Alto Escondido Intrusive Suite produced a U-Pb Zircon (TIMS method) age of 1332 ± 3 Ma and a ϵ_{Nd} of $+1.5$ (Rizzotto and Quadros, 2007). On the other hand, on the Paragua block of the Mato Grosso state two plutons related to the PGC have been recently reported. The Guaporeí granite has been dated by Pb-Pb evaporation in zircon grain yielding 1314 ± 2 Ma (Nalon et al., 2009); whereas the Passagem granite (Jesus et al., 2010) yielded by LA-ICP-MS in zircon grain 1291 ± 2 Ma. Both of them could be considered late- to post- kinematic granites related to the PGC of the San Ignacio orogeny.

Obs. Além do Colorado existe mais outra unidade geológica descrita pelo Rizzoto e Quadros. Incluir também nesta sua síntese

The orogenic magmatism and deformation of the Colorado Complex is coeval with the Pensamiento Granitoid Complex in the Bolivian counterpart which is interpreted as the major product of the San Ignacio (SI) orogeny affecting voluminous parts of the Paraguá block.

The San Ignacio orogeny is the most important geochronological event in the Precambrian shield of Bolivia. This is manifested by the PGC that consists of voluminous, intrusive plutonic and subvolcanic granitoid rocks, with subordinate syenites, granodiorites, tonalites, trondhjemites and diorites and dispersed tonalites and granodiorites to the southwest of the Paragua block. This magmatism has been divided into two intrusive events on the basis of the structural work: *i*) the syn- to late kinematic granitoid rocks. *ii*) the late- to post- kinematic granitoid rocks. Regarding the metamorphism, the area north of the PGC have undergone the superposition of Mo2 and Mo3 events (Litherland et al., 1986) and possesses a very low grade metasedimentary core bordered by prograde metamorphism passing to a medium grade composed by gneisses and granofelses. To the east of PGC, near to the Brazilian border (Huanchaca) an apparent telescoping occurred between low grade chlorite sericite fabric to higher grade of sillimanite and perthite. More sharp changes show the metamorphic grade in the San Ramón area from low grade (chlorite) to medium grade (garnet and kyanite) and high grade with sillimanite attributed to the imprint of Sunsás orogeny. The area of San Ignacio and San Antonio de Lomerío is characterized by the record of staurolite and garnet. The gneisses of the Chiquitania Complex that crops out between San Ignacio and San Ramón are of high grade and show complex metamorphic and tectonic history without

regional metamorphic hypersthene and cordierite that characterize the Lomas Manechis Complex.

In Bolivia, the southwestern limit of the of the SI orogeny (RSIP) is assigned to the mylonitic shear zone of the Rio Negro Front and along the south to the Santa Catalina Straight Zone (Fig.2). The latter structure also marks the limit of the RSIP with the Sunsás collisional belt (e.g, Litherland et al., 1986), as indicated in the San Ramon district (SW fringe of the Paraguá block) where the metamorphic basement is deformed by an important oblique tectonic style, with sinistral shear sense, as suggested by geophysical interpretation (Matos, 2009). On the other hand, the east-west San Diablo Shear Front cross-cuts the structures of San Ignacio orogeny outcrops whilst showing a transcurrent motion (Landivar and Gonzalez, 1997).

The metasedimentary and bimodal metaplutonic Nova Brasilândia belt has a heterogeneous metamorphic grade that increases from N to S. Two episodes of felsic magmatism were recognized, the syn-kinematic Rio Branco suite (1.13 to 1.0 Ga) and the post-kinematic Rio Pardo suite (1.0 Ga). The Rio Branco suite shows derivation from magma source mixed with crustal material. The Rio Pardo suite records a juvenile component. The Ji-Paraná Shear Zone of amphibolite-grade is a large scale lineament of hundreds of kilometers long, that cut the Amazonian basement. It consists of subvertical mylonitic zones with horizontal L-fabric that record a sinistral shear sense. The timing of this deformation ranges between Ca 1.18 Ga to 1.15 Ga.

Insert here Fig. 2

2. Precambrian geology of Bolivia and previous geochronology

Early views of the geological framework of the Bolivian Precambrian shield considered that three major lithostratigraphic units made up the crystalline basement, on the basis of geologic mapping, metamorphic and structural studies, as well as reconnaissance scale Rb-Sr and K-Ar geochronology (e.g., Litherland et al., 1986): i) the Lomas Maneches Granulite Complex, ii) the Chiquitania Gneiss Complex, and iii) the San Ignacio Schist Group. These basement rocks were intruded by the Pensamiento Granitoid Complex (PGC) of widespread occurrence in the Paraguá block, considered as the most representative geologic unit of the so-called San Ignacio orogen (Table 1). Concerning the tectonic framework of the Precambrian shield of Bolivia two regional metamorphic episodes, Mo2 and Mo3 have been attributed to the Do1/Do2 and Do3 deformation phases respectively. The Do3 is considered the last phase of penetrative deformation related to the San Ignacio orogeny that yielded the So3 planar mica fabric and K-feldspar megacrysts evidenced principally in the gneisses. Furthermore, tectonic events that postdate Do3 have been

labelled Do4 and Do5 characterized by non penetrative phases. Nevertheless, subsequent studies supported by SHRIMP U-Pb and Sm-Nd data allowed a more realistic tectonic framework (e.g., Boger et al., 2005; Santos et al., 2008; Matos et al., 2009) of the Precambrian shield of Bolivia (Table 2). Then, the complex framework that characterized the San Ignacio orogen is followed to the southwestern side of the Bolivian Precambrian shield by the younger Sunsás orogen formed by the collision against the RSIP yielding folded and metamorphosed rocks over the orogen and is flat lying over the Paragua block this last one represented by the Huanchaca sedimentary cover (Teixeira et al., 2009).

Insert Table 1 here

Insert the Table 2

2.1 The Lomas Manechis Granulite Complex

This unit comprises granulites massifs passing upwards to biotite (+ garnet) gneisses. The granulites consist of bands of charnockitic, enderbitic and basic hypersthene granulites (Litherland et al., 1986). Santos et al. (2008) dated the Lomas Manechis granulitic gneiss on the way of Ascensión - Las Rengas, with the magmatic zircons yielding a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1818 ± 13 which is the older age identified in the Complex up to the present. The Sm-Nd T_{DM} age is 2.07 Ga and the ϵNd of +0.53. The additional monazite analysis provided a metamorphic age of 1339 ± 4 Ma. In the same sector another sample has metamorphic zircons with a precise and concordant $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1334 ± 2.4 Ma.

Finally, K-Ar data reported by Litherland et al. (1986) on hornblende and biotite (samples 23 and 24), to the northeastern of San Ignacio, yielded apparent ages of 1336 ± 33 Ma and 1323 ± 33 Ma respectively (Darbyshire, 1979), pointing to the regional cooling of the San Ignacio tectonic event, to be presented below.

2.2 The Chiquitania Gneiss Complex

This is the most widespread unit of the Bolivian Precambrian shield. It consists mainly of amphibolite facies, partly migmatized rocks that, exhibit complex structural evolution such as interference folding features. The transitional contacts with the San Ignacio schists (Litherland et al., (1986) suggest that they represent a single unit with barrovian metamorphic zoning, instead of different ones. The bulk of the Chiquitania complex is composed of pale pink to gray, biotite gneiss (medium- to coarse- grained) and banded, micaceous quartz-feldspathic gneisses, without hypersthene and cordierite (Litherland et al., 1986). They may be intercalated with granite gneisses (Boger et al., 2005), interpreted to be either of volcanic or sedimentary origins such as in the San Ignacio area. These authors sampled rocks 20 km east of San Rafael (Fig. 3), where the zircon cores yielded ages between 1830 Ma and 1690

Ma, whereas less discordant zircon grains yielded a mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1333 ± 6 Ma interpreted as due to a partial melt episode related to the so-called San Ignacio orogeny.

According to Boger et al. (2005) the Chiquitania Gneiss Complex derives from sources of about 1765 Ma and contains detritic zircons as young as 1690 Ma. Santos et al. (2008) reported for another outcrop that the main population of detritic zircons yields $^{207}\text{Pb}/^{206}\text{Pb}$ ages in the 1690-1630 Ma range, whereas the T_{DM} crustal residence ages are of 1.86.

2.3 The San Ignacio Schist Group

The San Ignacio Schist Group (SISG) crops out as discrete belts composed of metapsamites, schists, phyllites, slates, mafic metatuffs, BIF, metachert, metalavas of tholeiitic and felsic composition (e.g., Litherland et al., 1986), intruded by granitic rocks such as the La Cruz and Refugio ones (see discussion afterward). In the northeastern sector of the SISG the recognized San Simón, El Cielo and Dalriada structures are crosscut by the Remancito augen gneiss and Discordancia rapakivi granite (no geochronological data). In the extreme northeast (Paraguá block), the SISG is unconformably overlaid by the flat-lying Huanchaca Formation, while in the southern area the Sunsás folded strata (Sunsás belt) overlies the San Ignacio rocks. Boger et al. (2005) reported a U-Pb age for a San Ignacio paragneiss between San Rafael and San Ignacio village. The largest population (29 zircons) yielded a concordant $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1764 ± 6 Ma indicating that the protolith derived from a major Paleoproterozoic source, in roughly agreement with the T_{DM} ages available for the Chiquitania rocks (see above). For these authors the San Ignacio Schist Group derived from Paleoproterozoic sources and was not deposited before 1690 Ma.

The San Ignacio Group has been better studied than the other Precambrian units due to its metallogenetic potential. The Puquio Norte gold mine, for example, has been described as an exhalative-sedimentary (SEDEX) deposit associated with gold-chert in BIFs of oxides, sulfides and carbonates phases assigned to the local Naranjal Group, metamorphosed at the greenschist to amphibolite facies. Chert, serpentinite and amphibolites also occur 30km southeastern of San Ramón (R. Matos; GEOBOL, open file report 1995), and may be therefore assigned to the Naranjal unit as well. At regional scale, the recognized gold mineralizations have been interpreted as genetically related with oceanic volcanism accompanying deposition of the San Ignacio Group (Pinto-Vasquez, 2001).

Metavolcanic rocks were also described by Biste and Gourlay (2000) at the Ascensión de Guarayos, at the western border of the Precambrian shield of Bolivia (Fig. 3), where amphibolite grade volcanogenic massive sulfide body occurs. Discontinuous outcrops of serpentinites indicate that the metavolcanic sequence probably extends 40km south of Guarayos (Fletcher, 1979). In sum, these occurrences of metavolcanic rocks, interlayered

BIF, and schists may represent a single unit at least 250 to 300 km long and 60 to 85 km wide (from the north of Ascensión de Guarayos to Lomerío), genetically related to a magmatic arc (Fig. 3).

2.4 The Lomas Manechis Suite

Granitoid sills were called by Boger et al. (2005) Lomas Manechis suite. One of these sills at the east of San Rafael (an orthopyroxene bearing granitoid rock), contains zircon cores that yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ SHRIMP zircon age of 1663 ± 13 Ma, inferred as the rock emplacement age. Additional analyses of the zircon rims yielded an age of 1320 ± 11 Ma, interpreted as the time of partial melting, and reinforcing the important role of the San Ignacio overprinting event (see above). South from San Rafael, a hornblende-biotite granitoid rock yielded a concordant $^{207}\text{Pb}/^{206}\text{Pb}$ zircon SHRIMP zircon age of 1689 ± 5 Ma (Table 2).

Santos et al. (2006; 2008) reported additional SHRIMP U-Pb ages in zircon, monazite and titanite from granitoid rocks near San Javier (Table 1): one of these, the Refugio granite, has zircons with no metamorphic rim, and yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1641 ± 4 Ma and Sm-Nd T_{DM} model age of 1.66 Ga ($\epsilon_{\text{Nd}(t)} = +4.06$). On the other hand the Refugio granite (according to Fletcher, 1979) exhibits tectonic contacts along the eastern and western sides, while on its northern border it is intrusive into the San Ignacio Schist Group. Similar crosscutting relationships with these schists are reported for the La Cruz granite in the San Ramón area (see discussion afterwards; Table 2). From the above, the Lomas Manechis suite is significantly younger than Chiquitania and San Ignacio Group, as well as some of the granulites assigned as the proper Lomas Manechis Complex.

2.5 The San Ramon granite

This granite represents an important rock generation event about 1430 Ma in the Precámbrrian shield of Bolivia that could be confirmed in the future associated to others plutons in the area. The San Ramón granite is an intrusive body of ca. 35 km², and host shear zones following NNW direction. This pluton (Santos et al., 2008) (Table 1), yielded similar zircon and titanite SHRIMP U/Pb age of 1429 ± 4 Ma and TDM age of 1.6 Ga ($\epsilon_{\text{Nd}(t)} = +2.3$), establishing therefore a distinct igneous episode within the PGC. O. Santos (verbal communication) obtained Hf isotope analysis from this granite yielding a model age of 1.7 Ga and a ϵ_{Hf} between + 3.49 and +5.47. This implies that the juvenile accretion event was mainly from a Mesoproterozoic mantle source, as similar as several recognized arc magmatic pulses in the Brazilian counterpart, such as the Santa Helena, Rio Branco and Rio Crespo suites (Payolla et al., 2002; Geraldès et al., 2001; Cordani and Teixeira, 2007).

2.6 The San Ignacio Granitoid Complex

Much of the San Ignacio granitoid rocks make up the bulk of the Pensamiento Granitoid Complex (PGC) at the Paragua block (Litherland et al., 1986), while to the south and southwest part of the Bolivian shield, coeval granitic bodies are intrusive into the Chiquitania Complex, the San Ignacio Schist Group and the Lomas Manechis Complex (see above). The PGC and the coeval plutons are composed of two major regional units tectonically related with the so-called San Ignacio orogeny: syn- to late-kinematic and late- to post-kinematic granitoid rocks Litherland et al. (1986); Matos et al. (2009). Preliminary Rb/Sr whole rock isochrones for these intrusive plutons yielded ages between 1391 to 1244 Ma (e.g., Florida, San Cristobal, and Padre Eterno granites), as reported by Litherland et al. (1986) and confirmed by K/Ar geochronology referred to the uplift and regional cooling of the Paraguá craton. The Do3, the major penetrative event in the area related to the San Ignacio orogeny, accompanies generation of the bulk syn-kinematic granitoid plutons. Some of the late- to post-kinematic granitoid plutons postdate Do3 phase and were emplaced following a markedly NNW trend. Darbyshire (2000) first reported the Sm-Nd characteristics for PGC rocks. The syn- to late- kinematic Puerto Alegre/La Junta granites display roughly comparable T_{DM} model ages of 1.99 and 2.09 Ga and $\epsilon_{Nd(T)}$ values of -1.5 and -2.8 respectively (personal communication). In contrast, the Piso Firme Granophyre (Rb/Sr whole rock isochron age of ~1325 Ma; Litherland et al., 1986), yields significant younger T_{DM} model ages (1.51 and 1.57 Ga), and positive $\epsilon_{Nd(T)}$ values (+3.3 to +3.9). In a similar way the contemporary late- to post-kinematic Diamantina and Orobayaya granites yielded positive $\epsilon_{Nd(T)}$ values (+1.0 to +1.4) and T_{DM} model ages of 1.69 and 1.73 Ga.

2.6.1 The La Junta and San Martín granites

According to Matos et al. (2009) the syn- to late-kinematic La Junta pluton, crops out on the southern part of PGC and is constituted by gneisses of monzogranite to syenogranite composition with biotite as the principal and subordinate hornblende mafic minerals, with titanite as the characteristic accessory phase. Its texture is porphyritic and is medium to coarse grained. The San Martín pluton occupy the western part of the PGC; this body has a syenogranite composition, exhibits a granular texture with biotite and hornblende defining a weak foliation. The San Martín and La Junta granites show SiO₂ contents from 69 to 77 wt%. The major oxides display decreasing Al₂O₃, MgO, CaO and Fe₂O₃Tot with increasing SiO₂. They are high-K and calc-alkaline, moderately fractionated in terms of LREE/HREE with a slightly negative Eu anomaly. They show negative peaks of Sr, P and Ti with the typical pattern of Andean-type igneous rock. The San Martín and La Junta samples yield calculated $^{87}\text{Sr}/^{86}\text{Sr}_i$ ratios from 0.7039 to 0.7061; these plutons yielded “normal” crustal differentiation $f_{\text{Sm/Nd}}$ ratios of -0.28 to -0.50. The T_{DM} model ages is of 1.7 and 2.0 Ga, respectively (Table

2). The $\epsilon_{\text{Nd}(1.33\text{Ga})}$ value for the San Martin Granite is +1.8 whereas the La Junta Granite shows a contrasting source given by the negative values between -2.9 to -4.3.

2.6.2 *The Porvenir and San Cristobal granites and the Piso Firme granophyre*

These late- to post- kinematic bodies crop out in the northern part of the PGC. The Porvenir is a hornblende syenogranite to monzogranite. The San Cristobal pluton corresponds to a biotitic monzogranite. These three plutons display negative correlations for Al_2O_3 , MgO , CaO and $\text{Fe}_2\text{O}_3\text{Tot}$ with increasing SiO_2 contents and a positive correlation to the Na_2O . They have narrow range in SiO_2 contents (74 to 76%) and plot in the high-K field. The Piso Firme granophyre and San Cristobal have metaluminous composition and the Porvenir shows a peraluminous composition. All three bodies show low REE fractionation and a subhorizontal tendency of HREE with negative Eu anomaly and show deeper negative peaks of Sr, P and Ti (Matos et al., 2009). The San Cristobal, Porvenir and Piso Firme plutons show a larger variation in $^{87}\text{Sr}/^{86}\text{Sr}_t$ ratios from 0.7017 to 0.7066. The $f_{\text{Sm/Nd}}$ ratios between -0.31 and -0.25, T_{DM} model ages from 1.58 to 1.74 Ga, and positive $\epsilon_{\text{Nd}(1.33\text{Ga})}$ values of +2.7 to +1.5 (Table 2). This reinforces the important role of Mesoproterozoic mantle source in the magma genesis of these rocks.

2.6.3 *The Diamantina granite*

This intrusive body has a subcircular or elongate shape of 53 km long (Klinck and O'Connor, 1982), and crops out on the middle of the PGC, close to the road to Piso Firme village. This rock is a biotite syenogranite massive to moderately foliated with equigranular anhedral to subhedral texture. In thin section the K- feldspar is microperthite and contains patches of plagioclase intergrowth with vermicular quartz. This body shows SiO_2 content that ranges from 72 to 75wt%, and is placed on the peraluminous composition. In the REE patterns two different signatures can be distinguished: i) show steep patterns of LREE and depletion in HREE, probably reflecting amphibole fractionation and/or allanite. ii) shows “gull wing-shaped” REE patterns with moderate negative Eu anomaly, typical of differentiated granites. In the multielement diagrams, the negative peaks of Sr, P, and Ti can be interpreted as fractionation of mica, feldspar, apatite, and Ti phases. The Sm-Nd data of Diamantina Granite displays T_{DM} model ages between 1.65 and 1.92 Ga ($f_{\text{Sm/Nd}}$ ratios between -0.50 and -0.25), and $\epsilon_{\text{Nd}(1.33\text{Ga})}$ values from +0.4 to -1.2; the Diamantina granite displays a characteristic crustal mixing nature (Matos et al., 2009).

2.6.4 *The San Rafael granite*

This pluton occur between the road of San Rafael and San Miguel and it is characterized by pavement outcrops. The rock is a biotite-muscovite metagranite, medium

grained and moderately foliated orthogneiss; in places it is a feldspar augen gneiss. Under the microscope this body shows a hypidiomorphic texture. The principal accessories are the zircon sphene and Fe-opaques (Litherland, 1979). Boger et al. (2005) reported a SHRIMP U/Pb age of 1334 ± 12 Ma for the syn-kinematic San Rafael granite, interpreted as the emplacement age. In addition, five zircon cores from this granite yielded an upper intercept age of 1686 ± 16 Ma, suggesting the derivation from a Paleo-Mesoproterozoic protolith likewise suggested by the Nd signatures reported for some PGC rocks by Darbyshire (2000).

2.6.5 The Santa Rita and Rio Fortuna orthogneiss

Santos et al. (2008) sampled the Santa Rita orthogneiss of granodioritic composition 34 km northeastern of San Ignacio. This rock probably correspond to the Espíritu metagranite that occur in this part as small out crops of homogeneous, medium-grained composed by quartz, microcline perthite, oligoclase and straw-coloured biotite (Litherland, 1979). Following Santos et al. (2008) this rock has magmatic zircons with SHRIMP U/Pb age of 1319 ± 6 Ma, whereas one inherited grain gives 1674 ± 21 Ma (see Table 2). In addition, the Rio Fortuna orthogneiss, eastern of San Ignacio. It is a dark gray, granodioritic to tonalitic composition and has two zircon populations. The first one, magmatic zircon and rim formed at 1336 ± 3 Ma, and the second one, inherited grains and cores at 1753 ± 10 Ma.

2.6.6 Talcoso granite

This pluton is exposed 18 km north of San Javier, it is characterized by the rounded form with its diameter of 13 km long. On colour composite imagery the granitoid show clear contacts with the host rock. Fletcher (1976) considered this body composed of quartz monzonite to granite and distinguished two phases, the first one occupy a band at the eastern side of the pluton and two portions in the western side. The second phase is more developed in the central part. There is not evidence of hydrothermal activity around the body and no metamorphic aureole have been observed. Litherland et al. (1986) reported a sample of pegmatite cutting the Talcoso granite yielding K-Ar age of 986 ± 27 Ma.

2.6.7 Limonal granite

The San Antonio de Lomerío area, localized to the southeastern of San Ramón, is characterized by two types of granites: Santa Rosario and Limonal (Fletcher, 1979), both groups hosted by the La Bella Group (a local name of the SISG). Whereas the first one resulted by interference model the second forms irregular bodies. Seven bodies form the Limonal granitoids, they are porphyroblastic leucosyenogranites, medium to coarse-grained. The K-feldspar is a microcline-perthite that forms scattered porphyroblast to subporphyroblast of about 2-3 cm. The biotite is the principal mafic mineral (3%),

accompanied by muscovite (3%). A foliation is commonly developed around the bodies containing ovoid patches of weakly deformed material. Some exposures of garnet bearing pegmatoids have been noted in a phase of this granite (Fletcher, 1979).

2.6.8 Cachuela granite

This intrusive body outcrops 22 km east of San Ramón, is a subcircular unit of 7 km long and it forms extensive rounded blocks and pavements. On the color composite image of airborne radiometric and magnetic data of the San Ramón area (Adamek et al., 1996) shows clear expression contacts, hosted by the San Ignacio Schist Group. The rock is pale pink medium to coarse-grained containing scattered K-feldspar megacrysts around 1 to 2 cm long. Under the microscope, this intrusive shows two generation of quartz, K-feldspar and plagioclase: major and minor components, both of them show an anhedral granular texture. The mafic scarce mineral is the green biotite with chlorite growing from biotite. TIMS analysis of multigrain fraction zircons from six points plotted in the Concordia diagram yielded upper intercept age of 1307.3 ± 6.6 Ma. Two concordant points yielded $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1309.5 Ma (0.52% of discordance) and 1310.9 Ma (-0.76% of discordance) Vargas-Mattos et al., 2008.

2.6.9 San Andrés granite

Santos et al. (2008), sampled the San Andrés granite west of Concepción on the road to San Javier. This body is one of the most developed in the area and follow an NNW trend; the rock is pale gray, coarse-grained leucocratic biotite granite with an inequigranular anhedral to subhedral texture. The outcrops form big exposures of rounded blocks; in places contains scattered K-feldspar megacrysts. Typically this body has a massive appearance forming an ovoid patch of weakly deformed material surrounded by strongly deformed rock due to Sunsás deformation and constituting a K-feldspar augen gneiss (R. Matos, verbal communication). This post-kinematic body could be considered the last pulse of the San Ignacio orogeny and yielded a SHRIMP U/Pb age of 1275 ± 7 Ma (Table 1), coeval with the Passagem granite of 1291 ± 2 Ma in Mato Grosso (Jesus et al., 2010).

3. Analytical methods

Zircon crystals were dated by U-Pb SHRIMP, TIMS and LA-MC-ICP-MS methods; the zircon grains were separated using conventional heavy liquid and magnetic techniques. The La Junta (sample LJ20512) and San Martín (CA0509), Diamantina (CP30507), La Cruz (LC0558) and San Andrés (SA0404) granites were dated by U-Pb SHRIMP. Representative

zircon grains were handpicked under binocular microscope and mounted in epoxy resin disc, and then polished and coated with gold film. Zircons were documented with transmitted and reflected light images as well as cathodoluminescence (CL) images to reveal their external and internal structures. The U-Pb isotopic analyses were performed using the Sensitive High-Resolution Ion Microprobe (SHRIMP-II) at the Chinese Academy of Geological Sciences (Beijing). Data were plotted on Concordia diagram using isoplot excel software (Ludwig, 2003). Details of the analytical procedures of zircons using SHRIMP were described by Compston et al. (1992). Inter-element fractionation ion emission of zircon was corrected relative to the RSES reference TEMORA 1 (417 Ma; Black et al., 2003). The uncertainties in ages are cited as 1σ and the weighted mean ages are quoted at the 95% confidence level (2σ). All ages described on the text are weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ ages (Table 3).

The Refugio (sample SR83) and Las Maras (sample LM81) granites were analyzed by U-Pb TIMS methodology following procedures outlined in Parrish et al. (1987). Prior to dissolution zircon fractions were strongly abraded to remove outer rims and minimize the effects of peripheral lead loss and individual grains carefully selected. Zircons were dissolved and Pb and U were separated using procedures following Basei et al. (1995) adapted of Krogh (1982). All samples were total- spiked with a mixed $^{205}\text{Pb}/^{235}\text{U}$ tracer solution. The U/Pb isotopic analyses were done in a multi-collector ion counting Finnigan MAT-262 mass spectrometer at the Geochronological Research Center (CPGeo) of the Instituto de Geociências at the University of Sao Paulo. The isotopic data are presented in Table 3. Zircon data were calculated using the Microsoft Excel version of Isoplot (Ludwig, 2003). Age uncertainties in the table, Concordia plots and text are presented at the 95% confidence level.

U-Pb LA-MC-ICP-MS were performed for the San Pablo (sample SP0601), Talcoso (sample BO418) and Limonal (sample MT544) granites. Selected grains were placed on epoxy mounts, polished and cleaned with 3% nitric acid before analysis. Backscattering electrons (BSE) images were used for spot targeting. BSE images were acquired with a JEOL 5510 scanning electron microscope at the Department of Geology of the Federal University of Ouro Preto, Brazil. The U-Pb analyses were performed on zircon grains using a Neptune MC-ICP-MS coupled with a Nd:YAG UP213 New Wave laser ablation system, installed in the Laboratory of Geochronology of the University of Brasilia. The U-Pb analyses on zircon grains were carried out using the standard-sample bracketing method using the GJ-1 standard zircon in order to control the ICP-MS fractionation. Two to four samples have been analyzed between GJ-1 standard analysis and $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ ratio have been time corrected. When possible, on larger zircon grains, laser induced U and Pb fractionation

was minimized using raster laser ablation with a spot size of 30 μm . On smaller zircon grains single spot laser induced fractionation the $^{206}\text{Pb}/^{238}\text{U}$ ratio was recalculated using the linear regression method (Kosler et al., 2001). The raw data processed off-line and reduced using an Excel worksheet (Buhn et al., 2008). During analytical session zircon standard Temora-2 has been analyzed as an unknown sample. Common lead (^{204}Pb) interference- and background correction is normally carried out monitoring the ^{202}Hg and ($^{204}\text{Hg}+^{204}\text{Pb}$) masses during analytical sessions and using a model Pb composition (Stacey and Kramer, 1975).

The Table 4 shows the samples that were analyzed by Sm-Nd whole-rock technique at the Geochronological Research Center (CPGeo) of the IGc-USP. Approximately 0.1 mg of powdered rock sample was dissolved in concentrated HNO_3 , HF and HCl. The Sm and Nd concentrations were determined by isotope dilution with a combined spike tracer, using the two-column technique, as described by Sato et al. (1995). The isotope ratios were measured on VG-354 multi-collector mass spectrometer. Laboratory blanks for the chemical procedure, during the period of analyses, yielded maximum values of 0.4 ng for Nd and 0.7 ng for Sm. The average $^{143}\text{Nd}/^{144}\text{Nd}$ for La Jolla standard was 0.511857 (46 analyses), with 2σ standard deviations reported in parentheses. The Sm-Nd T_{DM} model ages were calculated using DePaolo (1981) model parameters: $a=0.25$, $b=3$, $c=8.5$ as well as $^{143}\text{Nd}/^{144}\text{Nd}=0.7219$ to normalize the isotope ratios [$^{143}\text{Nd}/^{144}\text{Nd}(\text{CHUR})_0 = 0.512638$ and $^{147}\text{Sm}/^{144}\text{Nd}(\text{CHUR})_0 = 0.1967$]. The ϵ_{Nd} values were calculated using the simplified equation $\epsilon_{\text{Nd}(T)} = \epsilon_{\text{Nd}(0)} - Q_{\text{Nd}} f_{\text{Sm}/\text{Nd}} T$, with the $(\text{CHUR})_0$ values above and $Q_{\text{Nd}} = 25.09$. The ϵ_{Nd} values for the PGC samples were recalculated for the SHRIMP U-Pb age of 1.33 Ga, reported by Boger et al (2005). Table 4 presents the analytical data.

4. Results

4.1 Yarituses suite

The U-Pb geochronological SHRIMP, TIMS and laser ablation-ICP-MS from this study document Paleoproterozoic crust formation in the form of 1673 Ma to 1621 Ma of this granitic suite (after the Yarituses tribe that occupies the San Javier area where this suite crop out). The data shows that these granites not only are granitic sills as mentioned by Boger et al (2005), instead they represent a large portion of plutons in the Precambrian shield of Bolivia. This fact induce as to introduce the Yarituses suite as a new discovery instead of the Lomas Manechis suite of Boger et al. (2005), and maintain the Lomas Manechis Granulite Complex of Litherland as structurally the lowest and older unit as determined by Santos et al. (2008) for the granulite gneiss of 1818 ± 13 Ma in the area of San Matías. The Yarituses suite just to now comprises the La Cruz granite, Refugio granite and San Pablo Granite.

4.1.1 La Cruz granite.

This pluton crops out 15 km to the northeast of San Ramón, and constitutes two individual bodies hosted by the San Ignacio Schist Group (Fig. 3). As a whole it shows clearly contacts with the hosted San Ignacio Schist Group as can be seen in color composite satellite imagery and presents a roughly sigmoidal-shape showing the typical deformation trend of the Sunsás orogeny. The La Cruz intrusion (sample LC0558) is a pale pink leucocratic syenogranite with scarce biotite as the mafic mineral. The dominant texture is allotriomorphic granular. From the principal minerals the K-feldspar is characterized by a abundant flame-like or braided pattern perthite.

Zircons from the La Cruz granite are between 100-220 μm long and generally have ratios close to 2:1. The U content of zircon is variable from 138 to 932 ppm, only one grain contains 3134 ppm. The Th/U ratios vary between 0.27 and 0.92 (Table 3), suggesting a magmatic origin. The cathodoluminescent images show that most of the crystals are euhedral and have both parallel-faces zoning and distinct concentric growth. SHRIMP analysis of eight zircon grains (Table 3), and five cores lie on the Concordia with a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1673 ± 21 Ma (MSWD=1.6) (Fig. 4a and 4b), considered as the emplacement. This age compares within error with two ages obtained by Boger et al. (2005) and one by Santos et al. (2008) for the Lomas Manechis rocks in the range of 1689 to 1663 Ma. The Sm-Nd whole rock analyses for the La Cruz granite yielded crustal differentiation $f_{\text{Sm/Nd}}$ ratio of -0.42. Their T_{DM} model ages are 1.83 Ga (Table 4). The $\epsilon_{\text{Nd}(1.67\text{Ga})}$ value for this body is + 2.1.

4.1.2 Refugio granite

The Refugio granite is a large body that crops out on the northern side of the road San Javier – Concepción (Fig. 3). We have sampled this granite in two places: sample RF0408 and SR83. The first one was sampled 17 km. eastern of San Javier on the road to Concepción. It was sampled by Sm-Nd that will be discussed later. The rock is a syenogranite, weakly foliated, with hipidiomorphic-granular texture; the plagioclase tend to be euhedral, while the alkali feldspar is subhedral and quartz occupies irregular interspaces. Locally is observed a fine grained matrix of irregular patches of granulated quartz-feldspar material. The mafic mineral is the green biotite seldom chloritized. The SR83 was sampled at 8 km eastern of San Javier on the road to Talcoso hill. This rock is a leucogranite, white in color, masive to weakly foliated. The K-feldspar is the microcline and subordinately appears the orthoclase, the plagioclase tend to be euhedral. Both of them contain disseminated sericite-epidote alteration. The mafic mineral is the biotite scarcely distributed in the rock (<2%); the principal accessory is the brown granular sphene. Zircon mostly occurs as colourless elongate prisms, light brown stubby grains are also present. Core and oscillatory were observed in a number of grains by transmitted – light microscopy. TIMS analyses of four multigrain fractions yield

three concordant points and one discordant point (Fig 4c) with $^{207}\text{Pb}/^{206}\text{Pb}$ age of $1673 \pm 25\text{Ma}$, a MSWD of 36 taken as the best estimate for the time of crystallization of the pluton.

4.1.3 San Pablo granite

This body has 11 km long by 4 km wide and is exposed 25 km southern of San Antonio de Lomerío (Fig. 3). It is oriented WNW parallel to the San Diablo lineament and consequently the granite has been sheared; the rock is pink in color, fine to medium-grained and composed by a biotite quartz monzonite. In thin section the rock has an anhedral-granular texture. The plagioclase shows curved twins. Both K-feldspar and plagioclase show altered surfaces. The quartz is anhedral, occupying irregular spaces between the other constituents. The mafic mineral is the biotite, straw to green in color and often it carries dusty inclusions of iron ore. The rock has been crushed and it contains bands of finely comminuted material around the felsic grains. Zircons from the San Pablo quartz monzonite (sample SP0601) appear to be colorless, transparent, with well crystallized prismatic form. Rhyolite zoning, manifested by the CL images, indicates their magmatic origin. The analytical results are listed in Table 3. The all data combined yield an average age of $1621 \pm 80\text{ Ma}$ (2σ) (Fig. 4d).

Insert the Fig. 4 here

4.2 San Ramón granite

This pluton crop out at San Ramón town (Fig.3). Contact relations with the Chiquitania Gneiss Complex are largely masked by Cenozoic sediments; it probably extends farther west, but the limits are still unknown. The sample SR0401 of this body is gray in color, composed of biotite granodiorite with anhedral granular texture, where the mafic minerals in aggregates show an irregular distribution; the characteristic accessory minerals are titanite, allanite and zircon. The San Ramón granite has been sampled by Sm-Nd (see below).

4.3 San Ignacio granitoid rocks (SIG)

The SHRIMP U-Pb age determinations in zircon grains were performed in the San Martín, La Junta, Diamantina and San Andrés granites.

4.3.1 San Martín granite

This pluton is one of largest syn- to late-kinematic intrusions of the PGC and it crops out on the western side of PGC (Fig. 3). This weakly foliated granite has a granular appearance with biotite flakes and prismatic hornblende. The K-feldspar forms scattered phenocrysts from 1.5 to 3 cm long. In places a lens or augen-texture is developed. On the western side of the batholiths the mineral assemblage reached the medium metamorphic

grade conditions (Klinck and O'Connor, 1982). The analyzed zircon grains are commonly between 150 to 275 μm and mostly euhedral with ratios of 3-4:1. The U content is variable, from 160 to 2700 ppm. The Th/U ratios are between 0.24-0.47, but three of the analyses showed Th/U ratios as low as 0.02 -0.04. The most common zircon morphology shows oscillatory zoning in the cathodoluminescent (CL) imagery. However, some grains present a moderately gray-CL core (Table 3).

Ten analyses from various sites within different zircon grains from the two main populations were obtained (Table 3). Six magmatic cores yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1373 ± 20 Ma (MSWD = 0.83) whereas three metamorphic rims yielded 1318 ± 14 Ma (MSWD = 1.4) (Fig. 5a). Fig. 5b Given the concentrically zoned structure of the zircons of the first population, we interpret the upper intercept age obtained from the core analyses as the emplacement age of the San Martin granite, in agreement therefore with the the syn-kinematic phase of the San Ignacio Orogeny. The metamorphic rims are interpreted as high-grade metamorphism formed during the collision of San Ignacio orogeny against the Rio Negro-Juruena Province, as an extrapolation with comparable U/Pb data available for the Colorado Complex in Rondonia.

4.3.2 *La Junta granite*

This is one of the syn- to late-kinematic granitoids of the San Ignacio Orogeny. The body is exposed as sprinkled outcrops on the southern part of PGC (Fig. 3), and may become gneissic with a well developed planar tectonic fabric (Hawkins, 1982). However, the La Junta granite, for the most part shows a transition from saturated monzogranites to more differentiated syenogranites (Matos et al., 2009). The rocks are pinkish-grey in color, medium to coarse-grained, and show inequigranular subhedral to anhedral texture. The main mineral constituents are a porphyroblastic alkali feldspar and string perthitic microcline, aligned with the the biotite foliation. Prismatic hornblende is associated to quartz and plagioclase with myrmekitic intergrowth.

U-Pb data from the La Junta Granite (sample LJ0512) was collected following the road to Campamento (Fig. 3). Zircons from this sample are from 165 to 235 μm and commonly show well-formed euhedral terminations. The cathodoluminescent images the crystals generally have cores with gray light oscillatory zoning, surrounded by thin mantles of low-CL zircon. The low-CL rims show subtle concentric zoning, not developed in the cores. Some grains are gray dark due the high U content. Seven analyses of zircon grains performed in this sample. The zircon cores are characterized by U concentrations of 168 to 542 but one grain exceptionally has 3154 ppm. The Th/U ratios vary between 0.18 and 0.77, only one grain has

a value of 0.06 (Table 3). From five core analyses, an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1347 ± 21 Ma (MSWD = 4.5) was obtained (Fig. 5c) and constrains the age of emplacement. Grain 512.3 (Fig. 5.d) shows an inherited minimum age of 1486 ± 18 Ma.

4.3.3 *Diamantina granite*

This intrusion in contrast to the two bodies described above, represents the late- to post-kinematic granites of the San Ignacio Orogeny. This pluton makes up a north trending hill, forming an elliptical body about 53 km long (Klinck and O'Connor, 1982) and crops out as an “island” in the forest. The subcircular or elongate shape of the granitoid body is based on field relationship and it can not be seen on the color satellite imagery. The dominant rock type is a pale pink and non foliated biotitic syenogranite. This rock is a light-grey, weathering greyish-orange-pink in color, medium- to coarse-grained. Chemically the western side of the Diamantine granite is composed of tonalite and syenogranites but all bulk of the samples are monzogranites (Matos et al., 2009). One syenogranite sample (CP0507) was sampled at Cerro Pelado Hill. The zircons are between 160-270 μm long and some grains have ratios about 4:1. In this sample, the U content is variable, from 140 to 683 ppm, while Th/U ratios vary between 0.07 and 1.07 suggesting a magmatic origin. Two grains are metamorphic, containing U content of 2377 and 2753 ppm (Table 3). Cathodoluminescent images of these zircons show that all grains have distinct concentric growth zoning which is often truncated by the margins of the zircon grains. The concentric growth is interpreted to represent zircon growth at the time of emplacement of the granite. From six analyses on five zircons an upper intercept yield a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1340 ± 20 Ma (MSWD= 4.1) (Fig. 5e).

4.3.4 *Las Maras granite*

The granitoid forms a near rectangular body exposed 9 km NW of San Javier, with its long axis of 5 km oriented N. The wide in an E- W direction is of 2,5 km. On the color composite image of airborne radiometric and magnetic data of the San Ramón area (Adamek et al., 1996) has a marked expression hosted in the SISG. The characteristic rock is a light pink, weathering orange, coarse grained monzogranite. Pinkish gray- feldspar locally forms phenocryst up to 1,5 cm. long and the biotite occurs as scarce flakes. To the S, the Las Maras granite is hosted by a turbidity metasedimentary rock characterized by the graded beds, but the contacts are not exposed. To the N of the body the hosted rock is a crenulated muscovite schist. Petrographic analyses show a hipidiomorphic texture, The K-feldspar forms large anhedral crystals, the plagioclase is subhedral; both of them contain rectangular flakes of muscovite and the quartz in minor size occupies irregular interspaces. The mafic mineral is the straw green biotite scarcely distributed in the rock (<2%). Zircon shows prismatic elongate morphology. Some Core – overgrowth relationships have been observed by

transmitted – light microscopy. U –Pb TIMS analysis (Table 3) of four multigram fractions yield four concordant points (Fig. 5f), with $^{207}\text{Pb}/^{206}\text{Pb}$ of 1346.8 ± 9.3 Ma with a MSWD of 8.3. Taking into account field relationships with de SISG (ca 1.7 Ga) and an age comparable to the Diamantina granite (1340 ± 21 Ma by U-Pb SHRIMP) this granite is post-kinematic to the SIO.

4.3.5 Talcoso granite

This rounded body has a massive and coarse- grained character. The foliation in the host rock follow a NW trend as is seen on the satellite imagery at the northeastern side of the pluton. On the composite colour image of the airborne radiometric and magnetic data (Adamek et al., 1996) this pluton show S-C sinistral structure produced by the Sunsas orogeny that reimprinted the San Ignacio orogeny. In thin section the intrusive shows two generation of quartz microcline perthite and plagioclase: major and minor components. The major crystals consist of subhedral granular texture and the minor crystals form mosaic of anhedral fine grained texture between the grains boundaries. This second generation can be attributed to the granulation of the rock due to the Sunsas orogeny. The k-feldspar appears as perthite microcline with grain boundary embayed by mirmequite intergrowth, the quartz show fractured grains. The mafic mineral consists of strew – green biotite accompanied by scarce muscovite, with epidote as the principal secondary mineral. On the basis of its intrusive contacts respect the hosted Naranjal Group (a local name for the San Ignacio Schist Group), that follow a NW trend of foliation, and the isotropic character of the granite in hand sample the age of this rock can be considered post -kinematic with respect to the San Ignacio orogeny. Zircons from the Talcoso granite (TL0402) appear to be colorless, transparent, well crystallized with prismatic form. The analytical results are listed in Table 3. The weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age yielded 1333 ± 68 Ma for a MSWD= 75) (Fig. 5g).

4.3.6 Limonal granite

This pluton forms a group of bodies that crops out along a sheared narrow zone following a WNW trend formed during the Sunsas orogeny. This ductile shear zone record displacement between blocks where recognizable markers such as grain tail (we use grain in a general sense, in this case referred to large granitic body), that acted as rigid bodies. The tail of σ type lets us determine the sinistral shear sense as is shown in Fig 6. We have sampled one body (MT0544) of the Limonal granitoids. Zircon grains are mostly colorless, transparent, well crystallized with prismatic habit. The CL images show magmatic zoning. 30 μm spot sizes applied for this sample are listed in Table 3. The weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age yielded 1330 ± 36 Ma (MSWD = 81) (Fig. 5i).

4.3.7 San Andrés granite

This pluton is exposed to the western side of Concepcion (Fig. 3). The granite for the most part is heterogeneous varying from sheared feldspar-augen gneiss, migmatitic schlieren type with biotite defining short strings to a medium to coarse-grained massive rock. The color composite satellite imagery do not show contacts of this unit with other lithologies, however the composite radiometric and magnetometric image (Adamek et al 1996) shows a fish-like form (Fig. 3). Zircon grains are clear and euhedral prismatic. The crystals range from 50 to 120 μm in length, with ratios of 2:1 to 4:1. The CL images reveal that most grains have oscillatory zoning, indicating magmatic origin. A total of 15 analyses were performed on 14 zircons from sample SA0404. They have U contents ranging from 79 to 434 ppm and Th/U contents of 0.24 to 0.85 (Table 3). The data define an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1289 ± 19 interpreted as a magmatic age (Fig. 5j). Furthermore, one analysis of an inherited age (grain 1.13) yield a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1616 ± 18 (Fig. 5k).

Fig. 5: insert here

Fig. 6: insert here

4.4 Sm-Nd results

. Fifty five samples of the Bolivian Precambrian shield were investigated (Table 4) following De Paolo (1981); the Nd isotopic parameter were calculated according as reference SHRIMP U/Pb age of 1.8 Ga for the Lomas Maneches Complex; 1.67 to 1.62 for samples of the Chiquitania Complex and Yarituses suite; the San Ramón granite was modeled according to 1.4 Ga and the San Ignacio granites following 1.33 Ga and 1.27 for the San Andrés granite all these ages interpreted as the emplacement age respectively. The ϵ_{Nd} versus T diagram is shown in Fig. 7 and Fig.8 represents the isotopic boundaries based on the T_{DM} values. One sample of the Lomas Manechis Granulite Complex yield the oldest crystallization age of 1.8 Ga and another sample yields the oldest model age value of 2.2 Ga. The ϵ_{Nd} range from 3.32 to -1.44 indicating mantle- derived magmas variably contaminated with Paleoproterozoic crust in the evolution of the Lomas Maneches Complex.

The Chiquitania Gneiss Complex presents T_{DM} model ages values of 1.6 to 1.9 Ga and ϵ_{Nd} values from +4.2 to -0.61; the $f_{\text{Sm/Nd}}$ ratio is of -0.3 to -0.56. The ϵ_{Nd} values represent juvenile accretion and limited contamination of the parental magma with the country rocks. The Yarituses suite contains $f_{\text{Sm/Nd}}$ ratio of -0.38 to -0.56, T_{DM} model ages of 1.7 to 1.9 Ga, and

Further the continental substratum constituting the Paragua block in the extreme NE sector where the SISG is represented by San Simón, Dalriada and El Cielo were deformed during the San Ignacio orogeny (Fig 9). Arguably the anorogenic intrusives Remancito granitoid and Discordancia rapakivi granites (recognized in the Dalriada belt underlying Huanchaca according to Litherland, 1982) could represent the inboard manifestation of the San Ignacio collision of the Paragua Block against the RNJP, implying a within-plate origin for the Sunsás, Nova Brasilândia, and Aguapeí groups (Teixeira et al., 2010). Finally the the Rio Negro Jurueña province.

Fig. 7: insert here

Fig.8: insert here

5. Discussion and tectonic implications

5.1 Proterozoic tectonic history

The Lomas Manechis and the Chiquitania complexes and the San Ignacio Schist Group constitute the Paleoproterozoic polymetamorphic basement (Fig. 9), as supported by the available U-Pb evidence shown on Fig. 3 (Boger et al., 2005; Santos et al., 2008; Matos et al., 2009). The Lomas Manechis is comparable in age and Nd signature to the Alto Guaporé Metamorphic Complex of Brazil (Bettencourt et al., 2010), although they differ in the metamorphic grade corresponding to granulites and green schist-amphibolite respectively. The western side of Paragua block, the San Ramón District preserves an island- arc tectonic setting comprising mafic ultramafic bodies, BIF and chert that are similar in the lithologies and age to the Alto Jauru Group in Mato Grosso state (Geraldes et al., 2001; Teixeira et al., 2010). This lithological association was progressively amalgamated to the evolving continental margin, revealing a large oceanic domain in this area of Bolivia at the Paleoproterozoic time.

Supported by the U-Pb and Sm-Nd results three magmatic events mark the evolution of the Precambrian shield of Bolivia: The Yarituses suite, The San Ramón granite and the San Ignacio granites (Table 4). The San Ramón granite produced a crystallization age 1.43 Ga, T_{DM} model ages of 1.6-1.7 and positive ϵ_{Nd} values. This granite is comparable in age to the Santa Helena orogen (1.48-1.42 Ga). In the San Ignacio granites zircon geochronology has made it possible to identify magmatic and metamorphic events and interpret inherited grains in the eastern Precambrian rocks of Bolivia. These rocks represented by syn-to late-kinematic and late-to post-kinematic granitoids have magmatic age between 1.37 to 1.34 and metamorphic zircon ages from 1.32 to 1.3 Ga, therefore it is the major accretionary event in Bolivia. The protracted history of those rocks is envisaged for inherited zircon from 1.62 to 1.77 Ga, allowing to propose a crustal derivation from the Paraguá rocks (the Lomas

Manechis and the Chiquitania complexes) as well as a tectonic correlation with the Rio Negro-Juruena and Ventuari-Tapajos province. In the southeastern of Rondônia. Contemporary orogenic and post-orogenic granites make up the bulk of the 1.36-1.30 Ga Colorado Complex (Rizzotto and Quadros 2007). San Ramón area is characterized by an oblique tectonic style produced during the Sunsás orogeny over pre-San Ignacio rocks (Fig.6), with structures similar to the Nova Brasilândia and Ji-Parana shear zones (Tohver et al., 2002; Tohver et al., 2004; Tohver et al., 2005) with sinistral shear sense (Adamek et al., 1996; Matos, 2009). Such features are collectively related to the collision between Amazonia and Laurentia during Sunsás orogeny (Teixeira et al., 2010), and implying therefore to a continuity of structures from Rondônia to Bolivia. This scenario let us to conclude that the Paraguá Block was allochthonous with respect to the Rio Negro-Juruena and it moved to the ENE and accreted during the San Ignacio orogeny.

Fig. 9: insert here

5.2 Tectonic extrapolations:

5.2.1 The Cerro Uyarani

This unit in the Western Cordillera (Volcanic arc) of Bolivia (Fig. 1) represents one of the Paleoproterozoic inliers in the Andean chain. It shows a rounded shape of 4 km of diameter with exposures rising up 4500 m above the sea level, in some places covered by tertiary tuffs. In the outcrops a medium-fine grained gneissic leptite, mafic granulites, charnockites and amphibolites predominate (Worner et al., 2000) with the foliation following the NW direction. Additionally, 150 km north of Uyarani a metaconglomerate was described in the Azurite Formation (Tosdal 1996) and at the Cerro Chilla (R. Matos, personal communication). All these exposures are part of the Arequipa Antofalla Block, (AAB), a Proterozoic crustal block along the Central Andean margin. Wasteneys et al. (1995) considered the AAB a rifted margin of eastern Laurentia. According Tosdal (1996), the Pb isotopic composition of AAB overlaps those of the AC, supporting a link between them. Loewy et al. (2004) conclude that the AAB was accreted to AC during Sunsás orogeny. Based in geothermobarometry, geochemical and petrological studies at Cerro Uyarani, Worner et al. (2000) consider it as part as of the AAB; the zircon TIMS analysis from a charnockite of Cerro Uyarani defined a discordia with an upper intercept of 2024 ± 133 Ma and a lower intercept of 1157 ± 62 Ma; the $^{40}\text{Ar}/^{39}\text{Ar}$ spectrum age from amphiboles separated from an amphibolite of Cerro Uyarani defined a plateau age of 982.5 ± 1.7 Ma by 77.1% of the total ^{39}Ar released. A Sm-Nd isochron has been improved to get of the time of near-peak of high grade metamorphism giving an age of 1008 ± 16 Ma (Worner et al., 2000).

On the basis of our new data and geologic correlations we envisage the following evolution for the Precambrian shield of Bolivia (Fig 10) on the basis of the available Pb isotope composition regional study (Tosdal, 1996; Worner et al., 2000) of the AAB and accepting that this Proterozoic terrane was part of the Amazonian craton (Fig 10a).

1. Rifting during break up of Amazonian Craton in the late Paleoproterozoic led to separation of AAB from the AC (Paraguá Block) (Fig 10b). The boundary between the two crustal blocks constitute an ocean (here called Guarayos ocean).
2. Andean- type subduction between these two blocks originated the Yarituses suite at late Paleoproterozoic (1.7-1.6 Ga) (Fig 10c). The paleosuture of the ocean crust could be the San Ignacio Group of San Ramón area.
3. Later subduction led to the collision of the Paragua Block against RNJP during San Ignacio orogeny (1340-1320 Ma) (Fig 10d).
4. Eventually, during Sunsás orogeny occurred the collision of Laurentia against the AC and the accretion of AAB and the Sunsás belt against the Rondonian San Ignacio Province (Fig 10e).

Fig. 10: insert here

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SM – ND CHARACTERISTICS OF THE DIAMANTINA GRANITOID, RONDONIAN-SAN IGNACIO PROVINCE - BOLIVIAN EASTERN PRECAMBRIAN SHIELD

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Keywords: Bolivia, Pensamiento Granitoid Complex, San Ignacio Orogeny, Sm-Nd isotopic, Amazonian Craton.

INTRODUCTION

The recognized framework of the Amazonian craton comprises the Maroni-Itacaiunas (2.25-1.95 Ga), Ventuari-Tapajós (2.0-1.8 Ga), Rio Negro-Juruena (1.8-1.55 Ga), Rondonian-San Ignacio (1.55-1.30 Ga), and Sunsas (1.30-1.0 Ga) geochronological provinces (e.g., Teixeira et al., 1989; Tassinari et al., 2000). Sm-Nd studies (Cordani and Sato, 1999) have confirmed this general crustal architecture, supported by a large set of U-Pb and Rb-Sr data in granitoid rocks. The Rondonian- San Ignacio Province (RSIP) of widespread occurrence in the SW part of the Amazonian craton (Brazil and Bolivia) has been studied by several authors (Sato and Tassinari, 1997; Van Schmus et al., 1998; Bettencourt et al., 1999; Geraldès et al., 2000, 2001; Leite and Saes, 2000; Payola et al. 2002, Santos et al., 2000; Santos et al., 2005), but ages, structures, and composition of rocks units and orogenic events within the Bolivian territory are still poorly known.

The Diamantina, La Junta and San Martin granitoids of the Pensamiento Granitoid Complex are part of the San Ignacio Province in Eastern Precambrian shield of Bolivia (Litherland et al., 1986; Boger et al., 2005) in which granulites and gneisses of the Lomas Maneches Complex are similarly widespread. The Diamantina granitoid makes up a north trending hill, forming an elliptical body about 53 km long (Klinck and O'Connor, 1982), and crops out as a "island" in the forest, close to the road that joints Santa Rosa de la Roca and Piso Firme localities, Santa Cruz department, in Eastern Bolivia; approximately 110 km north from Santa Rosa de la Roca (Figure 1). The dominant rock type is a pale pink and non foliated biotite monzogranite. The host rocks to the Diamantina granite are the syn-to late kinematic San Martin and La Junta granites which are moderately foliated accordingly to the regional structure of the Complex.

This work, carried out at the Centro de Pesquisas Geocronológicas, in São Paulo, Brazil, presents preliminary Sm-Nd data of the Diamantina, San Martin, and La Junta granitoids, that place important isotopic constraints on rock protholiths of the RSIP, in the Bolivian territory. This is part of a project that aims to determine the Precambrian tectonic evolution of Eastern Bolivia and its relationship to Mesoproterozoic evolution of SW Amazonian craton.

PREVIOUS ISOTOPIC DATA

Previous Rb-Sr whole rock isochron for the Diamantina granitoid (Table 1) yielded an age of 1391 ± 70 Ma and $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio from 0.75949 to 0.77617 (Litherland et al., 1986). After Darbyshire (2000), Nd isotopic compositions of granulites and gneisses from the Lomas Maneches Complex, and the San Ignacio Supergroup demonstrate the important role of the Transamazonian orogeny for the protoliths, displaying $\epsilon_{\text{Nd}}(t)$ values of 1.0 to 1.4 and T_{DM} between 1.69 and 1.73 (Two stage model) for Diamantina and Orobayaya granites.

RESULTS AND CONCLUSIONS

For four samples of the Diamantina granite yield $\epsilon_{\text{Nd}}(1.4)$ values between -0.52 to +1.23 and T_{DM} ranging from 1.80 to 1.93 Ga (Two stage model; Table 2). This indicates that the original magma of this post-tectonic granite resulted predominantly from Proterozoic juvenile sources. One sample from San Martin granite have $\epsilon_{\text{Nd}}(1.4)$ value of +2.26, and T_{DM} age of 1.71 Ga; therefore indicating that the host rock of the Diamantina granite derived mostly from juvenile sources as well. In contrast, two samples from La Junta granite yield $\epsilon_{\text{Nd}}(1.4)$ values of -2.07 and -3.54 and T_{DM} ages of 2.05 and 2.16 Ga; the negative ϵ_{Nd} values show that the original magma was derived from a significant crustal component compared to the Diamantina and San Martin granitoids.

The above preliminary results from the Pensamiento Complex reveal distinct isotopic characteristics for three granitoids, although the

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obtained signatures are consistent with the idea that the Rondonian-San Ignacio orogeny makes up a major differentiation/accretion event in SW Amazonian craton.

Table 1. Rb-Sr whole rock data of Diamantina Granitoid (After Litherland et al., 1986)

BOL/AD Number	Rock type	Unit	Ppm Rb	Ppm Sr	87Rb / 86Sr	87Sr / 86Sr
158	Granite	Diamantina Granite	186	176	3.068	0.76206
159	Granite	Diamantina Granite	226	183	3.602	0.77197
160	Granite	Diamantina Granite	191	186	2.981	0.75949
161	Granite	Diamantina Granite	236	181	3.795	0.77617

Table 2. Sm-Nd analytical data of Diamantina, San Martin, and La Junta granites.

Granite	Sample)	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd	F _{Sm/Nd}	T _{DM} (Ga)	ε ₍₀₎	ε _{Nd(1.4)}
Diamantina	PECP0505	0.1019	0.511834	-0.48	1.80	-15.69	1.23
Diamantina	PECP20506	0.0989	0.511789	-0.50	1.82	-16.56	0.90
Diamantina	PECP30507	0.1145	0.511859	-0.42	1.93	-15.20	-0.52
Diamantina	PEME0508	0.1469	0.512202	-0.25	1.86	-8.51	0.38
San Martin	PECA0509	0.1424	0.512257	-0.28	1.71	-7.43	2.26
La Junta	PELJ20512	0.0988	0.511636	-0.50	2.05	-19.55	-2.07
La Junta	PELJ30513	0.1124	0.511685	-0.43	2.16	-18.59	-3.54

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Geochemistry and nd isotopic evidence of the pensamiento granitoid complex, rondonian san ignacio province, eastern bolivia: Petrogenetic constraints for a plutonic model

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The Pensamiento Granitoid Complex (PGC), forms part of the Rondonian- San Ignacio Province (RSIP; 1.55-1.30 Ga) in the SW Amazonian craton. The PGC crops out almost entirely within the Paragua craton, and is overprinted in places by low grade metamorphism and shearing tectonically linked with the Sunsas Orogeny. The PGC comprises plutonic granites and subvolcanic terms, and subordinately syenites, granodiorites, tonalites, trondhjemites and diorites. Tectonically these rocks have been distinguished as syn- to late-kinematic and late- to post- kinematic granitoids correlated to the RSI orogeny. Thirteen whole rock analysis for major, trace and REE in selected samples of the Pensamiento Granitoid Complex indicate that these rocks belong to the subalkaline series, whereas in the AFM diagram they plot in the calc-alkaline field. The syn- to late- kinematics La Junta and San Martin granites show wide range of SiO₂ contents and suggests an origin by fractional crystallization from mafic and intermediate terms. The REE patterns are moderately fractionated in terms of LREE/HREE with a slightly negative Eu anomaly. One sample shows no negative Eu anomaly. The spider diagram presents steep patterns because the high LILE contents of these rocks. Negative peaks of Sr, P, and Ti suggest fractionation of feldspar, apatite, and titanomagnetite and sphene, respectively. New SHRIMP U-Pb yielded ages of 1373 ±20 Ma and 1347±21 Ma respectively. Sm-Nd yielded TDM model ages between 1.7 to 2.0 Ga, and Nd(1330) values ranging from +1.8 to -4.3. The late- to post-kinematic Porvenir,

San Cristobal, Diamantina and Piso Firme calc-alkaline granitoids display SiO₂ content that ranges from 72 to 76wt%. They plot on the boundary between metaluminous to peraluminous composition. The Piso firme Granophyre, San Cristobal and Porvenir granites show low LREE fractionation, and subhorizontal tendency of HREE with negative Eu anomaly. They have deeper negative peaks of Sr, P and Ti. The Diamantina Granite displays REE patterns with two different signatures: first, steep patterns due to high contents of LREE and depletion in HREE with negative europium anomaly. Second, "gull wing" pattern with enriched HREE. In the multielement diagrams show negative peaks of Sr, P, and Ti. The Diamantina Granite yielded SHRIMP U-Pb ages of 1340 ±20 Ma. Sm-Nd data displays TDM model ages of 1.6 to 1.9 and Nd(1330) values from -1.25 to +0.39. The late- to post-kinematic granites yield Sm-Nd TDM model ages are of 1.6 to 1.7 Ga, and the Nd(1330) values of +1.5 to +2.7. Coupled litogeochemistry and Sm-Nd isotopic data indicate that the PGCrocks exhibit plutonic arc setting comprising mostly juvenile derived granitoids (Porvenir, San Cristobal, Diamantine and Piso Firme). However the La Junta and San Martin granitoids may be interpreted as fractionated or crustal contaminated magmas, as evidenced by their Nd signature intruded in a pre- San Ignacio Basement.

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GEOCHEMISTRY AND ISOTOPIC SIGNATURES OF THE PENSAMIENTO GRANITOID COMPLEX, RONDONIAN-SAN IGNACIO PROVINCE, EASTERN PRECAMBRIAN SHIELD OF BOLIVIA: PETROGENETIC CONSTRAINTS FOR A MESOPROTEROZOIC MAGMATIC ARC SETTING

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The Pensamiento Granitoid Complex (PGC), in Eastern Precambrian of Bolivia, is assigned to the evolution of the Rondonian- San Ignacio Province (1.55-1.30 Ga) of the SW Amazonian Craton. The Proterozoic evolution of the Craton results from development of NW-SE mobile belts that became successively younger to the southwest, as exemplified by the Rondonian/San Ignacio (1.36-1.30 Ga) and the Sunsas orogenies (1.20-1.00 Ga) in Bolivian and Brazilian territories. The PGC, as part of the Rondonian/San Ignacio Orogeny, crop outs almost entirely within the Paragua Craton and is partly overprinted by Sunsas low grade metamorphism and shearing episodes. The PGC comprises granites and subvolcanic terms, and subordinately syenites, granodiorites, tonalites, trondhjemites and diorites, tectonically characterized as syn- to late-kinematic and late-to post-kinematic granitoids. Thirteen whole rock chemical analysis for major, trace and REE in PGC plutonic rocks indicate subalkaline character. The syn- to late- kinematics La Junta and San Martin granites are peraluminous in composition, and show wide range of SiO₂ contents (69 to 77wt%) suggesting an origin by fractional crystallization from mafic and intermediate terms. Both plutons show moderately fractionated LREE/HREE patterns with a slightly negative Eu anomaly, and one sample has any negative Eu anomaly. The spider diagram presents steep patterns due to the high LILE contents of these rocks. Negative peaks of Sr, P, and Ti suggest fractionation of feldspar, apatite, and titanomagnetite and sphene, respectively. SHRIMP U-Pb zircon ages of the San Martin and La Junta plutons are comparable within error (1373 ±20 Ma and 1347±21 Ma), whereas they yield Sm-Nd T_{DM} model ages between 1.9 to 2.0 Ga and $\epsilon_{Nd(1330)}$ values ranging from +1.8 to -4.3, respectively. The late- to post-kinematic Porvenir, San Cristobal, Diamantina and Piso Firme calc-alkaline granitoid rocks display SiO₂ contents from 72 to 76wt%, and are metaluminous to peraluminous in composition. Regarding the REE patterns the Piso Firme Granophyre and San Cristobal and Porvenir granites show low LREE fractionation, and subhorizontal tendency of HREE with negative Eu anomaly. They have deeper negative peaks of Sr, P and Ti when compared with the La Junta and San Martin granites. These three plutons yielded Sm-Nd T_{DM} model ages between 1.6 to 1.7 Ga, and the positive $\epsilon_{Nd(1330)}$ values from +2.7 to +1.5. In contrast, the Diamantina Granite displays REE patterns with two different signatures: *i*) steep patterns due to the high contents of LREE and depletion in HREE with negative Eu anomaly; *ii*) “gull wing” pattern with enriched HREE contents. In the multi-element diagrams the samples show negative peaks of Sr, P, and Ti. Moreover, Diamantina Granite (SHRIMP U-Pb age of 1340 ±20 Ma) yields more variable Sm-Nd T_{DM} model ages (1.6 to 1.9 Ga) and $\epsilon_{Nd(1330)}$ values (+0.4 to -1.2) when compared with the other late- to post-kinematic plutons. Coupled litogeochemistry and Sm-Nd isotopic signatures of the Porvenir, San Cristobal, Diamantina and Piso Firme plutons are consistent with a plutonic arc setting thereby comprising mostly juvenile-derived granitoids. Meanwhile some of the studied syn- to late kinematic granitoid rocks may also be interpreted as subordinately derived from fractionated or crustal contaminated magmas, as suggested by the negative $\epsilon_{Nd(t)}$ parameters.

GEOLOGÍA ESTRUCTURAL TECTÓNICA

ESTILOS TECTÓNICOS FRONTAL Y OBLÍCUO EN LA EVOLUCIÓN DEL MESO- NEOPROTEROZOICO DE LA PROVINCIA SUNSÁS DEL PRECÁMBRICO BOLIVIANO

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Palabras claves: Bolivia, Sunsás, Orogenia San Ignacio, Cratón Amazónico.

INTRODUCCIÓN

Tectónica vertical versus tectónica horizontal ha sido un debate común en años recientes al discutir el crecimiento cortical durante el Proterozoico. Uno de los criterios de discriminación más común para uno u otro de estos estilos es el modelo de "strain" registrado en un segmento cortical considerado. El estilo tectónico horizontal se considera un proceso de la tectónica de placas de estilo moderno, responsable para el desarrollo de una foliación horizontal o de bajo ángulo. Contrariamente la tectónica vertical resulta del desarrollo de amplios dominios formados por la sobreposición de estructuras domo y cuenca. Por otro lado, la tectónica recumbente o nappe relacionada con la orogenia San Ignacio fue propuesta por Litherland et al. (1986, pag. 56), para San Joaquín, San Simón, El Cielo, Dalriada y el Esquisto Ascensión en las rocas del Precámbrico de la Chiquitanía Boliviana.

Este estudio presenta un ejemplo de una zona de deformación retrabajada por cizallamiento de deslizamiento de rumbo, predominantemente sinistral y otra zona de plegamiento horizontal normal. Ambos estilos de deformación reflejan dos sectores tectónicos distintos para un mismo lapso de tiempo. Los ejemplos provienen de la Provincia Sunsás del Precámbrico Boliviano localizada en la región sudoeste del Cratón Amazónico (Figura 1), formada durante la amalgamación final de esta provincia al citado cratón durante el Neoproterozoico Superior (1250- 1000 Ma) (Cordani y Teixeira 2007). Nuestros resultados arguyen dos estilos de deformación dentro de hasta ahora la misma provincia para un mismo lapso de tiempo 1,2 a 0,95 Ga, probablemente un estilo corresponde a una etapa temprana y el otro estilo formado en una etapa tardía.

La primera zona estudiada comprende desde Guarayos a San Antonio de Lomerío totalizando no menos de 300 kilómetros, incluyendo parte de las hojas geológicas Concepción, la parte sur de Ascensión de Guarayos y el sector noroeste de San José de Chiquitos. Esta zona se denomina Distrito San Ramón (Figura 2). La segunda, dentro de la misma provincia geológica, involucró pliegues normales horizontales vinculados a la intrusión del Complejo Ígneo del Rincón del Tigre datada en 992 ± 86 Ma, dentro de la Hoja Roboré- Santo Corazón (no mostrada en este trabajo).

Este trabajo, efectuado en el Instituto de Investigaciones Geológicas y del Medio Ambiente (IGEMA) de la UMSA y en el Instituto de Geociencias de la Universidad de Sao Paulo, Brasil es parte de un proyecto de doctorado que el autor, docente e investigador de la UMSA realiza en la USP de Sao

Paulo, Brasil. El propósito del estudio es determinar la evolución tectónica del Precámbrico del oriente de Bolivia y su relación a la evolución de la región sudoeste del Cratón Amazónico durante el Mesoproterozoico.

AREAS CON TÍPICA TECTÓNICA OBLÍCUA

Varios ejemplos de la Tectónica vertical versus tectónica horizontal pueden citarse dentro del Cratón Amazónico. Este cratón comprende las provincias geocronológicas Maroni-Itacaiunas (2.25-1.95 Ga), Ventuari-Tapajós (2.0-1.8 Ga), Rio Negro-Juruena (1.8-1.55 Ga), Rondoniana-San Ignacio (1.55-1.30 Ga), y Sunsás (1.30-1.0 Ga) (Cordani et al., 2000; Cordani y Teixeira, 2007). Las provincias Rondoniana-San Ignacio (PRSI) y Sunsás (PS), tienen amplia distribución en la región sudoeste del Cratón Amazónico, en particular en Bolivia (Figura 1). Esta área fue estudiada por varios autores (Litherland et al., 1986), sin embargo la edad, estructura, composición de las unidades rocosas y eventos orogénicos dentro del territorio boliviano aun son poco conocidos.

Dos ejemplos al suroeste del Cratón Amazónico, en el estado de Rondonia de edad Sunsás constituyen la Zona de Cizalla Ji-Paraná, caracterizada por una tectónica de transcurrancia sinistral y la Faja Metasedimentaria Nova Brasilândia, con un evento compresional inicial que desarrolló una fábrica al noreste y fue seguido por el desarrollo de zonas de cizalla de deslizamiento de rumbo sinistral. Ambos ejemplos se sitúan en el estado de Rondonia, Brasil.

Las regiones con típica tectónica oblicua se caracterizan por los siguientes factores (Figura 2, zona 6 y 9).

1. Zonas de cizalla de deslizamiento de rumbo paralelo a la faja móvil, con patrón de foliación S/C en los bloques intervinientes y una red interna de cizalla lenticular sigmoidal en todas las escalas de observación (Figura 2, zona 9).
2. Organización interna de ramificación compleja con diferentes bloques, mostrando diferentes edades, patrones estructurales sedimentarios y metamórficos unidos por zonas de cizalla transcurrente.
3. Pliegues en "echelon" oblicuos a la faja móvil, rotados a la dirección de cizalla de rumbo principal.
4. Lineación de estiramiento horizontal paralela u oblicua a la faja móvil.
5. Intrusiones graníticas siguiendo esa fábrica.

En el Distrito San Ramón las rocas del ciclo San Ignacio y protolitos más antiguos forman el basamento. Las rocas comprenden gneisses, una asociación volcánico-sedimentaria de ambiente oceánico a transicional compuesto por esquistos, filitas, metabasalto, metaríolitas, intrusivos ultramáficos y máficos y granitoides; el grado metamórfico es de bajo a alto (Litherland et al., 1986, Adamek et al., 1996, Witschard et al., 1993). Estas rocas sufrieron un pronunciado retrabajamiento durante la Orogenia Sunsás provocando la destrucción de las estructuras antiguas y sobreimprimiendo el actual patrón de afloramientos (Figura 2). Esta orogenia estuvo acompañada por la intrusión de granitos sin a tardicinemáticos y tardi a post cinemáticos por ejemplo Casa de Piedra, Talcoso y Taperas. Evidencias de campo de imágenes satelitales, geofísica y petrografía respaldan un estilo tectónico de estructuras s-c, granos fracturados colas de granos tipo σ_1 (sigma) y venas sigmoidales resultante de la cizalla de deslizamiento de rumbo siniestro (Figura 2).

ÁREAS TÍPICAS CON TECTÓNICA FRONTAL

Estas regiones poseen las siguientes características:

1. Fajas plegadas y corridas de rumbo paralelo a los bordes del antepaís con una clara vergencia al cratón.
2. Foliación inclinándose a la faja móvil, con grandes zonas con foliación suave asociados con nappes o mantos de traslape desarrollados en las áreas marginales.

Los sinclinales y anticlinales observados en el área de Rincón del Tigre (Mitchell, 1979), son pliegues normales horizontales desarrollados en los grupos Sunsás y Vibosi, incluyendo el sill estratificado del Complejo Igneo de Rincón del Tigre intruido entre ambos grupos. Los ejes de pliegue se hunden al sureste con un ángulo bajo ($\sim 10^\circ$). El área contiene diversas fallas de orientación noroeste con un paralelismo a la faja y perpendiculares a σ_1 . Este σ_1 es responsable de la deformación de la Serranía Las Conchas, Santo Corazón y Bella Boca, siguiendo una orientación NW-SE.

Los lineamientos orientados con dirección noreste podrían considerarse fracturas de tensión por compresión axial, bajo condiciones de baja presión de confinamiento. Estas fracturas son paralelas a σ_1 , un proceso conocido como partición longitudinal (Van der Pluijm y Marshak, 2005, pag. 121). La presión de confinamiento baja en la zona está respaldada por el grado de metamorfismo equivalente a la facies de los esquistos verdes.

CONCLUSIONES

En zonas de cizalla dúctil como el Distrito San Ramón, es razonable asumir un esfuerzo principal compresivo σ_1 haciendo un ángulo de aproximadamente 45° con la dirección C y perpendicular con la dirección externa S. La fábrica sigmoidal de las foliaciones se debe a la deformación de rotación acumulada. Desde el marco general de las fajas móviles frontales y oblicuas del Cratón Amazónico, es posible proponer un modelo de esfuerzos principales de

compresión WNW-ESE a SSW-NNE para el Distrito San Ramón. Sugerimos que esto representa los vectores de desplazamiento principal, de acuerdo con el cuadro coherente de la cinemática para la amalgamación del oeste del Cratón Amazónico, durante las etapas finales de la orogenia Sunsás.

Las estructuras desarrolladas en la zona Rincón del Tigre y el Distrito San Ramón (Mitchell, 1979; Fletcher, 1979), están relacionadas con la colisión del orogeno Sunsás. Las fases tardías de la deformación en el ciclo Sunsás, que causaron la colisión fueron citados por Adamek et al. (1996).

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Figura 1. Provincias geotectónicas de Sudamérica (según Cordani et al., 2000).

Figura 2. Subdivisión estructural del Distrito San Ramón. R: San Ramón, A: Ascensión de Guarayos, C: Concepción, T: Cerro Talcoso, F: Cerro San Francisco o Taperas. 1: Gneisses y granitos porfíricos, 2: Probablemente intrusivos básicos a ultrabásicos, 3: Migmatitas y gneisses, 4: Gneiss y granitoides, 5: Granitos porfiroides y gneisses indiferenciados, 6: Zona de rift, 7: Grupo Sunsás, 8: Terreno granito –gneiss, 9: Granitos y gneisses deformados (según Witschard et al., 1993).

U-Pb and Sm-Nd geochronology from Yarituses suite and San Ramón granite, SW Amazonian craton: implications for the crustal evolution of the Eastern Precambrian shield of Bolivia

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INTRODUCTION

Three dominant periods of granitic magmatism mark the evolution of the Paraguá terrane (Bettencourt et al., 2010), as supported by field geology, petrology and U-Pb (SHRIMP, TIMS and laser ablation-ICP-MS) and Sm-Nd results: the Yarituses suite, the San Ramón granite and the San Ignacio granites. The new U-Pb zircon ages document crust formation events during the time interval of 1673 Ma to 1621 Ma. Our data show that these granitoid rocks are not only the granitic sills, as reported by Boger et al. (2005) for the so-called Lomas Maneches suite, instead they represent several, large contemporary plutons, in the San Javier and San Ramón areas such as the La Cruz, Refugio and San Pablo granites. This fact allows us to propose the Yarituses suite for such a widespread plutonic event over the Paraguá Craton. Meanwhile, we maintain the Lomas Manechis Granulite Complex (Litherland et al., 1986) as the oldest chrono-stratigraphic unit of the Bolivian Precambrian shield, as supported by the 1818 ± 13 Ma SHRIMP zircon age of granulite gneiss in the Las Rengas area, to the eastern of San Ignacio town (Santos et al., 2008). The other basement units of the Paraguá terrane are the Chiquitania Complex and San Ignacio Schist Group, as supported by radiometric data in the range between 1690 and 1830 (Boger et al., 2005; Santos et al., 2008). This paper reports and integrates SHRIMP, TIMS U-Pb and Laser Ablation zircon ages for the Yarituses suite and the San Ramón granite coupled with new Sm-Nd T_{DM} ages. The data show that two granitic pulses, preceded the 1.37-1.34 Ga San Ignacio orogeny (Pensamiento Granitoid Complex), developed in an Andean-type magmatic arc.

The La Cruz granite crops out 15 km northeast from San Ramón, and constitutes two individual bodies hosted by the San Ignacio Schist Group. It shows clear contacts with the hosted San Ignacio Schist Group and presents a roughly sigmoidal-shape showing the typical deformation trend related to the 1.1-1.0 Ga Sunsás orogeny. This body (sample 558) is a pale pink leucocratic syenogranite with K-feldspar (perthite) and scarce biotite as the mafic mineral. The dominant texture is allotriomorphic granular. The Refugio granite is a large body that crops out along the road San Javier – Concepción. We have sampled this granite in two places: sample RF408 and SR83. The first one was collected 17 km eastern of San Javier, along the road to Concepción. The rock is a weakly foliated syenogranite, with hipidiomorfic-granular texture; the alkali feldspar is subhedral, the plagioclase tends to be euhedral and the quartz occupies irregular intergranular interspaces. The mafic mineral is green biotite seldom chloritized. SR83 was sampled 8 km eastern of San Javier on the road to Talcoso hill. This is a white, massive to weakly

foliated leucogranite. The K-feldspar is the microcline and orthoclase is subordinate. Plagioclase tends to be euhedral. The mafic mineral is biotite (<2%); the principal accessory mineral is brown granular sphene. Santos et al. (2008) reported SHRIMP U-Pb zircon, monazite and titanite ages from the Refugio granite, which has zircons with no metamorphic rim, and yields a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1641 ± 4 Ma and T_{DM} age of 1.66 Ga ($\varepsilon_{\text{Nd}(t)} = +4.06$). Finally the San Pablo granite, exposed 25 km southern of San Antonio de Lomerío, comprises an oriented batholith (11 km long by 4 km wide). The rock is a pink, fine to medium-grained biotite-quartz-monzonite with an anhedral-granular texture. The plagioclase shows curved twins and quartz is anhedral, occupying irregular intergranular spaces. Biotite is the mafic mineral, straw to green in color.

The San Ramón granite represents a distinct igneous episode dated at 1429 ± 4 Ma (Santos et al., 2008) which invaded the metamorphic basement (Paraguá terrane), and still to be confirmed in the near future as an important rock generation event associated to others plutons in the area. The San Ramón granite is an intrusive body of ca. 35 km² that hosts NNW shear zones, and probably extends farther west, but the contact relationships with the Chiquitania Gneiss Complex are largely hidden by Cenozoic sediments. The representative sample SR0401 is a gray, biotite granodiorite which has anhedral granular texture. Aggregates of mafic minerals show an irregular distribution. The main accessory minerals are: titanite, allanite and zircon. This pluton yields similar SHRIMP U/Pb zircon and titanite ages of 1429 ± 4 Ma (Santos et al., 2008). One coeval body has been recently reported on the Paragua terrane, close to the Brazilian-Bolivian boundary; zircons from the Cascata granite yields a $^{207}\text{Pb}/^{206}\text{Pb}$ zircon evaporation age of 1412 ± 5 Ma (Cabrera et al., 2009). On the other hand, J. O. Santos (oral comm., 2009) obtained Hf isotope analysis from the San Ramón granite yielding a T_{DM} model age of 1.7 Ga and a ε_{Hf} between +3.5 and +5.5. As such this suggests a juvenile accretion event of mainly Mesoproterozoic mantle source in Bolivia, as similar as recognized in the Brazilian counterpart, such as the Santa Helena and Rio Branco suites (Geraldes et al., 2001; Cordani and Teixeira, 2007; Bettencourt et al., 2010).

RESULTS AND DISCUSSION

Zircons from the La Cruz granite are between 100-220 μm long and generally have elongation ratios close to 2:1. The U content of zircon is variable from 138 to 932 ppm, only one grain (4.1) contains 1413 ppm. The Th/U ratios vary between 0.27 and 0.92, denoting magmatic origin. The cathodoluminescent images show that most of the crystals are euhedral and have both parallel-zoning faces and distinct oscillatory zoning. SHRIMP analysis were carried out on eight zircon spots; five cores lie on the Concordia, three are discordant and using all result with a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1673 ± 21 Ma (MSWD=0.67), considered as the crystallization age (Fig 1). This age compares, within error, with two ages obtained by Boger et al. (2005) and Santos et al. (2008) for the Lomas Manechis suite, ranging from 1689 to 1663 Ma.

Zircons from Refugio granite (sample SR83) mostly occur as colourless elongated prisms; light brown stubby grains are also present. Cores and oscillatory zoning were observed in a number of zircon grains by transmitted-light microscopy. U-Pb TIMS analyses among four multigrain zircon fractions yield three concordant points with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1673 ± 25 Ma (MSWD=36), taken as the best estimate for the time of crystallization of the pluton.

Zircons from the San Pablo quartz-monzonite (SP601) appear to be colorless, transparent, with well crystallized prismatic form. Oscillatory zoning, observed in CL images, indicates their magmatic origin of the zircons, as also suggested by Th/U ratios from 0.17 to 0.54. From the eighth analyses an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1621 ± 80 Ma (MSWD= 134 was obtained (2σ).

These La Cruz, Refúgio and San Pablo granites (Yarituses suite) show $f_{\text{Sm/Nd}}$ ratios from -0.38 to -0.56, T_{DM} model ages of 1.7 - 1.9 Ga, and calculated $\epsilon_{\text{Nd}}(t)$ values from +0.2 to +4.0. This suggests a significant contribution of a juvenile component in the petrogenetic process.

The 1.42 Ga San Ramón granite represents juvenile material accreted to the the metamorphic basement (Paraguá terrane) as is suggested by the ϵ_{Hf} between + 3.5 and +5.5 and the T_{DM} model age of 1.7 Ga. This pluton is coeval with the Cascata granite of 1.41 Ga (Cabrera et al., 2009) and the Santa Helena and Rio Branco suites (Geraldes et al., 2001).

CONCLUSIONS

The Lomas Manechis complex, Chiquitania complex and San Ignacio Schist Group constitute the Paleoproterozoic polymetamorphic basement formed during the 1.82-1.69 Ga time interval. U-Pb SHRIMP zircon and Sm-Nd isotopic data have identified three dominant periods of granitic magmatism in the Precambrian framework. These are the Yarituses suite, The San Ramón granite and the San Ignacio granites. The Yarituses suite represents a juvenile accretion event during the time interval 1.67 – 1.62 Ga. Figueiredo et al. (2009) reported a coeval pluton in the Mato Grosso state (Turvo orthogneiss) which yields a 207Pb-206Pb zircon age of 1651 ± 4 Ma, indicating a more regional scale for such event. U-Pb zircon data from the San Ramón granite yield 207Pb/206Pb age of 1.43 Ga, T_{DM} model ages of 1.6-1.7 and positive ϵ_{Nd} values. This granite is time correlated to the Santa Helena orogeny (1.48-1.42 Ga) and the Cascata granite (1.41 Ga).

The San Ignacio orogenic plutonism named the Pensamiento Granitoid Complex comprises syn- to late and late- to post-tectonic plutons that took place between 1370 and 1320 Ma, as constrained by the SHRIMP U/Pb ages and a T_{DM} ages of 2.04 – 1.87 Ga and 1.74 – 1.58 Ga respectively. The syn-tectonic plutons have Nd signatures consistent with derivation from mixing of juvenile material with older crust, possibly within a continental margin setting; conversely, the late- to post-tectonic granitic pulses were largely originated in an intra-oceanic arc setting (Matos et al, 2009). This multiple tectonic and magmatic evolution of the Paragua terrane is comparable to the events in the RNJP and the RSIP of the SW Amazonian craton.

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Figure 1. SHRIMP zircon U-Pb concordia diagram of the sample LC0558, La Cruz granite.

Apêndice A- Descrição sintética dos afloramentos visitados (continua)

No	Local	Unidade	Amostr	X (utm)	Y (utm)	
2004						
2	San Ramón	Granod. S. Ramón	401	552691	8263237	Rocha de cor cinza escuro, inequigranular, biotítica com foliação vertical fraca
10B	Talcoso	Suite S. Ignacio	402	559929	8221891	Rocha porfirítica de coloração cinza esbranquiçada a rosa, de granulação grossa
11	San Javier	Suite S. Ignacio	403	554236	8100752	Rocha de cor rosa, granulação média, biotítica com ligeira orientação preferencial
12	Candelaria	Granito San Andrés	404	591740	8203230	Gnaiss milonítico cinza claro, com porfiroclastos de feldspato potássico de 2 a 4 cm
13	Suponema	Suite S. Ignacio	405	741480	8173146	Rocha básica foliada de cor esverdeado, contendo anfibólio e plagioclásio.
14	Santa Ana	Granito San Rafael	406	745988	8152671	Rocha de granulação média de coloração cinza claro a rosa, biotítica
15	Pachorri	Suite S. Ignacio	407	728913	8149359	Gabro de granulação fina, coloração preta e estrutura maciça compacta.
17	San Silvestre	Granito Refugio	408	569982	8201088	Rocha de cor rosada, maciça e levemente porfirítica, granulação média
18	San Silvestre	Granito Pobrecito	409	569640	8203646	Rocha de granulação grossa e cor castanho claro, biotítico
19a	San Javier	Granito Primavera	410	548375	8201135	Rocha de cor branca a cinza, granulação média, friável caracterizada pela muscovita.
19b	El Cusi	Granito Taperas	411	564915	8189752	Rocha de cor castanho claro, maciça, granulação grossa e porfirítica em cristais de 4 cm
20	San Pedro	Granito San Pedro	412	580316	8157132	Rocha de granulação grossa, coloração rosada e porfirítica, com biotita em agregados
21a	San Luis	Granito Cachuela	413	576616	8166071	Rocha de granulação grossa, coloração rosada, porfirítica inequigranular e biotítica
24	Puquio Norte	G.X. San Ignacio	414	560411	8167249	BIF composto pela alternância de bandas centimétricas de chert e hematita
28	Pejichi	G.X. San Ignacio	415	560760	8165869	Metapelito de coloração ocre e estrutura foliada, metamorfoisado na fácies xisto verde
29	Pejichi	G.X. San Ignacio	416	560739	8165707	Grauvaca quartzosa, cor ocre e estrutura foliada, metamorfoisada na fácies xisto verde
41	Santa Rosa	G.X. San Ignacio	418	560293	8171681	Filito sericítico com foliação e lineação de crenulação. Fácies xisto verde
46	Fazen. Jalisco	G.X. San Ignacio	419	563410	8173549	Lajes compactas de basalto, com amígdalas preenchidas por quartzo e calcita
47	Fazen. La Cruz	Granito La Cruz	420	565194	8173479	Rocha de granulação fina a média e coloração rosada a vermelha, quase sem biotita
2005						
1	Piso Firme	Granófiro P. Firme	501	635376	8493848	Rocha de granulação fina, cor rosa pálido e estrutura maciça, rica em feldspato
2	Cerro El Puente	Granito S. Cristobal	502	623763	8479614	Rocha de cor rosa, foliação fraca com biotita em linhas irregulares.
3	Cerro Leyton	Granito S. Cristobal	503	625302	8474694	Rocha de cor rosa pálido, granulação fina a média e estrutura gnáissica
4	Porvenir	Granito Porvenir	504	653060	8445505	Rocha maciça de granulação fina a média e coloração rosada, contém hornblenda.
5	Cerro Pelado	Gran. Diamantina	505	661618	8392877	Rocha de cor rosa claro, estrutura maciça e inequigranular, porfirítica, com biotita dispersa
6	Cerro Pelado	Gran. Diamantina	506	662459	8385600	Rocha de granulação média a grossa e coloração esbranquiçada, biotita dispersa
7	Cerro Pelado	Gran. Diamantina	507	660835	8376150	Rocha de granulação média a grossa (cristais de 1cm) e cor branca, biotita dispersa
8	La Mechita	Gran. Diamantina	508	659335	8367510	Granito de granulação média a grossa, maciço e cor rosa esbranquiçado com biotita
9	Co. La Trampa	Gran. San Martín	509	642653	8367578	Gnaiss bandado e foliado, cor rosa com cristais prismáticos de hornblenda de 5 mm
10	Florestal	Granito La Junta	510	662154	8342436	Gnaiss de granulação grossa, coloração rosa, com bandas de clorita.
11	Santa Rosa	Granito La Junta	511	662601	8324646	Rocha branca rosada de granulação grossa, maciça, inequigranular; contém biotita
12	Florest-Camp	Granito La Junta	512	681788	8313212	Rocha de cor branca rosada, maciça e porfirítica, cristais de 2 a 3 cm.
13	Guadalupe	Granito La Junta	513	662293	8309407	Rocha cor cinza rosada, foliada, granulação média, fenocristais de 2 cm.
14	San Martín	C. L. Manechis	514	661623	8298287	Gnaiss com porfiroclastos de feldspato potássico de 2-3 cm, rico em biotita.
15	San Martín	C. L. Manechis	515	661282	8294599	Gnaiss leucocrático de granulação fina com hornblenda em bandas finas
16	Don Mario	Gran. Señoritas	516	214452	8080658	Rocha com assinatura pegmatítica com feldspato potássico, quartzo e muscovita.
1	Makanaté	C. L. Manechis	517	572289	8289767	Gnaiss bem foliado, com coloração cinza escuro e cisalhado.
2	Río Negro	C. L. Manechis	518	574318	8299328	Tonalito de cor cinza claro a esverdeado, fortemente cisalhado, contém porfiroblastos.
	Río Negro	C. L. Manechis	519	574318	8299328	Gnaiss de granulação fina e coloração cinza esbranquiçada.

	Río Negro	Pegmatita	520	574318	8299328	Rocha de cor castanho, granulação grossa cortando um tonalito
3a	Monte Verde	C. L. Manechis	521	574219	8298175	Tonalito de coloração cinza esverdeado, com fenocristais fortemente cisalhados
3b	San Pedro	C. L. Manechis	522	575188	8290147	Rocha de granulação fina, coloração cinza escuro rica em quartzo e biotita.
4	Faz. Las Lajas	C. L. Manechis	523	580780	8283204	Augen gnaiss com grãos de feldspato potássico de 4 cm, sentido sinistral
5	Faz. Las Lajas	C. L. Manechis	524	581086	8282637	Milonito gerado em uma zona de cisalhamento de 90 cm de largura
6	Fazenda 26	C. L. Manechis	525	581951	8280039	Gnaiss tonalítico bandado, com pequenas dobras e foliação transposta.
7	Faz. Tacucito	C. L. Manechis	526	585165	8276681	Gnaiss de granulação fina com quartzo, feldspato potássico e biotita.
8	Faz Tacucito	C. L. Manechis	527	588015	8276212	Gnaiss de granulação fina com quartzo, feldspato potássico e biotita.
9	San Antonio	C. L. Manechis	528	588576	8275523	Aplito de granulação fina, sacaroide cortando um gnaiss de granito biotítico
10	Sta. Catalina	C. L. Manechis	529	597232	8262192	Gnaiss de granulação fina com biotita e veios de granito grosso.
11	San Silvestre	C. L. Manechis	530	597239	8261268	Augen gnaiss com porfiroblastos de 3 cm diâmetro, cisalhamento sinistral
12	San Pablo	C. L. Manechis	531	599546	8255538	Gnaiss de granulação fina, cor castanho, com granada de até 2 mm
13	Fazenda Vibosi	C.G. Chiquitania	532	598509	8248041	Gnaiss com faixas de biotita parcialmente contínuas; bandamento de 1 a 5 cm
14	Fazenda Vibosi	C.G. Chiquitania	VB533	598213	8245104	Anfibolito de granulação fina e coloração esverdeada com estrutura foliada
15	Calama	Suite Sunsás	CL533	608512	8222073	Tonalito biotítico de cor cinza, granulação média e estrutura maciça
16	Santa Teresa	Suite Sunsás	534	610289	8216499	Granito biotítico porfirítico com cristais de feldspato potássico de 2 a 4 cm
17	Noviquia	C.G. Chiquitania	535	608345	8187286	Granito gnáissico biotítico, cor cinza, granulação média a grossa, porfirítico
18	Panorama	El Carmen	536	611094	8169631	Gnaiss biotítico, coloração rosada, granulação média e fenocristais de 2 cm
19	Cruce	G.X. San Ignacio	537	611743	8166226	Xisto quartzo micáceo, friável, estrutura foliada e coloração cinza clara
20	Santa Rosario	Suite S. Ignacio	538	611747	8162032	Granito gnáissico rosa, granulação média, faixas descontínuas de biotita
21	Surusubi	Suite S. Ignacio	539	612107	8150827	Gnaiss foliado de granulação média e dobras menores centimétricas
22	Río Tobosí	Suite S. Ignacio	540	619161	8151488	Gnaiss de cor rosa, granulação média com faixas de biotita em "Z" .
23	S.A. Lomerío	Série Sunsás	541	629973	8148317	Arenito de grão fino a médio, cor amarelo com camadas cruzadas
24	Motacusal	G.X. San Ignacio	542	632964	8139170	Rocha meta-sedimentar de granulação grossa e coloração castanha clara.
25	Motacusal	Suite S. Ignacio	543	631360	8142183	Gnaiss cor rosa claro, granulação média, com presença de biotita e muscovita
26	Motacusal	Suite S. Ignacio	544	629632	8142407	Lajes cor cinza esbranquiçada, granulação média e com biotita e muscovita
27	Monterito	Suite S. Ignacio	545	609682	8153006	Gnaiss de cor rosa, com granulação média e faixas de biotita de traço irregular
28	San Rafaelito	Suite S. Ignacio	546	592177	8160963	Granito de granulação grossa, róseo, biotita em agregados de 1 centímetro
29	Faz. Sujalito	G.X. San Ignacio	547	568635	8161055	Riolito cinza escuro de granulação muito fina, compacto com textura porfírica
30	Faz. Naranjal	G.X. San Ignacio	548	564611	8160509	Metabasalto foliado de cor cinza esverdeada em afloramentos de lajes
31	Faz. Limones	C.G. Chiquitania	549	535551	8180534	Gnaiss biotítico, cor acinzentado, fortemente foliado, granulação média
32	El Puente	Suite S. Ignacio	550	508916	8194888	Gnaiss granítico com biotita, foliado a maciço, de granulação grossa
33	El Cerrito	C.G. Chiquitania	551	492809	8223593	Gnaiss de granulação média, faixas de biotita, dobras decimétricas
34	Guarayos	Suite S. Ignacio	552	478547	8243487	Gnaiss de granulação média com faixas de biotita e magnetita dispersa
35	Puesto Nuevo	Suite S. Ignacio	553A	515793	8198302	Gnaiss granítico de granulação grossa, cor rosa, fenocristais de feldspato
35	Puesto Nuevo	Gran. Marimonos	553B	515793	8198302	Granito maciço de granulação grossa, fenocristais de feldspato
36	Sta. Rosa Mina	Suite S. Ignacio	554	555904	8170806	Gabro de cor esverdeada com manchas brancas e granulação grossa.
37	Sta. Rosa Mina	G.X. San Ignacio	555	559327	8171677	Filito sericítico de coloração verde acinzentada, brilho sedoso
38	Faz. La Honda	G.X. San Ignacio	556	560110	8171312	Filito de coloração esbranquiçada a castanho claro, friável.
39	Faz. Jalisco	G.X. San Ignacio	557	563196	8173324	Metabasalto cinza esverdeado, contendo magnetita de 1-2 mm.
40	Faz. La Cruz	Granito La Cruz	558	565017	8173086	Rocha de cor avermelhada e granulação fina média, estrutura maciça

1	Huanchaca	Dique Huanchaca	PNK71	747988	8381290	Diabásio cinza escuro esverdeado, granulação fina a média
2	Huanchaca	Granito Discordancia	PNK72	739867	8389035	Rocha de textura rapakivi en cristais de 2 a 4 cm, com biotita
3	Vera Cruz	Gran.Campamento	PNK73	725851	8326753	Gnaiss cinza claro, granulação grossa, friável, escasa biotita.
4	El Retiro	Gran.Campamento	PNK74	717774	8263573	Rocha maciça, granulação média, porfirítica, com quartzo defumado
5	Papayo	C. L. Manechis	PNK75	688339	8232314	Gnaiss foliado, cor cinza, com faixas de biotita ate 2 centímetros
2008						
1	Las Maras	Granito Las Maras	LM81	544000	8204744	Rocha maciça de granulação grossa, cor rosa esbranquiçada
2	Faz. Las Maras	G.X. San Ignacio	LM82	545054	8202521	Metaturbidita de cor cinza com estratificação gradada e cruzada
3	Santa Rosa	Granito Refugio	SR83	560392	8202484	Granito maciço, granulação grossa, cor esbranquiçada
4	Fazenda Suarez	Casa de Piedra	CS84	554580	8242059	Granito gnáissico com estrutura foliada, biotítico e cor esbranquiçada.
5	Aguas Frías	Casa de Piedra	AF85	554946	8239138	Granito gnáissico de cor rósea e biotita como mineral ferromagnésiano.
6	Turunapé	Casa de Piedra	CT86	555275	8236662	Granito de cor rosa, biotítico e com foliação pouco expressiva.

6	Turunapé	Casa de Piedra	CT87	555275	8236662	Gnaiss granoblástico com feldspato potássico de até 3 cm
7	Tacuaral	G.X. San Ignacio	GG88	552938	8231184	Metabasalto de coloração cinza esverdeada com estrutura maciça.
8	Atadijo	C.G. Chiquitania	AT89	538390	8201976	Gnaiss granoblástico de cor cinza com cisalhamento sinistral
9	Paraíso	G.X. San Ignacio	EP10	539791	8202079	Filito mosqueado com cristais octaédricos e tabulares de 2 a 3 mm.
1	San Diablo	Granito Tasseoro	TS81	731409	8075337	Rocha de granulação fina a média, cor cinza claro, contém magnetita
2	San Diablo	Granito Tasseoro	TS82	729847	8079332	Rocha de granulação fina a média, cor cinza claro, porfírico
3	San Diablo	Granito Tasseoro	TS83	731409	8075337	Rocha de granulação fina a média e cor cinza esbranquiçado.
4	San Diablo	Formação Piococa	PC84	733868	8073958	Arcócio esbranquiçado com FK de 3mm e litoclastos de quartzito
5	San Diablo	Serie Sunsás	SD85	754636	8097417	Milonito cor cinza, micáceo, brilho sedoso, lineação mineral
6	San Diablo	Serie Sunsás	SD86	754593	8098082	Milonito cinza, micáceo, brilho sedoso, com lineação de crenulação
7	San Diablo	Serie Sunsás	SD87	769051	8103935	Milonito cinza esbranquiçado, brilho sedoso, veios de quartzo leitoso
8	San Diablo	Granito Tarechi	TA88	776526	8108702	Granito fino a médio, biotítico, coloração cinza rosada
9	San Pablo	C.G. Chiquitania	SP89	192612	8047174	Granodiorito, tonalito de cor cinza, granulação média, faixas de biotita
10	San Pablo	Suite S. Ignacio	SP810	193647	8058205	Gabro cor cinza escuro, granulação fina a média
11	San Pablo	C.G. Chiquitania	SP811	194160	8052168	Gnaiss de cor cinza, granulação fina a média com veios migmatíticos
12	Chaquipoc	Suite S. Ignacio	SP812	208879	8053057	Anfibolito bandado, cor cinza claro a escuro e de origem sedimentar.
13	Chaquipoc	Suite S. Ignacio	SP813	218339	8053132	Anfibolita de cor cinza, maciça, granulação fina a média, compacta
14	San Juan	Granito Taucá	TU814	222414	8043149	Rocha de granulação fina a média, de cor cinza a rosa, pegmatítico
15	San Juan	Granito Taucá	TU815	222414	8043149	Gnaiss de granulação grossa, tonalítico, com biotita e magnetita
16	San Juan	Granito Taucá	TU816	216979	8041137	Gnaiss de granulação grossa, tonalítico, com biotita e magnetita
17	San Silvestre	Grupo El Portón	SS817A	221615	7976810	Arenito de granulação média a grossa, avermelhado e friável.
18	Murciélagos	Grupo Murciélagos	MU817	282326	7099881	Calcário laminar cruzado, de cor cinza claro com partes avermelhadas
19	Boquí	Grupo Boquí	BO818	285712	8002551	Diamictito com clastos angulosos de até 3 cm e cor vermelha.
21	Totomaca	Granito Correraca	CO820	288883	8002057	Rocha de granulação grossa, cor rosa, estrutura foliada
22	Correraca	Granito Correraca	CO821	293467	8002840	Rocha de granulação grossa, estrutura foliada, matriz de clorita e biotita
23	Correraca	Granito Correraca	CO822	295109	8002987	Rocha de granulação média, cor rosa, biotítica, estrutura maciça
24	Verano	Granito S. Corazón	CO823	305238	8009432	Rocha de granulação grossa, cor esbranquiçada e cisalhada
25	Santo Corazón	Granito S. Corazón	SC824	305238	8010134	Granito cinza esverdeado, quartzo translúcido e defumado e hornblenda
26	Santo Corazón	Granito S. Corazón	SC825	305238	8010134	Granito cinza esverdeado, quartzo translúcido e defumado e hornblenda
27	Santo Corazón	Granito S. Corazón	SC826	309081	8012348	Granito maciço, rosa, granulação fina a média, com quartzo translúcido
28	Fazenda Isabel	Rincón del Tigre	RT827	335372	8012420	Rocha máfica de cor cinza, estrutura foliada com veios de serpentina
	Fazenda Isabel	Rincón del Tigre	RT828	335372	8012420	Rocha da unidade ultramáfica, maciça de cor cinza.
29	Qda Fortuna	Rincón del Tigre	RT829	335372	8012420	Rocha de cor cinza esverdeada, maciça com piroxênio e olivino
30	Rincón d Tigre	Rincón del Tigre	RT830	348242	8002160	Rocha de cor cinza esverdeada, maciça com piroxênio e olivino
	Rincón d Tigre	Rincón del Tigre	RT831	348242	8002160	Rocha afanítica, foliada, com plagioclásio e vesículas estiradas.
31	Rincón d Tigre	Rincón del Tigre	RT832	367572	7988594	Rocha maciça, leve, cor cinza claro e intemperizada.
32	Portería	Rincón del Tigre	RT833	376073	7987032	Norito de granulação média, cor cinza escuro, com olivina e piroxênio
33	Portería	Rincón del Tigre	RT834	370696	7984011	Norito de granulação fina a média e cor cinza escuro.
34	Vibosi	Grupo Vibosi	RT835	370626	7981312	Diamictito pardo avermelhado, clastos angulosos a subarredondados
35	Don Mario	C.G. Chiquitania	RT836	205962	8075794	Gnaiss porfiroblástico bandado com K feldspato e faixas de biotita.

2009

1	Cachuela	Sunsás	CA101	555482	8210498	Rocha volcanosedimentar de cor cinza, porfírica; tem foliação transposta
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2	Moscú	G.X. San Ignacio	MO102	556149	8216244	Xisto actinolítico con granada dispersa de 2 a 3 mm. Granulação grossa a fina
3	Totaitú	Sunsás	TO103	550879	8202887	Gabro de granuloação fina a média, de cor cinza esverdeado, masivo, pirita dispersa
4	La Estrella	San Andrés		575130	8202196	Augen gnaiss milonítico, contém xenólitos de granodiorito; está migmatizado
5	San Andrés	San Andrés	SA104	590168	8189040	Augen gnaiss milonítico cor cinza con fenoblastos de FK de 2 a 3 cm.
6	San Pablo	Sunsás	SP105	591928	8193416	Fm. Zapocoz da série Sunsás. Cisalhamento S-C predominantemente dextral
7	Concepción	C.G Chiquitania	CO106	604475	8212958	Migmatitos flebíticos y gnaissicos com biotita como mineral máfico formando dobras
8	Villa Nueva	C.G.L. Manechis	VN107	682200	8236660	Matações arredondados de uma rocha compacta, cor cinza de granulação fina.
9	San Rafael	G.X. San Ignacio		729272	8154942	Xisto muscovítico alterado, friável, com granada de 3-5 mm de diâmetro
10	San Rafael	C.G Chiquitania	SRF108	754517	8127406	Migmatito gnaissico, flebítico; contém granada, biotita, plagioclásio e hornblenda
11	L. Manechis	C.G.L. Manechis	LM109	800063	8156066	Gnaiss leucocrático foliado com faixas claras e escuras, cor acinzentado
12	Sta Rosa Mina	G.X. San Ignacio	SM1010	556083	8171188	Metagabro de granuloação media, cor cinza esverdeado, masivo.
13	Sta Rosa Mina	G.X. San Ignacio	LH1011	560937	8171818	Filito sericítico cinza esverdeado cisalhado com foliação de crenulação

Apêndice B- Dados experimentais

Neste Apêndice apresentam-se as metodologias correspondentes a geoquímica e geocronologia no IGc-USP. Os dados estão subdivididos nas tabelas abaixo:

B1.Geoquímica

B2.Resultados analíticos U-Pb SHRIMP

B3.Resultados analíticos U-Pb TIMS

B4.Resultados analíticos U-Pb LA-ICP-MS

B5.Resultados analíticos Sm-Nd e Rb-Sr

Apêndice B1, Geoquímica

As análises de óxidos (SiO_2 , TiO_2 , Al_2O_3 , $\text{Fe}_2\text{O}_{3(\text{T})}$, MnO , MgO , CaO , Na_2O , K_2O e P_2O_5) e elementos traços (Ba, Ce, Cl, Co, Cr, Cu, F, Ga, La, Nb, Nd, Ni, Pb, Rb, S, Sc, Sr, Th, U, V, Y, Zn, e Zr), para as amostras de Pré-cambriano Boliviano, foram realizadas no Laboratório de Fluorescência de Raios-X (F-RX) do Departamento de Mineralogia e Geotectônica do Instituto de Geociências USP, com o equipamento instrumental automático da marca Philips, modelo PW2400. As pastilhas prensadas fornecem os dados dos elementos traços, enquanto a concentração dos maiores é dada pela amostra das pastilhas fundidas. O procedimento é analisar essas pastilhas, através da fluorescência de Raios-X (F-RX), cujo espectro faz a excitação das amostras, que fornecerão uma resposta de acordo com sua composição.

As análises de terras raras foram realizadas no Laboratório de Química e ICP-AES do Departamento de Mineralogia e Geotectônica, Instituto de Geociências da USP. O equipamento utilizado é o ICP-AES, um nebulizador ultrassônico acoplado ao espectrômetro de emissão atômica com plasma induzido

Apêndice B2 Métodos isotópicos e procedimentos analíticos

As análises geocronológicas foram realizadas no centro de Pesquisas Geocronológicas (CPGEO) do Instituto de Geociências (IGc) da Universidade de São Paulo (USP), tendo sido empregados tres métodos nos estudos das rochas do Pré-cambriano boliviano: U-Pb, Sm-Nd e Rb-Sr. Para a sistemática U-Pb os cristais de zircão foram datados por SHRIMP, TIMS e LA-MC-ICP-MS. Os estudos geocronológicos por SHRIMP foram realizados na Academia Chinesa de

Ciências Geológicas (Pequim) e os LA-ICPMS no laboratório geocronológico do Instituto de Geociências da UnB, em Brasília.

Análises U-Pb SHRIMP

As datações U-Pb (zircões) SHRIMP (Sensitive High Resolution Ion Microprobe) foram executadas através de cooperação científica com a Academia de Ciências da China. Os grãos de zircão foram escolhidos por catação manual sob lupa binocular e montados em discos de resina epóxi com 2,54 cm de diâmetro e 6 mm de espessura, em seguida, polido e revestido com película de ouro. Os zircões foram documentados com imagens de luz transmitida e refletida, bem como por catodoluminescência (CL) com o intuito de revelar as suas estruturas internas e externas. As análises isotópicas U-Pb foram realizadas utilizando o SHRIMP-II, operado remotamente desde do CPGeo. Detalhes dos procedimentos analíticos dos zircões usando SHRIMP foram descritos por Compston et al. (1984) e Williams (1997). Os padrões utilizados para medição das concentrações e das razões isotópicas foram o SL-13e AS-57. Os erros das contagens são absolutos e referem-se a 1σ , em quanto das idades são apresentadas com 2σ . Os resultados foram calculados em programa ISOPLOT/Ex, versão 2,10, de Ludwig (2003), observando-se as constantes recomendadas pela IUGS (Steiger e Jager, 1977).

Análises U-Pb TIMS

As amostras do estudo foram trituradas em britador, moídas em moinho de disco e posteriormente, peneirada em diferentes intervalos de granulometria para obtenção de concentrado de minerais. Este concentrado é separado numa mesa de Wiffley para a separação dos minerais pesados como o zircão que foi utilizado no presente caso.

Este novo concentrado é então levado a um separador magnético do tipo Frantz, cujo objetivo é separar a fração não magnetita (zircão) para posterior processamento em líquidos densos (Bromoformio $d=2,6$ e Iodeto de Metileno $d=3,2$). O concentrado de zircão é então lavado e secado em seguida, submetido ao separador magnético (Frantz), onde várias frações de zircão são obtidas em função da susceptibilidade magnética. A fração não magnética foi então processada em líquidos densos (bromoformio e iodeto de metileno) de onde resultou o concentrado com zircões. Os zircões produziram frações que variaram entre M(6) (fração mais magnética) a M(-2) (fração menos magnética). A seleção fina (multi-grãos) foi realizada por catação manual sob lupa binocular, utilizando-se para pesagem a relação densidade versus volume média dos cristais.

Os grãos foram dissolvidos em micro-bombas de teflon sob placa aquecedora, sendo que o Pb e U foram separados através de colunas de resina aniônica, segundo procedimentos descritos em Basei et al (1995) e Passarelli et al 2008. O traçador (Spike) utilizado no laboratório U-Pb foi o ^{205}Pb , e o branco total obtido foi da ordem de 10pg durante o período das análises.

As razões isotópicas foram medidas em um espectrômetro de massa multicollector Finnigan MAT-262. Os valores médios medidos para os padrões NBS-981 e NBS-983 são respectivamente de: $^{204}\text{Pb}/^{206}\text{Pb} = 0,05903 \pm 0,02\%$ e $0,000368 \pm 3\%$; $^{207}\text{Pb}/^{206}\text{Pb} = 0,9147 \pm 0,01\%$ e $0,071212 \pm 0,05\%$; $^{208}\text{Pb}/^{206}\text{Pb} = 2,1675 \pm 0,01\%$ e $0,013617 \pm 0,06\%$ com variação de 1σ . O fator de correção de fracionamento utilizado para normalização é de 0,095 u.m.a. (unidade de massa atômica). Os resultados foram calculados no programa Isoplot 2003 (Ludwig, 2003) e apresentados com desvios de 2σ . As constantes utilizadas são as recomendadas por Steiger e Jager (1977).

U-Pb LA-MC-ICP-MS

De maneira geral, este método proporciona resultados comparáveis aos obtidos pelo SHRIMP, muito embora o diâmetro da análise pontual seja maior, o que limita de certo modo a sua aplicação para cristais relativamente de maior granulação.

Os grãos de zircão selecionados foram montados em disco de resina epóxi, em seguida, polido e limpos com uma solução de ácido nítrico 3%. As análises espectrométricas foram realizadas em um espectrômetro Thermo Neptune MC-ICP-MS acoplado com um sistema de ablação por laser NewWave Nd: YAG UP213. Detalhes sobre o laboratório da UnB estão descritos em Buhn et al., (2009).

As análises espectrométricas foram realizadas utilizando os padrões GJ-1 e Temora-2, a fim de controlar o fracionamento das medidas pelo LA-ICP-MS. Para posterior normalização e/ou correção dos desvios ("bias") nas medidas de razões isotópicas Os dados brutos foram processados off-line e reduzidos utilizando uma planilha do Excel (Buhn et al., 2009), fazendo uso do modelo de composição de Pb de Stacey e Kramer, 1975.

Método Sm-Nd

As análises Sm-Nd foram realizadas em rocha total e os procedimentos utilizados seguiram os descritos em Sato (1998). No CPGeo os valores médios medidos para os padrões La Jolla e BCR-1, são $^{143}\text{Nd}/^{144}\text{Nd} = 0,511849 \pm 0,000025$ e $0,512662 \pm 0,000027$ respectivamente com variação de 1σ . Os erros máximos medidos das razões $^{143}\text{Nd}/^{144}\text{Nd}$ e $^{147}\text{Sm}/^{144}\text{Nd}$ em amostras foram

menores que 0,004% e 0,01% respectivamente, com nível de precisão de 2σ . As razões isotópicas de Nd foram obtidas em espectrômetro de massa multi-coletor Finnigan MAT-262, enquanto as de Sm em espectrômetro mono-coletor VG-354 do laboratório. O branco total foi baseado em valores publicados em DePaolo et al. (1991): $^{143}\text{Nd}/^{144}\text{Nd} = 0.7219$ e $^{143}\text{Nd}/^{144}\text{Nd} (\text{CHUR})_0 = 0.512638$, $^{147}\text{Sm}/^{144}\text{Nd} (\text{CHUR})_0 = 0.1967$ e $\lambda_{147} = 6,54 \times 10^{-12} \text{ anos}^{-1}$. Para as interpretações foram utilizadas idades modelo T_{DM} (representando eventos de diferenciação crosta-manto), bem como os valores de $\epsilon_{\text{(T)}}$, modelados para a idade obtida pelo método U-Pb, quando pertinente. Os cálculos estes parâmetros estão sumarizados abaixo (DePaolo, 1981)

O Sm e o Nd são elementos terras raras leves (LREEs), do grupo 3B da tabela periódica; formam íons de forte carga (+3) e têm número atômico elevado. Isso faz com que eles não se difundam facilmente no estado sólido e forneçam um sistema mais estável, do que das outras metodologias. Além da idade isocrônica, que tem interpretação similar a metodologia Rb-Sr e por isso não é o alvo desse trabalho, o sistema Sm-Nd oferece a Idade Modelo e a notação ϵ_{Nd} , como instrumentos de estudo, amplamente utilizados nessa metodologia.

O parâmetro petrogenético ϵ_{Nd} , como o de Sr, compara a razão inicial ($^{143}\text{Nd}/^{144}\text{Nd}$) da amostra com a do CHUR (reservatório condritico uniforme), para indicar a fonte que gerou a rocha. O Nd é um pouco mais incompatível do que o Sm, fazendo com que haja maior concentração de Nd em relação ao Sm, em rochas mais evoluídas, ou seja na crosta. Isso implica em razões Sm/Nd menores na crosta do que no manto, e conseqüentemente, menores razões $^{143}\text{Nd}/^{144}\text{Nd}$, já que o ^{143}Nd é fruto do decaimento radioativo do ^{147}Sm . Se a razão da amostra, na época de cristalização da rocha, for maior do que a do manto, o valor de ϵ_{Nd} será positivo, com enriquecimento relativo em ^{147}Sm , indicando que a fonte dessa rocha seria o manto, rico nos compatíveis. Se a razão for menor, o valor de ϵ_{Nd} será negativo, com empobrecimento em ^{147}Sm , indicando fonte rica em incompatíveis, a crosta. Todas as amostras com Nd coletado, também tiveram o Sr, para que possa ser feito o cálculo de ϵ_{Sr} e ϵ_{Nd} , para uma mesma amostra.

O comportamento geoquímico do Sm e do Nd é semelhante, sendo que o evento capaz de fracionar significativamente a razão Sm-Nd, é o processo de diferenciação manto-crosta (Sato et al., 1995). É esse fato, aliado à baixa difusão desses elementos no estado sólido, que permite o cálculo da Idade Modelo, ou seja, da época aproximada em que o magma parental da rocha estudada diferenciou-se do manto, qualquer que tenha sido a história geológica posterior. A Idade Modelo consiste na época em que a razão $^{143}\text{Nd}/^{144}\text{Nd}$ da amostra é igual a do manto. Os cálculos são baseados em valores para um manto empobrecido em incompatíveis (DM. "depleted mantle") e não terão valor algum se o manto que gerou a rocha for diferente. Alguns autores

como Zindler e Hart (1986) propõe vários tipos de manto, o que contesta os valores de Idade Modelo.

Apesar do comportamento geoquímico similar do Sm e do Nd, às vezes, durante alguns processos, pode haver fracionamento entre esses dois elementos, inviabilizando o cálculo da Idade Modelo em único estágio (Sato, 1998). Rochas enriquecidas em minerais que concentram seletivamente os terras-raras, ou fruto da mistura entre duas fontes distintas, ou ainda fruto da fusão parcial de sedimentos heterogêneos, podem dar idades-modelo sem significado geológico. Para resolver tal problema DePaolo et al. (1991) desenvolveu uma formula para calcular a Idade Modelo em estágio duplo. A necessidade de se realizar o cálculo em estágio duplo é indicado pelo fator de fracionamento, $f_{Sm/Nd}$ que mede o grau de fracionamento de uma amostra. O valor de $f_{Sm/Nd}$ deve estar por volta de $-0,44$, ou de uma razão Sm/Nd de $0,11 \pm 0,02$, que corresponde a valores de $f_{Sm/Nd}$ entre $-0,54$ e $-0,34$, para rochas granitoides acrescidas em arcos magmáticos. Esse valor foi estimado empiricamente, avaliando-se a distribuição dos dados existentes em histograma. Desta forma, para amostras com valores de $f_{Sm/Nd}$ fora desse intervalo, é necessário o cálculo da idade Modelo em dois estágios.

Cálculos e constantes envolvidas

DePaolo (1981) modelou uma evolução isotópica de Nd não linear para o manto superior fracionado, e neste caso a idade modelo é obtida resolvendo-se a seguinte equação:

$$\epsilon_{Nd}(T) = 0,25T^2 - 3T + 8,5 \text{ curva do manto empobrecido (DM)} \quad \text{eq. (1)}$$

$$\epsilon_{Nd}(T) = \epsilon_{Nd}(0) - Qf_{(Sm/Nd)} \{ = 0.512638 / (^{143}Nd / ^{144}Nd)_{CHUR}(T) \} [e^{\lambda T} - 1] \quad \text{eq.(2)}$$

$$\text{considerando } e^{\lambda T} - 1 \cong \lambda T \text{ e } 0.512638 / (^{143}Nd / ^{144}Nd)_{CHUR}(T) \cong 1$$

$$\epsilon_{Nd}(T) \cong \epsilon_{Nd}(0) - Qf_{(Sm/Nd)} T \text{ evolução da rocha crustal} \quad \text{eq.(3)}$$

onde o parâmetro Q_{Nd} é uma constante que insere o valor da constante de desintegração λ_{Sm} ,

$$Q_{Nd} = [10^4 \lambda_{Nd} (^{147}Sm / ^{144}Nd)_{CHUR}(0)] / (^{143}Nd / ^{144}Nd)_{CHUR}(0) \\ = [10^4 \times 0.00654 \times 0.1967] / 0.512638 = 25.09 \text{ b.a}^{-1}$$

O parâmetro $\epsilon_{Nd}(0)$ é definido como a razão atual $^{143}Nd/^{144}Nd$ da amostra sobre a razão $^{143}Nd/^{144}Nd$ do manto CHUR, subtraído de 1 e multiplicado por um fator 10000:

$$\epsilon_{Nd}(0) = \left\{ \frac{(^{143}Nd/^{144}Nd)_{(0) \text{ am}}}{(^{143}Nd/^{144}Nd)_{(0) \text{ CHUR}}} - 1 \right\} 10000 \quad \text{equação 4}$$

Por outro lado, o parâmetro $f_{Sm/Nd}$ indica o grau de fracionamento da razão $^{147}Sm/^{144}Nd$ da amostra em relação ao manto CHUR e em geral e da ordem de -0.5 a -0.4 em rochas ditas “crustais”:

$$f_{(Sm/Nd)} = \frac{(^{147}Sm/^{144}Nd)_{am} - (^{147}Sm/^{144}Nd)_{CHUR}}{(^{147}Sm/^{144}Nd)_{CHUR}} \quad \text{eq. 5}$$

Onde:

$Sm/Nd_{CHUR \text{ (hoje)}} = 0,1967$

$^{143}Nd/^{144}Nd_{(0)CHUR} = 0,512638$

$Q = 25,09 \text{ ba}^{-1}$ (parâmetro que insere a constante de desintegração)

$(0) =$ o tempo atual

am = amostra

T = qualquer tempo

A equação que define o parâmetro ϵ_{Nd} , para qualquer idade, é uma reta do gráfico de ϵ_{Nd} pelo tempo. O $f_{Sm/Nd}$ é o grau de fracionamento de Sm/Nd da amostra em relação ao manto CHUR e pode ser entendido graficamente como a inclinação dessa reta, já que é a constante que acompanha a variável x (T) (DePaolo et al., 1991). Matematicamente pode ser escrito como a derivada de ϵ_{Nd} em função do tempo.

$$\frac{\partial \epsilon_{Nd}}{\partial T} = Q_{Nd} f_{Sm/Nd}$$

A idade modelo T_{DM} é representada graficamente pelo ponto de intersecção da reta, que define a variação de ϵ_{Nd} no tempo, com a parábola que representa a evolução da razão $^{143}Nd/^{144}Nd$ do manto empobrecido, definida por DePaolo (1981). Matematicamente é obtida igualando-se a equação de ϵ_{Nd} , com a de evolução do manto:

$$\epsilon_{Nd}(T) = 0,25T^2 - 3T + 8,5 \quad (\text{equação de DePaolo, para evolução isotópica de Nd no manto empobrecido})$$

Esta é uma maneira simplificada de se calcular a idade modelo. Segundo Sato (1998), a diferença entre os resultados obtidos pela formula simplificada e a sem aproximação é pequena, não passando de aproximadamente 10 Ma para o Neoproterozóico, 15 Ma para o Paleoproterozóico e 35 Ma para o Arqueano.

O cálculo da Idade Modelo T_{DM} em dois estágios está definido por Sato (1998) e difere um pouco da proposta por DePaolo et al. (1991):

$$T_{DM} = \frac{1}{\lambda} \ln \left\{ 1 + \frac{(^{143}Nd/^{144}Nd)_{DM} - (^{143}Nd/^{144}Nd)_{am}}{e^{(\frac{^{147}Sm/^{143}Nd_e - ^{147}Sm/^{143}Nd_{am}}{^{147}Sm/^{143}Nd_{DM} - ^{147}Sm/^{143}Nd_e}) (e^{\lambda T_2} - 1)}} \right\}$$

Onde

λ = constante de decaimento

DM = valores de manto empobrecido

am = valores da amostra (hoje)

e = valores estimados, no caso 0,11

$$^{147}Sm/^{144}Nd_{DM} = 0,219$$

$$^{143}Nd/^{144}Nd_{DM} = 0,51315$$

T_2 = idade de um evento secundario, que possa ter fracionado a amostra

A idade de um evento secundario pode ser obtida por uma isócrona Rb/Sr ou Sm/Nd ou outros métodos.

Método Rb-Sr

A preparação das amostras de rocha foi similar àquela das amostras analisadas pelo método Sm/Nd. O procedimento químico foi de acordo com as rotinas do laboratório do CPGeo, onde branco laboratorial médio e da ordem de 4 ng de Sr. A quantificação de Rb e Sr foi obtida por fluorescência de RX. Os teores de Rb-Sr das amostras Gr-15^a, V-314, V-332, Gr-15, D-982, V-198, D-806-a,b foram determinadas por fluorescência de RX, com uma precisão de ≤ 1.4 % para Rb e ≤ 1.0 % para Sr. Já as concentrações Rb-Sr das amostras Gr-29. Gr-29 a,b,d,e,f,h,i, V-290 e D-806-c foram obtidas por diluição isotópica, com precisão superior. As razões $^{87}\text{Sr}/^{86}\text{Sr}$ foram determinadas em espectrômetro mono-coletor VG-354, tendo sido corrigidas para o valor médio do padrão NBS-987 (0,710254 $\pm$ 0.000022, nível 2 σ) e normalizadas a $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. A proporção $^{87}\text{Rb}/^{86}\text{Sr}$ foi obtida através de cálculos, a partir dos valores de Rb total e Sr total. Os teores de Rb-Sr das amostras Gr-15^a, V-314, V-332, Gr-15, D-982, V-198, D-806-a,b foram determinadas por fluorescência de Raio-X, com uma precisão de ≤ 1.4 % para Rb e ≤ 1.0 % para Sr. Já as concentrações Rb-Sr das amostras Gr-29. Gr-29 a,b,d,e,f,h,i, V-290 e D-806-c foram obtidas por diluição isotópica. Os dados Rb-Sr foram interpretados em diagramas binários Nd-Sr e também para fins da modelagem petrogenética das rochas granitoides.

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Apêndice B1. Análises de óxidos, traços e terras raras em rocha total dos granitoides da Zona Sul (continua).

Amostra	401	403	404	406	408	412	514	515	516	518	528	531
Unidade	SRamon	SJavier	SAndrés	SRafael	Refugio	SPedro	LManech	LManech	DonMario	RNegro	Silvestre	Spablo
SiO2	64,16	74,05	72,75	73,07	74,74	74,57	69,17	74,33	63,72	53,72	72,59	73,57
Al2O3	15,93	13,68	12,89	13,37	13,46	13,12	13,72	13,19	20,73	14,32	15,67	14,67
MnO	0,063	0,043	0,060	0,052	0,053	0,055	0,080	0,076	0,024	0,146	0,022	0,017
MgO	1,15	0,21	0,29	0,23	0,28	0,28	0,88	0,28	0,10	7,26	0,07	0,23
CaO	3,55	1,27	1,23	0,92	1,29	0,13	2,58	2,88	1,23	5,76	1,73	1,53
Na2O	4,24	3,73	2,79	2,88	3,93	0,56	2,72	5,01	5,55	2,10	3,85	3,56
K2O	2,74	4,52	5,24	5,35	4,00	2,76	3,66	0,57	6,58	4,98	5,37	5,03
TiO2	0,79	0,171	0,383	0,245	0,173	5,790	0,699	0,257	0,075	1,047	0,044	0,149
P2O5	0,254	0,051	0,087	0,078	0,043	0,154	0,200	0,068	0,133	0,627	0,023	0,039
Fe2O3	5,02	1,30	3,12	2,01	1,35	0,06	4,38	2,51	0,66	7,91	0,36	1,13
Loi	0,65	0,37	0,44	0,94	0,44	1,83	0,65	0,20	0,73	1,00	0,32	0,36
Total	98,55	99,40	99,28	99,15	99,76	99,31	98,74	99,37	99,53	98,87	100,05	100,29
Ba	1180	594	556	363	562	370	798	117	480	2471	1749	480
Nb	9	8	19	26	11	11	12	8	24	12	1	5
Pb	18	31	28	36	18	29	23	8	58	20	68	48
Rb	95	177	275	413	120	267	121	5	552	190	142	220
Sr	688	215	60	74	206	39	227	210	138	757	877	169
Th	16	14	32	35	13	13	46	8	30	14	1	18
U	11	3	5	6	3	5	2	1	5	1	1	25
V	70	10	22	14	9	9	45	16	9	112	9	9
Y	15	4	140	58	12	69	25	33	9	23	1	9
Zr	275	95	340	229	90	116	368	150	101	303	30	105
La	65,6	30,20	191,67	64,50	24,94	30,41	158,43	42,39	39,67	92,4	8,50	22,5
Ce	126	44,64	211,06	137,67	43,54	60,04	278,84	63,24	66,64	182	12,9	44,3
Pr	14,1	5,00	40,62	17,40	4,86	8,72	32,40	9,84	6,96	23,4	1,23	4,97
Nd	47,7	14,56	144,59	59,20	15,40	31,59	113,25	35,28	20,91	89,2	3,72	17,5
Sm	7,09	1,76	26,49	11,46	2,51	8,02	16,84	6,61	3,42	15,2	0,51	3,38
Eu	1,69	0,49	2,70	0,94	0,55	0,68	2,17	1,07	0,54	3,92	1,30	0,78
Gd	6,53	1,51	26,21	10,38	2,59	8,35	15,28	6,28	3,15	11,2	0,41	2,81
Tb	0,63	0,14	3,87	1,57	0,32	1,66	1,36	0,93	0,35	1,26	0,04	0,37
Dy	3,17	0,73	22,12	9,19	1,80	10,74	6,49	5,54	1,67	5,70	0,22	1,79
Ho	0,57	0,14	4,59	1,96	0,39	2,56	1,05	1,25	0,28	0,98	0,04	0,33
Er	1,50	0,44	12,59	5,87	1,14	7,24	2,74	3,52	0,72	2,39	0,11	0,85
Tm	0,21	0,06	1,82	1,03	0,18	1,15	0,31	0,55	0,09	0,30	0,01	0,11
Yb	1,26	0,49	12,31	7,98	1,29	7,74	1,71	3,82	0,58	1,79	0,12	0,69
Lu	0,19	0,09	1,74	1,23	0,20	1,11	0,25	0,57	0,08	0,26	0,01	0,10

Apêndice B1. Análises de óxidos, traços e terras raras em rocha total dos granitoides da Zona Sul (conclusão).

Amostra	532	533	534	535	538	546	547	549	550	551	552	553A	553B	558
Unidade	Vibosi	Calama	STeresa	EICarmen	SRosario	Rafaelito	Sujalito	Limones	EIPuente	Momené	Guarayos	PNuevo	PNuevo	LaCruz
SiO₂	71,31	62,02	63,18	63,90	76,57	75,09	75,45	61,41	72,68	80,04	76,49	72,61	72,74	76,78
Al₂O₃	13,46	14,45	14,79	15,30	11,98	13,01	11,94	16,90	14,10	10,12	11,68	14,01	14,40	12,33
MnO	0,064	0,099	0,087	0,074	0,028	0,032	0,053	0,070	0,027	0,032	0,038	0,028	0,027	0,021
MgO	0,38	1,72	1,66	1,64	0,01	0,19	0,08	1,61	0,44	< 0,01	0,08	0,53	0,32	0,16
CaO	1,66	3,63	3,38	2,78	0,58	0,75	0,26	4,20	1,66	0,53	0,70	1,76	1,28	0,20
Na₂O	2,67	3,12	3,18	3,70	3,14	2,91	3,73	4,46	3,42	2,40	2,35	3,15	3,37	3,26
K₂O	5,44	4,26	3,97	4,59	5,24	5,68	4,53	2,61	4,71	5,06	6,01	4,57	5,43	5,24
TiO₂	0,503	1,360	1,235	1,011	0,167	0,249	0,297	0,908	0,277	0,175	0,200	0,345	0,269	0,158
P₂O₅	0,157	0,533	0,477	0,357	0,008	0,049	0,025	0,325	0,089	0,005	0,022	0,131	0,066	0,012
Fe₂O₃	3,39	7,19	6,45	5,34	1,68	1,81	3,35	5,37	1,94	1,71	1,94	2,17	1,78	1,38
Loi	0,70	0,76	0,86	0,60	0,46	0,50	0,04	1,18	1,00	0,40	0,34	0,47	0,48	0,62
Total	99,73	99,14	99,27	99,29	99,86	100,27	99,76	99,04	100,34	100,47	99,85	99,77	100,16	100,16
Ba	729	1245	1243	1313	225	765	1381	3503	908	132	914	1123	746	740
Nb	26	32	30	30	27	15	20	9	10	24	17	9	11	20
Pb	30	25	23	35	29	25	22	10	43	36	33	34	65	21
Rb	270	186	171	243	302	227	87	43	197	2132	218	179	209	174
Sr	142	338	355	447	16	67	70	1093	310	15	75	367	187	56
Th	34	23	31	40	29	15	14	9	37	31	24	26	52	21
U	4	2	2	6	4	3	3	1	2	6	3	2	11	4
V	16	88	83	72	11	20	9	73	32	9	8	26	18	10
Y	89	80	85	66	113	47	75	9	30	160	91	17	11	70
Zr	333	946	813	502	288	190	434	357	207	237	305	240	209	174
La	95,2	148	162	157	78,4	36,0	102	141	75,4	82,0	84,6	55,2	59,4	68,4
Ce	244	323	338	295	151	111	133	224	151	182	195	99,6	122	129
Pr	25,1	43,0	44,5	33,9	19,1	10,3	25,2	22,8	17,0	24,0	20,7	11,1	12,6	16,1
Nd	89,8	153	154	115	70,2	37,0	94,8	71,0	59,1	93,5	74,6	37,7	42,0	58,3
Sm	17,3	25,6	26,3	18,0	14,6	7,31	17,3	7,58	10,2	22,8	14,6	5,98	6,56	11,1
Eu	2,08	3,46	3,45	2,75	1,07	0,99	3,09	3,18	1,60	0,99	1,60	1,62	1,19	1,19
Gd	16,3	21,4	22,0	15,7	15,4	6,94	15,3	5,92	8,53	25,4	14,4	5,25	4,87	10,7
Tb	2,68	2,97	3,10	2,18	2,74	1,20	2,29	0,52	1,24	4,71	2,43	0,70	0,53	1,75
Dy	16,0	15,8	16,6	11,8	17,1	7,38	12,8	2,27	6,47	28,8	14,6	3,47	2,31	10,3
Ho	3,57	3,21	3,34	2,44	3,96	1,69	2,77	0,37	1,26	6,58	3,29	0,64	0,40	2,36
Er	10,2	8,56	8,85	6,63	11,1	4,73	7,72	1,00	3,09	17,4	9,02	1,58	1,08	6,61
Tm	1,59	1,17	1,22	0,94	1,68	0,73	1,15	0,13	0,41	2,46	1,36	0,19	0,15	1,02
Yb	10,8	7,53	7,72	5,93	11,3	4,83	7,78	0,74	2,35	15,0	8,74	1,16	1,14	6,93
Lu	1,52	1,10	1,09	0,83	1,62	0,71	1,18	0,12	0,33	2,00	1,22	0,17	0,18	1,04

Apêndice B1. Análises de óxidos, traços e terras raras em rocha total do Complexo Granitóide Pensamento (continua).

Amostra	501	502	503	504	505	506	507	508	509
Unidade	PisoFirme	S.Cristobal	S.Cristobal	Porvenir	Diamant	Diamant	Diamant	Diamant	S Martín
SiO2	76,07	76,08	74,12	74,26	72,33	72,14	73,53	74,84	76,76
Al2O3	12,44	12,46	13,02	13,75	14,39	14,47	13,49	13,43	11,51
MnO	0,025	0,030	0,054	0,043	0,035	0,034	0,034	0,033	0,044
MgO	0,06	0,08	0,22	0,22	0,30	0,29	0,28	0,19	0,09
CaO	0,56	0,56	1,07	1,27	1,33	1,28	1,15	1,00	0,62
Na2O	4,47	3,73	3,49	3,74	3,19	3,21	2,96	3,36	2,41
K2O	4,07	4,88	4,86	4,53	5,52	5,94	5,44	5,07	5,63
TiO2	0,123	0,117	0,242	0,173	0,255	0,243	0,241	0,140	0,188
P2O5	0,017	0,017	0,048	0,047	0,068	0,062	0,067	0,051	0,025
Fe2O3	1,50	1,42	2,24	1,31	1,68	1,65	2,03	1,35	2,20
Loi	0,67	0,38	0,21	0,39	0,38	0,20	0,34	0,40	< 0,01
Total	100,01	99,75	99,57	99,73	99,48	99,52	99,56	99,86	99,48
Ba	811	336	614	822	902	776	690	429	721
Nb	11	10	8	22	9	7	12	8	7
Pb	6	13	12	21	44	39	44	55	22
Rb	100	157	158	179	245	212	249	251	144
Sr	24	24	59	21	215	201	153	176	69
Th	8	7	6	14	20	39	55	32	17
U	3	3	2	5	5	7	8	16	1
V	< 9	< 9	< 9	< 9	< 9	18	14	< 9	< 9
Y	45	66	54	148	23	18	18	122	95
Zr	215	142	197	360	178	197	185	118	292
La	31,4	33,0	34,8	65,1	69,7	99,5	70,0	24,2	91,6
Ce	60,1	61,7	55,9	179	128	128	182	56,9	212
Pr	7,83	8,97	9,45	19,3	15,2	21,3	17,8	6,49	26,8
Nd	29,2	35,1	36,4	76,0	52,4	71,1	61,2	23,5	106
Sm	6,44	8,13	8,33	17,9	8,55	11,0	11,2	5,95	24,1
Eu	0,64	0,44	1,12	1,88	1,20	1,27	1,24	0,79	2,70
Gd	6,61	8,59	8,30	20,1	7,34	9,21	9,28	7,96	24,3
Tb	1,13	1,52	1,48	3,57	0,77	0,90	1,00	1,92	3,88
Dy	7,10	9,36	8,98	22,3	3,75	4,06	4,45	14,1	21,0
Ho	1,69	2,23	2,07	5,26	0,72	0,66	0,72	3,82	4,16
Er	4,80	6,24	5,86	14,9	2,00	1,65	1,72	11,3	10,1
Tm	0,77	0,98	0,94	2,30	0,29	0,20	0,22	1,75	1,24
Yb	5,33	6,67	6,41	15,4	1,92	1,21	1,33	11,3	7,03
Lu	0,80	0,99	0,94	2,27	0,29	0,19	0,21	1,65	0,85
Hf	7,00	6,13	6,15	12,6	5,51	6,43	6,45	4,93	11,0
Ta	0,77	0,75	0,76	1,38	0,68	0,28	0,25	0,49	0,53

Apêndice B1. Análises química do Complexo Pensamiento e do Complexo Lomas Manechis (conclusão).

Amostra	510	511	512	513	514	515
Unidade	La Junta	La Junta	La Junta	La Junta	L.Manechis	L.Manechis
SiO2	69,27	71,26	74,19	68,63	69,17	74,33
Al2O3	14,83	14,48	14,16	15,46	13,72	13,19
MnO	0,034	0,032	0,022	0,030	0,080	0,076
MgO	0,75	0,43	0,24	0,59	0,88	0,28
CaO	1,24	1,33	2,04	1,80	2,58	2,88
Na2O	2,55	2,80	3,63	3,49	2,72	5,01
K2O	6,52	6,30	3,96	4,98	3,66	0,57
TiO2	0,477	0,330	0,106	0,442	0,699	0,257
P2O5	0,148	0,120	0,044	0,156	0,200	0,068
Fe2O3	2,79	2,05	1,33	3,24	4,38	2,51
Loi	0,82	0,40	0,19	0,67	0,65	0,20
Total	99,43	99,53	99,91	99,49	98,74	99,37
Ba	1515	776	805	525	798	117
Nb	13	12	4	20	12	8
Pb	26	40	20	36	23	8
Rb	165	224	141	223	121	5
Sr	287	168	296	109	227	210
Th	20	33	5	67	46	8
U	2	3	2	5	2	1
V	26	14	16	37	45	16
Y	54	23	7	43	25	33
Zr	206	216	110	314	368	150
La	64,0	70,5	17,2	110	158	42,4
Ce	130	148	31,8	220	279	63,2
Pr	20,2	17,3	3,55	25,9	32,4	9,84
Nd	76,1	60,5	11,6	91,0	113	35,3
Sm	14,0	10,8	1,77	16,3	16,8	6,61
Eu	1,95	1,10	0,59	1,15	2,17	1,07
Gd	12,5	9,81	1,75	15,6	15,3	6,28
Tb	1,71	1,08	0,21	1,86	1,36	0,93
Dy	9,39	4,99	1,15	9,11	6,49	5,54
Ho	1,90	0,85	0,25	1,56	1,05	1,25
Er	5,00	1,99	0,75	3,39	2,74	3,52
Tm	0,68	0,24	0,12	0,34	0,31	0,55
Yb	3,98	1,31	0,89	1,69	1,71	3,82
Lu	0,51	0,20	0,14	0,25	0,25	0,57
Hf	5,86	7,33	4,45	10,0	9,75	4,73
Ta	1,22	0,26	0,46	0,96	0,47	0,55

Apêndice B2, Tabela1. Resultados analíticos das datações U-Pb em zircão por SHRIMP (continua).

No ponto	U(ppm)	Th(ppm)	Th/U	Pb*(ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	f _{206%}	Idade (Ma)										%Disc
							²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²³⁵ U	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	
Amostra CA0509, granito San Martín																	
509.1	976	41	0,04	202	0,00010	0,16	0,240	0,48	2,841	0,93	0,085	0,68	1387	5,9	1334	16	-4
509.2	2782	61	0,02	502	0,00010	0,16	0,210	0,45	2,519	0,70	0,086	0,48	1228	5,0	1363	10	10
509.3	247	100	0,42	53	0,000000	0,00	0,250	0,77	3,052	1,50	0,085	1,40	1436	9,9	1398	25	-3
509.4	260	94	0,37	57	0,000000	0,00	0,253	0,75	3,156	1,50	0,087	1,30	1455	9,8	1433	24	-2
509.5	1008	276	0,28	215	0,00011	0,18	0,248	0,47	3,027	0,89	0,087	0,64	1428	6,0	1395	14	-2
509.6	1464	49	0,03	280	0,00011	0,19	0,222	1,10	2,583	1,50	0,084	0,88	1293	13,0	1301	19	1
509.7	163	54	0,34	39	0,00030	0,49	0,279	0,87	3,343	2,30	0,083	1,60	1587	12,0	1358	41	-17
509.8	271	93	0,35	59	0,00005	0,09	0,255	0,73	3,119	1,50	0,088	1,30	1463	9,5	1399	25	-5
509.9	259	117	0,47	60	0,00000	0,00	0,270	0,82	3,376	1,40	0,086	1,30	1540	11,0	1442	22	-7
509.1	218	51	0,24	42	0,00000	0,00	0,223	0,87	2,765	1,80	0,088	1,60	1295	10,0	1428	30	9
Amostra SA0404 granito San Andrés																	
404.1	149	89	0,61	27	0,00014	0,24	0,207	2,5	2,361	3,2	0,077	2,1	1213	27	1263	39	4
404.2	98	60	0,63	17	0,00045	0,76	0,204	2,5	2,224	3,8	0,082	2,3	1196	27	1175	57	-2
404.3	434	101	0,24	76	0,00065	1,08	0,201	2,3	2,217	3,3	0,081	1,2	1182	25	1194	47	1
404.4	79	45	0,59	13	0,00009	0,16	0,190	2,7	2,275	3,9	0,081	2,8	1121	27	1357	54	17
404.5	413	240	0,60	73	0,00000	0,00	0,205	2,3	2,382	2,5	0,078	1,2	1203	25	1298	22	7
404.6	130	54	0,42	24	0,00000	0,00	0,216	2,4	2,578	3	0,08	1,9	1262	28	1348	34	6
404.7	192	158	0,85	36	0,00000	0,00	0,220	2,3	2,539	2,8	0,074	1,8	1282	27	1286	30	0
404.8	92	57	0,64	17	0,00000	0,00	0,214	2,6	2,448	3,4	0,070	2,8	1250	29	1269	45	2
404.9	110	75	0,70	19	0,00016	0,27	0,202	2,5	2,322	3,4	0,078	2,4	1185	27	1279	45	7
404.1	293	126	0,44	56	0,00005	0,08	0,223	2,3	2,597	2,7	0,082	1,3	1295	27	1308	26	1
404.11	144	73	0,53	27	0,00013	0,21	0,214	2,4	2,441	3,2	0,078	2	1251	27	1261	41	1
404.12	175	143	0,85	31	0,00012	0,19	0,207	2,4	2,39	3,1	0,082	1,7	1211	26	1289	38	6
404.13	318	205	0,67	74	0,00007	0,12	0,270	2,3	3,705	2,5	0,094	1	1540	31	1616	18	5
404.14	312	153	0,51	49	0,00012	0,20	0,181	2,3	2,09	2,8	0,071	1,7	1073	23	1285	29	16

Apêndice B2, Tabela1. Resultados analíticos das datações U-Pb em zircão por SHRIMP (conclusão).

No ponto	U(ppm)			Th(ppm)	Th/U	Pb*(ppm)	²⁰⁴ Pb/ ²⁰⁶ Pb	f ₂₀₆ %	Idade (Ma)						%Disc		
	²⁰⁶ Pb/ ²³⁸ U ±	²⁰⁷ Pb/ ²³⁵ U ±	²⁰⁷ Pb/ ²⁰⁶ Pb ±						²⁰⁶ Pb/ ²³⁸ U ±	²⁰⁷ Pb/ ²⁰⁶ Pb ±							
Amostra LC0558 granito La Cruz																	
558-1.1	244	160	0,68	56	0,00191	3,02	0,257	1,5	3,670	3,8	0,1083	1,4	1473	20	1692	65	13
558-1.2	932	240	0,27	76	0,00136	2,16	0,093	1,4	1,276	3,0	0,0836	1,8	572	8	1618	49	65
558-1.3	257	136	0,55	64	0,00021	0,34	0,290	1,5	4,068	2,1	0,1037	1,1	1642	21	1656	27	1
558-1.4	1413	586	0,43	135	0,00266	4,16	0,107	1,4	1,568	3,4	0,1085	1,0	654	9	1741	57	62
558-1.5	186	122	0,68	45	0,00023	0,37	0,281	1,5	3,978	2,1	0,1273	1,0	1597	22	1673	27	5
558-1.6	138	123	0,92	35	0,00019	0,30	0,297	1,6	4,141	2,3	0,1014	1,5	1676	24	1646	30	-2
558-1.7	279	120	0,44	74	0,00017	0,27	0,306	1,5	4,372	2,2	0,1055	1,1	1720	23	1691	29	-2
558-1.8	317	192	0,62	79	0,00007	0,11	0,289	1,5	4,117	1,8	0,1054	1,0	1637	22	1684	19	3
Amostra LJ20512, granito La Junta																	
512.2	168	117	0,72	31	0,00003	0,06	0,217	2,4	2,639	2,8	0,0844	1,6	1265	27	1389	30	9
512.3	452	106	0,24	97	0,00002	0,03	0,249	2,3	3,195	2,5	0,08869	0,9	1435	29	1486	18	3
512.4	3134	190	0,06	548	0,00017	0,29	0,203	2,2	2,468	2,3	0,08593	0,4	1191	24	1387	10	14
512.5	259	127	0,51	52	0,00002	0,04	0,233	2,3	2,801	2,6	0,0831	1,3	1348	28	1368	25	1
512.6	542	101	0,19	79	0,00248	4,08	0,163	2,3	1,930	6,4	0,082	4,8	973	21	1339	120	27
512.7	442	78	0,18	84	0,00017	0,28	0,220	2,3	2,598	2,7	0,0857	1,2	1280	27	1332	27	4
512.8	176	131	0,77	34	0,00039	0,63	0,226	2,4	2,759	3,3	0,0795	1,8	1311	28	1398	45	6
Amostra CP0507, granito Diamantina																	
507.1	332	136	0,42	70	0,00003	0,05	0,245	0,7	2,955	1,3	0,0855	1,2	1413	8	1370	22	-3
507.2	2377	2452	1,07	400	0,00014	0,24	0,195	0,4	2,285	0,8	0,05988	1,0	1149	4	1314	12	13
507-3.1	683	47	0,07	125	0,00013	0,22	0,212	0,5	2,496	1,1	0,08657	0,8	1241	6	1321	19	6
507-3.2	2753	212	0,08	548	0,00038	0,62	0,230	0,4	2,764	0,8	0,08648	0,5	1334	5	1364	14	2
507.5	274	104	0,39	55	0,00019	0,31	0,231	0,8	2,849	2,0	0,0859	1,5	1339	10	1414	35	5
507.6	140	65	0,48	28	0,00042	0,70	0,229	1,1	2,656	3,3	0,0786	2,2	1330	14	1293	61	-3

Apêndice B3, Resultados analíticos U-Pb TIMS

Amostra: Syenogranito Refugio, SR83									
Fração	SPU	Peso	U	Pb	206/204*	207/235#	206/238#	207/206#	207/206
		(ug)	(ppm)	(ppm)					Age (Ma)
A (zr)	4064	5,4	388	227	52	3,001 ± 0,89	0,2080 ± 0,72	0,11046 ± 0,50	1708
B (zr)	4065	5,0	441	114	363	2,896 ± 0,81	0,2049 ± 0,80	0,10251 ± 0,15	1670
C (zr)	4066	9,0	240	64	311	2,743 ± 0,80	0,2079 ± 0,79	0,09567 ± 0,16	1542
D (zr)	4067	4,3	286	97	183	3,435 ± 1,07	0,2426 ± 1,06	0,10268 ± 0,19	1673

Amostra: Monzogranito Las Maras, LM81									
Fração		Peso	U	Pb	206/204*	207/235#	206/238#	207/206#	207/206
		(ug)	(ppm)	(ppm)					Age (Ma)
A (zr)	4680	21,8	70	18	94	1,936 ± 5,45	0,1617 ± 5,42	0,08682 ± 0,63	1357
C (zr)	4070	20,8	116	30	174	2,253 ± 3,17	0,1897 ± 3,14	0,08615 ± 0,40	1342
D (zr)	4071	11,9	107	35	81	2,275 ± 5,48	0,1892 ± 5,44	0,08720 ± 0,69	1365
E (zr)	4072	22,4	136	33	445	2,368 ± 1,32	0,1989 ± 1,31	0,08633 ± 0,17	1346

SPU: número de laboratório

Razões corrigidas pelo branco analítico e pelo chumbo inicial

* Não corrigidas pelo branco e pelo chumbo inicial

Concentrações de U and Pb total corrigidas para o branco analítico

Idades: em Ma calculadas com base nas constantes de decaimento recomendadas por Steiger e Jäger(1977)

Apêndice B4. Resultados analíticos das datações U-Pb em zircão por abrasão laser (continua).

Amostra 601 Granito San Pablo

Análises	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ erro (%)	$^{207}\text{Pb}/^{235}\text{Pb}$	1σ erro (%)	$^{206}\text{Pb}/^{238}\text{Pb}$	1σ erro (%)	ρ	$^{207}\text{Pb}/^{206}\text{Pb}$ idade	1σ erro (%)	$^{207}\text{Pb}/^{235}\text{Pb}$ idade	1σ erro (%)	$^{206}\text{Pb}/^{238}\text{Pb}$ idade	1σ erro (%)
10Z05	0,17	0,11822	1,0	5,5133	2,0	0,33824	1,8	0,84	1929,5	17,0	1902,7	17,3	1878,2	29,2
16Z8	0,31	0,09891	0,6	4,0912	1,5	0,30000	1,4	0,86	1603,6	10,9	1652,6	12,0	1691,3	20,2
17Z9	0,24	0,09867	0,6	4,4109	1,5	0,32422	1,4	0,87	1599,1	11,4	1714,4	12,6	1810,3	22,1
28Z14N	0,22	0,10061	0,7	4,3078	1,6	0,31054	1,4	0,84	1635,4	12,9	1694,9	13,1	1743,4	21,9
30z16	0,54	0,09394	1,5	2,8439	2,0	0,21956	1,4	0,82	1507,0	27,5	1367,2	15,2	1279,5	16,3
34Z17N	0,28	0,09978	0,8	4,3349	1,8	0,31510	1,6	0,86	1620,0	15,3	1700,0	15,0	1765,7	25,3
40Z21	0,20	0,09966	0,8	3,8267	1,9	0,27849	1,7	0,89	1617,7	14,4	1598,4	15,2	1583,8	24,3
41Z22	0,27	0,09801	0,8	4,1559	1,6	0,30752	1,4	0,83	1586,7	14,6	1665,4	13,1	1728,5	21,4

Apêndice B4. Resultados analíticos das datações U-Pb em zircão por abrasão laser.

Amostra 544 Granito Limonal

Análises	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ erro (%)	$^{207}\text{Pb}/^{235}\text{Pb}$	1σ erro (%)	$^{206}\text{Pb}/^{238}\text{Pb}$	1σ erro (%)	ρ	$^{207}\text{Pb}/^{206}\text{Pb}$ idade	1σ erro (%)	$^{207}\text{Pb}/^{235}\text{Pb}$ idade	1σ erro (%)	$^{206}\text{Pb}/^{238}\text{Pb}$ idade	1σ erro (%)
3z1	0,30	0,08329	1,0	2,8836	2,0	0,25111	1,8	0,84	1275,9	18,8	1377,6	15,3	1444,2	23,3
10Z4B	0,09	0,08408	0,5	1,3957	1,5	0,12039	1,4	0,91	1294,4	10,0	887,1	8,7	732,8	9,5
11Z05	0,30	0,08731	0,5	2,9316	1,3	0,24352	1,1	0,85	1367,4	10,2	1390,1	9,4	1405,0	14,3
12z06	0,13	0,08803	1,0	1,3956	2,1	0,11497	1,9	0,96	1383,2	18,3	887,1	12,5	701,6	12,6
16Z8	0,12	0,08634	0,6	2,4605	2,1	0,20668	2,0	0,95	1345,9	11,1	1260,5	15,0	1211,1	22,2
17Z9N	0,23	0,08822	0,4	3,0844	1,6	0,25356	1,6	0,95	1387,4	8,0	1428,8	12,4	1456,8	20,5
22Z10	0,21	0,08486	0,5	2,9784	1,9	0,25456	1,8	0,95	1312,3	10,1	1402,1	14,1	1462,0	23,5
23Z011B	0,03	0,09173	1,6	0,3800	22,0	0,03004	21,9	1,00	1461,9	30,7	327,0	59,6	190,8	41,1
24z011N	0,08	0,10890	5,4	1,9118	7,7	0,12732	5,5	0,89	1781,1	95,7	1085,2	50,1	772,6	39,8
33z15	0,23	0,08497	0,6	2,9890	2,0	0,25513	1,9	0,94	1314,9	11,5	1404,8	15,1	1464,9	25,0
39z16	0,14	0,08404	0,5	2,8142	1,5	0,24288	1,5	0,87	1293,4	9,7	1359,3	11,5	1401,6	18,4
40z17	0,64	0,07573	1,1	2,3390	2,1	0,22400	1,8	0,82	1088,0	21,5	1224,2	15,0	1303,0	21,6
41Z018	0,28	0,08115	0,5	2,6530	1,7	0,23709	1,7	0,95	1225,2	8,9	1315,5	12,8	1371,6	20,7
42z019	0,04	0,06870	0,9	1,5531	2,1	0,16396	1,9	0,95	889,8	18,8	951,7	12,8	978,7	17,0

Apêndice B4. Resultados analíticos das datações U-Pb em zircão por abrasão laser (conclusão).

Amostra 418, Granito Talcoso

Análises	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ erro (%)	$^{207}\text{Pb}/^{235}\text{Pb}$	1 σ erro (%)	$^{206}\text{Pb}/^{238}\text{Pb}$	1 σ erro (%)	ρ	$^{207}\text{Pb}/^{206}\text{Pb}$ idade	1 σ erro (%)	$^{207}\text{Pb}/^{235}\text{Pb}$ idade	1 σ erro (%)	$^{206}\text{Pb}/^{238}\text{Pb}$ idade	1 σ erro (%)
05Z03	0,18	0,08944	0,5	2,8934	1,5	0,23463	1,4	0,90	1413,6	9,9	1380,2	11,0	1358,7	16,8
015Z8	0,27	0,08591	0,8	2,5352	1,8	0,21402	1,6	0,86	1336,2	14,5	1282,2	13,0	1250,2	18,5
027Z14	0,21	0,08219	2,5	2,4528	2,9	0,21644	1,5	0,47	1250,1	48,4	1258,3	20,8	1263,1	17,0
029Z15	0,26	0,08688	0,7	2,6289	1,3	0,21947	1,2	0,82	1357,8	12,6	1308,8	9,8	1279,1	13,5
037Z18	0,11	0,09066	1,4	2,0528	2,0	0,16421	1,5	0,66	1439,5	26,1	1133,2	13,9	980,2	13,7
038z19	0,34	0,08068	0,9	1,9915	1,5	0,17902	1,2	0,84	1213,7	17,0	1112,6	10,1	1061,6	12,0
043Z22	0,22	0,08329	0,9	2,1369	1,6	0,18607	1,4	0,81	1276,1	16,6	1160,8	11,3	1100,1	14,2
044z23	0,18	0,08281	3,8	1,5939	4,2	0,13960	1,9	0,65	1264,8	72,3	967,8	26,0	842,4	14,6

Apêndice B5. Resultados analíticos Sm- Nd (continua).
San Ignacio Suite

Amostra	SPS	Unidade	Sm (ppm)	Nd (ppm)	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd	ε ₍₀₎	f _{Sm/Nd}	T _{DM} (Ga)	ε _(T1)
404	4396	San Andrés	30,760	161,515	0,1152	0,51188	-14,86	-0,41	1,8	-1,60
535	4983	San Andrés	19,105	126,586	0,0913	0,512027	-11,92	-0,54	1,3	+5,22
538	4984	El Carmen	14,564	73,080	0,1205	0,512177	-8,99	-0,39	1,4	+3,40
543*	5614	Limonal	10,511	49,300	0,1289	0,511978	-12,87	-1,34	1,9	-1,64
403	4395	San Javier	1,988	15,764	0,0763	0,51152	-21,79	-0,61	1,7	-1,31
406	4397	San Rafael	12,772	63,763	0,1211	0,51179	-16,57	-1,38	2,1	-3,72
501	4400	Piso Firme	6,830	30,375	0,1360	0,512229	-7,99	-0,31	1,7	+2,32
502	4401	San Cristóbal	7,826	32,431	0,1459	0,512337	-5,87	--	2,2	+2,75
503	4402	San Cristóbal	9,647	40,460	0,1442	0,512316	-6,28	--	1,7	+2,63
504	4234	Porvenir	19,278	79,089	0,1474	0,512285	-6,89	--	1,7	+1,48
505	4225	Diamantina	10,664	63,260	0,1019	0,511834	-15,69	-0,48	1,7	+0,39
506	4226	Diamantina	12,872	78,696	0,0989	0,511789	-16,56	-0,50	1,7	+0,03
507	4227	Diamantina	13,279	70,132	0,1145	0,511859	-15,20	-0,42	1,4	-1,25
508	4228	Diamantina	5,738	23,615	0,1469	0,512202	-8,51	--	1,7	-0,06
509	4229	San Martín	25,353	107,634	0,1424	0,512257	-7,43	--	1,6	+1,78
510	4230	La Junta	18,727	99,733	0,1135	0,511727	-17,77	-0,42	1,4	-3,66
511	4231	La Junta	14,692	80,734	0,1100	0,511720	-17,91	-0,44	1,6	-3,21
512	4232	La Junta	3,599	22,018	0,0988	0,511636	-19,55	-0,50	1,6	-2,94
513	4233	La Junta	18,697	100,573	0,1124	0,511685	-18,59	-0,43	1,6	-4,29
528	4978	San Luis	0,541	4,087	0,0801	0,511523	-21,75	-0,59	1,7	+2,99
546	4985	San Pedro	7,661	39,523	0,1172	0,511926	-13,88	-0,40	1,7	-0,37
547	4986	Sujalito	15,695	86,354	0,1099	0,511839	-15,59	-0,44	1,7	-0,83
549	4987	Limones	7,874	74,163	0,0642	0,511420	-23,75	-0,67	1,6	-1,23
552	4990	Guarayos	12,330	63,241	0,1179	0,511954	-13,35	-0,40	1,7	+0,05
553A	4991	Marimonos	6,245	38,574	0,0979	0,511803	-16,29	-0,50	1,6	+0,51
553B	4992	Marimonos	8,242	53,990	0,0923	0,511740	-17,51	-0,53	1,6	+0,24

T(Ma)=1,33 Ga calculado segundo a idade SHRIMP U-Pb (Boger et al., 2005). *Dado Obtido de Vargas Mattos, 2010

Apêndice B5. Resultados analíticos Sm- Nd (conclusão)

Granodiorito San Ramón

Amostra	SPS	Unidade	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$\epsilon_{(0)}$	$f_{\text{Sm/Nd}}$	$T_{\text{DM}} \text{ (Ga)}$	$\epsilon_{(T1)}$
401	4394	San Ramón	7,653	53,742	0,0861	0,51159	-20,45	-0,56	1,7	-0,29

T(Ma)=1,4 Ga calculado segundo a idade SHRIMP U-Pb (Santos et al., 2008).

Suite Yarituses

Amostra	SPS	Unidade	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$\epsilon_{(0)}$	$f_{\text{Sm/Nd}}$	$T_{\text{DM}} \text{ (Ga)}$	$\epsilon_{(T1)}$
558	4994	La Cruz	11,391	60,583	0,1137	0,51183	-11,59	-0,42	1,8	+2,12
601*	5615	San Pablo	1,541	7,583	0,1229	0,51203	-11,76	-0,38	1,7	+3,50
408	4398	Refugio	2,815	17,014	0,1000	0,51161	-20,04	-0,49	1,9	+0,18

T(Ma)=1,6 Ga calculado segundo a idade SHRIMP U-Pb (Santos et al., 2008) para as amostras 601 e 408. Amostra 558, T(Ma)=1,7 Ga

nesse trabalho. *Dado Obtido de Vargas-Mattos, 2010

Complexo Lomas Manechis

Amostra	SPS	Unidade	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$\epsilon_{(0)}$	$f_{\text{Sm/Nd}}$	$T_{\text{DM}} \text{ (Ga)}$	$\epsilon_{(T1)}$
514	4235	L.Manechis	17,132	0,092	0,1137	0,51158	-20,5	-0,53	1,8	-2,87
515	4236	L.Manechis	7,035	36,480	0,1166	0,51162	-19,83	-0,41	2,2	-2,84
518	4977	L.Manechis	17,152	100,626	0,1031	0,51180	-16,29	-0,48	1,7	-0,37

T(Ma)=1,7 Ga calculado segundo a idade SHRIMP U-Pb (Boger et al., 2005).

Apêndice B5. Resultados analíticos Rb- Sr (continua)
San Ignacio Suite

Amostra	SPR	Unidade	Rb (ppm)	Sr (ppm)	1/Sr	⁸⁷ Sr/ ⁸⁶ Sr	⁸⁷ Rb/ ⁸⁶ Sr	(⁸⁷ Sr/ ⁸⁶ Sr) _t p/T(Ma)
404	4396	San Andrés	299,10	79,60	0,0125	0,90317	11,089	-
535	4983	San Andrés	285,10	519,40	0,0019	0,73149	1,592	0,70114
538	4984	El Carmen	151,48	14,58	0,0686	0,63174	32,796	-
543*	5614	Limonal	488,20	63,30	0,0158	1,05431	23,070	-
403	4395	San Javier	176,10	233,00	0,0042	0,74494	2,196	0,70309
406	4397	San Rafael	450,30	95,20	0,0105	0,95290	14,015	-
501	4400	Piso Firme	111,59	27,68	0,0361	0,72473	11,687	-
502	4401	San Cristóbal	157,45	27,69	0,0361	1,03027	16,974	0,70664
503	4402	San Cristóbal	170,70	72,00	0,0139	0,83417	6,949	0,70169
504	4234	Porvenir	183,36	21,98	0,0455	1,18192	25,269	0,70015
505	4225	Diamantina	271,20	224,80	0,0044	0,76888	3,512	0,70193
506	4226	Diamantina	228,70	208,00	0,0048	0,76477	3,201	0,70374
507	4227	Diamantina	301,00	167,90	0,0060	0,79669	5,235	-
508	4228	Diamantina	232,90	166,10	0,0060	0,78021	4,086	0,70230
509	4229	San Martín	158,80	72,90	0,0137	0,82563	6,376	0,70407
510	4230	La Junta	169,30	287,40	0,0035	0,73644	1,710	0,70385
511	4231	La Junta	242,10	187,30	0,0053	0,77712	3,768	0,70529
512	4232	La Junta	140,10	323,00	0,0031	0,73006	1,258	0,70608
513	4233	La Junta	245,60	119,90	0,0083	0,81792	5,994	0,70364
528	4978	San Luis	69,66	675,82	0,0014	0,71467	0,298	0,70898
546	4985	San Pedro	241,10	67,40	0,0148	0,82125	10,464	-
547	4986	Sujalito	89,70	71,20	0,0140	0,78001	3,672	-
549	4987	Limones	48,44	878,65	0,0011	0,70530	0,159	0,70226
552	4990	Guarayos	227,40	74,90	0,0133	0,86200	8,922	
553A	4991	Marimonos	191,30	389,80	0,0025	0,72895	1,423	0,70182
553B	4992	Marimonos	281,70	194,80	0,0051	0,76944	4,211	-

T(Ma)=1,33 Ga calculado segundo a idade SHRIMP U-Pb (Boger et al., 2005). *Dado Obtido de Vargas Mattos, 2010

Apêndice B5. Resultados analíticos Rb- Sr (conclusão)
Granodiorito San Ramón

Amostra	SPS	Unidade	Rb (ppm)	Sr (ppm)	1/Sr	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{87}\text{Rb}/^{86}\text{Sr}$	$(^{87}\text{Sr}/^{86}\text{Sr})_t$ p/T(Ma)
401	4394	San Ramón	88,96	726,52	0,0014	0,71046	0,354	0,70324

T(Ma)=1,4 Ga calculado segundo a idade SHRIMP U-Pb (Santos et al., 2008).

Suite Yarituses

Amostra	SPS	Unidade	Rb (ppm)	Sr (ppm)	1/Sr	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{87}\text{Rb}/^{86}\text{Sr}$	$(^{87}\text{Sr}/^{86}\text{Sr})_t$ p/T(Ma)
558	4994	La Cruz	216,80	66,40	0,0150	0,90869	9,637	-
601*	5615	San Pablo	397,10	96,60	0,0103	0,89919	12,117	-
408	4398	Refugio	133,20	191,70	0,0075	0,74553	2,019	-

T(Ma)=1,6 Ga calculado segundo a idade SHRIMP U-Pb (Santos et al., 2008) para as amostras 601 e 408. Amostra 558, T(Ma)=

1,7 nesse trabalho. *Dado Obtido de Vargas Mattos, 2010

Complexo Lomas Manechis

Amostra	SPS	Unidade	Rb (ppm)	Sr (ppm)	1/Sr	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{87}\text{Rb}/^{86}\text{Sr}$	$(^{87}\text{Sr}/^{86}\text{Sr})_t$ p/T(Ma)
514	4235	L.Manechis	140,00	254,20	0,0071	0,73841	1,599	-
515	4236	L.Manechis	5,44	223,79	0,1838	0,70607	0,070	0,70435
518	4977	L.Manechis	103,54	614,42	0,0096	0,71894	0,488	0,70700

T(Ma)=1,7 Ga calculado segundo a idade SHRIMP U-Pb (Boger et al., 2005).

Apêndice C - Mapa Geológico do
Pré-Cambriano da Bolívia
(modificado de Litherland et al., 1986;
Boger et al., 2005; Landívar e Gonzales, 1997;
Adamek et al., 1996; Matos et al., 1996