Autorizo a reprodução e divulgação total ou parcial deste trabalho, por qualquer meio convencional ou eletrônico, para fins de estudo e pesquisa, desde que citada a fonte.

Serviço de Biblioteca e Documentação do IGc/USP

Ficha catalográfica gerada automaticamente com dados fornecidos pelo(a) autor(a)
via programa desenvolvido pela Seção Técnica de Informática do ICMC/USP

Bibliotecários responsáveis pela estrutura de catalogação da publicação:
Sonia Regina Yole Guerra - CRB-8/4208 | Anderson de Santana - CRB-8/6658

Iriarte Ibáñez, Álvaro Rodrigo
Geochronology of the granitic rocks of the Real
Cordillera of Bolivia / Álvaro Rodrigo Iriarte
Ibáñez; orientador Umberto Giuseppe Cordani. -- São
Paulo, 2021.
180 p.

Tese (Doutorado - Programa de Pós-Graduação em
Geoquímica e Geotectônica) -- Instituto de
Geociências, Universidade de São Paulo, 2021.

1. . I. Cordani, Umberto Giuseppe, orient. II.
Título.

UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE GEOCIÊNCIAS

**Geochronology of the granitic rocks of the Real Cordillera
of Bolivia**

ALVARO RODRIGO IRIARTE IBANEZ

Orientador: Prof. Dr. Umberto Giuseppe Cordani

Tese de Doutorado

Nº 636

COMISSÃO JULGADORA

Dr. Umberto Giuseppe Cordani

Dr^a. Suzanne Mahlburg Kay

Dr^a. Natalia Hauser

Dr. Victor Alberto Ramos

Dr. Francisco Enrique Isidoro Herve Allamand

Dr^a. Maria Helena Bezerra Maia de Hollanda

SÃO PAULO
2021

RESUMO

A presente tese de doutorado corresponde a um estudo geocronológico de granitoides e as suas rochas encaixantes localizadas na Cordilheira Real da Bolívia. Três artigos científicos são apresentados.

O primeiro trata da história geológica dos plutões Huayna Potosí e Zongo, assim também das encaixantes, usando os sistemas isotópicos Rb/Sr, K/Ar e U/Pb. Análises de Rb/Sr das encaixantes meta-sedimentares do Paleozoico inferior (formações Amutara e Cancañiri) produziram uma idade de isócrona de Rb/Sr de $344 \text{ Ma} \pm 38 \text{ Ma}$, indicando a ação do evento Gondwanide de caráter regional. Uma isócrona de cinco pontos do plutão Huayna Potosí gerou uma idade de $224 \pm 28 \text{ Ma}$. Para o plutão Zongo, uma grande quantidade de graus de zircão obtidos duma amostra das fácies Kutiucucho deu conteúdos extremadamente altos do urânio, produzindo idades aparentes de discórdia reversa. Contudo, devido que os pontos geraram uma linha aproximada, um cálculo de regressão lineal e o seu intercepto na linha de Concordia, resulto numa idade imprecisa de $220 \pm 20 \text{ Ma}$. O episódio final de cristalização magmática e a intrusão dos plutões na parte central da Cordillera Real ocorreu perto de $221.5 \pm 2.0 \text{ Ma}$. As discórdias reversas podem estar relacionadas a enriquecimentos em fluidos no final da cristalização dos plutões.

Para o segundo artigo, um estudo geocronológico de U/Pb baseado em dados SHRIMP em zircão dos outros plutões da Cordilheira Real é apresentado. O seu entorno tectônico, composições químicas e minérios, os posicionam dentro do chamado “arco magmático interno” o qual é diferente do atual “arco magmático” localizado ao oeste. O grupo Triássico, deu as seguintes idades: $239 \pm 22 \text{ Ma}$ para o granito Huato, $231 \pm 1 \text{ Ma}$ para o granodiorito Illampu, $221 \pm 3 \text{ Ma}$ para o granito Huayna Potosí e $223 \pm 2 \text{ Ma}$ para o granodiorito Taquesi. Pulsos magmáticos podem ser calculados em 223, 230, 242 and 248 Ma, respectivamente. O grupo Oligoceno, composto de duas amostras deu idades de 27 Ma para o batólito Quimsa Cruz. Uma grande quantidade relativa de zircão herdado foi encontrada nesses granitoides “frios”, sugerindo proveniência dos metapelitos paleozoicos. Aquela relativamente grande quantidade de heranças de xenocristais provavelmente registra a influência de processos de subdução durante a orogenia Gondwanide (336-205 Ma), atuando como um processo de arco magmático geral, acentuado no estágio final com a rubrica dum rifting continental (245-220 Ma).

Finalmente o terceiro artigo trata da relação entre os plutões da Cordilheira Real e as suas encaixantes, usando idades de U/Pb em zircão. As idades SHRIMP foram obtidas nos xenocristais de zircões dos plutões e as idades LA-ICP-MS foram obtidas em zircões detríticos de unidades meta-sedimentares. Alta correlação estatística, sugere assimilação dessas unidades pelos magmas félsicos. As idades são distribuídas em rangos de 300 até 2300 Ma. Picos altos com idades neoproterozóicas (500-750 Ma) são observados em todos os dados. São discutidas várias possibilidades acerca das fontes de proveniência: os cinturões Brasileiros ou Puncoviscanos, um cinturão oculto “in situ” dentro dos Andes Centrais, até a reciclagem de rochas sedimentares mais antigas.

Palavras-chave: Granitoides, Andes Centrais, U/Pb zircon ages, Cordilheira Real, Bolívia.

ABSTRACT

The present PhD thesis corresponds to a geochronological study of granitoids and their country rocks located at the Cordillera Real of Bolivia. Three scientific papers are presented. The first paper is about the geologic history of the Huayna Potosí and Zongo plutons as well as their country rocks, using Rb/Sr, K/Ar and U/Pb isotopic systems. Rb/Sr analyses of metapelitic country rocks of early Paleozoic (Amutara and Cancañiri Formations) yielded a Rb-Sr isochron age of 344 ± 38 Ma, indicating the action of an early Gondwanide regional event. A five-point Rb-Sr isochron from the Huayna Potosi pluton yielded an age of 224 ± 28 Ma. For the Zongo pluton, many of the zircon grains obtained from one sample of its Kuticucho facies yielded extremely high uranium content, which produced reverse discordant apparent ages. However, due to the fair alignment of the analytical points, it was made a regression calculation and the interception of the Concordia curve resulted in an imprecise age of 220 ± 20 Ma. The final magmatic crystallization and the intrusion of plutons in the central part of the Cordillera Real have occurred close to 221.5 ± 2.0 Ma. The reverse discordant apparent ages can be related to fluid enrichments at the final crystallization stage of these plutons.

For the second paper, a geochronological study of U/Pb zircon ages of the other plutons of the Cordillera Real is presented. It is based on SHRIMP data. Their tectonic setting, chemical and ore compositions make them part of the so-called “Inner Magmatic Arc”, which differs from the current “Magmatic Arc” located to the west. The Triassic group yielded the following results: 239 ± 2 Ma for the Huato granite, 231 ± 1 Ma for the Illampu granodiorite, 221 ± 3 Ma for the Huayna Potosí granite and 223 ± 2 Ma for the Taquesi granodiorite. Magmatic pulses can be calculated at 223, 230, 242 and 248 Ma. For the Oligocene group ages of 27 for two samples of the Quimsa Cruz batholith were obtained. Relatively abundant zircon inheritance was found in these “cold” granitoids, with ages suggesting provenance from early Paleozoic metapelites. This relatively abundant xenocrystic inheritance probably records the influence of the subduction process acting during the Gondwanide orogeny (336-205 Ma) as an overall subduction arc environment, punctuated at its final stage with the imprint of a continental rifting (245-220 Ma).

Finally, the third paper deals with the relationship of the plutons of the Cordillera Real and their country rocks. It uses U/Pb zircon ages. SHRIMP ages are from xenocrystal zircons of the plutons and LA-ICP-MS ages are from detrital zircons of meta-sedimentary units. High statistical correlation suggests assimilation of meta-sedimentary units by felsic melts. Ages distribution ranges from 300 to 2300 Ma. High peaks of Cambrian to late Neoproterozoic ages (500-750 Ma) are observed. There are discussed several possibilities about the provenance of these detrital zircons: Brasiliano or Puncoviscano belts, an “in situ” hidden belt within the Central Andes or recycling of pre-existent sedimentary rocks bearing those detrital zircons.

Key words: Granitoids, U/Pb zircon ages, Central Andes, Cordillera Real, Bolivia.

SUMMARY

RESUMO.....	1
ABSTRACT.....	3
1. CHAPTER 1 INTRODUCTION	6
1.1 Geological history of the Central Andes.....	6
1.2 Objectives and structure of the work.....	11
2. CHAPTER 2 PETROGRAPHY AND WHOLE-ROCK	
GEOCHEMISTRY OF THE STUDIED ROCKS.....	13
2.1 Petrographical features.....	14
Illampu pluton.....	14
Huayna Potosí pluton.....	15
Zongo pluton.....	20
Taquesi pluton.....	22
Huato pluton.....	23
Quimsa Cruz pluton.....	24
Country rock sedimentary units.....	24
2.2 Whole rock Geochemistry of the Huayna Potosí	
and Zongo plutons.....	27
2.3 Considerations of the geochemical features of	
the Cordillera Real granitoids.....	35
3. CHAPTER 3 Geochronological systematics of the Huayna Potosí,	
Zongo and Taquesi plutons, Cordillera Real of Bolivia, by the K/Ar,	
Rb/Sr and U/Pb methods - Brazilian Journal of Geology.....	39
4. CHAPTER 4 Geochronology of the Cordillera Real granitoids, the inner	
magmatic arc of Bolivia - Andean Geology.....	62
5. CHAPTER 5 Provenance study of Phanerozoic rocks from the Cordillera	
Real of Bolivia– Submitted to the Brazilian Journal of Geology.....	102
6. CHAPTER 6 CONCLUSIONS.....	143
7. BIBLIOGRAPHY.....	148
8. Annex table I.....	157
9. Annex II.....	176

CHAPTER I – INTRODUCTION

1.1 Geological history of the Central Andes

The Central Andes are a mountain belt located between 10° to 30° S and 80° to 60° W (fig.1) with 1900 km length, 640 km width and peaks above 6000 meters above sea level. Altiplano occupies the central part with a surface of $1.2 \times 10^5 \text{ km}^2$ (Lamb e Hoke et al., 1997) and a mean altitude of 4000 km. Following studies of the continental crust, its thickness is of 49 to 80 km (Dorbath et al., 1993; Lamb e Hoke, 1997; McQuarrie et al., 2002, McGlashan et al. 2008; Assumpção et al., 2013). These features indicate that the Altiplano is the second highest plateau of the World, following the Tibet and at the same time, it is the highest plateau related to slab subducting underneath a continental margin.

Fig. 1 Continental map showing the location of the area of study and the main geological units, square is zoomed in fig. 2. Modified after Cordani et al., (2019) and Collo et al. (2009).

Within the Central Andes, the Cordillera Real occupies a central position and it is characterized by an orogenic belt of 250 km in length made up of Triassic and Oligocene granitoids emplaced within early Paleozoic metapelites (figs. 2 and 3), which are the focus of this PhD research.

Fig.2 Regional geologic map showing main geological units of the Central Andes. Square is zoomed in fig. 3. After Cordani et al. (2016).

The geological and structural configuration of the Cordillera Real (northern part of the Eastern Cordillera of Bolivia) can be explained following the regional magmatic, sedimentary and structural development from pre-Cambrian time to nowadays.

Oldest crystalline basement outcrops to the east (Amazonia) ranging from 2.3 to 1.0 Ga and to the west (Arequipa-Antofalla) ranging from 2.0 to 1.8 Ga (Loewy et al., 2004). One important regional feature at the eastern terrains corresponds to the Trans Brasiliano Khandi lineament, over which several tectono-stratigraphic units were developed (Cordani et al., 2020, fig. 1).

These terrains were cratonized at the end of the Mesoproterozoic; with the onset of the Sunsás magmatic arc, a collision that generated another suture, between the Amazonian and Arequipa-Antofalla blocks (Ramos, 2008, fig. 1). This suture is a weakened zone that will be re-used later on to: 1) accommodate subsiding Paleozoic basins; 2) rise of mantle melts and 2) partial melting that will generate crustal magmatism during the whole Phanerozoic. Neoproterozoic belts surround these older cores along the whole continent (fig. 1).

During the early Paleozoic, sedimentation of large amount of material eroded away from the neighboring cratons occurred at these subsiding basins. During the interval from Devonian to Permian (380-280 Ma) deformation was recorded in Ordovician to Silurian metapelitic sediments as crenulation folding and local discordances, which has been described as the “Hercynian orogeny” (Mégard et al., 1971; Suarez, 2000; Jiménez et al., 2009).

Possibly, a volcanic arc was set on western Gondwana during the Carboniferous, with a larger part of the Central Andes basins remaining as a back arc position (or inner arc, Clark, 1990). These were full-filled by clastic, carbonatic and minor volcano-sedimentary sequences from the Pennsylvanian to the Permian (fig. 2).

During the mid to upper Triassic an extensional regime was set along the western border of Gondwana, with the following characteristics: basic to felsic magmatism, volcano-sedimentary rocks and rift-like basins located on central Perú, northern Chile and the Eastern Cordillera of Bolivia (Spikings et al., 2016). Triassic felsic magmatism at the Cordillera Real was recorded as granitoids at that interval of time (fig. 3). Lack of development of an actual oceanic crust and decrease on the extensional regime implied the cessation of the rifting stage at the end of the Triassic (Sempere et al., 2002; Spiking et al., 2016). This episode was followed by intense magmatic activity closer to the western continental border, at the main arc due to subduction during the Jurassic (see location of the main arc on fig. 2).

Fig. 3 Local geology showing the pluton distribution and a generalized stratigraphy of the region. Modified from the Geological Service of Bolivia (GEOBOL, 1995-2013).

Evidence of magmatic rocks associated to slab subduction is present at central Perú and northern Chile (e.g. Chocolate Fm.). At the Eastern Cordillera of Bolivia, this magmatism was absent, showing instead sedimentation in desert lakes, small volume of alkaline rocks and dikes swarms associated to extensive regime present through the whole Mesozoic (Sempere et al., 2002). Continental sedimentation with small transgressive events are present during the Cretaceous. In the Maastrichtian, a regional marine transgression is recorded. This transgression marks the finalization of regional marine incursions at the Central Andes.

During the Jurassic, Cretaceous and Paleogene a volcanic arc associated to slab subduction is set to the west of the Central Andes. Magmatic addition, thickening and shortening of the continental crust during the Oligocene to Miocene, produced the detachment of the lower parts of the continental crust, which were transformed to eclogites and ended up in a process of delamination (Kay et al., 1994; Ramos, 2009). Mafic and felsic magmatism (with large per-aluminous ignimbrite fields) is recorded through the Eastern Cordillera. Intrusion of granitoids such as the Illimani and Quimsa Cruz plutons are representative of this process at the Cordillera Real (Jiménez & López-Velázquez, 2008, Babeyko et al., in Oncken et al., 2006). Following the delamination process, occurred the rise of the Altiplano plateau, within a “thin skin-like” deformation front propagated to the east during the Pliocene (Kennan et al., 1995; Ramos, 2009).

1.2 - Objectives and structure of the work

The current PhD thesis has been organized in six chapters:

1. Chapter 1 – Introduction

2. Chapter 2 – Petrography and whole rock geochemistry of the studied rocks

3. Chapter 3 – **Cordani, U.G., Iriarte, A.R. & Sato, K. – 2019** - Geochronological systematics of the Huayna Potosí, Zongo and Taquesi plutons, Cordillera Real of Bolivia, by the K/Ar, Rb/Sr and U/Pb methods – Brazilian Journal of Geology

4. Chapter 4 – **Iriarte, A.R., Cordani, U.G., & Sato, K – 2021** - Geochronology of the Cordillera Real granitoids, the inner magmatic arc of Bolivia - Andean Geology

5. Chapter 5 - **Iriarte, A.R., Cordani, U.G., & Basei, M.A.S. – Submitted to the Brazilian Journal of Geology** - Provenance study of phanerozoic rocks from the Cordillera Real of Bolivia

6. Chapter 6 - Discussion and conclusions

7. Bibliography

The present introductory chapter was envisaged to present a very condensed history of the Central Andes, with special emphasis to its eastern segment, in which the Cordillera Real of Bolivia is located, and to indicate the specific objectives of the work.

Chapter 2 deals with the samples used in the following chapters 3 and 4, to describe their petrographical elements and their chemical composition (major oxides and trace elements) in order to help in the geological interpretations.

Three scientific articles are included in this thesis (Chapters 3, 4 and 5). Each one shows its separated methodology, discussion, conclusions and bibliography. Two of them were already published (chapters 3 and 4) and the other was submitted to the BJG. The final chapter presents a discussion gathering elements of the three articles published and general comments on the general history of Cordillera Real of Bolivia.

As it was mentioned at the section 1.1, the Triassic and Oligocene felsic magmatism at the Cordillera Real was formed by several plutons made up mainly by granitic rocks (fig. 3).

The purpose of the article presented in Chapter 3 is to review the age dating available for the Huayna Potosi and Zongo granitic plutons, recovering the ancient geochronological data produced in the São Paulo laboratory and adding several U-Pb SHRIMP zircon ages, in order to interpret the magmatic setting and the geologic history for this part of the Central Andes.

For Chapter 4, the objective is to obtain additional robust geochronological data for the Huayna Potosí and Zongo plutons, to understand better their magmatic evolution, and to constrain the crystallization ages of the other granitic plutons of the Real Cordillera to put the crystallization age of this “inner magmatic arc” in a regional context within the Central Andes.

For Chapter 5, the objective is to better understand the genetic relationship between the granites of the Cordillera Real and their sedimentary host rocks, comparing the U/Pb ages of their zircon xenocrystals with those of detrital zircons of the eo-Paleozoic sedimentary country rocks.

Following the objectives given in the three presented articles, the overall objectives of this PhD thesis are:

1. To review and present the geochronological date from the granitoids of the Cordillera Real in order to better understand the timing of formation.
2. To better understand the magmatic evolution of the granitoids of the Cordillera Real (CRG) taken in account available and newer whole rock geochemistry
3. To better understand the relationship of plutons and surrounding country rock, as well as the nature of the assimilation as well as the geological and regional connotation.

CHAPTER 2 – PETROGRAPHY AND WHOLE-ROCK GEOCHEMISTRY OF THE STUDIED ROCKS.

For the planned regional research project, on the granitic plutons of the Real Cordillera, a few representative samples were taken for each one (fig. 4) and they were the object of study in the articles presented in chapters 3 and 4. Each of these samples has been considered as petrographical representatives of each pluton (item 2.1). Moreover, those belonging to the Huayna Potosí and Zongo plutons were selected to be part of a special study of whole-rock geochemistry (item 2.2), with the objective to obtain some chemical elements regarding the type and variation of these specific granitic systems. In addition, samples RIB-51 and RIB-57, from the metasedimentary country-rocks of the Amutara and Coroico formations, are considered in chapter 5.

Fig. 4 Pluton location and sample sites. Samples with * correspond to sedimentary units considered on chapter 5.

2.1 Petrographical features

In this section, the granitic rocks showed in figure 4 will be petrographically described. These can be considered as “representative” samples for the plutons, especially for the granitic facies. Many of them will be characterized at the microscope and the modal analysis are included in Table 1 and displayed on the QAP classification diagram of fig. 13.

Illampu pluton

RIB-33 Granodiorite

This rock is characterized by granular texture showing euhedral to anhedral crystals of plagioclase (39%), quartz (26%), micro-perthite (5%), orthoclase (2%), biotite (15%), hornblende (7%), chlorite (3%), epidote (<1%), zircon (<1%) and iron oxides (<1%).

Plagioclase corresponds to the albite variety (An_{13}), some present oscillatory zoning and are slightly altered to sericitize. Quartz shows sometimes inclusions of biotite and plagioclase. Orthoclase also is slightly altered to sericite. Biotite is partially chloritized. Hornblende shows twinning and is slightly sericite. Epidote corresponds to the pistacite variety. Zircon occurs usually as inclusion on biotite. Iron oxides occur as inclusions on mafic minerals.

RIB-32 Granodiorite

This rocks is characterized by hipidiomorphic texture with subhedral to anhedral crystals of plagioclase (36%), quartz (28%), perthite (6%), orthoclase (2%), microcline (1%), biotite (15%), hornblende (10%), chlorite (2%), zircon (<1%), iron oxides (<1%).

Plagioclase corresponds to the oligoclase variety (An_{20}), some present oscillatory zoning and are slightly altered to sericite. Quartz has inclusions of biotite and plagioclase. Orthoclase is slightly sericitized. Biotite is slightly chloritized. Zircon is present as inclusions in quartz, plagioclase, biotite and hornblende.

RIB-15 Two mica granite

This rock is characterized by micro granular texture (fig. 5) with anhedral crystals of quartz (40%), microcline (20%), biotite (15%), plagioclase (5%), perthite (5%), muscovite (5%), apatite (3%), sericite (2%), zircon (1%) and iron oxides (4%).

Quartz exhibits deformed structure. Some microclines are large individuals with inclusions of biotite and quartz (poikilitic texture); it is slightly altered to sericite. Plagioclase corresponds to the albite variety (An_{10}) in some cases shows deformation. Biotite shows also some deformation. It has inclusions of zircon and apatite. Muscovite is larger than biotite and some are also deformed.

Fig. 5 A: Microcline surrounded by muscovite and quartz, polarized light, zoom 1.25x. B: Deformed crystals of muscovite and plagioclase. Plagioclase is slightly altered to sericite, polarized light, zoom 5x. Scale bar in mm is shown.

Huayna Potosí pluton

RIB-2 Granite

This rock is characterized by equigranular texture (fig. 6) with anhedral to subhedral crystals of microcline (30%), quartz (20%), plagioclase (10%), muscovite (20%), biotite (13%), apatite (4%), chlorite (1%) and iron oxides (2%).

Microcline is observed as large individuals with inclusion of quartz, plagioclase and muscovite in poikilitic texture. Plagioclase corresponds to the albite-oligoclase variety (An_{6-17}). Most quartz crystals present inclusions of apatite. Biotite is slightly transformed to chlorite and iron oxides, some of them show intergrowths with muscovite and some

present zircon and apatite as inclusions. Muscovite is usually fresh and some individuals show inclusions of apatite.

Fig. 6 Left: Subhedral biotite surrounded by muscovite and quartz, polarized light, zoom 5x. Right: Microcline surrounding muscovite (poikilitic texture), polarized light, zoom 5x. Scale bar in mm is shown.

RIB-4 Granite

This rock is characterized by equigranular texture (fig. 7) with subhedral to anhedral crystals of quartz (22%), microcline (20%), plagioclase (18%), muscovite (15%), biotite (8%), chlorite (7%), apatite (3%), sericite (1%), epidote (1%) and iron oxides (5%).

Quartz shows inclusions of apatite, some with undulatory extinction related to deformation. Microcline as large individuals surrounding quartz, plagioclase and muscovite (poikilitic texture). Plagioclase corresponds to the albite-oligoclase variety (An_{11-16}); it is altered to sericite and presents inclusions of iron oxides. Muscovite has apatite inclusions, with some individuals exhibiting deformation and inclusions of epidote. Biotite is slightly altered to chlorite and hematite; it has inclusions of apatite.

Fig. 7 A: equigranular texture showing crystals of biotite, quartz, orthoclase, muscovite, epidote, apatite and secondary chlorite. Muscovite shows inclusions of epidote, polarized light, zoom 5x. B: Crystal of quartz with inclusions of apatite, polarized light, zoom 10 x. Scale bar in mm is shown.

RIB-19 Granite

This rock is characterized by granular texture (fig. 8) showing anhedral to subhedral crystals of quartz (30%), microcline (30%), perthite (5%), plagioclase (10%), biotite (10%), muscovite (10%), apatite (2%), chlorite (1%), zircon (1%) and iron oxides (1%).

Quartz usually displays undulatory extinction related to deformation. Microcline as pokilitic individuals with inclusions of biotite, quartz, plagioclase and showing slightly alteration to sericite. Perthite usually is present on the borders of plagioclase crystals. Plagioclase corresponds to the oligoclase variety (An_{10-17}) and it is slightly altered to sericite. Biotite is strongly altered to chlorite, showing inclusions of apatite, zircon and iron oxides. Muscovite sometimes is observed as cumulates and is interstitial between larger crystals of feldspar.

Fig. 8 Left, granular texture showing crystals of quartz, perthite, biotite, muscovite, orthoclase and plagioclase. Natural light. Right: same view with polarized light, zoom 10x. Scale bar in mm is shown.

RIB-20 Granodiorite

This rock is characterized by granular texture (fig. 9) with anhedral to subhedral crystals of quartz (45%), microcline (10%), perthite (10%), plagioclase (18%), biotite (10%), muscovite (2%), apatite (1%), chlorite (1%), titanite (1%), zircon (1%) and iron oxides (1%).

Some crystals of quartz shows deformed structures, some with inclusions of apatite. Microcline as large individuals with inclusions of quartz and micas (poikilitic texture). Plagioclase corresponds to the albite-oligoclase variety (An_{12-15}), and it is altered to sericite. Biotite is slightly altered to chlorite, with inclusions of apatite, titanite, iron oxides and zircon. Muscovite is present as interstitial overgrowths.

Fig. 9 A: granular texture showing crystals of quartz, biotite and plagioclase, zircon and sphene. The plagioclase is zoned and shows preferential alteration on its core. Biotite shows inclusions of titanite and zircon. B: same view with polarized light, zoom 5x. Scale bar in mm is shown.

RIB-22 Granite

This rock is characterized by granular texture (fig. 10) with crystals of quartz (30%), microcline (25%), plagioclase (25%), biotite (5%), muscovite (5%), chlorite (4%), apatite (4%), titanite (1%) and iron oxides (1%).

Quartz shows deformed structure, most with inclusions of apatite. Microcline as large individuals with inclusions of quartz, muscovite and apatite (poikilitic texture). Plagioclase corresponds to the albite-oligoclase variety (An_{14-19}), some as large crystal with quartz inclusions (poikilitic texture); it is slightly altered to sericite. Biotite shows inclusions of apatite, iron oxides, zircon and titanite; it is slightly altered to chlorite; some individuals with rims of muscovite. Muscovite has inclusions of quartz and it is altered slightly to sericite.

Fig. 10 A: Crystal of biotite with inclusions of apatite and titanite. At the rims it has overgrowths of muscovite, zoom 5x. B: crystal of biotite, muscovite and quartz, the later with inclusions of apatite, polarized light zoom 10x. Scale bar in mm is shown.

RIB-53 Quartz-diorite

This rock is characterized by granular texture showing crystals of quartz (30%), plagioclase (30%), biotite (25%), apatite (4%), zircon (1%), chlorite (4%), sericite (2%) and iron oxides (4%).

Quartz presents inclusions of biotite. Plagioclase corresponds to the andesine variety (An_{32}) and some crystals present inclusions of biotite. Biotite has inclusions of zircon and iron oxides. It is slightly altered to chlorite.

Zongo pluton

RIB-5 Foliated granite (Kuticucho facies)

This rock is characterized by foliated texture (fig.11) with anhedral to subhedral crystals of microcline (40%), plagioclase (10%), quartz (16%), biotite (15%), muscovite (8%), sericite (6%), garnet (3%), apatite (1%) and titanite (1%).

Large deformed crystals of microcline surround quartz (poikilitic texture); some of them are slightly altered to sericite. Plagioclase corresponds to albite to oligoclase variety (An_{10-11}) and it is deformed; some with poikilitic texture surrounding crystals of muscovite, quartz and garnet. Quartz occurs forming equigranular deformed mosaic, sometimes as poikilitic grains surrounding muscovite. Biotite shows preferential orientation. Some are deformed with inclusions of titanite, apatite, iron oxides; sometimes it has muscovite overgrowths at the rims. Muscovite shows preferential orientation and it is transitional in size to smaller

sericite. Garnet is sometimes rounded, associated to foliated muscovite. Sometimes it is present as inclusion on plagioclase.

Fig.11 A: Overgrowths of preferentially oriented crystals of garnet and muscovite, polarized light, zoom 10x. Right: Preferentially oriented crystals of quartz, muscovite and biotite, polarized light, zoom 5x. Scale bar in mm is shown.

RIB-30 Foliated granite (Kuticucho facies)

This rock is characterized by slightly foliated texture showing anhedral to subhedral crystals of quartz (36%), plagioclase (15%), microcline (25%), biotite (10%), muscovite (10%), Al-silicate andalusite? (2%) and sericite (3%).

Quartz, plagioclase, biotite and muscovite are present as deformed crystals with inclusions of apatite and zircon. Microcline as large individuals surrounding smaller crystals of quartz and muscovite.

RIB-55 (granite, Sainani facies)

This rock is characterized by granular texture showing anhedral to subhedral crystals of quartz (33%), microcline (29%), plagioclase (8%), muscovite (15%), biotite (9%), hornblende (3%), apatite (1%), tourmaline (1%) and zircon (1%).

Quartz shows inclusions of apatite, tourmaline, iron oxides and zircon. Microcline occasionally shows inclusions of muscovite, quartz, iron oxides and zircon. Plagioclase corresponds to oligoclase variety (An_{28}); it has albite twinning. Muscovite has inclusions of apatite. Biotite has inclusions of zircon and iron oxides and sometimes is slightly foliated. Apatite bears inclusions of zircon and tourmaline. Tourmaline is seen as acicular inclusions on quartz and microcline.

RIB-56 (granite, Sainani facies)

This rock is characterized by granular texture showing anhedral to subhedral crystals of quartz (33%), microcline (29%), plagioclase (8%), muscovite (15%), biotite (9%), hornblende (3%), apatite (1%), tourmaline (1%), zircon (1%) and iron oxides (1%).

Quartz shows inclusions of apatite, tourmaline and zircon. Microcline occasionally bears inclusions of muscovite, quartz and iron oxides. Plagioclase corresponds to oligoclase variety (An_{28}) and it has albite twinning. Muscovite shows inclusions of apatite. Biotite is slightly altered to chlorite. Apatite presents inclusions of zircon and tourmaline. Tourmaline is acicular and is present as inclusions on quartz and microcline. Zircon present as inclusions on biotite, quartz microcline and apatite. Iron oxides present as inclusions of quartz, microcline and biotite.

Taquesi pluton

RIB-11 Granodiorite

This rock is characterized by granular texture (fig. 12) with anhedral to subhedral crystals plagioclase (two generations, 30%) surrounded by a mosaic of quartz (35%), orthoclase (10%), perthite (5%), biotite (15%), apatite (3%), zircon (1%) and iron oxides (1%).

Plagioclase corresponds to the albite-oligoclase variety (An_{6-18}); with inclusions of biotite and zircon; it is slightly altered to sericite. Perthite occurs as large individuals surrounding smaller crystals of biotite, quartz and plagioclase (poikilitic texture). Biotite is altered to chlorite and iron oxides; it has inclusions of apatite and titanite. Muscovite is usually associated to biotite and K-feldspar.

Fig. 12 A: Equigranular texture showing crystals of quartz, biotite, plagioclase and apatite. Biotite has inclusions of sphene. B: same view with polarized light, zoom 5x. Scale bar in mm is shown.

RIB-12 Quartz-diorite

This rock is characterized by granular texture showing crystals of quartz (35%), plagioclase (35%), biotite (15%), apatite (4%), zircon (1%), chlorite (4%), sericite (2%) and iron oxides (4%).

Some quartz crystals have inclusions of biotite. Plagioclase corresponds to oligoclase variety (An_{32}); it also presents inclusions of biotite. Biotite has inclusions of zircon and iron oxides. It is slightly altered to chlorite.

Huato pluton

RIB-27 Granite

This rock is characterized by equigranular texture showing anhedral to subhedral crystals of quartz (35%), plagioclase (30%), orthoclase (18%), perthite (6%), biotite (5%), muscovite (3%), epidote (1%), apatite (1%) and zircon (1%).

Quartz is sometimes present with deformed structure. Plagioclase corresponds to the albite-oligoclase variety (An_{9-30}), some as andesine variety (An_{41}); it presents slightly alteration to sericite. Orthoclase shows overgrowths of perthite, some seen as large individuals surrounding smaller crystals of biotite, quartz, epidote and plagioclase (poikilitic structure). Biotite is slightly altered to sericite, chlorite and iron oxides. Muscovite seen sometimes filling voids between larger plagioclase crystals.

Quimsa Cruz pluton

RIB-43 Granodiorite

This rock is characterized by equigranular texture showing subhedral to anhedral crystals of plagioclase (42%), orthoclase (18%), quartz (28%), biotite (10%), hornblende (2%), zircon (<1%), apatite (<1%), iron oxides (<1%).

Plagioclase corresponds to albite to oligoclase variety (An_{26}) is well shaped and presents oscillatory zoning. Quartz have inclusions of biotite and plagioclase. Orthoclase also shows inclusions of biotite and plagioclase. Biotite has inclusions of iron oxides and zircon. Hornblende shows inclusions of apatite.

RIB-46 Granodiorite

This rock is characterized by porphyritic texture showing euhedral to subhedral crystals of plagioclase (43%), quartz (26%), micro-perthite (6%), orthoclase (3%), biotite (11%), chlorite (5%), epidote (1%), muscovite (1%), zircon (1%), apatite (1%), tourmaline (1%) and iron oxides (1%).

Plagioclase corresponds to oligoclase variety (An_{28}) showing Carlsbad and albite twinning. Some present oscillatory zoning and are slightly altered to sericite. Orthoclase and micro-perthite are usually altered to sericite. Biotite is slightly chloritized and bears inclusions of iron oxides and zircon. Chlorite corresponds to the pennine variety and it was formed after alteration of biotite. Epidote is formed after biotite, chlorite and plagioclase. Tourmaline as acicular crystals usually as inclusion on biotite.

Country rocks sedimentary units

RIB-51- Sandstone of the Amutara Formation

This rock is characterized by detrital texture showing sub rounded to sun angular clasts of quartz (73%), muscovite (10%), apatite (1%), zircon (1%), tourmaline (1%), iron oxides (4%) and matrix (10%).

Muscovite is acicular and foliated following S_0 . Quartz shows inclusions of apatite and tourmaline. Matrix is made up of sericite and sometimes chlorite.

RIB-57 – Schist of the Coroico Formation

This rock is characterized by foliated texture showing porphyroblastic crystals of quartz (20%), muscovite (10%), biotite (17%), apatite (1%), zircon (1%), tourmaline (2%), andalusite (15%), iron oxides (5%) and matrix (29%).

Quartz presents inclusions of apatite, zircon and tourmaline. Andalusite shows inclusions of quartz. Biotite has inclusions of quartz, zircon and iron oxides. Zircon as inclusions on biotite. Matrix is made up of detrital quartz, muscovite and iron oxides.

Fig. 13 QAPF Modal mineralogical classification of Streckeisen (1976). Numbers correspond to: 1a, quartzolite; 1b, quartz-rich granitoids; 2, alkali-feldspar granite; 3, granite; 4, granodiorite; 5, tonalite; 6*, quartz alkali-feldspar syenite; 7*, quartz syenite; 8*, quartz monzonite; 9*, quartz monzodiorite/quartz monzogabbro; 10*, quartz diorite/quartz gabbro/quartz anorthosite; 6, alkali-feldspar syenite; 7, syenite; 8, monzonite; 9, monzodiorite/monzogabbro; 10, diorite/gabbro/anorthosite.

Pluton	Huato	Illampu				Taqesi		Huayna Potosí						Zongo				Quimsa Cruz		Fm. Amutara	Fm. Coroico
Sample	RIB- 27	RIB- 33	RIB- 32	RIB- 15	RIB- 11	RIB- 12	RIB- 53	RIB- 22	RIB- 20	RIB- 19	RIB- 4	RIB- 2	RIB- 5	RIB- 30	RIB- 56	RIB- 55	RIB- 43	RIB- 46	RIB-51	RIB-57	
Rock type/ minerals	Grte	Grdte	Qzd	Grte	Grdrte	Qzd	Qzd	Grte	Grdrte	Grte	Grte	Grte	Fol grte	Fol grte	Grte	Grte	Grdrte	Grdrte	Sand	Schist	
Quartz	35	26	3	40	35	35	30	30	45	30	22	20	16	36	30	33	27	26	73	20	
Plagioclase	30	39	35	5	30	35	30	25	18	10	18	10	10	15	8	8	41	43	-	-	
Orthoclase	18	2	25	-	10	-	-	-	-	-	-	-	-	-	-	-	17	3	-	-	
Microcline	-	-	-	20	-	-	-	25	10	30	20	30	40	25	30	29	-	-	-	-	
Perthite	6	5	8	5	5	-	-	-	10	5	-	-	-	-	-	-	-	6	-	-	
Muscovite	3	-	-	5	-	-	-	5	2	10	15	20	8	10	15	15	-	1	10	10	
Biotite	5	15	20	15	15	15	25	5	10	10	8	13	15	10	10	9	10	11	-	17	
Hornblende	-	7	6	-	-	-	-	-	-	-	-	-	-	-	3	3	2	-	-	-	
Apatite	1	-	1	3	3	4	4	4	1	2	3	3	1	-	1	1	1	1	1	1	
Zircon	1	1	1	1	1	1	1	-	1	1	-	-	-	-	1	-	1	1	1	1	
Garnet	-	-	-	-	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-	-	
Tormaline	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	-	1	1	2	
Chlorite	-	3	-	-	-	4	4	4	1	1	7	1	-	-	-	-	-	5	-	-	
Sericite	-	-	-	2	-	2	2	-	-	-	1	-	6	2	-	-	-	-	-	-	
Epidote	1	1	-	-	-	-	-	-	-	-	1	1	-	-	-	-	-	1	-	-	
Titanite	-	-	-	-	-	-	-	1	1	-	-	-	1	-	-	-	-	-	-	-	
Andalusite	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	15	
Fe oxides	-	1	1	4	1	4	4	1	1	1	5	2	-	-	1	1	1	1	4	5	
Matrix	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10	29	
TOTAL (%)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	

Table 1 Modal mineral proportion (% wt) of representative samples of granitoids and country rock of the Cordillera Real. Abbrev.

Grte = granite, Grdte = granodiorite, Qzdrte= quartzdiorite, Sand =sandstone.

2.2 - Whole rock Geochemistry of the Huayna Potosí and Zongo plutons

Five samples from Huayna Potosí and Zongo plutons, that represent different phases of the magmatic evolution, were selected to be part of a special study of whole-rock geochemistry. They were also compared with literature data (see annex Table 1).

The new analyses were done in the Geoanalítica Laboratory of the Universidade de São Paulo (USP), Brazil. The analytical results are shown in tables 2 and 3 and the diagrams of figs. 14, 15, 16 and 17 were elaborated using the GCDkit software (Janoušek et al., 2006).

They are compared with samples taken from Ávila, 1990; Jiménez and López-Velásquez, 2008; Sugaki et al., 1988 and Chambi, 2010.

The samples taken from Ávila (1990) correspond to a quartz-monzonite and an adamellite from Quimsa Cruz, 6 samples averaged from Chacaltaya (close to the Huayna Potosí pluton), a granodiorite from the Illimani, a leucogranite from Yani, a granodiorite from the Illampu and a biotite bearing monzogranite from Huato.

The samples taken from Jiménez and López-Velásquez (2008) correspond to a granite and a mafic inclusion from Huayna Potosí, 3 granodiorites from Taquesi and two granodiorites from Huato.

The samples taken from Sugaki et al. (1988) correspond to 2 granodiorites from Illampu, 2 granodiorites and a two mica granites from Huayna Potosí; an adamellite, a two mica adamellite and 2 granodiorites from Taquesi; 5 adamellites and a granodiorite from the Quimsa Cruz pluton.

The samples taken from Chambi (2010) in his study of the Illampu pluton correspond to a diorite, 2 monzonites 2 tonalites, an adamellite and 5 granodiorites.

Pluton	Huayna Potosí						Zongo			
Facies							Kuticucho		Sainani	
Sample	RIB-53	RIB-19	RIB-20	RIB-22	RIB-2	RIB-4	RIB-5	RIB-30	RIB-55	RIB-56
Rock	Qtz-monzonite	Granite	Granite	Granite	Granite	Granite	Granite	Granite	Granite	Granite
SiO ₂	61.20	70.66	64.30	69.31	73.26	74.19	72.12	72.49	72.72	71.99
TiO ₂	1.187	0.326	0.557	0.274	0.140	0.154	0.131	0.105	0.201	0.314
Al ₂ O ₃	16.71	15.20	17.17	16.37	14.49	14.45	14.92	15.33	14.72	14.65
Fe ₂ O ₃	6.62	2.56	4.77	2.58	1.32	1.37	1.43	1.36	1.73	1.84
MnO	0.091	0.051	0.074	0.062	0.032	0.033	0.030	0.053	0.031	0.023
MgO	2.78	0.69	1.44	0.62	0.20	0.19	0.16	0.14	0.27	0.40
CaO	3.46	1.38	1.58	0.94	0.74	0.67	0.67	0.48	0.75	0.91
Na ₂ O	3.22	3.36	3.40	3.07	3.16	3.10	2.71	3.23	2.49	2.16
K ₂ O	2.83	4.29	4.39	4.98	4.58	4.70	5.24	4.65	5.56	5.85
P ₂ O ₅	0.309	0.173	0.146	0.174	0.267	0.271	0.264	0.170	0.286	0.254
LOI	1.16	1.21	1.74	1.27	1.04	1.03	1.18	1.04	0.99	0.90
Total	99.57	99.90	99.57	99.65	99.23	100.16	98.86	99.05	99.75	99.29

Table 2 Unnormalized XRF whole rock analyses performed by the NAP GeoAnalítica laboratory at the USP.

Pluton	Huayna Potosí						Zongo			
Facies							Kuticucho		Sainani	
Sample	RIB-53	RIB-19	RIB-20	RIB-22	RIB-2	RIB-4	RIB-5	RIB-30	RIB-55	RIB-56
Rock	Qtz-monzonite	Granite	Granite	Granite	Granite	Granite	Granite	Granite	Granite	Granite
SiO ₂	62.61	71.78	66.05	70.64	74.71	74.95	73.95	74.07	73.76	73.3
TiO ₂	1.21	0.33	0.57	0.28	0.14	0.16	0.13	0.11	0.2	0.32
Al ₂ O ₃	17.1	15.44	17.64	16.68	14.78	14.6	15.3	15.66	14.93	14.92
FeO _T	6.09	2.34	4.41	2.37	1.21	1.25	1.32	1.25	1.58	1.69
MnO	0.09	0.05	0.08	0.06	0.03	0.03	0.03	0.05	0.03	0.02
MgO	2.84	0.7	1.48	0.63	0.2	0.19	0.16	0.14	0.27	0.41
CaO	3.54	1.4	1.62	0.96	0.75	0.68	0.69	0.49	0.76	0.93
Na ₂ O	3.29	3.41	3.49	3.13	3.22	3.13	2.78	3.3	2.53	2.2
K ₂ O	2.9	4.36	4.51	5.08	4.67	4.75	5.37	4.75	5.64	5.96
P ₂ O ₅	0.32	0.18	0.15	0.18	0.27	0.27	0.27	0.17	0.29	0.26
Sc	13.3	4.58	6.62	5.07	0	0	0	5	3.21	2.37
Rb	204	238	285	307	438	459	445	459	391	388
Sr	327	196	259	148	59	57.4	55.7	44.4	80.6	102
Y	36.2	12.3	17	13.6	10.9	12.2	15.1	9.12	14.9	10.7
Zr	247	67.6	66.9	75.7	52.7	65.8	58.6	22.6	68.7	132
Nb	28.8	28.1	35	22	20.8	20.1	22.3	27.2	22.2	8.37

Cs	16.7	7.6	12.3	24.8	33.5	41.8	59	62.6	42.6	17.8
Ba	699	429	493	327	183	173	175	103	191	439
Pb	10.6	30.6	24.1	36.5	28	27.3	32.3	24.1	41.3	39.5
La	49.1	23.2	26.1	20.2	15.5	17.5	16.9	4.34	20.2	49.4
Ce	96.3	46.2	55.6	43.9	30.6	36.4	29.5	9.33	42.6	103
Pr	11.3	5	5.91	4.6	3.94	4.69	3.76	1.05	4.82	12.7
Nd	40.6	18.3	21.4	16.9	15	17.9	14.1	3.88	18.5	45.3
Sm	7.93	3.73	4.15	3.66	3.13	3.8	3.43	1.13	4.94	9.63
Eu	1.38	0.97	1.11	0.82	0.47	0.46	0.43	0.24	0.91	1.4
Gd	6.84	3.02	3.22	3.04	2.47	2.94	3.11	1.31	4.94	5.68
Tb	1.03	0.45	0.5	0.46	0.39	0.45	0.53	0.26	0.74	0.65
Dy	5.55	2.25	2.64	2.32	1.89	2.14	2.6	1.52	3.17	2.49
Ho	1.15	0.4	0.52	0.43	0.31	0.34	0.43	0.28	0.47	0.36
Er	3.19	1.06	1.48	1.15	0.77	0.83	0.99	0.76	1.04	0.86
Tm	0.45	0.15	0.22	0.17	0.11	0.12	0.14	0.12	0.13	0.11
Yb	3.01	1	1.48	1.2	0.74	0.81	0.9	0.8	0.79	0.65
Lu	0.44	0.14	0.22	0.18	0.1	0.11	0.11	0.11	0.12	0.09
Hf	5.65	1.89	1.83	2.18	1.56	1.87	1.79	0.92	2.2	3.73
Th	11.9	6.3	6.52	6.39	6.75	8.14	6.54	1.93	6.68	19.2
U	6.91	1.74	2.34	3.87	8.78	7.15	4.26	5.37	10.1	5.43

Ga	21	18	26	20	21	21	20	23	19	20
----	----	----	----	----	----	----	----	----	----	----

Table 3 Normalized whole rock analyses. Major oxides were re-casted to 100 % wt, LOI free. Iron oxides are expressed as FeO_T and trace elements are in ppm. Limits of detection (in ppm) of trace elements are: La 0.01, Ce 0.01, Pr 0.01, Nd 0.08, Sm 0.01, Eu 0.01, Gd 0.01, Tb 0.01, Dy 0.01, Ho 0.01, Er 0.01, Tm 0.01, Yb 0.01, Lu 0.01, Rb 0.01, Zr 0.03, Nb 0.01, Ba 0.5, Hf 0.01, Y 0.01, Pb 0.02, Th 0.01, U 0.01, Cs 0.01.

Fig. 14 TAS diagram (Middlemost et al., 1994) showing database from several plutons of the Cordillera Real (literature, seen Annex 1) compared with the studied samples of the Huayna Potosí, the Zongo pluton (Kuticucho facies) and the Zongo (Sainani facies). Mafic enclaves from the Illampu pluton are displayed.

From the TAS diagram of fig. 14 (as well as the modal compositions of table 1 and fig. 13) it can be seen that most rock compositions correspond to diorites, monzonites, quartz monzonites, granodiorites and granites.

Fig. 15 R₁- R₂ diagram (De La Roche et al., 1980) showing database from several plutons of the Cordillera Real (literature, seen Annex 1) compared with the studied samples of the Huayna Potosí, the Zongo pluton (Kuticucho facies) and the Zongo (Sainani facies). Mafic enclaves from the Illampu pluton are displayed.

In the R₁-R₂ diagram of De La Roche et al., 1980 shown in fig.15, also there can be seen an overall path of samples starting with monzonite, monzo-diorite and diorite compositions evolving towards granitic compositions.

Fig. 16 AFM diagram (Irvine and Barragar, 1971) showing database from several plutons of the Cordillera Real (literature, seen Annex 1) compared with the studied samples of the Huayna Potosí, the Zongo pluton (Kuticucho facies) and the Zongo (Sainani facies). Mafic enclaves from the Illampu pluton are displayed.

On fig.16 showing the AFM diagram (Irvine and Barragar, 1971) most samples fall in the calc-alkaline field. This trend was also observed by Ávila, 1990 who related it to crystal fractionation of minerals such as plagioclase as the mechanism operating in the evolution of these melts. The Zongo, Yani and Huayna Potosí granites corresponds to the more evolved melts. This calc-alkaline trend is suggestive of a subduction setting, although it has to be compared along with other geochemical signatures. Anyway, this calc-alkaline trend is in agreement with Ramos, 2018 who describes the Gondwanide orogenic rocks and related extentional granites operating during most of the Carboniferous to Permian.

Fig. 17 Trace elements variation diagrams for granites (Pearce, 1984) showing database from several plutons of the Cordillera Real compared with the studied samples of the Huayna Potosí, the Zongo pluton (Kuticucho facies) and the Zongo (Sainani facies). Note that the distribution pattern is also recorded by literature data (Jiménez and López-Velásquez, 2008 and reference therein). See annex Table 1.

Two diagrams of granite tectonic discrimination of Pearce et al., 1984 are displayed in fig. 17. It can be seen that most mafic compositions (e.g. quartz-diorites) have a within plate signature (WPG), meanwhile the more evolved granites (e.g. Huayna Potosí and Zongo) fall within the fields of synchronous collisional granites (syn-COLG) and volcanic arc granites (VAG). This trend was also observed by Ávila (1990) and Jiménez and López-Velásquez (2008) and suggests the influence of within plate magmatism operating in the trace elements geochemistry. The enrichment in Rb and the low values of Y and Nb of the Huayna Potosí and Zongo granites are noticeable and will be further discussed.

2.3 Considerations of the geochemical features of the Cordillera Real granitoids

As it can be seen on figs. 14 to 17, the magmatic rocks of the Cordillera Real are a coherent suite of quartz diorites and tonalites “evolving” towards granodiorites and granites. Samples of two mica granites from the Huayna Potosí and Zongo plutons corresponds to the more evolved felsic melts.

To better understand these geochemical data, a brief review from the literature is made: Sugaki et al., (1988) defined the granitoids of the Cordillera Real as “I-type” (Chappell and White, 1974) and corresponding to the “ilmenite series”, which is associated to their tin enrichment.

Ávila (1990) defined that most of the granitoids of the Cordillera Real are “S-like” meanwhile; the Illampu pluton is “I-type”. He suggested that continued fractionation of plagioclase and associated sediment assimilation are the mechanisms that generated the Rb-rich granites (e.g. the Yani and Zongo plutons).

Jiménez and López-Velasquez (2008), characterized these granitoids as high-K compositions, calcalkaline affinities, most been peraluminous and some metaluminous. Their trace element ratios (e.g. La/Ta, Ba/La and Ti/V) suggest an origin in a within plate environment, although not all ratios follow this trend.

Chambi, 2010 recognizes three petrographical facies on the Illampu batholith: granodiorites and tonalites to the north (facies 1); adamellites to the center (facies 2) and granitoids to the south (facies 3). Facies I and II are considered to be as “I-type”, meanwhile facies III are considered to be as “S-type”. Xenoliths (mafic enclaves of quartz diorites and monzonites) are considered to be as “A-type”. This author suggests also that the emplacement of the batholith occurred in three stages:

Stage 1) Melting of the lithospheric mantle during lithospheric thinning (continental rifting); producing the xenoliths with “A-type” compositions.

Stage 2) Melting of meta igneous rocks from the lower crust, producing the “I –type” compositions.

Stage 3) Assimilated of upper crustal material by these “I type” melts yielding the “S-like” compositions.

In order to compare and analyze these geochemical signatures, in fig.18 is displayed a MORB normalized spider (Pearce, 1983) with representative end-members of the Cordillera Real magmatic rocks. Mafic enclaves of the Illampu, samples OLCOA and S-15 (see annex Table 1) are plotted with samples RIB-2 of the Huayna Potosí, sample RIB-56 of the Zongo pluton (Sainani facies) and RIB-5 (Kuticucho facies). To compare an average “A-type” granite is also displayed.

Fig. 18 Spider plot of Pearce (1983) comparing the mafic enclaves from the Illampu with granites of the Huayna Potosí, Zongo (Kuticucho and Sainani facies) and an average “A-type” granite (n=148) taken from Winter (2001).

On fig. 18, a pattern of trace elements is displayed. Mafic enclaves match well with the A-type (except by Sr). Overall, LILE elements such as K, Rb and Ba are enriched in all rocks, meanwhile HREE (e.g. Y and Yb) are depleted on the granites of Huayna Potosí and Zongo. This depletion is below the A-type values.

The geochronological data discussed on chapter 4 helps to better understand the temporal relationship of these representatives end members. The mafic enclaves correspond to the magmatic pulse of 230 Ma, meanwhile the granites of the Zongo and Huayna Potosí correspond to the final event of 223 Ma (see fig.18).

The element pattern seen on fig. 17, suggests that when the final pulse occurred (ca. 223 Ma), it was mafic and probably melted the upper crust including the older pulses (e.g. 230 Ma) generating the granites (Huayna Potosí and Zongo). Then the HREE behave compatibly, being depleted on the spider because of their tendency to stay in their source

(e.g. “refractory” mineral phases such as apatite, epidote, zircon, amphibole, with high compatibility of HREE).

To replicate the elemental behavior seen on fig. 18 (e.g. enriched LREE and depleted HREE), two batch melting models with some assumptions about the modal abundance and partition coefficient are presented in annex 2. Although not perfect, it can be seen that the elemental pattern of the melt produced looks like the ones seen on the granite samples of Huayna Potosí and Zongo. Therefore, it can be said that melting of the upper crust rocks (older pulses and country rocks as well) probably generated the geochemical compositions seen on these granites.

In this view, the trends of high Rb observed on fig. 18 suggest also assimilation of an important amount of upper crustal material that enriched further in LILE the two mica granites. Mechanism such as crystal fractionation or assimilation and crystal fractionation (AFC, DePaolo, 1981) are reasonably candidates to be considered.

As it was mentioned on chapter 1, systematics of melt enrichment of these granitoids are discussed on chapters 3 and 5 and aspects of the geochronology of their emplacement are discussed on chapter 4.

CHAPTER 3 – Geochronological systematics of the Huayna Potosí, Zongo and Taquesi plutons, Cordillera Real of Bolivia, by the K/Ar, Rb/Sr and U/Pb methods – Brazilian Journal of Geology

Cordani, U.G., Iriarte, A.R. & Sato, K. (2019)

Geochronological systematics of the Huayna Potosí, Zongo and Taquesi plutons, Cordillera Real of Bolivia, by the K/Ar, Rb/Sr and U/Pb methods

Umberto Giuseppe Cordani^{1*} , Alvaro Rodrigo Iriarte^{1,2} , Kei Sato¹

Abstract

The Huayna Potosí, Zongo and Taquesi are Triassic plutons located at the core of the Real Cordillera of Bolivia. In this paper, several Rb-Sr and K-Ar ages obtained in the past at the São Paulo Geochronology Laboratory, yet unpublished, will be presented, along with newer U-Pb Sensitive High-Resolution Ion Microprobe (SHRIMP) determinations made in the same laboratory, allowing us to redefine the geologic history of this part of the Central Andes. Rb/Sr analyses of some low grade metapelitic country rocks of the early Paleozoic (Amutara and Cancañiri Formations) yielded a Rb-Sr isochron age of 344 ± 38 Ma, indicating the action of an early Gondwanide regional event. A five-point Rb-Sr isochron from a granite outcrop of the Huayna Potosí pluton yielded an age of 224 ± 28 Ma. In addition, an important Ar loss in micas was detected in the Zongo granitoids and their country rocks, recording a thermal event that opened this isotopic system in the Oligocene. Newer U-Pb SHRIMP zircon ages of ca. 221 Ma were obtained in two other granitic outcrops of the Huayna Potosí granite. They confirmed its Triassic crystallization age, and a similar U-Pb SHRIMP age of 221.9 ± 1.5 Ma was obtained for one sample of the Taquesi pluton. For the Zongo pluton, many of the zircon grains obtained from one sample of its Kuticucho facies yielded extremely high uranium content, which produced reverse discordant apparent ages. However, due to the fair alignment of the analytical points in the Concordia diagram, possibly corresponding to a linear correlation, we made a regression calculation and the interception of the Concordia curve resulted in a rather imprecise age of 220 ± 20 Ma. Our conclusion was that the final magmatic crystallization and the intrusion of plutons in the central part of the Cordillera Real of Bolivia have occurred close to 221.5 ± 2.0 Ma, in late Triassic times. Finally, the U-Pb SHRIMP ages obtained in inherited zircon xenocrysts from the four available granitic rocks yielded very different ages, and many of them are related to previous magmatic episodes of the Andean Tectonic System. A few other age measurements indicated sources related to much older Proterozoic magmatic events associated with rocks from the Andean basement.

KEYWORDS: Granitoids; Real Cordillera; SHRIMP; zircon.

INTRODUCTION

The first dating of the Huayna Potosí pluton of the Cordillera Real of Bolivia (Fig. 1) was found by Evernden *et al.* (1977) using a few K/Ar measurements in micas. In 1978, the first author of this study provided a training course in geochronology in La Paz related to Proyecto Cordillera of GEOBOL (the Geological Service of Bolivia). A field trip took place in such occasion, where several samples were taken along a SW-NE geological profile, from the Milluni Mine, located within the sedimentary country rocks, near the southern contact of the Huayna Potosí pluton, to the limits of the Zongo pluton at Sainani (Figs. 2 and 3). At that

time, a series of samples was analyzed at the University of São Paulo laboratory, by the Rb/Sr and K/Ar methods, and a presentation was made at the Symposium on the “Magmatic Evolution of the Andes” within the International Geological Congress held in Paris, France, in 1980 (Cordani *et al.* 1980). This presentation had the support of only an abstract, which shall be considered as a preliminary geological piece of information for the region of interest. Later, other K/Ar, as well as Ar/Ar analyses were made for the Zongo granite (McBride *et al.* 1983, 1987, Kennan *et al.* 1995). Moreover, Farrar *et al.* (1990) and Gillis *et al.* (2006) dated several plutons of the Real Cordillera using the U/Pb method in zircon for the first time.

The preliminary results obtained on the old samples collected in 1978, as well as the additional geochronological work carried out later, had left important uncertainties about the tectonic history of the Cordillera Real. Therefore, in order to contribute to achieve a better understanding of it, our decision was to make some effort to constrain the crystallization age of the Huayna Potosí, Zongo and Taquesi plutons, located not far from each other, in the central part of the Cordillera Real, by means of a few robust

¹Universidade de São Paulo – São Paulo (SP), Brazil. E-mails: ucordani@usp.br, kei@usp.br, arodrigoiarte@usp.br

²Universidad Mayor de San Andrés – La Paz, Bolivia.

*Corresponding author.

U-Pb determinations on zircon. Thus, three samples of typical granitic rocks from large and fresh outcrops of Huayna Potosí and Zongo plutons (RIB-2, 4 and 5) were collected in 2016, following the same road along the Zongo River, where the first sample recollection was done in 1978. An additional sample (RIB-11) was collected from the nearby Taquesi pluton to the SE of the Zongo river. Zircon crystals were extracted from each sample for age dating and were carried out employing the Sensitive High-Resolution Ion Microprobe (SHRIMP) instrument at the Geochronology Research Center (CPGeo) of the Universidade de São Paulo (USP).

The purpose of this article is to present a comprehensive review of the age dating available for these granitic plutons, recovering the ancient geochronological data produced in São Paulo and adding the ones made by Evernden *et al.* (1977), McBride *et al.* (1983, 1987), Kennan *et al.* (1995), Farrar *et al.* (1988) and Gillis *et al.* (2006), as well as the new U-Pb zircon data. An attempt is made to interpret the magmatic setting and the geologic history for this part of the Cordillera Real of Bolivia.

GEOLOGICAL BACKGROUND

The Cordillera Real forms a prominent part of the mountainous relief of the Andes, at the core of the Eastern Cordillera of the Central Andes (Figs. 1 and 2), with a length of 250 km along strike and 40 km wide, and presenting a few peaks with an altitude of more than 6,000 meters above the sea level. In the tectonic map of South America (CGMW 2016), it is located within the Eastern Cordillera back thrust zone, where thrust faults have a general vergence to the west (Dorbath *et al.* 1993, McQuarrie *et al.* 2002, Gillis *et al.* 2006) and were formed by compressive tectonism during the Oligocene (Sergeotectmin 2011). Major acidic magmatism is present, which was formed in two pulses from the available ages. The first one had a long duration (280–200 Ma) and occupied most of the Permian and Triassic, and the later occurred in a short time in the Oligocene (23–26 Ma).

The older plutons, Huato, Illampu, Yani, Huayna Potosí, Zongo and Taquesi, are located to the North of 16°30' and the Oligocene plutons, Illimani, Quimsa Cruz and Santa Vera Cruz, are located to the South of this latitude. All of them present a variety of granitoid rocks, such as granodiorites,

Figure 1. Simplified tectonic setting of the Central Andes, showing the present study site.

Figure 2. Location of the granitic plutons of the Cordillera Real of Bolivia, within the Eastern Cordillera.

Figure 3. Geological map of the Huayna Potosi and Zongo plutons, with the location of the samples collected in 1978 (BO-4 and others) and 2016 (RIB-2, 4 and 5), along the road following the Zongo river.

quartz monzonites, and granites. Within the country rocks, Ordovician and/or Silurian metasedimentary pelites predominate. They correspond to Ordovician metapelites of the Amutara and Coroico formations and to Silurian siltstones, slates, glaci-marine deposits and sandstones of the Cancañiri, Catavi, Uncia and Llallagua formations.

Following the review made by Ramos (2018a) on the tectonic evolution of the Central Andes, the Phanerozoic tectonic history of the Cordillera Real could be briefly resumed as follows:

- From the late Neoproterozoic until middle-late Devonian times, the Famatinian orogenic cycle affected the entire proto-Pacific margin of South America, from Venezuela to Argentina (Ramos 2018b). In the Central Andes, metamorphic rocks and orthogneisses with Famatinian ages were identified within the northern part of the Eastern Cordillera of Peru, where the orogen was controlled by the old Grenvillian sutures. During the early Paleozoic, a thick sequence of Ordovician to Devonian sediments was deposited over continental basement in that region, in Peru and Bolivia, as a retro-arc basin of the Famatinian Orogeny (Sempere 1995);
- Later, starting in the early Carboniferous, the Gondwanide Orogeny, a strong and widespread intra-plate tectonic episode, affected most of the Andean realm of South America and was well represented in the Eastern Cordilleras of Peru and Bolivia (Dalmayrac *et al.* 1980). The Famatinian retro-arc basin underwent deformation, metamorphism, and granitic intrusions in two tectonic phases, 336–285 Ma and 280–235 Ma (Miskovic *et al.* 2009), known as the early and the late Gondwanide orogenies. They were practically coeval to the Hercynian continental collisions that formed the Pangea supercontinent;
- In the late Permian, the southern continents were subjected to a series of extensional episodes that started the breakup of Pangea. Pre-existing crustal weakness zones controlled the location of the main extensional systems (Ramos 2009). As to the Eastern Cordillera of Peru and Bolivia, the rift basins and associated igneous rocks, such as the volcano sedimentary sequences of the Mitu Group of SE Peru, followed the inherited terrane boundary represented by the ancient suture formed during Grenvillian times between the Arequipa Terrane and the Amazonian Craton, which was extensionally reactivated during the Famatinian. Mpodozis and Kay (1992) indicated that the associated volcanic rocks of the Choyoi can be followed from South America to Antarctica at the SW border of Gondwana;
- In Triassic times, after the late Gondwanide Orogeny, a series of granitic plutons intruded along extensional tectonic zones the early Paleozoic retro-arc platform in the Cordillera de Carabaya in Peru and in the Cordillera Real of Bolivia (Spikings *et al.* 2016), such as the peraluminous granitoid rocks dealt in this paper. Several plutons, mainly leucogranites, lacking subduction signature, were interpreted as due to magmatism occurred after the detachment of a previously formed subducting oceanic slab (Miskovic *et al.*

2009). These granitic plutons are controlled by the localized extension along the hanging-wall of previous sutures;

- The Cenozoic Andean evolution was dominated by a shallowing wave of the subducted slab. The consequent migration of magmatism to the foreland induced the formation of an “inner arc”, in which deep crustal melts were formed following crustal delamination and lithospheric mantle removal (Ramos 2018a). The Oligocene upper crustal granitoids (Illimani, Quimsa Cruz and Santa Vera Cruz plutons) related to compressional tectonics associated with the subduction slab steepening (Jiménez & López-Velásquez 2008) were dated by Gillis *et al.* (2006). Their K/Ar ages vary between 28 and 23 Ma (Evernden *et al.* 1977, McBride *et al.* 1983, Sugaki *et al.* 2003).

Hence, the Huayna Potosí, Zongo and Taquesi plutons are part of the Permo-Triassic magmatic event, and their petrographic facies include two mica granites, as well as quartz monzonites and granodiorites. The modal analyses of the four granitic rocks studied in this work are included in Table 1. The individual plutons usually grade between metaluminous to peraluminous, and crystal fractionation was their main differentiation mechanism (Ávila 1990). More mafic rocks, such as diorites or monzonites, are seen only as enclaves.

The Huayna Potosí batholith has an irregular shape, roughly rectangular with an E-W elongation (Fig. 3). In petrography, it varies between a granitic to granodioritic composition, where quartz, microcline and plagioclase are always the main components, making up usually more than 70% of the rock, while biotite and muscovite are also present in fair amounts. Small enclaves of diorite

Table 1. Modal analyses of samples RIB-2, 4, 5 and 11

Pluton sample	Huayna Potosí RIB-2	Kuticuchó RIB-4	Taquesi RIB-5	Taquesi RIB-11
Rock	Granite	Granite	Foliated granite	Granodiorite
Quartz	20	15	16	35
Plagioclase	10	10	10	30
Orthoclase				10
Microcline	27	43	40	
Perthite	3	2		5
Biotite	13	5	15	13
Muscovite	20	10	8	
Apatite	3	3	1	3
Zircon				1
Garnet			3	
Chlorite	1	5		
Sericite		1	6	
Epidote	1	1		
Titanite			1	
Tourmaline				2
Fe-oxides	2	5		1
Total	100	100	100	100

rocks are observed. Figures 4A and 4B are photographs taken in the field of one of Huayna Potosí batholith rocks, RIB-2. Figures 5A and 5B are microphotographs for RIB-2 and RIB-4, respectively. Textures are granular, hipidiomorphic and sometimes poikilitic. In Figure 5A, crystals of subhedral biotite and muscovite are shown along with quartz, orthoclase, and microcline. Slightly hydrothermal sericite alters the K-feldspars. In Figure 5B, subhedral muscovite and minor biotite are shown along with quartz. Garnet may be present in some samples, and apatite, zircon, titanite, and Fe-oxides are the main accessory minerals.

The Zongo pluton is essentially a granite with two micas and presents a mineralogical composition like the Huayna Potosi. As shown in Figure 3, this pluton seems to be located within two NW strike reverse fault systems with vergence to the SW, and it has been cut intensely by at least one set of faults with the same features. Two petrographic facies are found in the Zongo pluton: the foliated Kuticucho facies, which displays a moderate to strong macroscopic foliation affecting K-feldspars, quartz, and micas (see fieldwork photographs in Figs. 4C and 4D), and the Sainani microgranular facies to the NE (McBride *et al.* 1987, and references therein). Figure 5C is a microphotograph of RIB-5, in which sigmoidal and foliated

Figure 4. Field photographs: Huayna Potosí, Zongo and Taquesi plutons. (A) Two-mica granite at the SW margin of the Huayna Potosi pluton. (B) Dioritic enclave of the Huayna Potosi pluton. (C) Equigranular, slightly foliated granitic sample of the Zongo pluton. (D) Foliated Zongo granite, Kuticucho facies. (E) Small dioritic inclusion of the Taquesi pluton. (F) Granodiorite, southern margin of the Taquesi pluton.

muscovite is shown sheared with ondulatory quartz and deformed plagioclase.

The Taquesi pluton has an ellipsoidal shape, with a length of 15 km along its major axis, parallel to the NW-SE strike of the major Andean structures. It is composed mostly of a granular to microgranular biotite granodiorite (Figs. 4E and 4F) with quartz, plagioclase, k-feldspar, biotite, apatite, and Fe-oxides. Figure 5D is a microphotograph, in which subhedral biotite flakes are shown along with quartz and plagioclase. At its southern border, enclaves of hornfels from the country rock can be found, reaching sometimes almost 10 cm of length.

A few mineral occurrences were mined in the past, such as the Milluni mine at the southern contact of the Huayna Potosi pluton, composed by several veins bearing a Sn-W-Zn mineralization, cutting the Silurian slates of Catavi Formation (Ahlfeld & Schneider-Scherbina 1964). Moreover, the Chojlla Mine is located about 8 km east of the Taquesi pluton within a mineralized greisen (Sn-W), which was interpreted by the same authors as a small part of a cupula intruding the sedimentary roof at the top of this pluton.

ANALYTICAL METHODS

In this paper, the geochronological and isotopic data already available in literature will be discussed and reinterpreted in order

to evaluate the geological history of the studied region. K-Ar and U/Pb age dating can be found in the papers of Evernden *et al.* (1977), McBride *et al.* (1983, 1987), Kennan *et al.* (1995), Farrar *et al.* (1990) and Gillis *et al.* (2006). Description of the analytical methods used by these authors shall be looked after in the respective references. For the ages obtained in 1978 at the São Paulo laboratory (Cordani *et al.* 1980), the employed methods can be referred as follows:

- The techniques employed for the K-Ar analyses were those described by Amaral *et al.* (1966). The only difference is that a calibrated pipette was used for the addition of the ^{38}Ar tracer. Potassium content was measured by means of a flame photometer, with a normal error of about 1% or less. Argon extraction was made by means of an induction heater, and the isotopic ratios were determined in a Nuclide Reynolds-type instrument made of Pyrex glass. Average error of the analyses was around 2% for measurements with less than 90% of atmospheric correction;
- The techniques employed for the Rb-Sr method were described by Cordani & Iyer (1979). Total Rb and Sr contents were measured using X-ray fluorescence, and the Sr isotopic measurements were carried out in the Varian TH-5 solid-source mass spectrometer of the São Paulo laboratory, with a chart recorder output, and the isotopic ratios were determined by directly measuring the peak heights.

Bt: biotite; Mc: muscovite; Plg: plagioclase; Qz: quartz; Ort: orthoclase; Mcr: microcline.

Figure 5. Microphotographs: Huayna Potosí, Zongo and Taquesi plutons. The granites of Huayna Potosí and the granodiorite of Taquesi have hipidiomorphic textures, meanwhile the Zongo/Kuticucho granite has a foliated structure. (A) and (B) respectively, samples RIB-2 and RIB-4, for the Huayna Potosí granite. (C) Sample RIB-5 of the foliated Zongo/Kuticucho granite. (D) Sample RIB-11 of the Taquesi granodiorite.

The $^{87}\text{Sr}/^{86}\text{Sr}$ values were normalized to the 0.1194 value, and the Eimer & Amend Sr standard run concurrently yielded a $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.7082 ± 0.0013 (1 sigma). Regression analyses of the Rb/Sr data were carried out using the method of York (1968). Based on laboratory experimental data, the $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ relative standard deviations were assumed at 2.8% and 10^{-3} , respectively.

For the U/Pb SHRIMP analyses on single zircon crystals made recently for this paper, the SHRIMP II of the São Paulo laboratory at USP was employed and the procedures, based on Williams (1998), are described by Sato *et al.* (2014). Uranium abundance and U/Pb ratios were calibrated against the Z6266 and Temora 2 standards, and the individual ages were determined from five successive scans of the mass spectrum. Pooled ages calculated herein are weighted mean $^{206}\text{Pb}/^{238}\text{U}$ dates (one sigma level, rounded to the nearest million year). Age values in tables and figures are given with one sigma precision, and the average ages reported in the text are weighted-mean $^{207}\text{Pb}/^{206}\text{Pb}$ ages, with 95% confidence limits. Correction for common Pb was made based on the measured ^{204}Pb and the typical error component for the $^{206}\text{Pb}/^{238}\text{U}$ ratios was lower than 2%. Data were reduced by using SQUID software (Berkeley Geochronology Center), and the Concordia diagrams were prepared by using Isoplot/Excel (Ludwig 2003). U and Th contents, isotopic ratios and ages are shown in Table 2 (A to D). The analytical data were used to prepare the Concordia diagrams shown later.

GEOCHRONOLOGICAL RESULTS

Rb/Sr and K/Ar ages on the samples collected in 1978

During the field excursion mentioned in the introduction, organized in 1978 by geologists from the geological service of Bolivia, GEOBOL, La Paz, made along the Zongo River, under the leadership of Guillermo Cortez Arce and with the participation of UGC, few rock samples were collected from a few outcrops of the Paleozoic metasedimentary country rocks, the Huayna Potosi and the Zongo plutons. A few of these rocks were studied, and several Rb/Sr and K/Ar ages were obtained at the São Paulo Geochronology Laboratory. Tables 3 and 4 report the analytical data of the samples that were dated, and Figure 3 indicates the location of the collected samples.

Samples BO-4, 5, 6 and 7 were collected from the metapelitic sediments that form the country rocks of the SW edge of the Huayna Potosi pluton. They are all very low-grade metasedimentary rocks that can be generically called as “shales” or “slates” and are related to the early Paleozoic retro-arc basin of the Famatinian orogeny. BO-4 and BO-5, collected near the Milluni Mine, and BO-7, close to the contact with the Huayna Potosi granite, can possibly be related to the Ordovician Amutara Formation. However, sample BO-6 was collected very close to a tillitic outcrop and was indicated as belonging to the Silurian Cancañiri Formation. Samples BO-9, 10 and 11 were collected within the Huayna Potosi pluton, a typical equigranular granite

with millimetric minerals, where K-feldspars predominate. Biotite is ubiquitous, but muscovite is also present, especially in the BO-11 sample. Xenoliths of more mafic rocks were observed, as well as aplites and pegmatitic zones, especially in samples BO-9 and BO-10. Samples BO-12, 13 and 14 were taken from the Kuticucho facies of the Zongo pluton, where the granitic rock presents two-micas and is clearly deformed, with a strong NW-SE orientation. Finally, samples BO-16 and 17 came from the Sainani facies of the same Zongo pluton, with a similar mineralogy, but much less deformation.

Table 3 reports the analytical data of 15 Rb-Sr measurements. Four of them (BO-4, 5, 6 and 7) were made in the whole rock samples of the metapelitic Paleozoic country rocks. Five others were made from the outcrop BO-9 (A, C, D, H and I) of the Huayna Potosi pluton, near its southern border. The remaining six ones were made from outcrops of the Zongo pluton, five of which as whole rock samples (BO-12B, 13A, 14A, 14B and 17A) and one from a concentrate of K-feldspars of outcrop BO-13. Figure 6 is a Rb/Sr regression diagram that reports all the analytical points included in Table 3. The three groupings of samples, Paleozoic metasedimentary rocks, Huayna Potosi granite and Zongo granite, clearly occupy distinct places in Figure 6, thus, they had been subjected to different geological histories. The analytical points of the Paleozoic slates, BO-4, 5, 6 and 7, although not well aligned in the isochron diagram, present a reasonable tendency close to a least squares straight line that could correspond to a Rb/Sr “errorchron” with a 344 ± 38 Ma age and a $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio of about 0.720 ± 0.004 . The five granitic rock samples collected from the same BO-9 outcrop shall be considered cogenetic and showed a better alignment along a least square straight line, which could possibly correspond to a Rb/Sr isochron with a 224 ± 28 Ma age and a $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio of about 0.7103 ± 0.0016 . Moreover, the four analytical points for the Zongo granitic rocks, BO-13A, 14A, 14B and 17A, cluster quite close to one-another in the diagram, and three of them seem to be reasonably aligned. Such fact indicates a tendency corresponding to a Rb/Sr “errorchron” with a 186 ± 25 Ma age and a very high $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio of about 0.731 ± 0.008 .

Table 4 includes analytical data of 12 K-Ar measurements made in separated minerals or in whole-rock samples. There was no grouping within the set of age values; therefore, each rock sample had a proper and distinct thermal evolution, leading to an argon loss with a different proportion. Two samples from the regional slates, one of them analyzed in duplicate, yielded different K-Ar ages, all of them much younger than the age values attributed to early Paleozoic rocks. The K-Ar obtained from micas of the Huayna Potosi and Zongo plutons were also very different, the oldest of which was a biotite from granite BO-10 with 209 Ma and the youngest was the K-feldspar apparent age of sample BO-13A, with 63 Ma.

New U-Pb SHRIMP zircon ages

Four granitoid samples were recently collected by one of the authors, and their locations are indicated in Figure 3. The first two (RIB-2 and RIB-4), from the Huayna Potosi pluton, are light-grey two-mica granites (Fig. 4A) characterized

Table 2. U-Pb Sensitive High-Resolution Ion Microprobe (SHRIMP) analytical data. Errors are 1-sigma; Pb_c and Pb_i indicate the common and radiogenic portions, respectively. Error in standard calibration was 0.40% (not included in above errors but required when comparing data from different mounts. (1) Common Pb corrected using measured 204Pb. (2) Common Pb corrected by assuming 206Pb/238U – 207Pb/235U age concordance. (3) Common Pb corrected by assuming 206Pb/238Pb – 208Pb/232Pb age concordance.

(A) Sample RIB-2 – Huayna Potosi														
Spot	U (ppm)	Th (ppm)	7-corr 206Pb _i (ppm)	7-corr 208Pb _i (ppm)	232Th/238U	±%	(1) 206Pb/238U Age	(2) 206Pb/238U Age	(3) 206Pb/238U Age	(1) 207Pb/206Pb Age	(1) 208Pb/232Th Age	(2) 208Pb/232Th Age	(3) 207Pb/206Pb Age	% Discordant
RIB2-8.1	237	108	6.9	1.01	0.47	0.26	217 ± 2	216 ± 2	217 ± 3	222 ± 128	210 ± 12	210 ± 13	299 ± 101	+3
RIB2-12.1	373	213	11.0	1.99	0.59	0.21	219 ± 2	218 ± 2	218 ± 2	450 ± 34	227 ± 5	210 ± 5	339 ± 40	+52
RIB2-5.1	72	28	2.1	0.25	0.40	2.37	220 ± 5	220 ± 5	221 ± 6	216 ± 298	201 ± 26	202 ± 21	405 ± 162	-2
RIB2-6.1	314	58	9.4	0.52	0.19	0.32	221 ± 3	221 ± 3	221 ± 3	224 ± 94	203 ± 22	202 ± 24	310 ± 68	+1
RIB2-10.1	388	104	11.7	1.05	0.28	0.26	222 ± 3	222 ± 3	222 ± 3	251 ± 49	230 ± 8	225 ± 7	198 ± 38	+12
RIB2-4.1	518	170	16.2	1.61	0.34	0.37	230 ± 3	230 ± 3	231 ± 3	259 ± 67	216 ± 9	212 ± 6	374 ± 35	+11
RIB2-1.1	76	36	2.4	0.39	0.49	0.44	234 ± 4	234 ± 4	233 ± 5	340 ± 196	248 ± 20	239 ± 12	168 ± 94	+32
RIB2-9.1	1,334	88	43.3	0.92	0.07	0.45	239 ± 2	239 ± 2	239 ± 2	211 ± 18	217 ± 8	235 ± 11	246 ± 16	-14
RIB2-3.1	1,713	128	57.3	1.42	0.08	2.22	246 ± 3	246 ± 3	246 ± 3	235 ± 15	243 ± 8	249 ± 11	241 ± 18	-5
RIB2-11.1	138	76	4.6	0.72	0.57	0.97	247 ± 3	247 ± 3	250 ± 3	256 ± 339	214 ± 22	213 ± 24	655 ± 197	+3
RIB2-2.1	999	80	34.3	0.87	0.08	0.77	253 ± 2	253 ± 2	253 ± 2	244 ± 18	240 ± 8	245 ± 12	268 ± 20	-4
RIB2-7.1	437	279	36.7	7.61	0.66	0.36	602 ± 6	602 ± 6	601 ± 7	606 ± 15	606 ± 8	605 ± 9	581 ± 26	+1
RIB-2-13.1	576	460	18	4.36	0.82	0.14	227 ± 3	226 ± 3	228 ± 4	236 ± 29	213 ± 4	213 ± 4	510 ± 43	+4
RIB-2-22.1	507	64	16	0.67	0.13	0.54	236 ± 3	236 ± 3	236 ± 3	229 ± 46	233 ± 19	235 ± 19	240 ± 39	-3
RIB-2-15.1	1,006	359	33	3.83	0.37	0.28	244 ± 4	244 ± 4	244 ± 4	238 ± 20	238 ± 5	239 ± 6	288 ± 29	-2
RIB-2-21.1	777	76	26	0.86	0.10	0.25	247 ± 3	247 ± 3	247 ± 3	242 ± 21	252 ± 8	254 ± 12	231 ± 25	-2
RIB-2-17.1	391	63	13	0.59	0.17	0.31	248 ± 4	248 ± 4	249 ± 4	242 ± 58	207 ± 15	209 ± 12	387 ± 36	-3
RIB-2-24.1	1,950	77	68	0.93	0.04	0.43	257 ± 4	257 ± 4	257 ± 4	248 ± 14	260 ± 13	270 ± 19	245 ± 15	-4
RIB-2-16.1	931	147	40	2.80	0.16	0.26	312 ± 6	312 ± 6	309 ± 6	300 ± 46	421 ± 18	425 ± 17	48 ± 44	-4
RIB-2-14.1	175	78	12	2.14	0.46	0.73	509 ± 7	507 ± 7	500 ± 8	599 ± 44	631 ± 17	608 ± 16	38 ± 57	+16
RIB-2-19.1	1,282	41	102	1.13	0.03	0.63	573 ± 8	573 ± 8	573 ± 8	573 ± 14	607 ± 38	607 ± 54	565 ± 12	-0
RIB-2-18.1	28,696	349	2315	58.07	0.01	3.13	577 ± 13	579 ± 13	573 ± 13	474 ± 24	2,515 ± 166	3,447 ± 288	246 ± 28	-23
RIB-2-23.1	636	39	72	0.78	0.06	2.38	801 ± 13	798 ± 13	801 ± 13	881 ± 12	736 ± 37	451 ± 59	900 ± 12	+10
RIB-2-20.1	456	73	78	1.84	0.17	0.26	1186 ± 22	1169 ± 23	1182 ± 23	1472 ± 8	1,363 ± 33	557 ± 63	1,409 ± 10	+21

Continue...

Table 2. Continuation.

(B) Sample RIB-4 – Huayna Potosi														
Spot	U (ppm)	Th (ppm)	^{7-corr} ²⁰⁶ Pb* (ppm)	^{7-corr} ²⁰⁸ Pb* (ppm)	²³² Th/ ²³⁸ U	±%	(1) ²⁰⁶ Pb/ ²³⁸ U Age	(2) ²⁰⁶ Pb/ ²³⁸ U Age	(3) ²⁰⁶ Pb/ ²³⁸ U Age	(1) ²⁰⁷ Pb/ ²⁰⁶ Pb Age	(1) ²⁰⁸ Pb/ ²³² Th Age	(2) ²⁰⁸ Pb/ ²³² Th Age	(3) ²⁰⁷ Pb/ ²⁰⁶ Pb Age	% Discordant
RIB4-10.1	319	52	9.3	0.50	0.17	0.33	215 ± 3	215 ± 3	215 ± 3	226 ± 57	216 ± 13	214 ± 10	219 ± 37	+5
RIB4-8.1	393	11	11.6	0.11	0.03	0.65	217 ± 2	217 ± 2	217 ± 2	208 ± 52	208 ± 63	220 ± 55	215 ± 34	-5
RIB4-11.1	383	52	11.4	0.51	0.14	0.33	219 ± 2	219 ± 2	219 ± 2	264 ± 49	235 ± 9	222 ± 15	206 ± 48	+17
RIB4-9.1	729	162	21.8	1.56	0.23	0.26	221 ± 2	221 ± 2	221 ± 2	217 ± 40	216 ± 7	217 ± 7	245 ± 29	-2
RIB4-1.1	783	31	23.7	0.36	0.04	0.98	223 ± 2	223 ± 2	223 ± 2	216 ± 42	258 ± 27	265 ± 35	181 ± 35	-3
RIB4-2.1	457	66	14.1	0.68	0.15	0.30	228 ± 2	228 ± 2	228 ± 2	224 ± 68	228 ± 10	229 ± 18	223 ± 61	-2
RIB4-3.1	394	116	12.3	1.18	0.31	0.39	229 ± 2	229 ± 2	230 ± 2	223 ± 45	226 ± 7	227 ± 7	251 ± 33	-3
RIB4-5.1	500	20	26.4	0.30	0.04	2.79	385 ± 9	384 ± 9	385 ± 9	458 ± 33	469 ± 60	330 ± 51	414 ± 28	+16
RIB4-4.1	313	170	95.7	2.66	0.56	0.38	2070 ± 18	1,960 ± 20	2064 ± 20	2600 ± 4	2163 ± 26	351 ± 49	2572 ± 7	+24
RIB-4-26.1	615	17	18	0.11	0.03	0.54	215 ± 3	216 ± 3	216 ± 3	210 ± 39	142 ± 41	150 ± 38	263 ± 27	-3
RIB-4-11.2	1,247	49	39	0.43	0.04	0.95	228 ± 3	228 ± 3	228 ± 3	256 ± 37	229 ± 19	201 ± 38	255 ± 36	+11
RIB-4-14.1	514	199	17	1.91	0.40	0.36	238 ± 4	238 ± 4	239 ± 4	235 ± 33	215 ± 6	216 ± 6	442 ± 32	-1
RIB-4-17.1	1,500	96	49	0.90	0.07	0.25	238 ± 3	238 ± 3	239 ± 3	243 ± 26	214 ± 8	211 ± 17	279 ± 24	+2
RIB-4-12.1	181	71	6	0.73	0.41	0.86	240 ± 4	240 ± 4	241 ± 4	290 ± 108	236 ± 13	230 ± 9	332 ± 56	+17
RIB-4-22.1	838	144	28	1.40	0.18	0.74	245 ± 3	245 ± 3	246 ± 4	250 ± 49	219 ± 15	217 ± 12	354 ± 34	+2
RIB-4-16.1	224	60	8	0.70	0.28	0.31	247 ± 4	247 ± 4	246 ± 4	240 ± 126	263 ± 21	264 ± 12	138 ± 56	-3
RIB-4-25.1	1,233	103	42	1.02	0.09	1.00	251 ± 3	251 ± 3	251 ± 4	241 ± 48	217 ± 20	222 ± 25	305 ± 41	-4
RIB-4-18.1	952	95	34	1.24	0.10	0.29	263 ± 4	263 ± 4	263 ± 4	257 ± 79	289 ± 28	292 ± 29	201 ± 59	-2
RIB-4-13.1	426	130	15	1.67	0.31	0.79	265 ± 4	265 ± 4	264 ± 4	264 ± 54	288 ± 10	288 ± 9	101 ± 46	-1
RIB-4-20.1	194	26	7	0.37	0.14	0.45	275 ± 4	274 ± 4	273 ± 4	386 ± 121	370 ± 46	327 ± 45	120 ± 98	+30
RIB-4-11.1	530	46	21	0.47	0.09	0.32	287 ± 4	287 ± 4	288 ± 4	361 ± 31	273 ± 17	228 ± 16	383 ± 24	+21
RIB-4-21.1	279	134	18	3.74	0.49	1.04	468 ± 7	467 ± 7	455 ± 7	579 ± 30	646 ± 15	623 ± 14	-788 ± 85	+20
RIB-4-23.1	253	100	51	5.75	0.41	0.24	1364 ± 18	1,359 ± 19	1,364 ± 19	1,439 ± 10	1,360 ± 24	1,254 ± 35	1,443 ± 14	+6
RIB-4-24.1	393	268	97	16.29	0.70	0.17	1655 ± 21	1,624 ± 23	1,651 ± 23	1,934 ± 6	1,702 ± 28	1,328 ± 34	1,896 ± 15	+16
RIB-4-19.1	68	22	21	1.87	0.34	0.49	2026 ± 29	2,020 ± 34	2,029 ± 30	2,058 ± 13	1,938 ± 52	1,799 ± 141	2,082 ± 14	+2

Continue...

Table 2. Continuation.

(C) Sample RIB-11 – Taquesi granodiorite													
Spot	U (ppm)	Th (ppm)	7-corr 206Pb* (ppm)	7-corr 208Pb* (ppm)	232Th/238U	±%	(1) 206Pb/238U Age	(2) 206Pb/238U Age	(3) 206Pb/238U Age	(1) 207Pb/206Pb Age	(2) 208Pb/232Th Age	(3) 207Pb/206Pb Age	% Discordant
RIB11-9.1	247	45	7.3	0.50	0.19	1.90	218 ± 2	218 ± 2	217 ± 2	230 ± 67	250 ± 15	59.5 ± 51	+6
RIB11-5.1	217	166	6.5	1.58	0.79	0.23	219 ± 3	219 ± 3	220 ± 3	252 ± 81	214 ± 6	352 ± 70	+13
RIB11-8.1	248	195	7.4	1.89	0.81	0.22	219 ± 2	219 ± 2	219 ± 3	212 ± 84	217 ± 6	260 ± 74	-3
RIB11-12.1	179	248	5.3	2.41	1.43	0.22	220 ± 3	219 ± 3	220 ± 4	271 ± 340	220 ± 10	274 ± 721	+19
RIB11-2.1	449	34	13.4	0.30	0.08	0.42	221 ± 2	220 ± 2	221 ± 2	257 ± 53	219 ± 11	261 ± 52	+14
RIB11-7.1	378	193	11.4	1.84	0.53	0.77	221 ± 2	221 ± 2	222 ± 2	244 ± 109	216 ± 7	320 ± 88	+9
RIB11-6.1	336	199	10.1	2.05	0.61	0.54	221 ± 3	221 ± 3	220 ± 3	209 ± 305	230 ± 6	43.0 ± 337	-6
RIB11-10.1	512	335	15.4	3.23	0.68	0.73	221 ± 2	221 ± 2	222 ± 2	219 ± 33	216 ± 4	316 ± 46	-1
RIB11-3.1	514	163	15.9	1.53	0.33	1.57	228 ± 2	228 ± 2	228 ± 2	285 ± 34	219 ± 9	354 ± 40	+20
RIB11-4.1	813	80	25.2	0.91	0.10	0.28	228 ± 2	229 ± 2	228 ± 2	218 ± 25	251 ± 15	160 ± 28	-5
RIB11-1.1	1,441	144	44.9	1.43	0.10	0.60	230 ± 2	230 ± 2	230 ± 2	236 ± 15	225 ± 5	247 ± 17	+3
RIB11-11.1	226	142	18.1	3.76	0.65	1.70	573 ± 15	573 ± 15	571 ± 17	582 ± 34	591 ± 34	480 ± 102	+2

Continue...

Table 2. Continuation.

(D) Sample RIB-5 – Zongo/Kuticucho facies														
Spot	U (ppm)	Th (ppm)	7-corr 206Pb* (ppm)	7-corr 208Pb* (ppm)	232Th/238U ±%	(1) 206Pb/238U Age	(2) 206Pb/238U Age	(3) 206Pb/238U Age	(1) 207Pb/206Pb Age	(1) 208Pb/232Th Age	(2) 208Pb/232Th Age	(3) 207Pb/206Pb Age	% Discordant	
RIB5-3.1	1,157	522	34.5	4.86	0.47	220 ± 2	220 ± 2	221 ± 2	212 ± 20	208 ± 4	209 ± 4	357 ± 30	-4	
RIB5-1.1	522	36	16.1	0.38	0.07	228 ± 3	228 ± 3	228 ± 3	223 ± 35	229 ± 14	232 ± 20	221 ± 32	-2	
RIB5-8.1	197	50	8.7	0.92	0.26	326 ± 4	325 ± 3	321 ± 4	462 ± 87	443 ± 23	409 ± 16	-105 ± 60	+30	
RIB5-12.1	15,652	78	746.1	3.56	0.01	348 ± 5	348 ± 5	348 ± 5	314 ± 26	574 ± 73	1,010 ± 359	296 ± 26	-11	
RIB5-11.2	8,353	40	411.4	3.27	0.00	359 ± 11	359 ± 11	358 ± 11	273 ± 16	617 ± 97	1,753 ± 293	253 ± 15	-32	
RIB5-6.2	16,273	95	1,036.0	19.90	0.01	457 ± 17	461 ± 17	457 ± 17	182 ± 14	568 ± 70	4,250 ± 452	173 ± 14	-157	
RIB5-2.1	2,261	20	169.0	0.89	0.01	537 ± 5	538 ± 5	537 ± 5	502 ± 17	543 ± 42	999 ± 231	502 ± 17	-7	
RIB5-6.1	296	104	22.9	2.59	0.36	557 ± 6	557 ± 6	557 ± 6	542 ± 31	550 ± 13	556 ± 12	560 ± 24	-3	
RIB5-10.1	662	243	53.4	6.18	0.38	579 ± 6	579 ± 6	580 ± 7	573 ± 20	564 ± 16	566 ± 16	619 ± 31	-1	
RIB5-4.1	421	125	50.2	2.40	0.31	869 ± 32	839 ± 33	857 ± 34	1,579 ± 71	1,149 ± 71	429 ± 105	1,323 ± 91	+48	
RIB5-5.1	792	38	106.8	-9.97	0.05	940 ± 9	940 ± 9	984 ± 9	1,840 ± 7	1,342 ± 36	-6,996 ± 283	1,806 ± 7	+50	
RIB5-7.1	227	136	33.5	6.05	0.62	1,020 ± 10	1,021 ± 10	1,025 ± 11	986 ± 18	959 ± 16	976 ± 17	1,115 ± 21	-4	
RIB5-11.1	161	55	26.9	2.52	0.35	1,148 ± 12	1,148 ± 12	1,155 ± 12	1,149 ± 24	1,011 ± 28	1,010 ± 29	1,277 ± 18	+0	
RIB5-9.1	151	93	37.4	7.27	0.64	1,638 ± 16	1,636 ± 18	1,631 ± 18	1,661 ± 12	1,716 ± 25	1,685 ± 35	1,589 ± 17	+2	
RIB-5-1.2	483	36	16	0.4	0.08	239 ± 3	239 ± 3	239 ± 3	233 ± 27	265 ± 11	268 ± 19	186 ± 31	-3	
RIB-5-28.1	2,057	40	80	1.1	0.02	287 ± 4	286 ± 4	285 ± 4	388 ± 14	877 ± 30	602 ± 41	163 ± 16	+27	
RIB-5-18.2	1,958	298	90	7.3	0.16	335 ± 5	335 ± 5	330 ± 5	349 ± 15	551 ± 12	545 ± 13	-313 ± 28	+4	
RIB-5-25.1	705	162	38	3.6	0.24	395 ± 5	394 ± 5	390 ± 5	443 ± 32	516 ± 14	499 ± 16	20.9 ± 47	+11	
RIB-5-22.1	1,306	62	74	1.9	0.05	415 ± 5	412 ± 5	410 ± 6	659 ± 44	1,143 ± 93	696 ± 89	233 ± 50	+38	
RIB-5-26.1	759	171	50	4.1	0.23	479 ± 6	479 ± 6	477 ± 7	534 ± 24	564 ± 18	540 ± 21	325 ± 36	+11	
RIB-5-27.1	312	59	26	2.1	0.19	607 ± 9	590 ± 9	584 ± 10	1,286 ± 27	1,388 ± 41	781 ± 30	270 ± 43	+55	
RIB-5-23.1	291	258	65	17.8	0.92	1,503 ± 19	1,488 ± 20	1,486 ± 22	1,675 ± 21	1,634 ± 25	1,499 ± 31	1,469 ± 29	+12	
RIB-5-24.1	106	57	30	4.9	0.55	1,824 ± 24	1,827 ± 28	1,824 ± 26	1,802 ± 22	1,828 ± 36	1,872 ± 72	1,799 ± 24	-1	
RIB-5-21.1	5,470	68	174	0.3	0.0128	234 ± 4	234 ± 4	234 ± 4	175 ± 78	-88 ± 220.29	106 ± 128	272 ± 37	-34	
RIB-5-9.2	10,540	46	348	-0.2	0.0045	243 ± 4	243 ± 4	243 ± 4	188 ± 59	-641 ± 502.04	-99 ± 337	277 ± 32	-29	
RIB-5-1.2	6,475	17	222	-0.4	0.0027	252 ± 4	252 ± 4	252 ± 4	187 ± 83	-1,724 ± 1,354.39	-553 ± 773	297 ± 39	-35	
RIB-5-20.1	12,104	77	426	1.7	0.0066	259 ± 4	259 ± 4	259 ± 4	238 ± 29	353 ± 120	500 ± 204	225 ± 26	-9	
RIB-5-19.1	8,295	39	297	1.4	0.0049	263 ± 4	263 ± 4	263 ± 4	172 ± 35	-58 ± 235.74	821 ± 277	206 ± 25	-54	
RIB-5-16.1	10,295	44	378	1.6	0.0044	269 ± 4	270 ± 4	269 ± 4	166 ± 45	-350 ± 398.67	798 ± 318	222 ± 27	-63	
RIB-5-17.1	14,104	75	521	2.2	0.0055	271 ± 4	271 ± 4	271 ± 4	213 ± 34	130 ± 167	652 ± 290	229 ± 29	-28	
RIB-5-14.1	11,368	152	427	3.4	0.0138	276 ± 4	276 ± 4	276 ± 4	243 ± 56	382 ± 182	502 ± 132	213 ± 35	-14	
RIB-5-13.1	8,274	2,055	323	50.6	0.2566	287 ± 5	287 ± 5	276 ± 5	268 ± 30	544 ± 23	548 ± 24	#1NUM! #1NUM!	-7	
RIB-5-18.1	12,238	69	478	2.6	0.0058	286 ± 4	287 ± 4	286 ± 4	186 ± 35	-67 ± 210.00	828 ± 261	226 ± 25	-55	
RIB-5-10.2	14,647	128	583	2.8	0.0090	291 ± 4	292 ± 4	292 ± 4	185 ± 55	-188.18 ± 139	495 ± 265	258 ± 43	-59	
RIB-5-15.1	36,691	182	1,667	13.1	0.0051	331 ± 5	332 ± 5	331 ± 5	212 ± 17	154 ± 113	1,558 ± 370	227 ± 15	-58	

by a massive equigranular millimetric texture made of quartz, microcline, plagioclase, biotite, and muscovite. Sample RIB-5, from the Zongo/Kuticucho foliated pluton, is also a two-mica granite, with similar mineralogy, but presenting large

centimetric crystals of K-feldspar, some accessory garnet, and a strong NW-SE foliation (Fig. 4D). Sample RIB-11, from the Taquesi pluton, is a massive equigranular granodiorite (Fig. 4F), in which plagioclase predominates over K-feldspar.

Table 3. Rb-Sr analytical data acquired in 1978 at the Geochronology Laboratory of the Universidade de São Paulo.

Locality	Longitude S	Latitude W	Sample	Material	Rock	Rb (ppm)	Sr (ppm)	⁸⁷ Rb/ ⁸⁶ Sr	Error	⁸⁷ Sr/ ⁸⁶ Sr	Error	Age (1.42)	Error
Milluni	16°19'35"	68°09'0.58"	BO-4	WR	S	241.7	78.8	8.93	0.18	0.761	0.0017	440.8	24.2
Milluni	16°18'46"	68°08'10.4"	BO-5	WR	S	161.9	58.9	8	0.16	0.7604	0.0009	486.2	23.5
Milluni	16°18'9"2	68°07'51.8"	BO-6	WR	S	135.8	101.8	3.87	0.08	0.7383	0.0014	602.6	46.7
Milluni	16°17'52"	68°07'47.1"	BO-7	WR	S	141.6	203.1	2.02	0.04	0.7302	0.0017	873.4	94.3
HP	16°17'21"	68°07'45.8"	BO-9A	WR	G	133.1	315.9	1.22	0.02	0.7134	0.0015	483.3	144.8
HP	16°17'21"	68°07'45.8"	BO-9C	WR	G	127.2	356.8	1.03	0.02	0.7137	0.001	590.9	153.4
HP	16°17'21"	68°07'45.8"	BO-9D	WR	G	152.9	297.4	1.49	0.03	0.7153	0.0014	485.3	116.3
HP	16°17'21"	68°07'45.8"	BO-9I	WR	G	249.9	147.2	4.92	0.1	0.7266	0.0018	307.8	39.7
HP	16°17'21"	68°07'45.8"	BO-9H	WR	G	223.5	56.8	11.43	0.23	0.7464	0.0019	254.7	18.6
S	16°07'15"9	68°05'2.85"	BO-17A	WR	G	383.9	80.3	13.92	0.28	0.7722	0.0011	339.1	15
K	16°08'0"76	68°06'44.2"	BO-14A	WR	G	397.7	71.9	16.11	0.32	0.7741	0.0011	301.2	13.1
K	16°08'0"76	68°06'44.2"	BO-14B	WR	G	373.4	55.6	19.58	0.39	0.7831	0.0012	280.5	11.5
K	16°09'20"3	68°07'9.89"	BO-13A	WR	G	427.9	42.2	28.306	0.672	0.8069	0.0011	253.1	8.3
K	16°09'20"2	68°07'13.1"	BO-12B	WR	G	447.9	52.5	24.91	0.49	0.7967	0.0012	258.8	9.9
K	16°09'20"3	68°07'9.89"	BO-13A	F	G	214	45	14.533	0.372	0.7809	0.0021	366.7	16.8

HP: Huayna Potosí; K: Zongo pluton facies Kuticucho; S: Zongo pluton facies Sainani; M: muscovite; B: biotite; F: feldspar; WR: whole rocks; G: granite; Gd: granodiorite; Sh: shale; S: slates.

Table 4. K-Ar analytical data acquired in 1978 at the Geochronology Laboratory of the Universidade de São Paulo.

Locality	Sample	Longitude W	Latitude S	Rock	Material	%K	75%K	Ar ⁴⁰ Rad	Atm	Age (Ma)	Error (Ma)
Milluni	BO-4	68°09'0.58	16°19'35	Sh	WR	3.750	0.552	3.704×10^{-4}	14.6	237.86	3.9
Milluni	BO-4 (=4169)	68°09'0.58	16°19'35	Sh	WR	3.750	0.552	3.705×10^{-4}	8.29	249.5	3.06
Milluni	BO-4	68°09'0.58	16°19'35	Sh	WR	3.939	0.500	3.704×10^{-4}	14.6	227.13	3.69
Milluni	BO-5	68°08'10.4	16°18'46	S	WR	2.537	0.500	3.704×10^{-4}	5.26	314.25	3.99
HP	BO-10	68°07'30.1	16°17'11	G	B	4.254	0.500	3.660×10^{-4}	56.49	208.94	3.67
HP	BO-10	68°07'30.1	16°17'11	G	B	4.459	0.500	3.660×10^{-4}	56.49	199.82	3.51
HP	BO-9A	68°07'47.3	16°17'24	G	B	3.262	1.720	3.704×10^{-4}	63.12	146.14	8.29
HP	BO-9A	68°07'47.3	16°17'24	G	B	3.118	1.741	1.925×10^{-4}	63.12	152.6	8.67
HP	BO-11	68°07'7.34	16°16'53	G	M	4.781	2.723	3.532×10^{-4}	48.97	181.2	6.63
HP	BO-11	68°07'7.34	16°16'53	G	M	5.921	2.165	3.532×10^{-4}	48.97	147.62	4.82
K	BO-13A	68°07'9.89	16°09'20.3	G	F	2.586	0.500	6.661×10^{-4}	67.9	65.14	1.56
K	BO-13A	68°07'9.89	16°09'20.3	G	F	2.691	0.500	6.661×10^{-4}	67.9	62.65	1.5
K	BO-13A	68°07'9.89	16°09'20.3	G	B	5.924	0.510	1.854×10^{-4}	22.81	78.82	1.26
K	BO-13A	68°07'9.89	16°09'20.3	G	B	6.240	0.672	1.854×10^{-4}	22.81	74.91	1.24
K	BO-13A	68°07'9.89	16°09'20.3	G	B	5.924	0.510	1.854×10^{-4}	22.81	78.82	1.26
K	BO-13A	68°07'9.89	16°09'20.3	G	M	4.732	1.003	2.532×10^{-4}	27.9	132.8	3.28
K	BO-13B	68°07'9.89	16°09'20.3	G	M	7.542	1.484	5.685×10^{-4}	18.81	184.41	3.52
K	BO-13A	68°07'9.89	16°09'20.3	G	M	4.974	1.325	2.532×10^{-4}	27.9	126.61	3.32
S	BO-17B	68°05'13.3	16°07'22.4	G	M	8.018	1.367	5.685×10^{-4}	18.81	173.97	3.17
S	BO-17B	68°05'13.3	16°07'22.4	G	M	7.542	1.484	5.685×10^{-4}	18.81	184.41	3.52
S	BO-16	68°05'22.4	16°07'25.4	G	M	8.207	0.500	4.759×10^{-4}	21.64	143.43	2.24
S	BO-17A	68°05'13.3	16°07'22.4	G	M	6.741	1.581	2.082×10^{-4}	15.81	77.85	1.5

HP: Huayna Potosí; K: Zongo pluton facies Kuticucho; S: Zongo pluton facies Sainani; M: muscovite; B: biotite; F: feldspar; WR: whole rocks; G: granite; Gd: granodiorite; Sh: shale; S: slates.

The zircon crystals were extracted from these rocks in sizes between 100 and 250 μm mesh, by means of a normal preparation routine, using Wilfly table, magnetic separator, and heavy liquids. About 80 grains from each sample were mounted in one epoxy cylinder (SP-362), together with a few fragments of the Temora 2 standard, and the mounts were covered by a thin layer of gold (6–8 nm) to assure uniform electrical conductivity during the analyses. Scanning electron microscopy (SEM) was performed to produce cathode-luminescence (CL) images before the SHRIMP work in order to select the best zircon domains for the analytical work.

Figure 7 shows the CL images of the zircon crystals from the four studied samples as they were included in mount SP-362. For samples RIB-2 and RIB-4 of the Huayna Potosí pluton (Figs. 7A and 7B), the images of the zircon crystals are quite similar, while they present several forms, shapes, and structures. Some of them have prismatic habit with lengths mostly between 50 and 200 μm , a few longer up to 400 μm , as well as many fragments. Many grains include circular or elliptical white cores, surrounded by dark edges typical of high uranium content. Moreover, igneous oscillatory zoning is present in a few grains. In the case of the zircon grains from sample RIB-11 of the Taquesi pluton (Fig. 7D), they are well formed, prismatic and quite larger (300–600 μm length) than the ones from the previous samples. Igneous oscillatory zoning is frequent; however, white cores or black rims are rare. As shown in Table 2C, the uranium content of the grains from samples RIB-2, 4 and 11 was quite typical of magmatic zircon grains, usually below 1,000 ppm and presenting an average value between 300 and 400 ppm. The Th/U ratio, generally higher than 0.2, also corresponds to a normal igneous origin.

The numerous nuclei showing a sharp white coloration in the CL images, that were thought to be very low in uranium, presented normal-type uranium content, similarly to the domains with greyish oscillatory zones.

The CL images of sample RIB-5 from the Zongo pluton (Kuticucho facies) (Fig. 7C) are very different in zircon typology from those of the other samples. About half of the grains present a small white core associated with medium to large black edges. Within the cores, oscillatory zoned regions are not found, and in only a few zircon crystals, a faint ghost-type structure can be seen. Several grains are solid black fragments, and the black color is due to the very high uranium content, as it is evident from a quick examination of Table 2C. Moreover, there is another zircon population that shows a bulk dark matrix containing small white spots. In this paper, these crystals, probably completely metamict, were not analyzed. The small white cores of this sample presented similar uranium content as the correspondent white cores of the other three samples. However, in RIB-5, the large black domains present a very high proportion of uranium, and a somewhat different procedure had to be employed for their analyses. In order to cut the intensity of the ion beam that would hit the electrometer of the SHRIMP, it was filtered by partially closing the post-Electrostatic Analyzer slit (pESA), decreasing its intensity by a factor of 20. The black domains shown by sample RIB-5 may have extremely high uranium content, up to 37,000 ppm (RIB-5-15.1 in Tab. 2C). Fragments of the Temora zircon standard with high concentration (> 1,000 ppm) were chosen for normalization of the $^{206}\text{Pb} / ^{238}\text{U}$ ratios in that sample.

In the Concordia diagrams of Figures 8, 9 and 10, the samples RIB-2, 4 and 11 yielded robust Concordia ages,

Figure 6. Rb-Sr diagram with the best fit least squares straight lines for the Huayna Potosi and Zongo plutons and for the meta-sedimentary country rocks at the SW side.

which represent the Triassic magmatic pulse of this part of the Cordillera Real.

For sample RIB-2 of the Huayna Potosi pluton, 24 zircon grains were dated, always within their central region, in most cases occupied by a white nucleus. Several of them presented early Paleozoic or Neoproterozoic age (Tab. 2A and Fig. 8), the oldest of which, discordant, yielded a 207/206 age of 1472 Ma. In the insert I of Figure 8, 15 zircon nuclei plotted right along the Concordia curve, covering an age interval of about 40 Ma, from about 220 to 260 Ma. All these analytical points, however, were not compatible to be included in the same calculation for a Concordia age. As depicted in inserts II and III of Figure 8, two sets compatible for such calculation were indicated: 249.2 ± 2.5 Ma and 222.3 ± 2.4 Ma.

For sample RIB-4, also from the Huayna Potosi, 29 age measurements were made in 27 zircons. Like in the previous case, most of the analyses were taken in the whitish zircon cores, and several inherited grains were dated (Fig. 9). They indicate early Paleozoic, Proterozoic, and one Archean age. The rims of two of these inherited crystals were measured, yielding much younger ages and high uranium content. Like in sample RIB-2, many zircon crystals plotted right along the Concordia curve (Fig. 9I),

covering an age span of 30 Ma, from 220 to 250 Ma, but also including a few analytical points located on the Concordia up to 275 Ma. Two sets compatible for a Concordia age calculation were measured, yielding 243.3 ± 2.9 Ma and 220.8 ± 1.9 Ma (Figs. 9II and 9III). The younger Concordia ages obtained for RIB-2 and RIB-4 samples are identical within error, and we consider the age of 221 Ma to be the intrusion time of the Huayna Potosi pluton.

For sample RIB-11 of the Taquesi pluton, 12 zircon grains were analyzed, all of them presented clearly concordant ages. They form a quite homogeneous population of long prismatic crystals with oscillatory zoning, indicating magmatic crystallization. Only a small proportion of the zircon crystals have a restricted black rim. One of them, dated in its whitish core, yielded a late Proterozoic age of 573 Ma (Tab. 2C). All the remaining 11 measurements were compatible with a calculation for a Concordia age of 221.9 ± 1.5 Ma (Fig. 10), which is here considered as the main crystallization episode for the Taquesi pluton.

In the case of sample RIB-5 of the Zongo pluton, 35 measurements were carried out in 28 zircon crystals. As already indicated, the zircon typology of this sample is completely

Figure 7. CL images of zircon crystals for samples RIB-2, 4, 5, and 11. (A) Sample RIB-2: Huayna Potosi. (B) Sample RIB-4: Huayna Potosi. (C) Sample RIB-5: Zongo/Kutikucho. (D) Sample RIB-11: Taquesi.

Figure 8. Concordia diagram for sample RIB-2.

Figure 9. Concordia diagram for sample RIB-4.

different from the previous ones. Two types of grains are present: zircon crystals with small white nuclei presenting normal uranium content, possibly always representing inherited grains, and black or dark grey spotted grains, very likely metamict, presenting high or extremely high uranium content. All the zircon images of the dated grains were shown in Figures 11 or 12. The first one is related to the measurements taken on the whitish cores and the second includes the measurements made on the black edges of the crystals.

In the Concordia diagram of Figure 11, 20 inherited zircon grains with white nuclei were plotted. Most of them yielded concordant ages, and a few other yielded normal discordant ones. Their apparent ages span the 220–1820 Ma interval. Insert I indicates a predominance of Paleozoic inherited grains. The youngest dated crystal 3.1 shows a concordant age of 221 Ma, which is similar to the youngest ages measured for RIB-2, 4, and 11. We assume that most or all the dated whitish cores originate from zircon grains that were formed with primary magmatic zoning. Such original oscillatory zoning had been obliterated, probably when the black overgrowth was formed. However, despite the structural transformation, the position of the analytical point on or close to the Concordia in Figure 11 seems to indicate that the overall U/Pb ratio of these grains was not affected.

Figure 12A shows the 15 zircon crystals in which the age measurements were made on the black domains with extreme uranium content. Figures 12B and 12C present a normal Concordia and a Tera-Wasserburg diagram, in which all measurements have a reverse discordance mode, a situation that happens when the calculated U/Pb 206/238 age is older than 207/206. The Tera-Wasserburg diagram, where all the analytical points plot to the left of the curve, in such reverse discordance mode, is especially clear. In both diagrams, a fair alignment of the analytical points, possibly corresponding to a linear correlation, allowed us to make regression calculations to intercept the Concordia curve. The age results were, in the first case, 222 ± 20 Ma and 219 ± 21 Ma, in the second one. Although they are not very precise, these calculated ages came out similar to the ones obtained in Figures 8, 9 and 10, as representing the intrusion time of the Huayna Potosi and Taquesi plutons.

The extreme uranium concentration in the zircon crystals occurred during the final period of the petrogenetic process, when the black overgrowths were most likely formed from residual magmatic fluids. The synchronicity of the youngest measured crystallization ages encountered for the Huayna Potosi, Zongo and Taquesi plutons is remarkable, and therefore a common regional event could have been responsible for the generation of these granitoids. The final magmatic

Figure 10. Concordia diagram for sample RIB-11.

crystallization and the intrusion of the plutons of the central part of the Cordillera Real of Bolivia have occurred close to 221.5 ± 2.0 Ma, in late Triassic times.

DISCUSSION

The different isotopic systems dealt in this paper, U-Pb zircon, Rb-Sr whole-rock and K/Ar mica ages, record important data that can be used to understand the regional geological history of the Real Cordillera of Bolivia, taking into account the already known evidence described in item 2.

By far, the U-Pb SHRIMP method in zircon crystals produced the most precise ages for the granitoid plutons studied in this paper. However, regarding the intrusion time of the Cordillera Real plutons, the interpretation of the new U-Pb SHRIMP ages is not straightforward. Only sample RIB-11 of the Taquesi pluton yielded a robust age of 221.9 ± 1.5 Ma, which can be related to the zircon crystallization during a single magmatic pulse. However, samples RIB-2 and RIB-4 of the Huayna Potosi pluton, as shown in Figures 8 and 9, exhibited a series of grains right on the Concordia with single ages spanning more than 30 Ma. How could the ages of these zircon crystals, present in the same rock sample, span a time interval of a few tens of Ma, given that each of them seems to be perfectly characterized as formed during one given magmatic episode?

Could these different age values be all significant, revealing a series of distinct crystallization events in time, within the same original magma chamber? Could some restricted solid state Pb diffusion in any already crystallized zircon produce a small dislocation of its analytical point, but keeping a practically concordant situation, right over the Concordia curve?

The age measurements done at the SHRIMP were controlled by means of the Temora zircon standard, whose age is 416.8 Ma. All four samples dealt with in this paper were included in the same mount, SP-362, together with a few standard fragments. 36 Temora measurements were made in four different sessions, together with about 100 zircon measurements on grains of the RIB samples. Looking especially at the standard results, they were normal and showed an overall assigned Pb/U external error (1 sigma) of 1.10%. The odd piece of evidence, zircons with different ages in the same well crystallized granitic rock, has still to be investigated properly. A similar situation was encountered by Gillis *et al.* (2006), who also dated using U/Pb SHRIMP in zircon one sample of the Huayna Potosi pluton and another from the Zongo pluton. Like in this paper, they could not obtain a unique precise age for each sample and reported an interval between 241 and 218 Ma for the Huayna Potosi pluton, and an interval from 263 to 227 Ma to the Zongo pluton. Moreover, in our case, inserts II and III in Figure 8 show that Concordia ages can be

Figure 11. Concordia diagram for the measured spots of inherited zircon grains with whitish nuclei of the RIB-5 sample, and respective cathode-luminescence (CL) images.

calculated for two different populations of the RIB-2 zircon grains (249 ± 3 Ma and 222 ± 2 Ma). In addition, inserts II and III in Figure 9 show that two Concordia ages can be calculated for two different populations of the RIB-4 grains (243 ± 3 Ma and 221 ± 2 Ma). The age correspondence is remarkable. Considering that the two samples are located about 1 km apart, could that age similarities be just a coincidence?

As to sample RIB-5, as shown from its CL images, all magmatic zircon grains are either spotted metamict crystals or

black structured fragments or crystals showing an inherited core and a small or large black rim. All black domains bear high uranium content, and sometimes extreme uranium content. Most likely, the black zircon crystals were formed in the youngest magmatic crystallization episode of the Zongo pluton. As already indicated in Figures 11 and 12, the calculated regressions, considering all the reverse discordant ages of the black domains, yielded unprecise ages of ca. 220 Ma. The RIB-5 sample also has many inherited grains with preserved whitish

Figure 12. Concordia diagrams and cathode-luminescence (CL) images for the measured spots on black high-Uranium domains of zircon grains of the RIB-5 sample. (A) CL zircon images. (B) Concordia diagram for the black domains, showing the regressed reverse discordant analytical points. (C) Tera-Wasserburg diagram for the same black spots of Figure 12B.

nuclei, which yielded old apparent ages, in most cases pre-Triassic. The youngest of these cores, zircon 3.1 in Table 2D, presents a faint vestige of oscillatory zones and is surrounded by high-uranium black edges. Its age of 220 Ma, identical within error to the age of the youngest correspondent grains of the Huayna Potosi and Taquesi plutons, may indicate the highest limit to the final magmatic crystallization linked to the intrusion of the Zongo pluton.

Reverse discordant zircon crystals (Wiedenbeck 1995) are difficult to interpret, and the subject is open to debate. In general, zircon losing U in preference to Pb is usually not easily accepted, because U replaces Zr in the structural lattice of the crystals. Williams & Hergt (2000) already asked for caution when measuring the age of high U domains, and White & Ireland (2012) considered that a reverse discordance could be due to the possibility of enhancing the emission of Pb^+ relative to U, due to degradation of the zircon matrix from radiation damage. In our point of view, the anomalous U enrichment in the magmatic grains of the Zongo/Kuticucho foliated granites is a clear piece of evidence for their formation during the final stage of the magmatic process affecting these granites. We will not be surprised if the age of the strong NW-SE deformation that affected the Zongo/Kuticucho granite would be synchronous with that final magmatic (or metasomatic?) episode, in which the new zircon lattices with extremely high Uranium were formed. The modal analysis of RIB-5 (Tab. 1) contains a large amount of two generations of muscovite, the younger of which may correspond to the “hydrothermal muscovite” indicated by McBride *et al.* (1987). It could well have been formed throughout the same hydrothermal fluids that also brought about the high uranium amount, which was included in the black metamictic zircon crystals of the pluton.

Regarding inherited zircon crystals, Table 2 shows a total of about 40 grains with pre-Triassic U-Pb SHRIMP ages in the four studied samples of the Huayna Potosi, Zongo and Taquesi plutons, which indicate the existence of previously formed zircons in the four investigated Triassic granites. Most of the age values are concordant and precise, but there are also several discordant analytical points indicating some Pb loss. These grains are xenocrysts formed in igneous crystallization episodes occurred in different and older magmatic chambers, in some cases much before the event that produced the final crystallization and emplacement of the Cordillera Real plutons. The inherited grains usually include a circular or elliptical core that shows a sharp whitish coloration in the CL images, in which all the SHRIMP spots were located. As already indicated, these cores were thought to be very low in Uranium due to their color, but instead they presented normal-type content, and some of them exhibited phantom traces of oscillatory zoning typical of magmatic zircon. Since such whitish cores were present in all the studied samples of the Huayna Potosi and Zongo plutons, we have attributed the vanishing of pre-existing structures, such as domains with oscillatory zoning, to the action of metasomatic fluids during a widespread regional process. This was possibly synchronous with the formation of the black overgrowth rims, as evident in sample RIB-5.

The high zircon inheritance of these plutons is most likely representative of “cold magmas” (Bachmann *et al.* 2007, Miller *et al.* 2003), which are not hot enough to dissolve the inherited zircons acquired either from basement magmatic sources or from detrital material included within the Paleozoic country rocks. Looking at the bulk of inherited grains, only one is Archean, and only three others are Paleoproterozoic. Possible sources for them must be attributed to basement rocks that, in this case, may belong to some parts of the Arequipa Massif, which forms the crustal basement right below the main extensional zone of the Eastern Cordillera (Loewy *et al.* 2004, Ramos 2018a). Several inherited grains indicated Mesoproterozoic ages, for which the possible sources could be located in the Western part of the Amazonian Craton (Cordani *et al.* 2000), but only a few of them are clearly related to the Grenvillian Orogeny that is widespread all along the basement of the Andean Chain (Ramos & Alemán 2000). Neoproterozoic ages are important, and a cluster is noted close to 570-580 Ma that is clearly related to the Brasiliano Orogeny, widespread over the Brazilian Shield at the near eastern side of the Cordillera. Granitic rocks of this orogenic cycle may have brought important material to the Paleozoic meta-sedimentary sequences that were directly intruded by the Cordillera Real studied plutons. Finally, the Paleozoic apparent ages show that a large part of the inherited crystals presented ages associated with magmatic episodes of the Andean Cordillera, where the main sources could have been granitoids formed in the Famatinian or Gondwanide orogenies.

From the U-Pb SHRIMP ages obtained in this paper, the final magmatic crystallization and the intrusion of plutons of the central part of the Cordillera Real of Bolivia most likely occurred at 221.5 ± 2.0 Ma, in the late Triassic times. This is corroborated by the Rb-Sr isochron age shown in Figure 6 of 224 ± 28 Ma, which, although lacking adequate precision, is concordant within error with the indicated U-Pb SHRIMP results. The five-point Rb-Sr whole-rock isochron produced from the two-micas granite BO-9, located closely to the southern border of the Huayna Potosi pluton, yielded a $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio of 0.7103 ± 0.0016 . This indicates that the original magma is not juvenile and shall be considered compatible with substantial crustal contamination. This is confirmed by the obvious piece of evidence consisting of large amounts of inherited zircon grains, originated from basement rocks, found in the studied samples. Moreover, considering the Rb-Sr systematics related to the six measured samples from the Zongo/Kuticucho pluton (Fig. 6), taken from strongly deformed outcrops, the “errorchron” with a 186 ± 25 Ma age and a very high $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio of about 0.731 ± 0.008 is most likely related to a perturbation in their Rb/Sr ratios. Possibly, this occurred somewhat later in respect to the formation of the rock and will be considered below, when dealing with the interpretation of the available K-Ar ages.

Considering the Rb-Sr determinations on the four samples of metapelitic sedimentary rocks (BO-4 to 7) that belong to the early Paleozoic Amutara and Cancañiri formations, collected at the SW edge of the Huayna Potosi pluton, they may highlight the existence of an important tectonic event in the regional geological history. Figure 6

brings their Rb-Sr whole-rock isochron age of 344 ± 38 Ma, with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.72, and white mica is probably the main mineral constraining the Rb/Sr whole-rock ratio. The obtained age, although exhibiting a very large experimental error, shall be considered as a correspondence to a resetting during the widespread intra-plate early Gondwanide orogeny, affecting these rocks during the early Carboniferous (Dalmayrac *et al.* 1980). Important regional tectonic episodes of this age, represented by intra formation discordances and crenulated foliation, are described in the Central Andes of Perú and Bolivia (Mégard *et al.* 1971, Tawackoli *et al.* 1996).

Table 4 brings 12 K-Ar measurements measured long ago (Cordani *et al.* 1980), whose ages are presented in this paper for the first time. Many other K-Ar determinations, referred in Evernden *et al.* (1977), McBride *et al.* (1983, 1987), Farrar *et al.* (1990), Kennan *et al.* (1995) and Gillis *et al.* (2006), are available at present, totalizing about 100 K-Ar ages for rocks of the central part of the Cordillera Real. A few of them was obtained applying the Ar-Ar method. The great majority used micas, and in many cases biotite and muscovite were measured from the same rock specimen. In general, the overall results are coherent and can be interpreted in terms of critical temperature for argon retention in micas.

For muscovite and biotite belonging to the Huayna Potosi granite, in the southern part of the Zongo profile (Fig. 3), the measured K-Ar apparent ages resulted between 195 and 218 Ma. McBride *et al.* (1987) also analyzed a muscovite that yielded an Ar/Ar plateau of 214 Ma for this same pluton. Moreover, for the small Unduavi stock, at the eastern side of the Huayna Potosi pluton, and for the Chacaltaya stock at the southern side, a few micas yielded K/Ar ages between 202 and 213 Ma. Although less precise, these apparent ages, which must be attributed to the cooling of the pluton below 300°C, are not very different from the U-Pb zircon or Rb-Sr ages.

However, proceeding northerly and descending along the Zongo river towards the Bolivian Amazonian forest, the apparent K-Ar ages, either of muscovite or biotite, decrease from SW to NE, as it is clear when reaching the Kutiucucho and Sainani facies of the Zongo pluton. Such systematic Ar loss was already recognized by McBride *et al.* (1987), who showed the decrease of apparent ages of muscovite and biotite from close to 200 Ma down to less than 100 Ma. This is confirmed in Table 4, in which the biotite BO-10 at the Huayna Potosi yielded ca. 200 Ma, the muscovite at Kutiucucho ca. 130 Ma, and the muscovite at Sainani ca. 78 Ma. The gradual decrease continues until about 39 Ma (Oligocene), corresponding to a well-defined Ar-Ar plateau age of the biotite CR-370 from a granitic rock of the Sainani facies of the Zongo pluton (McBride *et al.* 1987). These authors, as well as Farrar *et al.* (1988) and Gillis *et al.* (2006), attributed this situation to the onset of a unique regional thermal event that opened the K/Ar isotopic system in the early Oligocene, related to the back-thrusting dynamics of the Andean orogeny and the associated Zongo-San Gaban thermal effect (Ramos 2018a).

CONCLUSIONS

The geochronological data available for the Huayna Potosi, Zongo and Taquesi plutons of the Real Cordillera of Bolivia are a relevant contribution to the assessment of the geological history of that region. The Rb-Sr ages of the early Paleozoic metasedimentary rocks of the Amutara and Cancañiri formations indicate the time for the tectonic activities associated with the early Gondwanide orogeny. The U-Pb zircon ages of the mentioned granitic plutons confirm their Triassic intrusion age associated with the post-tectonic magmatism of the late Gondwanide orogeny, within an important extensional tectonic zone linked to the Pangea disruption. Finally, the K-Ar and Ar-Ar ages of micas indicate the action in the Oligocene of a strong thermal episode of the Andean orogeny, the Zongo-San Gabán effect, related to the formation of a regional “inner arc”.

Moreover, in this paper, some factual pieces of evidence raised a few scientific questions that shall be considered in the future:

- The numerous inherited zircon grains encountered within the Huayna Potosi and Zongo samples, no matter their age, although showing normal uranium content, present a whitish coloration. A few of them have faint traces of light grey oscillatory zones and many show high uranium black rims. Most likely, they were probably decolored at the same time as the black rims were formed, during the final episode of the magmatic crystallization of the Triassic plutons. Such geochemical process shall be investigated and clarified;
- For the two dated samples of the Huayna Potosi pluton, as shown in Figures 8 and 9, a final crystallization age was not clearly indicated by one specific cluster of analytical points, considering that a unique Concordia age could not be obtained. The calculated single ages of many zircon grains plotted right on the Concordia curve, forming a continuous line corresponding to a time interval spanning something like 30–40 Ma. Regarding both RIB-2 and RIB-4, two different ages were calculated, using two selected clusters of analytical points. The younger cluster, whose age was close to 221 Ma in both cases, was significant for the final magmatic crystallization of the pluton;
- Finally, for the the Zongo/Kutiucucho foliated pluton, the black domains of sample RIB-5, presenting very high uranium content and yielding systematically reverse discordant ages, are interpreted as due to anomalous uranium enrichment during the late stage magmatic processes affecting that rock. The calculated regressions yielded unprecise ages near 220 Ma, which would agree with the regional geological history. However, as indicated in the discussion, the generation of reverse discordant zircon grains, linked to ion mobility and disturbance of the U/Pb ratio, is still subject to debate. In the present case, the correlation with extreme uranium content is evident, and perhaps future researches using our Zongo/Kutiucucho zircon crystals will be able to bring some new light towards a better interpretation of the phenomenon.

ACKNOWLEDGMENTS

We thank the Institute of Geosciences (IGc) of the USP for their help given in 1978 for the sample preparation and isotopic analyses done in the samples collected by the senior author in the Bolivian Andes. Also, we are thankful for the personnel of the Proyecto Cordillera of GEOBOL who guided the field trip made at that time along the Zongo River. On the work with the samples collected recently by the second author, we thank the same institute for giving

us the opportunity to use the facilities of the SHRIMP and LA-ICP-MS laboratories. Colleagues of the Carrera de Geología and Instituto de Investigaciones Geológicas y del Medio Ambiente (IGEMA) of the UMSA, La Paz, Bolivia, for their field work collaboration, support and advice. The technicians of the IGc-USP and the IGEMA-UMSA were of great help in the preparation of the analyzed samples. We would like to thank Mark Fanning for his help in the discussion related to the U-enrichment of zircon.

ARTICLE INFORMATION

Manuscript ID: 20190016. Received on: 03/05/2019. Approved on: 05/02/2019.

U. G. C. wrote the first draft of the manuscript and finalized it after revision by the co-authors; he was part of the SHRIMP analyses; compiled and interpreted the Rb-Sr and K-Ar ages made long ago by himself. This article is planned to be part of the author A. R. I. Doctorate. A. R. I. provided geological data on the Cordillera Real; prepared all figures and tables of the manuscript; was part of the SHRIMP analyses and improved the manuscript through corrections and suggestions. K. S. provided support and supervision to the SHRIMP analyses; wrote the chapter on methodology; contributed to the interpretation of the U-Pb zircon ages and improved the MS through corrections and suggestions. Competing interests: The authors declare no competing interests.

REFERENCES

- Ahlfeld F. & Schneider-Scherbina A. 1964. Los yacimientos minerales y de hidrocarburos de Bolivia. La Paz, Departamento Nacional de Geología, Ministerio de Minas y Petróleo, 388 p. (Boletín DENAGEO 5).
- Amaral G., Cordani U.G., Kawashita K., Reynolds J.H. 1966. Potassium-argon dates of basaltic rocks from Southern Brazil. *Geochimica et Cosmochimica Acta*, **30**(2):159-189. [http://dx.doi.org/10.1016/0016-7037\(66\)90105-0](http://dx.doi.org/10.1016/0016-7037(66)90105-0)
- Ávila W.A. 1990. Tin-bearing granites from the Cordillera Real, Bolivia; A petrological and geochemical review. In: Kay S.M. & Rapela C.W. (Eds.). *Plutonism from Antarctica to Alaska*. America, Geological Society of America, Special paper 241, p. 145-159.
- Bachmann O., Miller C.F., de Silva S.L. 2007. The volcanic-plutonic connection as a stage for understanding crustal magmatism. *Journal of Volcanology and Geothermal Research*, **167**(1-4):1-23. <http://doi.org/10.1016/j.jvolgeores.2007.08.002>
- CGMW (Commission of the Geological Map of the World). 2019. Cordani, U.G., Ramos, V.A., (Coordinators). *Tectonic Map of South America*, 2nd edition, scale 1:5000000.
- Cordani U.G., Iyer S.S. 1979. Geochronological investigation on the Precambrian granulitic terrain of Bahia, Brazil. *Precambrian Research*, **9**(3-4):255-274. [https://doi.org/10.1016/0301-9268\(79\)90006-8](https://doi.org/10.1016/0301-9268(79)90006-8)
- Cordani U.G., Kawashita K., Cortez G. 1980. Chronology of the tectonomagmatic events of the Cordillera Real of Bolivia. In: International Geological Congress, 26., Paris. *Abstracts...*, p. 32.
- Cordani U.G., Sato K., Teixeira W., Tassinari C.C.G., Basei M.A.S. 2000. Crustal evolution of the South American platform. In: Cordani U.G., Milani E.J., Thomaz-Filho A., Campos D.A. (Eds.), *Tectonic evolution of South America*: Rio de Janeiro, Brazil, 31st International Geological Congress, p. 19-40.
- Dalmayrac B., Laubacher G., Marocco R., Martinez C., Tomasi P. 1980. La Chaîne Hercynienne d'Amerique du Sud. Structure et evolution d'une orogène intracratonique. *Geologische Rundschau*, **69**(1):1-21. <http://dx.doi.org/10.1007/BF01869020>
- Dorbath C., Granet M., Poupinet G., Martinez C. 1993. A teleseismic Study of the Altiplano and the Eastern Cordillera in Northern Bolivia: New Constraints on a Lithospheric Model. *Journal of Geophysical Research*, **98**(B6):9825-9844. <https://doi.org/10.1029/92JB02406>
- Evernden J.F., Kriz S.J., Cherroni M.C. (1977). Potassium-argon ages of some Bolivian rocks - a discussion. *Economic Geology*, **72**:1042-1061.
- Farrar E., Clark A.H., Heinrich S.M. 1990. The Age of the Zongo Pluton and the Evolution of the Zongo San Gaban Zone in the Cordillera Real, Bolivia. In: Symposium international "Géodynamique andine". *Résumés des communications*, p. 171-174.
- Gillis R.J., Horton B.K., Grove M. 2006. Thermochronology, geochronology, and upper crustal structure of the Cordillera Real: Implications for Cenozoic exhumation of the central Andean plateau. *Tectonics*, **25**(6):1-22. <http://doi.org/10.1029/2005TC001887>
- Jiménez N. & López-Velásquez S. 2008. Magmatism in the Huarina belt, Bolivia, and its geotectonic implications. *Tectonophysics*, **459**(1-4):85-106. <http://doi.org/10.1016/j.tecto.2007.10.012>
- Kennan L., Lamb S., Rundle C. 1995. K-Ar dates from the Altiplano and Cordillera Oriental of Bolivia: implications for stratigraphy and tectonics. *Journal of South American Earth Sciences*, **8**(2):163-186. [https://doi.org/10.1016/0895-9811\(95\)00003-X](https://doi.org/10.1016/0895-9811(95)00003-X)
- Loewy S.L., Connelly J.N., Dalziel I.W.D. 2004. An orphaned basement block: The Arequipa-Antofalla Basement of the central Andean margin of South America. *Bulletin of the Geological Society of America*, **116**(1-2):171-187. <http://doi.org/10.1130/B25226.1>
- Ludwig K.R. 2003. Isoplot 3: A Geochronological Toolkit for Microsoft Excel. Berkeley, Berkeley Geochronology Center Special Publication, no. 4.
- McBride S.L., Robertson R.C.R., Clark A.H., Farrar E. 1983. Magmatic and Metallogenic Episodes in the Northern Tin Belt, Cordillera Real, Bolivia. *Geologische Rundschau*, **72**(2):685-713.
- McBride S.L., Clark A.H., Farrar E., Archibald D.A. 1987. Delimitation of a cryptic Eocene tectono-thermal domain in the Eastern Cordillera of the Bolivian Andes through K-Ar dating and 40Ar-39Ar step-heating. *Journal of the Geological Society*, **144**(2):243-255. <https://doi.org/10.1144/gsjgs.144.2.0243>
- McQuarrie N. 2002. The kinematic history of the central Andean fold-thrust belt, Bolivia: Implications for building a high plateau. *Bulletin of the Geological Society of America*, **114**(8):950-963. [http://doi.org/10.1130/0016-7606\(2002\)114<0950:TKHOTC>2.0.CO;2](http://doi.org/10.1130/0016-7606(2002)114<0950:TKHOTC>2.0.CO;2)
- Mégard F., Dalmayrac B., Laubacher G., Marocco R., Martinez C., Paredes J., Tomasi P. 1971. Le chaîne Hercynienne au Pérou et en Bolivie Premiers Résultats. *Cahiers Orstom*, **III**(1):5-44. Série Géologie.
- Miller C.F., McDowell S.M., Mapes R.W. 2003. Hot and cold granites: Implications of zircon saturation temperatures and preservation of inheritance. *Geology*, **31**(6):529-532. [http://doi.org/10.1130/0091-7613\(2003\)031<0529:HACGIO>2.0.CO;2](http://doi.org/10.1130/0091-7613(2003)031<0529:HACGIO>2.0.CO;2)

- Miskovic A., Schaltegger U., Chew D. 2009. Carboniferous plutonism along the Eastern Peruvian Cordillera: Implications for the Late Paleozoic to Early Mesozoic Gondwanan tectonics. *In: International Symposium on Andean Geodynamics*, 6., Barcelona. *Extended Abstracts...*, p. 508-511.
- Mpodzois C. & Kay S.M. 1992. Late Paleozoic to Triassic evolution of the Gondwana margin: Evidence from Chilean Frontal Cordilleran batholiths (28°S to 31°S). *Geological Society of America Bulletin*, **104**(8):999-1014.
- Ramos V.A. 2009. Anatomy and global context of the Andes: Main geologic features and the Andean orogenic cycle. *In: Kay S.M., Ramos V.A., Dickinson W.R. (Eds.), Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision*. America: Geological Society of America, p. 31-65. (Memoirs, v. 204). [http://doi.org/10.1130/2009.1204\(02\)](http://doi.org/10.1130/2009.1204(02))
- Ramos V.A. 2018a. Tectonic Evolution of the Central Andes: From Terrane Accretion to Crustal Delamination. *In: Zamora Valcarce G., McClay K., Ramos V.A. (Eds.), Petroleum Basins and Hydrocarbon Potential of the Andes of Peru and Bolivia*. United States, American Association of Petroleum Geologists, p. 1-34. <http://doi.org/10.1306/13622115M1172855>
- Ramos V.A. 2018b. The Famatinian orogeny along the protomargin of western Gondwana. Evidence of a nearly continuous Ordovician magmatic arc between Venezuela and Argentina. *In: Folguera A., Contreras Reyes E., Heredia N., Encinas A., B. Iannelli S., Oliveros V., M. Dávila F., Collo G., Giambiagi L., Maksymowicz A., Iglesia Llanos M.P., Turienzo M., Naipauer M., Orts D., D. Litvak V., Alvarez O., Arriagada C. (Eds.), The evolution of the Chilean-Argentinean Andes*. New York: Springer, p. 154-184. (Springer Earth System Sciences).
- Sato K., Tassinari C.C.G., Basei M.A.S., Siga Jr. O., Onoe A.T., De Souza M.D. 2014. Sensitive High Resolution Ion Microprobe (SHRIMP IIe/MC) of the Institute of Geosciences of the University of São Paulo, Brazil: Analytical method and first results. *Geologia USP - Série Científica*, **14**(3):3-18. <http://doi.org/10.5327/Z1S19-874X201400030001>
- Sempere T. 1995. Phanerozoic evolution of Bolivia and adjacent regions. *In: Tankard A., Suárez S. R., Welsink H. (Eds.), Petroleum basins of South America: AAPG Memoir 62*. America: Geological Society of America Memoirs, p. 207-230.
- Sergeotecmin 2011. *Carta Geológica de Bolivia*. Hoja Charazani 584. Publicación SGT-M-Serie I-CGB-62. Scale 1:100000. Bolivia: Servicio Geológico de Bolivia.
- Spikings R., Reitsma M.J., Boekhout F., Mišković A., Ulianov A., Chiaradia M., Gerdes A., Schaltegger U. 2016. Characterisation of Triassic rifting in Peru and implications for the early disassembly of western Pangaea. *Gondwana Research*, **35**:124-143. <http://doi.org/10.1016/j.gr.2016.02.008>
- Sugaki A., Shimada N., Ueno H., Kano S. 2003. K-Ar ages of tin-polymetallic mineralization in the Oruro mining district, central Bolivian tin belt. *Resource Geology*, **53**(4):273-282.
- Tawackoli S., Kley J., Jacobshagen V. 1996. Evolución tectónica de la Cordillera Oriental del Sur de Bolivia. *In: XII Congreso Geológico de Bolivia*, 12., Tarija. *Memorias...*, p. 91-96, Tarija.
- White L.T. & Ireland T.R. 2012. High-uranium matrix effect in zircon and its implications for SHRIMP U-Pb age determinations. *Chemical Geology*, **306-307**:78-91. <http://doi.org/10.1016/j.chemgeo.2012.02.025>
- Wiedenbeck M. 1995. An example of reverse discordance during ion microprobe zircon dating: An artifact of enhanced ion yields from a radiogenic labile Pb. *Chemical Geology*, **125**(3-4), 197-218. [http://doi.org/10.1016/0009-2541\(95\)00072-T](http://doi.org/10.1016/0009-2541(95)00072-T)
- Williams I.S. 1998. U-Th-Pb geochronology by ion microprobe. *In: McKibben M.A., Shanks I., Ridley W.C.P., Ridley W.I. (Eds.), Application of Microanalytical Techniques to Understanding Mineralizing Processes*. Reviews in Economic Geology. United States: Society of Economic Geologists, 7:1-35.
- Williams I.S. & Hergt J.M. 2000. U-Pb dating of Tasmania dolerites: A Cautionary Tale of SHRIMP Analyses of High-U Zircon. *In: Woodhead J.D., Hergt J.M., Noble W.P. (Eds.), Beyond 2000: New Frontiers in Isotope Geoscience*, Lorne, 2000. *Abstracts and Proceedings...*, 185-188.
- York D. 1968. Least Squares Fitting of a Straight Line with Correlated Errors. *Earth and Planetary Science Letters*, **5**:320-324. [https://doi.org/10.1016/S0012-821X\(68\)80059-7](https://doi.org/10.1016/S0012-821X(68)80059-7)

CHAPTER 4 – Geochronology of the Cordillera Real granitoids, the inner magmatic arc of Bolivia - Andean Geology

Iriarte, A.R., Cordani, U.G., & Sato, K, (2021)

Geochronology of the Cordillera Real granitoids, the inner magmatic arc of Bolivia

*Alvaro Rodrigo Iriarte^{1,2}, Umberto G. Cordani¹, Kei Sato¹

¹ Instituto de Geociências, Universidade de São Paulo - USP, Rua do Lago 562, CEP 05508-080, São Paulo, Brasil.
arodrigoirarte@gmail.com; ucordani@usp.br; kei@usp.br

² Universidad Mayor de San Andrés (UMSA), Campus Universitario Cota Cota, Calle 27, La Paz, Bolivia.

* Corresponding author: arodrigoirarte@gmail.com

ABSTRACT. The Cordillera Real granitoids are a suite of Triassic and Oligocene plutons in the core of the Eastern Cordillera of the Central Andes of Bolivia. Their tectonic setting, chemical and ore compositions make them part of the so-called “Inner Magmatic Arc”, which differs from the current “Magmatic Arc” located immediately to the west. U-Pb SHRIMP data were obtained in order to constrain crystallization ages. The Triassic group yielded the following results: 239±2 Ma for the Huato granite, 231±1 Ma for the Illampu granodiorite, 221±3 Ma for the Huayna Potosi granite and 223±2 Ma for the Taquesi granodiorite. For the Oligocene group we obtained ages of 27 Ma for two samples of the Quimsa Cruz granite. Secondary processes related to regional thermal anomalies and magmatic melt-enrichment, reset the K-Ar and U-Pb isotopic systems, producing: **a)** younger ages by Ar loss and **b)** anomalous data plot in the Concordia diagram by reorganization of U-Pb isotopic ratios. As noted in previous studies, most zircon analysed from the Zongo/Kuticucho Triassic granite exhibited extremely high U enrichment, producing reverse discordia curves that obscure the true crystallization age. Relatively abundant zircon inheritance was found in these “cold” granitoids, with ages suggesting provenance from early Paleozoic metapelites that also contained recycled older sources. This relatively abundant xenocrystic inheritance probably records the influence of the subduction process acting during the Gondwanide orogeny (336-205 Ma) as an overall subduction arc environment, punctuated at its final stage with the imprint of a continental rifting (245-220 Ma).

Keywords: Granitoids, U-Pb zircon age dating, Geochronology, SHRIMP, Central Andes.

RESUMEN. Geocronología de los granitoides de la Cordillera Real, el arco magmático interno de Bolivia. Los granitoides de la cordillera Real de Bolivia son un conjunto de plutones triásicos y oligocenos, ubicados en el núcleo de la cordillera Oriental de los Andes Centrales. Las características estructurales, geoquímicas y de composición de menas asociadas, los agrupan dentro del llamado “arco magmático interno” que se distingue del “arco magmático” actual ubicado directamente hacia el oeste. Datos de U-Pb SHRIMP de estos granitoides fueron obtenidos para intentar definir sus edades de cristalización. El grupo de plutones del Triásico dio los siguientes resultados: 239±2 Ma para el granito Huato, 231±1 Ma para la granodiorita Illampu, 221±3 Ma para el granito Huayna Potosí y 223±2 Ma para la granodiorita Taquesi. Para el grupo de plutones del Oligoceno, obtuvimos edades de 27 Ma para dos muestras del granito Quimsa Cruz. Procesos secundarios relacionados con anomalías termales y enriquecimiento tardío de fluidos magmáticos resetearon los sistemas isotópicos K-Ar y U-Pb produciendo: **a)** edades más jóvenes debido a pérdida de Ar y **b)** anomalías en el diagrama Concordia debido a reorganización de las razones isotópicas de U-Pb. Como se ha indicado en estudios previos, la mayoría de los zircones analizados en el granito triásico Zongo/Kuticucho presentan un enriquecimiento de U extremadamente alto, que producen gráficos de discordia inversos, dificultando la determinación de su verdadera edad de cristalización. Una cantidad relativamente abundante de circones heredados fue encontrada en estos granitoides “fríos”, con edades que sugieren fuentes provenientes de las metapelitas del Paleozoico temprano, las cuales también re trabajaron fuentes más antiguas. Esta abundancia relativa de xenocristales heredados, probablemente registra la influencia de los procesos de subducción ocurridos durante la orogenia Gondwánica (336-205 Ma), mediante un ambiente regional de tipo arco magmático, caracterizado por un estadio final de *rifting* continental (245-220 Ma).

Palabras clave: Granitoides, Datación U-Pb en zircón, SHRIMP, Andes Centrales.

1. Introduction

The Cordillera Real granitoids are located in the Eastern Cordillera of the Central Andes (Fig. 1). They are represented by eight syn-orogenic plutons, six of which are Triassic (~220 Ma) and the other two are Oligocene (~26 Ma) in age. The Triassic ones were emplaced along a rifted area that trends northwest towards SW Perú and coincides with the contemporaneous granitoids of the Carabaya Cordillera. This rift was widespread along the western border of the South American continent. The two Oligocene plutons were emplaced in a compressional regime, apparently related to subduction, coeval with uplifting of large plateaux (Altiplano and Puna), delamination of the lower crust and widespread mafic flows (Jiménez and López-Velásquez, 2008; Ramos, 2018). The country rocks for these anatectic granitoids are lower Paleozoic metapelites. Older basement crops out several hundred kilometers to the east (Rondonia-San Ignacio) and to the west (Arequipa-Antofalla). Along with these regional features, the chemical, mineral and ore compositions of this “inner magmatic arc” (Clark *et al.*, 1990) are sharply different from the purely slab related magmatic arc of the Western Cordillera.

One of the enigmas about the generation of granitic rocks is the precise time span of their emplacement. It has been shown by high precision geochronology that many plutons of batholithic size have been assembled in several magmatic pulses that can last several million years (*e.g.*, Tuolumne suite, Coleman *et al.*, 2004; the Altiplano Puna Magmatic Body, De Silva and Gosnold, 2007). However, thermal modelling, geophysical and rheological constrains preclude longer times for large amounts of magma to remain melted within the crust (Lundstrom and Glazner, 2016). In this context more precise geochronology studies are needed to understand this enigma and ultimately the development of the continental crust.

Geochronological studies have shown that the age of the Real Cordillera granitic suite is not easy to determine. K-Ar age determinations are complicated due to thermal anomalies that reset this isotope system during tectonic events in the Oligocene (McBride *et al.*, 1987; Farrar *et al.*, 1988, 1990). Nevertheless this method defined a cooling age of the Real Cordillera granitoids at 211 Ma (Grant *et al.*, 1979; Evernden *et al.*, 1977; McBride *et al.*, 1983, 1987). Previous U-Pb zircon age dating have shown a long time interval for the crystallization age of this granitic belt (Gillis *et al.*, 2006). These authors found age

FIG.1. Main morphostructural units of the Central Andes region, modified from Cordani *et al.*, 2016. The rectangle shows the area included in figure 2.

ranges varying from 217 to 273 Ma indicating the necessity of better constraint on the emplacement age of the granitoids. Cordani *et al.* (2019) indicated the difficulty of obtaining reliable crystallization ages for the Huayna Potosí and Zongo plutons. Using new U-Pb zircon dates measured in the SHRIMP II laboratory of the University of São Paulo (USP), we set the following two objectives: a) to constrain the crystallization ages of the other granitic plutons of the Real Cordillera to put the crystallization age of this “inner magmatic arc” in a regional context within the Central Andes and b) to obtain additional robust geochronological data for the Huayna Potosí and Zongo plutons to understand better the evolution of their crystallization.

2. Regional framework and geological history

The Central Andes is an orogenic belt of 4,700 km length located at the middle part of the western border of the South American continent (Fig. 1). It is limited to the north and to the south by the Northern and Southern Andes respectively and differs from them by the lack of accreted Phanerozoic terrains or obducted oceanic crust (Ramos, 2009). It includes the Central Volcanic Zone (CVZ) that is the actual volcanic chain of Holocene to modern age.

To the west, older rocks correspond to the Arequipa-Antofalla basement located at the southern part of Perú and northern Chile. Following Loewy *et al.* (2004) it is divided in three domains: the northern domain, with Paleoproterozoic ages of about 2.0 Ga, the central domain represented by metavolcanic and migmatitic rocks of Mesoproterozoic age of 1.2 Ga and the southern domain with Phanerozoic granitoids that range in age from 467 to 434 Ma. At the eastern side of the Andean orogen another group of older rocks crops out and forms the western border of the Amazonian craton: the Rondonian-San Ignacio Province (1.56-1.3 Ga, Litherland *et al.*, 1989; Bettencourt *et al.*, 2010) that corresponds to a composite orogen of accreted oceanic and continental terrains.

Retro-arc pelites to metapelites associated with the Famatinian magmatic arc of late Neoproterozoic to middle and late Devonian age are represented in the study area as Ordovician, Silurian and Devonian formations (Ramos, 2018).

Magmatism went on from the early Paleozoic to practically nowadays, with intraplate and peraluminous magmatic compositions characterizing the Eastern Cordillera and “pure arc type”, calc-alkaline and

subduction related magmatism characterizing the Western Cordillera. This sharp difference is also compositional, with mostly “I-type” granitoids bearing Cu-Mo mineralization located to the west and mostly “S-type” granitoids bearing Sn-W mineralization located to the east (Burnham, 1979; Romer and Kroner, 2016). These contrasting geotectonic environments, mineralogy, chemical composition of magmas and ores, are the basis over which we follow the distinction made by Clark *et al.* (1990) in regard to differentiate the “Western Cordillera magmatic arc” from the “Eastern Cordillera inner magmatic arc”. For these authors, the petrochemical assemblages are essential for the distinction between these two domains. The Main Arc, located under the Cordillera de la Costa and the entire Western Cordillera, is considered ultimately of mantle origin with several proportions of assimilated middle and upper crust, meanwhile the Inner Arc, restricted to the Eastern Cordillera of SE Perú and NW Bolivia, has been mainly formed by extensive anatexis of early Paleozoic metapelites.

3. Geological descriptions for the granitic plutons of the Cordillera Real

The felsic plutons of the Real Cordillera comprise granites, granodiorites, monzogranites and tonalites with minor quartz-diorites, aplites and pegmatites. The Huato, Illampu, Yani, Huayna Potosí, Zongo and Taquesi plutons are Triassic, whereas Illimani, Quimsa Cruz and Santa Vera Cruz are Oligocene (Fig. 2). Some bear two micas (Huato, Illampu, Huayna Potosí and Zongo) and are metaluminous to peraluminous in composition (Ávila, 1990; Jiménez and López-Velásquez, 2008; Cordani *et al.*, 2019). They commonly bear 0.1-0.5 m rounded mafic enclaves of quartz-diorite. Aplites and pegmatites cut the granites and granodiorites. Near the contacts with the country rocks there are pegmatites 1-2 m thick, usually with greisen halos of Mo, Sn and W mineralization (Fabulosa and Chojlla mines). The country rocks consist of metapelites, hornfels, mica schists, sandstones and siltstones of the Silurian Catavi and Uncia and the Ordovician Amutara and Coroico formations. Hornfelses form the contact aureoles, although schists bearing mica, cordierite, sillimanite and garnet are present along the eastern edges of the Illampu, Yani and Zongo plutons (Bard *et al.*, 1974). Concise description of the sampled granitoids follow: sample locations are shown in figure 2.

FIG. 2. Distribution of the plutons included in this work along the Cordillera Real and location of the analyzed samples.

3.1. Huato granite

This pluton is located in the northern part of the Real Cordillera. It has an ellipsoidal shape with a dimension of 19x11 km. In the northern part of the pluton, towards its western border, the granite shows an equigranular texture of *ca.* 0.5 cm quartz, feldspar and biotite crystals. Muscovite appears in the assemblage towards the centre of the pluton. Feldspar shows alteration to sericite. The country rocks are hornfels and slates with millimetric veins of quartz and pyrite. A sample of the Huato granite (RIB-27) was taken in the north along the road from Charazani to Apolo.

3.2. Illampu batholith

The Illampu batholith is the largest of the Triassic granitoid bodies. It has an elongated shape with a length of 50 km and about 14 km width. Three units were distinguished: granodiorites and tonalites in the north, adamellites in the middle and granites to the south. Enclaves of quartz-diorites are common. Aplites and mineralized pegmatites are common towards the south. One sample of granodiorite (RIB-33) and one of quartz-diorite enclave (RIB-32) were taken from the northern unit. The granodiorite has quartz, feldspar, hornblende and biotite with clots of biotite and amphibole up to 5 cm long. The

quartz-diorite enclave is rounded and quite mafic (abundant biotite, amphibole and iron oxides) with some crystals of subhedral quartz and feldspar. A further sample, of a two-mica granite (RIB-15) was taken in the southern part of the batholith (Fig. 2). The sample is quite felsic, exhibiting large euhedral crystals of feldspar (2-4 cm long), smaller quartz and biotite crystals and a lesser amount of muscovite. Sometimes it is possible to recognize garnet (up to 0.5 cm) in these granites.

3.3. Huayna Potosí granite

The Huayna Potosí pluton has an irregular, almost rectangular, shape with dimensions of 16x5 km. The rock is fresh and is generally two-mica granite with quartz, feldspar, biotite and muscovite, with lesser amounts of sericite and sometimes tourmaline. Aplites cutting the granite are widespread. It is also common to find rounded mafic enclaves 1 to 10 cm long of quartz-diorite. Samples from the SW edge of this pluton are RIB-2, RIB-4, RIB-19 and RIB-22 (granites), and RIB-20 (granodiorite).

3.4. Zongo granite

The Zongo granite occurs to the northwest of the Huayna Potosí pluton. It also has an irregular shape and is cut by several systems of NW-striking faults. It is noticeably folded, showing oriented crystals 1 to 10 cm long of quartz, K-feldspar and two micas. In some outcrops the texture seems to vary gradually to coarsely pegmatitic. Towards the northern contact with the country rock, mica schists with porphyroblasts of cordierite up to 10 cm long define a metamorphic aureole. Two granitic facies were recognized in this pluton (McBride *et al.*, 1987): the foliated Kutiucucho located to the SW and the non-foliated and equigranular Sainani to the NE. Two samples from the foliated Kutiucucho facies were taken for this study, samples RIB-5 and RIB-30.

3.5. Taquesi granodiorite

The Taquesi granodiorite has a regular elliptical shape with dimensions of 15x9 km, with the longest axis following the NW trend of the cordillera. Granodiorites bearing quartz-diorite enclaves, along with tonalites, two-mica granites and aplites are characteristic of this pluton. Towards the SW

rim the granodiorites have an equigranular texture made of crystals 1 to 2 cm long of quartz, feldspar, biotite and iron oxides. At its SW border, the country rock is a Silurian hornfels. Samples RIB-11 and RIB-12 from a granodiorite and a quartz-diorite enclave, respectively, were taken from this pluton.

3.6. Quimsa Cruz batholith

The Quimsa Cruz is an ellipsoidal batholith in the south of the Real Cordillera. It has a dimension of 35x13 km. Along with the Illimani pluton and the Cohoni volcanic and pyroclastic formation it forms the southern Oligocene band of the Real Cordillera belt. The Geological Service of Bolivia recognized two facies in this batholith: porphyritic granites and granodiorites to the north and equigranular granodiorites to the south (Geobol, 1968). Fractures affect this granite, filled by centimetric to metric scale vein mineralization of W-Sn and Fe-S, with a general E-W strike. K-Ar dating distinguishes this rock from the Triassic granites, yielding ages of 25 to 23 Ma (Evernden *et al.*, 1977; McBride *et al.*, 1983; Gillis *et al.*, 2006). Two samples of fresh granite were taken: one to the west close to the Viloco mine (RIB-43) and other to the SE closer to the Pacuni mine (RIB-46).

4. Previous age dating

Early K-Ar geochronological studies on the age of the granitic magmatism of the Cordillera Real of Bolivia are summarized in table 1. Ages show wide ranges (e.g., 180-190 and 60-40 Ma), a characteristic observed also in the Carabaya granites (Kontak *et al.*, 1990). This led to several studies (Kontak *et al.*, 1990; McBride *et al.*, 1987; Sandeman *et al.*, 1995; Ramos, 2018) to define the Zongo-San Gabán regional thermal anomaly that opened the K-Ar isotopic system to Ar loss by heating associated with thrusting of the Andean orogeny.

McBride *et al.* (1987) defined systematic Ar loss in some profiles that cut the granites of the Zongo pluton. The apparent ages range from 210 to 39 Ma through a horizontal distance of 14 km and a vertical difference of almost 1.5 km. In the same study, a biotite yielded a well-defined Ar/Ar plateau of 39 Ma. They associated this descend in K-Ar ages with opening of the isotopic system (250-350 °K) due to regional Andean back-thrusting, with the biotite of 39 Ma recording this thermal event.

TABLE 1. K-Ar PUBLISHED AGES FOR PLUTONS OF THE REAL CORDILLERA.

Pluton	Age (Ma)	Mineral	Author
Huato	218-225	M	4
	254	H	4
Illampu	219-202	B	4
	180	B	1
	195	B	2
Huayna Potosí	211	B	3
	205-218	M	4
Zongo	150-162	MU	3
	199	B	3
Taqesi	195	B	2
	211	B	4
Mina Chojlla	195-203	MU	4
Illimani	27-28	B	4
	26	B	3
	26	B	3
Quimsa Cruz	24	B	2
	24-26	B	4
Santa Vera Cruz	23	B	2

Mineral abbreviations: M, micas, B, biotite, Mu, muscovite. **Authors:** 1. Evernden (1961) cited in Clark and Farrar (1973), 2. Cordani (1967) cited in Clark and Farrar (1973), 3. Evernden *et al.* (1977); 4. McBride *et al.*, 1983.

Farrar *et al.*, 1990 were the first in study the Zongo granite using the U-Pb method in zircon and also described the K-Ar age decrease of the micas of this pluton. The age obtained for the Zongo/Kuticucho granite was $222.2 \pm 7.7/-9.1$ and for the Zongo/Sainani granite was $225.1 \text{ Ma} \pm 4.1/-4.4$, both recording an important inherited zircon component of Proterozoic age. Following the work of McBride *et al.* (1987), Farrar *et al.* (1988) defined the “cryptic tectonothermal zone” between the Carabaya and Real cordilleras at 39 Ma, calling it as the “Zongo-San Gabán Zone” (ZSGZ).

Gillis *et al.* (2006) studied the effects of the thermal anomaly associated to the uplift of the cordillera using Ar/Ar modelling in micas as well as fission track ages in apatites. They found a good $^{49}\text{Ar}/^{30}\text{Ar}$ age with a well-defined plateau for the Huayna Potosí pluton that yielded an age of 218 ± 4 Ma. They also determined large intervals of U-Pb crystallization ages for the Triassic plutons (e.g., 249 to 218 Ma for the Huayna Potosí granite and 251 to 226 Ma for

the Illampu batholith) and an age for the Oligocene Quimsa Cruz pluton at 26 Ma.

More recently U-Pb zircon dating for the Huayna Potosí and Zongo granites (Cordani *et al.*, 2019) also yielded large ranges of zircon crystallization ages for the Huayna Potosí (240 to 220 Ma) along with anomalous U-rich zircons of the Zongo pluton, associating them with protracted pluton crystallization and a final event of U enrichment.

5. U-Pb SHRIMP zircon analyses

U-Pb dating was made in the Sensitive High Resolution Ion Microscope (SHRIMP IIe) of the Laboratory of the University of São Paulo, Brazil. Samples were crushed, milled and sieved. Then zircon crystals were concentrated from magnetic fractions using a Franz magnetic separator and then purified using bromoform and methylene iodide following standard laboratory steps. Then zircon mounts were prepared and cathode luminescence

imaging (CL) was obtained with a FEI Quanta 250 Scanning Electron Microscope (SEM) and XMAX CL detector (Oxford Instruments) to reveal inner structures. SHRIMP analyses were run on single zircon crystals. U abundance and U/Pb ratios were calibrated against Z6266 and TEMORA II (416.78 Ma) standards. Pooled ages are weighted mean $^{206}\text{Pb}/^{238}\text{U}$ dates. Common Pb was corrected using the measured abundance of ^{204}Pb . On tables 2A to 2O, errors on isotopic ratios are given as percentage and error on ages are reported as 1 sigma. The typical error component for the $^{206}\text{Pb}/^{238}\text{U}$ ratios was lower than 2%. Then isotopic ratios were reduced using the SQUID 2.5 software and Concordia diagrams were made using the software Isoplot 4 (Ludwig, 2009). Further technical and acquisition data processing are described in Williams (1998) and Sato *et al.* (2014).

5.1. U-Pb zircon ages

The location of the collected samples is displayed in figure 2. Analytical results are shown in tables 2A to 2O and U-Pb Concordia curves are shown in figures 4 to 20. For the calculation of Concordia ages, we selected U-Pb ages younger than 300 Ma and discordances of less than 10%. Discordant spots with large error were also excluded. Selected spots for individual Concordia age calculation are displayed on the figure captions (Figs. 6 to 16) and in bold on tables 2A to 2O. CL images of the representative analysed zircon crystals are shown in figure 3. A summary of Concordia ages, MSWD values and associated errors at 1 and 2 sigma and 95% confidence is presented in table 3.

The Huayna Potosí samples (RIB-2 and RIB-4), belonging to the same pluton, and studied previously

FIG. 3. Cathodoluminescence images of zircons from the analyzed samples with spot sites and $^{238}\text{U}/^{204}\text{Pb}$ ages.

TABLE 2. U/Pb ZIRCON SHRIMP ANALYSES.

TABLE 2A. RIB-27 HUATO GRANITE.

Spot	Site	Ch/h	U (ppm)	Th (ppm)	Th/U	% ²⁰⁶ Pb _c	²⁰⁶ Pb/ ²³⁸ U age (Ma)	±1σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma)	±1σ (Ma)	% Disc	²³⁸ U/ ²⁰⁶ Pb ⁺	±%	²⁰⁷ Pb ⁺ / ²⁰⁶ Pb ⁺	±%	²⁰⁷ Pb ⁺ / ²³⁵ U	±%	²⁰⁶ Pb ⁺ / ²³⁸ U	±%	Err corr
RIB27-9.1	rim	osc, p	1,470	70	0.05	0.16	247	3	238	21	-4	25.6	1.2	0.05094	0.9	0.274	1.5	0.0391	1.2	0.8
RIB27-8.1	rim	osc, p	1,087	65	0.06	0.25	238	3	230	57	-4	26.6	1.3	0.05075	2.5	0.263	2.8	0.0375	1.3	0.5
RIB27-3.1	rim	osc, p	1,527	34	0.02	0.10	248	3	242	17	-3	25.5	1.2	0.05102	0.7	0.276	1.4	0.0392	1.2	0.9
RIB27-1.1	rim	osc, p	2,003	936	0.47	4.40	254	4	249	135	-2	24.8	1.4	0.05118	5.9	0.284	6.0	0.0403	1.4	0.2
RIB27-10.1	core	hb, p	477	282	0.59	0.28	610	7	609	24	-0	10.1	1.2	0.06016	1.1	0.823	1.6	0.0993	1.2	0.8
RIB27-7.1	rim	osc, p	1,569	96	0.06	0.07	241	3	241	16	-0	26.3	1.2	0.05100	0.7	0.268	1.4	0.0381	1.2	0.9
RIB27-13.1	core	hb, ov	235	22	0.09	0.19	790	9	793	23	+0	7.7	1.2	0.0656	1.1	1.18	1.6	0.130	1.2	0.7
RIB27-6.1	rim	osc, p	1,124	189	0.17	0.17	241	3	242	24	+1	26.3	1.4	0.05103	1.0	0.268	1.7	0.0381	1.4	0.8
RIB27-14.1	core	sz, p	461	159	0.35	0.96	235	2	239	99	+2	26.9	0.9	0.0510	4.3	0.26	4.4	0.037	0.9	0.2
RIB27-5.1	rim	osc, p	1,579	95	0.06	0.33	244	3	250	28	+2	25.9	1.2	0.05119	1.2	0.273	1.7	0.0386	1.2	0.7
RIB27-12.1	core	osc, p	521	52	0.10	1.17	213	4	218	129	+2	29.8	1.8	0.05049	5.6	0.234	5.8	0.0336	1.8	0.3
RIB27-2.1	rim	osz, p	764	94	0.12	0.48	234	3	242	56	+3	27.0	1.4	0.05103	2.4	0.260	2.8	0.0370	1.4	0.5
RIB27-11.1	core	hb, p	271	92	0.34	0.75	218	3	226	109	+4	29.1	1.3	0.05067	4.7	0.240	4.9	0.0344	1.3	0.3
RIB27-15.1	core	hb, ov	135	18	0.13	3.38	299	5	314	427	+5	21.0	1.7	0.0527	18.8	0.35	18.8	0.048	1.7	0.1
RIB27-4.1	rim	osc, p	535	106	0.20	0.39	231	3	246	55	+6	27.4	1.3	0.05111	2.4	0.257	2.7	0.0365	1.3	0.5

TABLE 2B. RIB-32 ILLAMPU QUARTZDIORITE ENCLAVE.

Spot	Site	Ch/h	U (ppm)	Th (ppm)	Th/U	% ²⁰⁶ Pb _c	²⁰⁶ Pb/ ²³⁸ U age (Ma)	±1σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma)	±1σ (Ma)	% Disc	²³⁸ U/ ²⁰⁶ Pb ⁺	±%	²⁰⁷ Pb ⁺ / ²⁰⁶ Pb ⁺	±%	²⁰⁷ Pb ⁺ / ²³⁵ U	±%	²⁰⁶ Pb ⁺ / ²³⁸ U	±%	Err corr
RIB32-2.1	rim	osc, p	661	281	0.43	0.38	245	2	217	53	-13	25.8	1.0	0.0505	2.3	0.27	2.5	0.039	1.0	0.4
RIB32-9.1	rim	osc, p	762	263	0.34	0.33	235	2	215	49	-9	27.0	0.9	0.0504	2.1	0.26	2.3	0.037	0.9	0.4
RIB32-11.1	core	sz, p	685	482	0.70	0.47	232	2	214	43	-9	27.2	0.9	0.0504	1.9	0.26	2.1	0.037	0.9	0.4
RIB32-6.1	rim	osc, fr	544	165	0.30	0.39	236	2	222	50	-6	26.8	1.0	0.0506	2.1	0.26	2.4	0.037	1.0	0.4
RIB32-4.1	rim	osc, p	539	181	0.34	0.52	234	3	221	73	-6	27.1	1.2	0.0506	3.2	0.26	3.4	0.037	1.2	0.3
RIB32-1.1	rim	osc, p	585	165	0.28	0.35	245	2	237	57	-4	25.8	1.0	0.0509	2.5	0.27	2.7	0.039	1.0	0.4
RIB32-3.1	rim	osc, p	485	186	0.38	0.58	234	2	227	98	-3	27.1	1.0	0.0507	4.3	0.26	4.4	0.037	1.0	0.2
RIB32-12.1	rim	osc, p	799	627	0.78	0.88	235	2	231	110	-2	26.9	0.9	0.0508	4.7	0.26	4.8	0.037	0.9	0.2
RIB32-13.1	core	hb, ov	430	218	0.51	3.19	232	3	229	259	-1	27.3	1.1	0.0507	11.2	0.26	11.3	0.037	1.1	0.1
RIB32-14.1	core	hb, rd	618	356	0.58	0.52	234	2	231	59	-1	27.1	0.9	0.0508	2.6	0.26	2.7	0.037	0.9	0.3
RIB32-8.1	rim	osc, p	702	324	0.46	0.51	234	3	235	60	+0	27.0	1.1	0.0509	2.6	0.26	2.8	0.037	1.1	0.4
RIB32-15.1	core	hb, p	634	521	0.82	0.91	232	2	238	71	+3	27.3	1.0	0.0509	3.1	0.26	3.2	0.037	1.0	0.3
RIB32-7.1	rim	osc, p	599	186	0.31	0.53	236	2	244	71	+3	26.8	0.9	0.0511	3.1	0.26	3.2	0.037	0.9	0.3
RIB32-5.1	rim	osc, p	381	154	0.41	1.29	234	2	243	137	+4	27.1	0.9	0.0511	5.9	0.26	6.0	0.037	0.9	0.2
RIB32-16.1	core	hb, ov	604	295	0.49	0.53	235	2	249	69	+6	26.9	0.9	0.0512	3.0	0.26	3.1	0.037	0.9	0.3
RIB32-10.1	rim	osc, p	635	186	0.29	0.41	241	2	258	44	+7	26.2	0.9	0.0514	1.9	0.27	2.1	0.038	0.9	0.4

TABLE 2C. RIB-33 ILLAMPU GRANODIORITE.

Spot	Site	Ch/h	U (ppm)	Th (ppm)	Th/U	% ²⁰⁶ Pb _c	²⁰⁶ Pb/ ²³⁸ U age (Ma)	±1σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma)	±1σ (Ma)	% Disc	²³⁸ U/ ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²³⁵ U	±%	²⁰⁶ Pb* / ²³⁸ U	±%	Err corr
RIB33-1.1	core	osz, p	785	274	0.35	0.11	232	2	221	25	-5	27.3	0.85	0.05056	1.1	0.256	1.4	0.0367	0.85	0.6
RIB33-7.1	rim	sz, p	481	217	0.45	1.62	231	2	223	103	-4	27.4	0.93	0.05062	4.5	0.255	4.6	0.0365	0.93	0.2
RIB33-2.1	rim	osc, p	616	179	0.29	0.19	230	2	222	32	-3	27.6	0.98	0.05059	1.4	0.253	1.7	0.0363	0.98	0.6
RIB33-4.1	rim	osc, p	610	216	0.35	0.26	229	2	224	57	-3	27.6	0.80	0.05063	2.5	0.253	2.6	0.0362	0.80	0.3
RIB33-11.1	rim	osc, p	644	195	0.30	0.30	230	2	227	40	-1	27.5	0.94	0.05070	1.7	0.254	2.0	0.0364	0.94	0.5
RIB33-5.1	rim	osc, p	446	170	0.38	0.22	227	3	225	40	-1	27.9	1.13	0.05066	1.7	0.250	2.1	0.0358	1.13	0.5
RIB33-6.1	rim	osc, p	672	221	0.33	0.25	232	2	236	36	+1	27.2	0.97	0.05089	1.5	0.258	1.8	0.0367	0.97	0.5
RIB33-10.1	rim	osc, p	584	205	0.35	0.35	228	2	232	65	+2	27.7	0.81	0.05081	2.8	0.253	2.9	0.0360	0.81	0.3
RIB33-8.1	rim	osc, p	712	276	0.39	0.20	233	2	238	30	+2	27.2	0.86	0.05094	1.3	0.259	1.6	0.0368	0.86	0.6
RIB33-9.1	core	hb, p	376	275	0.73	0.63	231	2	255	87	+10	27.4	0.96	0.05131	3.8	0.258	3.9	0.0365	0.96	0.2
RIB33-3.1	rim	osc, p	588	175	0.30	0.19	233	2	257	34	+10	27.2	0.88	0.05135	1.5	0.260	1.7	0.0367	0.88	0.5
RIB33-10.2	core	hb, p	383	106	0.28	1.01	214	2	244	92	+12	29.6	1.07	0.05107	4.0	0.238	4.1	0.0337	1.07	0.3

TABLE 2D. RIB-15 ILLAMPU GRANITE.

Spot	Site	Ch/h	U (ppm)	Th (ppm)	Th/U	% ²⁰⁶ Pb _c	²⁰⁶ Pb/ ²³⁸ U age (Ma)	±1σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma)	±1σ (Ma)	% Disc	²³⁸ U/ ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²³⁵ U	±%	²⁰⁶ Pb* / ²³⁸ U	±%	Err corr
RIB15-12.1	core	sz, p	644	669	1.04	0.60	222	3	235	78	+5	28.5	1.2	0.0509	3.4	0.25	3.6	0.035	1.2	0.3
RIB15-10.1	core	hb, p	196	53	0.27	1.83	223	3	223	286	-0	28.4	1.5	0.0506	12.4	0.25	12.4	0.035	1.5	0.1
RIB15-6.1	core	hb, fr	1,114	819	0.73	0.55	225	2	226	56	+0	28.2	1.0	0.0507	2.4	0.25	2.6	0.036	1.0	0.4
RIB15-11.2	rim	osc, p	5,014	20	0.00	0.32	225	3	235	32	+4	28.1	1.2	0.0509	1.4	0.25	1.8	0.036	1.2	0.6
RIB15-4.1	core	sz, p	573	285	0.50	1.08	227	2	237	128	+4	27.9	1.1	0.0509	5.5	0.25	5.7	0.036	1.1	0.2
RIB15-9.2	rim	hd, p	2,244	38	0.02	5.08	230	4	231	338	+0	27.6	1.9	0.0508	14.6	0.25	14.8	0.036	1.9	0.1
RIB15-1.1	core	osc, p	699	58	0.08	1.90	230	3	233	179	+1	27.5	1.1	0.0508	7.8	0.25	7.8	0.036	1.1	0.1
RIB15-7.2	rim	sz, p	1,962	43	0.02	0.40	231	2	237	36	+3	27.5	1.0	0.0509	1.6	0.26	1.9	0.036	1.0	0.5
RIB15-3.1	core	sz, p	935	313	0.33	0.57	238	3	245	78	+3	26.6	1.2	0.0511	3.4	0.26	3.6	0.038	1.2	0.3
RIB15-2.1	rim	osc, p	2,596	1062	0.41	0.23	240	2	238	23	-1	26.3	1.0	0.0509	1.0	0.27	1.4	0.038	1.0	0.7
RIB15-8.2	rim	osc, p	2,282	462	0.20	0.20	241	3	236	28	-2	26.3	1.1	0.0509	1.2	0.27	1.6	0.038	1.1	0.7
RIB15-5.1	rim	osc, p	2,633	85	0.03	0.08	242	3	230	18	-5	26.2	1.1	0.0508	0.8	0.27	1.3	0.038	1.1	0.8
RIB15-14.2	core	hb, rd	1,929	25	0.01	0.29	242	5	229	39	-6	26.1	1.9	0.0507	1.7	0.27	2.6	0.038	1.9	0.7
RIB15-7.1	core	hb, p	317	159	0.50	0.78	469	5	471	61	+1	13.3	1.1	0.0565	2.8	0.59	3.0	0.075	1.1	0.4
RIB15-13.1	core	hb, p	395	553	1.40	0.40	579	6	583	34	+1	10.6	1.1	0.0594	1.6	0.77	1.9	0.094	1.1	0.6
RIB15-11.1	core	hb, rd	76	40	0.52	1.97	610	8	645	185	+6	10.1	1.4	0.0612	8.6	0.84	8.7	0.099	1.4	0.2
RIB15-9.1	core	osc, p	247	113	0.46	0.24	1091	11	1073	24	-2	5.4	1.1	0.0752	1.2	1.91	1.7	0.184	1.1	0.7
RIB15-8.1	core	hb, ov	159	46	0.29	5.29	1217	13	1937	20	+41	4.8	1.2	0.1187	1.1	3.40	1.6	0.208	1.2	0.7
RIB15-14.1	rim	osc, p	164	99	0.61	1.17	2046	21	2132	17	+5	2.7	1.2	0.1326	0.9	6.83	1.5	0.374	1.2	0.8

TABLE 2E. RIB-2 HUAYNA POTOSÍ GRANITE.

Spot	Site	Ch/h	U (ppm)	Th (ppm)	Th/U	% ²⁰⁶ Pb _c	²⁰⁶ Pb/ ²³⁸ U age (Ma)	±1σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma)	±1σ (Ma)	% Disc	²³⁸ U/ ²⁰⁶ Pb ⁺	±%	²⁰⁷ Pb ⁺ / ²⁰⁶ Pb ⁺	±%	²⁰⁷ Pb ⁺ / ²³⁵ U	±%	²⁰⁶ Pb ⁺ / ²³⁸ U	±%	Err corr
RIB2-9.1	core	osc, p	1,334	88	0.07	--	239	2	211	18	-14	26.5	1.0	0.0503	0.8	0.262	1.2	0.0378	1.0	0.8
RIB2-5.1	core	hb, p	72	28	0.39	1.70	220	5	216	298	-2	28.8	2.4	0.0505	12.9	0.241	13.1	0.0347	2.4	0.2
RIB2-8.1	core	osc, p	237	108	0.46	0.63	217	2	222	128	+3	29.3	1.1	0.0506	5.5	0.238	5.6	0.0342	1.1	0.2
RIB2-6.1	core	osc, p	314	58	0.18	0.53	221	3	224	94	+1	28.7	1.2	0.0506	4.0	0.243	4.2	0.0348	1.2	0.3
RIB-2-22.1	core	osc, p	507	64	0.13	0.26	236	3	229	46	-3	26.8	1.4	0.0507	2.0	0.261	2.4	0.037	1.4	0.6
RIB2-3.1	core	osc, p	1,713	128	0.07	--	246	3	235	15	-5	25.7	1.0	0.0509	0.6	0.273	1.2	0.0389	1.0	0.9
RIB-2-13.1	rim	osc, p	576	460	0.80	0.08	227	3	236	29	+4	28.0	1.4	0.0509	1.2	0.251	1.9	0.036	1.4	0.8
RIB-2-15.1	rim	hd, p	1,006	359	0.36	--	244	4	238	20	-2	25.9	1.7	0.0509	0.9	0.271	1.9	0.039	1.7	0.9
RIB-2-17.1	rim	hb, p	391	63	0.16	0.35	248	4	242	58	-3	25.5	1.7	0.0510	2.5	0.276	3.0	0.039	1.7	0.6
RIB-2-21.1	core	osc, p	777	76	0.10	--	247	3	242	21	-2	25.6	1.4	0.0510	0.9	0.275	1.7	0.039	1.4	0.8
RIB2-2.1	rim	osc, p	999	80	0.08	--	253	2	244	18	-4	25.0	1.0	0.0511	0.8	0.282	1.3	0.0400	1.0	0.8
RIB-2-24.1	rim	osc, fr	1,950	77	0.04	0.03	257	4	248	14	-4	24.6	1.4	0.0512	0.6	0.287	1.5	0.041	1.4	0.9
RIB2-10.1	core	osc, p	388	104	0.27	0.36	222	3	251	49	+12	28.5	1.3	0.0512	2.1	0.248	2.5	0.0351	1.3	0.5
RIB2-11.1	core	osc, p	138	76	0.55	3.19	247	3	256	339	+3	25.6	1.3	0.0513	14.7	0.277	14.8	0.0391	1.3	0.1
RIB2-4.1	core	osc, p	518	170	0.33	0.84	230	3	259	67	+11	27.5	1.3	0.0514	2.9	0.258	3.2	0.0363	1.3	0.4
RIB-2-16.1	core	hb, p	931	147	0.16	0.25	312	6	300	46	-4	20.2	1.8	0.0523	2.0	0.358	2.7	0.050	1.8	0.7
RIB2-1.1	core	hb, p	76	36	0.48	1.59	234	4	340	196	+32	27.0	1.9	0.0533	8.7	0.272	8.9	0.0370	1.9	0.2
RIB2-12.1	core	osc, p	373	213	0.57	0.60	219	2	450	34	+52	28.9	1.0	0.0559	1.6	0.267	1.9	0.0346	1.0	0.5
RIB-2-18.1	rim	osc, p	28,696	349	0.01	--	577	13	474	24	-23	10.7	2.3	0.0565	1.1	0.730	2.5	0.094	2.3	0.9
RIB-2-19.1	rim	osc, p	1,282	41	0.03	0.14	573	8	573	14	-0	10.8	1.4	0.0592	0.6	0.759	1.5	0.093	1.4	0.9
RIB-2-14.1	core	hb, ov	175	78	0.44	0.63	509	7	599	44	+16	12.2	1.5	0.0599	2.0	0.678	2.5	0.082	1.5	0.6
RIB2-7.1	core	hb, p	437	279	0.64	0.00	602	6	606	15	+1	10.2	1.0	0.0601	0.7	0.810	1.2	0.0978	1.0	0.8
RIB-2-23.1	core	hb, p	636	39	0.06	0.48	801	13	881	12	+10	7.6	1.7	0.0684	0.6	1.248	1.8	0.132	1.7	0.9
RIB-2-20.1	core	hb, ov	456	73	0.16	1.64	1186	22	1472	8	+21	5.0	2.1	0.0922	0.4	2.568	2.1	0.202	2.1	1.0

TABLE 2F. RIB-4 HUAYNA POTOSÍ GRANITE.

Spot	Site	Ch/h	U (ppm)	Th (ppm)	Th/U	% ²⁰⁶ Pb _c	²⁰⁶ Pb/ ²³⁸ U age (Ma)	±1σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma)	±1σ (Ma)	% Disc	²³⁸ U/ ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²³⁵ U	±%	²⁰⁶ Pb* / ²³⁸ U	±%	Err corr
RIB4-10.1	core	osc, p	319	52	0.16	0.39	215	3	226	57	+5	29.5	1.2	0.0507	2.5	0.237	2.8	0.0339	1.2	0.4
RIB-4-26.1	core	hd, p	615	17	0.03	0.21	215	3	210	39	-3	29.4	1.6	0.0503	1.7	0.236	2.3	0.0340	1.6	0.7
RIB4-8.1	core	hd, p	393	11	0.03	0.34	217	2	208	52	-5	29.2	1.0	0.0503	2.3	0.238	2.5	0.0343	1.0	0.4
RIB4-11.1	core	osc, p	383	52	0.14	0.20	219	2	264	49	+17	28.9	1.0	0.0515	2.1	0.245	2.4	0.0345	1.0	0.4
RIB4-9.1	rim	hb, p	729	162	0.22	0.25	221	2	217	40	-2	28.7	1.0	0.0505	1.7	0.242	2.0	0.0348	1.0	0.5
RIB4-1.1	core	hd, p	783	31	0.04	0.28	223	2	216	42	-3	28.4	1.0	0.0505	1.8	0.245	2.1	0.0353	1.0	0.5
RIB4-2.1	core	osc, p	457	66	0.14	0.18	228	2	224	68	-2	27.8	1.0	0.0506	2.9	0.251	3.1	0.0360	1.0	0.3
RIB-4-11.2	core	osc, p	1,247	49	0.04	0.19	228	3	256	37	+11	27.7	1.5	0.0513	1.6	0.255	2.2	0.0361	1.5	0.7
RIB4-3.1	core	hb, p	394	116	0.30	0.23	229	2	223	45	-3	27.6	1.0	0.0506	2.0	0.253	2.2	0.0362	1.0	0.5
RIB-4-14.1	core	osc, p	514	199	0.39	0.13	238	4	235	33	-1	26.6	1.6	0.0509	1.4	0.264	2.2	0.0376	1.6	0.8
RIB-4-17.1	core	osc, p	1,500	96	0.06	0.08	238	3	243	26	+2	26.6	1.4	0.0510	1.1	0.265	1.8	0.0377	1.4	0.8
RIB-4-12.1	core	osc, p	181	71	0.39	1.01	240	4	290	108	+17	26.3	1.6	0.0521	4.7	0.273	5.0	0.0380	1.6	0.3
RIB-4-22.1	core	osc, p	838	144	0.17	0.50	245	3	250	49	+2	25.8	1.4	0.0512	2.1	0.274	2.5	0.0388	1.4	0.6
RIB-4-16.1	core	oscz, fr	224	60	0.27	1.21	247	4	240	126	-3	25.6	1.5	0.0510	5.5	0.275	5.7	0.0391	1.5	0.3
RIB-4-25.1	core	osc, p	1,233	103	0.08	0.39	251	3	241	48	-4	25.2	1.4	0.0510	2.1	0.279	2.5	0.0397	1.4	0.6
RIB-4-18.1	rim	osc, p	952	95	0.10	0.56	263	4	257	79	-2	24.0	1.4	0.0514	3.4	0.295	3.7	0.0417	1.4	0.4
RIB-4-13.1	core	hb, p	426	130	0.30	0.32	265	4	264	54	-1	23.8	1.4	0.0515	2.4	0.298	2.8	0.0420	1.4	0.5
RIB-4-20.1	core	hb, ov	194	26	0.13	1.19	275	4	386	121	+30	23.0	1.6	0.0544	5.4	0.326	5.6	0.0435	1.6	0.3
RIB-4-11.1	core	osc, p	530	46	0.09	0.40	287	4	361	31	+21	21.9	1.4	0.0538	1.4	0.338	2.0	0.0456	1.4	0.7
RIB4-5.1	core	hb, ov	500	20	0.04	0.62	385	9	458	33	+16	16.2	2.5	0.0561	1.5	0.477	2.9	0.0616	2.5	0.9
RIB-4-21.1	core	hb, ov	279	134	0.48	0.55	468	7	579	30	+20	13.3	1.5	0.0593	1.4	0.616	2.0	0.0754	1.5	0.7
RIB-4-23.1	core	osc, p	253	100	0.40	0.53	1364	18	1439	10	+6	4.2	1.5	0.0907	0.5	2.945	1.6	0.2356	1.5	0.9
RIB-4-24.1	core	hb, ov	393	268	0.68	2.19	1655	21	1934	6	+16	3.4	1.4	0.1185	0.3	4.784	1.5	0.2927	1.4	1.0
RIB-4-19.1	core	hb, ov	68	22	0.33	0.49	2026	29	2058	13	+2	2.7	1.7	0.1271	0.8	6.470	1.8	0.3692	1.7	0.9
RIB4-4.1	core	osc, p	313	170	0.54	6.21	2070	18	2600	4	+24	2.6	1.0	0.1744	0.3	9.105	1.1	0.3787	1.0	1.0

TABLE 2G. RIB-19 HUAYNA POTOSÍ GRANITE.

Spot	Site	Ch/h	U (ppm)	Th (ppm)	Th/U	% ²⁰⁶ Pb _c	²⁰⁶ Pb/ ²³⁸ U age (Ma)	±1σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma)	±1σ (Ma)	% Disc	²³⁸ U/ ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²³⁵ U	±%	²⁰⁶ Pb* / ²³⁸ U	±%	Err corr
RIB19-6.1	core	hb, p	336	61	0.18	0.55	213	2	232	67	+8	29.78	0.84	0.05080	2.9	0.2352	3.0	0.03358	0.84	0.28
RIB19-2.2	core	hb, p	143	67	0.47	1.98	214	2	232	253	+8	29.67	1.06	0.05080	11.0	0.2361	11.0	0.03370	1.06	0.10
RIB19-3.1	rim	osc, p	265	94	0.36	0.62	215	2	214	148	-0	29.52	1.12	0.05042	6.4	0.2355	6.5	0.03387	1.12	0.17
RIB19-7.1	core	osc, p	310	56	0.18	0.55	221	2	230	65	+4	28.62	0.84	0.05075	2.8	0.2445	2.9	0.03494	0.84	0.29
RIB19-10.2	core	hb, p	331	36	0.11	0.19	222	2	219	48	-2	28.48	0.99	0.05052	2.1	0.2446	2.3	0.03511	0.99	0.43
RIB19-5.1	core	hb, p	505	47	0.09	0.35	223	2	238	44	+6	28.35	0.99	0.05094	1.9	0.2478	2.1	0.03528	0.99	0.46
RIB19-16.1	core	osc, p	532	47	0.09	1.47	224	3	251	113	+11	28.32	1.22	0.05121	4.9	0.2494	5.1	0.03531	1.22	0.24
RIB19-2.1	rim	osc, p	407	57	0.14	0.52	224	2	221	52	-1	28.27	0.84	0.05057	2.3	0.2466	2.4	0.03537	0.84	0.35
RIB19-14.1	core	hb, p	235	123	0.52	0.74	224	2	221	116	-2	28.24	1.01	0.05055	5.0	0.2468	5.1	0.03541	1.01	0.20
RIB19-9.1	core	hb, ov	372	92	0.25	0.51	224	2	235	111	+5	28.22	0.83	0.05088	4.8	0.2486	4.9	0.03544	0.83	0.17
RIB19-11.1	core	osc, p	466	265	0.57	0.38	225	2	226	45	+1	28.16	0.81	0.05068	1.9	0.2482	2.1	0.03552	0.81	0.39
RIB19-4.1	core	hd, p	757	114	0.15	0.19	225	5	224	28	-1	28.12	2.04	0.05063	1.2	0.2482	2.4	0.03556	2.04	0.86
RIB19-18.1	rim	osc, p	452	117	0.26	0.38	226	2	215	63	-5	28.04	0.95	0.05042	2.7	0.2479	2.9	0.03566	0.95	0.33
RIB19-17.1	core	osc, p	229	45	0.20	5.26	226	3	225	368	-0	28.03	1.34	0.05066	15.9	0.2492	16.0	0.03567	1.34	0.08
RIB19-1.1	rim	osc, p	396	46	0.12	0.29	229	2	235	42	+3	27.69	0.83	0.05087	1.8	0.2533	2.0	0.03612	0.83	0.41
RIB19-12.1	core	osc, fr	709	85	0.12	0.17	229	2	231	29	+1	27.67	0.79	0.05079	1.3	0.2531	1.5	0.03615	0.79	0.53
RIB19-8.1	core	hb, p	540	229	0.42	0.53	232	2	227	53	-2	27.34	0.93	0.05070	2.3	0.2557	2.5	0.03657	0.93	0.38
RIB19-13.1	core	hb, p	247	91	0.37	0.82	232	2	227	104	-2	27.27	0.87	0.05069	4.5	0.2563	4.6	0.03667	0.87	0.19
RIB19-15.1	rim	osc, p	899	244	0.27	0.14	235	2	224	23	-5	26.98	0.79	0.05064	1.0	0.2588	1.3	0.03707	0.79	0.62
RIB19-10.1	core	hb, p	225	133	0.59	0.36	599	5	633	32	+6	10.26	0.89	0.06083	1.5	0.8173	1.7	0.09744	0.89	0.51

TABLE 2H. RIB-20 HUAYNA POTOSÍ GRANITE.

Spot	Site	Ch/h	U (ppm)	Th (ppm)	Th/U	% ²⁰⁶ Pb _c	²⁰⁶ Pb/ ²³⁸ U age (Ma)	±1σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma)	±1σ (Ma)	% Disc	²³⁸ U/ ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²³⁵ U	±%	²⁰⁶ Pb* / ²³⁸ U	±%	Err corr
RIB20-6.1	rim	osc, p	0.73	415	68	0.16	227	3	219	88	-4	27.9	1.4	0.05051	3.8	0.249	4.0	0.0358	1.4	0.3
RIB20-7.1	rim	osc, p	0.10	920	636	0.69	237	3	229	37	-3	26.7	1.3	0.05075	1.6	0.262	2.1	0.0374	1.3	0.6
RIB20-8.1	rim	osc, p	1.15	294	55	0.19	220	3	216	138	-2	28.8	1.3	0.05045	5.9	0.242	6.1	0.0347	1.3	0.2
RIB20-6.2	core	hd, p	10.35	1,574	163	0.10	254	5	251	335	-1	24.9	1.8	0.05122	14.6	0.284	14.7	0.0402	1.8	0.1
RIB20-5.1	rim	hd, p	0.64	747	304	0.41	230	3	231	66	+0	27.5	1.4	0.05077	2.9	0.255	3.2	0.0364	1.4	0.4
RIB20-2.1	core	osc, p	0.26	937	62	0.07	233	3	235	52	+1	27.1	1.2	0.05088	2.3	0.258	2.6	0.0368	1.2	0.5
RIB20-4.1	rim	osc, p	0.63	578	54	0.09	237	3	239	83	+1	26.7	1.2	0.05097	3.6	0.263	3.8	0.0374	1.2	0.3
RIB20-10.1	rim	osc, p	0.39	673	110	0.16	224	3	228	43	+2	28.3	1.4	0.05073	1.9	0.247	2.3	0.0354	1.4	0.6
RIB20-14.1	core	hb, ov	0.62	504	56	0.11	236	2	241	66	+2	26.8	1.1	0.0510	2.9	0.26	3.0	0.037	1.1	0.4
RIB20-11.1	core	hb, p	1.29	545	52	0.10	245	2	252	138	+3	25.8	1.0	0.0512	6.0	0.27	6.1	0.039	1.0	0.2
RIB20-3.1	rim	osc, p	0.36	475	99	0.21	230	3	238	50	+3	27.5	1.5	0.05094	2.2	0.255	2.6	0.0363	1.5	0.6
RIB20-1.1	rim	osc, fr	0.69	600	62	0.10	230	3	244	73	+6	27.5	1.5	0.05108	3.2	0.256	3.5	0.0364	1.5	0.4
RIB20-10.2	core	hb, p	0.69	559	149	0.27	229	3	264	76	+13	27.6	1.3	0.05151	3.3	0.257	3.5	0.0362	1.3	0.4
RIB20-9.1	rim	osc, p	0.53	580	57	0.10	228	3	267	78	+15	27.8	1.2	0.05159	3.4	0.256	3.6	0.0360	1.2	0.3
RIB20-1.2	rim	osc, fr	0.83	258	30	0.12	210	3	260	96	+19	30.2	1.7	0.05142	4.2	0.235	4.5	0.0332	1.7	0.4
RIB20-12.1	core	hb, p	1.08	298	72	0.24	221	3	327	124	+33	28.7	1.2	0.0529	5.5	0.25	5.6	0.035	1.2	0.2
RIB20-13.1	core	osc, p	0.28	121	32	0.27	1413	18	2023	13	+34	4.1	1.4	0.1246	0.8	4.21	1.6	0.245	1.4	0.9
RIB20-9.2	rim	hb, p	0.85	533	109	0.20	454	8	1600	29	+74	13.7	1.9	0.09869	1.6	0.993	2.4	0.0730	1.9	0.8

TABLE 21. RIB-22 HUAYNA POTOSÍ GRANITE.

Spot	Site	Ch/h	U (ppm)	Th (ppm)	Th/U	% ²⁰⁶ Pb _c	²⁰⁶ Pb/ ²³⁸ U age (Ma)	±1σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma)	±1σ (Ma)	% Disc	²³⁸ U/ ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²³⁵ U	±%	²⁰⁶ Pb* / ²³⁸ U	±%	Err corr
RIB22-2.2	rim	osc, fr	2,461	40	0.02	0.10	275	3	243	18	-13	22.92	0.93	0.05105	0.8	0.3071	1.2	0.04362	0.93	0.76
RIB22-15.1	rim	osc, p	985	100	0.10	0.24	242	2	230	36	-5	26.15	0.79	0.05076	1.6	0.2676	1.8	0.03824	0.79	0.45
RIB22-18.1	core	hb, ov	518	87	0.17	0.23	222	2	217	57	-2	28.56	0.82	0.05047	2.5	0.2437	2.6	0.03502	0.82	0.32
RIB22-4.1	core	hb, p	682	43	0.06	0.13	230	2	225	27	-2	27.54	0.91	0.05065	1.2	0.2536	1.5	0.03631	0.91	0.62
RIB22-7.1	rim	osc, p	868	132	0.15	0.16	232	2	228	24	-2	27.33	0.84	0.05071	1.0	0.2558	1.3	0.03659	0.84	0.64
RIB22-8.1	core	osc, p	307	53	0.17	0.40	222	2	221	80	-1	28.50	0.85	0.05056	3.5	0.2446	3.6	0.03509	0.85	0.24
RIB22-1.1	rim	osc, p	820	67	0.08	0.16	232	2	230	26	-1	27.29	0.79	0.05077	1.1	0.2565	1.4	0.03664	0.79	0.58
RIB22-3.1	core	hb, p	372	137	0.37	0.48	224	2	225	52	+0	28.25	0.97	0.05064	2.2	0.2472	2.4	0.03540	0.97	0.40
RIB22-6.1	core	osc, p	310	102	0.33	0.47	225	2	226	58	+0	28.14	0.95	0.05067	2.5	0.2483	2.7	0.03553	0.95	0.36
RIB22-9.1	core	osc, p	587	67	0.11	0.38	235	2	237	43	+1	26.97	0.82	0.05091	1.9	0.2603	2.0	0.03708	0.82	0.40
RIB22-14.1	core	hb, p	434	43	0.10	0.33	227	2	231	47	+2	27.90	0.82	0.05079	2.1	0.2510	2.2	0.03584	0.82	0.37
RIB22-12.1	core	hb, p	271	46	0.17	0.58	228	2	236	105	+4	27.82	1.01	0.05090	4.5	0.2523	4.6	0.03595	1.01	0.22
RIB22-10.1	core	hb, p	688	293	0.43	0.22	227	2	236	52	+4	27.94	0.80	0.05090	2.2	0.2512	2.4	0.03579	0.80	0.34
RIB22-11.1	rim	osc, p	748	208	0.28	0.26	229	3	240	33	+5	27.65	1.12	0.05099	1.4	0.2543	1.8	0.03616	1.12	0.62
RIB22-5.1	rim	osc, p	401	123	0.31	0.41	238	3	252	53	+6	26.58	1.11	0.05125	2.3	0.2659	2.6	0.03763	1.11	0.43
RIB22-13.1	rim	osz, p	114	45	0.40	1.77	219	2	240	242	+9	28.90	1.07	0.05097	10.5	0.2432	10.5	0.03461	1.07	0.10
RIB22-17.1	rim	osc, fr	480	204	0.42	0.39	214	2	238	46	+10	29.66	0.82	0.05093	2.0	0.2367	2.1	0.03371	0.82	0.38
RIB22-16.2	rim	osc, ov	290	73	0.25	0.23	759	6	878	21	+14	8.00	0.85	0.06832	1.0	1.1773	1.3	0.12497	0.85	0.64
RIB22-16.1	core	osc, ov	301	84	0.28	0.14	733	7	865	28	+16	8.30	1.01	0.06789	1.3	1.1272	1.7	0.12042	1.01	0.60
RIB22-2.1	core	hb, fr	154	94	0.61	0.48	500	8	786	42	+38	12.41	1.62	0.06537	2.0	0.7263	2.6	0.08058	1.62	0.63

TABLE 2J. RIB-5 ZONGO/KUTICUCHO GRANITE.

Spot	Site	Ch/h	U (ppm)	Th (ppm)	Th/U	% ²⁰⁶ Pb _c	²⁰⁶ Pb/ ²³⁸ U age (Ma)	±1σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma)	±1σ (Ma)	% Disc	²³⁸ U/ ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²³⁵ U	±%	²⁰⁶ Pb* / ²³⁸ U	±%	Err corr
RIB5-3.1	core	osc, p	1,157	522	0.45	0.01	220	2	212	20	-4	28.8	1.0	0.0504	0.8	0.241	1.3	0.0348	1.0	0.8
RIB5-1.1	core	osc, ov	522	36	0.07	0.05	228	3	223	35	-2	27.8	1.2	0.0506	1.5	0.251	1.9	0.0360	1.2	0.6
RIB-5-21.1	rim	hd, p	5,470	68	0.01	0.24	234	4	175	78	-34	27.1	1.6	0.04957	3.4	0.252	3.7	0.0369	1.6	0.4
RIB-5-1.2	rim	osc, ov	483	36	0.07	--	239	3	233	27	-3	26.5	1.4	0.0508	1.2	0.26	1.8	0.038	1.4	0.8
RIB-5-9.2	rim	hd, ov	10,540	46	0.00	0.11	243	4	188	59	-29	26.1	1.5	0.04986	2.6	0.264	3.0	0.0384	1.5	0.5
RIB-5-1.2	rim	osc, ov	6,475	17	0.00	0.20	252	4	187	83	-35	25.1	1.7	0.04983	3.6	0.273	3.9	0.0398	1.7	0.4
RIB-5-20.1	rim	hd, fr	12,104	77	0.01	--	259	4	238	29	-9	24.4	1.6	0.05095	1.3	0.288	2.0	0.0410	1.6	0.8
RIB-5-19.1	rim	hd, p	8,295	39	0.00	--	263	4	172	35	-54	24.0	1.5	0.04951	1.5	0.284	2.2	0.0416	1.5	0.7
RIB-5-16.1	rim	hd, p	10,295	44	0.00	--	269	4	166	45	-63	23.5	1.5	0.04938	1.9	0.290	2.5	0.0426	1.5	0.6
RIB-5-17.1	rim	hd, p	14,104	75	0.01	--	271	4	213	34	-28	23.3	1.6	0.05039	1.5	0.298	2.1	0.0429	1.6	0.7
RIB-5-14.1	core	hd, fr	11,368	152	0.01	0.31	276	4	243	56	-14	22.9	1.6	0.05105	2.4	0.308	2.9	0.0437	1.6	0.5
RIB-5-18.1	core	hb, p	12,238	69	0.01	--	286	4	186	35	-55	22.0	1.6	0.04980	1.5	0.312	2.2	0.0454	1.6	0.7
RIB-5-13.1	core	hd, fr	8,274	2,055	0.25	--	287	5	268	30	-7	22.0	1.7	0.05160	1.3	0.323	2.2	0.0455	1.7	0.8
RIB-5-28.1	core	hb, ov	2057	40	0.02	0.35	287	4	388	14	+27	22.0	1.3	0.0544	0.6	0.34	1.5	0.046	1.3	0.9
RIB-5-10.2	rim	hd, p	14,647	128	0.01	--	291	4	185	55	-59	21.6	1.5	0.04978	2.4	0.317	2.8	0.0462	1.5	0.5
RIB5-8.1	core	hb, ov	197	50	0.25	1.34	326	4	462	87	+30	19.3	1.1	0.0562	3.9	0.402	4.1	0.0519	1.1	0.3
RIB-5-15.1	rim	hd, fr	36,691	182	0.00	--	331	5	212	17	-58	19.0	1.5	0.05037	0.7	0.366	1.7	0.0527	1.5	0.9
RIB-5-18.2	rim	hd, p	1,958	298	0.15	0.21	335	5	349	15	+4	18.8	1.4	0.0535	0.7	0.39	1.5	0.053	1.4	0.9
RIB5-12.1	rim	hd, p	15,652	78	0.00	--	348	5	314	26	-11	18.0	1.5	0.0527	1.1	0.403	1.8	0.0554	1.5	0.8
RIB5-11.2	rim	hd, p	8,353	40	0.00	--	359	11	273	16	-32	17.5	3.1	0.0517	0.7	0.408	3.2	0.0572	3.1	1.0
RIB-5-25.1	core	hb, fr	705	162	0.23	0.33	395	5	443	32	+11	15.8	1.4	0.0558	1.4	0.49	2.0	0.063	1.4	0.7
RIB-5-22.1	core	hb, ov	1,306	62	0.05	1.45	415	5	659	44	+38	15.0	1.4	0.0616	2.0	0.57	2.5	0.067	1.4	0.6
RIB5-6.2	rim	hd, fr	16,273	95	0.01	--	457	17	182	14	-157	13.6	3.8	0.0497	0.6	0.504	3.9	0.0735	3.8	1.0
RIB-5-26.1	core	hb, ov	759	171	0.23	0.21	479	6	534	24	+11	13.0	1.4	0.0581	1.1	0.62	1.8	0.077	1.4	0.8
RIB5-2.1	core	hd, ov	2,261	20	0.01	--	537	5	502	17	-7	11.5	1.0	0.0573	0.8	0.686	1.2	0.0869	1.0	0.8
RIB5-6.1	core	hb, ov	296	104	0.35	0.27	557	6	542	31	-3	11.1	1.0	0.0583	1.4	0.725	1.7	0.0902	1.0	0.6
RIB5-10.1	core	osc, ov	662	243	0.37	0.23	579	6	573	20	-1	10.6	1.1	0.0592	0.9	0.767	1.4	0.0940	1.1	0.8
RIB-5-27.1	core	hd, fr	312	59	0.19	3.44	607	9	1286	27	+55	10.1	1.6	0.0837	1.4	1.14	2.1	0.099	1.6	0.8
RIB5-4.1	core	hb, p	421	125	0.30	3.72	869	32	1579	71	+48	6.9	4.0	0.0976	3.8	1.942	5.5	0.1443	4.0	0.7
RIB5-5.1	core	hb, ov	792	38	0.05	5.10	987	9	1840	7	+50	6.0	1.0	0.1125	0.4	2.566	1.1	0.1654	1.0	0.9
RIB5-7.1	core	hb, ov	227	136	0.60	0.09	1020	10	986	18	-4	5.8	1.1	0.0720	0.9	1.701	1.4	0.1713	1.1	0.8
RIB5-11.1	core	hb, p	161	55	0.34	0.44	1148	12	1149	24	+0	5.1	1.1	0.0781	1.2	2.099	1.6	0.1950	1.1	0.7
RIB-5-23.1	core	hb, ov	291	258	0.89	1.32	1503	19	1675	21	+12	3.8	1.4	0.1028	1.1	3.72	1.8	0.263	1.4	0.8
RIB5-9.1	rim	hd, ov	151	93	0.62	0.27	1638	16	1661	12	+2	3.5	1.1	0.1020	0.6	4.070	1.3	0.2893	1.1	0.9
RIB-5-24.1	core	hb, ov	106	57	0.53	--	1824	24	1802	22	-1	3.1	1.5	0.1101	1.2	4.97	2.0	0.327	1.5	0.8
RIB-5-1.3	rim	hd,ov	6,475	17	0.00	0.2	252	4	187	83	-35	25.1	1.7	0.04983	3.6	0.273	3.9	0.0398	1.7	0.4
RIB-5-12.1	rim	hd, p	15,652	78	0.00	--	348	5	314	26	-11	18	1.5	0.0527	1.1	0.403	1.8	0.0554	1.5	0.8

TABLE 2K. RIB-30 ZONGO/KUTICUCHO GRANITE.

Spot	Site	Ch/h	U (ppm)	Th (ppm)	Th/U	% ²⁰⁶ Pb _c	²⁰⁶ Pb/ ²³⁸ U age (Ma)	±1σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma)	±1σ (Ma)	% Disc	²³⁸ U/ ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²³⁵ U	±%	²⁰⁶ Pb* / ²³⁸ U	±%	Err corr
RIB30-15.1	rim	hd, fr	16,246	69	0.004	0.10	226	5	220	62	-3	28.0	2.39	0.05053	2.7	0.248	3.6	0.0357	2.39	0.7
RIB30-12.1	rim	hd, ov	19,962	102	0.005	0.00	226	4	261	53	+14	28.0	1.65	0.05145	2.3	0.253	2.8	0.0357	1.65	0.6
RIB30-11.1	rim	hd, p	15,325	108	0.007	--	229	2	214	65	-7	27.6	0.81	0.05041	2.8	0.252	2.9	0.0362	0.81	0.3
RIB30-14.1	rim	hd, fr	18,210	62	0.003	0.08	231	2	286	50	+20	27.4	0.80	0.05201	2.2	0.261	2.3	0.0365	0.80	0.3
RIB30-9.1	rim	hd, fr	15,565	2624	0.169	1.16	236	2	300	108	+22	26.8	0.84	0.05234	4.7	0.269	4.8	0.0373	0.84	0.2
RIB30-4.1	rim	hd, fr	14,259	67	0.005	--	244	2	229	43	-6	26.0	0.79	0.05075	1.9	0.270	2.0	0.0385	0.79	0.4
RIB30-10.1	rim	hd, p	18,372	60	0.003	--	252	3	209	41	-21	25.1	1.26	0.05030	1.8	0.276	2.2	0.0399	1.26	0.6
RIB30-5.1	rim	hd, p	17,042	65	0.004	0.10	259	4	226	60	-15	24.4	1.42	0.05068	2.6	0.287	3.0	0.0410	1.42	0.5
RIB30-7.1	rim	hd, p	18,524	155	0.008	--	263	2	263	76	+0	24.0	0.79	0.05150	3.3	0.295	3.4	0.0416	0.79	0.2
RIB30-8.1	rim	hd, p	1,8333	444	0.024	0.42	298	3	224	47	-34	21.1	0.86	0.05064	2.1	0.331	2.2	0.0474	0.86	0.4
RIB30-2.1	core	osc, p	15,654	213	0.014	--	301	2	283	35	-6	20.9	0.82	0.05194	1.6	0.342	1.8	0.0477	0.82	0.5
RIB30-13.1	rim	hd, fr	15,917	98	0.006	--	303	3	216	58	-41	20.8	0.92	0.05045	2.5	0.335	2.7	0.0481	0.92	0.3
RIB30-6.1	rim	hd, p	17,698	104	0.006	0.38	306	3	205	52	-50	20.5	0.89	0.05022	2.2	0.337	2.4	0.0487	0.89	0.4
RIB30-3.1	core	sz, fr	829	139	0.167	0.63	216	3	100	285	-117	29.3	1.21	0.04802	12.1	0.226	12.1	0.0341	1.21	0.1
RIB30-17.1	rim	osc, fr	425	269	0.634	1.05	236	3	236	98	+0	26.8	1.4	0.05089	4.3	0.262	4.5	0.0373	1.4	0.3
RIB30-1.1	core	osc, fr	1,888	162	0.086	--	237	2	281	73	+16	26.7	0.88	0.05191	3.2	0.268	3.3	0.0375	0.88	0.3
RIB30-18.1	rim	hb, p	454	122	0.269	0.28	241	3	246	44	+2	26.2	1.3	0.05111	1.9	0.269	2.3	0.0381	1.3	0.6
RIB30-19.1	core	sz, fr	860	61	0.071	0.46	262	3	272	59	+4	24.1	1.3	0.05170	2.6	0.296	2.9	0.0415	1.3	0.5
RIB30-20.1	core	sz, p	1,694	113	0.067	0.03	266	3	252	20	-6	23.7	1.2	0.05124	0.9	0.298	1.5	0.0421	1.2	0.8
RIB30-2.2	rim	hd, p	1,990	188	0.095	0.83	291	4	292	164	+1	21.7	1.41	0.05216	7.2	0.332	7.3	0.0461	1.41	0.2
RIB30-16.1	core	hb, p	488	185	0.380	0.34	507	6	529	27	+4	12.2	1.2	0.05797	1.2	0.654	1.7	0.0818	1.2	0.7
RIB30-22.1	core	hb, p	201	46	0.228	0.50	974	13	1167	34	+18	6.1	1.4	0.07878	1.7	1.771	2.2	0.1631	1.4	0.6
RIB30-21.1	core	hb, fr	191	63	0.330	0.56	1228	17	1291	42	+5	4.8	1.5	0.08392	2.2	2.429	2.7	0.2099	1.5	0.6
RIB30-24.1	core	hb, p	89	70	0.790	4.01	1451	27	1425	111	-2	4.0	2.1	0.08995	5.8	3.131	6.2	0.2525	2.1	0.3
RIB30-23.1	core	hb, fr	119	47	0.400	0.40	1661	25	1993	14	+19	3.4	1.7	0.12251	0.8	4.966	1.9	0.2940	1.7	0.9
RIB30-25.1	core	hb, p	594	307	0.517	0.14	2323	33	2603	10	+13	2.3	1.7	0.17473	0.6	10.451	1.8	0.4338	1.7	0.9

TABLE 2L. RIB-11 TAQUESI GRANODIORITE.

Spot	Site	Ch/h	U (ppm)	Th (ppm)	Th/U	% ²⁰⁶ Pb _c	²⁰⁶ Pb/ ²³⁸ U age (Ma)	±1σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma)	±1σ (Ma)	% Disc	²³⁸ U/ ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²³⁵ U	±%	²⁰⁶ Pb* / ²³⁸ U	±%	Err corr
RIB11-9.1	core	hb, p	247	45	0.18	0.36	218	2	230	67	+6	29.1	1.1	0.0508	2.9	0.240	3.1	0.0343	1.1	0.3
RIB11-8.1	core	osc, p	248	195	0.79	0.58	219	2	212	84	-3	28.9	1.1	0.0504	3.6	0.240	3.8	0.0346	1.1	0.3
RIB11-5.1	core	hb, p	217	166	0.77	0.60	219	3	252	81	+13	28.9	1.3	0.0512	3.5	0.244	3.7	0.0346	1.3	0.3
RIB11-12.1	core	sz, p	179	248	1.38	5.00	220	3	271	340	+19	28.8	1.3	0.0517	14.8	0.247	14.9	0.0347	1.3	0.1
RIB11-2.1	core	osz, p	449	34	0.08	0.13	221	2	257	53	+14	28.7	1.0	0.0514	2.3	0.247	2.5	0.0348	1.0	0.4
RIB11-6.1	core	osc, p	336	199	0.59	--	221	3	209	305	-6	28.6	1.2	0.0503	13.2	0.242	13.2	0.0349	1.2	0.1
RIB11-7.1	core	osc, p	378	193	0.51	0.81	221	2	244	109	+9	28.6	1.0	0.0511	4.7	0.246	4.8	0.0349	1.0	0.2
RIB11-10.1	core	osc, p	512	335	0.65	0.08	221	2	219	33	-1	28.6	1.0	0.0505	1.4	0.243	1.7	0.0350	1.0	0.6
RIB11-3.1	core	sz, p	514	163	0.32	0.28	228	2	285	34	+20	27.8	1.0	0.0520	1.5	0.258	1.8	0.0360	1.0	0.6
RIB11-4.1	core	osc, p	813	80	0.10	0.03	228	2	218	25	-5	27.7	1.0	0.0505	1.1	0.251	1.5	0.0361	1.0	0.7
RIB11-1.1	core	sz, p	1,441	144	0.10	0.04	230	2	236	15	+3	27.6	1.0	0.0509	0.7	0.255	1.2	0.0363	1.0	0.8
RIB11-11.1	core	sz, p	226	142	0.63	0.30	573	15	582	34	+2	10.8	2.7	0.0594	1.6	0.761	3.1	0.0929	2.7	0.9

TABLE 2M. RIB-12 TAQUESI QUARTZDIORITE (ENCLAVE).

Spot	Site	Ch/h	U (ppm)	Th (ppm)	Th/U	% ²⁰⁶ Pb _c	²⁰⁶ Pb/ ²³⁸ U age (Ma)	±1σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma)	±1σ (Ma)	% Disc	²³⁸ U/ ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²³⁵ U	±%	²⁰⁶ Pb* / ²³⁸ U	±%	Err corr
RIB12-13.1	rim	sz, p	282	123	0.44	0.54	213	2	227	75	+7	29.8	1.19	0.05071	3.2	0.235	3.4	0.0336	1.19	0.3
RIB12-9.1	rim	osz, p	186	100	0.54	1.28	216	2	234	162	+8	29.3	0.97	0.05086	7.0	0.239	7.1	0.0341	0.97	0.1
RIB12-11.2	core	osc, p	1,631	206	0.13	0.14	221	2	229	27	+4	28.7	0.87	0.05075	1.2	0.244	1.5	0.0348	0.87	0.6
RIB12-7.1	rim	osc, p	785	197	0.25	0.21	225	2	222	48	-1	28.1	0.80	0.05059	2.1	0.248	2.2	0.0356	0.80	0.4
RIB12-3.1	rim	sz, p	512	427	0.83	0.43	226	2	231	68	+3	28.1	1.07	0.05079	3.0	0.250	3.1	0.0356	1.07	0.3
RIB12-14.1	rim	osc, p	821	190	0.23	0.15	226	2	207	27	-9	28.1	0.79	0.05027	1.2	0.247	1.4	0.0356	0.79	0.6
RIB12-4.1	rim	osc, p	1,037	135	0.13	0.05	226	2	226	19	-0	28.0	0.78	0.05067	0.8	0.250	1.1	0.0357	0.78	0.7
RIB12-10.1	rim	osc, p	898	109	0.12	0.33	226	2	203	33	-12	28.0	1.03	0.05017	1.4	0.247	1.7	0.0358	1.03	0.6
RIB12-5.1	rim	osc, p	550	313	0.57	0.43	227	2	236	45	+4	28.0	0.91	0.05090	2.0	0.251	2.2	0.0358	0.91	0.4
RIB12-12.1	rim	osc, p	1,483	189	0.13	0.02	228	2	220	15	-4	27.8	0.89	0.05055	0.6	0.251	1.1	0.0360	0.89	0.8
RIB12-6.1	rim	osc, p	563	43	0.08	0.25	230	2	235	36	+2	27.5	0.80	0.05087	1.6	0.255	1.8	0.0363	0.80	0.5
RIB12-15.1	rim	osc, p	1,897	250	0.13	--	231	2	234	14	+1	27.4	0.98	0.05084	0.6	0.256	1.2	0.0365	0.98	0.8
RIB12-8.1	rim	osc, p	1,333	538	0.40	0.04	233	2	222	16	-5	27.1	0.87	0.05060	0.7	0.257	1.1	0.0368	0.87	0.8
RIB12-2.1	rim	osc, p	1,687	211	0.13	0.09	234	2	206	16	-14	27.1	0.77	0.05023	0.7	0.256	1.0	0.0369	0.77	0.7
RIB12-1.1	rim	osc, p	1,332	48	0.04	0.12	236	2	196	29	-21	26.9	0.78	0.05002	1.3	0.257	1.5	0.0372	0.78	0.5
RIB12-11.1	core	hb, ov	211	121	0.57	0.62	530	8	698	44	+25	11.7	1.61	0.06271	2.0	0.740	2.6	0.0856	1.61	0.6

TABLE 2N. RIB-43 QUIMSA CRUZ GRANITE.

Spot	Site	Ch/h	U (ppm)	Th (ppm)	Th/U	% ²⁰⁶ Pb _c	²⁰⁶ Pb/ ²³⁸ U age (Ma)	±1σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma)	±1σ (Ma)	% Disc	²³⁸ U/ ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²³⁵ U	±%	²⁰⁶ Pb* / ²³⁸ U	±%	Err corr
RIB43-15.1	rim	osc, eq	509	228	0.45	2.95	25.9	0.4	87.4	464	+71	248.8	1.6	0.0478	19.6	0.03	19.6	0.004	1.6	0.1
RIB43-12.1	core	osc, p	950	171	0.18	2.74	26.4	0.5	48.8	426	+46	244.1	1.9	0.0470	17.8	0.03	17.9	0.004	1.9	0.1
RIB43-7.1	core	osc, p	739	263	0.36	2.04	26.5	0.4	25.5	415	-4	243.2	1.4	0.0465	17.3	0.03	17.4	0.004	1.4	0.1
RIB43-1.1	rim	osc, p	468	280	0.60	3.82	26.5	0.6	47.2	595	+44	242.7	2.2	0.0470	24.9	0.03	25.0	0.004	2.2	0.1
RIB43-9.1	rim	osc, p	734	300	0.41	4.10	26.6	0.5	59.8	631	+56	241.9	1.7	0.0472	26.5	0.03	26.5	0.004	1.7	0.1
RIB43-5.1	rim	osc, p	704	200	0.28	2.85	26.6	0.5	49.2	403	+46	241.7	2.0	0.0470	16.9	0.03	17.0	0.004	2.0	0.1
RIB43-2.1	rim	osc, p	467	162	0.35	5.92	26.7	0.5	-20	837	+234	241.0	1.8	0.0457	34.6	0.03	34.6	0.004	1.8	0.1
RIB43-13.1	rim	osc, p	627	185	0.30	3.55	26.7	0.5	4.8	475	-453	241.0	1.7	0.0461	19.7	0.03	19.8	0.004	1.7	0.1
RIB43-10.1	rim	osc, p	504	201	0.40	3.09	27.0	0.5	67.1	498	+60	238.2	1.9	0.0474	20.9	0.03	21.0	0.004	1.9	0.1
RIB43-8.1	core	osc, p	932	326	0.35	1.88	27.5	0.4	48.0	256	+43	233.5	1.5	0.0470	10.7	0.03	10.8	0.004	1.5	0.1
RIB43-6.2	rim	osc, p	752	174	0.23	1.65	27.7	0.4	64.2	215	+57	232.2	1.5	0.0473	9.0	0.03	9.2	0.004	1.5	0.2
RIB43-11.1	rim	osc, p	1,001	273	0.27	3.00	27.8	0.4	57.5	324	+52	231.1	1.4	0.0472	13.6	0.03	13.7	0.004	1.4	0.1
RIB43-3.1	rim	osc, p	1,105	301	0.27	1.55	28.0	0.3	45.4	256	+38	229.9	1.2	0.0469	10.7	0.03	10.8	0.004	1.2	0.1
RIB43-4.1	rim	osc, p	1,386	270	0.20	1.23	33.7	0.4	51.7	206	+35	190.7	1.1	0.0470	8.6	0.03	8.7	0.005	1.1	0.1
RIB43-14.1	rim	osc, p	740	176	0.24	0.55	324	3	907	29	+66	19.4	0.9	0.0693	1.4	0.49	1.7	0.052	0.9	0.5
RIB43-6.1	core	osc, p	257	95	0.37	0.31	600	5	606	33	+1	10.3	0.9	0.0601	1.5	0.81	1.8	0.097	0.9	0.5

TABLE 2O. RIB-46 QUIMSA CRUZ GRANITE.

Spot	Site	Ch/h	U (ppm)	Th (ppm)	Th/U	% ²⁰⁶ Pb _c	²⁰⁶ Pb/ ²³⁸ U age (Ma)	±1σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma)	±1σ (Ma)	% Disc	²³⁸ U/ ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²⁰⁶ Pb*	±%	²⁰⁷ Pb* / ²³⁵ U	±%	²⁰⁶ Pb* / ²³⁸ U	±%	Err corr
RIB46-3.1	rim	osc, p	931	170	0.18	2.36	25.9	0.4	49.4	317	+48	248.0	1.69	0.04700	13.3	0.026	13.4	0.0040	1.69	0.1
RIB46-8.2	core	hb, p	347	135	0.39	10.76	26.5	1.0	138	1487	+81	242.7	3.62	0.04880	63.3	0.028	63.4	0.0041	3.62	0.1
RIB46-8.1	rim	osc, p	834	188	0.23	2.66	26.5	0.3	40.7	437	+35	242.4	1.11	0.04683	18.3	0.027	18.3	0.0041	1.11	0.1
RIB46-6.1	rim	osc, p	834	230	0.28	1.19	26.6	0.5	78.5	211	+66	242.1	1.71	0.04758	8.9	0.027	9.0	0.0041	1.71	0.2
RIB46-13.1	rim	osc, p	734	278	0.38	3.81	26.7	0.4	75.9	534	+65	241.1	1.65	0.04753	22.5	0.027	22.6	0.0041	1.65	0.1
RIB46-5.1	rim	osc, p	1,068	204	0.19	1.48	26.7	0.3	49.7	228	+46	240.5	1.10	0.04701	9.6	0.027	9.6	0.0042	1.10	0.1
RIB46-12.1	rim	osc, p	944	197	0.21	0.98	26.8	0.3	28.8	156	+7	239.8	1.22	0.04660	6.5	0.027	6.6	0.0042	1.22	0.2
RIB46-11.1	rim	osc, p	552	122	0.22	2.40	26.8	0.4	25.7	423	-4	239.8	1.34	0.04654	17.6	0.027	17.7	0.0042	1.34	0.1
RIB46-4.1	rim	osc, p	719	220	0.31	1.88	26.9	0.6	74.8	432	+64	239.5	2.35	0.04751	18.2	0.027	18.3	0.0042	2.35	0.1
RIB46-11.2	rim	osc, p	899	173	0.19	1.03	26.9	0.3	58.2	207	+54	239.3	1.14	0.04718	8.7	0.027	8.8	0.0042	1.14	0.1
RIB46-7.1	rim	osc, p	679	265	0.39	1.57	27.0	0.3	77.8	257	+65	238.6	1.10	0.04757	10.8	0.027	10.9	0.0042	1.10	0.1
RIB46-9.1	rim	osc, p	1,220	143	0.12	1.03	27.2	0.3	11.9	276	-128	236.3	1.15	0.04627	11.5	0.027	11.5	0.0042	1.15	0.1
RIB46-2.2	rim	osc, p	1,544	143	0.09	1.36	27.3	0.3	38.8	149	+30	235.5	1.13	0.04680	6.2	0.027	6.3	0.0042	1.13	0.2
RIB46-1.1	rim	osc, p	1,352	386	0.29	1.37	28.0	0.3	43.7	150	+36	229.7	1.19	0.04689	6.3	0.028	6.4	0.0044	1.19	0.2
RIB46-10.2	rim	osc, p	1,465	147	0.10	2.06	29.8	0.5	58.9	255	+49	215.6	1.53	0.04719	10.7	0.030	10.8	0.0046	1.53	0.1
RIB46-10.1	core	osc, p	367	211	0.57	0.07	1608	12	1707	7	+7	3.5	0.82	0.10461	0.4	4.087	0.9	0.2833	0.82	0.9
RIB46-2.1	core	sz, p	121	102	0.84	0.40	1648	28	1645	30	-0	3.4	1.93	0.10114	1.6	4.063	2.5	0.2913	1.93	0.8

Ch/ corresponds to textural zircon characteristics (**osc** oscillatory zoning, **hb** homogeneous bright, **hd** homogeneous dark and **sz** sector zoning). /**h** corresponds to habit (**p** prismatic, **ov** oval and **fr** fragment). % ²⁰⁶Pb_c is percentage of measured common ²⁰⁶Pb. ±1sigma reported error in ages. % **Disc** is percentage of discordance. Following Faure and Mensing (2005), isotopic ratios correspond as follows: $\frac{^{238}\text{U}}{^{206}\text{Pb}^*} = \frac{1}{e^{\lambda_1 t_1 - 1}}$; $\frac{^{207}\text{Pb}^*}{^{206}\text{Pb}^*} = \frac{1}{137.88} \frac{(e^{\lambda_2 t_1} - 1)}{(e^{\lambda_1 t_1} - 1)}$, $\frac{^{207}\text{Pb}^*}{^{235}\text{U}} = e^{\lambda_2 t_1} - 1$ and $\frac{^{206}\text{Pb}^*}{^{238}\text{U}} = e^{\lambda_1 t_1} - 1$. “**t**” is the age, λ_1 is the decay constant of ²³⁸U and equals to 1.55125 * 10⁻¹⁰ y⁻¹ and λ_2 is the decay constant of ²³⁵U and equals to 9.8485 * 10⁻¹⁰ y⁻¹ (Steiger and Jäger, 1977). Spot sites chosen to calculate Concordia ages are shown as bold text.

TABLE 3. SUMMARY OF CONCORDIA AGES CALCULATED FOR THE STUDIED PLUNTONS FROM THE CORDILERA REAL.

Sample	Age (Ma)	±1 sigma (Ma)	±2 sigma (Ma)	±95% confidence (Ma)	MSWD
RIB-2	220.7	1.3	2.7	-	1.1
RIB-2	247.6	1.2	2.4	3.6	1.9
RIB-4	222.9	0.96	1.9	3.2	2.3
RIB-4	243.9	1.6	3.1	3.1	1.18
RIB-11	222.9	0.87	1.7	2.7	2
RIB-12	227.8	0.65	1.3	-	1.03
RIB-15	226.9	1	2	-	0.78
RIB-15	240.3	1.2	2.5	-	0.19
RIB-19	213.6	1.2	2.4	-	0.09
RIB-19	226	0.57	1.1	1.4	1.4
RIB-20	230.7	0.94	1.9	2.7	1.9
RIB-22	226.9	0.61	1.2	1.6	1.6
RIB-22	238.3	1.2	2.4	3.7	1.5
RIB-27	239.5	0.96	1.9	2.8	0.39
RIB-32	234.2	0.65	1.3	-	0.2
RIB-33	230.7	0.63	1.3	-	0.46
RIB-43	27	0.12	0.24	0.29	1.3
RIB-46	27	0.1	0.2	-	0.8

MSWD: values and errors at 1, 2 sigma and 95% confidence as calculated by the Isoplot 4.0 of Ludwig (2009).

by Cordani *et al.* (2019), are a good example of a sample of Cordillera Real granitoids displaying a composite range of ages (Figs. 4 and 5). In the case of RIB-2, the U-Pb zircon ages range from 217 to 257 Ma. This wide range of ages does not allow a single crystallization age to be obtained (*e.g.*, Isoplot software cannot calculate Concordia age, Fig. 4). When displaying the Concordia ages in a histogram plot, peaks are observed at 220 and 240 Ma (histogram in inset of figure 4, see also Cordani *et al.*, 2019). The CL image shows prismatic zircon crystals always with oscillatory zoning and some with dark rims (Fig. 3). Xenocrystal inheritance ages related to detrital zircon ranges from 312 to 1,186 Ma. Given this wide range, concordant spots were selected to calculate Concordia ages (Fig. 6). In the case of the younger population of sample RIB-2, a Concordia age of 221 ± 3 Ma (2σ) was obtained. For the older population, a Concordia age of 248 ± 4 Ma (95% confidence) was also obtained.

For sample RIB-4, the U-Pb zircon ages range from 215 to 265 Ma. This sample also shows a wide range of ages in the histogram inset of figure 5. It can be seen in the CL images (Fig. 3) that zircons present dark U-rich rims, some almost completely dark with small bright U-poor cores (*e.g.*, RIB4-17.1 and RIB4-25.1). Presumed xenocrysts yielded ages of 362, 468, 1364, 1655, 2026 and 2070 Ma. Given also the wide range of ages, two populations were separated to obtain concordant ages (Fig. 7). For the younger population a Concordia age of 223 ± 3 Ma (95% confidence) was obtained. For the older population a Concordia age of 244 ± 3 Ma (95% confidence) was calculated. Rejected spot were 10.1 for having large error and 18.1 and 13.1 (with U/Pb of 263 and 265 Ma, respectively) that we considered as “early antecrysts”.

Sample RIB-19 presented U-Pb zircon ages ranging from 213 to 235 Ma. The CL image shows prismatic crystals with oscillatory zones some with

FIG. 4. Concordia diagram with entire dataset of sample RIB-2 (Huayna Potosí granite, see table 2E) with histogram of Concordia ages in the inset. Spot sites with large errors or discordance >10% were excluded from Concordia age calculation and are shown as grey ellipses. Magmatism is recorded continuously by means of zircon ages from nearly 250 to 220 Ma. This large interval of ages does not allow Isoplot software to calculate a single Concordia age. Two groups can be distinguished at around 240 and near 220 Ma, respectively.

FIG. 5. Concordia diagram with entire dataset of sample RIB-4 (Huayna Potosí granite, see table 2F) with histograms of Concordia ages in the inset. Spot sites with large errors or discordance >10% were excluded from Concordia age calculation and are shown as grey ellipses. Magmatism is recorded continuously by means of zircon ages from nearly 290 to 215 Ma. This large interval of ages does not allow Isoplot software to calculate a single Concordia age. Two groups can be distinguished at 220 and 240 Ma with spots at around 270 Ma considered as “early antecrysts”.

FIG. 6. Concordia diagrams for sample RIB-2 (Huayna Potosí granite) displaying two calculated Concordia ages. For the younger age (A), four spot sites were chosen (8.1, 6.1, 10.1, and 13.1) displayed as bold text in table 2E. For the older age shown below (B), seven spots were chosen (22.1, 15.1, 3.1, 21.1, 17.1, 2.1 and 24.1) displayed also as bold text on table 2E. Grey ellipses were excluded from the age calculation and the light blue ellipses correspond to the calculated Concordia ages.

FIG. 7. Concordia diagrams for sample RIB-4 (Huayna Potosí granite) displaying two Concordia ages. For the younger age (A), six spot sites were chosen (26.1, 8.1, 9.1, 1.1, 2.1 and 3.1) displayed as bold text in table 2F. For the older age shown below (B), five spots were chosen (14.1, 17.1, 22.1, 16.1 and 25.1) displayed also as bold text in table 2F. Grey ellipses were excluded from the age calculation and the light blue ellipses correspond to the calculated Concordia ages.

dark rims and an appearance similar to sample RIB-2. An inherited core of 600 Ma rimmed by a younger edge of 222 Ma was measured in spots RIB19-10.1 and RIB19-10.2 respectively. For the calculation of the Concordia age (Fig. 8) the selected spots yielded a Concordia age of 226 ± 1 Ma (2σ). Spots 6.1, 2.2 and 3.1 that defined a younger Concordia age of 214 Ma were rejected for having large analytical error.

Sample RIB-20 presented U-Pb zircon ages ranging from 216 to 251 Ma. CL image shows prismatic crystals with oscillatory zoning some with darker rims and domains (Fig. 3). Two xenocrystal zircon grains yielded discordant ages of 454 and 1413 Ma. For the age calculation (Fig. 9) the selected spots yielded a Concordia age of 231 ± 3 Ma (95% confidence).

Sample RIB-22 presented U-Pb zircon ages ranging from 214 to 242 Ma. Three xenocrystal zircon grains yielded ages of 500, 733 and 759 Ma. For the age calculation (Fig. 10) the selected spots yielded a Concordia age of 227 ± 2 Ma (95% confidence). We also obtained an older Concordia age of 238 ± 2 Ma using spots 9.1, 5.1 and 15.1. Then this sample also shows the bimodal distribution of samples RIB-2 and RIB-4.

For the Kutiucucho facies of the Zongo pluton, two granitic samples were dated, both presenting clear deformation shown by the orientation of quartz, K-feldspar, biotite and muscovite. One of them (RIB-5) was already considered by Cordani *et al.* (2019). For this sample, the U-Pb zircon ages range from 220 to 291 Ma. CL images for dated zircons are presented in figure 3, having dark rims surrounding relictic bright cores. The low Th/U ratios probably yielded a reverse Discordia line forced through the origin (Fig. 11), with a poor constrained lower intercept at 222 ± 25 Ma. Inheritances are abundant especially as bright cores that yielded ages of 333, 1020, 1503, 1638 and 1,824 Ma (Fig. 3). For sample RIB-30, the U-Pb zircon ages range from 216 to 298 Ma also generating a reverse Discordia with a poor constrained lower intercept at 240 ± 28 Ma. This sample displays crystals with dark domains, some of them completely dark, similar to sample RIB-5. This dark rims on zircons, reflecting high U also yielded a reverse discordance as the sample RIB-5 (Fig. 11). However, some of the crystals do not have these dark domains and show instead a normal oscillatory zoning (spots RIB30-3.1, RIB30-17.1 and RIB30-18.1 and RIB30-19.1). Xenocrystic zircons yielded 1,451 and 2,323 Ma.

FIG. 8. Concordia diagram for sample RIB-19 (Huayna Potosí granite). Thirteen zircon spot sites were chosen for the Concordia age calculation (7.1, 10.2, 5.1, 2.1, 14.1, 9.1, 11.1, 4.1, 18.1, 1.1, 12.1, 8.1 and 13.1), displayed as bold text in table 2G. Three spots (6.1, 2.2 and 3.1) define a younger age of 214 Ma, however they were rejected due their large error ellipses (in grey). Light blue ellipse corresponds to the calculated Concordia age.

FIG. 9. Concordia diagram for sample RIB-20 (Huayna Potosí granodiorite). Ten zircon spot sites were chosen for the Concordia age calculation (8.1, 10.1, 6.1, 3.1, 1.1, 5.1, 2.1, 14.1, 4.1 and 7.1), displayed as bold text in table 2H. Grey ellipses were excluded from the age calculation and the light blue ellipse corresponds to the calculated Concordia age.

FIG. 10. Concordia diagram for sample RIB-22 (Huayna Potosí granite). Eleven zircon spot sites were chosen for the Concordia age calculation (18.1, 8.1, 3.1, 6.1, 10.1, 14.1, 12.1, 11.1, 4.1, 7.1 and 1.1). Three spots (9.1, 5.1 and 15.1) defined an older age of 238 Ma. These chosen spots are displayed as bold text in table 2I. Grey ellipses were excluded from the age calculation and the light blue ellipse corresponds to the calculated Concordia age.

FIG. 11. Concordia diagram for samples RIB-5 (top) and RIB-30 (bottom) of Zongo/Kuticucho granite. Both samples from the same granite, display a reverse Discordia line above the Concordia curve. This feature might be related to damage in the zircon crystal lattice (Kusiak *et al.*, 2013). Fifteen spots were chosen for the RIB-5 (1.3, 12.1, 11.2, 6.2, 21.1, 9.2, 20.1, 19.1, 16.1, 17.1, 14.1, 13.1, 18.1, 10.2 and 15.1), meanwhile 13 were chosen for the RIB-30 (15.1, 12.1, 11.1, 14.1, 9.1, 4.1, 10.1, 5.1, 7.1, 8.1, 2.1, 13.1 and 6.1). These chosen spots are displayed as bold text in tables 2J and 2K, respectively.

For the Taquesi pluton, two samples were analysed. One of these is a typical granodiorite (RIB-11) and the other is a mafic enclave (RIB-12) extracted from the same rock. For the RIB-11 sample, the U-Pb zircon ages range from 218 to 230 Ma. Only one zircon xenocryst was found, with an age of 573 Ma. For the calculated age (Fig. 12) selected spots yielded a Concordia age of 223 ± 3 Ma (95% confidence). On the RIB-12 mafic enclave, the U-Pb zircon ages range from 213 to 233 Ma. As seen in sample RIB-11, the CL images of zircon crystals show prismatic habits, with oscillatory zoning, some of them showing dark rims and domains. The only xenocryst analyzed yielded an age of 530 Ma. For the age calculation (Fig. 13) the selected spots yielded a Concordia age of 228 ± 1 Ma (2σ).

For the RIB-27 sample of the Huato granite, the U-Pb zircon ages range from 213 to 249 Ma. Some of the zircon crystals measured have low Th/U ratios (lower than 0.1). Some dark domains are also present in the CL images. Two xenocrystal zircons (spots RIB27-11.1 and RIB27-13.1) reported ages of 610 Ma and 790 Ma. For the age calculation (Fig. 14) selected spots yielded a Concordia age of 239 ± 3 Ma (95% confidence). Spots 1.1, 11.1, 12.1 were rejected for because of their large error.

For the Illampu batholith three samples were analysed. One is a typical granodiorite (RIB-33) of the northern part, the other is a mafic enclave (RIB-32) hosted by this granodiorite and the third sample (RIB-15) comes from a two mica granite located to the southern part of the batholith. For the RIB-33 granodiorite the U-Pb zircon ages range from 227 to 233 Ma. In the CL image (Fig. 3), all zircons have prismatic habit with well-developed oscillatory zoning. Th/U ratios are generally magmatic (Table 2C). No inheritance was measured in this sample. For the calculated age (Fig. 15), selected spots yielded a Concordia age of 231 ± 1 Ma (2σ). For the RIB-32 enclave, the U-Pb zircon ages range from 232 to 236 Ma. The CL images show some zircon crystals with oscillatory zoning but also with massive or irregular core suggesting for the cores a xenocrystic or antecrystic origin (see for instance Corfu *et al.*, 2003). For the calculated age (Fig. 16), the selected spots yielded a Concordia age of 234 ± 1 Ma (2σ). For the RIB-15 granite, the U-Pb zircon ages range from 222 to 242 Ma. As in the case of the two-mica granites of the Huayna Potosí pluton, it also shows a wide range of Concordia ages (histogram inset in Fig. 17), suggesting also a protracted age interval for these granites.

FIG. 12 Concordia diagram for sample RIB-11 (Taquesi granodiorite). Seven zircon spot sites were chosen for the Concordia age calculation (9.1, 8.1, 6.1, 7.1, 10.1, 4.1 and 1.1), displayed as bold text in table 2L. Grey ellipses were excluded from the age calculation and the light blue ellipse corresponds to the calculated Concordia ages.

FIG. 13. Concordia diagram for sample RIB-12 (Taquesi quartzdiorite enclave). Nine zircon spot sites were chosen for the Concordia age calculation (7.1, 3.1, 14.1, 4.1, 5.1, 12.1, 6.1, 15.1 and 8.1), displayed as bold text on table 2M. Grey ellipses were excluded from the age calculation and the light blue ellipse corresponds to the calculated Concordia age.

FIG. 14. Concordia diagram for sample RIB-27 (Huato granite). Nine zircon spot sites were chosen for the Concordia age calculation (4.1, 2.1, 14.1, 8.1, 7.1, 6.1, 5.1, 9.1 and 3.1), displayed as bold text on table 2A. Two spots (12.1 and 11.1) define a younger age of 216 Ma, however they were rejected due their large error ellipses. Grey ellipses were excluded from the age calculation and the light blue ellipse corresponds to the calculated Concordia age.

FIG. 15. Concordia diagram for sample RIB-33 (Illampu granodiorite). Eleven zircon spot sites were chosen for the Concordia age calculation (5.1, 10.1, 4.1, 2.1, 11.1, 9.1, 7.1, 1.1, 6.1, 3.1 and 8.1), displayed as bold text on table 2C. Grey ellipses were excluded from the age calculation and the light blue ellipse corresponds to the calculated Concordia age.

FIG. 16. Concordia diagram for sample RIB-32 (Illampu quartzdiorite enclave). Twelve zircon spot sites were chosen for the Concordia age calculation (15.1, 11.1, 5.1, 14.1, 3.1, 4.1, 8.1, 9.1, 16.1, 12.1, 6.1 and 7.1), displayed as bold text on table 2B. Grey ellipses were excluded from the age calculation and the light blue ellipse corresponds to the calculated Concordia age.

FIG. 17. Concordia diagram with entire dataset for sample RIB-15 (Illampu granite, see table 2D) with histograms of Concordia ages in the inset. As it was observed on the samples of the Huayna Potosí, magmatism is recorded continuously by means of zircon ages from nearly 240 to 220 Ma. This large age interval does not allow Isoplot software to calculate a single Concordia age. Two groups can be distinguished at 240 and near 220 Ma.

The CL image displays prismatic zircon crystals with oscillatory zoning, some with dark rims as it was observed in the zircons from the Huayna Potosí granite. Xenocrystal zircon yielded ages of 471, 583, 645, 1073, 1937 and 2132 Ma. For the age calculations, as we did on samples RIB-2 and RIB-4 two groups were differentiated (Fig. 18). Selected spots yielded a younger Concordia age of 227 ± 2 Ma (2σ). A second group of selected spots yielded an older Concordia age of 240 ± 2 Ma (2σ).

Finally, two samples (RIB-43 and RIB-46) were dated from the Quimsa Cruz granite. Sample RIB-43 presented U-Pb zircon ages ranging from 26 to 28 Ma. Zircon CL images show prismatic zircons with well-developed oscillatory zoning (Fig. 3). Xenocrystal zircon grains have ages of 34, 324 and 600 Ma. Spots used to calculate the age (Fig. 18) yielded a Concordia age of 27 ± 0.2 Ma (2σ). Spot 4.1 with U-Pb age of 33.7 Ma was considered a xenocrystal. Sample RIB-46 presented U-Pb ages ranging from 26 to 30 Ma. Its CL image shows prismatic zircons with well-developed oscillatory zoning similar to sample RIB-43. Xenocrystal zircons have ages of 1608 and 1655 Ma. Spots used

to the calculate age (Fig. 19) yielded a Concordia age of 27 ± 0.2 Ma (2σ). This younger Oligocene pulse of felsic magmatism yielded good analytical quality results, possibly related to the good looking appearance of its prismatic oscillatory zoned zircons, almost without dark domains (Fig. 3).

5.2. Zircon inheritance and saturation temperature

From the zircon CL images shown in figure 3, all studied granitic plutons present a significant amount of inherited zircon grains that record U-Pb ages older than 250 Ma. Tables 2A to 2O, show the existence of xenocrystal grains with ages from 330 to 2300 Ma. This is not dissimilar to other zircon age distributions found in Ordovician pelites from other localities of the Eastern Cordillera (e.g., Bahlburg *et al.*, 2011). However, some Proterozoic grains (found in the Zongo/Kuticucho granite) are distinctive of the Cordillera Real. Considering that the country rocks for the studied granitoids are metapelites of Ordovician and Silurian formations, which may also have recycled older sources, it is noticeable that some zircon ages range from 300 to 400 Ma.

FIG. 18. Concordia diagrams for sample RIB-15 (Illampu granite) displaying two calculated Concordia ages. For the younger age shown on top (A), Six spot sites were chosen (12.1, 6.1, 11.2, 4.1, 1.1 and 7.2) displayed as bold text on table 2D. For the older age shown below (B), 5 spots were chosen (3.1, 2.1, 8.2, 5.1 and 14.2) displayed also as bold text on table 2D. Grey ellipses were excluded from the age calculation and the light blue ellipses correspond to the calculated Concordia ages.

FIG. 19. Concordia diagram for sample RIB-43 (Quimsa Cruz granite). Thirteen zircon spot sites were chosen for the Concordia age calculation (15.1, 12.1, 7.1, 1.1, 9.1, 5.1, 2.1, 13.1, 10.1, 8.1, 6.2, 11.1 and 3.1), displayed as bold text on table 2N. Grey ellipses were excluded from the age calculation and the light blue ellipse corresponds to the calculated Concordia age.

FIG. 20. Concordia diagram for sample RIB-46 (Quimsa Cruz granite). Fourteen zircon spot sites were chosen for the Concordia age calculation (3.1, 8.2, 8.1, 6.1, 13.1, 5.1, 12.1, 11.1, 4.1, 11.2, 7.1, 9.1, 2.2 and 1.1), displayed as bold text on table 2O. Grey ellipses were excluded from the age calculation and the light blue ellipse corresponds to the calculated Concordia age.

The zircon grains that yield these ages have low Th/U ratios, and probably reflect some degree of U enrichment. A few of the grains record ages older than 2.2 Ga, and this age was also found nearby in the Amutara and Coroico (Ordovician) formations (Reimann *et al.*, 2010).

The zircon saturation temperature model of Watson and Harrison (1983) provides a good way to estimate temperatures and compositions at which magmas saturate in Zr and therefore crystallize zircon. Granites with high amount of inheritance have been termed as “cold granites”

by Miller *et al.* (2003) that described them as melts that do not reach temperatures sufficient to dissolve xenocrystal zircon, therefore showing high population of inheritance and less newly formed zircon autocrysts. These inherited xenocrysts saturate the melts in Zr at their sources; therefore, the temperatures obtained for this method are the upper limits for magmatic temperatures. Following the study of Miller *et al.* (2003), the assumed maximum temperature for cold granites is 766 °C.

Table 4 displays the “M values”, associated to the whole rock composition and the Zr saturation temperatures calculated for the Huayna Potosí and Illampu plutons, using the software GCDkit 5.0. It is shown in table 4 and in figure 21, which displays a histogram of zircon saturation temperatures and a diagram of these temperatures *versus* SiO₂. The mean calculated Zr saturation temperatures are 735 °C for granites, 76 °C for granodiorites and 774 °C for quartz-diorites.

TABLE 4. ZIRCON SATURATION TEMPERATURES AND M VALUES OF THE HUAYNA POTOSÍ AND ILLAMPU PLUTONS, BASED ON WATSON AND HARRISON (1983).

Sample	Pluton	Rock	M	SiO ₂	Temp. Zr. sat. °C
OL-COA	Illampu	Quartz-diorite	2.27	57.8	760
O-2	Illampu	Quartz-diorite	1.51	58.2	801
S-12-X	Illampu	Quartz-diorite	1.75	58.3	768
S-15	Illampu	Quartz-diorite	1.70	59.8	772
XE 1A	Huayna Potosí	Quartz-diorite	2.46	60.3	739
RIB-53	Huayna Potosí	Quartz-diorite	1.50	62.6	810
Geometric mean of Zr saturation temperatures (°C) quartz-diorites					774.4
RIB-20	Huayna Potosí	Granodiorite	1.25	66.0	740
O-7A	Illampu	Granodiorite	1.69	66.5	752
O-1	Illampu	Granodiorite	1.60	67.2	766
S-3	Illampu	Granodiorite	1.59	68.1	787
O-3	Illampu	Granodiorite	2.26	68.2	715
OL-Oc	Illampu	Granodiorite	1.26	68.4	786
S-22	Illampu	Granodiorite	1.58	68.6	786
Geometric mean of Zr saturation temperatures (°C) granodiorites					761.1
RIB-22	Huayna Potosí	Granite	1.13	70.64	742
RIB-19	Huayna Potosí	Granite	1.24	71.78	738
RIB-56	Huayna Potosí	Granite	1.14	73.30	790
RIB-55	Huayna Potosí	Granite	1.12	73.76	749
GRS 1	Huayna Potosí	Granite	1.70	73.93	724
RIB-5	Huayna Potosí	Granite	1.09	73.95	734
RIB-30	Huayna Potosí	Granite	1.06	74.07	678
RIB-2	Huayna Potosí	Granite	1.13	74.71	728
RIB-4	Huayna Potosí	Granite	1.12	74.95	726
S-19-Apl	Illampu	Aplite	1.47	78.55	750
Geometric mean of Zr saturation temperatures (°C) granites					735.4

Whole rock data was taken from unpublished compiled data. M values correspond to the ratio of $\frac{(Na+K+2Ca)}{(Al*Si)}$, SiO₂ in wt%.

The quartzdiorite enclaves of the Illampu and Taquesi granodiorites both yielded slightly older ages than their hosts. This can be explained by the zircon saturation temperatures discussed above, where higher

temperatures are needed for mafic magmas to saturate in Zr (Siégel *et al.*, 2018). Therefore, it is possible that the enclaves simply did not crystallize zircon and probably host antecrystal zircons from older pulses.

FIG. 21. Zircon saturation temperatures. **Top:** Histogram of Zr saturation temperatures. **Bottom:** Temperatures (°C) versus SiO₂ (wt%) diagram. Unpublished whole rock dataset for granitoids from the Cordillera Real.

6. Discussion

6.1. Magmatic pulses

The main goal of this paper is to obtain a better knowledge of the crystallization age of the Cordillera Real granitoids. However, as it can be seen in the Concordia diagrams of figures 4 to 20, it is not an easy task to obtain a single Concordia age to constrain the crystallization of these plutons.

At the larger regional scale we should consider the longevity of granitoid formation in continental arcs. Magmatism above subduction zones (melts, mushes, etc.) is episodic in space and time, at scales ranging from entire arcs to simple volcanoes. To study the temporal histories of magmatic arcs, several hundred (or more) U-Pb zircon measurements may be needed.

A large number of ages recording the periodicity of large arc-related magmatic systems has been documented along the western coast of the American continent (Paterson and Ducea, 2015). Time intervals for Mesozoic magmatic and bedrocks average 60–70 Ma, while for Cenozoic rocks the average is 20–30 Ma. For the case of the well studied and purely slab-related Sierra Nevada Batholith, a period of 72 Ma during the Triassic was found. In this context, relatively short time intervals of high magma addition rates are termed “flare-ups”. A well documented flare-up has been studied by De Silva and Gosnold (2007) in the Central Andes, known as the Altiplano Puna Volcanic Complex (APVC), which lasted 10 Ma and implies the construction of a batholith over that interval of time. These magmatic pulses and their protracted character is also supported by geochronological, geophysical, field and thermodynamic evidence, implying that plutons of batholithic size accumulate in several pulses over protracted time intervals (Glazner *et al.*, 2004). Following their model, a “regular” magma chamber of 5 km thick and 20 km wide, at 900 °C and a normal gradient of 20 °C/km will be completely crystallized in less than 1 Ma.

In our case, we have a long-lasting subduction system during the Gondwanide orogeny that started at 336 to 285 Ma (early stage) and ended at 230 to 205 Ma (late stage, Ramos, 2018). The wide range of observed zircon ages from 200 to 280 Ma for these cool magmas suggests the presence of antecrysts produced in earlier flare-up pulses of a protracted magmatic

arc (Paterson and Ducea, 2015). From the previous Concordia plots (Figs. 4 to 18), we believe that our plutons may record a final crystallization episode, in which pre-existing zircon crystals formed during former magmatic pulses are present. These zircon antecrysts may not have been reabsorbed due to the low temperature of these “cool magmas” (section 5.2), although their CL images (Fig. 3) show that they are indistinguishable from the new zircon crystals, formed during the final crystallization episode.

In order to visualize better this magmatic pulses, the Concordia ages obtained in our study (Figs. 4 to 20), were used to elaborate the figure 22 that displays histogram plots and respective kernel density curves, calculated using the software R (R Core Team, 2020)¹. For the case of the Huato pluton, the 11 Concordia ages of sample RIB-27 were used. For the case of the Illampu pluton samples RIB-32, RIB-33 and RIB-15 were combined (n=34). For the Taquesi pluton, we combined samples RIB-11 and RIB-12 (n=16). For the case of the Huayna Potosí pluton, samples RIB-2, RIB-4, RIB-19, RIB-20 and RIB-22 were combined (n=59). The few zircon ages that range from 260 to 280 were considered as early Gondwanide zircons and ages older than 400 Ma were rejected as we considered them as xenocrysts derived from the country rocks. Although subtle, two predominant peaks seem to appear on the populations of these four plutons.

In figure 23, two histograms display all measured Triassic and Oligocene Concordia ages. For the case of the Quimsa Cruz pluton, the two samples (RIB-43 and RIB-46) were combined, n=29. The age range suggests a main magmatic pulse from 28 to 25 Ma, with an early “antecrystic” population at 29–30 Ma. In the case of the Triassic ages, a protracted range of 60 Ma is displayed, possibly characterized by two pulses at 220 and 235 Ma.

Although it is tempting to constrain these two peaks of Concordia ages at 220 and 235 Ma for the whole Cordillera Real Triassic magmatism, as proposed by Cordani *et al.* (2019), we remain cautious and rather suggest a long time interval, probably biased by the existence of antecrysts formed in preceding pulses. This overall interval of 60 Ma falls within the range studied by Paterson and Ducea (2015) for arc-related Mesozoic magmatism: the age range recorded in the zircon antecrysts of the Cordillera Real plutons corresponds to magmatic pulses that were precursors of the final magmatic episode at 220 Ma.

¹ R Core Team 2020. R.A. Language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>.

FIG. 22. Histogram plots of Concordia ages of the Huato, Taquesi, Illampu and Huayna Potosí plutons showing number of samples (n) and in red the kernel density curves. In each case, the age distribution seems to display two peaks near 220 and between 230 to 240 Ma, maybe related to climatic flare-ups. Overall, the age pattern shows a protracted magmatism of about 60 Ma.

FIG. 23. Probability density plot of Concordia ages of the Triassic and Oligocene (Quimsa Cruz) plutons from the Cordillera Real showing number of samples (n) and in red the kernel density curves.

6.2. Xenocrystic population

As mentioned in Section 5.2, tables 2A to 2O include xenocrystal zircons with ages older than 300 Ma. Ages between 300 to 400 Ma could correspond to late Paleozoic magmatic rocks belonging to the Gondwanide orogeny. Some older ages are probably related to the early Paleozoic Famatinian arc and the largest peaks can be assigned to a late Neoproterozoic (Brasiliano) cycle. Even older sources are represented, sometimes by single zircon grains, with ages spanning the Proterozoic eon up to 2500 Ma.

Locally, the geodynamical environment in which the Triassic Real Cordillera granitoids were formed corresponds to a continental rift linked to the breakup of Pangea (Jiménez and López Velásquez, 2008; Sempere *et al.*, 2002; Ramos, 2018). The volcano-sedimentary Mitu Group in SE Perú is representative of this environment and the younger detrital zircon population from these sequences yields a U-Pb age of around 255 Ma (Spikings *et al.*, 2016). The probable “antecryst age” of about 250 Ma recorded in many of the zircon crystals of the Huayna Potosí pluton can be considered coeval with the initiation of the Mitu Rift. If the younger crystallization age of 222 Ma is considered as the end of both plutonism and the rifting stage, then it can be said that the duration of this local extensional regime was probably about 30 Ma. This interval seems to be reasonable for this type of environment and even falls within the shorter category when compared to longer time estimates (e.g., 55 Ma for the Norwegian-Greenland Sea Rift, Ziegler and Cloetingh, 2004).

6.3. The end of the magmatism. Rapid cooling and secondary processes

If we take in consideration the Ar-Ar age obtained by Gillis *et al.*, 2006, for the Huayna Potosí pluton (which was not affected by the thermal anomaly of the ZSGZ), with a well-defined plateau at 218 ± 3 Ma, it is the same, within experimental error, with our statistically optimal U-Pb age of 221 ± 3 Ma for the RIB-2 sample. Therefore, these two isotopic systems may have been closed at almost the same time, with fast cooling after this last magmatic pulse. Probably it means that the regional Sn-W mineralization may also have been contemporaneous with the crystallization and cooling of this pluton.

The final enrichment in fluids, bearing highly incompatible elements at the final stage of the pluton consolidation could be associated with the

U anomalies, sometimes bringing excess U and Pb to the zircons of the Cordillera Real granitoids. Probable remobilization of U and Pb associated to damage of the zircon crystal lattice and a potential matrix-related calibration bias during secondary ion mass spectrometry (SIMS) analysis (Kusiak *et al.*, 2013) produced the reverse discordias of figure 11.

Conclusions

The granitic plutons of the Cordillera Real fall within the “inner magmatic arc”, in a regional context of the Central Andes and holding an intraplate imprint reflected in the geotectonic and temporal environment. We have also contributed to the understanding of the generation of these plutons, indicating a possible time span for their emplacement and evolution.

All plutons of the Cordillera Real yielded U-Pb zircon ages showing the succession of magmatic events in time. It seems that all record a final crystallization episode with a similar Late Triassic age, preceded by magmatic pulses whose age is recorded by antecrysts. The Huayna-Potosí is the pluton with the most data and accounts for a protracted magmatic system history of about 60 Ma. One sample yielded an ^{40}Ar - ^{39}Ar age of 218 ± 3 Ma, which can be considered as a cooling age of the pluton. The overlap of the younger zircon population of sample RIB-2 (221 ± 3) and the mentioned ^{40}Ar - ^{39}Ar age indicates a rapid cooling interval for the granite.

The zircon saturation method yielded “low” average temperatures suggesting that the Real Cordillera plutons correspond to cold and consequently inheritance-rich granitoids. These cold granites recorded important xenocrystal and antecrystal inheritance, reflecting important geological events of magmatic crystallization from Precambrian to Phanerozoic times. U-Pb zircon geochronological studies of the antecrysts included in the plutons of the Cordillera Real could be of great help in deciphering the history and duration of the magmatic pulses, which would be very important to understanding the origin and development of the continental crust. The studied plutons also record the influence of the Gondwanide orogeny (336-205 Ma) as an overall subduction arc environment, punctuated in its final stage by continental rifting (245-220 Ma) related to the Mitu Rift.

Enrichment of residual melts in incompatible elements, probably related to the W-Sn mineralization stage, as well as posterior damage of the zircon crystal lattice could be the cause of reverse Discordia recorded by the Zongo/Kuticucho granite.

Acknowledgments

We would like to thank to the technical staff of the Centro de Pesquisas Geocronológicas (CPGeo), the professors of the Instituto de Geociências of the University of São Paulo and the professors of the Universidad Mayor de San Andrés for their help, dedication and technical support during the realization of the present paper. Special thanks to W. Vivallo and R.J. Pankhurst who kindly and thoroughly reviewed our paper.

References

- Ávila, W.A. 1990. Tin granites from the Cordillera Real, Bolivia; A petrological and geochemical review. Geological Society of America, Special paper 241: 145-159.
- Bahlburg, H.; Vervoort, J.D.; Andrew DuFrane, S.; Carlotto, V.; Reimann, C.; Cárdenas, J. 2011. The U-Pb and Hf isotope evidence of detrital zircons of the Ordovician Ollantaytambo Formation, southern Peru, and the Ordovician provenance and paleogeography of southern Peru and northern Bolivia. *Journal of South American Earth Sciences* 32 (3): 196-209. doi: 10.1016/j.jsames.2011.07.002.
- Bard, J.P.; Botello, R.; Martínez, C.; Subieta, T. 1974. Relations entre tectonique, métamorphisme et mise en place d'un granite Éohercynien a deux micas dans la Cordillere Real de Bolivie (massif de Zongo-Yani). *Orstom, IRD, VI*: 3-18.
- Bettencourt, J.S.; Leite, W.B.; Ruiz, A.S.; Matos, R.; Payolla, 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 (1): 28-46. doi: 10.1016/j.jsames.2009.08.006.
- Burnham, C. 1979. Magmas and hydrothermal fluids. *In* Geochemistry of Hydrothermal Ore Deposits (Second Edition) (Barnes, H.L.; editor). Wiley and Sons: 71-136. New York.
- Clark, A.H.; Farrar, E. 1973. The Bolivian tin province: Notes on the available geochronological data. *Economic Geology* 68: 102-116.
- Clark, A.H.; Farrar, E.; Kontak, D.J.; Langridge, R.J.; Arenas, F.M.J.; France, L.J.; McBride, S.L.; Woodman, P.L.; Wasteneys, H.A.; Sandeman, H.A.; Archibald, D.A. 1990. Geologic and geochronologic constraints on the metallogenic evolution of the Andes of southeastern Peru. *Economic Geology* 85 (7): 1520-1583. doi: 10.2113/gsecongeo.85.7.1520.
- Coleman, D.S.; Gray, W.; Glazner, A.F. 2004. Rethinking the emplacement and evolution of zoned plutons: geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California. *Geology* 32: 433-436.
- Cordani, U.G.; Ramos, V.A.; Fraga, L.M.; Cegarra, M.; Delgado, I.; De Souza, K.G.; Gomes, F.E.M.; Schobbenhaus, C. 2016. Tectonic Map of South America.
- Cordani, U.G.; Iriarte, A.R.; Sato, K. 2019. Geochronological systematics of the Huayna Potosí, Zongo and Taquesi plutons, Cordillera Real of Bolivia, by the K/Ar, Rb/Sr and U/Pb methods. *Brazilian Journal of Geology*. doi: 10.1590/2317-4889201920190016.
- Corfu, F.; Hanchar, J.M.; Hoskin, P.W.O.; Kinny, P. 2003. Atlas of Zircon Textures. *In* Zircon (Hanchar, J.M.; Hoskin, P.W.O.; editors). Reviews in Mineralogy and Geochemistry, Mineralogical Society of America 53: 469-500.
- De Silva, S.L.; Gosnold, W.D. 2007. Episodic construction of batholiths: Insights from the spatiotemporal development of an ignimbrite flare-up. *Journal of Volcanology and Geothermal Research* 167 (1-4): 320-335. doi: 10.1016/j.jvolgeores.2007.07.015.
- Evernden, J.F.; Kriz, S.J.; Cherroni M., C.C. 1977. Potassium-argon ages of some Bolivian rocks-a discussion. *Economic Geology* 72: 1042-1061. doi: 10.2113/gsecongeo.74.3.702.
- Farrar, E.; Clark, A.H.; Kontak, D.J.; Archibald, D.A. 1988. Zongo-San Gabán zone: Eocene foreland boundary of the Central Andean orogen, northwest Bolivia and southeast Peru. *Geology* 16 (1): 55-58. doi: 10.1130/0091-7613(1988)016<0055:ZSGNZE>2.3.CO;2.
- Farrar, E.; Clark, A.H.; Heinrich, S.M. 1990. The Age of the Zongo Pluton and the Evolution of the Zongo San Gaban Zone in the Cordillera Real, Bolivia. *In* Symposium International "Géodynamique andine": résumés des communications: 171-174. Grenoble.
- Faure, G.; Mensing, T.M. 2005. Isotopes Principles and Applications. Third Edition. John Wiley and Sons: 928 p. New Jersey.
- Geobol, 1968. Investigaciones Preliminares sobre Tectónica y Metalogénesis en las Cordilleras Real y Quimsa Cruz. División de Tecnología Minera, Ministerio de Minas, Servicio Geológico de Bolivia, Boletín 9: 24-25.
- Grant, J.N.; Halls, C.; Salinas, W.A.; Snelling, N. J. 1979. K-Ar ages of igneous rocks in mineralization in part of the Bolivian tin belt. *Economic Geology* 74 (4): 838-851. doi: 10.2113/gsecongeo.74.4.838.
- Gillis, R.J.; Horton, B.K.; Grove, M. 2006. Thermochronology, geochronology, and upper crustal structure of the Cordillera Real: Implications for Cenozoic exhumation of the central Andean plateau. *Tectonics* 25 (6): 1-22. doi: 10.1029/2005TC001887.
- Glazner, A.F.; Bartley, J.M.; Coleman, D.S.; Gray, W.; Taylor, R.Z. 2004. Are plutons assembled over millions of years by amalgamation from small magma chambers? *GSA Today* 14 (4-5): 4-11. doi: 10.1130/1052-5173(2004)0142.0.CO;2.
- Jiménez, N.; López-Velásquez, S. 2008. Magmatism in the Huarina belt, Bolivia, and its geotectonic implications. *Tectonophysics* 459 (1-4): 85-106. doi: 10.1016/j.tecto.2007.10.012.

- Kontak, D.J.; Clark, A.H.; Farrar, E.; Archibald, D.A.; Baadsgaard, H. 1990. Late Paleozoic-early Mesozoic magmatism in the Cordillera de Carabaya, Puno, southeastern Peru: Geochronology and petrochemistry. *Journal of South American Earth Sciences* 3 (4): 213-230.
- Kusiak, M.A.; Whitehouse, M.J.; Wilde, S.A.; Nemchin, A.A.; Clark, C. 2013. Mobilization of radiogenic Pb in zircon revealed by ion imaging: Implications for early Earth geochronology. *Geology* 41-3: p. 291-294. doi: 10.1130/G33920.1.
- Litherland, M.; Annells, R.N.; Darbyshire, D.P.F.; Fletcher, C.J.N.; Hawkins, M.P.; Klinck, B.A.; Mitchell, W.I.; O'Connor, E.A.; Pitfield P.E.J.; Power, G.; Webb, B.C. 1989. The proterozoic of Eastern Bolivia and its relationship to the Andean mobile belt. *Precambrian Research* 43 (3): 157-174. doi: 10.1016/0301-9268(89)90054-5.
- Loewy, S.L.; Connelly, J.N.; Dalziel, I.W.D. 2004. An orphaned basement block: The Arequipa-Antofalla Basement of the central Andean margin of South America. *Bulletin of the Geological Society of America* 116 (1-2): 171-187. doi: 10.1130/B25226.1.
- Ludwig, K. 2009. SQUID 2: A User's Manual, rev. 12 Apr, 2009. Berkeley Geochronology Center, Special Publication 5: 110 p.
- Lundstrom, C.C.; Glazner, A.F. 2016. Silicic magmatism and the volcanic-plutonic connection. *Elements* 12 (2): 91-96. doi: 10.2113/gselements.12.2.91.
- Mcbride, S.L.; Robertson, R.C.R.; Clark, A.H.; Edward, F. 1983. Magmatic and Metallogenetic Episodes in the Northern Tin Belt, Cordillera Real. Bolivia. *Geologische Rundschau* 72 (2): 685-713.
- Mcbride, S.L.; Clark, A.H.; Farrar, E.; Archibald, A. 1987. Delimitation of a cryptic Eocene tectono-thermal domain in the Eastern Cordillera of the Bolivian Andes through K-Ar dating and ^{40}Ar - ^{39}Ar step-heating. *Journal of the Geological Society* 144: 243-255. London.
- Miller, C.F.; McDowell, S.M.; Mapes, R.W. 2003. Hot and cold granites: Implications of zircon saturation temperatures and preservation of inheritance. *Geology* 31 (6): 529-532. doi: 10.1130/00917613(2003)031<0529:HA CGIO>2.0.CO;2.
- Paterson, S.R.; Ducea, M.N. 2015. Arc magmatic tempos: Gathering the evidence. *Elements* 11 (2): 91-98. doi: 10.2113/gselements.11.2.91.
- Ramos, V.A. 2009. Anatomy and global context of the Andes: Main geologic features and the Andean orogenic cycle. *Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision*. Geological Society of America, Memoirs 1204 (204): 31-65. doi: 10.1130/2009.1204(02).
- Ramos, V.A. 2018. Tectonic evolution of the central Andes: From terrane accretion to crustal delamination. In *Petroleum basins and hydrocarbon potential of the Andes of Peru and Bolivia* (Zamora, G.; McClay, K.M.; Ramos, V.A.; editors). American Association of Petroleum Geologists, Memoir 117: 1-34. doi: 10.1306/13622115M1172855.
- Reimann, C.R.; Bahlburg, H.; Kooijman, E.; Berndt, J.; Gerdes, A.; Carlotto, V.; López, S. 2010. Geodynamic evolution of the early Paleozoic Western Gondwana margin 14°-17°S reflected by the detritus of the Devonian and Ordovician basins of southern Peru and northern Bolivia. *Gondwana Research* 18 (2-3): 370-384. doi: 10.1016/j.gr.2010.02.002.
- Romer, R.L.; Kroner, U. 2016. Phanerozoic tin and tungsten mineralization-Tectonic controls on the distribution of enriched protoliths and heat sources for crustal melting. *Gondwana Research* 31: 60-95. doi: 10.1016/j.gr.2015.11.002.
- Sandeman, H.A.; Clark, A.H.; Farrar, E. 1995. An Integrated Tectono-Magmatic Model for the Evolution of the Southern Peruvian Andes (13-20°S) since 55 Ma. *International Geology Review* 37 (12): 1039-1073. doi: 10.1080/00206819509465439.
- Sato, K.; Tassinari, C.C.G.; Basei, M.A.S.; Siga, O.; Onoe, A.T.; De Souza, M.D. 2014. Sensitive High Resolution Ion Microprobe (SHRIMP IIe/MC) of the Institute of Geosciences of the University of São Paulo, Brazil: Analytical method and first results. *Geologia, University of São Paulo, Serie Científica* 14 (3): 3-18. doi: 10.5327/Z1519-874X201400030001.
- Sempere, T.; Carlier, G.; Soler, P.; Fornari, M.; Carlotto, V.; Jacay, J.; Arispe, O.; Néraudeau, D.; Cárdenas, J.; Rosas, S.; Jiménez, N. 2002. Late Permian-Middle Jurassic lithospheric thinning in Peru and Bolivia, and its bearing on Andean-age tectonics. *Tectonophysics* 345 (1-4): 153-181. doi: 10.1016/S0040-1951(01)00211-6.
- Siégl, C.; Bryan, S.E.; Allen, C.M.; Gust, D.A. 2018. Use and abuse of zircon-based thermometers: A critical review and a recommended approach to identify antecrystic zircons. *Earth-Science Reviews* 176: 87-116. doi: 10.1016/j.earscirev.2017.08.011.
- Spikings, R.; Reitsma, M.J.; Boekhout, F.; Mišković, A.; Ulianov, A.; Chiaradia, M.; Gerdes, A.; Schaltegger, U. 2016. Characterisation of Triassic rifting in Peru and implications for the early disassembly of western Pangaea. *Gondwana Research* 35: 124-143. doi: 10.1016/j.gr.2016.02.008.
- Steiger, R.H.; Jäger, E. 1977. Subcommission on Geochronology: Convention on the use of decay constants in geo- and cosmochronology. *Earth and Planetary Science Letters* 36: 359-362.

- Watson, E.B.; Harrison, T.M. 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth and Planetary Science Letters* 64: 295-304.
- Williams, I.S. 1998. U-Th-Pb geochronology by ion microprobe. *In* *Application of Microanalytical Techniques to Understanding Mineralizing Processes* (McKibben, M.A.; Shanks, I.; Ridley, W.C.P.; Ridley, W.I.; editors). *Reviews in Economic Geology* 7: 1-35.
- Ziegler, P.A.; Cloetingh, S. 2004. Dynamic processes controlling evolution of rifted basins. *Earth-Science Reviews* 64 (1-2): 1-50. doi: 10.1016/S0012-8252(03)00041-2.

**CHAPTER 5 – Submitted to the Brazilian Journal of Geology - Provenance
study of phanerozoic rocks from the Cordillera Real of Bolivia**

Iriarte, A.R., Cordani, U.G., & Basei, M.A.S. (2021)

ARTICLE

Provenance study of Phanerozoic rocks from the Cordillera Real of Bolivia

Alvaro Rodrigo Iriarte^{1,2*}, Umberto Giuseppe Cordani¹, Miguel Basei¹

¹Universidade de São Paulo – São Paulo (SP), Brazil. E-mails: arodrigoiriarte@usp.br, ucordani@usp.br, baseimas@usp.br

²Universidad Mayor de San Andrés – La Paz, Bolivia.

*Corresponding author.

Supplementary data

Supplementary data associated with this article can be found in the online version: Supplementary Table 1 (<http://sfbjg.siteoficial.ws/Sf/2021/4889202120210036.pdf>).

Abstract

U/Pb ages of detrital zircon from two samples of Ordovician sediments were determined and, based on similar published data, were compared with xenocrystal inheritance of Triassic and Oligocene granitoids of the Cordillera Real in order to gain a better understanding of their genetic relationship and sources. The results show that the detrital zircon in the Ordovician sandstone and the inherited zircon cores in granitoids are statistically correlated. This correlation suggests assimilation of these sedimentary units by the felsic melts. Ages ranging from 300 to 2300 Ma were recorded by these inherited zircons. A high peak of Cambrian to late Neoproterozoic ages (500–750 Ma) is observed through metasedimentary units of the entire belt. We discuss the possibilities that the main sources could be associated with several candidates: Brasileiro or Pampean belts and/or an “in situ” hidden belt within the Central Andes or recycling of pre-existent sedimentary rocks bearing those detrital zircons. It is also possible that the sources lie below the modern sedimentary covers and, at the time, formed high reliefs supplying recycled material into the Ordovician basins.

KEYWORDS: U/Pb zircon dating; Central Andes; granitoids; Ordovician sediments.

INTRODUCTION

The dating of sedimentary sequences has been improved over the last decades thanks to the use of mass spectrometers capable of analyzing large numbers of mineral samples, so that the ages of stratigraphic units can be better understood. Mass spectrometers used to date zircon and other key minerals are Sensitive High-Resolution Ion Micro Probe (SHRIMP) (secondary ionization) and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) (laser excitation). The latter is more extensively used in provenance studies, because of the relatively low cost and rapid results.

The Central Andes, from southern Peru to northern Chile, are cored by an orogenic belt along the western border of South America. It is mostly characterized by Phanerozoic sedimentary and metamorphic sequences intruded by Paleozoic to Recent granitoids. Several regional studies have shown a complex history through geological time, consisting of terrane amalgamation, mobile belt tectonism, mountain building, erosion, and recycling (Franz *et al.* 2006, Jiménez and López-Velásquez 2008, Ramos 2018). U/Pb zircon ages and geochemical signatures reflect these processes. In this sense, it has been shown that most sources of detrital materials are located in neighboring eastern Amazonia (Reimann *et al.* 2010; Calle *et al.* 2017, Vasconcelos 2018).

For the case of the Cordillera Real of Bolivia, Triassic granitic intrusive magmas interacted with pre-existing sedimentary sequences. As shown by field evidence and isotopic signature (Cordani *et al.* 2019), processes such as AFC (assimilation and crystal fractionation, DePaolo 1981) can be easily envisioned as plausible during emplacement.

Analyses of U/Pb ages recorded (and conserved) in zircon crystals of granites and their country rocks have been very useful to understand “hidden” basement rocks below the surface, which are the potential sources for these granitic melts (e.g., the Lachlan fold belt, Keay *et al.* 1999).

The objectives of this paper are: to compare the U/Pb ages of detrital zircons of early-Paleozoic sedimentary country rocks with those of xenocrystal zircon crystals from the granitoids of the Cordillera Real in order to better understand the genetic relationship between granites and their sedimentary envelope; and to picture the potential paleo-relief in South America during Triassic times, and envisage potential source areas of detrital zircon grains.

GEOLOGICAL BACKGROUND

The Cordillera Real granitoids (CRG) are a group of upper crustal plutons emplaced at ca. 220 Ma, with a younger pulse at ca. 27 Ma (Gillis *et al.* 2006, Cordani *et al.* 2019, Iriarte *et al.* 2021). Their country rocks have early Paleozoic ages (Fig. 1) and continue towards SE Peru. There, Kontak *et al.* (1990) described the intrusive suite of the Carabaya Cordillera, as a complex suite of felsic and mafic magmatic units. Regionally, this magmatism corresponds to the Gondwanide Orogeny (336–200 Ma, Ramos 2018), characterized by an overall subduction system, which was synchronous at 240 Ma with a regional continental rift.

Cordillera Real Granitoids

The CRGs are a suite of sub-circular to elliptical plutons, emplaced along the NW strike axis of the Eastern Cordillera (Fig. 1). They are composed of quartz-diorites, monzonites, granodiorites, and two mica granites with calc-alkaline within plate affinities, some being peraluminous.

U/Pb SHRIMP dating (Gillis *et al.* 2006, Iriarte *et al.* 2021) revealed a protracted history of magmatism of nearly 60 Ma, starting at ca. 280 and ending at ca. 220 Ma. Quartz diorites and tonalites were emplaced at the beginning of the continental rift (~280 Ma). Magmas “evolved” via an AFC process towards more calc-alkaline compositions, during final pluton crystallization at 220 Ma.

Because of the relatively low zircon saturation temperatures, oversaturation, and, therefore, better preservation of inheritance and assimilated wall rock material, zircon antecrysts and xenocrysts were conserved (Tab. 1 and Fig. 1, Iriarte *et al.* 2021). Ages of inherited zircons range from ca. 330 Ma (initiation of the Gondwanide orogeny) to ca. 2300 Ma. Most are inherited cores surrounded by younger overgrowths (Cordani *et al.* 2019). As the country rocks are early Paleozoic sediments, most xenocrysts were probably derived from these stratigraphic units during the emplacement of S-like granites (Ávila 1990).

Figure 1 shows that, except for the Oligocene Quimsa Cruz pluton, all the others are Triassic in age. The distance between the Huato pluton in the NW and the Quimsa Cruz pluton in the SE is about 250 Km. Moreover, Figure 1 shows that all plutons cut through the entire thickness of the Amutara Formation, of the order of several hundred meters, as well as through the sedimentary pile underneath, belonging to the Eastern Andes. To check the

possibility that the xenocrysts encountered in the Cordillera Real plutons could be grains inherited from these sedimentary rocks, we tried to compare them with the detrital grains included in the Ordovician sediments.

Source: modified from published maps of the Geological Service of Bolivia (GEOBOL 1994, 1995, 1997, 2013).

Figure 1. Cordillera Real granitoids (CRGs) showing their U/Pb crystallization ages (in black) and age ranges of inherited xenocrystal zircons (in red). The country rock is mostly represented by the Amutara Fm.

Table 1. SHRIMP U, Th/U, percentage of Concordia discordance, dates ± 1 sigma error (Ma), isotopic ratios $\pm 1\%$ error from the granitoids of Cordillera Real (Iriarte *et al.* 2021). Ranges from 298 to 479 Ma, n = 20 (in italic) were excluded for statistical comparison with the Ordovician units. Highly discordant zircon spots are discussed by Cordani *et al.* (2019). Errors in U/Pb ages are ± 1 sigma (corresponding to $\sim 1\%$ of calculated age).

<i>Pluton</i>	<i>Sample</i>	<i>U</i>	<i>Th/U</i>	<i>% Disc.</i>	<i>²⁰⁷Pb/²⁰⁶Pb (Ma)</i>	<i>$\pm 1s$ (Ma)</i>	<i>²⁰⁶Pb/²³⁸U (Ma)</i>	<i>$\pm 1s$ (Ma)</i>	<i>²⁰⁷Pb*/²³⁵U</i>	<i>$\pm\%$</i>	<i>²⁰⁶Pb*/²³⁸U</i>	<i>$\pm\%$</i>	<i>err corr</i>
Huato n = 3	<i>RIB-27</i>	<i>135</i>	<i>0.131</i>	+5	<i>314</i>	<i>427</i>	<i>299</i>	<i>5</i>	<i>0.350</i>	<i>18.8</i>	<i>0.048</i>	<i>1.70</i>	<i>0.1</i>
	<i>RIB-27</i>	<i>477</i>	<i>0.591</i>	-0	<i>609</i>	<i>24</i>	<i>610</i>	<i>7</i>	<i>0.823</i>	<i>1.6</i>	<i>0.099</i>	<i>1.20</i>	<i>0.8</i>
	<i>RIB-27</i>	<i>235</i>	<i>0.095</i>	+0	<i>793</i>	<i>23</i>	<i>790</i>	<i>9</i>	<i>1.180</i>	<i>1.6</i>	<i>0.130</i>	<i>1.20</i>	<i>0.7</i>
Illampu n = 6	<i>RIB-15</i>	<i>317</i>	<i>0.5</i>	+1	<i>471</i>	<i>61</i>	<i>469</i>	<i>5</i>	<i>0.590</i>	<i>3</i>	<i>0.075</i>	<i>1.10</i>	<i>0.4</i>
	<i>RIB-15</i>	<i>395</i>	<i>1.4</i>	+1	<i>583</i>	<i>34</i>	<i>579</i>	<i>6</i>	<i>0.770</i>	<i>1.9</i>	<i>0.094</i>	<i>1.10</i>	<i>0.6</i>
	<i>RIB-15</i>	<i>76</i>	<i>0.52</i>	+6	<i>645</i>	<i>185</i>	<i>610</i>	<i>8</i>	<i>0.840</i>	<i>8.7</i>	<i>0.099</i>	<i>1.40</i>	<i>0.2</i>
	<i>RIB-15</i>	<i>247</i>	<i>0.46</i>	-2	<i>1,073</i>	<i>24</i>	<i>1,091</i>	<i>11</i>	<i>1.910</i>	<i>1.7</i>	<i>0.184</i>	<i>1.1</i>	<i>0.7</i>
	<i>RIB-15</i>	<i>159</i>	<i>0.29</i>	+41	<i>1,937</i>	<i>20</i>	<i>1,217</i>	<i>13</i>	<i>3.400</i>	<i>1.6</i>	<i>0.208</i>	<i>1.2</i>	<i>0.7</i>
	<i>RIB-15</i>	<i>164</i>	<i>0.61</i>	+5	<i>2,132</i>	<i>17</i>	<i>2,046</i>	<i>21</i>	<i>6.830</i>	<i>1.5</i>	<i>0.374</i>	<i>1.2</i>	<i>0.8</i>
Huayna Potosí n = 19	<i>RIB-2</i>	<i>931</i>	<i>0.16</i>	-4	<i>300</i>	<i>46</i>	<i>312</i>	<i>6</i>	<i>0.358</i>	<i>2.7</i>	<i>0.050</i>	<i>1.8</i>	<i>0.7</i>
	<i>RIB-20</i>	<i>533</i>	<i>0.2</i>	+74	<i>1,600</i>	<i>29</i>	<i>454</i>	<i>8</i>	<i>0.993</i>	<i>2.4</i>	<i>0.0730</i>	<i>1.9</i>	<i>0.8</i>
	<i>RIB-4</i>	<i>500</i>	<i>0.04</i>	+16	<i>458</i>	<i>33</i>	<i>385</i>	<i>9</i>	<i>0.477</i>	<i>2.9</i>	<i>0.062</i>	<i>2.5</i>	<i>0.9</i>
	<i>RIB-4</i>	<i>279</i>	<i>0.48</i>	+20	<i>579</i>	<i>30</i>	<i>468</i>	<i>7</i>	<i>0.616</i>	<i>2</i>	<i>0.075</i>	<i>1.5</i>	<i>0.7</i>

	RIB-22	154	0.61	+38	786	42	500	8	0.726	2.6	0.081	1.6	0.6
	RIB-2	175	0.44	+16	599	44	509	44	0.678	2.5	0.082	1.5	0.6
	RIB-22	301	0.28	+16	865	28	733	7	1.127	1.7	0.120	1.0	0.6
	RIB-22	290	0.25	+14	878	21	759	6	1.177	1.3	0.125	0.8	0.6
	RIB-2	1,282	0.03	-0	573	14	573	8	0.759	1.5	0.093	1.4	0.9
	RIB-2	28,696	0.01	-23	474	24	577	13	0.730	2.5	0.094	2.3	0.9
	RIB-19	225	0.59	+6	633	32	599	5	0.817	1.7	0.097	0.9	0.5
	RIB-2	437	0.64	+1	606	15	602	6	0.810	1.2	0.098	1.0	0.8
	RIB-2	636	0.06	+10	881	12	801	13	1.248	1.8	0.132	1.7	0.9
	RIB-2	456	0.16	+21	1,472	8	1,186	22	2.568	2.1	0.202	2.1	1.0
	RIB-4	253	0.4	+6	1,439	10	1,364	18	2.945	1.6	0.236	1.5	0.9
	RIB-20	121	0.27	+34	2,023	13	1,413	18	4.210	1.6	0.245	1.4	0.9
	RIB-4	393	0.68	+16	1,934	6	1,655	21	4.784	1.5	0.293	1.4	1.0
	RIB-4	68	0.33	+2	2,058	13	2,026	29	6.470	1.8	0.369	1.7	0.9
	RIB-4	313	0.54	+24	2,600	4	2,070	18	9.105	1.1	0.379	1.0	1.0
Zongo n = 30	<i>RIB-30</i>	<i>18,333</i>	<i>0.024</i>	<i>-34</i>	<i>224</i>	<i>47</i>	<i>298</i>	<i>3</i>	<i>0.331</i>	<i>2.2</i>	<i>0.047</i>	<i>0.86</i>	<i>0.4</i>
	<i>RIB-30</i>	<i>15,654</i>	<i>0.014</i>	<i>-6</i>	<i>283</i>	<i>35</i>	<i>301</i>	<i>2</i>	<i>0.342</i>	<i>1.8</i>	<i>0.048</i>	<i>0.82</i>	<i>0.5</i>
	<i>RIB-30</i>	<i>15,917</i>	<i>0.006</i>	<i>-41</i>	<i>216</i>	<i>58</i>	<i>303</i>	<i>3</i>	<i>0.335</i>	<i>2.7</i>	<i>0.048</i>	<i>0.92</i>	<i>0.3</i>
	<i>RIB-30</i>	<i>17,698</i>	<i>0.006</i>	<i>-50</i>	<i>205</i>	<i>52</i>	<i>306</i>	<i>3</i>	<i>0.337</i>	<i>2.4</i>	<i>0.049</i>	<i>0.89</i>	<i>0.4</i>
	<i>RIB-5</i>	<i>197</i>	<i>0.25</i>	<i>+30</i>	<i>462</i>	<i>87</i>	<i>326</i>	<i>4</i>	<i>0.402</i>	<i>4.1</i>	<i>0.052</i>	<i>1.1</i>	<i>0.3</i>
	<i>RIB-5</i>	<i>36,691</i>	<i>0.005</i>	<i>-58</i>	<i>212</i>	<i>17</i>	<i>331</i>	<i>5</i>	<i>0.366</i>	<i>1.7</i>	<i>0.053</i>	<i>1.5</i>	<i>0.9</i>

	RIB-5	1,958	0.15	+4	349	15	335	5	0.393	1.5	0.053	1.4	0.9
	RIB-5	15,652	0.005	-11	314	26	348	5	0.403	1.8	0.055	1.5	0.8
	RIB-5	8,353	0.005	-32	273	16	359	11	0.408	3.2	0.057	3.1	1.0
	RIB-5	705	0.23	+11	443	32	395	5	0.485	2.0	0.063	1.4	0.7
	RIB-5	1,306	0.05	+38	659	44	415	5	0.565	2.5	0.067	1.4	0.6
	RIB-5	16,273	0.01	-157	182	14	457	17	0.504	3.9	0.074	3.8	1.0
	RIB-5	759	0.23	+11	534	24	479	6	0.619	1.8	0.077	1.4	0.8
	RIB-30	488	0.38	+4	529	27	507	6	0.654	1.7	0.082	1.2	0.7
	RIB-5	2,261	0.01	-7	502	17	537	5	0.686	1.2	0.087	1.0	0.8
	RIB-5	296	0.35	-3	542	31	557	6	0.725	1.7	0.090	1.0	0.6
	RIB-5	662	0.37	-1	573	20	579	6	0.767	1.4	0.094	1.1	0.8
	RIB-5	312	0.19	+55	1,286	27	607	9	1.139	2.1	0.099	1.6	0.8
	RIB-5	421	0.3	+48	1,579	71	869	32	1.942	5.5	0.144	4.0	0.7
	RIB-30	201	0.228	+18	1,167	34	974	13	1.771	2.2	0.163	1.4	0.6
	RIB-5	792	0.05	+50	1,840	7	987	9	2.566	1.1	0.165	1.0	0.9
	RIB-5	227	0.6	-4	986	18	1,020	10	1.701	1.4	0.171	1.1	0.8
	RIB-5	161	0.34	+0	1,149	24	1,148	12	2.099	1.6	0.195	1.1	0.7
	RIB-30	191	0.33	+5	1,291	42	1,228	17	2.429	2.7	0.210	1.5	0.6
	RIB-30	89	0.79	-2	1,425	111	1,451	27	3.131	6.2	0.252	2.1	0.3
	RIB-5	291	0.89	+12	1,675	21	1,503	19	3.721	1.8	0.263	1.4	0.8
	RIB-5	151	0.62	+2	1,661	12	1,638	16	4.070	1.3	0.289	1.1	0.9

	RIB-30	119	0.4	+19	1,993	14	1,661	25	4.966	1.9	0.294	1.7	0.9
	RIB-5	106	0.53	-1	1,802	22	1,824	24	4.965	2.0	0.327	1.5	0.8
	RIB-30	16,246	0.004	+13	2,603	10	2,323	33	10.451	1.8	0.434	1.7	0.9
Taquesi n = 2	RIB-11	226	0.6	+2	582	34	573	15	0.761	3.1	0.093	2.7	0.9
	RIB-12	211	0.6	+25	698	44	530	8	0.740	2.6	0.086	1.61	0.6
Quimsa Cruz n = 4	<i>RIB-43</i>	<i>740</i>	<i>0.2</i>	<i>+66</i>	<i>907</i>	<i>29</i>	<i>324</i>	<i>3</i>	<i>0.492</i>	<i>1.7</i>	<i>0.052</i>	<i>0.9</i>	<i>0.5</i>
	RIB-43	257	0.4	+1	606	33	600	5	0.807	1.8	0.097	0.9	0.5
	RIB-46	367	0.6	+7	1,707	7	1,608	12	4.087	0.9	0.283	0.82	0.9
	RIB-46	121	0.8	-0	1,645	30	1,648	28	4.063	2.5	0.291	1.93	0.8

Table 1 shows that a total of 64 zircon xenocrysts was recovered from the plutons studied by Iriarte *et al.* (2021). Twelve of them are younger than the Ordovician Amutara Formation and, therefore, must be considered as grains ultimately inherited from igneous intrusions related to the Famatinian or Gondwanan magmatic rocks. It is also possible that these detrital zircons came from sedimentary sources bearing older xenocrysts (> ca. 480 Ma).

These 44 zircon crystals, with U-Pb SHRIMP Precambrian or Cambrian ages, most likely originated as detrital grains within the Ordovician units. Many of these zircon grains were scattered in the Zongo (17) and Huayna Potosi (15) plutons, located not far from the location of RIB-51 and RIB-57 samples (see Figure 1). The remaining 12 grains were from the Huato (2), Illampu (5) Taquesi (2), and Quimsa Cruz (3) plutons. Assuming that these xenocrysts were indeed previous detrital zircon crystals belonging to the country rocks, to achieve a better statistical representation, all pre-Ordovician ages were grouped as composite sample CRG.

Stratigraphy of Ordovician country rocks

Ordovician sedimentary units are widespread along the Central Andes, including the Altiplano, the Western and Eastern cordilleras. Locally, they belong to the Tacsarian Cycle, which includes Cambrian and Ordovician sedimentary sequences (Suárez-Soruco 1992).

The oldest outcropping unit of the area of study is the Coroico Formation (Suárez-Soruco 1992) a thick metapelite sequence of shales and mudstones deposited in a deep marine shelf. It grades upwards to coarser grain size banks. Fossil fauna suggests a Llanvirnian age (~470 Ma). The passage from the Coroico Formation to the upper Amutara Formation is transitional. The Tacsarian Cycle ends in the northern Eastern Cordillera with an alternation of sandstones, and mudstones of hundreds of meters thick. These rocks are considered to be Upper Ordovician in age and were designated as the Amutara Formation (Fig. 1, Voges 1962). They were deposited in a marine shelf within a foreland basin. Fossil fauna suggests a Sandbian age (~458 Ma).

Sample site description

We took samples from two sedimentary units near the contact with plutons representative of the CRG for our study of provenance and then we compared our results with results related to sedimentary units from published data.

Sample RIB-51 was taken from the NE flank of a small anticline at the SW border of the Huayna Potosí granite (S16°17'36.33", W68°7'56.61", Fig. 1). It is characterized by 5 to 10 cm thick laminated banks of sandstone affected by the veining of iron oxides. It strikes N136°W dipping 53° NE. A thin section analysis shows rounded clasts of quartz (74%), muscovite (10%), and a matrix made mostly of clays (10%), minor tourmaline (< 1%), (30 to 100 µm) rounded zircon, and iron oxides.

Sample RIB- 57 was taken from a sequence of schists cropping out at the NE border of the Zongo granite (S16°6'17.84", W68°3'58.69", Fig. 1). It is characterized by porphyroblasts of andalusite (up to 5 cm in length) surrounded by a matrix of micas and quartz. It strikes N170°S dipping 65° NE. A thin section analysis shows rounded porphyroblasts of quartz (20%), andalusite (15%), biotite (18%), muscovite (10%), clastic matrix (30%), tourmaline (2%), minor amounts (< 1%) of anhedral zircon (10 to 100 µm), apatite, and iron oxides.

METHODOLOGY: LA-ICP-MS ANALYSES

Sample preparation, cathodoluminescence imaging (CL), and geochronological analyses were carried out at Centro de Pesquisas Geocronológicas, at Universidade de São Paulo, Instituto de Geociências. Zircon crystals were extracted from crushed and sieved rocks using magnetic and heavy liquid separation methods. Hand-picked crystals from each sample were arranged in rows, cast into epoxy resin discs, and polished to reveal grain internal structures. The reference standard used to calibrate the measured U/Pb ratios was GJ-1 (Wiedenbeck *et al.* 1995, Black *et al.* 2003, Elhlou *et al.* 2006). Prior to LA-ICP-MS analysis, CL and transmitted images were obtained from zircon crystals, so that the best sites for analysis could be chosen.

All analyses were performed using a Neptune multi-collector inductively plasma mass spectrometer (ICP–MS) coupled with an Analyte G2 excimer laser ablation (LA) system. The analyses were conducted in groups of 13 samples, each sample providing 40 sequential measurements (integration time ca. 1 s/cycle). Seven isotopes signals were synchronously

measured: four in Faraday cups (greatest amplitude): 206, 208, 232, 238 and three in Multiple Ion Counters (greater sensitivity): 202, 204 and 207. The U–Pb analysis was done in the following order: two blanks, two NIST standard glasses, three external standards, 13 unknown samples, two external standards, and two blanks. An interpolation of the four blank measurement sequences, two before and two after the samples (bracketing method), was subtracted from each one of the seven measured masses (202, 204, 206, 207, 208, 232 and 238).

A final bracketing (three before and two after the samples) of the standard minerals was then used to correct the effect of the fractionation on the four ratios ($^{206}\text{Pb}/^{238}\text{U}$, $^{207}\text{Pb}/^{235}\text{U}$, $^{207}\text{Pb}/^{206}\text{Pb}$, $^{208}\text{Pb}/^{232}\text{Th}$), before they could finally be extrapolated through best line fits to $t = 0$ and then used to calculate the respective ages. Errors in all simple arithmetic operations were algebraically propagated. Least-squares fitting was the choice for the best line fits and, on all final results and plots, the 2σ error calculated by Isoplot 3.70 (Ludwig 2009) was adopted. CL images are shown in Figures 2 and 3. Analytical data are shown in the Supplementary Table 1.

Figure 2. CL images of selected detrital zircons for sample RIB-51 (sandstone, Amutara Fm.). Spot site is marked by a circle.

Figure 3. CL images of selected detrital zircons for sample RIB-57 (schist, Coroico Fm.). Spot site is marked by a circle.

HISTOGRAM AND STATISTICAL ANALYSES

Figure 4 is a probability density plot of the $^{206}\text{Pb}/^{238}\text{U}$ xenocrystic zircon ages of the CRGs, and Figures 3 and 4 are probability density plots of $^{206}\text{Pb}/^{238}\text{U}$ detrital zircon ages for samples RIB-51 (sandstone of the Amutara Formation) and RIB-57 (schist from the Coroico Formation). To build the histograms we used $^{206}\text{Pb}/^{238}\text{U}$ values for ages up to 1300 Ma and $^{207}\text{Pb}/^{206}\text{Pb}$ values for ages older than 1300 Ma. We chose values with a concordance range of $100 \pm 10\%$ only. The histograms were built using the Isoplot software (Ludwig 2009) and their “x” axes were set to match those by Chew *et al.* (2008) in their study of detrital zircon provenance of the Central Andes.

Figure 4. Probability density plot of the $^{206}\text{Pb}/^{238}\text{U}$ xenocrystic zircon ages for Cordillera Real granitoids (CRGs).

Figure 5. Probability density plot of the $^{206}\text{Pb}/^{238}\text{U}$ detrital zircon ages for sample RIB-51, corresponding to a sandstone from the Ordovician Amutara Fm. The age shown corresponds to the youngest population-weighted mean.

Figure 6. Probability density plot of the $^{206}\text{Pb}/^{238}\text{U}$ detrital zircon ages for sample RIB-57, corresponding to schist from the Ordovician Coroico Fm. The age shown corresponds to the youngest population-weighted mean.

The histogram of the CRGs (Fig. 4) shows the highest peak ranging from 490 to 640, characterized by several smaller peaks within that interval. Smaller peaks of older ages are widespread between 700 to 2300 Ma. Observed intervals are at 700–900, 950–1050, 1100–1300, 1300–1500, 1600–1700, 1750–1850, 2000–2100 and 2300 Ma.

For RIB-51 sandstone (Fig. 5), the highest peak is within the range of 500 to 750 Ma. The weighted mean age of younger grains ($n = 10$) was 533 ± 7 Ma. The overall spread of ages is from 800 to 2900 Ma. Observed intervals are at 800–900, 1000–1100, 1100–1350 and 1350–1600. Individual grains are at 1750, 1950, 2350, 2650, 2750 and 2900 Ma.

For RIB-57 schist (Fig. 6), the highest peak is within the range of 480 to 700 Ma. The weighted mean age of younger grains ($n = 8$) was 527 ± 8 Ma. Smaller peaks at 750–800, 900, 1150, 1350, 1400, 1700–1800, and 1850–2150 Ma.

Figure 7. Stacked histograms showing U/Pb zircon age distribution for samples of the Sandia, Amutara, and Coroico formations, as well as CRG inherited xenocrysts. Data sources are from Reimann *et al.* (2010) and Iriarte *et al.* (2021).

In order to have a better picture of the detrital material deposited on the Ordovician western margin of Gondwana, the probability density plots of the Bolivian samples RIB-51 and RIB-57 were compared with similar diagrams for Ordovician sedimentary rocks in south-eastern Peru. These data were taken from Reimann *et al.* (2010), whose work included samples San-12 and San-17 from the Sandia Formation, which consists of 1,500 to 2,000 m thick sequences of sandstone and siltstone. In the same article, two other samples, Cor-18 and Am-20, from the Amutara Formation in Bolivia, were also considered for comparison.

Figure 7 shows the whole set of stacked histograms and Figure 8 shows the location of all these samples, with their respective histogram. The probability density plot of the xenocrystal zircons of the granitic plutons is also included in the figure. It is remarkable how the six Ordovician samples, as well as the xenocrystal zircons, show a very similar pattern, with notable peaks at 750–530 Ma, related to Neoproterozoic to Cambrian sources.

The Kolmogorov-Smirnov test (K-S) was employed to investigate the distribution and affinity of ages between the inherited zircon age population of the CRG, and the detrital zircon age population of the Ordovician units. The p-values of the K-S test (Conover 1971) are used to calculate the probability of a pair of samples being from the same source. We reject the hypothesis that two samples came from the same source when the probability is lower than 0.05. Higher values indicate nearly identical age spectra (Berry *et al.* 2001).

Table 2 shows the calculated p-values and the density curves of the histograms of Figures 7 and 8, calculated using “R” software (R Core Team 2020). The samples seem to be quite related to each other, except for RIB-57, whose p-value does not show any relationship with the other datasets. Maybe this could be related to some difference in its age of deposition. Similarly, sample Am-20 is highly related to San-12, but shows less correlation with the others.

Table 2. Calculated p-values using the K-S test (pairs with p-values < 0.05 are not correlated).

	San-12	San-17	Cor-18	Am-20	RIB-51	RIB-57	CRG
San-12		0.245	0.179	0.615	0.017	0.000	0.340
San17			0.108	0.019	0.584	0.007	0.407
Cor-18				0.031	0.216	0.011	0.425
Am-20					0.091	0.000	0.238
RIB-51						0.012	0.128
RIB-57							0.004
CRG							

DISCUSSION

In order to better understand and compare the U/Pb ages of detrital zircons from sedimentary country rocks with those of xenocrystal inheritance of CRGs, and to picture the potential paleo-relief in South America during Triassic times, we will analyze the age distribution of Figures 7 and 8.

Figure 8. Granitoids and their early Paleozoic country rocks along with histograms showing zircon age distribution. Outcrops of Lower Paleozoic sedimentary units were taken and modified from Cordani *et al.* (2016).

In Figures 7 and 8, we compile U/Pb detrital zircon age from the database of Reimann *et al.* (2010) along with our two samples, RIB-51 and RIB-57, and the inherited xenocrystal zircon ages of CRGs (Iriarte *et al.* 2021). All the sedimentary formations are from the upper Ordovician. We will discuss the most noticeable peaks seen on the histograms of Figure 7 and correlate them to major known geological events of the region.

Histograms in Figure 8 include the CRG xenocrysts. They share a common feature of noticeable peaks at 500 to 750 Ma along with different distribution of older ages. It was shown that they could be related to a common source. Ordovician ages corresponding to the Famatinian arc (upper Cambrian to early Ordovician, Otamendi *et al.* 2012) are scarce. There are also smaller peaks of Grenvillian ages (~1000 Ma). These Grenvillian peaks are frequent along the Central Andes (Bahlburg *et al.* 2011, Rezende de Oliveira *et al.*, 2017; Ramos 2010, 2018). Finally, there is an older population from 1650 to 2700 Ma. We will discuss the possible sources of these detrital grains.

Because of its proximity, it is expected that the source of these detrital zircon lies in the Amazonian craton that exposes extensive Paleo to Mesoproterozoic rocks covering older Archean cores. Single zircon ages from 1650 to 2700 Ma can be the result of these older units being recycled from the Amazonian craton (e.g., RNJ to CA provinces of Fig. 9).

The Neoproterozoic to Cambrian ages (500 to 1000 Ma) show larger peaks from 500 to 600 Ma (Cambrian to Ediacaran) along with smaller peaks from 600 to 700 Ma (Cryogenian) and from 700 to 1000 Ma (Tonian). These probably reflect the recycling of magmatic and metamorphic rocks. Belts uplifted during 500 to 900 Ma along the Trans Brazilian-Kandi lineament (Cordani *et al.* 2020) and/or the Pampean belts (Escayola *et al.* 2011) could be the primary source of detrital zircons (Fig. 8). Other candidates could be the “hidden Neoproterozoic belt” within the Andes itself (Chew *et al.* 2008, Bahlburg *et al.* 2011) or recycling of previous sedimentary rocks (e.g. Tucavaca basin, McNamee 2001).

Source: modified from Cordani *et al.* (2020) and Collo *et al.* (2009).

Figure 9. Distribution of Neoproterozoic belts on the South American continent along with main geological provinces. Neoproterozoic ages were compiled from Moura *et al.* (2008), Manzano *et al.* (2008), Escayola *et al.* (2007), and Pimentel (2016).

Source 1: Transbrazilian-Kandi Lineament

Reimann *et al.* (2010) inferred Brasiliano sources (450–700 Ma) probably to the east. In this sense, important relief was produced during the Brasiliano orogenic cycle, with the closure of the Goiás-Pharusian Ocean, along the Trans-Brazilian-Kandi lineament, a place where successive sutures and collisions occurred (Fig. 9, Cordani *et al.* 2020). By that time, Gondwana had become almost completely assembled. In the transition from Rodinia to Gondwana, the Goiás-Pharusian Ocean was consumed by means of subduction-to-collision, roughly between 900 and 500 Ma. This process formed juvenile arcs and a large volume of granitoids (Goiás and Santa Quitéria, Ganade de Araujo *et al.* 2014). This was followed by a continental collision between Amazonia and Congo, forming a Himalayan type relief (700–540 Ma, Cordani *et al.* 2020).

This Goiás magmatic arc is a major area of collision and accretion of the Amazonian Craton margin made up essentially by Neoproterozoic granitoids with juvenile signatures and predominantly calc-alkaline chemistry related to subduction (Ganade de Araujo *et al.* 2014, Pimentel 2016). U-SHRIMP ages on overgrowth rims of zircon of eclogites in NE Brazil (Ceará) yielded ca. 616. Granitoids and gneisses, which supply detrital zircons, are formed under this high to moderate regional metamorphism, at 15–25 km deep. They are exhumed during the rise of mountain belts. When eclogites that form at depths greater than 100 km are exhumed, the result is a Himalayan type cordillera (10 km high).

These high Himalayan-like mountains could have persisted at least until 540 Ma as estimated from the age of several post-collisional granitoids (Ganade de Araujo *et al.* 2014). The oldest orogenic belt of this “modern type plate tectonics” is, in fact, associated with the formation of Western Gondwana.

This could be the main source of detrital zircon of 900 to 600 Ma, with a predominance of Ediacaran ages (650–600 Ma). Terrains of these ages may lie beneath the sediments of the Paraná, Paranaíba, and Pampean basins (Fig. 9). To the west of the TB-Kandi lineament, the Ediacaran sedimentary sequence of the Paraguay belt bears detrital zircons of that interval of age (Chamani *et al.* 2011).

In other regions, this Neoproterozoic age peak is absent. For instance, in the Araguaia aulacogen, detrital zircons do not bear Brasiliano ages (Pinheiro *et al.* 2003, Barros and Gorayeb *et al.* 2019) showing instead, a major peak of Grenvillian age (1000 Ma). Cambrian

ages of granites in the Paraguay belt and post-tectonic granites in the Brasiliano belts could also mean potential sources, although they represent a smaller area.

Source 2: Pampean Belt

An important relief was also associated with the closure of the Puncoviscana Ocean during the Cambrian Pampean orogeny (Larrovere *et al.* 2021), which occurred throughout larger parts of the Sierras Pampeanas. This relief was created by a collision between the Arequipa-Antofalla block and the western part of Pampia (Escayola *et al.* 2011). Today, the whole area is covered by modern sediment. This Cambrian relief, exposing peraluminous granitoids, could be also the source of detrital zircon deposited in the Ordovician basins.

Source 3: Central Andes

Chew *et al.* (2008) suggested the presence of Neoproterozoic orogenic belts within the Central Andes that are covered by younger sediments. The study of Bahlburg *et al.* (2011) on Hf isotopes in zircon also suggested the presence of Neoproterozoic magmatic belts within the Central Andes. Their study shows the presence of juvenile and evolved Neoproterozoic zircon, suggesting the reworking of juvenile and evolved magmatic or metamorphic rocks. This “hidden” belt could be the continuation of the Pampean belts towards the Marañon complex of northern Peru (Chew *et al.* 2008, Cardona *et al.* 2009).

Source 4: recycling of pre-existing sedimentary sources — Tucavaca Basin

Primary Cambrian to Neoproterozoic sources could be eroded, transported, and deposited in several sub-basins (e.g., Tucavaca) and then recycled and re-deposited in the Ordovician units.

The closest Neoproterozoic outcrop to the Cordillera Real is located in the Tucavaca basin, near the SE border of Bolivia, next to the Amazonian shield (Durand 1993, McNamee 2001, Ramos 2008). It is part of the Paraguay belt and is characterized by clastic and carbonate sedimentary sequences deposited along a rifted basin (500 x 60 km), striking N 40° W. Ramos (2008), interpreted it as an “aulacogen” pointing towards the Andes.

Basement units on the Paraguayan side were dated by McGee *et al.* (2015) using LA-ICP-MS technique and yielded a U/Pb age of 686 ± 2 Ma. For the upper part, the Corumbá Group in Brazil (equivalent to the carbonate Murciélago Formation in Bolivia), a U/Pb age of 543 ± 2 Ma was obtained (Souza de Alvarenga *et al.* 2011). Thus, the deposition of Tucavaca basin can be constrained between 686 and 543 Ma (Fig. 8).

Detrital zircons in the Paraguay belt basins are mainly Ediacaran (Babinski *et al.* 2013, McGee *et al.* 2015, Vasconcelos 2018), so the sediments of the Tucavaca basin may bear detrital zircon grains of that age as well. Their original source could be located within the Brasiliano or Pampean belts. It is possible that, subsequently, the “Tucavaca Trough” acted as a positive relief whose rocks were eroded and deposited in the Ordovician basins. It is also possible that Neoproterozoic rocks were recycled more than once over time. Other possible sources of recycled Neoproterozoic zircon ages could be the Cambrian Sama Fm. of southern Bolivia and the clastic to carbonate sequences of the Limbo Group in the core of the Eastern Cordillera (Suárez-Soruco 2000).

CONCLUSIONS

The age distribution of both sedimentary sequences and the xenocrysts of CRGs, as well as their statistical relationship and geochemical evidence support processes such as AFC as plausible during emplacement.

Based on this geochronological record, we can suggest potential sources of these detrital zircons, as well as a better picture of the potential paleo-relief in South America during Ordovician to Triassic times.

Ordovician sedimentary sequences from SE Peru and NW Bolivia received zircon grains from the same sources. The main source is Neoproterozoic to Cambrian in age and probably is derived from mountains formed during the Brasiliano cycle through the Tranbrazilian-Khandi tectonic corridor. We cannot rule out sources related to the Sierras Pampeanas, Neoproterozoic belts hidden within the Central Andes, or recycled from pre-existent sedimentary units (such as the Tucavaca basin). Older sources (> 1000 Ma) possibly lie within the Amazonian craton. Finally, the Triassic plutons of the Cordilleras Real and Carabaya incorporated a large amount of Famatinian to Gondwanian detrital zircons, taken from their host basement or recycled from the Andean Paleozoic, mainly the Amutara Fm., or equivalents (such as the Sandia Fm.).

ACKNOWLEDGMENTS

We would like to thank the technicians of Centro de Pesquisas Geocronológicas (CPGeo), Instituto de Geociências of Universidade de São Paulo, Brasil, and Instituto de Investigaciones Geológicas y del Medio Ambiente, IGEMA (part of the Universidad Mayor de San Andrés, Bolivia) for the dedicated sample and analytical work. In addition, we would like to thank Dr. Heinrich Bahlburg, who kindly sent us the Bolivian data when we requested.

ARTICLE INFORMATION

Manuscript ID: 20210036. Received on: 05/06/2021. Approved on: 09/09/2021.

A.I. wrote the drafts of the manuscript and prepared all figures and tables. U.C. provided general advice concerning the whole text. He also provided key information about the Brasiliano sources for detrital zircon and improved the manuscript. M.B. wrote the LA-ICP-MS methodology, prepared the U/Pb database presented as tables, and improved the manuscript.

Competing interests: The authors declare no competing interests.

REFERENCES

Ávila W.A. 1990. Tin-bearing granites from the Cordillera Real, Bolivia; A petrological and geochemical review. *In*: Kay S.M., Rapela C.W. (Eds.). *Plutonism from Antarctica to Alaska*. America, Geological Society of America, Special paper, 241, p. 145-159.

Babinski M., Boggiani P.C., Trindade R.I.F., Fanning C.M. 2013. Detrital zircon ages and geochronological constraints on the Neoproterozoic Puga diamictite and associated BIFs in the southern Paraguay Belt, Brazil. *Gondwana*, **23**(3):988-997. <http://dx.doi.org/10.1016/j.gr.2012.06.011>

Bahlburg H., Vervoort J.D., DuFrane A.S., Carlotto V., Reimann C., Cárdenas J. 2011. The U-Pb and Hf isotope evidence of detrital zircons of the Ordovician Ollantaytambo Formation, southern Peru, and the Ordovician provenance and paleogeography of southern Peru and northern Bolivia. *Journal of South American Earth Sciences*, **32**(3):196-209. <https://doi.org/10.1016/j.jsames.2011.07.002>

Barros L.D., Gorayeb P.S.S. 2019. Serra do Tapa Ophiolite Suite - Araguaia Belt: Geological characterization and Neoproterozoic evolution (central-northern Brazil). *Journal of South American Earth Sciences*, **96**:102323. <https://doi.org/10.1016/j.jsames.2019.102323>

Black L.P., Kamo S.L., Allen C.M., Aleinikoff J.N., Davis D.W., Korsch R.J., Foudoulis C. 2003. Temora 1: A new zircon standard for Phanerozoic U-Pb geochronology. *Chemical Geology*, **200**(1-2):155-170. [https://doi.org/10.1016/S0009-2541\(03\)00165-7](https://doi.org/10.1016/S0009-2541(03)00165-7)

Berry R.F., Jenner G.A., Meffre S., Tubrett M.N. 2001. A North American provenance for Neoproterozoic to Cambrian sandstones in Tasmania? *Earth and Planetary Science Letters*, **192**(2):207-222. [https://doi.org/10.1016/S0012-821X\(01\)00436-8](https://doi.org/10.1016/S0012-821X(01)00436-8)

Calle A., Horton B.K., Garcia-Duarte R., Flaig P.P. 2017. Neoproterozoic-paleozoic tectonics and paleogeography of the West-Central South America convergent margin from detrital zircon geochronology. In: GSA Annual Meeting, Seattle, 2017. *Conference Paper*. The Geological Society of America. <https://doi.org/10.1130/abs/2017AM-305408>

Cardona A., Cordani U.G., Ruiz J., Valencia V.A., Armstrong R., Chew D., Nutman A., Sanchez A.W. 2009. U-Pb zircon geochronology and Nd isotopic signatures of the pre-mesozoic metamorphic basement of the eastern peruvian andes: Growth and provenance of a late neoproterozoic to carboniferous accretionary orogen on the northwest margin of gondwana. *Journal of Geology*, **117**(3):285-305. <https://doi.org/10.1086/597472>

Chamani M.A.C. 2011. *Tectônica intraplaca e deformação sinsedimentar induzida por abalos sísmicos: o Lineamento Transbrasileiro e estruturas relacionadas na Província Parnaíba, Brasil*. Tese de Doutorado, Universidade de São Paulo, São Paulo, SP, Brazil.

Chew D.M., Magna T., Kirkland C.L., Mišković A., Cardona A., Spikings R., Schaltegger U. 2008. Detrital zircon fingerprint of the Proto-Andes: Evidence for a Neoproterozoic active margin? *Precambrian Research*, **167**(1-2):186-200. <https://doi.org/10.1016/j.precamres.2008.08.002>

Collo G., Astini R.A., Cawood P.A., Buchan C., Pimentel M. 2009. U – Pb detrital zircon ages and Sm – Nd isotopic features in low-grade metasedimentary rocks of the Famatina belt: implications for late Neoproterozoic – early Palaeozoic evolution of the proto-Andean margin of Gondwana. *Journal of the Geological Society*, **166**(2):303-319. <https://doi.org/10.1144/0016-76492008-051.U>

Conover W.C. 1971. *Practical nonparametric statistics*. New York: John Wiley & Sons.

Cordani U.G., Fairchild T.R., Ganade C.E., Babinski M., Moraes Leme J. 2020. Dawn of metazoans: To what extent was this influenced by the onset of “modern-type plate tectonics”? *Brazilian Journal of Geology*, **50**(2):e20190095. <https://doi.org/10.1590/2317-4889202020190095>

Cordani U.G., Iriarte A.R., Sato K. 2019. Geochronological systematics of the Huayna Potosí, Zongo and Taquesi plutons, Cordillera Real of Bolivia, by the K/Ar, Rb/Sr and U/Pb methods. *Brazilian Journal of Geology*, **49**(2):e20190016. <https://doi.org/10.1590/2317-4889201920190016>

Cordani U.G., Ramos V.A., Fraga L.M., Cegarra M., Deldgado I., Souza K.G., Gomes F.E.M., Schobbenhaus C. 2016. *Tectonic Map of South America*. 2^a ed. Commission for the Geological Map of the World.

DePaolo D.J. 1981. Assimilation and isotopic effects of combined wallrock assimilation and fractional crystallization. *Earth and Planetary Science Letters*, **53**(2):189-202. [https://doi.org/10.1016/0012-821X\(81\)90153-9](https://doi.org/10.1016/0012-821X(81)90153-9)

Durand FR. 1993. Las icnofacies del basamento metasedimentario en el Noroeste Argentino: Significado cronológico y aspectos paleogeográficos. In: XII Congr. Geol. Argent. *Actas...* 2:260-267.

Elhlou S., Belousova E., Griffin W.L., Pearson N.J., O'Reilly S.Y. 2006. Trace element and isotopic composition of GJ-red zircon standard by laser ablation. *Geochimica et Cosmochimica Acta*, **70**(18 Suppl.):A158. <https://doi.org/10.1016/j.gca.2006.06.1383>

Escayola M.P., Pimentel M.N., Armstrong R. 2007. Neoproterozoic backarc basin: Sensitive high-resolution ion microprobe UPb and Sm-Nd isotopic evidence from the Eastern Pampean Ranges, Argentina. *Geology*, **35**(6):495-498. <https://doi.org/10.1130/G23549A.1>

Escayola M.P., van Staal C.R., Davis W.J. 2011. The age and tectonic setting of the Puncoviscana Formation in northwestern Argentina: An accretionary complex related to Early Cambrian closure of the Puncoviscana Ocean and accretion of the Arequipa-Antofalla block. *Journal of South American Earth Sciences*, **32**(4):438-459. <https://doi.org/10.1016/j.jsames.2011.04.013>

Franz G., Lucassen F., Kramer W., Trumbull R.B., Trumbull Romer R.L., Wilke H.G., Viramonte J.G., Becchio R., Siebel W. 2006. Crustal evolution at the Central Andean continental margin: a geochemical record of crustal growth, recycling and destruction. In: Oncken O., Chong G., Franz G., Giese P., Gotze H.J., Ramos V.A., Strecker M., Wigger P. (eds.). *Frontiers in Earth Science*. The Andes Active Subduction Orogeny, p. 45-64. Cham: Springer.

Ganade de Araujo C.E., Rubatto D., Hermann J., Cordani U.G., Caby R., Basei M.A.S. 2014. Ediacaran 2,500-km-long synchronous deep continental subduction in the West Gondwana Orogen. *Nature Communications*, **5**:5198. <https://doi.org/10.1038/ncomms6198>

Gillis R.J., Horton B.K., Grove M. 2006. Thermochronology, geochronology, and upper crustal structure of the Cordillera Real: Implications for Cenozoic exhumation of the central Andean plateau. *Tectonics*, **25**(6):1-22. <https://doi.org/10.1029/2005TC001887>

Iriarte A.R., Cordani U.G., Sato K. 2021. Geochronology of the Cordillera Real granitoids, the inner magmatic arc of Bolivia. *Andean Geology*, **48**(3):403-441. <http://dx.doi.org/10.5027/andgeoV48n3-3326>

Jiménez N., López-Velásquez S. 2008. Magmatism in the Huarina belt, Bolivia, and its geotectonic implications. *Tectonophysics*, **459**(1-4):85-106. <https://doi.org/10.1016/j.tecto.2007.10.012>

Keay S., Steele D., Compston W. 1999. Identifying granite sources by SHRIMP U-Pb zircon geochronology: An application to the Lachlan foldbelt. *Contributions to Mineralogy and Petrology*, **137**(4):323-341. <https://doi.org/10.1007/s004100050553>

Kontak D.J., Clark A.H., Farrar E., Archibald D.A., Baadsgaard H. 1990. Late Paleozoic-early Mesozoic magmatism in the Cordillera de Carabaya, Puno, southeastern Peru: Geochronology and petrochemistry. *Journal of South American Earth Sciences*, **3**(4):213-230. [https://doi.org/10.1016/0895-9811\(90\)90004-K](https://doi.org/10.1016/0895-9811(90)90004-K)

Larrovere M.A., Casquet C.R., Aciar H.R., Baldo E.G., Alasino P.H., Rapela C.W. 2021. Extending the Pampean orogen in western Argentina: New evidence of Cambrian magmatism and metamorphism within the Ordovician Famatinian belt revealed by new SHRIMP U–Pb ages. *Journal of South American Earth Sciences*, **109**:103222. <https://doi.org/10.1016/j.jsames.2021.103222>

Ludwig K. 2009. *SQUID 2: A User's Manual*. Berkeley: Berkeley Geochronology Center, Special Publication, 5, 110 p.

Manzano J.C., Godoy A.M., Marques L., Araújo Marques Barbosa L. 2008. Contexto tectônico dos granitoides neoproterozoicos da faixa de dobramentos Paraguai, MS e MT. *Geociências*, **27**(4):493-507.

McGee B., Collins A.S., Trindade R.I.F., Payne J., 2015. Age and provenance of the Cryogenian to Cambrian passive margin to foreland basin sequence of the northern Paraguay Belt, Brazil. *GSA Bulletin*, **127**(1-2):76-86. <https://doi.org/10.1130/B30842.1>

McNamee J. 2001. The Tucavaca Through: Potential for Sedex type base metal/Ag mineralization in a late Proterozoic rift in Eastern Bolivia. Estilos de mineralización en Bolivia. *Colegio de Geólogos de Bolivia*, 21-24.

Moura C.A.V., Pinheiro B.L.S., Nogueira A.C.R., Gorayeb P.S.S., Galarza M.A. 2008. Sedimentary provenance and palaeoenvironment of the Baixo Araguaia supergroup: Constraints on the palaeogeographical evolution of the Araguaia Belt and assembly of West Gondwana. In: Pankhurst R.J., Trouw R.A., Brito Neves B.B., De Wit M.J. (eds.). *West Gondwana: Pre-Cenozoic Correlations Across the South Atlantic Region*. The Geological Society of London. Special Publications, **294**(1):173-196. <https://doi.org/10.1144/SP294.10>

Otamendi J.E., Ducea M.N., Bergantz G.W. (2012). Geological, petrological and geochemical evidence for progressive construction of an Arc crustal section, sierra de valle fértil, famatinian Arc, Argentina. *Journal of Petrology*, **53**(4), 761-800. <https://doi.org/10.1093/petrology/egr079>

Pimentel M. 2016. The tectonic evolution of the Neoproterozoic Brasília Belt, central Brazil: a geochronological and isotopic approach. *Brazilian Journal of Geology*, **46**(Suppl. 1):67-82. <https://doi.org/10.1590/2317-4889201620150004>

Pinheiro B.L.S., Moura C.A.V., Klein E.L. 2003. Estudo de proveniência em arenitos das formações Igarapé de Areia e Viseu, nordeste do Pará, com base em datação de monocristais de zircão por evaporação de chumbo. In: 8º Simpósio de Geologia da Amazônia, Manaus. *Resumos expandidos...* CD-ROM.

Ramos V.A. 2008. The basement of the Central Andes: the Arequipa and related terranes. *Annual Review of Earth and Planetary Sciences*, **36**(1):289-324. <https://doi.org/10.1146/annurev.earth.36.031207.124304>

Ramos V.A. 2010. The Grenville-age basement of the Andes. *Journal of South American Earth Sciences*, **29**(1):77-91. <https://doi.org/10.1016/j.jsames.2009.09.004>

Ramos V.A. 2018. Tectonic Evolution of the Central Andes: From Terrane Accretion to Crustal Delamination. In: Zamora G., McClay K.M., Ramos V.A. (eds.). Petroleum basins and hydrocarbon potential of the Andes of Peru and Bolivia. *AAPG Memoir*, 117, p. 1-34. <https://doi.org/10.1306/13622115M1172855>

R Core Team. 2020. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Available at: <https://www.R-project.org/>. Accessed on: Jan, 2021.

Reimann C.R., Bahlburg H., Kooijman E., Berndt J., Gerdes A., Carlotto V., López S. 2010. Geodynamic evolution of the early Paleozoic Western Gondwana margin 14°-17°S reflected by the detritus of the Devonian and Ordovician basins of southern Peru and northern Bolivia. *Gondwana Research*, **18**(2-3):370-384. <https://doi.org/10.1016/j.gr.2010.02.002>

Rezende de Oliveira J., Aguilar de Sousa M.Z., Salina Ruiz A., Matos Salinas G.R. 2017. Granulito Uyarani - Uma janela estrutural Pré-Cambriana no Altiplano Boliviano: Petrogênese e significado tectônico. *Geologia USP. Série Científica*, **17**(2):223-245. <https://doi.org/10.11606/issn.2316-9095.v17-385>

Servicio Geológico de Bolivia (GEOBOL). 1994. *Carta geológica de Bolivia*. Hoja Chulumani (6044). Escala 1:100,000. Bolivia: GEOBOL.

Servicio Geológico de Bolivia (GEOBOL). 1995. *Carta geológica de Bolivia*. Hoja Sapahaqui (6043). Escala 1:100,000. Bolivia: GEOBOL.

Servicio Geológico de Bolivia (GEOBOL). 1997. *Carta geológica de Bolivia*. Hoja Inquisivi (6143). Escala 1:100,000. Bolivia: GEOBOL.

Servicio Geológico de Bolivia (GEOBOL). 2013. *Carta geológica de Bolivia*. Hoja Challana (5946). Escala 1:100,000. Bolivia: GEOBOL.

Souza de Alvarenga C.J., Boggiani P.C., Babinski M., Dardenne M.A., Figueiredo M.F., Dantas E.L., Uhlein A., Santos R.V., Sial A.N., Trompette R. 2011. Glacially influenced sedimentation of the Puga Formation, Cuiabá Group and Jacadigo Group, and associated carbonates of the Araras and Corumbá groups, Paraguay Belt, Brazil. *Journal of the Geological Society*, **36**(1):487-497. <https://doi.org/10.1144/M36.45>

Suárez-Soruco R. 1992. El Paleozoico Inferior de Bolivia y Perú. In: Gutiérrez M.J.G., Saavedra J., Rábano I. (eds.). *El Paleozoico Inferior de Ibero-América*. Badajoz, España, Universidad de Extremadura, p. 225-239.

Suárez-Soruco R. 2000. Compendio de Geología de Bolivia. *Revista Técnica de Yacimientos Petrolíferos Fiscales de Bolivia*, **18**(1-2).

Vasconcelos B.R. 2018. *Proveniência sedimentar do Grupo Cuiabá na faixa Paraguai Meridional*. Tese de Doutorado, Universidade de Brasília, Brasília.

Voges A. 1962. *Geología y yacimientos metalíferos de la región de Oruro*. Misión Geológica Alemana en Bolivia (MGAB).

Wiedenbeck M., Allé P., Corfu F., Griffin W.L., Meier M., Oberli F., Von Quadt A., Roddick J.C., Spiegel W. 1995. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace-element and REE analyses. *Geostandards Newsletter*, **19**(1):1-23. <https://doi.org/10.1111/j.1751-908X.1995.tb00147.x>

CHAPTER 6 – CONCLUSIONS

The objective of this chapter is to present a review of the many discussions and conclusions offered in chapters 2 to 5, and to try making the appropriate relative connections among them.

6.1 Conclusions of chapter 2

In this chapter, the Huayna Potosí and Zongo plutons were selected to be part of a special study of whole-rock geochemistry and some of their samples were analysed to be compared with analogous samples from other plutons. Figure 15 shows clearly that all plutons of the Real Cordillera belong to a calc-alkalic series. Its magmatic evolution probably occurred by means of crystal fractionation or assimilation/crystal fractionation processes, and the HP and Z granitic samples were the more evolved. This calc-alkalic trend, along with the trace elements ratios, probably indicates that a regional subduction arc operated during the emplacement of the Cordillera Real triassic plutons whose final episode of crystallization coincides with a continental rift episode. On fig. 16, less evolved rocks (such as quartz-diorites) fall within the within-plate field, meanwhile the granites fall within the fields of synchronous collisional granites (syn-COLG) and volcanic arc granites (VAG), respectively. These former compositions account for the rifting stage.

The later enrichment of LILE elements in the highly evolved granites can be a consequence of the operation of two mechanisms: crystal fractionation from the enriched quartz-dioritic melts towards the granites, and/or assimilation of metapelitic country rocks and crystal fractionation process (AFC, accordingly to De Paolo, 1981). This process is a plausible mechanism of pluton emplacement, given the high correlation of zircon age distribution between granitoids and their meta-sedimentary country rocks of the Amutara Formation, as discussed on chapter 5). Processes of crystal fractionation and AFC account for highly LILE enriched granitic melts and possibly influenced the hydrothermal system as well.

After the rifting stage, (245 Ma), the quartz-dioritic magmas probably crystallized within the upper crust. Later they were re-melted by the youngest pulse (223 Ma), yielding the depleted HREE pattern observed on fig. 17. Probably the LILE (such as

Rb) were enriched by AFC process assimilating material from the Ordovician meta-sedimentary country rocks.

6.1 Conclusions of chapter 3.

The article published in the Brazilian Journal of Geology (2019) deals with the temporal evolution of the CR, and all the geochronological elements available and produced for the Huayna Potosi and Zongo plutons were reviewed. This included a series of dates by means of K-Ar and Ar-Ar in micas, Rb-Sr whole-rock isochron methods, as well as U-Pb measurements performed in zircon crystals.

Taking into account the modal compositions of the studied samples, as well as the whole rock analyses presented on chapter 2, the magmatic suite of the Cordillera Real is characterized by granites as the more felsic compositions. They are characterized by omnipresence of K-feldspars, sodic plagioclase, quartz, biotite, muscovite, tourmaline, apatite and zircon (table 1); as well as their position on the trends of AFM, TAS and R1-R2 diagrams (figs. 13, 15 and 16) where the granites of the Huayna Potosí and Zongo plutons occupy the more evolved positions. In fact, Castro (2013) considers their compositions as corresponding to melts (or cotectic liquids). The Ordovician to Silurian country rocks (Amutara and Cancañiri formations) were also investigated. Their Rb/Sr whole-rock isochron age of 344 Ma seems to confirm the tectonic influence of the Gondwanide orogeny on these meta-sedimentary units.

Due to an abundant presence of “antecrysts” on both of these plutons, a unique Concordia age was not obtained. The Triassic U/Pb age of 220 Ma indicates that the last episode of emplacement was coeval with a regional continental rift. The older age of a cluster of zircon crystals that yielded a Concordia age of 240 Ma needs to be further understood and discussed. A further interpretation of the meaning of that older ages was done on chapters 4 and 5, in the context of the entire Cordillera Real.

Fluid enrichment at the end of the process of crystallization is also considered. It probably generated the U/Pb reverse Concordias seen on samples of the Zongo pluton. This fluid enrichment must be further investigated. Comparison can be done with other ore deposits, such as the Mississippi Valley in the US (S. Kay personal communication, September 2021). These are carbonate-hosted lead and zinc

sulfides formed under relatively low temperature conditions, White (2005). Probably, during Triassic times, desert-like environments, such as those recorded on the Tiquina Fm Suárez (2000), which crop out nearby, produced saline brines that interacted with the magmatic fluids. Kelly and Turneure (1970) presented evidence of boiling in several major deposits of the Cordillera Real suggesting that these ores deposited at depths of less than 3,000 m with temperatures ranging from 530 to 70 degrees °C. Therefore, the hydrothermal system takes in account: a) U/Pb enrichment (maybe LILE as well) from pluton crystallization, producing reverse Concordias and b) further enrichment following the AFC process (see chapter 5). A final process c) must be investigated relating interaction of these magmatic fluids with saline brines coming from the evaporitic formations above.

Finally, the K-Ar and Ar-Ar showed a systematic decrease of ages on magmatic and country rocks micas (e.g. 200, 130, 100, 78 and 39 Ma) that was assigned to the structural and orogenic Zongo-San Gabán effect during the Andean orogeny on the Oligocene at 39 Ma.

6.2 Conclusion of chapter 4.

With the objective of studying the temporal magmatic evolution of the entire Cordillera Real, several U/Pb zircon crystallization ages of most of these plutons are described and discussed. Their ages were put in a regional context to understand better their geotectonic environment. They are ascribed to the inner magmatic arc located to east of the western volcanic arc.

Most of the granites yielded a late Triassic crystallization U/Pb age of ca. 220 Ma. However, many zircon crystals with older apparent ages were found, and were considered to be antecrysts. Early (premonitory) zircons at 280 Ma were also assigned to the magmatic system. Then the overall magmatism is of nearly 60 Ma.

This age range (280-220 Ma) accounts for a rather protracted magmatism episode, occurred at the same time with the Gondwanide orogeny (336-205 Ma) and ending up during the continental rifting affecting western Gondwana (245-220 Ma). The conservation of the antecrystal zircons seems to be associated to the relatively low zircon saturation temperatures calculated on the whole rock compositions. In contrast, the Oligocene Quimsa Cruz pluton shows a rather rapid age of

emplacement, with zircon ages clustering at 26 Ma and a rather isolated xenocrystal inheritance at 30 Ma.

Fig. 19 Comparative boxplots for U/Pb ages of the Triassic plutons of the Cordillera Real. Numbers correspond to samples of each pluton (e.g. RIB-2, RIB-4, etc.). Boxplots show median (50% quartile) as thick black line. Whiskers are displayed as broken lines. Statistical outliers are shown as circles. Concordia ages are shown as light blue circles with $\pm$ to $\sqrt{\text{MSWD}}$ error bars. Calculated weighted means are displayed in red. Samples used to calculate these weighted means are: 250 Ma (RIB-2); 240 Ma (RIB-4, 15 and 7); 230 Ma (RIB-12, 20, 22, 32 and 33) and for 220 (RIB-2, 4, 11, 15 and 19).

On fig. 19, it can be seen comparative boxplot diagram of U/Pb ages, calculated Concordias and antecrysts ages of the Huayna Potosí, Illampu, Taquesi and Huato plutons. The Concordia ages obtained were used to calculate the 4 weighted means: at 248, 242, 230 and 223 Ma. They can be interpreted as magmatic pulses.

The younger age at 223 Ma accounts for the final crystallization pulse. In the case of the samples of the Huayna Potosí (e.g. RIB-2 and RIB-4) this youngest pulse contains the record of the older pulses by means of conserved antecrysts. It is suggested that this youngest pulse (probably mafic at the beginning) partially melted

and eventually generate the chemical pattern seen on fig. 18 and discussed on chapter 2.

6.3 Conclusion of chapter 5

Trying to understand the relationship between granitoids and their country rock envelope, a provenance study was done in some Ordovician sedimentary sequences from SE Perú and NW Bolivia (Sandia and Amutara formations, respectively). This was submitted to the Brazilian Journal of Geology and presented in chapter 5. The objective was to compare the detrital zircons of the sedimentary rocks with the xenocrystal inheritance from the granitoids of the Cordillera Real.

For the granitic plutons, the ages of “antecrystal” zircons were constrained between 220 to 280 Ma; older ages were assumed as “xenocrystals”. Their age distribution is characterized by Gondwanide to Famatinian ages (300 to 450 Ma), Cambrian to Ediacaran ages (500 to 650 Ma), as well as minor older ages up to the late Archean.

The statistical relationship between the sedimentary country rocks and the xenocrystal inheritance on the granitoids is high, and this can be used as an evidence that the granites assimilated a great deal of the metapelitic country rocks during their emplacement on the upper crust. Coeval crystal fractionation of several major phases, such as plagioclase, are the characteristics of this AFC process, (De Paolo, 1981).

The main age peak recorded either in the detrital zircons of the Ordovician country rocks, or in the granites' xenocrysts, is Cambrian to Ediacaran (500 to 650 Ma). A few sources of that age with potential to be eroded away and whose material was deposited on the Ordovician basins were suggested, such as the, high reliefs along the Tranbrasiliano-Kandi tectonic corridor (Cordani et al., 2020), or the Puncoviscana complex located at northwestern Argentina (Aparicio Gonzales et al., 2020; Escayola et al., 2007). Moreover, a possibility is that some relief with rocks of such age existed hidden below the quaternary sediments of the Bolivian or Argentinian foreland basins.

BIBLIOGRAPHY

- Ahfeld, F. & Schneider-Scherbina, A., (1964). Los yacimientos minerales y de hidrocarburos de Bolivia. Boletín DENAGEO 5 (especial), La Paz, 388 p.
- Amaral, G., Cordani, U. G., Kawashita, K. and Reynolds, J. H. (1966). Potassium-argon dates of basaltic rocks from Southern Brazil. *Geoch. Et Cos, Acta* 30: 159-189.
- Aparicio González P. A., Hauser N., de Oliveira Carvalho, M., de Morisson Valeriano C., Cayo L. E., Barrientos A., Impicini A., Reimold W. U., Heilbron M., and Pimentel M. (2020). The Neoproterozoic-lower Paleozoic sequence of the Sierra de Mojotoro, Eastern Cordillera: Sedimentary provenance (Sr–Nd, U–Pb, and clay mineralogy) and its tectonic implications for western Gondwana, *Journal of South American Earth Sciences*, Volume 104. <https://doi.org/10.1016/j.jsames.2020.102818>
- Assumpção, M., Feng, M., Tassara, A., & Julià, J. (2013). Models of crustal thickness for South America from seismic refraction, receiver functions and surface wave tomography. *Tectonophysics*, 609, 82–96. <https://doi.org/10.1016/j.tecto.2012.11.014>
- Ávila W.A. (1990). Tin-bearing granites from the Cordillera Real, Bolivia; A petrological and geochemical review. In: Kay S.M. & Rapela C.W. (Eds.). *Plutonism from Antarctica to Alaska*. America, Geological Society of America, Special paper 241, p. 145-159.
- Babinski M., Boggiani P.C., Trindade R.I.F., Fanning C.M., (2013). Detrital zircon ages and geochronological constraints on the Neoproterozoic Puga diamictite and associated BIFs in the southern Paraguay Belt, Brazil. *Gondwana*, 23, 988–997.
- Bachmann, O., Miller, C. F., & de Silva, S. L. (2007). The volcanic-plutonic connection as a stage for understanding crustal magmatism. *Journal of Volcanology and Geothermal Research*, 167(1–4), 1–23. <http://doi.org/10.1016/j.jvolgeores.2007.08.002>
- Bahlburg, H., Vervoort, J. D., Andrew DuFrane, S., Carlotto, V., Reimann, C., & Cárdenas, J. (2011). The U-Pb and Hf isotope evidence of detrital zircons of the Ordovician Ollantaytambo Formation, southern Peru, and the Ordovician provenance and paleogeography of southern

Peru and northern Bolivia. *Journal of South American Earth Sciences*, 32(3), 196–209.
<https://doi.org/10.1016/j.jsames.2011.07.002>

Bard, J. P.; Botello, R.; Martinez, C.; Subieta, T. (1974). Relations entre tectonique, métamorphisme et mise en place d'un granite Éohercynien a deux micas dans la Cordillere Real de Bolivie (massif de Zongo-Yani). *Orstom, IRD, VI*: 3–18.

Barros, L. D., & Gorayeb, P. S. de S. (2019). Serra do Tapa Ophiolite Suite - Araguaia Belt: Geological characterization and Neoproterozoic evolution (central-northern Brazil). *Journal of South American Earth Sciences*, 96(August), 102323.
<https://doi.org/10.1016/j.jsames.2019.102323>

Black, L. P., Kamo, S. L., Allen, C. M., Aleinikoff, J. N., Davis, D. W., Korsch, R. J., & Foudoulis, C. (2003). Temora 1: A new zircon standard for Phanerozoic U-Pb geochronology. *Chemical Geology*, 200(1–2), 155–170. [https://doi.org/10.1016/S0009-2541\(03\)00165-7](https://doi.org/10.1016/S0009-2541(03)00165-7)

Berry, R. F., Jenner, G. A., Meffre, S., & Tubrett, M. N. (2001). A North American provenance for Neoproterozoic to Cambrian sandstones in Tasmania? *Earth and Planetary Science Letters*, 192(2), 207–222. [https://doi.org/10.1016/S0012-821X\(01\)00436-8](https://doi.org/10.1016/S0012-821X(01)00436-8)

Bettencourt, J. S.; Leite, W. B.; Ruiz, A. S.; Matos, R.; Payolla, 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(1): 28–46. <https://doi.org/10.1016/j.jsames.2009.08.006>

Burnham, C. (1979). Magmas and hydrothermal fluids. In *Geochemistry of Hydrothermal Ore Deposits (Second Edition)* (Barnes, H.L.; editor). Wiley and Sons: 71–136. New York.

Calle, A., Horton, B., K., Flaig, P., P. (2017). Neoproterozoic-paleozoic tectonics and paleogeography of the West-Central South America convergent margin from detrital zircon geochronology. Conference Paper. Geological Society of America.

Cardona, A., Cordani, U. G., Ruiz, J., Valencia, V. A., Armstrong, R., Chew, D., ... Sanchez, A. W. (2009). U-Pb zircon geochronology and Nd isotopic signatures of the pre-mesozoic metamorphic basement of the eastern peruvian andes: Growth and provenance of a late

neoproterozoic to carboniferous accretionary orogen on the northwest margin of gondwana. *Journal of Geology*, 117(3), 285–305. <https://doi.org/10.1086/597472>

Chamani, M., A., C. (2011). Tectônica intraplaca e deformação sinsedimentar induzida por abalos sísmicos: o Lineamento Transbrasileiro e estruturas relacionadas na Província Parnaíba, Brasil. Tese de Doutorado, Universidade de São Paulo, São Paulo, SP. Brasil.

Chew, D. M., Magna, T., Kirkland, C. L., Mišković, A., Cardona, A., Spikings, R., & Schaltegger, U. (2008). Detrital zircon fingerprint of the Proto-Andes: Evidence for a Neoproterozoic active margin? *Precambrian Research*, 167(1–2), 186–200. <https://doi.org/10.1016/j.precamres.2008.08.002>

Clark, A. H.; Farrar, E. (1973). The Bolivian tin province: Notes on the available geochronological data. *Scientific Communications. Economic Geology* 68: 102-116.

Clark, A. H.; Farrar, E.; Kontak, D. J.; Langridge, R. J.; Arenas, F. M. J.; France, L. J.; McBride, S.L; Woodman, P.L.; Wasteneys, H.A.; Sandeman, H.A.; Archibald, D. A. (1990). Geologic and geochronologic constraints on the metallogenic evolution of the Andes of southeastern Peru. *Economic Geology* 85(7): 1520–1583. <https://doi.org/10.2113/gsecongeo.85.7.1520>

Chambi T., O. (2010). Estudio Petrológico del Intrusivo Sorata. Modelo y Procesos Genéticos Responsables de su Emplazamiento (Segmento Norte de la Cordillera Real). Undergraduate thesis. Universidad de Mayor de San Andrés. La Paz, Bolivia.

CGMW (Commission of the Geological Map of the World). (2019). Cordani, U.G., Ramos, V.A., (Coordinators). *Tectonic Map of South America*, 2nd edition, scale 1:5000000

Cordani U.G., Iyer S.S. (1979). Geochronological investigation on the Precambrian granulitic terrain of Bahia, Brazil. *Precambrian Research*, 9(3- 4):255-274. [https://doi.org/10.1016/0301-9268\(79\)90006-8](https://doi.org/10.1016/0301-9268(79)90006-8)

Cordani, U.G., Kawashita, K. and Cortez, G. (1980) – Chronology of the tectonomagmatic events of the Cordillera Real of Bolivia – 26th International Geological Congress, Paris, France – Abstracts, pg. 32.

Cordani, UG, Ramos, VA, Fraga, LM, Cegarra, M., Delgado, I., Souza, KG de, Gómez, F., Schobbenhaus C. (2016). Mapa tectónico de América del Sur. Comisión para el Mapa Geológico del Mundo. <http://rigeo.cprm.gov.br/xmlui/handle/doc/16750>

Cordani, UG, Ramos, VA, Fraga, LM, Cegarra, M., Delgado, I., Souza, KG de, Gómez, F., Schobbenhaus C. (2016). Mapa tectónico de América del Sur. Comisión para el Mapa Geológico del Mundo. <http://rigeo.cprm.gov.br/xmlui/handle/doc/16750>

Cordani U.G., Sato K., Teixeira W., Tassinari C.C.G., Basei M.A.S. (2000). Crustal evolution of the South American platform. In: Cordani U.G., Milani E.J., Thomaz-Filho A., Campos D.A. (Eds.), Tectonic evolution of South America: Rio de Janeiro, Brazil, 31st International Geological Congress, p. 19-40.

Cordani, U. G.; Ramos, V. A.; Fraga, L. M.; Cegarra, M.; Delgado, I.; de Souza, K. G.; Gomes, F. E.M.; Schobbenhaus, C. (2016). Tectonic Map of South America. Second edition, scale 1:5000000.

Cordani, U.G.; Iriarte, A.R.; Sato, K. (2019). Geochronological systematics of the Huayna Potosí, Zongo and Taquesi plutons, Cordillera Real of Bolivia, by the K/Ar, Rb/Sr and U/Pb methods. Brazilian Journal of Geology. <https://doi.org/10.1590/2317-4889201920190016>

Cordani, U. G., Fairchild, T. R., Ganade, C. E., Babinski, M., & De Moraes Leme, J. (2020). Dawn of metazoans: To what extent was this influenced by the onset of “modern-type plate tectonics”? Brazilian Journal of Geology, 50(2). <https://doi.org/10.1590/2317-4889202020190095>

Coleman, D.S.; Gray, W.; Glazner, A.F. (2004). Rethinking the emplacement and evolution of zoned plutons: geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California. Geology 32: 433-436.

Collo, G., Astini, R. A., Cawood, P. A., Buchan, C., & Pimentel, M. (2009). U – Pb detrital zircon ages and Sm – Nd isotopic features in low-grade metasedimentary rocks of the Famatina belt: implications for late Neoproterozoic – early Palaeozoic evolution of the proto-Andean margin of Gondwana. *Journal of the Geological Society, London*, 166, 303–319. <https://doi.org/10.1144/0016-76492008-051.U>

Corfu, F.; Hanchar, J. M.; Hoskin, P. W. O.; Kinny, P. (2003). Atlas of Zircon Textures. In Zircon (Hanchar, J.M; Hoskin, P.W.O.; editors) *Reviews in Mineralogy and Geochemistry*, Mineralogical Society of America Vol. 53: 469–500.

Conover, W., C. (1971). *Practical Nonparametric Statistics*. New York: John Wiley & Sons. Pages 295–301 (one-sample Kolmogorov test), 309–314 (two-sample Smirnov test).

Dalmayrac, B., G. Laubacher, R. Marocco, C. Martinez, and P. Tomasi, (1980), La Chaîne Hercynienne d’Amérique du Sud. Structure et evolution d’une orogène intracratonique: *Geologische Rundschau*, v. 69, p. 1–21.

De la Roche, H., Leterrier, J., Grandclaude, P., Marchal, M. (1980). A classification of volcanic and plutonic rocks using R1R2-diagram and major-element analyses. Its relationships with current nomenclature, *Chemical Geology*, Volume 29, Issues 1–4, Pages 183-210. [https://doi.org/10.1016/0009-2541\(80\)90020-0](https://doi.org/10.1016/0009-2541(80)90020-0)

Dorbath, C., Granet, M., Poupinet, G., & Martinez, C. (1993). A teleseismic Study of the Altiplano and the Eastern Cordillera in Northern Bolivia: New Constraints on a Lithospheric Model. *Journal of Geophysical Research*, 98, 9825–9844.

de Silva, S. L.; Gosnold, W. D. (2007). Episodic construction of batholiths: Insights from the spatiotemporal development of an ignimbrite flare-up. *Journal of Volcanology and Geothermal Research* 167(1–4): 320–335. <https://doi.org/10.1016/j.jvolgeores.2007.07.015>

Depaolo, D. J. (1981). Assimilation and isotopic effects of combined wallrock assimilation and fractional crystallization. *Earth and Planetary Science Letters*, 53, 189–202.

Durand FR. (1993). Las icnofacies del basamento metasedimentario en el Noroeste Argentino: Significado cronológico y aspectos paleogeográficos. XII Congr. Geol. Argent. *Actas* 2:260–67

Elhlou S., Belousova, E., Griffin W.L., Pearson, N.,J., and O'Reilly S.,Y., (2006). Trace element and isotopic composition of GJ-red zircon standard by laser ablation. Goldschmidt Conference abstracts, A-5.

Escayola, M., Scientific, N., & Armstrong, R. (2007). Neoproterozoic backarc basin: Sensitive high-resolution ion microprobe UPb and Sm-Nd isotopic evidence from the Eastern Pampean Ranges, Argentina. *Geology*, (October 2015). <https://doi.org/10.1130/G23549A.1>

Escayola, M. P., van Staal, C. R., & Davis, W. J. (2011). The age and tectonic setting of the Puncoviscana Formation in northwestern Argentina: An accretionary complex related to Early Cambrian closure of the Puncoviscana Ocean and accretion of the Arequipa-Antofalla block. *Journal of South American Earth Sciences*, 32(4), 438–459. <https://doi.org/10.1016/j.jsames.2011.04.013>

Evernden, J. F., Kriz, S. J., & M., C. C. (1977). Potassium-argon ages of some Bolivian rocks - a discussion. *Economic Geology*, 72, 1042–1061. <http://doi.org/10.2113/gsecongeo.74.3.702>

Farrar, E., Clark, A. H., & Heinrich, S. M. (1990). The Age of the Zongo Pluton and the Evolution of the Zongo San Gaban Zone in the Cordillera Real, Bolivia. In *Symposium international "Géodynamique andine" : résumés des communications* (pp. 171–174).

Farrar, E.; Clark, A. H.; Kontak, D. J.; Archibald, D. A. (1988b). Zongo-San Gabán zone: Eocene foreland boundary of the Central Andean orogen, northwest Bolivia and southeast Peru. *Geology* 16(1): 55–58. [http://doi.org/10.1130/0091-7613\(1988\)016<0055:ZSGNZE>2.3.CO;2](http://doi.org/10.1130/0091-7613(1988)016<0055:ZSGNZE>2.3.CO;2)

Faure, G.; Mensing, T. M. (2005). *Isotopes Principles and Applications*. Third Edition. John Wiley and Sons: 928 p. New Jersey.

Franz, G., Lucassen, F., Kramer, W., Trumbull, R., B., Trumbull, Romer, R., L., Wilke, H.,G., Viramonte, J., G., Becchio, R., Siebel, W. (2006) *Crustal Evolution at the Central Andean Continental Margin: a Geochemical Record of Crustal Growth, Recycling and Destruction*. Chapter 3 from Oncken et al., (2006). *The Andes Active Subduction Orogeny*.

Ganade De Araujo, C. E., Rubatto, D., Hermann, J., Cordani, U. G., Caby, R., & Basei, M. A. S. (2014). Ediacaran 2,500-km-long synchronous deep continental subduction in the West Gondwana Orogen. *Nature Communications*, 5. <https://doi.org/10.1038/ncomms6198>

GEOBOL, (1968). Investigaciones Preliminares sobre Tectónica y Metalogénesis en las Cordilleras Real y Quimsa Cruz. División de Tecnología Minera. Ministerio de Minas Servicio Geológico de Bolivia. Boletín 9: 24-25

GEOBOL- Servicio Geológico de Bolivia (2013). Carta geológica de Bolivia. Hoja Challana (5946). Escala 1:100000.

GEOBOL- Servicio Geológico de Bolivia (1994). Carta geológica de Bolivia. Hoja Chulumani (6044). Escala 1:100000.

GEOBOL- Servicio Geológico de Bolivia (1995). Carta geológica de Bolivia. Hoja Sapahaqui (6043). Escala 1:100000.

GEOBOL- Servicio Geológico de Bolivia (1997). Carta geológica de Bolivia. Hoja Inquisivi (6143). Escala 1:100000.

Gillis, R. J., Horton, B. K., & Grove, M. (2006). Thermochronology, geochronology, and upper crustal structure of the Cordillera Real: Implications for Cenozoic exhumation of the central Andean plateau. *Tectonics*, 25(6), 1–22. <https://doi.org/10.1029/2005TC001887>

Glazner, A. F.; Bartley, J. M.; Coleman, D. S., Gray, W.; Taylor, R. Z. (2004). Are plutons assembled over millions of years by amalgamation from small magma chambers? *GSA Today* 14(4-5): 4–11. doi: 10.1130/1052-5173(2004)0142.0.CO;2

Grant, J. N.; Halls, C.; Salinas, W. A.; Snelling, N. J. (1979). K-Ar ages of igneous rocks in mineralization in part of the Bolivian tin belt. *Economic Geology* 74(4): 838–851. <https://doi.org/10.2113/gsecongeo.74.4.838>

Iriarte, A.R, Cordani, U.G., Sato, K., (2021). Geochronology of the Cordillera Real granitoids, the inner magmatic arc of Bolivia. *Andean Geology*. Vol. 48-3.

Irvine, T. N., & Baragar, W. R., A. (1971). A guide to the chemical classification of the common volcanic rocks. *Can. J. Earth Sci.* 8, 523–48.

Janoušek, V., Farrow, C. M. & Erban, V. (2006). Interpretation of whole-rock geochemical data in igneous geochemistry: introducing Geochemical Data Toolkit (GCDkit). *Journal of Petrology* 47(6):1255-1259.

Jiménez, N., & López-Velásquez, S. (2008). Magmatism in the Huarina belt, Bolivia, and its geotectonic implications. *Tectonophysics*, 459(1–4), 85–106.
<https://doi.org/10.1016/j.tecto.2007.10.012>

Jiménez, N., López-Velásquez, S., & Santiváñez, R. (2009). Evolución tectonomagmática de los Andes Bolivianos. *Revista de La Asociacion Geologica Argentina*, 65(1), 36–67.

Jiménez, N., & López-Velásquez, S. (2008). Magmatism in the Huarina belt, Bolivia, and its geotectonic implications. *Tectonophysics*, 459(1–4), 85–106.
<http://doi.org/10.1016/j.tecto.2007.10.012>

Kay, S. M., Coira, B., & Viramonte, J. (1994). Young mafic back arc volcanic rocks as indicators of continental lithospheric delamination beneath the Argentine Puna Plateau, central Andes. *Journal of Geophysical Research: Solid Earth*, 99(B12), 24323–24339.
<https://doi.org/10.1029/94JB00896>

Keay, S., Steele, D., & Compston, W. (1999). Identifying granite sources by SHRIMP U-Pb zircon geochronology: An application to the Lachlan foldbelt. *Contributions to Mineralogy and Petrology*, 137(4), 323–341. <https://doi.org/10.1007/s004100050553>

Kelly, W. C., and Turneaure, F. S., 1970, Mineralogy, paragenesis and geothermometry of the tin and tungsten deposits of the eastern Andes, Bolivia. *Bulletin of the Society of Economic Geologist*. 65, p. 609-680.

Kennan, L., Lamb, S., & Rundle, C. (1995). K-Ar dates from the Altiplano and Cordillera Oriental of Bolivia: implications for stratigraphy and tectonics. *Journal of South American Earth Sciences*, 8, 163–186.

- Kontak, D. J.; Clark, A. H.; Farrar, E.; Archibald, D. A.; Baadsgaard, H. (1990). Late Paleozoic-early Mesozoic magmatism in the Cordillera de Carabaya, Puno, southeastern Peru: Geochronology and petrochemistry. *Journal of South American Earth Sciences* 3(4): 213–230.
- Kusiak, M. A.; Whitehouse, M. J.; Wilde, S. A.; Nemchin, A. A.; Clark, C. (2013). Mobilization of radiogenic Pb in zircon revealed by ion imaging : Implications for early Earth geochronology. *GEOLOGY* 41- 3; p. 291–294. <https://doi.org/10.1130/G33920.1>
- Lamb, S., & Hoke, L. (1997). Origin of the high plateau in the Central Andes, Bolivia, South America. *Tectonics*, 16, 623–649.
- Larrovere, M., A., Casquet C., R., Aciar, H., R., Baldo E., G., Alasino, P., H., Rapela C., W. (2021). Extending the Pampean orogen in western Argentina: New evidence of Cambrian magmatism and metamorphism within the Ordovician Famatinian belt revealed by new SHRIMP U–Pb ages. *Journal of South American Earth Sciences*. Volume 109.
- Loewy, S. L., Connelly, J. N., & Dalziel, I. W. D. (2004). An orphaned basement block: The Arequipa-Antofalla Basement of the central Andean margin of South America. *Bulletin of the Geological Society of America*, 116(1–2), 171–187. <https://doi.org/10.1130/B25226.1>
- Lehmann, B. (1987). Tin granites, geochemical heritage, magmatic differentiation. *Geologische Rundschau*, 76(1), 177–185. <https://doi.org/10.1007/BF01820581>
- Litherland, M.; Annells, R. N.; Darbyshire, D. P. F.; Fletcher, C. J. N.; Hawkins, M. P.; Klinck, B. A.; Mitchell, W. I.; O'Connor, E. A.; Pitfield P. E. J.; Power, G.; Webb, B. C. (1989). The proterozoic of Eastern Bolivia and its relationship to the Andean mobile belt. *Precambrian Research* 43(3): 157–174. [https://doi.org/10.1016/0301-9268\(89\)90054-5](https://doi.org/10.1016/0301-9268(89)90054-5)
- Ludwig, K. R., (2003), *Isoplot 3: A Geochronological Toolkit for Microsoft Excel* (rev. August 27, 2003), Berkeley Geochr. Ctr. Spec. Pub. 4.
- Ludwig, K. (2009). *SQUID 2: A User's Manual*, rev. 12 Apr, 2009. Berkeley Geochronology Center, Special Publication 5: 110 p.

- Lundstrom, C. C.; Glazner, A. F. (2016). Silicic magmatism and the volcanic-plutonic connection. *Elements* 12(2): 91–96. <https://doi.org/10.2113/gselements.12.2.91>
- Manzano, J. C., Godoy, A. M., Marques, L., & de Araújo Marques Barbosa, L. (2008). Contexto tectônico dos granitoides neoproterozoicos da faixa de dobramentos paraguai, MS e MT. *Geociências*, 27, 493–507.
- Mcbride, S. L., Robertson, R. C. R., Clark, A. H., & Edward, F. (1983). Magmatic and Metallogenetic Episodes in the Northern Tin Belt, Cordillera Real. Bolivia. *Geologische Rundschau*, 72(2), 685–713.
- Mcbride, S. L., Clark, A. H., Farrar, E., & A., A. (1987). Delimitation of a cryptic Eocene tectono-thermal domain in the Eastern Cordillera of the Bolivian Andes through K-Ar dating and ⁴⁰Ar-³⁹Ar step-heating. *Journal of the Geological Society, London*, 144, 243–255.
- McGee B., Collins A.S., Trindade R.I.F., Payne J., (2015). Age and provenance of the Cryogenian to Cambrian passive margin to foreland basin sequence of the northern Paraguay Belt, Brazil. *GSA Bulletin*, 127, 76-86.
- Mcglashan, N., Brown, L., & Kay, S. (2008). Crustal thickness in the central Andes from teleseismically recorded depth phase precursors. *Geophysical Journal International*, 175(3), 1013–1022. <https://doi.org/10.1111/j.1365-246X.2008.03897.x>
- McQuarrie, N. (2002). The kinematic history of the central Andean fold-thrust belt, Bolivia: Implications for building a high plateau. *Bulletin of the Geological Society of America*, 114(8), 950–963. [http://doi.org/10.1130/0016-7606\(2002\)114<0950:TKHOTC>2.0.CO;2](http://doi.org/10.1130/0016-7606(2002)114<0950:TKHOTC>2.0.CO;2)
- McNamee J. (2001). The Tucavaca Through: Potential for Sedex type base metal/Ag mineralization in a late Proterozoic rift in Eastern Bolivia. *Estilos de mineralización en Bolivia*. Colegio de Geólogos de Bolivia.

Mégard, F., Dalmayrac, B., Laubacher, G., Marocco, R., Martinez, C., Paredes, J., & Tomasi, P. (1971). Le chaine Hercynienne au Pérou et en Bolivie Premiers Résultats. Cahiers Orstom. Série Géologie, III, 1, 5–44.

Middlemost, E. A., K., (1994). Naming material in the magma/igneous rock system. Earth Sci. Rev. 37, 215–224.

Miller, C. F., McDowell, S. M., & Mapes, R. W. (2003). Hot and cold granites: Implications of zircon saturation temperatures and preservation of inheritance. Geology, 31(6), 529–532. [http://doi.org/10.1130/0091-7613\(2003\)031<0529:HACGIO>2.0.CO;2](http://doi.org/10.1130/0091-7613(2003)031<0529:HACGIO>2.0.CO;2)

Miškovic, A., U. Schaltegger, and D. Chew, (2009b), Carboniferous plutonism along the Eastern Peruvian Cordillera: Implications for the Late Paleozoic to Early Mesozoic Gondwanan tectonics, in 6th International Symposium on Andean Geodynamics (ISAG 2005, Barcelona), Extended Abstracts, p. 508–511.

Mpodozis, C., & Kay, S. M. (1992). Late Paleozoic to Triassic evolution of the Gondwana margin: Evidence from Chilean Frontal Cordilleran batholiths (28°S to 31°S). Geological Society Of America Bulletin, 104, 999–1014.

Moura, C. A. V., Pinheiro, B. L. S., Nogueira, A. C. R., Gorayeb, P. S. S., & Galarza, M. A. (2008). Sedimentary provenance and palaeoenvironment of the Baixo Araguaia supergroup: Constraints on the palaeogeographical evolution of the Araguaia Belt and assembly of West Gondwana. Geological Society Special Publication, 294(75), 173–196. <https://doi.org/10.1144/SP294.10>

Otamendi, J. E., Vujovich, G. I., de la Rosa, J. D., Tibaldi, A. M., Castro, A., Martino, R. D., & Pinotti, L. P. (2009). Geology and petrology of a deep crustal zone from the Famatinian paleoarc, Sierras de Valle Fértil and La Huerta, San Juan, Argentina. Journal of South American Earth Sciences, 27(4), 258–279. <https://doi.org/10.1016/j.jsames.2008.11.007>

Oncken, O., Chong, G., Franz, G., Giese, P., Gotze, H. J., Ramos, V. A., ... Wigger, P. (2006). The Andes Active Subduction Orogeny.

Paterson, S. R.; Ducea, M. N. (2015). Arc magmatic tempos: Gathering the evidence. *Elements* 11(2): 91–98. <https://doi.org/10.2113/gselements.11.2.91>

Pearce, J. A., Harris, N. B., & Tindle, A. G. (1984). Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of petrology*, 25(4), 956–983.

Pimentel, M. (2016). The tectonic evolution of the Neoproterozoic Brasília Belt, central Brazil: a geochronological and isotopic approach. *Brazilian Journal of Geology*, 46(June), 67–82. <https://doi.org/10.1590/2317-4889201620150004>

Pinheiro, B., L., S., Moura, C., A., V., Klein, E., L. (2003). Estudo de proveniência em arenitos das formações Igarapé de Areia e Viseu, nordeste do Pará, com base em datação de monocristais de zircão por evaporação de chumbo. 8th Simpósio de Geologia da Amazônia.

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>

Ramos, V. A. (2008). The Basement of the Central Andes: The Arequipa and Related Terranes. *Annual Review of Earth and Planetary Sciences*, 36(1), 289–324. <https://doi.org/10.1146/annurev.earth.36.031207.124304>

Ramos, V. A. (2009). Anatomy and global context of the Andes: Main geologic features and the Andean orogenic cycle. *Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision: Geological Society of America Memoirs*, 1204(204), 31–65. [https://doi.org/10.1130/2009.1204\(02\)](https://doi.org/10.1130/2009.1204(02)).

Ramos, V. A. (2010). The Grenville-age basement of the Andes. *Journal of South American Earth Sciences*, 29(1), 77–91. <https://doi.org/10.1016/j.jsames.2009.09.004>

Ramos, V. A. (2018a). Tectonic Evolution of the Central Andes: From Terrane Accretion to Crustal Delamination. 1–34. <https://doi.org/10.1306/13622115M1172855>

Ramos, V. A. (2018b), Tectonic evolution of the central Andes: From terrane accretion to crustal delamination. In *Petroleum basins and hydrocarbon potential of the Andes of Peru and Bolivia* (Zamora, G.; McClay, K. M. ; Ramos, V.A.; editors). AAPG Memoir 117: pp. 1–34. <https://doi.org/10.1306/13622115M1172855>

Rezende de Oliveira, J., Aguilar de Sousa, M. Z., Salina Ruiz, A., & Matos Salinas, G. R. (2017). Granulito Uyarani - Uma janela estrutural Pré-Cambriana no Altiplano Boliviano: Petrogênese e significado tectônico. *Geologia USP - Serie Cientifica*, 17(2), 223–245.

<https://doi.org/10.11606/issn.2316-9095.v17-385>

Reimann, C. R.; Bahlburg, H.; Kooijman, E.; Berndt, J.; Gerdes, A.; Carlotto, V.; López, S. (2010). Geodynamic evolution of the early Paleozoic Western Gondwana margin 14°-17°S reflected by the detritus of the Devonian and Ordovician basins of southern Peru and northern Bolivia. *Gondwana Research* 18(2–3): 370–384. <https://doi.org/10.1016/j.gr.2010.02.002>

Romer, R. L.; Kroner, U. (2016). Phanerozoic tin and tungsten mineralization-Tectonic controls on the distribution of enriched protoliths and heat sources for crustal melting. *Gondwana Research* 31: 60–95. <https://doi.org/10.1016/j.gr.2015.11.002>

Sandeman, H. A.; Clark, A. H.; Farrar, E. (1995). An Integrated Tectono-Magmatic Model for the Evolution of the Southern Peruvian Andes (13–20°S) since 55 Ma. *International Geology Review* 37(12): 1039–1073. <https://doi.org/10.1080/00206819509465439>

Sato, K., Tassinari, C.C.G., Kawashita, K., Petronilho, L.A., (1995). O método geocronológico Sm-Nd no IGc-USP e suas aplicações. *Anais da Academia Brasileira de Ciências*, 3(67), 313-336.

Sato, K.; Tassinari, C. C. G.; Basei, M. A. S., Siga, O.; Onoe, A. T.; De Souza, M. D. (2014). Sensitive High Resolution Ion Microprobe (SHRIMP Ile/MC) of the Institute of Geosciences of the University of São Paulo, Brazil: Analytical method and first results. *Geologia USP - Serie Cientifica* 14(3): 3–18. <https://doi.org/10.5327/Z1519-874X201400030001>

Spikings, R., Reitsma, M. J., Boekhout, F., Mišković, A., Ulianov, A., Chiaradia, M., ... Schaltegger, U. (2016). Characterisation of Triassic rifting in Peru and implications for the early disassembly of western Pangaea. *Gondwana Research*, 35(January), 124–143. <https://doi.org/10.1016/j.gr.2016.02.008>

Sempere, T., (1995), Phanerozoic evolution of Bolivia and adjacent regions, in A. Tankard, S. R. Suárez, and H. Welsink, eds., *Petroleum basins of South America*: AAPG Memoir 62, p. 207–230.

Sempere, T., Carlier, G., Soler, P., Fornari, M., Carlotto, V., Jacay, J., ... Jiménez, N. (2002). Late Permian-Middle Jurassic lithospheric thinning in Peru and Bolivia, and its bearing on Andean-age tectonics. *Tectonophysics*, 345(1–4), 153–181. [https://doi.org/10.1016/S0040-1951\(01\)00211-6](https://doi.org/10.1016/S0040-1951(01)00211-6)

Sergeotecmin (2011). Carta Geológica de Bolivia. Hoja Charazani 584. Publicación SGTM-Serie I-CGB-62. Scale 1:100000. Bolivia: Servicio Geológico de Bolivia.

Siégel, C.; Bryan, S. E.; Allen, C. M.; Gust, D. A. (2018). Use and abuse of zircon-based thermometers: A critical review and a recommended approach to identify antecrystic zircons. *Earth-Science Reviews* 176: 87–116. <https://doi.org/10.1016/j.earscirev.2017.08.011>

Souza De Alvarenga, C. J., Babinski, M., Figueiredo, M. F., & Santos, R. V. (2011). Glacially influenced sedimentation of the Puga Formation , Cuiabá Group and Jacadigo Group , and associated carbonates of the Araras and Corumbá ´ groups , Paraguay Belt, Brazil. *Geological Society, London*, (May), 487–497. <https://doi.org/10.1144/M36.45>

Spikings R., Reitsma M.J., Boekhout F., Mišković A., Ulianov A., Chiaradia M., Gerdes A., Schaltegger U. (2016). Characterisation of Triassic rifting in Peru and implications for the early disassembly of western Pangaea. *Gondwana Research*, 35:124-143. <http://doi.org/10.1016/j.gr.2016.02.008>

Staudigel, H., Albarède, F., Blichert-Toft, J., Edmond, J., McDonough, B., Jacobsen, S. B., White, W. (1998). Geochemical Earth Reference Model (GERM): description of the initiative. *Chemical Geology*, 145(3-4), 153–159. [https://doi.org/10.1016/S0009-2541\(97\)00141-1](https://doi.org/10.1016/S0009-2541(97)00141-1)

Steiger, R. H.; Jäger, E. (1977). Subcomission on Geochronology: Convention on the use of decay constants in geo-and cosmochronology. *Earth and Planetary Science Letters*, 36:359-362.

Streckeisen, A. (1976). To each plutonic rock its proper name. *Earth Science Reviews*, 12(1), 1–33. [https://doi.org/10.1016/0012-8252\(76\)90052-0](https://doi.org/10.1016/0012-8252(76)90052-0)

Suárez Soruco, R. (1992). El Paleozoico Inferior de Bolivia y Perú (in: Paleozoico Inferior de Ibero- América, Universidad de Extremadura, España) p. 225–239.

Suarez S., R. (2000). Compendio de Geología de Bolivia.

Sugaki, A., Kusachi, I., & Nobutaka, S. (1988). Granite-series and -types of Igneous Rocks in the Bolivian Andes and their Genetic Relation to Tin-Tungsten Mineralization. 38(2), 121–130.

Sugaki A., Shimada N., Ueno H., Kano S. (2003). K-Ar ages of tin-polymetallic mineralization in the Oruro mining district, central Bolivian tin belt. *Resource Geology*, 53(4):273-282.

Tawackoli S., Kley J., Jacobshagen V. (1996). Evolución tectónica de la Cordillera Oriental del Sur de Bolivia. In: XII Congreso Geológico de Bolivia, 12., Tarija. Memorias..., p. 91-96, Tarija.

Vasconcelos, B.,R. (2018). Proveniência sedimentar do Grupo Cuiabá na faixa Paraguai Meridional. Tese de Doutorado. Universidade de Brasília.

Voges, A. (1962). Geología y yacimientos metalíferos de la región de Oruro. Informe interno. Misión Geológica Alemana en Bolivia (MGAB).

Watson, E. B.; Harrison, T. M. (1983). Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth and Planetary Science Letters* 64: 295–304.

White W.M. (2005). *Geochemistry*. Wiley and Blackwell.

White L.T. & Ireland T.R. (2012). High-uranium matrix effect in zircon and its implications for SHRIMP U-Pb age determinations. *Chemical Geology*, 306-307:78-91. <http://doi.org/10.1016/j.chemgeo.2012.02.025>

Wiedenbeck, M., P., Alle, F. Corfu, W.L. Griffin, M. Meier, F. Oberli, A. Vonquadt, J.C. Roddick, W. Spiegel. (1995). Three natural zircon standards for U-Th-Pb, Lu-Hf, trace-element and REE analyses. *Geostand. Newslett.*, 19, pp. 1-23.

Wiedenbeck, M. (1995). An example of reverse discordance during ion microprobe zircon dating: An artifact of enhanced ion yields from a radiogenic labile Pb. *Chemical Geology*, 125(3-4), 197-218. [http://doi.org/10.1016/0009-2541\(95\)00072-T](http://doi.org/10.1016/0009-2541(95)00072-T)

Williams I.S. (1998). U-Th-Pb geochronology by ion microprobe. In: McKibben M.A., Shanks I., Ridley W.C.P., Ridley W.I. (Eds.). *Application of Microanalytical Techniques to Understanding Mineralizing Process. Reviews in Economic Geology*. United States: Society of Economic Geologists, 7:1-35.

Williams I.S. & Hergt J.M. (2000). U-Pb dating of Tasmania dolerites: A Cautionary Tale of SHRIMP Analyses of High-U Zircon. In: Woodhead J.D., Hergt J.M., Noble W.P. (Eds.). *Beyond 2000: New Frontiers in Isotope Geoscience*, Lorne, 2000. Abstracts and Proceedings, 185-188.

Winter J.D. (2001). *An introduction to igneous and metamorphic petrology*. Prentice Hall Inc..Upper Saddle River, New Jersey.

York D. (1968). Least Squares Fitting of a Straight Line with Correlated Errors. *Earth and Planetary Science Letters*, 5:320-324. [https://doi.org/10.1016/S0012-821X\(68\)80059-7](https://doi.org/10.1016/S0012-821X(68)80059-7)

Ziegler, P. A.; Cloetingh, S. (2004). Dynamic processes controlling evolution of rifted basins. *Earth-Science Reviews* 64(1-2): 1-50. [https://doi.org/10.1016/S0012-8252\(03\)00041-2](https://doi.org/10.1016/S0012-8252(03)00041-2)

Unnormalized Major Elements (Weight %):

Sample	WA-1 ^a	H100C ^b	H101 ^b	Y-7 ^a	CG14 ^b
Locality	Huato	Huato	Huato	Yani	Taquesi
Rock	Monzogranite	Granodiorite	Granodiorite	Leucogranite	Granodiorite
SiO ₂	66.55	65.24	65.99	72.54	67.68
TiO ₂	0.59	0.74	0.69	0.14	0.48
Al ₂ O ₃	15.01	15.1	14.85	15.01	15.95
Fe ₂ O ₃ T	NA	3.86	3.71	NA	3.03
FeOT	NA	3.47	3.34	NA	2.73
FeO	2.23	NA	NA	0.96	NA
Fe ₂ O ₃	1.1	NA	NA	0.7	NA
MnO	0.02	0.02	0.02	0.03	0.05
MgO	1.86	1.87	1.86	0.04	1.06
CaO	2.12	2.02	2.18	0.98	2.38
2O	3.59	3.37	3.39	2.78	3.82
K ₂ O	4.94	5.25	4.95	4.97	4.4
P ₂ O ₅	0.08	0.07	0.06	0.21	0.27
H ₂ O+	1.08	NA	NA	1.02	NA
H ₂ O-	0.11	NA	NA	0.14	NA
LOI	NA	1.5	1.17	NA	0.83

Normalized Major Elements (Weight %):

SiO ₂	67.92	67.15	67.80	73.80	68.49
TiO ₂	0.60	0.76	0.71	0.14	0.49
Al ₂ O ₃	15.32	15.54	15.26	15.27	16.14
FeOT	3.29	3.57	3.43	1.62	2.76
MnO	0.02	0.02	0.02	0.03	0.05
MgO	1.90	1.92	1.91	0.04	1.07
CaO	2.16	2.08	2.24	1.00	2.41
2O	3.66	3.47	3.48	2.83	3.87
K ₂ O	5.04	5.40	5.09	5.06	4.45
P ₂ O ₅	0.08	0.07	0.06	0.21	0.27

Trace elements (Weight in ppm):

Sc	NA	NA	NA	NA	6.4
Be	NA	3.00	5.00	NA	NA
V	NA	32.00	56.00	NA	NA
Cr	NA	NA	NA	NA	NA
Co	NA	56.00	75.00	NA	53.00
Zn	NA	NA	NA	NA	NA
Rb	NA	NA	NA	NA	216.00
Sr	NA	180.00	560.00	NA	445.00
Y	NA	10.00	56.00	NA	29.00
Zr	NA	160.00	320.00	NA	288.00

Trace elements, weight in ppm (continuation):

Sample	WA-1 ^a	H100C ^b	H101 ^b	Y-7 ^a	CG14 ^b
Locality	Huato	Huato	Huato	Yani	Taquesi
Rock	Monzogranite	Granodiorite	Granodiorite	Leucogranite	Granodiorite
Nb	NA	32.00	32.00	NA	54.00
Cs	NA	NA	NA	NA	10.00
Ba	NA	180.00	320.00	NA	1256.00
Pb	NA	56.00	100.00	NA	NA
La	NA	NA	NA	NA	74.00
Ce	NA	NA	NA	NA	150.00
Pr	NA	NA	NA	NA	NA
Nd	NA	NA	NA	NA	59.00
Sm	NA	NA	NA	NA	8.3
Eu	NA	NA	NA	NA	1.6
Gd	NA	NA	NA	NA	NA
Tb	NA	NA	NA	NA	1.00
Dy	NA	NA	NA	NA	NA
Ho	NA	NA	NA	NA	NA
Er	NA	NA	NA	NA	NA
Tm	NA	NA	NA	NA	NA
Yb	NA	NA	NA	NA	2.00
Lu	NA	NA	NA	NA	0.3
Hf	NA	NA	NA	NA	5.5
Ta	NA	3.2	1.8	NA	3.00
Th	NA	NA	NA	NA	13.00
U	NA	NA	NA	NA	6.00
Ni	NA	NA	NA	NA	NA
Cu	NA	NA	NA	NA	NA
Ga	NA	NA	NA	NA	NA
Ge	NA	NA	NA	NA	NA
As	NA	NA	NA	NA	NA
Mo	NA	NA	NA	NA	NA
Ag	NA	NA	NA	NA	NA
In	NA	NA	NA	NA	NA
Sn	NA	NA	NA	NA	NA
Sb	NA	NA	NA	NA	NA
W	NA	NA	NA	NA	NA
Tl	NA	NA	NA	NA	NA
Bi	NA	NA	NA	NA	NA

Unnormalized Major Elements (Weight %):

Sample	GC24 ^b	GC31 ^b	77082912 ^c	80032213 ^c	80080302 ^c
Locality	Taquesi	Taquesi	Taquesi	Taquesi	Taquesi
Rock	Granodiorite	Granodiorite	Adamelite	Adamelite	Granodiorite
SiO ₂	68.29	67.11	72.59	71.91	65.93
TiO ₂	0.58	0.6	0.05	0.11	0.36
Al ₂ O ₃	15.65	16.64	14.06	14.05	14.94
Fe ₂ O ₃ T	2.93	3.28	NA	NA	NA
FeOT	2.64	2.95	NA	NA	NA
FeO	NA	NA	0.16	0.15	1.54
Fe ₂ O ₃	NA	NA	0.74	0.6	1.39
MnO	0.06	0.06	0.04	0.01	0.03
MgO	1.18	1.52	0.03	0.05	1.75
CaO	2.53	3.12	1.07	0.95	2.94
2O	3.52	4.03	4.28	4.42	3.33
K ₂ O	3.74	3.69	3.81	3.74	4.11
P ₂ O ₅	0.24	0.25	0.05	0.1	0.04
H ₂ O+	NA	NA	1.6	1.91	1.97
H ₂ O-	NA	NA	0.91	1.37	1.28
LOI	0.49	0.35	NA	NA	NA

Normalized Major Elements (Weight %):

SiO ₂	69.38	67.13	74.99	74.88	68.52
TiO ₂	0.59	0.60	0.05	0.11	0.37
Al ₂ O ₃	15.90	16.64	14.52	14.63	15.53
FeOT	2.68	2.95	0.85	0.72	2.90
MnO	0.06	0.06	0.04	0.01	0.03
MgO	1.20	1.52	0.03	0.05	1.82
CaO	2.57	3.12	1.11	0.99	3.06
2O	3.58	4.03	4.42	4.60	3.46
K ₂ O	3.80	3.69	3.94	3.89	4.27
P ₂ O ₅	0.24	0.25	0.05	0.10	0.04

Trace elements (Weight in ppm):

Sc	8.1	9.00	NA	NA	NA
Be	NA	NA	NA	NA	NA
V	NA	NA	NA	NA	NA
Cr	36.00	34.00	NA	NA	NA
Co	54.00	36.00	NA	NA	NA
Zn	NA	120.00	NA	NA	NA
Rb	190.00	180.00	NA	NA	NA
Sr	309.00	389.00	NA	NA	NA
Y	33.00	28.00	NA	NA	NA
Zr	189.00	212.00	NA	NA	NA

Trace elements, weight in ppm (continuation):

Sample	GC24 ^b	GC31 ^b	77082912 ^c	80032213 ^c	80080302 ^c
Locality	Taquesi	Taquesi	Taquesi	Taquesi	Taquesi
Rock	Granodiorite	Granodiorite	Adamelite	Adamelite	Granodiorite
Nb	33.00	39.00	NA	NA	NA
Cs	9.3	12.00	NA	NA	NA
Ba	660.00	790.00	NA	NA	NA
Pb	NA	NA	NA	NA	NA
La	44.00	48.00	NA	NA	NA
Ce	99.00	110.00	NA	NA	NA
Pr	NA	NA	NA	NA	NA
Nd	41.00	47.00	NA	NA	NA
Sm	6.5	7.2	NA	NA	NA
Eu	1.2	1.6	NA	NA	NA
Gd	NA	NA	NA	NA	NA
Tb	0.8	1.2	NA	NA	NA
Dy	NA	NA	NA	NA	NA
Ho	NA	NA	NA	NA	NA
Er	NA	NA	NA	NA	NA
Tm	NA	NA	NA	NA	NA
Yb	3.00	3.00	NA	NA	NA
Lu	0.3	0.4	NA	NA	NA
Hf	3.6	4.4	NA	NA	NA
Ta	2.7	2.8	NA	NA	NA
Th	15.00	16.00	NA	NA	NA
U	4.4	6.3	NA	NA	NA
Ni	NA	NA	NA	NA	NA
Cu	NA	NA	NA	NA	NA
Ga	NA	NA	NA	NA	NA
Ge	NA	NA	NA	NA	NA
As	NA	NA	NA	NA	NA
Mo	NA	NA	NA	NA	NA
Ag	NA	NA	NA	NA	NA
In	NA	NA	NA	NA	NA
Sn	NA	NA	NA	NA	NA
Sb	NA	NA	NA	NA	NA
W	NA	NA	NA	NA	NA
Tl	NA	NA	NA	NA	NA
Bi	NA	NA	NA	NA	NA

Unnormalized Major Elements (Weight %):

Sample	80080303 ^c	O1 ^a	U-1 ^a	CA-01 ^a	81020505 ^c
Locality	Taquesi	Illimani	Illimani	Quimsa Cruz	Quimsa Cruz
Rock	Granodiorite	Average (n=6)	Granodiorite	Adamelite	Adamelite
SiO ₂	69.72	71.28	64.02	63.24	61.47
TiO ₂	0.48	0.22	0.48	0.54	0.76
Al ₂ O ₃	13.73	14.32	16.87	15.71	16.87
Fe ₂ O ₃ T	NA	2.5	NA	NA	NA
FeOT	NA	2.25	NA	NA	NA
FeO	0.47	NA	2.77	1.62	3.73
Fe ₂ O ₃	1.41	NA	1.18	2.05	0.04
MnO	0.01	0.04	0.05	0.01	0.03
MgO	0.4	0.3	1.35	1.93	2.16
CaO	1.62	0.54	2.37	3.37	3.52
2O	3.42	3.13	3.02	3.13	3.02
K ₂ O	5.58	4.6	4.81	5.05	4.71
P ₂ O ₅	0.1	0.26	0.4	0.1	0.13
H ₂ O+	1.64	NA	1.49	1.91	2.13
H ₂ O-	1.01	NA	0.12	0.93	0.98
LOI	NA	NA	NA	NA	NA

Normalized Major Elements (Weight %):

SiO ₂	72.03	73.53	65.86	65.50	63.74
TiO ₂	0.50	0.23	0.49	0.56	0.79
Al ₂ O ₃	14.18	14.77	17.36	16.27	17.49
FeOT	1.80	2.32	3.94	3.59	3.91
MnO	0.01	0.04	0.05	0.01	0.03
MgO	0.41	0.31	1.39	2.00	2.24
CaO	1.67	0.56	2.44	3.49	3.65
2O	3.53	3.23	3.11	3.24	3.13
K ₂ O	5.76	4.75	4.95	5.23	4.88
P ₂ O ₅	0.10	0.27	0.41	0.10	0.13

Trace elements (Weight in ppm):

Sc	NA	NA	NA	NA	NA
Be	NA	NA	NA	NA	NA
V	NA	NA	NA	NA	NA
Cr	NA	NA	NA	NA	NA
Co	NA	NA	NA	NA	NA
Zn	NA	NA	NA	NA	NA
Rb	NA	NA	NA	NA	NA
Sr	NA	NA	NA	NA	NA
Y	NA	NA	NA	NA	NA
Zr	NA	NA	NA	NA	NA

Trace elements, weight in ppm (continuation):

Sample	80080303 ^c	O1 ^a	U-1 ^a	CA-01 ^a	81020505 ^c
Locality	Taquesi	Illimani	Illimani	Quimsa Cruz	Quimsa Cruz
Rock	Granodiorite	Average (n=6)	Granodiorite	Adamelite	Adamelite
Nb	NA	NA	NA	NA	NA
Cs	NA	NA	NA	NA	NA
Ba	NA	NA	NA	NA	NA
Pb	NA	NA	NA	NA	NA
La	NA	NA	NA	NA	NA
Ce	NA	NA	NA	NA	NA
Pr	NA	NA	NA	NA	NA
Nd	NA	NA	NA	NA	NA
Sm	NA	NA	NA	NA	NA
Eu	NA	NA	NA	NA	NA
Gd	NA	NA	NA	NA	NA
Tb	NA	NA	NA	NA	NA
Dy	NA	NA	NA	NA	NA
Ho	NA	NA	NA	NA	NA
Er	NA	NA	NA	NA	NA
Tm	NA	NA	NA	NA	NA
Yb	NA	NA	NA	NA	NA
Lu	NA	NA	NA	NA	NA
Hf	NA	NA	NA	NA	NA
Ta	NA	NA	NA	NA	NA
Th	NA	NA	NA	NA	NA
U	NA	NA	NA	NA	NA
Ni	NA	NA	NA	NA	NA
Cu	NA	NA	NA	NA	NA
Ga	NA	NA	NA	NA	NA
Ge	NA	NA	NA	NA	NA
As	NA	NA	NA	NA	NA
Mo	NA	NA	NA	NA	NA
Ag	NA	NA	NA	NA	NA
In	NA	NA	NA	NA	NA
Sn	NA	NA	NA	NA	NA
Sb	NA	NA	NA	NA	NA
W	NA	NA	NA	NA	NA
Tl	NA	NA	NA	NA	NA
Bi	NA	NA	NA	NA	NA

Unnormalized Major Elements (Weight %):

Sample	83063019 ^c	84071401 ^c	84071425 ^c	81020606 ^c	81020402 ^c
Locality	Quimsa Cruz	Quimsa Cruz	Quimsa Cruz	Quimsa Cruz	Quimsa Cruz
Rock	Adamelite	Adamelite	Adamelite	Adamelite	Adamelite
SiO ₂	61.85	63.23	65.58	59.84	64.55
TiO ₂	0.61	0.54	0.38	0.85	0.65
Al ₂ O ₃	16.04	15.71	15.67	16.85	17.06
Fe ₂ O ₃ T	NA	NA	NA	NA	NA
FeOT	NA	NA	NA	NA	NA
FeO	3.06	1.62	1.45	3.18	1.24
Fe ₂ O ₃	0.35	2.05	1.48	0.86	1.46
MnO	0.04	0.01	0.01	0.04	0.03
MgO	2.1	1.93	1.68	3.48	1.71
CaO	4.22	3.37	2.62	3.84	2.86
ZnO	2.86	3.13	2.97	2.94	3.02
K ₂ O	4.13	5.05	4.99	4.39	4.86
P ₂ O ₅	0.11	0.1	0.08	0.07	0.1
H ₂ O ⁺	2.7	1.91	1.73	2.04	1.64
H ₂ O ⁻	1.53	0.93	1.02	0.94	1.5
LOI	NA	NA	NA	NA	NA

Normalized Major Elements (Weight %):

SiO ₂	64.88	65.50	67.77	62.17	66.28
TiO ₂	0.64	0.56	0.39	0.88	0.67
Al ₂ O ₃	16.82	16.27	16.19	17.51	17.52
FeOT	3.54	3.59	2.88	4.11	2.62
MnO	0.04	0.01	0.01	0.04	0.03
MgO	2.20	2.00	1.74	3.62	1.76
CaO	4.43	3.49	2.71	3.99	2.94
ZnO	3.00	3.24	3.07	3.05	3.10
K ₂ O	4.33	5.23	5.16	4.56	4.99
P ₂ O ₅	0.12	0.10	0.08	0.07	0.10

Trace elements (Weight in ppm):

Sc	NA	NA	NA	NA	NA
Be	NA	NA	NA	NA	NA
V	NA	NA	NA	NA	NA
Cr	NA	NA	NA	NA	NA
Co	NA	NA	NA	NA	NA
Zn	NA	NA	NA	NA	NA
Rb	NA	NA	NA	NA	NA
Sr	NA	NA	NA	NA	NA
Y	NA	NA	NA	NA	NA
Zr	NA	NA	NA	NA	NA

Trace elements, weight in ppm (continuation):

Sample	83063019 ^c	84071401 ^c	84071425 ^c	81020606 ^c	81020402 ^c
Locality	Quimsa Cruz	Quimsa Cruz	Quimsa Cruz	Quimsa Cruz	Quimsa Cruz
Rock	Adamelite	Adamelite	Adamelite	Adamelite	Adamelite
Nb	NA	NA	NA	NA	NA
Cs	NA	NA	NA	NA	NA
Ba	NA	NA	NA	NA	NA
Pb	NA	NA	NA	NA	NA
La	NA	NA	NA	NA	NA
Ce	NA	NA	NA	NA	NA
Pr	NA	NA	NA	NA	NA
Nd	NA	NA	NA	NA	NA
Sm	NA	NA	NA	NA	NA
Eu	NA	NA	NA	NA	NA
Gd	NA	NA	NA	NA	NA
Tb	NA	NA	NA	NA	NA
Dy	NA	NA	NA	NA	NA
Ho	NA	NA	NA	NA	NA
Er	NA	NA	NA	NA	NA
Tm	NA	NA	NA	NA	NA
Yb	NA	NA	NA	NA	NA
Lu	NA	NA	NA	NA	NA
Hf	NA	NA	NA	NA	NA
Ta	NA	NA	NA	NA	NA
Th	NA	NA	NA	NA	NA
U	NA	NA	NA	NA	NA
Ni	NA	NA	NA	NA	NA
Cu	NA	NA	NA	NA	NA
Ga	NA	NA	NA	NA	NA
Ge	NA	NA	NA	NA	NA
As	NA	NA	NA	NA	NA
Mo	NA	NA	NA	NA	NA
Ag	NA	NA	NA	NA	NA
In	NA	NA	NA	NA	NA
Sn	NA	NA	NA	NA	NA
Sb	NA	NA	NA	NA	NA
W	NA	NA	NA	NA	NA
Tl	NA	NA	NA	NA	NA
Bi	NA	NA	NA	NA	NA

Unnormalized Major Elements (Weight %):

Sample	A-2 ^a	79101812 ^c	80060708 ^c	80060711 ^c
Locality	Quimsa Cruz	Huayna-Potosí	Huayna-Potosí	Huayna-Potosí
Rock	Quartz-monzonite	Granodiorite	Granodiorite	Granodiorite
SiO ₂	66.02	64.67	63.16	64.43
TiO ₂	0.3	0.46	0.55	0.6
Al ₂ O ₃	15.7	15.91	16.58	16.23
Fe ₂ O ₃ T	NA	NA	NA	NA
FeOT	NA	NA	NA	NA
FeO	3.2	2.32	2.82	2.36
Fe ₂ O ₃	1.1	0.98	0.25	1.05
MnO	0.18	0.05	0.04	0.04
MgO	0.68	1.74	1.33	1.37
CaO	2.56	3.2	3.56	2.99
2O	2.15	3.56	3.54	3.48
K ₂ O	5.47	3.8	4.04	3.47
P ₂ O ₅	0.38	0.21	0.06	0.07
H ₂ O+	1.2	2.51	2.19	2.13
H ₂ O-	0.15	1.17	1.25	1.06
LOI	NA	NA	NA	NA

Normalized Major Elements (Weight %):

SiO ₂	67.62	66.81	65.86	67.13
TiO ₂	0.31	0.48	0.57	0.63
Al ₂ O ₃	16.08	16.44	17.29	16.91
FeOT	4.29	3.31	3.18	3.44
MnO	0.18	0.05	0.04	0.04
MgO	0.70	1.80	1.39	1.43
CaO	2.62	3.31	3.71	3.12
2O	2.20	3.68	3.69	3.63
K ₂ O	5.60	3.93	4.21	3.62
P ₂ O ₅	0.39	0.22	0.06	0.07

Trace elements (Weight in ppm):

Sc	NA	NA	NA	NA
Be	NA	NA	NA	NA
V	NA	NA	NA	NA
Cr	NA	NA	NA	NA
Co	NA	NA	NA	NA
Zn	NA	NA	NA	NA
Rb	NA	NA	NA	NA
Sr	NA	NA	NA	NA
Y	NA	NA	NA	NA
Zr	NA	NA	NA	NA

Trace elements, weight in ppm (continuation):

Sample	A-2 ^a	79101812 ^c	80060708 ^c	80060711 ^c
Locality	Quimsa Cruz	Huayna-Potosí	Huayna-Potosí	Huayna-Potosí
Rock	Quartz-monzonite	Granodiorite	Granodiorite	Granodiorite
Nb	NA	NA	NA	NA
Cs	NA	NA	NA	NA
Ba	NA	NA	NA	NA
Pb	NA	NA	NA	NA
La	NA	NA	NA	NA
Ce	NA	NA	NA	NA
Pr	NA	NA	NA	NA
Nd	NA	NA	NA	NA
Sm	NA	NA	NA	NA
Eu	NA	NA	NA	NA
Gd	NA	NA	NA	NA
Tb	NA	NA	NA	NA
Dy	NA	NA	NA	NA
Ho	NA	NA	NA	NA
Er	NA	NA	NA	NA
Tm	NA	NA	NA	NA
Yb	NA	NA	NA	NA
Lu	NA	NA	NA	NA
Hf	NA	NA	NA	NA
Ta	NA	NA	NA	NA
Th	NA	NA	NA	NA
U	NA	NA	NA	NA
Ni	NA	NA	NA	NA
Cu	NA	NA	NA	NA
Ga	NA	NA	NA	NA
Ge	NA	NA	NA	NA
As	NA	NA	NA	NA
Mo	NA	NA	NA	NA
Ag	NA	NA	NA	NA
In	NA	NA	NA	NA
Sn	NA	NA	NA	NA
Sb	NA	NA	NA	NA
W	NA	NA	NA	NA
Tl	NA	NA	NA	NA
Bi	NA	NA	NA	NA

Unnormalized Major Elements (Weight %):

Sample	80060716 ^c	XE 1A ^b	RIB-53	GRS 1 ^b
Locality	Huayna-Potosí	Huayna Potosí	Huayna Potosí	Huayna Potosí
Rock	Granodiorite	Diorite	Diorite	Granite
SiO ₂	67.78	58.92	61.2	72.54
TiO ₂	0.52	1.18	1.187	0.27
Al ₂ O ₃	14.51	17.06	16.71	14.5
Fe ₂ O ₃ T	NA	6.72	NA	1.72
FeOT	NA	6.05	NA	1.55
FeO	0.48	NA	NA	NA
Fe ₂ O ₃	1.14	NA	6.62	NA
MnO	0.01	0.15	0.091	0.02
MgO	0.73	3.79	2.78	0.37
CaO	3.15	4.77	3.46	0.75
2O	3.69	2.71	3.22	2.65
K ₂ O	4.96	2.6	2.83	5.21
P ₂ O ₅	0.06	0.4	0.309	0.26
H ₂ O+	1.36	NA	NA	NA
H ₂ O-	0.97	NA	NA	NA
LOI	NA	1.84	1.16	0.97

Normalized Major Elements (Weight %):

SiO ₂	69.94	60.35	62.61	73.93
TiO ₂	0.54	1.21	1.21	0.28
Al ₂ O ₃	14.97	17.47	17.10	14.78
FeOT	1.55	6.20	6.09	1.58
MnO	0.01	0.15	0.09	0.02
MgO	0.75	3.88	2.84	0.38
CaO	3.25	4.89	3.54	0.76
2O	3.81	2.78	3.29	2.70
K ₂ O	5.12	2.66	2.90	5.31
P ₂ O ₅	0.06	0.41	0.32	0.26

Trace elements (Weight in ppm):

Sc	NA	20.00	13.30	3.00
Be	NA	3.00	0.00	4.00
V	NA	140.59	0.00	7.00
Cr	NA	50.67	0.00	0.00
Co	NA	42.79	0.00	45.00
Zn	NA	110.54	0.00	85.10
Rb	NA	150.23	204.00	332.23
Sr	NA	577.28	327.00	98.32
Y	NA	32.25	36.20	12.17
Zr	NA	225.47	247.00	96.23

Trace elements, weight in ppm (continuation):

Sample	80060716 ^c	XE 1A ^b	RIB-53	GRS 1 ^b
Locality	Huayna-Potosí	Huayna Potosí	Huayna Potosí	Huayna Potosí
Rock	Granodiorite	Diorite	Diorite	Granite
Nb	NA	32.95	28.80	12.44
Cs	NA	6.36	16.70	16.71
Ba	NA	1160.00	699.00	323.34
Pb	NA	14.43	10.60	52.19
La	NA	68.26	49.10	37.95
Ce	NA	124.47	96.30	87.82
Pr	NA	14.08	11.30	9.75
Nd	NA	52.44	40.60	36.12
Sm	NA	9.09	7.93	8.40
Eu	NA	1.97	1.38	0.94
Gd	NA	7.44	6.84	5.46
Tb	NA	1.14	1.03	0.72
Dy	NA	6.03	5.55	2.95
Ho	NA	1.18	1.15	0.41
Er	NA	3.52	3.19	1.06
Tm	NA	0.51	0.45	0.14
Yb	NA	3.25	3.01	0.78
Lu	NA	0.51	0.44	0.10
Hf	NA	6.2	5.65	3.11
Ta	NA	1.94	0.00	1.74
Th	NA	17.11	11.90	14.70
U	NA	4.28	6.91	4.10
Ni	NA	NA	11.00	NA
Cu	NA	NA	10.00	NA
Ga	NA	NA	21.00	NA
Ge	NA	NA	NA	NA
As	NA	NA	NA	NA
Mo	NA	NA	NA	NA
Ag	NA	NA	NA	NA
In	NA	NA	NA	NA
Sn	NA	NA	NA	NA
Sb	NA	NA	NA	NA
W	NA	NA	NA	NA
Tl	NA	NA	NA	NA
Bi	NA	NA	NA	NA

Unnormalized Major Elements (Weight %):

Sample	RIB-19	RIB-20	RIB-22	RIB-2
Locality	Huayna Potosí	Huayna Potosí	Huayna Potosí	Huayna Potosí
Rock	Granite	Granite	Granite	Granite
SiO ₂	70.66	64.3	69.31	73.26
TiO ₂	0.326	0.557	0.274	0.14
Al ₂ O ₃	15.2	17.17	16.37	14.49
Fe ₂ O ₃ T	NA	NA	NA	NA
FeOT	NA	NA	NA	NA
FeO	NA	NA	NA	NA
Fe ₂ O ₃	2.56	4.77	2.58	1.32
MnO	0.051	0.074	0.062	0.032
MgO	0.69	1.44	0.62	0.2
CaO	1.38	1.58	0.94	0.74
ZnO	3.36	3.4	3.07	3.16
K ₂ O	4.29	4.39	4.98	4.58
P ₂ O ₅	0.173	0.146	0.174	0.267
H ₂ O+	NA	NA	NA	NA
H ₂ O-	NA	NA	NA	NA
LOI	1.21	1.74	1.27	1.04

Normalized Major Elements (Weight %):

SiO ₂	71.78	66.05	70.64	74.71
TiO ₂	0.33	0.57	0.28	0.14
Al ₂ O ₃	15.44	17.64	16.68	14.78
FeOT	2.34	4.41	2.37	1.21
MnO	0.05	0.08	0.06	0.03
MgO	0.70	1.48	0.63	0.20
CaO	1.40	1.62	0.96	0.75
ZnO	3.41	3.49	3.13	3.22
K ₂ O	4.36	4.51	5.08	4.67
P ₂ O ₅	0.18	0.15	0.18	0.27

Trace elements (Weight in ppm):

Sc	4.58	6.62	5.07	0.00
Be	0.00	0.00	0.00	0.00
V	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00
Co	0.00	0.00	0.00	0.00
Zn	0.00	0.00	0.00	80.00
Rb	238.00	285.00	307.00	438.00
Sr	196.00	259.00	148.00	59.00
Y	12.30	17.00	13.60	10.90
Zr	67.60	66.90	75.70	52.70

Trace elements, weight in ppm (continuation):

Sample	RIB-19	RIB-20	RIB-22	RIB-2
Locality	Huayna Potosí	Huayna Potosí	Huayna Potosí	Huayna Potosí
Rock	Granite	Granite	Granite	Granite
Nb	28.10	35.00	22.00	20.80
Cs	7.60	12.30	24.80	33.50
Ba	429.00	493.00	327.00	183.00
Pb	30.60	24.10	36.50	28.00
La	23.20	26.10	20.20	15.50
Ce	46.20	55.60	43.90	30.60
Pr	5.00	5.91	4.60	3.94
Nd	18.30	21.40	16.90	15.00
Sm	3.73	4.15	3.66	3.13
Eu	0.97	1.11	0.82	0.47
Gd	3.02	3.22	3.04	2.47
Tb	0.45	0.50	0.46	0.39
Dy	2.25	2.64	2.32	1.89
Ho	0.40	0.52	0.43	0.31
Er	1.06	1.48	1.15	0.77
Tm	0.15	0.22	0.17	0.11
Yb	1.00	1.48	1.20	0.74
Lu	0.14	0.22	0.18	0.10
Hf	1.89	1.83	2.18	1.56
Ta	NA	NA	NA	NA
Th	6.30	6.52	6.39	6.75
U	1.74	2.34	3.87	8.78
Ni	NA	NA	NA	NA
Cu	NA	NA	NA	NA
Ga	18.00	26.00	20.00	21.00
Ge	NA	NA	NA	NA
As	NA	NA	NA	NA
Mo	NA	NA	NA	NA
Ag	NA	NA	NA	NA
In	NA	NA	NA	NA
Sn	NA	NA	NA	NA
Sb	NA	NA	NA	NA
W	NA	NA	NA	NA
Tl	NA	NA	NA	NA
Bi	NA	NA	NA	NA

Unnormalized Major Elements (Weight %):

Sample	RIB-4	RIB-5	RIB-30	RIB-55
Locality	Huayna Potosí	Huayna Potosí	Huayna Potosí	Huayna Potosí
Rock	Granite	Granite	Granite	Granite
SiO ₂	74.19	72.12	72.49	72.72
TiO ₂	0.154	0.131	0.105	0.201
Al ₂ O ₃	14.45	14.92	15.33	14.72
Fe ₂ O ₃ T	NA	NA	NA	NA
FeOT	NA	NA	NA	NA
FeO	NA	NA	NA	NA
Fe ₂ O ₃	1.37	1.43	1.36	1.73
MnO	0.033	0.03	0.053	0.031
MgO	0.19	0.16	0.14	0.27
CaO	0.67	0.67	0.48	0.75
2O	3.1	2.71	3.23	2.49
K ₂ O	4.7	5.24	4.65	5.56
P ₂ O ₅	0.271	0.264	0.17	0.286
H ₂ O+	NA	NA	NA	NA
H ₂ O-	NA	NA	NA	NA
LOI	1.03	1.18	1.04	0.99

Normalized Major Elements (Weight %):

SiO ₂	74.95	73.95	74.07	73.76
TiO ₂	0.16	0.13	0.11	0.20
Al ₂ O ₃	14.60	15.30	15.66	14.93
FeOT	1.25	1.32	1.25	1.58
MnO	0.03	0.03	0.05	0.03
MgO	0.19	0.16	0.14	0.27
CaO	0.68	0.69	0.49	0.76
2O	3.13	2.78	3.30	2.53
K ₂ O	4.75	5.37	4.75	5.64
P ₂ O ₅	0.27	0.27	0.17	0.29

Trace elements (Weight in ppm):

Sc	0.00	0.00	5.00	3.21
Be	0.00	0.00	0.00	0.00
V	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00
Co	0.00	0.00	0.00	0.00
Zn	92.00	82.00	0.00	0.00
Rb	459.00	445.00	459.00	391.00
Sr	57.40	55.70	44.40	80.60
Y	12.20	15.10	9.12	14.90
Zr	65.80	58.60	22.60	68.70

Trace elements, weight in ppm (continuation):

Sample	RIB-4	RIB-5	RIB-30	RIB-55
Locality	Huayna Potosí	Huayna Potosí	Huayna Potosí	Huayna Potosí
Rock	Granite	Granite	Granite	Granite
Nb	20.10	22.30	27.20	22.20
Cs	41.80	59.00	62.60	42.60
Ba	173.00	175.00	103.00	191.00
Pb	27.30	32.30	24.10	41.30
La	17.50	16.90	4.34	20.20
Ce	36.40	29.50	9.33	42.60
Pr	4.69	3.76	1.05	4.82
Nd	17.90	14.10	3.88	18.50
Sm	3.80	3.43	1.13	4.94
Eu	0.46	0.43	0.24	0.91
Gd	2.94	3.11	1.31	4.94
Tb	0.45	0.53	0.26	0.74
Dy	2.14	2.60	1.52	3.17
Ho	0.34	0.43	0.28	0.47
Er	0.83	0.99	0.76	1.04
Tm	0.12	0.14	0.12	0.13
Yb	0.81	0.90	0.80	0.79
Lu	0.11	0.11	0.11	0.12
Hf	1.87	1.79	0.92	2.20
Ta	NA	NA	NA	NA
Th	8.14	6.54	1.93	6.68
U	7.15	4.26	5.37	10.10
Ni	NA	NA	NA	NA
Cu	NA	NA	NA	NA
Ga	21.00	20.00	23.00	19.00
Ge	NA	NA	NA	NA
As	NA	NA	NA	NA
Mo	NA	NA	NA	NA
Ag	NA	NA	NA	NA
In	NA	NA	NA	NA
Sn	NA	NA	NA	NA
Sb	NA	NA	NA	NA
W	NA	NA	NA	NA
Tl	NA	NA	NA	NA
Bi	NA	NA	NA	NA

Unnormalized Major Elements (Weight %):

Sample	RIB-56	S-12-X ^d	OL-COA ^d	O-2 ^d	S-15 ^d	O-1 ^d
Locality	Huayna Potosí	Illampu	Illampu	Illampu	Illampu	Illampu
Rock	Granite	Diorite	Monzonite	Monzonite	Granodiorite	Tonalite
SiO ₂	71.99	57.23	56.95	57.37	58.67	66.69
TiO ₂	0.314	1.029	1.082	1.059	1.052	0.618
Al ₂ O ₃	14.65	16.28	16.32	15.46	16.39	15.36
Fe ₂ O ₃ T	NA	NA	NA	NA	NA	NA
FeOT	NA	NA	NA	NA	NA	NA
FeO	NA	5.214	5.36	5.752	6.008	2.847
Fe ₂ O ₃	1.84	1.825	2.144	2.013	2.103	1.139
MnO	0.023	0.188	0.151	0.153	0.084	0.057
MgO	0.4	4	3.55	4.074	4.11	1.846
CaO	0.91	6.27	4.995	6.412	4.27	3.638
2O	2.16	3.87	3.698	4.071	2.05	3.766
K ₂ O	5.85	2	4.207	1.957	3.32	3.212
P ₂ O ₅	0.254	0.35	0.306	0.521	0.24	0.169
H ₂ O+	NA	NA	NA	NA	NA	NA
H ₂ O-	NA	NA	NA	NA	NA	NA
LOI	0.9	0.89	0.64	0.51	1.82	0.34

Normalized Major Elements (Weight %):

SiO ₂	73.30	58.35	57.79	58.16	59.81	67.21
TiO ₂	0.32	1.05	1.10	1.07	1.07	0.62
Al ₂ O ₃	14.92	16.60	16.56	15.67	16.71	15.48
FeOT	1.69	6.99	7.40	7.67	8.05	3.90
MnO	0.02	0.19	0.15	0.16	0.09	0.06
MgO	0.41	4.08	3.60	4.13	4.19	1.86
CaO	0.93	6.39	5.07	6.50	4.35	3.67
2O	2.20	3.95	3.75	4.13	2.09	3.80
K ₂ O	5.96	2.04	4.27	1.98	3.38	3.24
P ₂ O ₅	0.26	0.36	0.31	0.53	0.24	0.17

Trace elements (Weight in ppm):

Sc	2.37	18.00	29.20	20.10	19.00	10.60
Be	0.00	5.00	0.00	0.00	2.00	0.00
V	0.00	164.00	151.20	147.20	149.00	75.70
Cr	0.00	50.00	77.90	110.40	60.00	83.70
Co	0.00	39.00	38.50	39.50	25.00	63.10
Zn	0.00	130.00	90.40	78.20	160.00	45.70
Rb	388.00	126.00	238.00	114.10	179.00	132.60
Sr	102.00	305.00	246.90	381.00	275.00	377.20
Y	10.70	41.00	62.90	58.00	25.00	21.60
Zr	132.00	174.00	246.40	208.10	175.00	150.40

Trace elements, weight in ppm (continuation):

Sample	RIB-56	S-12-X ^d	OL-COA ^d	O-2 ^d	S-15 ^d	O-1 ^d
Locality	Huayna Potosí	Illampu	Illampu	Illampu	Illampu	Illampu
Rock	Granite	Diorite	Monzonite	Monzonite	Granodiorite	Tonalite
Nb	8.37	28.00	33.80	34.10	15.00	18.10
Cs	17.80	14.20	17.70	11.10	22.10	10.00
Ba	439.00	548.00	113.50	571.40	583.00	973.50
Pb	39.50	24.00	10.10	5.70	12.00	7.80
La	49.40	32.90	29.10	76.20	39.70	47.20
Ce	103.00	78.90	79.90	167.00	72.80	89.70
Pr	12.70	10.80	11.60	21.00	8.37	9.76
Nd	45.30	43.90	51.30	82.10	32.10	34.40
Sm	9.63	9.00	12.80	15.50	6.20	5.87
Eu	1.40	1.58	1.71	2.13	1.22	1.30
Gd	5.68	7.20	12.60	13.90	5.00	5.56
Tb	0.65	1.20	1.97	1.94	0.90	0.76
Dy	2.49	7.50	11.47	10.56	5.00	4.28
Ho	0.36	1.50	2.24	2.02	0.90	0.84
Er	0.86	4.60	6.41	5.99	2.90	2.52
Tm	0.11	0.72	0.92	0.85	0.42	0.37
Yb	0.65	4.60	5.98	5.68	2.70	2.53
Lu	0.09	0.69	0.88	0.85	0.42	0.40
Hf	3.73	5.00	9.40	7.00	4.90	0.00
Ta	0.00	3.30	0.00	5.10	1.10	0.00
Th	19.20	9.80	9.30	12.60	10.40	14.40
U	5.43	6.60	5.10	3.60	3.10	5.20
Ni	0.00	0.00	39.30	55.40	0.00	32.50
Cu	0.00	30.00	13.30	19.90	20.00	6.10
Ga	20.00	21.00	22.70	21.90	23.00	19.80
Ge	NA	2.00	2.40	2.80	1.00	2.40
As	NA	8.00	6.60	3.60	30.00	4.90
Mo	NA	7.00	1.40	NA	NA	NA
Ag	NA	0.70	0.00	NA	NA	NA
In	NA	0.00	0.00	NA	NA	NA
Sn	NA	10.00	4.10	6.80	5.00	NA
Sb	NA	16.10	0.00	0.00	13.90	NA
W	NA	272.00	178.90	214.50	140.00	397.10
Tl	NA	0.80	3.30	0.00	1.90	2.30
Bi	NA	1.80	3.10	1.60	2.70	NA

Unnormalized Major Elements (Weight %):

Sample	O-7A ^d	O-3 ^d	79101904 ^c	79101906 ^c	S-9 ^d	S-3 ^d
Locality	Illampu	Illampu	Illampu	Illampu	Illampu	Illampu
Rock	Tonalite	Adamelite	Granodiorite	Granodiorite	Granodiorite	Granodiorite
SiO ₂	65.97	67.7	63.28	64.16	66.05	67.45
TiO ₂	0.618	0.513	0.37	0.7	0.27	0.68
Al ₂ O ₃	15.56	15.75	15.37	16.04	15.8	14.68
Fe ₂ O ₃ T	NA	NA	NA	NA	NA	NA
FeOT	NA	NA	NA	NA	NA	NA
FeO	2.93	2.19	3.25	2.98	3.71	3.09
Fe ₂ O ₃	1.172	1.096	0.53	0.04	2.4	1.236
MnO	0.074	0.068	0.04	0.04	0.12	0.074
MgO	1.75	1.043	2.28	2.02	0.7	1.92
CaO	3.936	2.75	3.82	4.57	3.91	3.22
2O	3.81	3.938	3.44	2.63	2.51	3.19
K ₂ O	3.341	4.187	3.53	2.08	5.02	3.4
P ₂ O ₅	0.179	0.153	0.13	0.13	0.13	0.23
H ₂ O+	NA	NA	2.27	2.89	0.75	NA
H ₂ O-	NA	NA	1.36	1.11	0.21	NA
LOI	0.34	0.37	NA	NA	NA	1.46

Normalized Major Elements (Weight %):

SiO ₂	66.49	68.19	65.93	67.26	65.80	68.10
TiO ₂	0.62	0.52	0.39	0.73	0.27	0.69
Al ₂ O ₃	15.68	15.86	16.01	16.82	15.74	14.82
FeOT	4.02	3.20	3.88	3.16	5.85	4.24
MnO	0.07	0.07	0.04	0.04	0.12	0.07
MgO	1.76	1.05	2.38	2.12	0.70	1.94
CaO	3.97	2.77	3.98	4.79	3.90	3.25
2O	3.84	3.97	3.58	2.76	2.50	3.22
K ₂ O	3.37	4.22	3.68	2.18	5.00	3.43
P ₂ O ₅	0.18	0.15	0.14	0.14	0.13	0.23

Trace elements (Weight in ppm):

Sc	13.00	8.20	NA	NA	NA	11.00
Be	0.00	0.00	NA	NA	NA	3.00
V	74.20	52.50	NA	NA	NA	78.00
Cr	65.00	51.60	NA	NA	NA	30.00
Co	58.80	57.70	NA	NA	NA	53.00
Zn	56.90	93.10	NA	NA	NA	110.00
Rb	172.20	254.00	NA	NA	NA	153.00
Sr	282.40	230.20	NA	NA	NA	286.00
Y	21.90	21.80	NA	NA	NA	28.00
Zr	136.50	138.60	NA	NA	NA	192.00

Trace elements, weight in ppm (continuation):

Sample	O-7A ^d	O-3 ^d	79101904 ^c	79101906 ^c	S-9 ^d	S-3 ^d
Locality	Illampu	Illampu	Illampu	Illampu	Illampu	Illampu
Rock	Tonalite	Adamellite	Granodiorite	Granodiorite	Granodiorite	Granodiorite
Nb	21.50	20.70	NA	NA	NA	19.00
Cs	11.60	30.60	NA	NA	NA	5.70
Ba	755.70	783.00	NA	NA	NA	827.00
Pb	10.00	11.30	NA	NA	NA	31.00
La	33.30	92.00	NA	NA	NA	46.70
Ce	68.60	166.00	NA	NA	NA	83.80
Pr	7.81	17.40	NA	NA	NA	9.44
Nd	29.10	57.90	NA	NA	NA	34.30
Sm	5.94	8.94	NA	NA	NA	6.40
Eu	1.24	1.20	NA	NA	NA	1.20
Gd	5.71	7.81	NA	NA	NA	5.00
Tb	0.81	0.93	NA	NA	NA	0.90
Dy	4.60	4.50	NA	NA	NA	5.30
Ho	0.88	0.83	NA	NA	NA	1.00
Er	2.53	2.45	NA	NA	NA	3.10
Tm	0.36	0.34	NA	NA	NA	0.46
Yb	2.46	2.46	NA	NA	NA	2.90
Lu	0.37	0.37	NA	NA	NA	0.45
Hf	0.00	3.50	NA	NA	NA	5.40
Ta	3.50	0.00	NA	NA	NA	2.30
Th	15.00	23.80	NA	NA	NA	18.30
U	3.00	4.00	NA	NA	NA	8.30
Ni	34.40	29.00	NA	NA	NA	NA
Cu	0.00	0.00	NA	NA	NA	10.00
Ga	19.90	20.50	NA	NA	NA	20.00
Ge	2.90	2.60	NA	NA	NA	1.00
As	0.00	6.50	NA	NA	NA	NA
Mo	0.00	0.00	NA	NA	NA	NA
Ag	0.00	0.00	NA	NA	NA	0.70
In	0.00	0.00	NA	NA	NA	NA
Sn	0.00	16.30	NA	NA	NA	5.00
Sb	0.00	0.00	NA	NA	NA	17.30
W	411.80	432.80	NA	NA	NA	466.00
Tl	0.00	0.00	NA	NA	NA	1.10
Bi	1.10	0.00	NA	NA	NA	2.70

Unnormalized Major Elements (Weight %):

Sample	S-22 ^d	OL-Oc ^d
Locality	Illampu	Illampu
Rock	Granodiorite	Granodiorite
SiO ₂	66.97	67.85
TiO ₂	0.636	0.512
Al ₂ O ₃	14.61	15.3
Fe ₂ O ₃ T	NA	NA
FeOT	NA	NA
FeO	2.918	2.157
Fe ₂ O ₃	1.167	1.079
MnO	0.028	0.053
MgO	1.8	1.24
CaO	3.15	3.106
2O	3.03	3.902
K ₂ O	3.17	3.999
P ₂ O ₅	0.22	0.147
H ₂ O+	NA	NA
H ₂ O-	NA	NA
LOI	1.24	0.42

Normalized Major Elements (Weight %):

SiO ₂	68.63	68.37
TiO ₂	0.65	0.52
Al ₂ O ₃	14.97	15.42
FeOT	4.07	3.15
MnO	0.03	0.05
MgO	1.84	1.25
CaO	3.23	3.13
2O	3.11	3.93
K ₂ O	3.25	4.03
P ₂ O ₅	0.23	0.15

Trace elements (Weight in ppm):

Sc	10.00	6.00
Be	3.00	0.00
V	73.00	51.40
Cr	30.00	39.60
Co	64.00	79.20
Zn	70.00	47.00
Rb	144.00	170.30
Sr	260.00	249.60
Y	26.00	17.90
Zr	187.00	142.20

Trace elements, weight in ppm (continuation):

Sample	S-22 ^d	OL-Oc ^d
Locality	Illampu	Illampu
Rock	Granodiorite	Granodiorite
Nb	19.00	19.80
Cs	11.50	0.00
Ba	688.00	742.70
Pb	22.00	11.40
La	37.50	26.30
Ce	67.70	58.20
Pr	7.45	6.43
Nd	27.00	23.50
Sm	5.20	4.55
Eu	1.16	1.07
Gd	4.60	4.41
Tb	0.80	0.62
Dy	4.90	3.53
Ho	0.90	0.70
Er	2.80	2.05
Tm	0.45	0.30
Yb	2.90	2.11
Lu	0.46	0.32
Hf	5.90	3.60
Ta	2.30	3.80
Th	19.40	14.50
U	7.70	3.70
Ni	0.00	30.00
Cu	90.00	0.00
Ga	19.00	18.60
Ge	2.00	2.40
As	NA	3.20
Mo	NA	NA
Ag	NA	NA
In	NA	NA
Sn	3.00	4.80
Sb	9.00	3.20
W	664.00	593.20
Tl	1.50	NA
Bi	0.90	NA

Annex II: R codes, partition coefficients and modal compositions used in melting models

Batch model I

```
x <- read.table("melting_data.txt")
x <- as.matrix(x)
REE <- colnames(x)
OLCOA <- x["OL-COA",]    # OLCOA composition
O2 <- x["O-2",]          # O2 composition
S15 <- x["S-15",]        # S15 composition

kd <- x[c(-1,-2,-3),]    # table of distribution coefficients
m <- read.table("modal_compositions.txt")
m <- as.matrix(m)        # table of mineral props after melting
dd <- m%*%kd              # bulk distrib. coeff.
print(round(dd,3))

ff <- c(0.05,0.1)        # degrees of melting
                          # function calculating batch melt composition
batch <- function(c0,ff,dd){
  out <- sapply(ff,function(i){
    z <- c0/(dd+i*(1-dd))
    return(z)
  })
  out<-t(out)
  rownames(out)<-ff
  return(out)
}

# Melting, calculation
shallow1 <- batch(OLCOA,ff,dd["1",])# OLCOA
print(shallow1,3)

# Melting, plotting - OLCOA
mantle1 <- rbind(OLCOA)    # Two sources
col0<-c("#DAA520")
spider(mantle1,"Pearce 1983",0.1,1000,pch=16,cex=1.5,lwd=1.5,col=col0,main="Batch melting ")

col1 <- selectPalette(nrow(shallow1),"greens")
shallow<-rbind(shallow1)
col<-c(col1)
spider(shallow,"Pearce 1983",pch="",col=col,add=TRUE)# adds to existing
legend("topright",legend=rep(ff,1),pch=15,col=col,bg="white",ncol=2,title="Partial melting")
```


Melting data I (partition coefficients for peraluminous granites from GERMS database, Staudigel, and White, 1998):

	Cs	Rb	Ba	Th	U	Nb	Ta	La	Ce	Pb	Pr	Sr
OL-COA	17.7	238.0	113.5	9.3	5.1	33.8	0.0	29.1	79.9	10.1	11.6	246.9
O-2	11.1	114.1	571.4	12.6	3.6	34.1	5.1	76.2	167.0	5.7	21.0	381.0
S-15	22.1	179.0	583.0	10.4	3.1	15.0	1.1	39.7	72.8	12.0	8.4	275.0
bt	26.8	7.0	0.6	0.0	0.3	24.5	29.1	0.1	0.1	0.0	0.1	0.0
plg	0.4	0.1	0.2	0.0	0.7	0.0	0.0	4.6	3.9	0.8	4.2	6.0
ap	0.0	0.0	0.0	41.0	43.7	0.0	0.0	456.0	569.0	0.0	764.0	0.0
zrc	0.0	0.00001	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Nd	Zr	Sm	Eu	Gd	Dy	Ho	Er	Tm	Y	Yb	Lu
OL-COA	51.3	246.4	12.8	1.7	12.6	11.5	2.2	6.4	0.9	62.9	6.0	0.9
O-2	82.1	208.1	15.5	2.1	13.9	10.6	2.0	6.0	0.9	58.0	5.7	0.9
S-15	32.1	175.0	6.2	1.2	5.0	5.0	0.9	2.9	0.4	25.0	2.7	0.4
bt	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.2
plg	2.6	0.1	1.5	3.0	2.1	1.9	1.8	1.9	1.6	0.8	0.8	1.3
ap	855.0	0.0	1105.0	23.8	2133.0	3257.0	3143.0	4231.0	3769.0	162.0	2216.0	2981.0
zrc	0.0	3100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	200	0.0	0.0

Modal compositions:

bt	plg	ap	zrc
0.31	0.68	0.0095	0.0005

Batch model II

```
x <- read.table("melting_data_II.txt")
x <- as.matrix(x)
REE <- colnames(x)
OLCOA <- x["OL-COA",]      # OLCOA composition
O2 <- x["O-2",]           # O2 composition
S15 <- x["S-15",]         # S15 composition

kd <- x[c(-1,-2,-3),]      # table of distribution coefficients
m <- read.table("modal_compositions_II.txt")
m <- as.matrix(m)          # table of mineral props after melting
dd <- m%*%kd               # bulk distrib. coeff.
print(round(dd,3))

ff <- c(0.05,0.1)         # degrees of melting
# function calculating batch melt composition
batch <- function(c0,ff,dd){
  out <- sapply(ff,function(i){
    z <- c0/(dd+i*(1-dd))
    return(z)
  })
  out<-t(out)
  rownames(out)<-ff
  return(out)
}

# Melting, calculation
shallow1 <- batch(OLCOA,ff,dd["1",])# OLCOA
print(shallow1,3)

# Melting, plotting - OLCOA
mantle1 <- rbind(OLCOA)    # Two sources
col0<-c("#DAA520")
spider(mantle1,"Pearce 1983",0.1,1000,pch=16,cex=1.5,lwd=1.5,col=col0,main="Batch melting")

col1 <- selectPalette(nrow(shallow1),"greens")
shallow<-rbind(shallow1)
col<-c(col1)
spider(shallow,"Pearce 1983",pch="",col=col,add=TRUE)# adds to existing
legend("topright",legend=rep(ff,1),pch=15,col=col,bg="white",ncol=2,title="Partial melting")
```

Melting data II (partition coefficients for dacites from GERMS database, Staudigel and White, 1998):

	Cs	Rb	Ba	Th	U	Nb	Ta	La	Ce	Pb	Pr	Sr
OL-COA	17.7	238.0	113.5	9.3	5.1	33.8	0.0	29.1	79.9	10.1	11.6	246.9
O-2	11.1	114.1	571.4	12.6	3.6	34.1	5.1	76.2	167.0	5.7	21.0	381.0
S-15	22.1	179.0	583.0	10.4	3.1	15.0	1.1	39.7	72.8	12.0	8.4	275.0
bt	2.4	5.27	13.9	0.3	0	7.5	0	0.27	16.6	0.9	0	0.31
plg	0.8	0.24	1.05	0.1	0	2.5	0.1	0.49	0.24	1.3	0	10.7
ap	0	0	0	0	0	0	0	28.2	52.5	0	0	0
amp	0	0.18	0.28	0	0	2.5	0.3	0.74	1.52	0.5	0	0.6

	Nd	Zr	Sm	Eu	Gd	Dy	Ho	Er	Tm	Y	Yb	Lu
OL-COA	51.3	246.4	12.8	1.7	12.6	11.5	2.2	6.4	0.9	62.9	6.0	0.9
O-2	51.3	246.4	12.8	1.7	12.6	11.5	2.2	6.4	0.9	62.9	6.0	0.9
S-15	82.1	208.1	15.5	2.1	13.9	10.6	2.0	6.0	0.9	58.0	5.7	0.9
bt	32.1	175.0	6.2	1.2	5.0	5.0	0.9	2.9	0.4	25.0	2.7	0.4
plg	0	0.59	0.39	0.3	0.4	0.1	0	0.16	0	0.6	0.67	0.74
ap	0.2	0.55	0.13	2.1	0.1	0.5	0	0.08	0	0.5	0.08	0.06
amp	81	0.91	89.8	50	96	69	0	41.6	0	0	37	30.2
	4.3	0.34	7.77	5.1	10	13	0	12	0	2.5	8.4	6

Modal compositions II:

bt	plg	ap	amp
0.385	0.5	0.015	0.1