UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE GEOCIÊNCIAS

**Thermal history and fluid circulation in deformational structures associated with the
Bambuí Group at the fold-and-thrust zone, western margin of the São Francisco
Craton**

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"All seats provide equal viewing of the universe."

(informal communication, Hayden Planetarium)

ABSTRACT

P-T conditions existing at the tectonic event that acted at the fold-and-thrust zone of the western margin of the São Francisco Craton were estimated on the basis of structural, microstructural, petrographic and fluid inclusion study of syntectonic veins. The presence of veins of different generations in the fold-and-thrust zone is evidenced by fluids operating at different scenarios of paleostress throughout the deformation history. The area are composed of weakly deformed rocks of the Bambuí Group recording a metamorphism with conditions ranging from diagenetic to sub-greenschist facies. Two tectonic events were identified by vein geometric arrangement and folded surface, a major early NE-SW compression (D_1 - σ_1 sub-horizontal SW-trending and σ_3 subvertical), related with subhorizontal NW-trending syntectonic veins formed at conditions that have reached at least 140°C and pressures around 200-363 MPa; and later NW-SE compression (D_2 - σ_1 subhorizontal NW-trending and σ_3 subhorizontal NE-trending), related with subvertical syntectonic cleavage-parallel veins formed at the same range of temperature and pressures between 181-295 MPa. Indication of fluctuations in pressure during these events played a crucial role as fluids significantly influence the mechanical processes, deformation mechanisms and chemical reactions that operate in fold-thrust belts. Fluids show H_2O - $NaCl$ - $CaCl_2$ composition where mixing process of different fluids sources (metamorphic and meteoric) are evidenced by evolutive trending of homogenization temperatures and salinities resulting in some variation in salinity (12 against 4 wt.% $NaCl$ eq. for subhorizontal and cleavage-parallel veins respectively). This research confirms that combine the reconstruction of the paleostress states and fluid inclusion studies can provide fundamental information of relationship between fluid flow and tectonic of orogenic terrains contributing to the scientific knowledge about the deformational/metamorphic evolution of the Bambuí Group and the fold-and-thrust zone of the western margin of the São Francisco Craton.

KEYWORDS: Bambuí Group; São Francisco Craton; Fold-and-thrust; Fluid inclusions

RESUMO

As condições de pressão e temperatura existentes no evento tectônico que atuou na zona de *fold-and-thrust* da margem oeste do Cráton do São Francisco foram estimadas com base em estudos estruturais, microestruturais, petrográficos e de inclusões fluidas de veios sintectônicos. A presença de veios de diferentes gerações na zona de *fold-and-thrust* é evidenciada por fluidos atuando em diferentes cenários de paleoestresse ao longo da história deformacional da área. A área é composta por rochas do Grupo Bambuí fracamente deformadas que registram condições de metamorfismo que variam de diagênese a fácies sub-xisto verde. Dois eventos tectônicos foram identificados através da disposição geométrica dos veios e da superfície dobrada: (i) uma compressão principal NE-SW (D_1) com σ_1 sub-horizontal de orientação SW e σ_3 sub-vertical, relacionado à formação de veios sintectônicos sub-horizontais de orientação NW formados em condições que atingiram pelo menos 140-160°C e pressões em torno de 200-363 MPa; (ii) uma compressão posterior NW-SE (D_2) com σ_1 sub-horizontal de orientação NW e σ_3 também sub-horizontal de orientação NE. Estão relacionados à D_2 a formação de veios sintectônicos sub-verticais paralelos à clivagem, formados nas mesmas condições mínimas de temperatura de 140-160°C e pressões entre 181-295 MPa. A indicação de flutuações na pressão durante esses eventos desempenhou um papel crucial, pois os fluidos influenciam significativamente os processos mecânicos, os mecanismos de deformação e as reações químicas que operam em cinturões de *fold-and-thrust*. Os fluidos apresentam composição formada por H_2O -NaCl- $CaCl_2$, onde o processo de mistura de diferentes fontes de fluidos (metamórficas e meteóricas) é evidenciado pela tendência evolutiva de temperaturas de homogeneização e salinidades, resultando em alguma variação na salinidade (12 contra 4% em peso equivalente de NaCl para os veios sub-horizontais e para os paralelos à clivagem, respectivamente). Este trabalho confirma que a combinação entre a reconstrução do paleoestresse e o estudo de inclusões fluidas podem fornecer informações fundamentais sobre a relação entre o fluxo de fluidos e a tectônica de terrenos orogênicos, contribuindo para o conhecimento científico sobre a evolução deformacional/metamórfica do Grupo Bambuí e, consequentemente, da zona de *fold-and-thrust* da margem ocidental do Cráton do São Francisco.

PALAVRAS-CHAVE: Grupo Bambuí; Cráton do São Francisco; Inclusões fluidas

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CHAPTER 1.

INTRODUCTION

1.1 ORGANIZATION OF THE DISSERTATION

I present the geological context in which the dissertation develops, introducing the concepts about the São Francisco Craton and the Brasília Belt from the perspective of the fold-and-thrust zone in which the area is located. The research aims that justify this work and all the analytical methods used to reach the main objective are still in this chapter.

The presentation of the results is in the form of a scientific article in the process of submission to an international journal. The article contains all the results achieved by this work, being the chapter 2 composed of the article titled "*Fluid flow and syntectonic veining in an Ediacaran foreland fold-and-thrust zone, western margin of the São Francisco Craton, Brazil*", the subsequent chapters are the discussion of the results and consequent conclusions.

1.2 GEOLOGICAL SETTING

1.2.1 São Francisco Craton and Basin

Focus of various studies since the nineteenth century (e.g., Derby, 1879; Rimann, 1917; Costa and Branco, 1961; Braun, 1968; Pflug and Renger, 1973; Schöll, 1973, Dardenne, 1978, 1981; Menezes-Filho et al., 1977; Alkmim et al., 1993; Alkmim and Martins-Neto, 2001, 2012; Martins-Neto, 2009; Martins-Neto et al., 2001; Pimentel et al., 2011) the São Francisco Basin corresponds to an intracraton basin that covers an area of ca. 350.000km² of the homonymous craton in east-central Brazil. The São Francisco-Congo Craton and all other cratonic terranes of South America and African continents are understood as the most interior and stable portions of the plates that, at the end of Neoproterozoic, have been amalgamated through a series of collisions to form the west portion of Gondwana continent (Fig. 1) (Brito Neves et al., 1999; Campos Neto, 2000; Alkmim et al., 2001). The cratonic portion was spare from the orogenic processes of the Brasiliano event, but the margins became, by the action of the collisions, in orogenic belts (Fig. 1) (e.g., Brito Neves et al., 1999; Campos Neto, 2000; Alkmin et al., 2001; Pedrosa-Soares et al., 2001).

The Archean-Paleoproterozoic basement is exposed at the southern and northeast areas of the craton (Teixeira et al., 2000; Alkmim and Martins-Neto, 2012). The western, northern and eastern boundaries of São Francisco basin coincide with the limits of the craton traced along the suture zones characterized at the Brasiliano orogens (Alkmim et al., 1993, 2001) given by Brasília, Rio Preto and Araçuaí marginal belts, respectively (Fig. 1). The craton boundaries are somewhat arbitrary and still contentious, but the current usage (after Almeida, 1981) commonly considers areas of thin-skinned foreland fold-and-thrust belts as parts of the cratonic zone, which is limited by thick-skinned zones where Archean-Paleoproterozoic basement rocks were intensely involved in the Neoproterozoic deformation and metamorphism. This concept is also adopted in this work. The southern boundary is erosional and at the remaining part, the basin is bounded by the Paramirim Corridor, an intracratonic deformation zone that affects the neighboring Paramirim aulacogen (Cruz and Alkmim, 2006; Reis et al., 2017).

Fig. 1: Geological map of the West Gondwana at ca. 540Ma and geological map of São Francisco Craton (modified by Alkmim et al., 1993), emphasizing the distribution of units and major structural

Many geological aspects of the São Francisco Basin are still poorly understood. The paucity of available sub-surface data has limited the studies to a few seismic lines, drill cores, and relatively scarce good-quality exposures (e.g., Coelho et al., 2008; Zalán and Romeiro-Silva, 2007; Hercos, 2008; Martins-Neto, 2009; Reis, 2011; Alkmim and Martins-Neto, 2012; Reis et al., 2017). Nevertheless, the recent outset of hydrocarbon exploration programs and the resumption of regional mapping programs, aerogeophysical surveys, geochronological and geochemical studies are changing the knowledge scenario of São Francisco Basin (e.g., Santos et al., 2000; Babinski et al., 2007; Vieira et al., 2007; Rodrigues et al., 2010, 2012; Kuchenbecker, 2011; Pedrosa-Soares and Alkmim, 2011; Pimentel et al., 2011; Alvarenga, 2012; Lopes, 2012; Reis et al., 2012, 2013, 2017; Alvarenga et al., 2014).

The Precambrian fill units of the São Francisco Basin were caught by the Brasiliano orogenic fronts, which propagated from the Brasília, Rio Preto and Araçuaí belts towards the craton interior during the Ediacaran Period (Alkmim et al., 1996; Brito-Neves et al., 1999; Brito-Neves, 2004; Valeriano et al., 2004a,b; Alkmim et al., 2006; Pedrosa-Soares et al., 2001, 2007; Caxito, 2010). The Neoproterozoic units cover most of the basin, where the Bambuí Group is the unit of greatest expression in area and was developed during the propagation of Brasília Belt orogenic front (Fragoso et al., 2011). The knowledge about this unit has undergone many changes over the past decade, which are crucial for the understanding of the assembly of the Gondwana continent during the Neoproterozoic era and the paleoenvironmental changes in the ocean and inland seas (Reis et al., 2017). Its sedimentary succession encompasses multiple and superimposed basin-fill cycles younger than 1.8 Ga., which reflect tectonic and climatic events, some of global significance, that have affected the São Francisco-Congo lithosphere after the Paleoproterozoic Era (e.g., Campos and Dardenne, 1997a,b; Martins-Neto, 2009; Alkmim and Martins-Neto, 2001; Alkmim et al., 2011; Babinski et al., 2012; Caxito et al., 2012).

The lithostratigraphy of the Bambuí Group is currently divided into into five units (Dardenne, 1978) namely, from base to top: (i) Sete Lagoas Formation, which comprises limestone and dolostones with interbedded pelitic layers (thickness $\leq 500\text{m}$); (ii) Serra de Santa Helena Formation, mainly composed of shale and siltstone with interbedded limestone and sandstone (640m); (iii) Lagoa do Jacaré Formation, which displays limestone, siltstone and marlstones (350m); (iv) Serra da Saudade Formation, constituted of siltstone, green shale

and subordinately limestone (100 m); and (v) Três Marias Formation, composed of arkosic sandstone and siltstone (100 m) (Fig. 2). Unit thicknesses given here are based on Iglesias and Uhlein (2009).

		Lithology
Bambuú Group	Três Marias Fm.	Arcoseans and green siltstones
	Serra da Saudade Fm.	Green shales, pelites, siltstones and limestone lenses
	Lagoa do Jacaré Fm.	Black limestones, siltstones and marls
	Serra de Santa Helena Fm.	Shales, siltstones, limestone lenses and sandstones
	Sete Lagoas Fm.	Stromatolite limestones, dolostones, siltstones and shales
	Jequitai Fm.	Matrix supported conglomerate, massive sandstones and fine grained sediments
	Basement	

Fig. 2: Stratigraphy column of the Bambuí Group (after Dardenne, 1978)

Provenance studies and facies distribution of Bambuí Group point toward two main source areas: Neoproterozoic orogenic origin linked to the Brasília belt on the west side; and Archean-Proterozoic sources related to the craton basement and older basin fill units (Reis et al., 2017). The large occurrence of shallow carbonate facies in the central and eastern portions of the basin associated with the progradational seismic patterns suggest that the craton basement contributed as sediments source during deposition of the Bambuí Group (Nobre-Lopes, 1995, 2002; Vieira et al., 2007; Iglesias and Uhlein, 2009; Costa, 2011; Reis et al., 2017). Available detrital zircon U-Pb age data also indicate cratonic and orogenic sources (Rodrigues, 2008; Lima, 2011; Pimentel et al., 2011; Reis et al., 2012).

The Bambuí Group was interpreted as one of the post-glacial Neoproterozoic units that would record the extreme shifts in the planet's climate (Hoffman et al., 1998; Hoffman and Schrag, 2002). However, detrital zircons U-Pb analyses (Paula-Santos et al., 2015) from

marlstones and limestones indicate depositional ages around 560-545 Ma, which is in agreement with the discovery of *Cloudina* sp. remnants (Warren et al., 2014). These data reveal that the Bambuí Group was probably deposited around or after the Ediacaran-Cambrian limit following the Adamastor Ocean closure from east of the São Francisco craton (Paula-Santos et al., 2017).

1.2.2 Brasília Belt

The Brasília Belt, developed along the western margin of the craton, is one of the most complete and complex Neoproterozoic orogens in western Gondwana (Fig. 1) and as a whole extends for more than 1200 km along the western margin of the São Francisco Craton. It formed during the convergence of the Amazonian, São Francisco-Congo, Paranapanema and Rio de La Plata cratons, as well as smaller allochthonous blocks (Brito Neves et al., 1999, 2014; Brito Neves and Fuck, 2014; Pimentel, 2016). The evolution of the foreland belt was partially accompanied by the extensional reactivation of pre-existing structures (e.g.: Pirapora aulacogen) (Reis et al., 2017).

The protuberant shape of the western São Francisco paleocontinent margin, as inferred from gravimetric data (Lesquer et al., 1981; Ussami, 1993), subdivides the Brasília Belt into two segments S-N (Fig. 3), a NE-trending segment called the northern segment (Fonseca et al., 1995) and a NW-trending southern segment (target area) (Valeriano, 2017), which exhibit remarkable differences in tectonic style (Reis et al., 2017). The northern and southern segments of the Brasília Belt merge along a highly deformed E-W trending zone, currently referred to as the Pirineus syntaxis (Araújo Filho, 2000).

The southern Brasília Belt (SBB) is a wide orogenic belt essentially composed of metasedimentary rocks that extend for ca. 800 km along the southwestern margin of the São Francisco Craton. Subduction of distal units of the passive margin, accretionary tectonics and associated nappe exhumation took place relatively early (~650-630 Ma) in the SBB when compared to other orogenic belts that surround the São Francisco Craton (Valeriano, 2017). Thus the SBB provides the oldest records of the tectonic process involving the continental growth around the craton (Valeriano et al., 2008). The overall structure of the SBB consists of a fold-thrust belt involving Neoproterozoic metasedimentary rocks covered by a system of sub-horizontal spoon-shaped metamorphic nappes (Valeriano, 2017). According to a structural style, metamorphic grade and lithostratigraphic content, the tectonic zoning of the

SBB and adjoining São Francisco Craton can be defined as follows, from east to west, the cratonic zone (fold-and-thrust zone), the external metamorphic fold-and-thrust belt (external zone) and the upper nappe complex (internal zone) (Uhlein et al., 2012; Valeriano, 2017), where the metamorphic degree increases from east to west (Fig. 3).

Fig. 3: Simplified structural map of Brasília Belt with indication of the zones and of the northern and southern segments (modified from Uhlein et al., 2012). Cities: P-Palmeirópolis; U-Uruaçu; Ni-Niquelândia; Co-Colinas; DF-Distrito Federal; Pi-Pirenópolis; Go-Goiânia; Pj-Piracanjuba; Cn-Caldas Novas; Pa-Paracatú; Un-Unaiá; Pas-Passos

The cratonic zone is characterized by basement assemblages older than 1.8Ga unconformably overlain by the Neoproterozoic strata of the Vazante and Bambuí groups (e.g., Brito Neves et al., 1999; Alkmim and Martins-Neto, 2012; Valeriano, 2017). The truly cratonic zone, where the Neoproterozoic cover is virtually undeformed and unmetamorphosed is restricted to the central portion of São Francisco Craton (Fig 4), despite that, the delimitation of the craton (presented in Almeida 1967) is boundary to include the ca. 100-wide thin-skinned foreland fold-and-thrust belt of the SBB in the western cratonic zone (target area) (Valeriano, 2017).

Fig. 4: Simplified geological map of the São Francisco Basin, emphasizing the distribution of the units and major structural features (modified from Alkmim and Martins-Neto, 2001)

Therefore, the cratonic zone encompasses a thin-skinned foreland fold-and-thrust belt and a central domain, where Neoproterozoic strata are undeformed, featuring two structural compartments, a west compartment corresponding to the fold-and-thrust belt and a central compartment undeformed (Fig. 4). Regional seismic sections (Coelho et al., 2008; Reis, 2011; Reis et al., 2012; Reis and Alkmim, 2015) reveal that the foreland fold-and-thrust belt involving the Bambuí Group rocks is detached over of a sub-horizontal basement surface. Beneath this E-verging thin-skinned fold-and-thrust zone, in surface exposures, the slates and carbonic rocks of the Bambuí Group commonly display upright chevron and box folds, wich are progressively replaced by isolated kink bands towards the central of the craton (Reis and Alkmim, 2015, Reis et al., 2017). The evolution of the foreland belt was partially accompanied by the extensional reactivation of pre-existing structures (e.g.: Pirapora aulacogen) (Reis et al., 2017). Previous work reports sub-greenschist facies metamorphic to diagenetic conditions in the cratonic domain (e.g., Coelho et al., 2008; Hercos et al., 2008).

1.3 RESEARCH AIMS

The fundamental goal of this project is to study the thermal history of the lithotypes of the Bambuí Group located at the fold-and-thrust zone of the western margin of the São Francisco Craton, with focus on the evaluation of thermal data and fluid circulation along deformational structures. In view of the above, the second component of this research is to:

- (a) characterize the syntectonic hydrothermal veins at the macro and microscopic scales and their relationship to local and regional structures;
- (b) infer the paleo-stress regime at the moment of vein formation;
- (c) determine the compositions, temperatures, and pressures involved in the entrapment of fluids during vein crystallization;
- (d) characterize the metamorphic conditions of the main deformation event.

Furthermore, this study should contribute to our comprehension of the geological, structural and metamorphic evolution of the fold-and-thrust zone of the western margin of the São Francisco Craton.

1.4 METHODOLOGY

In order to reach the objectives, macro and microscopic structural analyses together with c-axis fabric, geochemistry and pseudosections and fluid inclusion microtermometric analyses were performed. A general description of these methods is given below:

1.4.1 Structural analysis

The structural analysis was performed applying procedures that involve recognition of geometric and kinematic relationship between tectonic features in the field, structural data collection with compass and their hierarchization based on superposition criteria (e.g., Turner and Weiss, 1963; Ramsay and Huber, 1983, 1987). The obtained data were statistically treated for elaboration of stereoplots using the software Stereo32 – version 1.0.3 (Roller and Trepmann, 2011) in the Schmidt-Lambert stereographic network (lower hemisphere projection). The vein samples were collected in known structural context, which allowed to evaluate the coupled deformation and fluid flow processes.

1.4.2 Petrographic and microstructural analysis

The petrography studies included analyzes of 27 thin sections of metapelite rocks and hosted quartz veins examined for mineralogy and microstructures (Bucher and Grapes, 2011; Blenkinsop, 2002; Passchier and Trouw, 2005; Vernon, 2004). Vein petrographic analyzes aim to characterize primary growth and secondary deformation structures and their relationships with assemblages of fluid inclusions. Photomicrographs were acquired at the Petrographic Microscopy Laboratory of the Geosciences Institute, University of São Paulo (Brazil), using an Olympus Camedia C-5050 digital camera coupled to an Olympus BXP-50 microscope. Microtectonic analyses were carried out on thin sections following the standard procedures and terminology described in Passchier and Trouw (2005).

1.4.3 Whole-rock geochemistry and pseudosections

Six samples were selected for whole-rock geochemical analysis of major elements compositions by x-ray fluorescence technique (XRF) performed at the X-Ray Fluorescence Laboratory - NAP GeoAnalítica of the Geosciences Institute, University of São Paulo (Brazil), using a spectrometer Philips PW2400. For these, powder samples of granulometry

<0.074mm crushed at a porcelain grail were used. After that, 1g of sample was mixed with nine parts of lithium tetraborate for preparation of molten tablet that were analyzed to obtain the quantities of major elements.

Geochemical information obtained was used for chemical characterization and to perform pseudosections. Pseudosections are an important tool for modern metamorphic modeling and calculations were performed at one sample in the model chemical system KFMASH (K_2O , FeO , MgO , Al_2O_3 , SiO_2 e H_2O) for a representative aluminous metapelite bulk compositions with the software program Perple_X (Connolly, 2005) and an updated version of the internally consistent thermodynamic database of Holland and Powell (1998).

1.4.4 X-ray diffraction

X-ray diffraction analyses were performed in the X-ray diffraction Laboratory of the Geosciences Institute, University of São Paulo (Brazil), equipped with a D5000 Siemens/Brucker diffractometer with copper tube, in a range from 02 to 70° (2 θ) with step of 0.02° (2 θ). Whole rock and clay fraction analyses were performed. Powder samples obtained for XRF analyses and for separation of clay fraction were used for whole rock analyses. The powder samples were submitted to pipetting, following Stokes' law, and after, the samples were dried at room temperature, solvated with ethylene glycol under vacuum and subsequently, heated at 490-500°C for a period of four hours. The identification of the minerals was done through the Bruker AXS DIFFRAC.EVA V2.1 program with PC-PDF database.

1.4.5 Quartz c-axis fabrics

The measurements of crystallographic axis <c> of quartz (c-axis) were performed on 5 samples (deformed quartz veins, metapsamites and metapelites), on sections cut perpendicular to the foliation and parallel to the stretching lineation, equivalent to the XZ plane of the finite deformation ellipsoid (where $X > Y > Z$) (Law, 2014; Heilbronner and Tullis, 2006; Faleiros et al., 2010, 2016). The samples were analyzed at the Petrographic Microscopy Laboratory of the Geosciences Institute, University of São Paulo (Brazil), using a Leitz Wetzlar binocular microscope equipped with a 4-axis universal stage. Systematic measurements of whole domains of the individual samples were performed to prevent bias during analysis. Pole figures representative of detrital and recrystallized grains were displayed in the Schmidt-

Lambert stereographic network (lower hemisphere projection) separately using the program Stereo32 version 1.0.3 (Röller and Trepmann, 2011).

Quartz c-axis fabrics has proven to be a powerful deformation thermometer for natural metamorphic rocks. Several reasons place these thermometer as an advantageous method to quantify temperatures in deformed rocks (Faleiros et al., 2016): (1) quartz is one of the most common rock-forming minerals of crustal rocks; (2) its deformation behavior generally dominates the rheology of the crust (Carter, 1976); (3) it is stable over the full range of crustal metamorphic conditions and can accommodate crystal-plastic deformation from diagenetic (≤ 150 °C) (Wenk and Kolodny, 1968) to ultra-high-temperature conditions (up to 1150 °C) (e.g., Moraes et al., 2002); (4) the thermometer is applicable to rocks that lack index metamorphic minerals; and (5) reliable quartz c-axis fabrics can be easily obtained from standard thin sections using inexpensive optical or computer integrated polarization techniques.

1.4.6 Fluid inclusion petrography and microthermometry

Fluid inclusion petrography was carried out on 100 μm -thick, Double-polished sections of quartz veins, from which 7 samples with different vein-growth microstructures and deformation were chosen for microthermometric measurements. Double-polished sections were investigated in order to map the associations of fluid inclusions, classifying them according to the origin, mode of occurrence and composition of the phases, to select regions for microthermometric studies. This detailing allows us to discriminate if the fluid inclusions are primary, generated by a closing of the irregularities created during the mineral crystallization or result from the healing of later deformational features, whether by fracturing or ductile deformation (Wilkins and Barkas, 1978; Roedder, 1984).

The petrography study and microthermometric data were carried out at the Fluid Inclusion Laboratory of the Geosciences Institute, University of São Paulo (Brazil), using a CHAIXMECA MTM 85 heating-cooling stage attached in a Leitz Wetzlar binocular microscope. The stage was calibrated to the Merck Signotherm standard for low temperatures and Merck MSP standard for high temperatures (De Vivo and Frezzotti, 1994; Hurai et al., 2015; Samson et al., 2003; Shepherd et al., 1985; Roedder, 1984). Thermometric data were interpreted using the computer software packages FLUIDS (Bakker, 2003), which, in terms of composition, density of the trapped fluids and volumetric proportions uses equations

developed by Zhang & Frantz (1987) and for densities and salinities of the aqueous phase equations of state and ion interaction model developed by Archer (1992).

The fluid inclusion study plays a fundamental role as they allows the characterization of the composition and estimates of the pressure and temperature conditions of the fluid inclusion trapped in the veins, being the only realistic way of quantifying transient values of fluid pressure along exhumed faults (e.g. Parry and Bruhn, 1990; Parry et al., 1991; Robert et al., 1995; Henderson and MacCaig, 1996; Dugdale and Hagemann, 2001; Montomoli et al., 2001; Faleiros et al., 2007, 2014).

1.4.7 Geothermobarometry

Estimates of the pressure and temperature (P-T) conditions of fluids trapped during the crystallization of the quartz veins were calculated through isochores calculated based on equations by Bodnar and Vityk (1995) and Knight and Bodnar (1989) with the computer software ISOC (Bakker, 2003). The isochores were drawn through the data obtained in the microtermometry analyses of fluid inclusion.

CHAPTER 2.

FLUID FLOW AND SYNTECTONIC VEINING IN AN EDIACARAN FORELAND FOLD-AND-THRUST ZONE, WESTERN MARGIN OF THE SÃO FRANCISCO CRATON, BRAZIL

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ABSTRACT

P-T conditions existing at the tectonic event that acted at the fold-and-thrust zone of the western margin of the São Francisco Craton were estimated on the basis of structural, microstructural, petrographic and fluid inclusion study of syntectonic veins. The presence of veins of different generations in the fold-and-thrust zone is evidenced by fluids operating at different scenarios of paleostress throughout the deformation history. The area are composed of weakly deformed rocks of the Bambuí Group recording a metamorphism with conditions ranging from diagenetic to sub-greenschist facies. Two tectonic events were identified by vein geometric arrangement and folded surface, a major early NE-SW compression (D_1 - σ_1 sub-horizontal SW-trending and σ_3 subvertical), related with subhorizontal NW-trending syntectonic veins formed at conditions that have reached at least 140°C and pressures around 200-363 MPa; and later NW-SE compression (D_2 - σ_1 subhorizontal NW-trending and σ_3 subhorizontal NE-trending), related with subvertical syntectonic cleavage-parallel veins formed at the same range of temperature and pressures between 181-295 MPa. Indication of fluctuations in pressure during these events played a crucial role as fluids significantly influence the mechanical processes, deformation mechanisms and chemical reactions that operate in fold-thrust belts. Fluids show H_2O -NaCl- $CaCl_2$ composition where mixing process of different fluids sources (metamorphic and meteoric) are evidenced by evolutive trending of homogenization temperatures and salinities resulting in some variation in salinity (12 against 4 wt.% NaCl eq. for subhorizontal and cleavage-parallel veins respectively). This research confirms that combine the reconstruction of the paleostress states and fluid inclusion studies can provide fundamental information of relationship between fluid flow and tectonic of orogenic terrains contributing to the scientific knowledge about the deformational/metamorphic evolution of the Bambuí Group and the fold-and-thrust zone of the western margin of the São Francisco Craton.

KEYWORDS: Bambuí Group; São Francisco Craton; Fold-and-thrust; Fluid inclusions

2.1 INTRODUCTION

Studies have demonstrated that fluids significantly influence the mechanical processes, deformation mechanisms and chemical reactions that operate in fold-thrust belts and on a long time-scale the result of such fluid flow may be recorded in veins (Crispini and Frezzotti, 1998; Fitz-Diaz et al., 2011; Huang et al., 2012; Jacques et al., 2014). Fold-and-thrust belts undergone polyphase tectonics may develop multi-generation veins, which recorded different stages of fluid flow (Swennen et al., 2000; Ferket et al., 2003; Huang et al., 2012). While a mineralogical, geometrical and kinematic analysis of vein systems can give indications on the relative timing and metamorphic conditions of different veining events, a fluid inclusion study can directly provide constraints on the composition and trapping conditions of fluids within an orogen during its tectonometamorphic evolution (Jacques et al., 2014). Several studies have already integrated structural and microthermometric analysis and the relative timing of different vein-related deformation events (e.g. Cathelineau et al., 1993; Evans, 1995; Xu, 1997; Crispini and Frezzotti, 1998; Evans and Battles, 1999; Hanks et al., 2006; Roure et al., 2009; Becker et al., 2010; Fitz-Diaz et al., 2011; Lacroix et al., 2011; Evans et al., 2012; Jacques et al., 2014).

The Brasília Belt is a thick- to thin-skinned complete and complex Neoproterozoic-Cambrian orogen in western Gondwana, developed along the western margin of the São Francisco craton, east-central Brazil (Pimentel, 2016). The Bambuí Group, settled at the thin-skinned foreland fold-and-thrust zone in the western portion of the craton, is featured by a heterogeneous tectono-structural pattern intensely deformed with abundant fold and shear zone-related quartz vein systems with well preserved original vein-growth microstructures and syn-veining clusters of fluid inclusions. The fluid circulation along these deformational structures allows characterization of the formation conditions of syntectonic veins and the evaluation of the relation with the folding- and fault-related processes.

In this paper we investigate deformational zones of high fluid flow that cut the Bambuí Group along the fold-and-thrust zone of the western margin of the São Francisco Craton, east-central Brazil, aiming the elaboration of a model about fluid circulation and vein formation along deformational structures. Detailed fluid inclusion microthermometry, integrated with geometrical and microstructural analysis of hydrothermal veins and host rocks, was used to determine P–T conditions and fluid evolution during stages of vein crystallization and deformation. Besides the determination of the thermal history with implications for comprehension of the geological, structural and metamorphic conditions, the results

contribute to the scientific knowledge about the deformational/metamorphic evolution of the Bambuí Group and the fold-and-thrust zone of the western margin of the São Francisco Craton.

2.2. GEOLOGICAL SETTING

2.2.1. *Tectonic framework*

The São Francisco Craton is one of the main large-scale Precambrian nucleus of the South America and together with its African counterpart, the Congo Craton, have been considered in most of the available reconstruction of the Gondwana, Rodinia and Columbia supercontinents (Cordani et al., 2009; Heilbron et al., 2017). The craton presents a peninsular shape and is bounded by five Neoproterozoic (Brasiliano) accretionary-to-collisional orogens (Fig. 5). The craton boundaries are somewhat arbitrary and still contentious, but the current usage (after Almeida, 1981) commonly considers areas of thin-skinned foreland fold-and-thrust belts as parts of the cratonic zone, which is limited by thick-skinned zones where Archean-Paleoproterozoic basement rocks were intensely involved in the Neoproterozoic deformation and metamorphism. This concept is also adopted in this work.

The Brasília Belt, developed along western margin of the craton, is one of the most complete and complex Neoproterozoic orogens in western Gondwana (Fig. 5) and as a whole extends for more than 1200km along the western margin of the São Francisco Craton. It formed during the convergence of the Amazonian, São Francisco-Congo, Paranapanema and Rio de La Plata cratons, as well as smaller allochthonous blocks (Brito Neves et al., 1999; Pimentel, 2016). The protuberant shape of the western São Francisco paleocontinent margin, as inferred from gravimetric data (Lesquer et al., 1981; Ussami, 1993), subdivides the Brasília Belt into two segments S-N (Fig. 6), a NE-trending segment called the northern segment (Fonseca et al., 1995) and a NW-trending southern segment (target area) (Valeriano, 2017), which exhibit remarkable differences in tectonic style (Reis et al., 2017). The northern and southern segments of the Brasília Belt merge along highly deformed E-W trending zone, currently referred to as the Pirineus syntaxis (Araújo Filho, 2000).

Fig. 5: Geological map of the West Gondwana at ca. 540Ma and the São Francisco Craton (modified from Alkmin et al., 2006)

The southern Brasília Belt (SBB) is a wide orogenic belt essentially composed of metasedimentary rocks that extends for ca. 800km along the southwestern margin of the São Francisco Craton. Subduction of distal units of the passive margin, accretionary tectonics and associated nappe exhumation took place relatively early (~650-630Ma) in the SBB when compared to other orogenic belts that surround the São Francisco Craton (Valeriano, 2017).

Thus the SBB provides the oldest records of the tectonic process involving the continental growth around the craton (Valeriano et al., 2008). The overall structure of the SBB consists of a fold-and-thrust belt involving Neoproterozoic metasedimentary rocks covered by a system of sub-horizontal spoon-shaped metamorphic nappes (Valeriano, 2017). According with a structural style, metamorphic grade and litostratigraphic content, the tectonic zoning of the SBB and adjoining São Francisco Craton can be defined as follows, from east to west, the cratonic zone (fold-and-thrust zone), the external metamorphic fold-and-thrust belt (external zone) and the upper nappe complex (internal zone) (Uhlein et al., 2012; Valeriano, 2017), where the metamorphic degree increases westward (Fig. 6).

Fig. 6: Simplified structural map of Brasília Belt with indication of the zones and of the northern and southern segments (modified from Uhlein et al., 2012). Cities: P-Palmeirópolis; U-Uruaçu; Ni-Niquelândia; Co-Colinas; DF-Distrito Federal; Pi-Pirenópolis; Go-Goiânia; Pj-Piracanjuba; Cn-Caldas Novas; Pa-Paracatú; Un-Unaí; Pas-Passos

The cratonic zone is characterized by basement assemblages older than 1.8Ga unconformably overlain by the Neoproterozoic strata of the Vazante and Bambuí groups (e.g., Brito Neves et al., 1999; Alkmim and Martins-Neto, 2012; Valeriano, 2017). The truly cratonic zone, where the Neoproterozoic cover is virtually undeformed and unmetamorphosed is restricted to the central portion of São Francisco Craton (Fig 5), despite that, the delimitation of the craton (presented in Almeida 1967) includes the ca. 100-wide thin-skinned foreland fold-and-thrust belt of the SBB in the western cratonic zone (target area) (Valeriano, 2017).

Therefore, the cratonic zone encompasses a thin-skinned foreland fold-and-thrust belt and a central domain, where Neoproterozoic strata are undeformed, featuring two structural compartments, a west compartment corresponding to the fold-and-thrust belt and a central undeformed compartment. Regional seismic sections (Coelho et al., 2008; Reis, 2011; Reis et al., 2012; Reis and Alkmim, 2015) reveal that the foreland fold-and-thrust belt involving the Bambuí Group rocks is detached over of a sub-horizontal basement surface. Beneath this E-verging thin-skinned fold-and-thrust zone, in surface exposures, the slates and carbonatic rocks of the Bambuí Group commonly display upright chevron and box folds, which are progressively replaced by isolated kink bands towards the central of the craton (Reis and Alkmim, 2015, Reis et al., 2017). The evolution of the foreland belt was partially accompanied by the extensional reactivation of pre-existing basement structures (e.g.: Pirapora aulacogen) (Reis et al., 2017). Previous work reports sub-greenschist facies metamorphic to diagenetic conditions in the cratonic domain (e.g., Coelho et al., 2008; Hercos et al., 2008).

2.2.2. The Bambuí Group

The Bambuí Group is one of the most expressive units of the São Francisco Craton. Its lithostratigraphy is currently divided into five units from the base to top: Sete Lagoas Formation, Serra de Santa Helena Formation, Lagoa do Jacaré Formation, Serra da Saudade Formation and Três Marias Formation (Dardenne, 2000).

Provenance studies and facies distribution of Bambuí Group rocks point toward two main sources: Neoproterozoic orogenic origin linked to the Brasília belt on the west side; and Archean-Proterozoic sources related to the craton basement and older basin fill units (Reis et al., 2017). The large occurrence of shallow carbonate facies in the central and eastern portions of the basin associated with the progradational seismic patterns suggest that the craton basement contributed as sediments source during deposition of the Bambuí Group (Nobre-

Lopes 1995, 2002; Vieira et al., 2007; Iglesias and Uhlein, 2009; Costa, 2011; Reis et al., 2017). Available detrital zircon U-Pb age data also indicate cratonic and orogenic sources (Rodrigues, 2008; Lima, 2011; Pimentel et al., 2011; Reis et al., 2012).

The Bambuí Group was interpreted as one of the post-glacial Neoproterozoic units that would record the extreme shifts in the planet's climate (Hoffman et al., 1998; Hoffman and Schrag, 2002). However, detrital zircons U-Pb analyses (Paula-Santos et al., 2015) from marlstones and limestones indicate depositional ages around 560-545 Ma, which is in agreement with the discovery of *Cloudina sp.* remnants (Warren et al., 2014). These data reveal that the Bambuí Group was probably deposited around or after the Ediacaran-Cambrian limit following the Adamastor Ocean closure from east of the São Francisco craton (Paula-Santos et al., 2017).

2.3. STRUCTURE AND PETROGRAPHY

The Bambuí Group comprises a succession of sub-greenschist facies metapelitic rocks (metasiltstone, slate, phyllite) with metasandstone limestone lenses. As the sedimentary characteristics of protoliths are largely preserved the prefix “meta” has been removed from all further rock descriptions. A key sector of the Bambuí Group at the foreland fold-and-thrust zone in the western margin of the São Francisco Craton (Unaí area) was selected for study (Fig. 7). The formal subdivisions of the Bambuí Group cannot be applied to the Unaí area and an informal scheme adapted from Baptista (2014) is adopted in this work.

The Serra da Saudade Formation is restricted to the northeastern-most area (Fig. 7) and composed by alternation between centimetric to decimetric tabular layers (S_0) of micaceous sandstone and siltstone, with parallel and cross stratification. Both layers show muscovite with preferential orientation parallel to S_0 , defining a continuous cleavage (S_1), or randomly oriented. The Unit A corresponds to metric tabular sandstone with cross-stratification with associated deformation and occurrence of millimeter to centimetric slate with well-developed continuous cleavage associated with foliation plans, phyllite and gray to dark gray limestone lenses with centimetric columnar stromatolites, intraclasts, ripple marks and sulfides. The Unit B comprises centimetric sandstone layers with truncated cross-laminate, millimeter to centimetric slate, phyllite and intensely deformed limestone lenses.

Fig. 7: Simplified geological map of the study area (modified from Baptista, 2014)

The structures of the Bambuí Group in the Unaí area were subdivided into two continuous deformational phases (D_1 and D_2). The macrostructure comprises a series of kilometric, tight to isoclinal, normal folds with NW-SE-trending axial traces (Fig. 7). D_1 -related structures consist of macroscopic tight to isoclinal WSW- to ENE-verging overturned folds. In stereographic projection poles to S_0/S_1 distributed along great circle girdles reveal the presence of cylindrical folds with reconstructed SE-trending sub- to horizontal axes and an upright axial-plane (Fig. 8). The folded surface is the sedimentary beds (S_0) and the folds present an axial-plane, steep, NW-trending continuous cleavage (S_1) developed in all metasedimentary lithotypes (Fig. 8). A L_1 grain-type stretching lineation was developed only on slates. Locally, with the increase of progressive deformation, the S_1 cleavage is transposed by a NE-trending disjunctive cleavage (S_2) dipping to SE. This cleavage is coherent with mapped, km-scale, gentle folds with ENE-trending traces (Fig. 7). Folds can show some deformation style variations related with the same folding phase, as some conical folds. Quartz-rich aggregates oriented along the SL_1 fabric show restricted bulging recrystallization around of its boundaries (cf., Stipp et al., 2002; Faleiros et al., 2010) as well as weak undulose extinction and deformation lamellae. Folds and faults geometry suggests a paleo-stress regime of NE/SW-trending sub-horizontal maximum compressive stress (σ_1) and sub-vertical minimum compressive stress (σ_3).

An associated regional fracture system characterized by two extension fracture groups sealed with quartz and carbonate veins (see later) resulted from a posterior brittle deformation that affect all rocks from the Bambuí Group. The D_1 -related fracture/vein system generally shows NW-trending, gentle dip (10° - 35°) to northeastward, and occurs oblique to the slaty cleavage (S_1) (Fig. 8). The sub-vertical NW-trending fracture/vein system occurs parallel to the main foliation (S_1) and is related with a subsequent deformational phase (D_2). The sub-vertical system shows association with a NW- to SE-plunging subvertical stretching lineation (Fig. 8).

Fig. 8: Equal-area, lower hemisphere stereonet with plots of cleavage (S1) poles, frequency lines of the S0 folded poles and fold axis, and plots of subhorizontal and cleavage-parallel vein poles.

2.4 METAMORPHIC HISTORY

Deciphering the metamorphic history of the metasedimentary rocks from the Bambuí Group from petrography is difficult due to the absence of identifiable index metamorphic minerals. Thus, the petrographic evidence was combined with determination of bulk rock composition by x-ray fluorescence analysis (XRF) and identification of mineral phases using x-ray diffraction analysis (XRD) performed at laboratories of the NAP GeoAnalítica of the Geosciences Institute, University of São Paulo (Brazil). Major element composition of six representative samples of metapelites was determined using a spectrometer Philips PW2400 (Table 1). The clay minerals were investigated by XRD using a D5000 Siemens/Brucker diffractometer equipped with copper tube, in a range from 02 to 70° (2 θ) with step of 0.02° (2 θ). The XRD analyses were performed in whole-rock and clay fraction samples according to the preparation routine of the laboratory. For clay fraction analysis, the samples were dried at room temperature (N), after they were solvated with ethylene glycol under vacuum (G), subsequently, they were heated at 490-500°C for a period of four hours (A). The identification of the minerals was done through the Bruker AXS DIFFRAC.EVA V2.1 program with PC-PDF database.

The Bambuí Group metapelites are dominated by preserved detrital minerals, primarily quartz, muscovite, biotite, feldspar and opaque minerals. These minerals are strongly deformed, elongated and rotated along the S_1 cleavage, whereas cryptocrystalline phyllosilicates grew in restricted cleavage domains, also oriented along the S_1 cleavage, are clearly of metamorphic origin. XRD results (Fig. 9) indicate the presence of kaolinite, vermiculite and interstratified vermiculite-smectite.

Table1- Major elements of the samples analyzed by X-ray Fluorescence. Values in percentage

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LoI	Total
UN02B	66.69	0.9	15.54	5.54	0.03	1.67	0.04	0.94	2.93	0.09	4.74	99.12
UN03A	63.07	0.87	18.17	4.1	0.02	1.44	0.08	0.01	8.63	0.05	2.92	99.35
UN04	62.98	0.84	17.73	4.71	0.02	1.4	0.19	0.24	6.46	0.04	4.06	98.67
UN14	59	0.86	15.92	10.2	0.02	1.86	0.02	0.02	7.71	0.06	3.53	99.20
UN33A	70.92	0.58	13.7	4.35	0.04	1.1	0.16	2.13	2	0.03	3.78	98.78
UN33B	73.56	0.67	11.79	3.99	0.04	1.18	0.46	2.39	1.83	0.18	2.93	99.02

Fig. 9: X-ray diffraction patterns of the samples UN02B and UN33B showing the identification of kaolinite, vermiculite and a vermiculite+smectite interstratified

Mineral assemblages and chemical analyses indicate that metapelites have, in general, high Fe contents when compared to Mg, variations are observed in relation to K and two main compositions represented by medium (Al-rich) and low (Al-poor) values of A ratio ($\text{Al}_2\text{O}_3 - 3\text{K}_2\text{O} / \text{Al}_2\text{O}_3 - 3\text{K}_2\text{O} + \text{FeO} + 5 \text{MgO}$) (Fig. 10). Kaolinite is the only index phase present in the Bambuí Group metapelites, while biotite is always of clastic origin. Prograde metamorphism at the beginning of greenschist facies metamorphism will replace kaolinite by pyrophyllite at about 300°C following the continuous reaction (1) involving the consumption

of kaolinite and quartz (Bucher and Grapes, 2011). Kaolinite is rare in rocks metamorphosed at temperatures above 200 °C because the common presence of methane-bearing fluids, but for a methane-absent aqueous fluid regime kaolinite can survive to temperatures of 270-300 °C.

The Al-rich ($A \sim 0.4$) compositions is close to chlorite and chloritoid compositional fields and the occurrence of these minerals would be expected if sufficient temperature conditions and chemical equilibrium were attained. The first truly metamorphic mineral commonly formed in aluminous metapelitic rocks is chloritoid at about 300°C by the reaction (2). Thus, the presence of kaolinite and absence of pyrophyllite and chloritoid in the Bambuí Group medium A metapelites is robust evidence of metamorphic temperatures below 300 °C.

The low A ratio metapelites have composition where the occurrence of biotite would be favored. The assemblage of K-feldspar and chlorite will be consumed to form biotite at conditions of temperatures of 380-420°C from the reaction (3) (Bucher and Grapes, 2011).

The absence of chlorite in low A ratio rocks prevents the formation of others index metamorphic phases and the main mineral assemblage suggest that the upper temperature limit are about 300°C (limit of kaolinite stability). The presence of detrital biotite at these temperatures suggests that the assemblage is far from reaching the metamorphic equilibrium.

Fig. 10: Thompson's AFM diagram (1957) with the plotting of the samples analyzed by X-ray fluorescence

An isochemical phase diagram (Fig. 11) was calculated in the model chemical system KFMASH (K_2O , FeO , MgO , Al_2O_3 , SiO_2 e H_2O) for a representative aluminous metapelite bulk compositions (sample UN33B) using the Perple_X software (Connolly, 2005) and an updated version of the internally consistent thermodynamic database of Holland and Powell (1998). The solution models for chloritoid, biotite, garnet, staurolite and muscovite are from Holland and Powell (1998), and for chlorite and stilpnomelane from Lanari et al. (2014) and Massone and Willner (2008), respectively. H_2O is considered a saturated phase component. The phase diagram calculated for sample UN33B (Fig. 11) indicate that the assemblage with kaolinite and absence of stilpnomelane and chloritoid is stable at conditions of 140-270°C and 1-9 kbar.

Fig. 11: P-T pseudosection of the sample UN33B in the KFMASH system showing the occurrence of each mineral depending on temperature and pressure in the sidebars

2.5. DEFORMATIONAL TEMPERATURES

In order to understand the relationships between metamorphic and deformation conditions the temperature conditions estimated from petrological evidence are compared with deformational temperatures estimated from quartz microstructures and quartz c-axis fabrics. Quartz microstructures as undulose and patchy extinction, overgrowth, deformation bands and lamellae, dislocation deformations and bulges indicate the occurrence of recrystallization in the development of the microstructures (Fig. 12 and 16). Two mechanisms occur: pressure-solution and bulging recrystallization. The process termed pressure-solution is the principal mechanism of deformation in the upper crust and is associated with the mechanism of diffusive mass transfer. Occur at area of stress where grains dissolve into fluid film then migrate to region of low stress and recrystallize at contact points between grains (Bons, 2000; Vernon, 2004; Passchier and Trouw, 2005) (Fig. 12c) and under diagenetic and

low metamorphic grade conditions up to 200–400°C (Weyl, 1959, Durney, 1972, Elliott, 1973, Rutter, 1983).

Dynamic recrystallization occurs by localized grain boundary migration that affects only the boundary region of porphyroclasts, forming relatively small recrystallized grain characterizing the mechanism of bulging recrystallization (BLG) (Fig. 12d) (Stipp et al., 2002a,b). The microstructures present in the Bambuí Group samples is typical of the lower temperature portion of the BLG regime, or BLG-I regime of Stipp et al. (2002), which is active at temperatures around 300 °C. In this recrystallization regime the proportion of recrystallized grains is very small and the elongation of porphyroclasts by crystal plastic deformation is insignificant. Hirth and Tullis (1992) suggest that the transition from the regime I to II corresponds to a change from dominantly strain-induced grain boundary migration to dislocation-climb-accommodated recovery.

Fig. 12: Photomicrographs of quartz microstructures (cross polarized light). (a) quartz crystals showing overgrowth texture (red arrows), sample UN06A; (b) quartz crystals showing deformation lamellae, sample UN06A; (c) dislocation deformations that occur in pressure-solution mechanism, sample UN06A; (d) mechanism of bulging recrystallization, sample UN05B

Quartz c-axis orientations were measured on 5 samples (non-recrystallized grains of metasandstones and metapelites) on sections cut perpendicular to the foliation and parallel to the stretching lineation using a Leitz Wetzlar binocular microscope equipped with a 4-axis universal stage. Systematic measurements of whole domains of the individual samples were performed. Pole figures were constructed using the program Stereo32 version 1.0.3 (Röller and Trepmann, 2011).

The c-axis fabric pattern of all samples is characterized by point c-axis maxima around Y and at intermediate positions between X and Z with an opening angle centered in Z of 71-82° relative to Z (Fig. 13).

Concentrations of quartz c-axis around Y suggest dominant slip of <a> prismatic crystallographic axis of quartz (Lister and Hobbs, 1980; Jessel and Lister, 1990; Passchier and Trouw, 1996, Takeshita et al., 1999). Mostly, the activation of these plans suggests higher temperature conditions (Tullis et al., 1973, Lister and Dornsiepen, 1982, Burg et al., 1984, Schmid and Casey, 1986; Wenk et al., 1989). The transition between the activation of the <a> prism for [c] prism is estimated at temperatures in the order of 550 - 600°C. However, the estimation of temperature conditions by the analysis of c-axis is influenced by other factors, such as strain rate, fluid activity and recrystallization mechanism, where measurements of non-recrystallized quartz have an influence.

Natural and experimental data and numerical simulations of deformation have indicated that the opening angle (OA) of quartz c-axis fabrics is strongly temperature dependent (Tullis et al., 1973; Lister and Hobbs, 1980; Gleason et al., 1993; Kruhl, 1998; Morgan and Law, 2004; Law et al., 2004; Law, 2014; Faleiros et al., 2016). Kruhl (1998) observed an approximately linear increase in the opening angle with temperature for natural deformations and proposed a deformation thermometer applicable to rocks deformed within the interval ~250-700 °C, which was slightly improved by Morgan and Law (2004) and Law et al. (2004). Faleiros et al. (2016) expanded the thermometer cover range for temperatures up to 1050 °C, identified a secondary pressure dependence of the opening angle, and formulated the following thermometer equation (with an uncertainty of ±50 °C):

$$T (^{\circ}\text{C}) = 410.44 \ln \text{OA (degrees)} + 14.22P (\text{Kbar}) - 1272$$

The opening angle thermometer was formulated considering data from fully recrystallized quartz aggregates and cannot be safely applied to non-recrystallized aggregates such as those from the Bambuí Group rock samples. The OA values vary between 71 and 82°, yielding temperatures bounded between 513 and 572°C (Fig. 13), which are overestimated

and unrealistic, as the petrological and microstructural evidence are diagnostic of temperatures of 250-300 °C. On the other hand, the strong quartz crystallographic fabrics are diagnostic of deformational temperatures above 250 °C and are coherent with the estimative of beginning of dynamic recrystallization of quartz by BLG between 250-300 °C in different tectonic settings (Voll, 1976; Sibson et al., 1979; Dunlap et al., 1997; Van Daalen et al., 1999; Stöckhert et al., 1999; Stipp et al., 2002a,b; Faleiros et al., 2010).

Fig. 13: Optically measured quartz c-axis fabrics; lower hemisphere equal area projections also showing the opening-angles represented by arcs and the temperature data.

2.6 SYNTECTONIC VEINS

2.6.1 Macroscopic and microscopic morphology

The study area comprises two main vein systems hosted by deformed rocks of the Bambuí Group: (i) sub-horizontal veins and (ii) subvertical cleavage-parallel veins.

2.6.1.1 Subhorizontal veins

The subhorizontal veins are very plentiful in the study area, occurring as tabular bodies with 1-15 cm-thick, and extending 1-3 m laterally. Field relationships suggest that these veins were crystallized in a late D₁-related deformational stage, once they cut the main foliation (S₁) and do not show deformation structures (e.g. laps, movement and dilation along

the array). The veins are exclusively formed by quartz and classified as syntaxial (Bons et al., 2012) where the vein-filling minerals grow out from the wall rock of the vein from both sides towards the center, showing an elongated block microstructure composed by subhedral quartz grains (1-3 mm-sized) (Fig. 14). The elongated quartz presents a subvertical orientation near perpendicular to the vein walls. The veins also present weak undulose extinction and deformation bands, as well as inclusion trails and bands that suggest several crack-seal events at the beginning of vein growth (Fig. 14). The shape of a vein system is commonly controlled by the fracture mechanisms where the opening mode is the most important factor (Pollard and Segall, 1987; Scholz, 2002). The internal vein growth morphology indicates that the subhorizontal veins are true extensional fractures, which experience zero shear stress and an effective extensional normal stress, forming an opening vector perpendicular to the plane (Bons et al., 2012). Geometric patterns of the subhorizontal veins suggest a subhorizontal NE-SW-trending maximum compression (σ_1) and a subvertical least compressive stress (σ_3), which is also consistent with the paleo-stress indicated by the D₁ deformation phase elements (folds, faults and S₁ axial-plane cleavage) (Fig. 15).

Fig.14: Photomicrographs of subhorizontal quartz veins microstructures (cross polarized light). (a) elongate blocky texture in a quartz vein. Vein crystals grew towards the centre of the vein, sample UN05; (b) deformations domains at the beginning of vein growth, sample UN05; (c) bands of fluid inclusion at the beginning of vein growth, sample UN05

Fig. 15: Schematic representation (not to scale) of the D₁ deformation phase elements and geometric patterns of the veins with respective inferred stress field (main compressive stresses; $\sigma_1 > \sigma_2 > \sigma_3$)

2.6.1.2 Cleavage-parallel veins

The cleavage-parallel veins are rare and occur coexisting with subhorizontal veins, exhibiting 5-70 mm-thick and extending laterally up to 1 m. Quartz represents almost all the totality of veins, which also contains small carbonate contents. Deformation microstructures in quartz as strong undulose extinction, deformation bands and bulging recrystallization indicate a low degree of dynamic recrystallization, under temperatures between ~280 and ~300°C (Fig. 16) (e.g., Stipp et al., 2002a,b; Faleiros et al., 2010).

These veins can be classified as ataxial (Passchier and Trouw, 1996) or stretched (Durney and Ramsay, 1973) or even bitaxial as introduced by Hilgers et al. (2001) for veins with elongate blocky texture, which grown from wall-rock of the vein in both sides with a random position parallel to the microcracks. Some veins also show fibrous aspect (Bons et al., 2012) that are formed by elongated quartz grains oriented at an angle of 80-90° to the vein walls (Fig. 16). The presence of solid inclusion bands with the same composition of veins walls suggests several crack-seal processes during its formation. These growth microstructures indicate that cleavage-parallel veins are also extensional veins that were crystallized in D₂-related deformational stage. The geometric patterns of the cleavage-parallel veins suggest a subhorizontal NW-SE-trending maximum compression (σ_1) and a subhorizontal NE-SW-trending least compressive stress (σ_3) (Fig. 15).

Fig. 16: Photomicrographs of subvertical quartz veins, sample UN26 (crossed polarized light). (a) elongate blocky crystals with both side growth, sometimes with appearance of fibrous veins; (b) deformation microstructures as strong undulose extinction and deformation bands; (c) deformation microstructure as deformation bands; (d) bulging recrystallization

2.6.2. Fluid inclusion petrography

Fluid inclusion petrography was carried out on 100 μm -thick, double-polished sections of extensional and cleavage subparallel quartz veins, from which 7 samples with different vein-growth and deformation microstructures were chosen for microthermometric measurements.

One type of fluid inclusions ranging from 70 μm to 2 μm in size were identified in quartz from subhorizontal and cleavage-parallel veins based on phases observed at room temperature and components identified from heating-freezing experiments. All the fluid inclusions are aqueous saline inclusions with elongated, negative crystal or irregular shaped inclusions, and show two phases (liquid and vapor H_2O) whereas H_2O vapor comprises about 10% of volumetric proportion. A summary of fluid inclusion types, modes of occurrence and microstructures is shown in Table 2.

The fluid inclusions present two different modes of occurrence: intragranular trails in different orientations and three-dimensional clustered and randomly distributed assemblages within single grains. The two fluid inclusion assemblages coexist at both types of veins.

Table 2- Summary of fluid inclusion and modes of occurrence related to vein types

Sample	Vein geometry	Growth microstructure	Fluid inclusion (modes of occurrence)
UN05A	Subhorizontal	Elongated blocky	three-dimensional clusters
UN05B	Host rock of subhorizontal vein	——	intragranular trail
UN06B	Subhorizontal	Elongated blocky	three-dimensional clusters
UN26D	Cleavage- parallel	Elongated blocky/Fibrous	three-dimensional clusters
UN26E	Cleavage- parallel	Elongated blocky/Fibrous	three-dimensional clusters
UN28D	Subhorizontal	Elongated blocky	three-dimensional clusters

2.6.3. Microthermometric data

Fluid inclusion microthermometric analyses were carried out at the Fluid Inclusion Laboratory of the Geosciences Institute, University of São Paulo (Brazil), using a CHAIXMECA MTM 85 heating-cooling stage. The stage was calibrated to the Merck MSP standard for high temperatures and Merck Signotherm standard for low temperatures. Thermometric data were interpreted using the computer software packages FLUIDS (Bakker, 2003), which, in terms of composition, density of the trapped fluids and volumetric proportions uses equations developed by Zhang and Frantz (1987) and for densities and salinities of the aqueous phase equations of state and ion interaction model developed by Archer (1992). A summary of microthermometric results is shown in Table 3. Although only one type of fluid inclusion (H₂O-NaCl inclusions) was identified in terms of phases at room temperature and main components, the fluid inclusions show a large variation in eutectic (T_E) and ice melting (T_{mice}) temperatures and based on these conditions they were subdivided into two fluid inclusion assemblages (FIA) (FIA-1 and FIA-2). FIA-1 inclusions present irregular and negative crystal shapes and occur within single quartz grains in clusters and along intragranular trail within detrital quartz grain exclusively in subhorizontal veins. T_E values range from -62 to -36 °C, and T_{mice} values range from -18 to -1.2°C, corresponding to

salinities of 21 to 2 wt.% eq. NaCl. Total homogenization temperature (T_h) values (to the liquid state) vary between 56 to 213°C (Fig. 17). FIA-2 inclusions occur exclusively in cleavage-parallel veins as elongated and irregular shaped inclusions in clusters whereas H₂O vapor varies from 5 to 30% of vapor volumetric. T_E values vary between -48 to -34°C. T_{mice} and related salinities range from -3 to 0°C and 0 to 6 wt. % eq. NaCl, respectively. These type inclusions homogenize to the liquid state in the interval of 106 to 303°C (Fig. 17).

Table 3- Summary of the microthermometric fluid inclusion data for subhorizontal and cleavage-parallel veins

Vein type	Sample	Type of inclusion	Mode of occurrence	Fluid system	T_E	T_{mice}	T_h	Salinity	n
Subhorizontal	UN05A	1	cluster	H ₂ O-NaCl-CaCl ₂	-53.4 to -38.8	-9.6 to -1.2	83.1 to 177.1	2.1 to 13.74	106
	UN05B	1	trail	H ₂ O-NaCl-CaCl ₂	-62.6 to -42.4	-9.7 to -1.6	70.2 to 135.2	2.76 to 13.85	30
	UN06B	1	cluster	H ₂ O-NaCl-CaCl ₂	-56.9 to -36.7	-6.5 to -1.5	87.9 to 213.9	2.6 to 10.01	77
	UN28D	1	cluster	H ₂ O-NaCl-CaCl ₂	-59.9 to -45	-18 to -2.3	56.2 to 184.6	3.91 to 21.51	61
Cleavage-parallel	UN26D	2	cluster	H ₂ O-NaCl-CaCl ₂	-48.1 to -34.5	-3.8 to -0.1	106.1 to 303.4	0.23 to 6.23	32
	UN26E	2	cluster	H ₂ O-NaCl-CaCl ₂	-48.4 to -36.8	-3 to -1.1	124.6 to 187.2	1.93 to 5.01	26

Fig. 17: Histograms showing microthermometric data obtained for FIA-1 and FIA-2 fluid inclusions

2.6.4. Stages of fluid circulation

Based on fluid composition, density and homogenization temperature, FIA-1 and FIA-2 inclusions, present in subhorizontal and cleavage-parallel veins, respectively, represent the syn-vein growth episode of fluid entrapment. The abundance of these inclusions randomly arranged within veins with well-preserved original growth microstructures is good evidence that ‘primary’ fluid inclusions are preserved (Fig. 18). Fluid inclusions trapped in healed fractures present in detrital quartz grains of sandstone hosting extensional veins despite not

‘primary’ in origin are associated with the same episode of fluid circulation responsible to syn-vein growth, as evidenced by microthermometric data. Although weak undulose extinction and very restricted bulging recrystallization microstructures may occur in studied samples, this restricted deformation of low temperature could not have destroyed totally the primary fluid inclusions and inclusions present in undeformed domains of heterogeneously deformed samples commonly preserve original densities (Kerrick, 1976; Faleiros et al., 2007, 2014).

Fig. 18: Photomicrographs of fluid inclusion. (a-b) very abundant fluid inclusion in cluster of FIA-1 within quartz from subhorizontal veinlet, sample UN05A (a) and UN06B (b); (c-e) Cluster and some small size trails of FIA-1 fluid inclusion, samples UN05A (c and e) and UN06B (d); (f-g) Cluster and some small size trails of FIA-2 fluid inclusion, samples UN26D (f) and UN26E (g)

Eutectic melting temperatures from FIA-1 and FIA-2 inclusions range mainly between -55 to -40°C, suggesting solutions of the $\text{H}_2\text{O}-\text{NaCl}-\text{CaCl}_2$ system (e.g. Roedder, 1984; Goldstein and Reynolds, 1994). Variations in relation to the stable eutectic of this pure system ($T_E = -52^\circ\text{C}$) may indicate the presence of other dissolved salts (likely MgCl_2) or may be

related to the metastability of the H_2O – NaCl – CaCl_2 system (e.g., Goldstein and Reynolds, 1994). There is a tendency of higher TE values for FIA-2 in comparison with FIA-1 inclusions.

FIA-1 inclusions show a bivariate plot where there is a higher concentration of data in a point around 140°C of T_h and salinity of the order of about 9-11 wt.% NaCl eq. representing the data from unaltered fluid (Fig. 19a-c). The diagram relating T_h and T_{mice} for FIA-1 inclusions exhibits two evolution trajectories, one shows decrease in T_{mice} (from -7.5 to -1.5°C) concomitantly with decrease in T_h (from 158 to 77°C) suggesting a heterogeneous interaction of hotter metamorphic fluids with colder meteoric fluids that cause dilution of the aqueous–saline fluids concomitant with temperature decrease. The second trajectory shows constant T_{mice} with also decrease in T_h (from 158 to 76°C), suggesting pressure fluctuation during entrapment of a metamorphic fluid (e.g., Montomoli et al., 2001; Faleiros et al., 2007).

FIA-2 inclusions also show a bivariate plot (Fig. 19d) where the higher concentration of data are around 140°C of T_h and about 4 wt.% NaCl eq. The diagram relating T_h and T_{mice} for FIA-2 inclusions also exhibits two evolution trajectories. One trend show decrease in T_{mice} (from -2.5 to -2°C) concomitantly with increase in T_h (from 150 to 196°C) suggesting an interaction between a hotter fluid with low salinity and a high salinity cold fluid that cause dilution of the fluids concomitant with increase in temperature. The other trajectory shows decrease in T_{mice} (from -2.7 to -0.6°C) for a T_h constant, representing the interaction with meteoric fluids that cause the reduction of salinity.

Fig. 19: Plots of salinity against homogenization temperatures for FIA-1 (a-c) and for FIA-2 (d)

2.6.5. *P-T conditions of vein crystallization*

Fluid inclusions isochores were calculated based on equations by Bodnar and Vityk (1995) and Knight and Bodnar (1989) with the computer software ISOC (Bakker, 2003). For aqueous saline inclusions homogeneously trapped only minimum P–T conditions of trapping can be obtained in the absence of other estimates of pressure or temperature (Roedder et al., 1984).

Isochore intersections with the range of temperatures of 250 and 300°C, estipulated based on the other methods (dynamic recrystallization, P-T pseudosections and quartz c-axis fabric evidence), provide entrapment pressure conditions of 200–363 MPa (FIA-1) and 181–295 MPa (FIA-2) (Fig. 20). In the absence of evidence for significant post-trapping modifications, this pressure variation (163 MPa for FIA-1 and 114 MPa for FIA-2) was interpreted as result of fluid pressure fluctuation during vein crystallization into the two deformation events where the fluctuation related with subhorizontal veins is greater than that observed in the cleavage-parallel veins. This phenomenon is normal and expected as the pressure acting on the opening of vertical veins is lower, thus, subhorizontal veins, when subjected to the fault-valve behavior, tend to register greater pressure fluctuation.

Fig. 20: P–T diagram with isochores for (a) FIA-1 and (b) FIA-2 fluid inclusion. Shaded vertical boxes are the minimum and maximum temperatures estimated by dynamic recrystallization, P-T pseudosections and quartz c-axis fabric evidence

The pressure variation for the subhorizontal veins, measured through the fluid inclusions of the trajectory interpreted as result of pressure fluctuation, shows evidence of significant difference for temperatures of 270°C (from 193 to 459 MPa for sample 05A, 300 to 482 MPa for sample 05B and 94 to 430 MPa for sample 06B)(Fig. 21). The ability to

determine the presence of strong pressure fluctuations is of interest for determination the role of fluids in deformational zones (Montomoli et al., 2001) and the fault-valve behavior is the best applicable model to explain pressure drops. Sibson (1990, 1994, 2000) proposes that pressure cycling between lithostatic and infra-lithostatic can occur in orogenic terrains where compressional regime is the most favorable tectonic setting for the fault-valve mechanism.

Fig. 21: P–T diagram with isochores for (a) sample UN05A; (b) sample UN06B; (c) sample UN05B. The vertical trace represents the temperature of 270 °C

CHAPTER 3.

DISCUSSION

Experimental and natural examples of deformation have demonstrated that fluids significantly influence the rheology, mechanical processes, deformation mechanisms and chemical reactions that operate in deforming rocks along orogenic belts, including fold-thrust belts (Crispini and Frezzotti, 1998; Swennen et al., 2000; Ferket et al., 2003; Fitz-Diaz et al., 2011; Huang et al., 2012; Jacques et al., 2014). Fluids involved in polyphase deformation of metamorphic terranes may be recorded in syntectonic vein systems, which are fossil products of different stages of fluid flow (e.g., Robert, 1995; Dugdale and Hagemann, 2001; Montomoli et al., 2001; Faleiros et al., 2007). The presence of veins of different generations in the fold-and-thrust zone of the western margin of the São Francisco Craton is evidence of fluids operating at different scenarios of paleostress throughout the deformation history. Coupling the reconstruction of the paleostress states and fluid inclusion studies can provide fundamental information about the relationship between fluid flow and tectonic process.

The structural pattern of the fold-and-thrust zone along the western margin of the São Francisco Craton was mainly formed during the Neoproterozoic, which was the result of the orogenic process of the Brasiliano event and Gondwana Assembly. The paleostress field during this tectonic episode in the study area was represented by intense compression and, under this tectonic scenario, the fluid was syntectonically squeezed out of the rocks and flowed into the fractures where the veins precipitated. Two main tectonic events with different stress regime orientation were identified by vein geometric arrangement and the geometry of fold and thrust elements, a major early NE-SW compression (D_1) and the later NW-SE compression (D_2).

Two generations of syntectonic veins can be identified in the fold-and-thrust zone: the subhorizontal NW-trending veins (D_1 -related) and subvertical cleavage-parallel veins (D_2 -related). Both syntectonic veins show dominantly elongated block and fibrous texture suggesting that true extensional fractures have been filled and indicating that the material in the veins is locally derived and that the rate of vein opening (strain) was faster than the transportation of material inside the vein implying that the most likely mechanism of transport was diffusion (Kirschner et al., 1994; Bons et al., 2000; Oliver and Bons, 2001). Thus, the fluid inclusion trapped within the vein minerals can be considered as records of the main fluid

involved on the regional metamorphism of the Bambuí Group. True tensile stresses in Earth's crust are uncommon because all the main stresses tend to be in the compressional field, thus the existence of extensional veins in metamorphic environments is a robust evidence of hydraulic fracturing derived from episodic buildup of fluid pressure (Cosgrove, 1995).

Subhorizontal veins are omnipresent in the study area and has important implications for its paleostress history as they were emplaced at a time when the fluid pressure was sufficiently elevated (supra-lithostatic values) to allow subhorizontal fractures to open against the vertical load. In this scenario the vertical stress (σ_v) must be the smallest principal stress (σ_3), and differential stress must be small enough ($\sigma_1 - \sigma_3 < 4t$ (t = tensile strength); e.g., Cosgrove, 1995) to prevent shear failure to occur. Structural evidence of this phenomenon in natural examples has been commonly observed elsewhere and has been successfully explained in other fold-and-thrust belts (Jessell et al., 1994; Hilgers et al., 2006). Opening of subvertical extensional veins does not require supralithostatic fluid pressures, once the least compressive stress (σ_3) is lower than the vertical stress (σ_v). For both veins, σ_1 take place at compressive field, as inferred from the Mohr's diagram and σ_3 at tensile field, being formed by the opening mode.

The evidence collected from fluid inclusion studies were performed on fault-related veins, despite the regional fracture system are related to the compressive tectonic scenario, the fault-related veins were chosen because occur in greater volume and are more expressive, suggesting that the failure, which occur concomitant with folding, has potentiated the circulation of fluids. All the fluid inclusions are aqueous saline inclusions with elongated, negative crystal or irregular shape presenting different modes of occurrence where in subhorizontal veins fluid inclusion occur within single quartz grains in clusters and along intragranular trail within detrital quartz grain and in cleavage-parallel veins, fluid inclusions occur exclusively in clusters. Both veins system fluid inclusion data suggest solutions of H_2O - $NaCl$ - $CaCl_2$ system (e.g. Roedder, 1984; Goldstein and Reynolds, 1994) and some variations in relation to the stable eutectic of this pure system may be result of the presence of other dissolved salts or related to the metastability of the system. The fluid inclusion assemblage of subhorizontal veins (FIA-1) shows a higher concentration at 140-160°C of homogenization temperature and salinity of about 9-11 wt.% $NaCl$ eq., representing the data from unaltered fluid. From this point of greater T_h and salinity, derive two lines of evolution, one shows decrease in salinity concomitantly with decrease in T_h suggesting a heterogeneous interaction

of hotter metamorphic fluids, deeper, with colder meteoric fluids that circulate from the surface, causing dilution of the aqueous–saline fluids concomitant with temperature decrease; and an second trajectory with constant salinity and decrease in T_h , suggesting pressure fluctuation during entrapment of a metamorphic fluid (e.g., Montomoli et al., 2001; Faleiros et al., 2007). The fluid inclusion assemblage of cleavage-parallel veins (FIA-2) shows the higher concentration at homogenization temperature of 140-160 °C and salinities of about 4 wt.% NaCl eq.. The fluid evolution also show two trajectories, decrease in salinity concomitantly with increase in T_h , suggesting an interaction between a hotter fluid with low salinity and a high salinity cold fluid that cause dilution of the fluids concomitant with increase in temperature; and decrease in salinity for a T_h constant, representing the interaction with meteoric fluids that cause only dilution, generating reduction of salinity.

The distribution of both homogenization temperatures and salinities, suggest that the fluids were mixtures of two different sources (metamorphic and meteoric), where the difference in the geometry of the veins and the time of seals of the fractures are the reason of the difference in interaction efficiency between the two sources resulting in a salinity difference. For the cleavage-parallel veins, the lower salinity with less variation is a result of a greater interaction with meteoric fluids, once they were form during the early high fluid pressure stages of D₂ phase by opening preexistent vertical S₁ planes because the lower resistance of this weakness plane, as evidenced by field data and geological map analysis that confirm the existence of folds with vertical axis and vertical axial plane ENE-trending that fit the regime of paleostress indicated by the geometry of the veins.

Once subvertical fractures have link with atmospheric conditions, the interaction with meteoric fluid are much more effective, suggesting that these veins shows the history of a fluid which had suffered an effective mixture of sources before crystallization, representing a fast crystallization of a homogenized fluid with lower salinity. The higher salinity with greater variation of the subhorizontal veins suggest that they were formed at late stages of D₁ phase keeping the entire evolutive history of the fluids that act in the deformation episode. The higher salinity can be explain as subhorizontal fractures were in part prevented from meteoric fluid penetration (wich contributed to enhanced pore fluid pressure to supra-lithostatic conditions).

Aqueous-saline inclusions were homogeneously trapped, as the fluid inclusion data is representative of the unaltered fluid, original solution, and only minimum P–T conditions

have been obtained and these must be considered with caution. For this reason, other parameters were considered for making assumptions of pressure and temperature at veining. Deformation microstructures in quartz point into two mechanism of recrystallization, pressure-solution, which occur under diagenetic and low metamorphic grade (200–400°C) (Weyl 1959, Durney 1972, Elliott 1973, Rutter 1983) and into the lower temperature portion of the bulging recrystallization regime which is active at temperatures around 280–350 °C (Stipp et al. 2002a,b; Faleiros et al., 2010).

Mineral assemblages and chemical analyses indicate the presence of kaolinite and absence of pyrophyllite and chloritoid (for medium A metapelites) and the absence of chlorite in low A ratio which prevent the formation of others index metamorphic phases is robust evidence of metamorphic temperatures below 300 °C (limit of kaolinite stability). This thermometer is in agreement with the constraints from modeled P-T pseudosection, where the assemblage with kaolinite and absence of stilpnomelane and chloritoid is stable at conditions of 140–270°C and 1–9 kbar. Despite the c-axis-based thermometer does not provide a reliable temperature estimation, as it had influence of factors as measurements of non-recrystallized grains, the result shows a very strong crystallographic fabric, characteristic of quartz fabrics that were subjected to a minimal temperature of about 250°C (e.g., Passchier and Trouw, 2005 and references therein). The minimum temperature of entrapment achieved by fluid inclusion study was 140–160°C, but the combination of all thermometers (P-T pseudosection, deformation mechanisms, quartz c-axis fabrics and fluid inclusion evidence) allowed stipulating a reliable temperature range of 250–300°C of vein formation.

Combination of fluid inclusion isochores and independent temperature estimation indicates that the subhorizontal veins (D₁ deformational phase) were formed under near-lithostatic to supralithostatic fluid pressure conditions (200–363 MPa at 250–300 °C) and the cleavage-parallel veins (D₂ phase) were crystallized primarily under hydrostatic to lithostatic fluid pressure conditions (181–295 MPa at 250–300°C). The pressure difference between the two vein systems was expected and mostly linked with the different tectonic stress acting at the two deformational events. The pressure fluctuation difference is explained as during vertical veining, the fluctuation is usually much smaller than those during horizontal veining as to open horizontal fractures the fluid pressure should be greater in order to overcome the lithostatic load.

The pressure fluctuation observed in the FIA-1 fluid inclusions should be considered as significant, once it was demonstrated the absence of evidence for significant post-entrapment fluid inclusion modifications. Similar studies which used fluid inclusions in order to estimate fluid pressure fluctuations during veining are presented by Parry and Bruhn (1990), Parry et al. (1991), Robert et al. (1995), Henderson and MacCaig (1996), Montomoli et al. (2001), Faleiros et al. (2007, 2014). The pressure fluctuation observed on fluid inclusions during the development of the syntectonic subhorizontal veins are 266 MPa, 182 MPa and 336 MPa (samples UN05A, UN05B and UN06B respectively). This phenomenon may be related to cyclic decompressions associated to tectonic activity and fissure extension and/or hydraulic fracturing (Montomoli et al., 2001). The main mechanisms invoked to explain pressure drops are decreases in fluid pressure due to an increase in porosity resulting from the opening of dilatant fractures and propagation of cracks related to changes in shear stress and fluid pressure draining away along a rupture zone as proposed in the fault-valve model (Sibson, 1981; Mac Caig, 1988; Sibson et al., 1988; Parry and Bruhn, 1990; Sibson, 1990, 2000; Boullier and Robert, 1992; Henderson and Mac Caig, 1996; Dugdale and Hagemann, 2001; Faleiros et al., 2007, 2014). The studied samples of veins hosted by the Bambuí Group rocks were collected in the proximities of mapped thrust fault zones (Fig. 7) where the veins are much more abundant. This evidence indicates that besides associated with folding, the formation of the studied veins had a direct influence of faulting processes.

In the specific case, the best applicable model to explain pressure drops is the fault-valve behavior in compressive tectonic regime as suggested by structural data. Sibson (1990, 1994, 2000) proposes that pressure cycling between lithostatic and infra-lithostatic can occur in orogenic terrains where compressional regime is the most favorable tectonic setting for the mechanism, which perfectly applies to the foreland fold-and-thrust belt at the western margin of the São Francisco Craton.

CHAPTER 4.

CONCLUSIONS

Fluid inclusion data, petrographic, structural and microstructural analysis of the fault-related veins from the fold-and-thrust zone of the western margin of the São Francisco Craton provides good evidence of cyclic fluid pressure and tectonic variation related to fault-valve behavior offering important considerations about veining mechanisms, fluid flow and P–T conditions during the deformational history.

The structural pattern of the fold-and-thrust zone along the western margin of the São Francisco Craton proposes two main tectonic events with different stress regime orientation, a major early NE-SW compression (D_1) with σ_1 sub-horizontal SW-trending and σ_3 subvertical, related with subhorizontal NW-trending syntectonic veins; and the later NW-SE compression (D_2) with σ_1 subhorizontal NW-trending and σ_3 subhorizontal NE-trending), related with subvertical syntectonic cleavage-parallel veins.

Both subhorizontal and cleavage-parallel veins present a aqueous saline fluid inclusion dominated by H_2O - $NaCl$ - $CaCl_2$ system, with some variation in salinity (12 against 4 wt.% $NaCl$ eq. for subhorizontal and cleavage-parallel veins respectively) result of mixing, more or less effective, between two different sources (metamorphic and meteoric). A general fluid evolution towards salinity depletion and dilution occurs for both fluid inclusion assemblages. A constant salinity evolution of fluid related with subhorizontal veins suggests pressure fluctuation.

The minimum temperature of entrapment of fluids occurred around 140-160°C and as only these minimum conditions have been obtained, other parameters were considered. Mineral assemblages, P-T pseudosection, deformation microstructures and quartz c-axis fabrics allowed to stipulate a reliable temperature range of 250-300°C of vein formation.

The subhorizontal veins were formed under near-lithostatic to supralithostatic fluid pressure conditions (200-363 MPa at 250-300 °C) at late stages of D_1 and the cleavage-parallel veins were crystallized primarily under hydrostatic to lithostatic fluid pressure conditions (181-295 MPa at 250-300°C) during the early high fluid pressure stages of D_2 . The pressure difference between the two veins systems are related with the different tectonic stress

acting at the two deformational events. The pressure fluctuation observed on fluid inclusions during the development of the syntectonic subhorizontal veins is related with the fault-valve behavior.

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APPENDIX

Appendix- Complete microthermometric data

Sample	Field	N° fluid inclusion	TE	Tmice	Vv/Vt	Thtotal (Liq)	D	H2O	Na+	Cl-	Vmeasured	Salinity
05A	1A	1	-45	-5.7	10%	133.1	0.985769	0.944478	0.02776	0.027761	9.68	8.94
05A	1A	2	-47.2	-5.6	10%	150.8	0.973175	0.945328	0.02734	0.027336	10.71	8.81
05A	1A	3	-50	-4.3	8%	116.1	0.985605	0.956769	0.02162	0.021615	7.93	6.97
05A	1A	4	-52	-5.3	10%	X		0.947903	0.02605	0.026049		8.39
05A	1A	5	-50.2	-5.1	10%	166.8	0.957345	0.949641	0.02518	0.02518	11.57	8.12
05A	1A	6	-51	-5.3	8%	88.8	1.008329	0.947903	0.02605	0.026049	7.11	8.39
05A	1A	8	-46.8	-5.8	10%	149.1	0.975903	0.943632	0.02818	0.028184	10.7	9.08
05A	1A	9	-48	-4.1	10%	152.3	0.959896	0.958595	0.0207	0.020702	10.07	6.68
05A	1A	10	-47	-1.2	5%	107.5	0.96621	0.98703	0.00649	0.006485	5.24	2.1
05A	1A	11	-47.5	-5.2	10%	143	0.975434	0.94877	0.02562	0.025615	10.02	8.26
05A	1A	12	-50	-3.7	10%	X		0.962302	0.01885	0.018849		6.08
05A	1A	13	-49.1	-3.4	10%	128.5	0.970753	0.965128	0.01744	0.017436	8.1	5.63
05A	1A	14	-49	-5.4	10%	150.4	0.971891	0.94704	0.02648	0.02648	10.59	8.53
05A	1A	15	-50.4	-5.3	10%	150.1	0.971314	0.947903	0.02605	0.026049	10.52	8.39
05A	1A	16	-50.7	-4.9	10%	152.6	0.96633	0.951396	0.0243	0.024302	10.49	7.83
05A	1A	17	-48.1	-5.2	10%	140.8	0.976918	0.94877	0.02562	0.025615	9.88	8.26
05A	1A	18	-49.6	-5.3	10%	X		0.947903	0.02605	0.026049		8.39
05A	1A	19	-49	-5.1	10%	X		0.949641	0.02518	0.02518		8.12
05A	1A	20	-49.4	-5.4	10%	X		0.94704	0.02648	0.02648		8.53
05A	1A	21	-49.7	-3.8	10%	160.8	0.95074	0.961368	0.01932	0.019316	10.53	6.23

05A	1A	22	-47.4	-4.9	12%	177.1	0.947339	0.951396	0.0243	0.024302	12.25	7.83
05A	1A	23	-49.9	-3.7	10%	X		0.962302	0.01885	0.018849		6.08
05A	1A	24	-47.8	-5.6	10%	143.2	0.978391	0.945328	0.02734	0.027336	10.23	8.81
05A	1A	25	-49.1	-4.3	8%	108	0.99032	0.956769	0.02162	0.021615	7.48	6.97
05A	1A	26	-48.4	-4.3	10%	X		0.956769	0.02162	0.021615		6.97
05A	1A	27	-48.3	-4.5	10%	X		0.954961	0.02252	0.02252		7.26
05A	1A	28	-45.6	-2.3	8%	131.5	0.959477	0.97583	0.01209	0.012085	7.6	3.91
05A	1A	29	-50.2	-5.1	12%	146.8	0.97204	0.949641	0.02518	0.02518	10.21	8.12
05A	1A	30	-48	-5.4	12%	153.8	0.969481	0.94704	0.02648	0.02648	10.81	8.53
05A	1A	31	-52.1	-1.7	5%	112.3	0.967279	0.981883	0.00906	0.009059	5.93	2.93
05A	1A	32	-49.6	-2.5	5%	114.6	0.972348	0.973846	0.01308	0.013077	6.65	4.23
05A	1A	33	-50.1	-5.1	8%	106.6	0.997173	0.949641	0.02518	0.02518	7.89	8.12
05A	1A	34	-47.7	-4.9	10%	149.6	0.968478	0.951396	0.0243	0.024302	10.29	7.83
05A	1A	35	-47.9	-5.4	10%	165.2	0.961069	0.94704	0.02648	0.02648	11.59	8.53
05A	1A	36	-50.8	-4.3	5%	83.1	1.003571	0.956769	0.02162	0.021615	6.25	6.97
05A	1A	37	-48.4	-5.8	12%	155.2	0.971624	0.943632	0.02818	0.028184	11.09	9.08
05A	1A	38	-48.8	-5.7	10%	151.7	0.973322	0.944478	0.02776	0.027761	10.82	8.94
05A	1A	39	-47.7	-5.2	10%	140	0.977453	0.94877	0.02562	0.025615	9.83	8.26
05A	1A	40	-49.8	-5.5	12%	151.2	0.972113	0.946182	0.02691	0.026909	10.69	8.67
05A	1A	41	-49.1	-5.7	12%	147.5	0.976236	0.944478	0.02776	0.027761	10.55	8.94
05A	1A	42	-50.6	-5	10%	151.4	0.968001	0.950516	0.02474	0.024742	10.46	7.98
05A	1A	43	-48.6	-5.4	10%	152.1	0.970692	0.94704	0.02648	0.02648	10.7	8.53
05A	1A	44	-51.5	-4.3	12%	152	0.961809	0.956769	0.02162	0.021615	10.15	6.97
05A	1A	45	-49.5	-4.4	10%	151.7	0.962867	0.955863	0.02207	0.022069	10.18	7.12
05A	1B	1	-49.8	-5.3	10%	162.2	0.962519	0.947903	0.02605	0.026049	11.33	8.39
05A	1B	2	-48.1	-5.6	8%	X		0.945327	0.02734	0.027336		8.81
05A	1B	3	-49.5	-5.6	9%	149.4	0.974151	0.945328	0.02734	0.027336	10.62	8.81

05A	1B	4	-47.9	-2.8	9%	149.2	0.950794	0.970901	0.01455	0.01455	9.15	4.7
05A	1B	5	-49.1	-1.8	9%	X		0.980864	0.00957	0.009568		3.09
05A	1B	6	-49.5	-5.8	8%	X		0.943632	0.02818	0.028184		9.08
05A	1B	7	-48.4	-4.7	8%	X		0.95317	0.02342	0.023415		7.55
05A	1B	8	-47.1	-5.4	9%	X		0.94704	0.02648	0.02648		8.53
05A	1B	9	-49.7	-5.1	10%	X		0.949641	0.02518	0.02518		8.12
05A	1B	11	-49.3	-5.6	10%	161.4	0.965543	0.945328	0.02734	0.027336	11.41	8.81
05A	1B	12	-50.1	-5.9	10%	X		0.942791	0.02861	0.028605		9.21
05A	1B	13	-49.7	-4.2	10%	X		0.95768	0.02116	0.02116		6.83
05A	1B	14	-49.9	-5.6	10%	148.6	0.974706	0.945328	0.02734	0.027336	10.57	8.81
05A	1B	15	-49.5	-6.3	8%	105.9	1,006,567	0.939467	0.03027	0.030266	8.49	9.74
05A	1B	16	-49.1	-3.8	8%	137.6	0.967902	0.961368	0.01932	0.019316	8.92	6.23
05A	1B	17	-48	-1.3	5%	99.1	0.972085	0.985994	0.007	0.007003	4.83	2.26
05A	1B	18	-48.7	-1.7	10%	156.9	0.933849	0.981883	0.00906	0.009059	9.18	2.93
05A	1B	19	-49.5	-1.6	8%	139.1	0.947566	0.982905	0.00855	0.008547	7.69	2.76
05A	1B	20	-49.8	-4.1	8%	117.9	0.982982	0.958595	0.0207	0.020702	7.9	6.68
05A	1B	21	-48.2	-6.3	10%	155.4	0.975324	0.939467	0.03027	0.030266	11.33	9.74
05A	1B	22	-48.4	-5.2	9%	114.9	0.993155	0.948769	0.02562	0.025615	8.39	8.26
05A	1B	23	-50.2	-5.9	10%	147.1	0.97804	0.942791	0.02861	0.028605	10.62	9.21
05A	1B	24	-49.8	-5.4	10%	X		0.94704	0.02648	0.02648		8.53
05A	1B	25	-48.7	-5.8	10%	160.4	0.967869	0.943632	0.02818	0.028184	11.44	9.08
05A	1B	26	-49.5	-3.7	10%	154.1	0.955077	0.962302	0.01885	0.018849	9.99	6.08
05A	1B	27	-50.8	-5.4	9%	144.7	0.975834	0.94704	0.02648	0.02648	10.23	8.53
05A	1B	28	-50.1	-5.7	9%	126.2	0.990103	0.944478	0.02776	0.027761	9.28	8.94
05A	1B	29	-48	-6	10%	143.1	0.981496	0.941954	0.02902	0.029023	10.42	9.35
05A	1B	30	-50.6	-2.5	8%	135.4	0.958436	0.973846	0.01308	0.013077	7.99	4.23
05A	1B	31	-49.2	-5.8	9%	159.4	0.968599	0.943632	0.02818	0.028184	11.37	9.08

05A	1B	32	-51.8	-5.6	12%	151.6	0.972614	0.945328	0.02734	0.027336	10.76	8.81
05A	1B	33	-48.9	-5.9	10%	157.5	0.970757	0.942791	0.02861	0.028605	11.29	9.21
05A	1B	34	-49.8	-6	10%	152.8	0.974864	0.941954	0.02902	0.029023	11.03	9.35
05A	1B	35	-50.8	-5.7	10%	114.2	0.997312	0.944478	0.02776	0.027761	8.62	8.94
05A	1B	36	-47.4	-5.6	5%	~78,1	1,016,155	0.945327	0.02734	0.027336	6.77	8.81
05A	1B	37	-50.8	-3.1	5%	X		0.967995	0.016	0.016003		5.17
05A	1B	38	-48.4	-8.7	12%	158.4	0.990482	0.920854	0.03957	0.039573	12.52	12.71
05A	1B	39	-49.9	-6.6	12%	153.6	0.978838	0.937018	0.03149	0.031491	11.35	10.14
05A	1B	40	-48.1	-1.9	8%	128.3	0.958263	0.979849	0.01008	0.010075	7.11	3.26
05A	N	1	-38.8	-7.1	10%	135.5	0.99454	0.933016	0.03349	0.033492	10.49	10.78
05A	N	2	-45.2	-3.5	8%	130.8	0.970045	0.964181	0.01791	0.017909	8.3	5.78
05A	N	3	-44.6	-8.3	10%	139	1,000,790	0.923806	0.0381	0.038097	11.21	12.24
05A	N	4 (	-44.3	-2.8	8%	135.9	0.960677	0.970901	0.01455	0.01455	8.21	4.7
05A	N	5	-45.6	-2.6	8%	127.6	0.964735	0.97286	0.01357	0.01357	7.53	4.38
05A	N	6	-44.7	-9.6	10%	134	1,013,057	0.914415	0.04279	0.042792	11.41	13.74
05A	N	7	-41.5	-6	10%	150.3	0.976604	0.941954	0.02902	0.029023	10.87	9.35
05A	N	8	-43	-5	10%	134.4	0.979597	0.950516	0.02474	0.024742	9.39	7.98
05A	N	9	-41.6	-7.8	6%	X		0.927578	0.03621	0.036211		11.64
05A	N	10	-53.4	-5.8	8%	120.8	0.994141	0.943632	0.02818	0.028184	9.03	9.08
05A	N	11	-42.8	-5.7	10%	X		0.944478	0.02776	0.027761		8.94
05A	N	12	-43.7	-7.5	10%	139.6	0.99476	0.929886	0.03506	0.035057	10.91	11.27
05A	N	13	-42.2	-6.2	10%	X		0.940292	0.02985	0.029854		9.61
05A	N	14	-42.8	-6.6	10%	132.8	0.99263	0.937018	0.03149	0.031491	10.11	10.14
05A	N	15	-52.6	-6.8	10%	148	0.984149	0.935405	0.0323	0.032297	11.1	10.39
05A	N	16	-40.3	-2.7	8%	131.7	0.96277	0.971878	0.01406	0.014061	7.87	4.54
05A	N	17	-50	-6.4	10%	154.4	0.976782	0.938647	0.03068	0.030677	11.32	9.88
05A	N	18	-49.8	-6.1	10%	151	0.97688	0.941121	0.02944	0.02944	10.96	9.48

05A	N	19	-50.7	-6.1	7%	X		0.941121	0.02944	0.02944		9.48
05A	N	20	-52.8	-6.2	10%	149.7	0.978533	0.940292	0.02985	0.029854	10.93	9.61
05A	N	21	-49.1	-5.9	10%	133.1	0.987268	0.942791	0.02861	0.028605	9.78	9.21
05A	N	22	-47.3	-5.8	10%	149	0.975972	0.943632	0.02818	0.028184	10.69	9.08
05A	N	24	-46.8	-5.2	8%	135.1	0.980682	0.94877	0.02562	0.025615	9.54	8.26
05B	1 (T)	1	-51.6	-7.7	8%	111.7	1,013,562	0.928343	0.03583	0.035828		11.52
05B	1 (T)	2	-52.1	-4.4	5%	70.2	1,010,585	0.955863	0.02207	0.022069	5.73	7.12
05B	1 (T)	3	-52.6	-9.3	8%	88.2	1,040,035	0.916531	0.04174	0.041735	8.76	13.4
05B	1 (T)	4	-53.4	-9.2	8%	91.1	1,037,431	0.917243	0.04138	0.041379	8.89	13.29
05B	1 (T)	5	-51.0	-9	8%	81.8	1,041,534	0.918677	0.04066	0.040662	8.32	13.06
05B	1 (T)	6	-51.2	-6.5	6%	X		0.93783	0.03109	0.031085		10.01
05B	1 (T)	7	-50.8	-9.4	10%	X		0.915822	0.04209	0.042089		13.51
05B	1 (T)	8	-50.7	-9.1	10%	117.2	1,020,383	0.917958	0.04102	0.041021	10.29	13.17
05B	1 (T)	9	-51.9	-9	9%	93.8	1,034,185	0.918677	0.04066	0.040662	8.97	13.06
05B	1 (T)	10	-50.8	-8.8	9%	X		0.920125	0.03994	0.039938		12.83
05B	1 (T)	11	-49.7	-9.5	8%	87.5	1,042,095	0.915117	0.04244	0.042442	8.78	13.63
05B	1 (T)	12	-51.2	-5.4	8%	87.8	1,009,618	0.94704	0.02648	0.02648	7.12	8.53
05B	1 (T)	13	-51.1	-9	8%	86.9	1,038,414	0.918677	0.04066	0.040662	8.6	13.06
05B	1 (T)	14	-48.6	-3.2	5%	90.3	0.991545	0.967035	0.01648	0.016483	5.84	5.32
05B	1 (T)	15	-52.5	-7.6	8%	76.6	1,033,027	0.929112	0.03544	0.035444	7.59	11.4
05B	1 (T)	16	-56.3	-8.6	8%	98.4	1,028,280	0.921587	0.03921	0.039207	9.08	12.6
05B	1 (T)	17	-54.9	-2.5	8%	135.2	0.95858	0.973846	0.01308	0.013077	7.98	4.23
05B	1 (T)	18	-53.2	-3.8	5%	97.4	0.992373	0.961368	0.01932	0.019316	6.61	6.23
05B	1 (T)	19	-49.9	-8.8	10%	97	1,030,670	0.920125	0.03994	0.039938	9.08	12.83
05B	1 (T)	20	-49.7	-6.3	10%	133.7	0.989855	0.939467	0.03027	0.030266	10.01	9.74
05B	1 (T)	21	-51.3	-9	10%	134.1	1,008,847	0.918677	0.04066	0.040662	11.2	13.06
05B	1 (T)	22	-55.8	-8.6	8%	81	1,038,715	0.921587	0.03921	0.039207	8.16	12.6

05B	1 (T)	23	-52.0	-8.7	8%	96.1	1,030,443	0.920854	0.03957	0.039573	9	12.71
05B	1 (T)	25	-56.7	-6.1	8%	131	0.990086	0.941121	0.02944	0.02944	9.76	9.48
05B	1 (T)	26	-60.9	-9.7	8%	85.2	1,045,192	0.913716	0.04314	0.043142	8.7	13.85
05B	1 (T)	27	-62.0	-9.2	10%	132.3	1,011,407	0.917243	0.04138	0.041379	11.17	13.29
05B	1 (T)	28	-62.6	-5.7	8%	92.6	1,009,380	0.944478	0.02776	0.027761	7.51	8.94
05B	1 (T)	29	-58.9	-7	10%	131.5	0.996359	0.933809	0.0331	0.033096	10.22	10.65
05B	1 (T)	30	-54.5	-1.6	8%	131.8	0.953089	0.982905	0.00855	0.008547	7.15	2.76
05B	1 (T)	31	-51.7	-5.6	5%	108.9	0.976611	0.97286	0.01357	0.01357	6.39	4.38
05B	4	1	-44.5	-5.4	10%	140	0.978997	0.94704	0.02648	0.02648	9.94	8.53
06B	1	1	-54.7	-5.7	10%	148.1	0.975824	0.944478	0.02776	0.027761	10.59	8.94
06B	1	2	-53.1	-6	10%	157.8	0.971318	0.941954	0.02902	0.029023	11.35	9.35
06B	1	3	-54.1	-5.9	8%	112.1	1.000026	0.942791	0.02861	0.028605	8.61	9.21
06B	1	4	-53.5	-5.8	8%	104.2	1,003,783	0.943632	0.02818	0.028184	8.15	9.08
06B	1	5	-54.2	-6	10%	158.5	0.970814	0.941954	0.02902	0.029023	11.4	9.35
06B	1	6	-53.3	-5.7	10%	148.6	0.975479	0.944478	0.02776	0.027761	10.62	8.94
06B	1	7	-55.5	-5.3	10%	159.4	0.964606	0.947903	0.02605	0.026049	11.14	8.39
06B	1	8	-50.6	-5.8	8%	106.6	1,002,431	0.943632	0.02818	0.028184	8.27	9.08
06B	1	9	-50.3	-5.8	10%	135.8	0.984787	0.943632	0.02818	0.028184	9.89	9.08
06B	1	10	-50.9	-6.1	10%	137.7	0.9858	0.941121	0.02944	0.02944	10.15	9.48
06B	1	11	-51	-5.4	8%	120.7	0.991211	0.94704	0.02648	0.02648	8.81	8.53
06B	1	12	-50.5	-5.5	10%	137.2	0.981607	0.946182	0.02691	0.026909	9.82	8.67
06B	1	13	-54.6	-5.9	10%	127.7	0.990665	0.942791	0.02861	0.028605	9.47	9.21
06B	1	14	-49.7	-1.6	12%	X		0.982905	0.00855	0.008547		2.76
06B	1	15	-51.6	-5.6	10%	124.9	0.990155	0.945328	0.02734	0.027336	9.16	8.81
06B	1	16	-52.4	-6	10%	123.8	0.993809	0.941954	0.02902	0.029023	9.3	9.35
06B	1	17	-51	-6	10%	124.4	0.993442	0.941954	0.02902	0.029023	9.33	9.35
06B	1	18	-52.5	-6.1	12%	153.9	0.974857	0.941121	0.02944	0.02944	11.15	9.48

06B	1	19	-52.8	-6	12%	153.3	0.974513	0.941954	0.02902	0.029023	11.06	9.35
06B	1	20	-48.9	-5.9	10%	149.6	0.97804	0.942791	0.02861	0.028605	10.62	9.21
06B	1	21	-51.9	-5.9	10%	147.1	0.97804	0.942791	0.02861	0.028605	10.62	9.21
06B	1	22	-51.2	-6	10%	150.5	0.976465	0.941954	0.02902	0.029023	10.88	9.35
06B	1	23	-51.9	-5.9	12%	161.4	0.967924	0.942791	0.02861	0.028605	11.55	9.21
06B	1	24	-50.1	-5.5	12%	161.4	0.96474	0.946182	0.02691	0.026909	11.37	8.67
06B	1	25	-49.5	-6.1	12%	160.4	0.970215	0.941121	0.02944	0.02944	11.57	9.48
06B	1	26	-50.7	-5.9	8%	103.6	1,004,870	0.942791	0.02861	0.028605	8.17	9.21
06B	1	27	-49.7	-6.1	8%	100.5	1,008,104	0.941121	0.02944	0.02944	8.12	9.48
06B	1	28	-50.4	-6.1	8%	109.6	1,002,959	0.941121	0.02944	0.02944	8.59	9.48
06B	1	29	-48.6	-4.9	8%	110.1	0.993676	0.951396	0.0243	0.024302	7.96	7.83
06B	1	30	-51.6	-3.1	8%	139	0.961045	0.967995	0.016	0.016003	8.6	5.17
06B	1	31	-52.9	-5.8	10%	X		0.943632	0.02818	0.028184		9.08
06B	1	32	-51.6	-5.5	8%	X		0.946182	0.02691	0.026909		8.67
06B	1	33	-53.3	-5.8	8%	115.3	0.997413	0.943632	0.02818	0.028184	8.73	9.08
06B	1	34	-50.8	-5.4	10%	145.7	0.975151	0.94704	0.02648	0.02648	10.29	8.53
06B	1	35	-48	-3.8	8%	114.7	0.982575	0.961368	0.01932	0.019316	7.54	6.23
06B	1	36	-48.3	-5.8	8%	87.9	1,012,643	0.943632	0.02818	0.028184	7.34	9.08
06B	1	37	-51.4	-5.7	8%	133.8	0.985321	0.944478	0.02776	0.027761	9.72	8.94
06B	1	38	-53.1	-6.3	10%	142.9	0.983873	0.939467	0.03027	0.030266	10.56	9.74
06B	1	39	-50.7	-3.7	8%	93.1	0.993895	0.962302	0.01885	0.018849	6.33	6.08
06B	1	40	-51.9	-6.5	10%	134.4	0.99088	0.93783	0.03109	0.031085	10.15	10.01
06B	1	41	-51	-1.8	5%	117	0.965084	0.980864	0.00957	0.009568	6.3	3.09
06B	1	42	-53.6	-2.5	8%	131.5	0.961201	0.973846	0.01308	0.013077	7.72	4.23
06B	1	43	-52.7	-1.4	8%	X		0.984961	0.00752	0.00752		2.43
06B	1	44	-48.7	-1.5	8%	132.1	0.951966	0.983931	0.00803	0.008034	7.11	2.6
06B	1	45	-51.2	-5.6	8%	132.5	0.985399	0.945328	0.02734	0.027336	9.59	8.81

06B	1	46	-53.8	-1.8	8%	144.2	0.945433	0.980864	0.00957	0.009568	8.2	3.09
06B	1	47	-53.9	-5.5	10%	X		0.946182	0.02691	0.026909		8.67
06B	1	48	-52.6	-5.4	12%	X		0.94704	0.02648	0.02648		8.53
06B	1	49	-55.4	-5.6	8%	X		0.945327	0.02734	0.027336		8.81
06B	1	50	-54.5	-4.6	10%	X		0.954063	0.02297	0.022969		7.41
06B	1	51	-56.9	-5.9	8%	X		0.942791	0.02861	0.028605		9.21
06B	1	52	-51.1	-5.8	10%	X		0.943632	0.02818	0.028184		9.08
06B	1	53	-54.5	-5.8	12%	X		0.943632	0.02818	0.028184		9.08
06B	G	1	-45.5	-6.2	10%	159.2	0.971855	0.940292	0.02985	0.029854	11.54	9.61
06B	G	2	-47	-6.1	10%	156.9	0.972734	0.941121	0.02944	0.02944	11.34	9.48
06B	G	3	-47.2	-5.3	10%	161.6	0.962969	0.947903	0.02605	0.026049	11.29	8.39
06B	G	4	-44.3	-5.5	10%	165.2	0.961887	0.946182	0.02691	0.026909	11.63	8.67
06B	G	5	-39.2	-4.2	10%	164.1	0.951688	0.95768	0.02116	0.02116	10.97	6.83
06B	G	6	-39.4	-4.9	10%	164.8	0.957207	0.951396	0.0243	0.024302	11.33	7.83
06B	G	7	-44.4	-5.6	8%	213.9	0.920524	0.945328	0.02734	0.027336	15.54	8.81
06B	G	8	-43.4	-5.8	10%	X		0.943632	0.02818	0.028184		9.08
06B	G	10	-49.7	-5.9	10%	155.7	0.972045	0.942791	0.02861	0.028605	11.17	9.21
06B	G	11	-38.2	-5.9	10%	162.9	0.966819	0.942791	0.02861	0.028605	11.65	9.21
06B	G	12	-40.6	-5.6	10%	166.3	0.961866	0.945328	0.02734	0.027336	11.75	8.81
06B	G	13	-41.7	-5.6	10%	156.7	0.96898	0.945328	0.02734	0.027336	11.1	8.81
06B	G	14	-40.7	-6.3	10%	163.7	0.969355	0.939467	0.03027	0.030266	11.88	9.74
06B	G	15	-38.9	-6	10%	158.7	0.97067	0.941954	0.02902	0.029023	11.41	9.35
06B	G	16	-39.1	-5.3	8%	124	0.988452	0.947903	0.02605	0.026049	8.94	8.39
06B	G	17	-37.3	-4.2	8%	X		0.95768	0.02116	0.02116		6.83
06B	G	18	-36.7	-4.4	10%	X		0.955863	0.02207	0.022069		7.12
06B	G	19	-38	-5.7	10%	164.6	0.963959	0.944478	0.02776	0.027761	11.68	8.94
06B	G	20	-39.2	-5.5	10%	147.4	0.97476	0.946182	0.02691	0.026909	10.45	8.67

06B	G	21	-38	-5.9	10%	149.9	0.976117	0.942791	0.02861	0.028605	10.8	9.21
06B	G	22	-36.7	-5.4	10%	154.3	0.969123	0.94704	0.02648	0.02648	10.84	8.53
06B	G	23	-39.5	-6	10%	147.8	0.978322	0.941954	0.02902	0.029023	10.71	9.35
06B	G	24	-37.8	-3.7	10%	157.7	0.952289	0.962302	0.01885	0.018849	10.25	6.08
06B	G	25	-47.3	-5.4	10%	151.1	0.971399	0.94704	0.02648	0.02648	10.64	8.53
26D	A	1	-41.1	-2.5	10%	135.8	0.958148	0.973846	0.01308	0.013077	8.02	4.23
26D	A	2	-46.9	-2.2	10%	129.5	0.96002	0.976829	0.01159	0.011585	7.39	3.74
26D	A	3	-47.5	-2.5	8%	136.1	0.957932	0.973846	0.01308	0.013077	8.04	4.23
26D	A	4	-47.3	-2.7	8%	X		0.971878	0.01406	0.014061		4.54
26D	A	5	-46.9	-3.8	8%	122.2	0.977997	0.961368	0.01932	0.019316	7.97	6.23
26D	A	6	-44.5	-2.4	7%	147.6	0.948366	0.974836	0.01258	0.012582	8.81	4.07
26D	A	7	-45.9	-2.3	10%	106.1	0.975894	0.97583	0.01209	0.012085	6.01	3.91
26D	A	8	-46.5	-2.5	7%	150	0.9474	0.973846	0.01308	0.013077	9.05	4.23
26D	A	9	-47.5	-2.6	7%	152	0.94674	0.97286	0.01357	0.01357	9.26	4.38
26D	A	10	-39	-3.6	9%	151.3	0.95633	0.963239	0.01838	0.01838	9.74	5.93
26D	A	11	-40.2	-3.2	6%	143.4	0.958723	0.967035	0.01648	0.016483	8.96	5.32
26D	A	13	-40.9	0.4	10%	138.4	0.930233	1	0	0	6.8	0
26D	A	14	-38.4	-3.3	8%	136.8	0.964297	0.966079	0.01696	0.01696	8.57	5.48
26D	A	15	-48.1	-2.3	8%	124.9	0.964034	0.97583	0.01209	0.012085	7.16	3.91
26D	A	16	-44.9	-2.3	8%	161.7	0.935737	0.97583	0.01209	0.012085	9.88	3.91
26D	A	17	-44.7	-2.2	10%	139.2	0.952988	0.976829	0.01159	0.011585	8.07	3.74
26D	F	1	-39.1	-2.3	10%	172.5	0.925997	0.97583	0.01209	0.012085	10.82	3.91
26D	F	2	-38.8	-0.6	8%	146	0.932132	0.993309	0.00335	0.003346	7.64	1.08
26D	F	3	-40.4	-1.9	10%	164.5	0.929137	0.979849	0.01008	0.010075	9.93	3.26
26D	F	4	-38.5	-2	8%	X		0.978839	0.01058	0.010581		3.42
26D	F	5	-45.8	-2.2	10%	162.8	0.933762	0.976829	0.01159	0.011585	9.93	3.74
26D	F	7	-36.9	-2.1	8%	148.2	0.945076	0.977832	0.01108	0.011084	8.69	3.58

26D	F	8	-34.5	-2.2	10%	158	0.937927	0.976829	0.01159	0.011585	9.52	3.74
26D	F	9	-34.8	-1.7	7%	X		0.981883	0.00906	0.009059		2.93
26D	F	10	-44.6	-0.7	5%	114.1	0.957743	0.992256	0.00387	0.003872	5.27	1.25
26D	F	11	-40.9	-0.1	8%	161.2	0.91245	0.998565	0.00072	0.000718	8.8	0.23
26D	F	12	-38.8	-2	10%	195.2	0.89944	0.978839	0.01058	0.010581	12.96	3.42
26D	F	13	-42.7	-1.7	20%	296.4	0.74027	0.981883	0.00906	0.009059	28.01	2.93
26D	F	14	-38.7	-2	10%	196.3	0.898222	0.978839	0.01058	0.010581	13.07	3.42
26D	F	15	-40.5	-0.6	20%	303.4	0.697204	0.993309	0.00335	0.003346	30.92	1.08
26D	F	16	-37.3	-1.6	10%	164.1	0.926322	0.982905	0.00855	0.008547	9.76	2.76
26D	F	17	-38.3	-1.9	10%	191.5	0.902246	0.979849	0.01008	0.010075	12.54	3.26
26E	5	1	-39.9	-2.2	10%	184.3	0.913388	0.976829	0.01159	0.011585	11.89	3.74
26E	5	2	-39.4	-2.2	10%	175.7	0.921883	0.976829	0.01159	0.011585	11.07	3.74
26E	5	3	-37.5	-2.1	10%	183.8	0.912741	0.977832	0.01108	0.011084	11.81	3.58
26E	5	4	-38.4	-1.9	10%	187.2	0.906851	0.979849	0.01008	0.010075	12.09	3.26
26E	5	5	-36.8	-2.1	8%	146.1	0.946751	0.977832	0.01108	0.011084	8.53	3.58
26E	5	6	-43.9	-2.1	8%	141.7	0.950181	0.977832	0.01108	0.011084	8.19	3.58
26E	5	7	-37.4	-2.2	8%	140.3	0.952159	0.976829	0.01159	0.011585	8.15	3.74
26E	7	1	-41.5	-2.5	8%	141.7	0.953809	0.973846	0.01308	0.013077	8.43	4.23
26E	7	2	-43.8	-2.3	8%	124.6	0.964236	0.97583	0.01209	0.012085	7.14	3.91
26E	7	4	-39.7	-2.6	7%	X		0.97286	0.01357	0.01357		4.38
26E	7	5	-41.3	-2.7	10%	156.5	0.944037	0.971878	0.01406	0.014061	9.66	4.54
26E	7	6	-39.7	-2.6	10%	X		0.97286	0.01357	0.01357		4.38
26E	7	7	-41.6	-2.5	8%	125.8	0.965109	0.973846	0.01308	0.013077	7.35	4.23
26E	7	8	-42.8	-1.7	5%	126.4	0.95786	0.981883	0.00906	0.009059	6.84	2.93
26E	7	9	-38.6	-2.7	8%	145	0.953114	0.971878	0.01406	0.014061	8.79	4.54
26E	8	5	-48.4	-1.1	8%	141	0.941312	0.98807	0.00597	0.005965	7.53	1.93
26E	8	6	-42.6	-2.9	8%	141.4	0.957575	0.969928	0.01504	0.015036	8.65	4.86

26E	8	7	-43.3	-2.8	8%	129.1	0.965397	0.970901	0.01455	0.01455	7.76	4.7
26E	8	11	-44.2	-2.8	8%	137.7	0.959391	0.970901	0.01455	0.01455	8.33	4.7
26E	8	12	-42.2	-2.5	8%	142.2	0.953433	0.973846	0.01308	0.013077	8.47	4.23
26E	8	13	-44.8	-2.7	10%	158.8	0.942136	0.971878	0.01406	0.014061	9.84	4.54
26E	8	16	-40.8	-3	10%	151.6	0.950747	0.968959	0.01552	0.015521	9.44	5.01
26E	8	17	-47.9	-2.7	10%	155.1	0.945179	0.971878	0.01406	0.014061	9.55	4.54
26E	8	19	-42.2	-3	10%	184.8	0.921825	0.968959	0.01552	0.015521	12.2	5.01
26E	8	20	-41.8	-2.5	10%	154.2	0.944016	0.973846	0.01308	0.013077	9.37	4.23
26E	8	24	-42.4	-2.8	8%	124.9	0.968204	0.970901	0.01455	0.01455	7.49	4.7
28D	G	1	-50.7	-8.8	10%	123.7	1,014,123	0.920125	0.03994	0.039938	10.54	12.83
28D	G	2	-59.9	-18	20%	X		0.865191	0.06741	0.067405		21.51
28D	G	3	-56	-6.4	5%	X	1,039,794	0.938647	0.03068	0.030677	5.59	9.88
28D	G	4	-57.8	-6.6	5%	X	1,041,225	0.937018	0.03149	0.031491	5.7	10.14
28D	G	7	-56.7	-6	8%	100.2	1,007,517	0.941954	0.02902	0.029023	8.05	9.35
28D	G	8	-58.5	-3.8	7%	X		0.961368	0.01932	0.019316		6.23
28D	G	9	-57.5	-7	10%	142.5	0.989273	0.933809	0.0331	0.033096	10.86	10.65
28D	G	10	-55	-8	12%	179.4	0.970366	0.926058	0.03697	0.036971	13.61	11.88
28D	G	11	-56.9	-7.5	5%	59.5	1,041,657	0.929886	0.03506	0.035057	6.71	11.27
28D	G	12	-58.6	-4.4	5%	77.1	1,007,290	0.955863	0.02207	0.022069	6.03	7.12
28D	G	13	-57.9	-6.4	10%	125.2	0.995904	0.938647	0.03068	0.030677	9.58	9.88
28D	G	14	-57.5	-5.5	10%	125.4	0.989097	0.946182	0.02691	0.026909	9.13	8.67
28D	G	15	-59.4	-8.1	10%	125.6	1,007,946	0.925304	0.03735	0.037348	10.37	12.01
28D	G	16	-58.2	-6.1	5%	70	1,024,261	0.941121	0.02944	0.02944	6.64	9.48
28D	G	17	-54.9	-5.9	8%	129	0.989855	0.942791	0.02861	0.028605	9.54	9.21
28D	G	18	-58.4	-6.1	5%	73	1,022,732	0.941121	0.02944	0.02944	6.78	9.48
28D	G	19	-55.5	-2.4	10%	X		0.974836	0.01258	0.012582		4.07
28D	G	20	-52	-2.7	5%	56.2	1,003,582	0.971878	0.01406	0.014061	3.96	4.54

28D	G	21	-47	-7.4	5%	61.2	1,039,846	0.930662	0.03467	0.034669	6.76	11.15
28D	G	22	-48.8	-5.4	5%	62.5	1,022,236	0.94704	0.02648	0.02648	5.96	8.53
28D	G	23	-51.4	-4.7	8%	115.3	0.989137	0.95317	0.02342	0.023415	8.12	7.55
28D	G	24	-48.2	-8.1	8%	63	1,044,995	0.925304	0.03735	0.037348	7.07	12.01
28D	G	25	-50.7	-4.2	8%	132	0.974892	0.95768	0.02116	0.02116	8.79	6.83
28D	G	26	-48.9	-7.5	10%	127.7	1,002,343	0.929886	0.03506	0.035057	10.23	11.27
28D	G	27	-57	-5.2	5%	79.3	1,012,417	0.948769	0.02562	0.025615	6.61	8.26
28D	G	28	-46.6	-9.6	10%	113	1,026,691	0.914415	0.04279	0.042793	10.22	13.74
28D	G	29	-47.9	-10.1	10%	113.8	1,029,834	0.910954	0.04452	0.044523	10.42	14.29
28D	G	30	-47.5	-8.1	10%	139.4	0.99913	0.925304	0.03735	0.037348	11.15	12.01
28D	G	31	-59.2	-4.7	5%	80.7	1,007,840	0.95317	0.02342	0.023415	6.38	7.55
28D	G	32	-49.2	-7.6	10%	141.8	0.994034	0.929113	0.03544	0.035444	11.08	11.4
28D	G	33	-55.5	-7.4	8%	113.8	1,010,105	0.930662	0.03467	0.034669	9.42	11.15
28D	G	34	-56	-7.5	10%	140.7	0.994043	0.929886	0.03506	0.035057	10.97	11.27
28D	G	35	-58.2	-8.7	10%	122.4	1,014,233	0.920854	0.03957	0.039573	10.43	12.71
28D	G	36	-48.4	-6.1	8%	84.5	1,016,761	0.941121	0.02944	0.02944	7.33	9.48
28D	G	37	-58.9	-5.9	8%	85.3	1,014,785	0.942791	0.02861	0.028605	7.27	9.21
28D	G	38	-57.6	-10.3	5%	X		0.909592	0.0452	0.045204		14.5
28D	B	1	-45.1	-6.4	10%	184.6	0.953992	0.938647	0.03068	0.030677	13.38	9.88
28D	B	2	-51	-5.9	10%	X		0.942791	0.02861	0.028605		9.21
28D	B	3	-48.9	-4.1	20%	X		0.958595	0.0207	0.020702		6.68
28D	B	4	-51.6	-2.3	8%	X		0.97583	0.01209	0.012085		3.91
28D	B	5	-52.8	-3.2	9%	X		0.967035	0.01648	0.016483		5.32
28D	B	6	-49	-6.5	10%	136.6	0.98947	0.93783	0.03109	0.031085	10.28	10.01
28D	B	7	-51	-2.9	5%	112.8	0.97665	0.969928	0.01504	0.015036	6.83	4.86
28D	B	8	-54	-2.6	5%	111.5	0.975051	0.97286	0.01357	0.01357	6.54	4.38
28D	B	9	-51.5	-5.6	12%	X		0.945328	0.02734	0.027336		8.81

28D	B	10	-47.2	-6.9	10%	135.7	0.992966	0.934605	0.0327	0.032698	10.41	10.52
28D	B	11	-52	-4.2	8%	126.8	0.978247	0.95768	0.02116	0.02116	8.48	6.83
28D	K	1	-51.8	-4.3	8%	129.6	0.977242	0.956769	0.02162	0.021615	8.71	6.97
28D	K	2	-56.4	-2.5	5%	112.9	0.973398	0.973846	0.01308	0.013077	6.55	4.23
28D	K	3	-52	-3.5	5%	100.2	0.988561	0.964181	0.01791	0.017909	6.55	5.78
28D	K	4	-55.7	-4.1	8%	123.4	0.979604	0.958595	0.0207	0.020702	8.22	6.68
28D	K	5	-50.4	-5.6	8%	87.2	1,011,470	0.945327	0.02734	0.027336	7.2	8.81
28D	K	6	-45	-2.6	5%	106.3	0.978142	0.97286	0.01357	0.01357	6.25	4.38
28D	K	7	-46.8	-3.5	10%	X		0.964181	0.01791	0.017909		5.78
28D	K	8	-46.9	-6.3	7%	X		0.939467	0.03027	0.030266		9.74
28D	K	9	-54.4	-6.5	5%	X		0.93783	0.03109	0.031085		10.01
28D	K	10	-48.1	-7.8	8%	X		0.927578	0.03621	0.036211		11.64
28D	K	11	-59.4	-4.9	8%	124.3	0.98523	0.951396	0.0243	0.024302	8.74	7.83
28D	K	12	-57.7	-3.2	5%	108.9	0.981325	0.967035	0.01648	0.016483	6.82	5.32
28D	K	13	-57	-5.2	8%	122.3	0.988735	0.948769	0.02562	0.025615	8.79	8.26
28D	K	14	-49.8	-3.8	5%	90.6	0.995957	0.961368	0.01932	0.019316	6.28	6.23