

Petrography and detrital zircon U-Pb geochronology of sedimentary rocks of the Campo Alegre Basin, Southern Brazil: implications for Gondwana assembly

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Abstract

The Campo Alegre Basin is a volcano-sedimentary sequence covering an area of about 500 km², located at the northeast portion of Santa Catarina state (Brazil), and formed during the late stages of the Neoproterozoic era. Three main stratigraphic units compose this basin, the lowermost of which is the Bateias Formation, corresponding to the pre-volcanic stage. It is characterized by the fanglomeratic sediments at the basin's northern boundary, which were deposited in a fluvial environment and progressively replaced by fluvial sandstones towards the south. Poorly sorted conglomerates and breccias compound the fanglomeratic facies, which comprises angular to subrounded fragments in a matrix ranging from sand fractions to fragments larger than gravel. The ubiquitous presence of volcanogenic and metamorphic fragments in the fanglomeratic facies strongly suggests that the Piên Magmatic Arc and a volcanic manifestation coeval with the earlier stages of the basin formation were important source areas, as well as the basin basement (the Luís Alves Terrane). In this sense, geological, petrographic, and detrital zircon geochronology data are combined in order to interpret the mechanisms that had acted during the deposition of these sedimentary rocks and to constraint the maximum depositional ages of Bateias Formation at ca. ~606 Ma.

KEYWORDS: *Campo Alegre Basin; detrital zircons; provenance; collisional orogeny; volcano-sedimentary basin; U-Pb geochronology.*

INTRODUCTION

Sedimentary provenance studies have long been applied to understand the influence of the sedimentary mechanisms and different tectonic environments involved during the transportation and sedimentation of rock particles, as well as the diversity of source areas and physicochemical transformations (Pettijohn 1975, Dickinson & Suczek 1979, Dickinson *et al.* 1983, Morton & Hallsworth 1999). In the last decades, however, the application of detrital zircon ages spectra has improved the significance of provenance studies, revealing maximum depositional ages and adding time constraints to tectonic settings of sedimentary sequences (Hawkesworth *et al.* 2009, Dickinson & Gehrels 2009, Cawood *et al.* 2013, Moreira *et al.* 2016, Zinconne & Oliveira 2017, Lemos-Santos *et al.* 2019). In the case of transitional basins at Southern Brazil, particularly the Campo Alegre Basin, in the state of Santa Catarina, detrital U-Pb zircon geochronology has the potential of improving time constraints and the comprehension of tectonic settings that acted during the late

stages of the Brasiliano/Pan-African orogenic cycle, during the consolidation of western Gondwana.

The Brasiliano/Pan-African orogenic cycle extended from 900 to 540 Ma (Silva *et al.* 2005), culminating in the amalgamation of western Gondwana, through the collision and marginal deformation of several crustal segments, resulting in the main geological framework of Southeastern Brazil (Brito Neves *et al.* 1999, Basei *et al.* 1998b, 2000, 2008, Cordani *et al.* 2000, 2003, 2009). The complexity of each tectonic unit involved in this cycle can be associated with its own evolutionary process in several scenarios, inserted into diachronic and overlapping events (Hasui 2010). These main units comprise three different Neoproterozoic belts and smaller allochthonous Archean and Paleoproterozoic terranes, coupled with Late Proterozoic basins. In the southern Brazilian states of Santa Catarina and Paraná, the Ribeira and the Dom Feliciano belts, associated with the Curitiba and Luís Alves terranes, characterize the main geological configuration (Fig. 1).

In this region, the Guaratubinha, Campo Alegre (604–598 Ma, Basei *et al.* 1998a) and Corupá volcano-sedimentary basins were formed and filled during the collisional stage of the Curitiba and Luís Alves terranes, followed by the intrusion of several A-type granitic bodies (583–580 Ma, Vlach *et al.* 2011) from the Graciosa Province (Vlach and Gualda 2007). An important epiclastic unit, the Bateias Formation, composed mainly by polymythic conglomerate-types, arkosic sandstones, and lacustrine mudstone (Ebert 1971, Citroni *et al.* 2001), initially filled the Campo Alegre Basin. The presence at the northern boundary of Campo Alegre Basin of conglomerate boulders and pebbles composed mostly by volcanogenic clasts — intermediate

Supplementary material

Supplementary data associated with this article can be found in the online version: [Supplementary Table 1](#).

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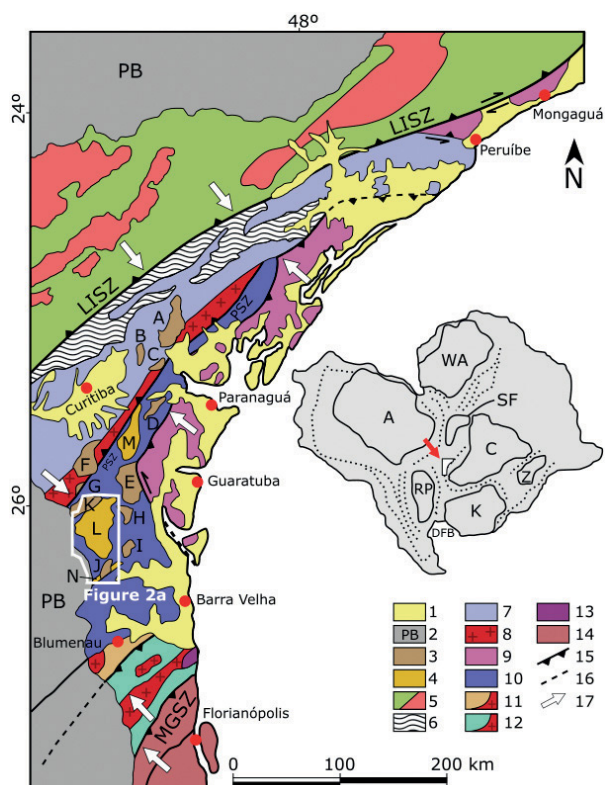


to acid lavas and pyroclastic fragments — strongly suggest an important contribution of Neoproterozoic volcanic sources. In this sense, the Piên Magmatic Arc and/or a volcanic event coeval with the basin's early depositional stages, lacking in the stratigraphic record due to its low preservability, might represent possible source areas.

Based on this information, U-Pb zircon provenance studies, associated with the spatial distribution of the sedimentary sequences within the Campo Alegre Basin, and with the magmatic arc and anorogenic intrusions ages, might lead to important time constraints of the deposition of the Bateias Formation. It also has the potential of constraining the final stages of the assembly processes of the Luís Alves and Curitiba terranes, as the initial filling of the Campo Alegre Basin coincides with the

collisional tectonic scenario (Citroni *et al.* 2001). In this context, provenance studies can be particularly relevant to estimate the maximum depositional ages, and, in this case, might constraint the time involved in this orogenic collage.

Herein, we present geological, petrographic, and new U-Pb laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) detrital zircon data from the sedimentary rocks of the Bateias Formation, and discuss their probable source areas, the early stages of tectonic subsidence and sedimentation of the Campo Alegre Basin, and the regional correlations for the pre-Gondwana paleogeography at this region. To estimate the main source areas, we used a large amount of detrital zircon U-Pb ages and compared them with the main regional events. Additionally, the new data was combined with petrographic analysis and paleo-current data of previous works, which we used to interpret the observed variations as the result of the location of early volcanic manifestations and sedimentary transportation effects throughout the basin sequences.



LISZ: Lincinha Itariri Suture Zone; PSZ: Piên Suture Zone; MGSZ: Major Gercino Suture Zone.

Figure 1. Regional geological map of Southern Brazil between Mongaguá (SP) and Florianópolis (SC) (Basei *et al.* 2009). The main terranes and major structures related to the formation of the Campo Alegre Basin are represented: (1) Cenozoic cover; (2) Paraná Basin sedimentary cover; (3) Graciosa Province — A-type granitoids: (a) Graciosa; (b) Avanhangava; (c) Marumbi; (d) Serra da Igreja; (e) Morro Redondo; (f) Palermo; (g) Agudos do Sul; (h) Dona Francisca; (i) Pirai; (j) Corupá; (k) Rio Negro; (4) non-deformed volcano-sedimentary basins: (l) Campo Alegre; (m) Guaratubinha; (n) Corupá; (5) low-grade metasediments (green) and major calc-alkaline batholiths (red). Curitiba Terrane: (6) Capiçu and Setuva metasedimentary covers; (7) Atuba Complex; (8) Piên Batholith, deformed arc-related calc-alkaline granitoids; (9) Paranaguá batholith; (10) Luís Alves Terrane, high-grade metamorphic rocks. Dom Feliciano Belt: (11) Itajaí foreland basin and Subida granite; (12) Brusque schist belt and intrusive granitoids; (13) Basement inlier, gneisses and migmatites of the Camboriú Complex; (14) Florianópolis Batholith, arc-related granitoids; (15) Major thrust faults; (16) inferred geological contacts; (17) Neoproterozoic tectonic transport.

GEOLOGICAL SETTINGS

The Campo Alegre Basin overlies high-grade metamorphic rocks of the Paleoproterozoic Luís Alves Terrane, and it is adjacent to the Neoproterozoic Piên Magmatic Arc. Both the basin's initial subsidence and the filling process have been associated with convergent tectonics, which resulted in the collage between the Luís Alves and Curitiba terranes and the emplacement of the Piên Magmatic Arc, during the Brasiliano/Pan-African orogenic cycle (Citroni *et al.* 2001). Although the sedimentary infill of the basin is most likely a reflection of its subsidence in the Neoproterozoic, older sedimentary sequences covering the Paleoproterozoic Luís Alves Terrane may also be associated, and can, therefore, be recognized by means of provenance studies. The understanding of the tectonic relationship and mutual evolution between these sedimentary sequences and the regional domains is necessary to elucidate possible source areas for the detrital zircon grains, as well as to explain the generation and earlier subsidence stages of this basin during the Brasiliano orogenic cycle. In this sense, this section briefly describes the geological and geochronological background in which the Campo Alegre Basin is inserted and the most recent tectonic evolution model.

Crystalline Basement

The Luís Alves Terrane comprises Archean and Paleoproterozoic rocks from the Santa Catarina Granulitic Complex (2800–1700 Ma), as well as Neoproterozoic units represented by volcano-sedimentary basins (600–590 Ma), and late granitic intrusions (583–580 Ma) from the Graciosa Province (Basei 1985, Siga Jr. 1995, Basei *et al.* 1998b, 1999, 2000, Harara 2001, Vlach *et al.* 2011). The Santa Catarina Granulitic Complex represents the basement of the Luís Alves Terrane, and it is characterized by a number of different lithotypes, with the predominance of migmatites and orthogneisses with mafic and quartz-feldspathic alternated bands, affected by granulitic metamorphic facies, and some

mafic and metasedimentary contributions (Basei *et al.* 1998b). The Santa Catarina Granulitic Complex has a long multi-event evolution, constrained by numerous geochronological methods, as summarized in Table 1.

Overlying the Luis Alves Terrane, there are four important Neoproterozoic volcano-sedimentary basins: the Campo Alegre, Corupá, Guaratubinha, and Itajaí basins. The latter is a foreland basin located in the terrane's southern boundary, while the formers, located in the northern boundary, are characterized by extensional tectonics, resulting in mechanical

subsidence during the initial infilling stage. Those extensional basins are very similar, and are characterized by an epiclastic basal unit, comprehending conglomerates and arkosean sediments, covered by a thick volcanic pile composed mainly of intermediate to acid volcanic and volcanoclastic rocks (Citroni *et al.* 2001, Basei *et al.* 2009, Passarelli *et al.* 2018).

Anorogenic alkaline-peralkaline granitic bodies from the Serra do Mar Suite also constitute important Neoproterozoic components at this region (590–550 Ma), including several scattered oval-shaped plutons, and aligned parallel to the

Table 1. Compilation of the main geochronological constraints in the Campo Alegre region.

Event	Characteristics	Methods	Age (Ga)	References
Piên Ultramafic Suite				
<i>Mafic emplacement</i>	Tholeiitic gabbro	U-Pb in zircon (SHRIMP)	0.632–0.618	Harara (2001), Harara <i>et al.</i> (2004)
Piên Magmatic Arc				
<i>Pre-collisional granites</i>	Calc-alkaline granites	U-Pb in zircon	0.620–0.615	Harara (2001)
<i>Syn-collisional granites</i>	Calc-alkaline granites	U-Pb in zircon	0.615–0.610	Harara (2001)
<i>Collisional gap</i>	Cooling at the collision zone	K-Ar in mineral	0.607–0.598	Harara (2001), Harara <i>et al.</i> (2004)
Graciosa Province				
<i>Granitic magmatism</i>	A-type granitic bodies	U-Pb in zircon	0.583–0.580	Vlach <i>et al.</i> (2011)
Volcano-sedimentary basins				
<i>Volcanism</i>	Felsic volcanism	U-Pb in zircon	0.604–0.598	Basei <i>et al.</i> (1998a)
Santa Catarina Granulite Complex				
<i>Local Reactivation</i>	Near contact with adjacent terranes, internal faults	K-Ar in mineral	0.660–0.620	Siga Jr. (1995)
<i>Tectonic Stabilization</i>	Regional cooling	K-Ar in mineral	1.80–1.70	Girardi <i>et al.</i> (1974), Hartmann <i>et al.</i> (1979), Machiavelli (1991), Siga Jr. (1995), Harara (2001)
<i>Retrograde metamorphism</i>	Retrometamorphism at the upper crust	U-Pb in mineral	2.00–1.90	Basei (1985), Siga Jr. (1995)
<i>Amphibolite-facies regional metamorphism</i>	Metamorphism at the middle crust	Pb-Pb, Rb-Sr WR isochrons, U-Pb in mineral, Sm-Nd mineral isochrons	2.10–2.00	Girardi <i>et al.</i> (1974), Machiavelli (1991), Basei (1985), Basei <i>et al.</i> (1998b, 1999, 2000), Harara (2001)
<i>Granulite-facies event</i>	Felsic granulite at the middle crust	U-Pb in zircon (SHRIMP)	2.17	Hartmann <i>et al.</i> (2000)
<i>Magmatism</i>	Intrusion of deformed granitoids	U-Pb in zircon (SHRIMP)	2.25–2.15	Siga Jr. (1995), Basei <i>et al.</i> (2009)
<i>Granulite-facies regional metamorphism</i>	Development of orthopyroxene in many rocks	U-Pb zircon, Sm-Nd mineral isochron	2.35	Siga Jr. (1995), Basei <i>et al.</i> (1998b, 2009)
<i>Mantle/crust differentiate</i>	Addition of mantle-derived material to the crust	Sm-Nd T _{DM}	2.40–2.30	Siga Jr. (1995), Hartmann <i>et al.</i> (1998)
<i>Amphibolite-facies event</i>	Felsic granulite	U-Pb in zircon (SHRIMP)	2.48	Siga Jr. (1995), Harara (2001)
<i>Magmatism</i>	Intrusion of igneous rocks	Rb-Sr WR isochrons	2.60	Basei (1985), Harara (2001)
<i>Granulite-facies event</i>	middle crust felsic granulite	U-Pb in zircon (SHRIMP)	2.68	Hartmann <i>et al.</i> (1979, 2000)
<i>Magmatism</i>	TTG igneous activity	U-Pb in zircon (SHRIMP), Rb-Sr WR isochrons	2.70	Siga Jr. (1995), Hartmann <i>et al.</i> (2000)
<i>Mantle/crust differentiation</i>	Addition of mantle-derived material to the crust	SM-Nd T _{DM}	3.40?; 2.8–2.7	Basei (1985), Siga Jr. (1995), Harara (2001)

TTG: tonalite-trondjemite-granodiorite; SHRIMP: sensitive high mass-resolution ion microprobe; WR: whole rock.

modern Brazilian coastline (Kaul 1984, Passarelli *et al.* 2018). Those intrusions, posteriorly classified as Graciosa Province (Vlach & Gualda 2007), represent anorogenic granites and syenites (A-type), associated to a post-collisional extensional environment after the climax of the Brasiliano/Pan-African orogeny. These intrusions were emplaced at shallow crustal levels, in connection with transcurrent displacements along the NE-SW trend of major shear zones (Kaul 1984, Vlach & Gualda 2007). Nonetheless, they are mostly isotropic, not recording widespread deformation. They intrude different domains, as the Luís Alves Terrane, the Curitiba Terrane, and in the Piên Magmatic Arc. The volcano-sedimentary basins and the Graciosa Province are usually interpreted as contemporaneous igneous manifestations (Gualda & Vlach 2007), and should be interpreted in the evolutionary tectonic context of the Campo Alegre Basin.

The Curitiba Terrane is located north of the Luís Alves Terrane, limited by the Lancinha-Cubatão shear zone to the north and the Serra do Azeite shear zone, to the south, where it is adjacent to the Piên Magmatic Arc (Faleiros *et al.* 2011, Passarelli *et al.* 2018). The Curitiba Terrane comprehends three major components, represented by the Atuba Complex, composed by a tonalite-trondhjemite-granodiorite (TTG) type migmatitic orthogneiss suite, and the Capiuru and Turvo-Cajati formations, composed by Neoproterozoic shallow continental-shelf metasedimentary assemblages. All units from the Curitiba Terrane have been strongly metamorphosed during the Neoproterozoic orogenic collision. However, the Atuba Complex also comprehends Archaean, Rhyacian, and Statherian inherited zircon cores that recorded previous orogenic cycles (Faleiros *et al.* 2011).

The contact between the Luís Alves and Curitiba terranes occurs along the Piên shear zone, an NE-SW oriented suture zone that defines an important regional tectonic trend. It comprehends the calc-alkaline Piên Magmatic Arc and the Piên Ultramafic Suite (Siga Jr. 1995, Harara 2001). This tectonic configuration results from the closure of the Adamastor Ocean, in a context of plate subduction from southeast to northwest underneath the Curitiba Terrane — based on the actual distribution. In this context, the Piên-Maribituba Granitoid Belt was emplaced during subduction as a magmatic arc at the southern boundary of the Curitiba Terrane, and its emplacement started at the accretionary stage of the orogeny (620–615 Ma) lasting until the collision (615–610 Ma). Also as a product of Adamastor's ocean closure, the Piên Ultramafic Suite might represent an oceanic plate fragment, tectonically emplaced along the suture zone (Basei *et al.* 2000, Harara 2001). The main regional geological events mentioned above and its geochronological constraints are summarized in Table 1.

Campo Alegre Basin

Over the past years, the Campo Alegre Basin was described and interpreted from many different viewpoints. The volcanogenic rocks were first described by Almeida (1949), which interpreted these sequences as an Eopaleozoic unit, comparable to the acid volcanic rocks from Itajaí Basin. Later, due to compositional similarities and geographical

proximity, this sequence was grouped with the acid volcanic rocks from the Guaratubinha Basin, initially defined as the Guaratubinha Formation (Fuck *et al.* 1967, Trein *et al.* 1969). Albuquerque *et al.* (1971) were the first to recognize the relationship between the epiclastic sequences and the volcanogenic rocks of the Campo Alegre Basin, thus establishing the first version of the basin's boundaries, though still as part of the Itajaí Basin.

Based on the inclusion of these distinct sequences into the Campo Alegre Basin, the first detailed stratigraphic section defined:

- the Bateias Formation, composed mainly by the basal conglomerates and arkoses;
- the Campo Alegre and the Rio Turvo formations, which comprises the volcanogenic sequences.

In this conception, the Campo Alegre Basin was considered disconnected from the Itajaí Basin, but it was still correlated with the closest volcano-sedimentary basins, the Guaratubinha and Corupá basins (Ebert 1971). From prospective data obtained during economic researches, a more detailed stratigraphic perspective of the Campo Alegre Basin recognized five depositional sequences formed at distinct moments, which corresponds to the Bateias Formation and four different volcanogenic sequences (Daitx 1979a, 1979b, Daitx & Carvalho 1981).

Despite these variations in the literature, all authors agree that the basin's stratigraphy comprises an initial epiclastic unit overlapped by a thick bi-modal volcanogenic sequence. The volcanogenic sequence comprehends felsic and subordinated mafic rocks, associated with pyroclastic and epiclastic sediments. More recently, Citroni *et al.* (2001) recognized three main different fill stages for the basin (Fig. 2A):

1. the pre-volcanic sediments;
2. the volcanic sequences;
3. the caldera stage.

Each of these stages records a specific tectonic context during the basin's development and evolution. Figure 2B represents the stratigraphic column of the main units from the Campo Alegre Basin, including their estimated thickness.

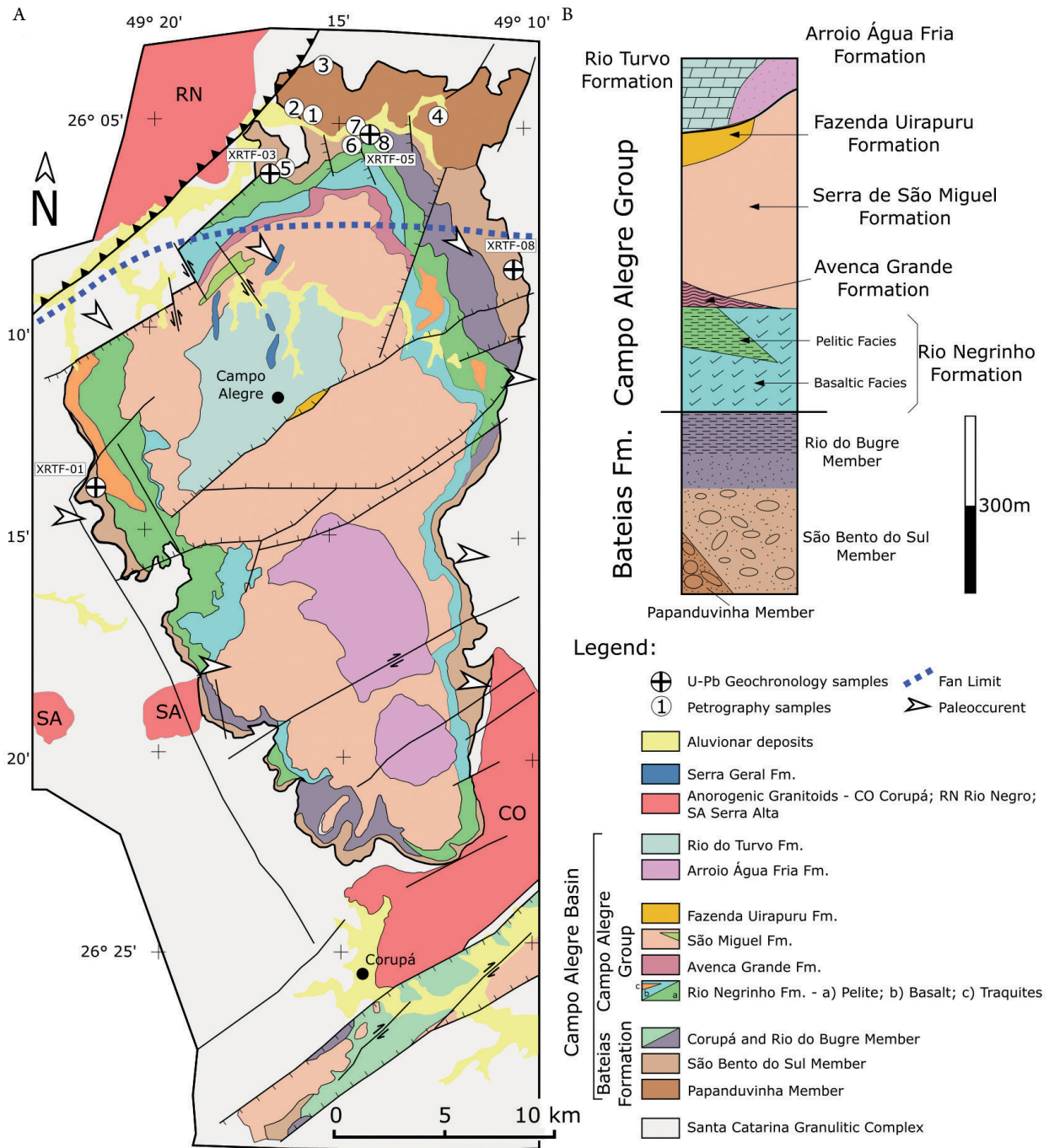
The pre-volcanic stage corresponds to the main initial stage and formation of the basin, grouping epiclastic into the Bateias Formation. This formation can be subdivided into three members, which are:

- Papanduvinha Member, composed by polymythic matrix-supported conglomerates;
- São Bento do Sul Member, composed by polymythic clast-supported conglomerates with some intercalated arkose sandstone lenses;
- Rio do Bugre Member, composed mainly by arkose sandstones and subordinated pelitic levels (Citroni *et al.* 2001).

As it represents the first depositional unit, the Bateias Formation outcrops are mainly restricted to the basin boundaries and are more expressive at the northern region, in direct contact with the basement rocks (Figs. 3A and 3B).

During the collision between the Luís Alves and the Curitiba terranes (ca. 605 Ma — Harara 2001), the regional stress regime resulted in a major extensional component orthogonal to the principal stress. This strain arrangement probably resulted in the uplift of the northwest boundary of the basin by reverse faults (Fig. 2A), and the generation

of roughly NW-SE oriented normal faults. Thus, the earlier stages of sedimentary deposition took place in a high-energy environment, resulting in polymythic conglomerates (Figs. 3B, 3C and 3D) especially closest to the northern boundaries, which have acted as the main source area for the epiclastic unit. Consequently, the basin subsidence was initiated



Fm.: formation.

Figure 2. (A) Geological map of the Campo Alegre Basin (Citroni *et al.* 2001). Note the location of the thrust front and of the samples used for petrographic and provenance studies, mostly from the northern boundary of Campo Alegre Basin. (B) Lithostratigraphic chart of the Campo Alegre Basin. Disposed from bottom to the top are presented: Bateias Formation, formed by Papanduvinha (polymythic matrix-supported conglomerates), São Bento do Sul (polymythic clast-supported conglomerates with some intercalated arkose sandstone lenses) and Rio do Bugre (arkose sandstones and subordinated pelitic levels) members. Campo Alegre Group, formed by Rio Negrinho (basaltic and andesitic lava flows interbedded with pelitic layers), Avenca Grande (varied pyroclastic fragments, lithic clasts, and pyroclastic flows structures), Serra de São Miguel (trachytic to quartz-trachytic lava flows with subordinate rhyolitic and trachyandesitic members, and some pyroclastic occurrences), Fazenda do Uirapuru (coarse-grained breccia) formations. And Arroio Agua Fria (rhyolitic lava flows, ignimbrites, and acid tuffs) and Rio do Turvo (pelitic and turbiditic rocks beside acid lava flows, tuffs, and some ignimbrites) formation (Citroni *et al.* 2001).

by extensional tectonics, and its evolution was probably related to continuous sedimentary load. These events led to the development of a flanglomerate deposit (Papanduvinha Mb.) close to the uplifted region, that progressively evolved into braided rivers (São Bento do Sul Mb. — Fig. 3E) and lacustrine (Rio do Bugre Mb. — Fig. 3F) environments in the distal region at east/southeast, which seem to gradually change (Citroni *et al.* 2001).

The volcanic sequences are gathered into the Campo Alegre Group. It comprises mostly basic rocks at the bottom, typically basalts and andesites, and a majority of acid volcanic and volcanoclastic rocks at the intermediate and upper layers, mostly with rhyolitic composition with minor rhyodacite and dacite components. These rocks are interpreted as two distinct volcanic phases, a mafic and a felsic one, in which the end of each phase is marked by explosive events, thus defining four different formations:

- Rio Negrinho, composed by basic to intermediate rocks;
- Serra de São Miguel, composed by acid lavas and subordinated volcanoclastic rocks;
- Avenca Grande;
- Fazenda Uirapuru, representing the explosive events.

The eruptive events are usually associated with NNW-trending basic and acid dikes, thus constraining the structural control of the basin during the extrusion of the Campo Alegre Group (Citroni *et al.* 2001).

The Rio Negrinho Formation corresponds to the mafic volcanism phase and comprises basaltic and andesitic lava flows (Fig. 3G) interbedded with pelitic layers. There are also rare occurrences of dacites, rhyodacite, and quartz trachytes. The pelitic layers exhibit a laminated structure, indicating a subaqueous depositional environment. A thick pyroclastic package (Fig. 3H) occurs overlying the Rio Negrinho Formation, formed during a first explosive event, corresponding to the Avenca Grande Formation. This unit comprises varied pyroclastic fragments, lithic clasts, and pyroclastic flows structures. The occurrence of these layers represents the transition from basic to silicic compositions (Citroni *et al.* 2001).

The felsic volcanism stage corresponds to the Serra de São Miguel Formation, the thickest formation within the Campo Alegre Group, mainly composed by trachytic to quartz-trachytic lava flows (Fig. 3I), with subordinate rhyolitic and trachyandesitic members, and some pyroclastic



Figure 3. (A) and (B) Field aspects of the metamorphic rocks from the Santa Catarina Granulitic Complex and (C), (D), (E), (F), (G), (H) and (I) of units of the Campo Alegre Basin: (A) folded migmatite; (B) gneiss. Bateias Formation sediments: (C) conglomerate from Papanduvinha member exhibiting clasts of metamorphic protoliths. (D) Clasts of volcanic origin, very similar to volcanic rocks from the Campo Alegre Basin. (E) Sandstones from São Bento do Sul member exhibiting cross-stratification. (F) Stratified phyllite from Rio do Bugre member. (G) Andesite from Rio Negrinho Formation. (H) Lapilli-tuff from Avenca Grande Formation. (I) Trachytic lava flows from Serra de São Miguel Formation. See text for discussion.

occurrences. This unit comprehends a massive layer of acid lavas, formed by magmatic breccia, autoclastic and vitreous fragments at the bottom, and banded lava flows at the top (Citroni *et al.* 2001).

Restricted to the central portion of the basin, the pyroclastic Fazenda Uirapuru Formation comprises coarse-grained breccia, characterized by pyroclastic fragments and xenoliths from the basement and from the pre-erupted volcanic rocks. Citroni *et al.* (2001) interpret the Fazenda Uirapuru Formation as an explosive event, associated with the formation of vitreous lava domes aligned with the E-NE trending-fractures. The authors also interpreted this explosive activity with a probably dipper-subsidence of the northern portion of the Campo Alegre Basin.

The last evolutionary stage comprehends the formation of a caldera structure, related to an explosive event more expressive than the previous events (Avenca Grande and Fazenda Uirapuru formations). The paleogeography conditioned by the caldera allowed the establishment of two different depositional environments:

- extra-caldera;
- intra-caldera.

They correspond to the Arroio Água Fria Formation and the Rio Turvo Formation, respectively. The Arroio Água Fria Formation comprises rhyolitic lava flows, ignimbrites, and acid tuffs, restricted to the southern region of the Campo Alegre Basin. On the other hand, the Rio Turvo Formation was deposited after the thermal subsidence of the caldera, which allowed the establishment of a lacustrine environment at its central portion, restricted to the northern region of the Campo Alegre Basin. Besides pelitic and turbiditic rocks, the Rio Turvo Formation comprises acid lava flows, tuffs, and some ignimbrites.

The subsidence and preservation of these Neoproterozoic basins overlaying pre-Cambrian terranes at Southern Brazil, especially covering the Luís Alves Terrane, are still in debate. However, geophysical results indicate very similar positive gravimetric anomalies over the areas of Campo Alegre and Guaratubinha basins (Hallinan *et al.* 1993), interpreted as regional magmatic underplating. In this sense, the probable installation of a huge magma chamber might be interpreted as the magmatic reservoir for the widespread volcanism present in these basins, while the solidification of this magma chamber could be responsible for their late subsidence.

METHODS

Sampling and sample preparation

Twelve samples from the Bateias Formation were collected for provenance studies and combined compositional and textural maturity analysis of this sedimentary unit, using U-Pb geochronology in detrital zircon and petrographic analysis. Four samples were collected along the northern boundary of the Campo Alegre Basin, for zircon provenance studies, and eight samples were selected for petrography. The samples comprehend the three main members of the formation:

Papanduvinha; São Bento do Sul, and Rio do Bugre. To ensure the sample's representativeness in the conglomerate sequences, zones with coarse-grained clasts were avoided both for petrographic and geochronological studies, prioritizing the matrix or arenitic lens present in the Papanduvinha and São Bento do Sul members. Zircon extraction was carried out in the laboratories of the Institute of Geosciences at the Universidade de São Paulo (IGc-USP), in São Paulo (SP), Brazil, following the usual routines.

After heavy mineral separation, the zircons concentrate selected for U-Pb dating by LA-ICP-MS were organized in 25 mm epoxy mounts, in which 256 zircons randomly selected per sample were organized in 8 by 8 squares, further polished and covered with carbon. Finally, the zircons were imaged by transmitted light to recognize external features such as fractures and inclusions. They were also imaged using cathodoluminescence (CL), in order to point out internal features such as zoning, inherited cores, and metamitic areas. Twelve zircons per sample were selected for analysis of secondary and backscatter electrons, under scanning electron microscopy (SEM), with the aim of examining superficial features that might indicate transportation. In this approach, the zircons were arranged in stubs and covered with gold.

Petrographic analysis

Thin sections were analyzed for textural and compositional studies and imaged in the IGc-USP. The equipment employed was a Carl Zeiss microscope model Axioplan 1, coupled with a Leica Application Suite (LAS) photographic camera. The main point of the petrographic descriptions was to recognize and measure the compositional, textural, and granulometric variability between samples. The criteria used for maturity texture is described by Folk (1951), in addition to the compositional and granulometric classification, also described by Folk (1974). Compositional measurements were performed by the conventional point-counting method (Chayes 1956), resulting in 1,500 points per sample. The obtained compositional and textural results are summarized in Table 2.

Analytical procedures

The U-Pb *in-situ* analysis was performed in the Geochronology Research Center of the IGc-USP, with an inductively coupled plasma (ICP) multi-collector Neptune (Thermo) spectrometer, coupled to a 193 nm Excimer Laser (Photon Machines). Ablation was performed for 40 seconds in a 32 μm spot at the frequency of 6 Hz and intensity of 7 mJ, and the ablated material was carried by Ar (0.7 L/min) and He (0.6 L/min) gas flux. The analytical routine of data acquisition measurements followed the sequence of two blanks, two National Institute of Standards and Technology (NIST)-612, three international standard GJ-1, 13 zircon crystals, two more GJ-1 standards and finally two blanks. To ensure that the zircon population might cover all detrital spectrum and suitability for provenance study, at least 96 zircon analysis were performed per sample, including eventually discarded ages.

The LA-ICP-MS data reduction was performed using SQUID 1.02 (Ludwig 2001), while the Concordia plots

were constructed with the ISOPLOT 4.11 spreadsheet (Ludwig 2003). Analyses with common lead content over 6% and discordance over 10% were discarded. For zircons younger than 1300 Ma, $^{206}\text{Pb}/^{238}\text{U}$ ages were preferred, while for older zircons the $^{207}\text{Pb}/^{206}\text{Pb}$ ages were preferably used. The detrital age distribution by probability density was performed using the Kernel Density Estimation (Vermeesch 2012), in general resulting into two main distributions, marked by a short Neoproterozoic range and a long Paleoproterozoic/Archean extent.

Zircon surface imaging was performed in the scanning electron microscope (SEM) Laboratory of the IGc-USP, using an LEO 440I microscope. For each selected zircon, secondary electron and backscattered electron images were made to compare the principal features in crystal topography surface. Part of the images was generated focusing on the whole crystal with 1.35k to 1.70k magnification, while the other part focusing on smaller details close to grain's tips used 4.50k magnification. Those composite images were used to analyze the surface of the grains and infer possibly abrasion features due to transportation.

RESULTS

Compositional and textural analysis

Samples selected for petrographic analyses, compositional and textural measurements were preferentially collected in sandstone layers and matrix zones of conglomerate outcrops, as well as in the sandstone levels of Rio do Bugre Member. The analyzed sequences represent three main compositional and granulometric groups, which are:

1. sandy gravel lithic arkose;
2. sandy gravel to gravelly sandy arkose from the conglomerate matrix;
3. sand arkose with no rock-fragments.

Regarding their compositional nature, in all samples, it was possible to recognize a high (~66%) and almost constant modal concentration of feldspar grains.

Although lithic-fragments are also an important detrital component, it is considerably less abundant than feldspar grains and is absent in sand samples (Group III). Among the

observed types of lithic fragments, there is a variable content of volcanic, metamorphic (gneissic), and igneous (granitic) clasts (Tab. 2). This signature results from the contribution of contrasting source areas, especially at the northern basin limit, and the contrasting weathering susceptibility of the different rock fragments suggest an almost instantaneous deposition. Chlorite, carbonates, and Fe-oxides represent the most expressive diagenetic components in these rocks, in which evidence of post-depositional weathering are ubiquitous.

Based on the geographic distribution of samples, the compositional and granulometric characteristics exhibit roughly continuous gradational changes. Generally, it is possible to observe an almost continuous decrease in the content of rock fragments between samples placed in the northwest, closest to basin's northern boundary, and samples located to the east and towards the central portion of the basin. Analogously, the compositional decrease in the content of lithic fragments is accompanied by a progressively increase in quartz abundance, in which the samples with no lithic fragments have the highest quartz content and represent the arkose layers present at the uppermost sedimentary pile at the most distal regions (Fig. 4A).

The large variety of grain sizes compounding the sedimentary layers within a restricted area is remarkable, ranging from gravel to sand in the conglomerate matrix. The blend of contrasting grain sizes occurs in different proportions for each sample, though with predominance of the sand fraction, whereas the proportion of fragments in gravel fraction shown decrease towards the basin's interior (Fig. 4B). The compositional and textural characterization, associated with the spatial distribution of analyzed samples, strongly suggests that the sedimentary transportation from the basin was from its northern and northwestern boundaries to its central region, accompanied by an accentuated reworking.

Additionally, among the most common features observed in all of the thin sections, the presence of quartz and feldspar fragments with very low-grade grain sphericity and low-grade roundness is remarkable. Quartz fragments are frequently coarser than feldspar grains and exhibit less spherical boundaries. The samples that represent conglomerate matrixes are commonly poorly sorted, while sandstone samples exhibit a more varied degree of sorting, ranging from

Table 2. Petrographic and compositional aspects of the analyzed samples.

Sample	Rock Name	Detrital Components		
		Q	F	RF
XR 1	Sandy boulder conglomerate: immature lithic arenite	9,17	66,05	24,77
XR 2	Pebbly coarse sand: immature arkose	10,81	66,48	22,70
XR 3	Sandy boulder conglomerate: immature arkose	20,54	65,75	13,39
XR 4	Sandy boulder conglomerate: immature arkose	22,38	65,67	11,94
XR 5	Pebbly coarse sand: immature arkose	16,48	74,72	8,79
XR 6	Well-sorted fine sand: mature arkose	32,25	67,75	-
XR 7	Poorly sorted medium sandstone: sub-mature arkose	32,60	67,40	-
XR 8	Poorly sorted medium sandstone: sub-mature arkose	31,58	68,48	-

Q: quartz; F: feldspar; RF: rock fragments.

poorly to well sorted. The main petrographic and compositional aspects are given in Table 2, and the most common petrographic textural and structural characteristic aspects are shown in Figure 5.

U-Pb geochronology

Samples from the sedimentary sequences were preferably collected along the eastern, northern, and western boundaries of Campo Alegre Basin, considering different localities and stratigraphic levels, which allowed the dating of the sedimentary sequence and disclose important information about earlier

volcanic stages on this basin. Figure 6 presents CL images for each analyzed sample, illustrating the main zircon typologies. As it is typical of sedimentary units, a large variety of morphologies and internal textures of zircon grains can be observed. The zircon grain size usually varies between 100–300 μm, and the most common morphological types include rounded and oval-shaped crystals, associated with rare prismatic occurrences presenting preserved pyramidal terminations. Zircon crystals with pyramidal terminations are typically small (100–150 μm), and are more frequent in the samples closest to the basin border and bottom sequences.

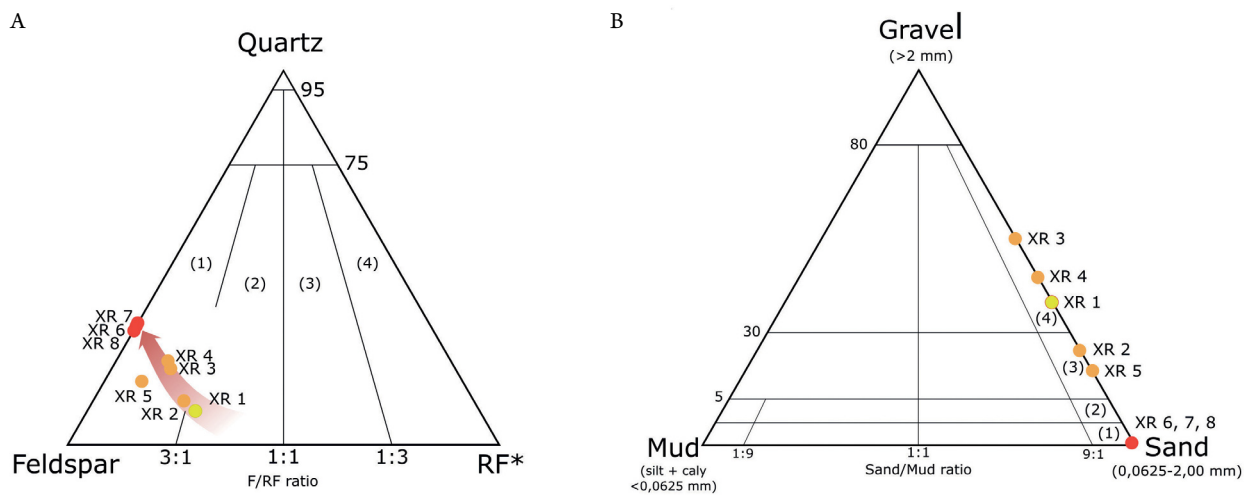


Figure 4. Diagrams of compositional and granulometric classification (Folk 1951, 1974). (A) Diagram of relative quartz, feldspar and rock fragment abundance. Note the tendency observed in the sedimentary rocks of the Bateias Formation, marked by the increase in quartz content (red arrow). Compositional fields: (1) Arkose; (2) lithic arenite; (3) feldspathic litharenite; (4) litharenite. (B) Diagram of textural classification based on the relative abundance of gravel, mud, and sand. Compositional fields: (1) sand; (2) slightly gravelly sand; (3) gravelly sand; (4) sandy gravel.

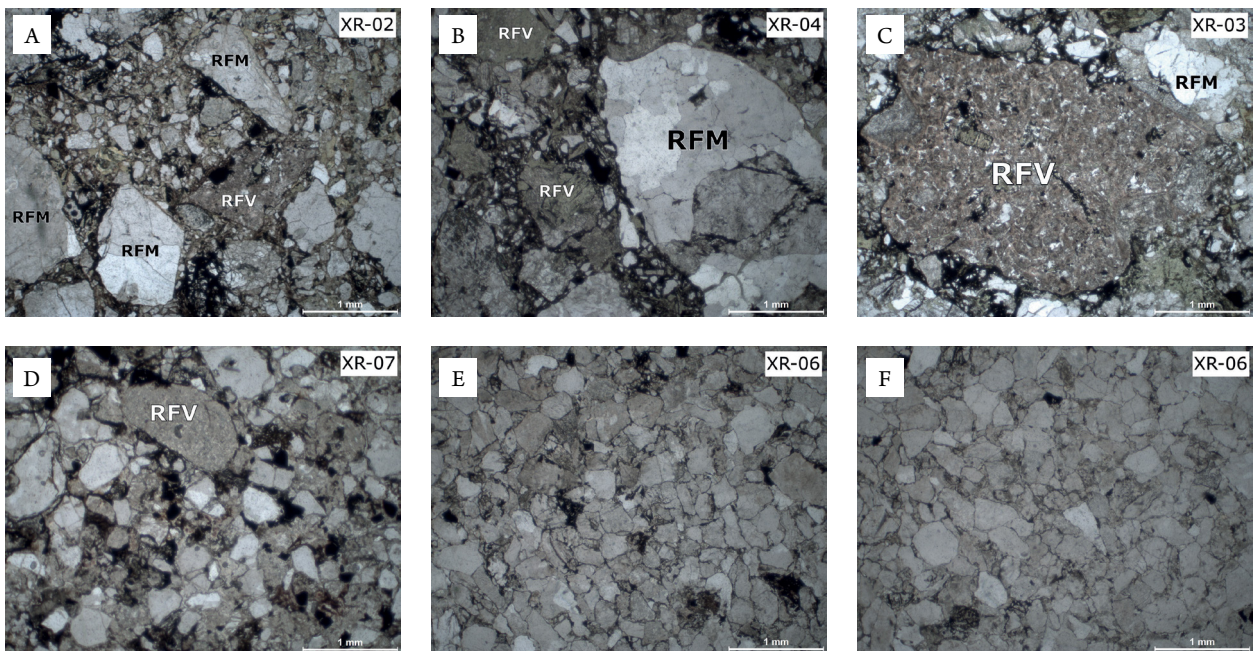


Figure 5. Petrographic aspects of sedimentary rocks from the Bateias Formation. Poorly sorted sandy gravel, composed by low-spherical and low-rounded grains, mainly represented by quartz, feldspars, and rock fragments from (A) metamorphic (RFM) and (B) volcanic (RFV) origin. (C) Detail of a rock fragment of volcanic origin. Note the fine-grained texture and the presence of alkali-feldspar crystals. (D) Detail of a rock fragment of metamorphic origin. Note the presence of smaller fragments of volcanic origin. (E) Very well sorted and (F) well-sorted arkosic sandstones from the Rio do Bugre member, mainly composed of quartz and feldspar. Note the low degree of sphericity and roundness of the main fragments.

Among the most common zircon internal features, it is possible to observe:

- inherited cores;
- overgrowth rims;
- fractures (less frequent);
- rare inclusions, following the classification of Corfu *et al.* (2003).

The analyzed zircon grains are predominantly of metamorphic origin, exhibiting typical internal textures such as

oscillatory and sector zoning. Although zircon crystals with typical igneous zoning are less frequent, they usually occur as overgrowth rims at the surface of metamorphic grains, and as small well-formed crystals. The same typologies of zircon grains can be found in all the analyzed samples, presenting similarities in shape, size distribution, and internal features, differing only in the relative frequency. These similarities might indicate

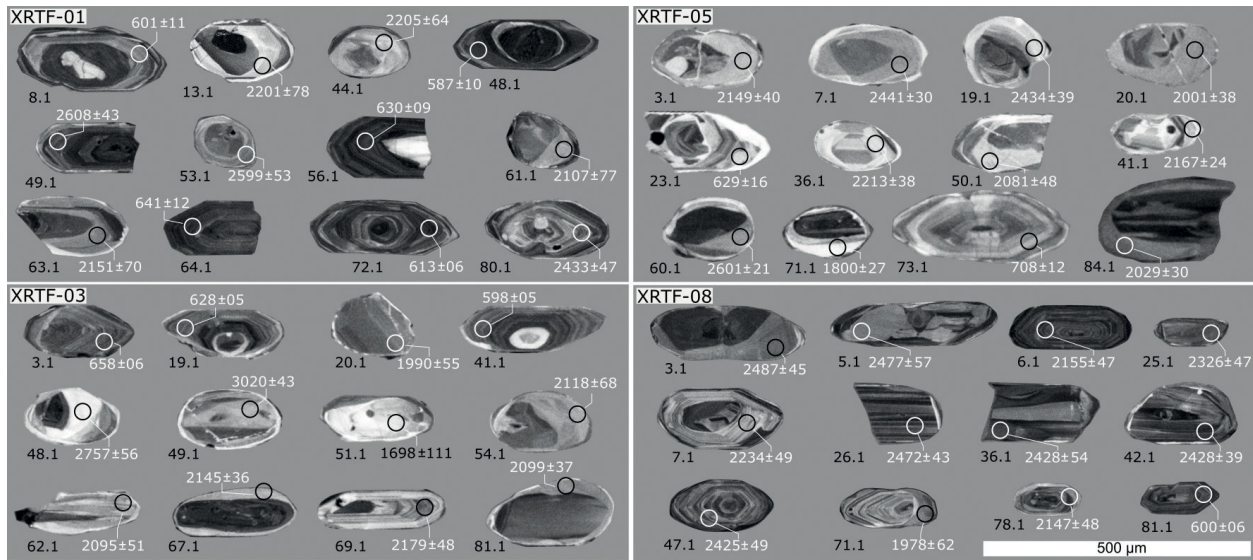


Figure 6. Cathodoluminescence images of zircon grains from the four analyzed samples with the location of the analyzed spots and in situ U-Pb ages. The complete data set, listed by spot number, are present in the supplementary data file. Note the great variety of zircon grain sizes, shapes, internal structures, ages, and especially the increasing frequency of younger crystals from proximal (XRTF-01) to distal (XRTF-08) samples. See the text for discussion.

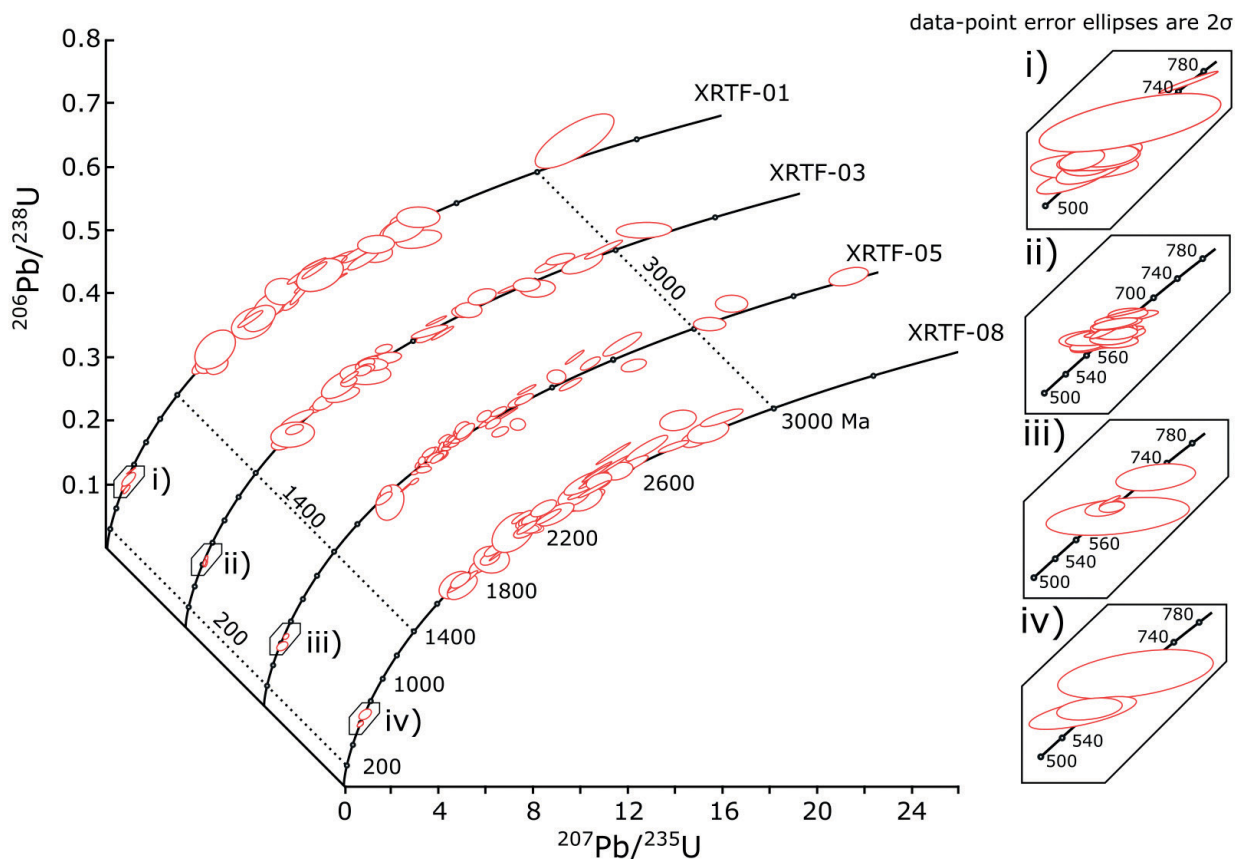


Figure 7. U-Pb laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) results for detrital zircon grains of the Bateias Formation. The Concordia diagrams represent less than 10% discordant results. Insets (i-iv) detail the Neoproterozoic ages for each sample. See the text for discussion.

influences of the same source areas, while the discrepancies in frequency might result from transportation effects.

U-Pb geochronological results for all samples are depicted in Figure 7, plotted over the Concordia diagram, and analytical U-Pb data are present in the Supplementary Material. In this diagram, it is possible to distinguish at least two predominant age ranges:

- a younger one, varying between ca. 580 and 670 Ma;
- a more disperse range, occupying the interval between ca. 1500 and 3000 Ma, with only limited presence of older ages, especially in samples XRTF-03 and XRTF-05.

Ages in the first cluster were frequently obtained in zircon grains with typical igneous zoning and subhedral crystal habits, while the oldest ages are common in crystals exhibiting metamorphic oscillatory zonings and rounded shapes. From sample XRTF-01 to XRTF-08, there is a considerable increase in the intermediate sedimentary sequences in the range and size of the second cluster (Paleoproterozoic to Archean ages), coupled with frequency systematic decrease of Neoproterozoic influence.

Samples in Figure 7 were organized according to the previous results of textural maturity, ordered from proximal (XRTF-01) to distal (XRTF-08). In this sense, the smaller range of detrital zircon ages from the oldest cluster recognized in the most evolved sample can represent the prevalence of the most important source areas. In contrast, the Neoproterozoic range is progressively less disperse in the intermediate sequences, and less expressive in the number of zircon grains for the distal sediments. The two most proximal samples are those that present the most considerable proportion of Neoproterozoic zircon ages. Nevertheless, it is possible to observe a subtle but consequent decrease in the range of Neoproterozoic ages towards the basin's interior, from ca. 540–670 Ma to ca. 560–660 Ma, with the youngest grains often present in the proximal sequences.

In general, the same age distribution and clusters can be observed in the four analyzed samples, which reflects the contribution of the same source areas. In order to provide a more detailed view of the relative abundance of the different age populations, Figure 8 presents Kernel Density Estimation plots, coupled with pie charts for each sample, revealing some important discrepancies. The established age-intervals were defined based on the observed concentration of the main age peaks in most samples.

Samples are ordered from the most proximal sample to the most distal one according to textural maturity, thus highlighting a marked decrease in the proportion of Neoproterozoic ages. Associated with this pattern, an inwards increase of the weighted-mean ages of the Neoproterozoic component is clearly observed, coupled with an increasing age dispersion, reflected in the values of standard deviation for each sample. The considerable decrease in frequency of younger zircon grains might indicate the distancing and re-working of sediments from Neoproterozoic sources. These variations suggest that the Piên Magmatic Arc can be considered as an important source area for the Bateias Formation.

In all samples, there is a distinct lack of Mesoproterozoic contributions, while a small and constant contribution of roughly Statherian ages (1550–1800 Ma) is ubiquitous. Additionally, age clusters in the intervals 1,800–2,200 and 2,200–2,500 are represented in detrital zircons of all samples and represent expressive portions of the detrital population. A marked increase of zircon ages proportions in the Orosirian/Rhyacian interval is observed from the most proximal to more distal sequences, probably as a result of the decreasing influence of Neoproterozoic sources. On the other hand, the Rhyacian/Siderian interval exhibits an almost constant contribution, abruptly increased only in one sample (XRTF-08), which occurs closest to the eastern limit of this basin. Hence, it might suggest a preferable contribution of different sources at the northeastern basin boundary. Finally, detrital zircons exhibiting Archean ages (> 2500 Ma) are also present in all samples, showing the same behavior seen in the Neoproterozoic range, in which its abundance is progressively decreasing from proximal to distal samples, probably

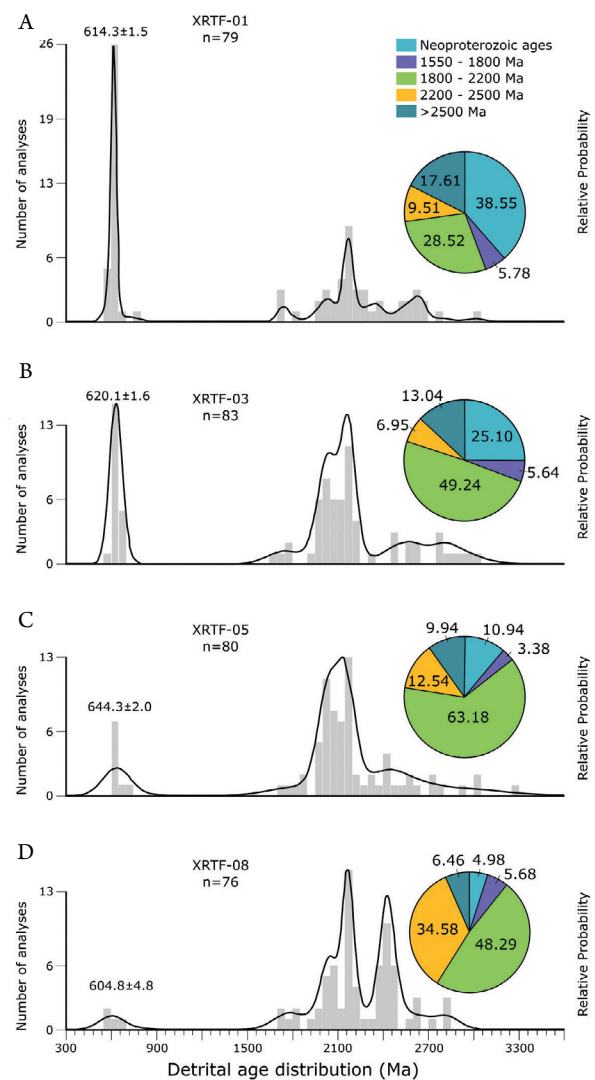


Figure 8. Kernel Density Estimation Diagrams (after Vermeesch 2012) showing the age spectra of detrital zircon grains and relative probability of five main age clusters. (A) Sample XRTF-01, which represents the most proximal conglomeratic sediments present at the western boundary. (B) Sample XRTF-03 and (C) XRTF-05, which are localized at the northern limit and comprehend conglomerate matrixes. (D) sample XRTF-08, located at the eastern limit of the Campo Alegre Basin. See the text for discussion.

suggesting proximity between Neoproterozoic and Archean source areas at the basin north boundary.

DISCUSSION

In the next sections, we present an integrative interpretation of the new results, in which the petrographic textural analyses, the U-Pb detrital zircon ages, and the available geological data are combined to provide a detailed overview of the time constraints and evolution of the Campo Alegre Basin. Furthermore, this section provides insights into the tectonic evolution during the final stages of the orogenic cycle in this area.

Textural maturity of the Bateias Formation

From petrographic analyses, it is possible to distinguish two main rock groups, based on the grain-size variations, textural maturity, and abundance of volcanic rock fragments. Group 1, composed by samples XR-01 to XR-04, is characterized by more immature sediments, with abundant coarse-grained fragments (> 2 mm), frequently of volcanogenic origin. On the other hand, Group 2, composed by samples XR-05 to XR-08, represents a progressive increase in sediment maturity, exhibiting relatively fine-grained (< 2 mm) fragments, and absent of volcanic clasts in the most distal sedimentary layers.

As proposed by Citroni *et al.* (2001), the Bateias Formation is composed of three main members:

- Papanduvinha, which comprehends proximal sedimentary deposits marked by alluvial fan conglomerates;
- São Bento do Sul, which represents braided river deposits, composed by conglomerates and sandstones, in a west-to-east paleo-current direction;
- Rio do Bugre, which includes sandstones and siltstones of more distal rivers.

Spatially and compositionally, the petrographic analyses describe the same behavior of incremental maturity from west to east. Group 1 samples correspond to the Papanduvinha Member, while Group 2 includes the São Bento do Sul Member and the Rio do Bugre Member, being thus compatible with the transportation trend previously interpreted by Citroni *et al.* (2001).

During the collisional stage between the Luís Alves and Curitiba terranes, the active tectonic mechanism results in the accretion of the Piên Magmatic Arc at the northern boundary of the Luís Alves Terrane, as well as the uplift of the northern portion of the Luís Alves Terrane along the suture line (Citroni *et al.* 2001). The building of a steep topography at northern portion of Luís Alves Terrane favored the emplacement of an alluvial fan depositional system in a high-energy sedimentary setting close to the uplifted region, which gradated to a system of braided rivers towards most distal regions. The elevated region also propitiated the setting of the main source area for the epiclastic unit of Campo Alegre Basin. In this sense, both the Luís Alves Terrane and the just added Piên Magmatic arc served as the main source areas for the epiclastic unit of Campo Alegre Basin.

In this scenario, the proximity to the source area culminated in the deposition of immature sediments with abundant rock

fragments and large grain-size variability, represented by samples from Group 1, and corresponding to the Papanduvinha Member. Among the lithic fragments, metamorphic, plutonic (granitoid), and volcanic fragments were observed. The compositional and granulometric variety preserved suggests short transportation. The detrital components of the São Bento do Sul and Rio do Bugre members (Group 2) correspond to more distal environments. In this way, the detrital components of those distal members might include transportation and reworking of sediments from the Papanduvinha Member.

Although the lacking of sedimentary structures indicating the fluvial paleo-currents, Citroni *et al.* (2001) inferred a fan limit at the basin north portion and a preferred transportation direction roughly from west to east, based on the distribution of conglomerate types and some alignment of pebbles. In this sense, the obtained pattern of increase in the textural maturity is in accordance with the previous inferred transportation directions, and represents an important input to describe the infilling processes of Campo Alegre Basin. The variability of sedimentary maturity is marked by a decrease in unstable fragments content; such as feldspar grains and volcanic rock fragments in distal samples from São Bento do Sul and Rio do Bugre members. As the Neoproterozoic zircon population was predominantly found in crystals with igneous features, the lack of volcanic components on the distal units reflects the lesser representativeness of zircon populations of Neoproterozoic ages in these rocks. While the most significant volcanic source at the time of deposition was probably the Piên Magmatic Arc, the volcanic fragments might also represent a different magmatic event contemporaneous to the initial filling of the Campo Alegre Basin, as discussed in the next section.

Zircon U-Pb ages and possible source areas

The petrographic characteristics of the Bateias Formation, such as the variability in size and composition of fragments of distinct origins, strongly suggest close proximity with its source areas, especially at the northern boundary of the Campo Alegre Basin. Based on these characteristics, the Luís Alves Terrane basement, represented by the Santa Catarina Granulitic Complex, and the Piên Magmatic Arc are interpreted as the main contributors to the infill of the Campo Alegre Basin.

During the stage of convergence between the Luís Alves and Curitiba terranes, the closing of Adamastor Ocean branch was responsible for the origin of the Piên Magmatic Arc. In this sense, this association of intrusive rocks and volcanic units provide the best constraints on the minimum depositional ages of Bateias Formation sediments. Additionally, the ubiquitous presence of volcanic clasts of acid compositions in the Papanduvinha member should also be taken into account when assessing the contribution of igneous volcanic sources during the early evolutionary stages of the Campo Alegre Basin, as they do not form an important component in the present association of the Piên Magmatic Arc. These acid volcanic rocks can be tentatively explained either by an early stage of volcanism associated with the opening of the basin or by the

probable volcanic activity that must have occurred related to the Piên magmatic arc.

The consolidation history of the Santa Catarina Granulitic Complex occurred approximately at the end of the Paleoproterozoic era. Earlier episodes of formation, metamorphism, and magmatic intrusion are also recognized and were estimated by different dating methods (Tab. 1). It is estimated that the formation of this unit records episodic additions and reworking of Archean juvenile material (Nd TDM model ages up to 2700 Ma). After that, between 2700 and 1900 Ma, this segment was submitted to successive regional magmatic and metamorphic events. Cooling ages indicate that tectonic stability occurred only around 1700 Ma, while Neoproterozoic K-Ar ages, restricted to shear zones close to the suture, indicate that the Brasiliano/Pan-African orogenic cycle did not thermally affect this crustal segment.

During the Brasiliano/Pan-African accretion stage, the Piên Magmatic Arc rocks were accreted to the Luís Alves Terrane northern limit. These rocks were initially formed during the earlier stages of the subduction process and continued simultaneously with the collision, resulting in two main compositional magmatic manifestations with different age ranges, between 620–615 and 615–610 Ma, respectively (Harara 2001). The tectonic stability stage of these granitoids was estimated based on regional cooling ages, for which a range of 607 to 595 Ma was obtained by the K-Ar method (Harara 2001). Other regional units are the volcanic rocks of the upper portion

of the Campo Alegre Basin, dated between 604 and 598 Ma (Basei *et al.* 1998a), as well as the A-type granitic intrusions of the Graciosa Province, of which emplacement ages range between 583 and 580 Ma (Vlach *et al.*, 2011).

In Figure 9, we present an integration of the U-Pb zircon provenance ages, through a Kernel Density Estimate plot considering all the four samples, correlated with the available regional ages. Generally, the main clusters obtained in our dataset are coincident with the regional ages. In this sense, the Paleoproterozoic to Archean range is, most probably, associated with the polyphasic evolution of the Santa Catarina Granulitic Complex, and strongly suggests that the basement of the Campo Alegre Basin was the principal source area for the Bateias Formation sediments. The interpretation that sediments of the Bateias Formation were formed during the collisional stage, and thus do not represent a pre-collisional cratonic sedimentary cover, is strongly supported by the population of Neoproterozoic ages obtained in the more proximal deposits. These results also suggest the participation of other important sources, in addition to the Santa Catarina Granulitic Complex.

Neoproterozoic ages were obtained mainly in zircon grains with typical igneous zoning, which suggests that the source of this population is related to the regional igneous manifestations. The obtained age range (~670–580 Ma) strongly suggests the participation of the Piên Magmatic Arc as an important source area, and the interval is compatible with the volcanic manifestation of the Campo Alegre Basin. Although the oldest pre-collisional ages of the Piên Magmatic Arc suggests its crystallization between 620 and 610 Ma, older detrital zircons might represent previous volcanic rocks from the arc as important contributors during the early stages of the Campo Alegre Basin infilling.

An important aspect of the age clusters is the variation between the relative proportion of Neoproterozoic ages (Figs. 7 and 8). From the interpretation that the Neoproterozoic ages have a volcanic origin, the progressive decrease in the significance of this population from west to east presents a pattern similar to that obtained in the petrographic results of Group 2, which shows decrease of volcanic fragments accompanying the sedimentary transportation direction. Volcanic components are more susceptible to erosive and transportation weathering processes, which means that its preservation decreases along the sedimentary transport and is, therefore, more frequent close to the source area.

The northwest region of the Campo Alegre Basin is most probably the main source area of Bateias Formation sedimentary rocks, where it is possible to recognize the Santa Catarina Granulitic Complex and the Piên Magmatic Arc, later intruded by the A-type Rio Negro granitic body of the Graciosa Province. Zircon grains from older sources (*i.e.*, the Santa Catarina Granulitic Complex) frequently exhibit rounded morphologies, superficial fractures, and transport-related features, as observed in Figure 10. Generally, these zircon grains can present low to high degrees of sphericity (Figs. 10A, 10B and 10D), and sizes ranging from 150 to 300 μm . Their surfaces often present polishing features, resulting in very high-spherical geometries, generated by previous geological

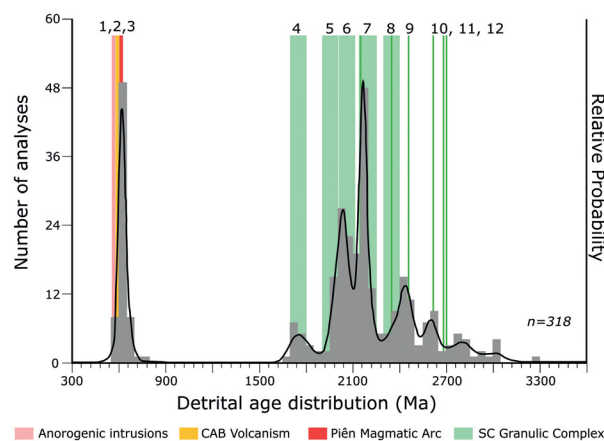


Figure 9. Integration of laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) U-Pb results using the Kernel Density Estimation diagram for all samples from the Bateias Formation (after Vermeesch 2012). The regional age intervals correspond to Neoproterozoic events, including (1) A-type granitic bodies of the Graciosa Province (583–580 Ma). (2) Campo Alegre volcanism (598–604 Ma). (3) Piên Magmatic Arc emplacement (610–620 Ma); and tectonics events in the Santa Catarina Granulitic Complex: (4) Regional cooling and tectonic stabilization (1.7–1.8 Ga). (5) Retrometamorphism at the upper crust (1.9–2.0 Ga). (6) Amphibolite-facies regional metamorphism at the middle crust (2.0–2.1 Ga). (7) Granitoid intrusions (2.15–2.25 Ga) and granulite-facies event at the middle crust (2.17 Ga). (8) Addition of mantle-derived material to the crust (2.30–2.40 Ga) and granulite facies regional metamorphism (2.35 Ga). (9) Amphibolite-facies event (2.48 Ga). (10) Intrusions emplacement (2.60 Ga). (11) Granulite-facies event at the middle crust (2.60 Ga). (12) Magmatic activity (2.70 Ga). References for regional events are given in Table 1.

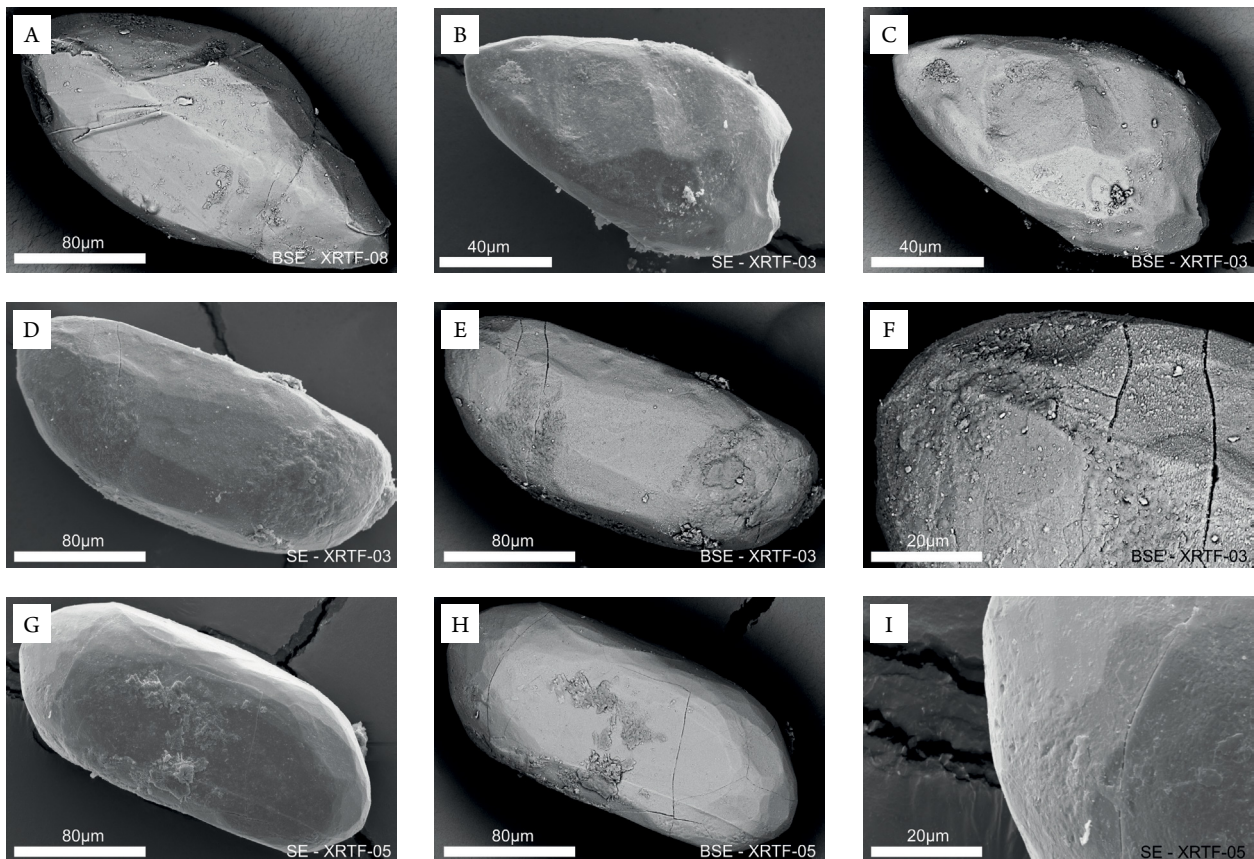


Figure 10. Secondary electrons (SE) and back-scattered electrons (BSE) images from Paleoproterozoic and Archean zircon grains of the Bateias Formation. Low-spherical and fractured grains compose this population, mainly with (A) superficial fractures, (B) few preserved edges, (C) superficial transport features. The biggest grains are mostly: (D), (E), (F), (G) very rounded, exhibiting (E), (F), (G), (H) superficial fractures, (F) transport-related features and (I) polished tips.

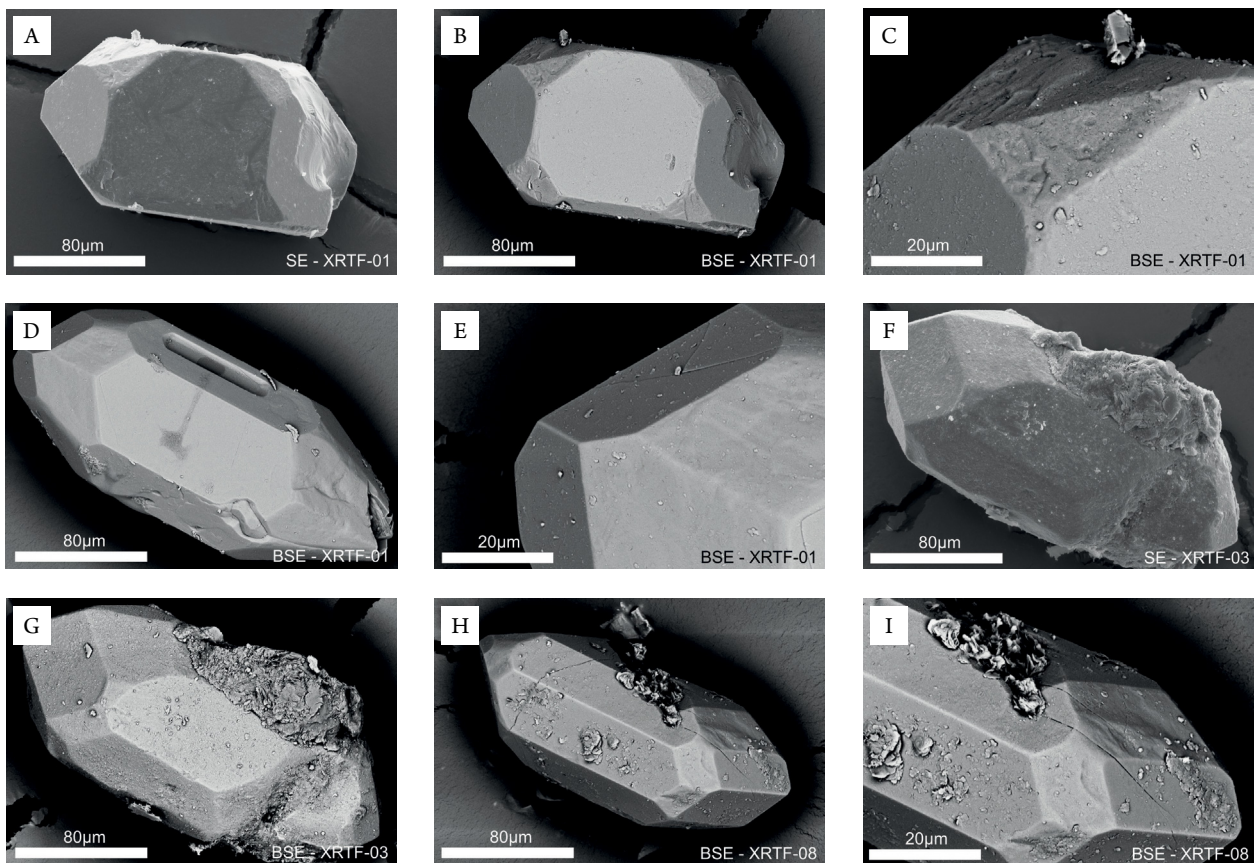


Figure 11. Secondary electrons (SE) and back-scattered electrons (BSE) images from Neoproterozoic zircon grains of the Bateias Formation. Well-formed and prismatic grains compose this population, mainly with (A) preserved faces and (B), (C), (D) edges. (C), (D), (E) Crystals might present no superficial transport features. The biggest grains are mostly (F) and (G) very well formed, exhibiting very low superficial features or polished tips, and Fe-oxide covering. Some grains might present (H) superficial fractures, with no (I) transport-related features.

events and possible transportation during the deposition of Bateias Formation.

On the other hand, zircon grains from the youngest sources are no bigger than 180 μm (Fig. 11). They are typically euhedral crystals (Figs. 11A, 11D and 11G), presenting low degrees of sphericity and roundness, and are frequently covered by Fe-oxides and clay minerals (Figs. 11F, 11G and 11H). The igneous zircon crystals often exhibit preserved edges and faces, indicating a smaller degree of transportation. Although some zircon grains can present superficial transport-related features, the smallest grains are often relatively more preserved, exhibiting no superficial covers and fractures. In this sense, the igneous zircons might indicate a volcanic activity coeval with the deposition of the lower sequences of Campo Alegre Basin.

Despite the clear decreasing proportion in the Neoproterozoic population between samples, when plotted in diagrams of cumulative density function (Fig. 12), the inflections of the curves have very similar positions and may indicate the same detritic populations. The greater discrepancies between samples are observed mainly in the Neoproterozoic intervals, and in some cases in the Paleoproterozoic populations between spatially distant samples (*i.e.*, XRTF-01 and XRTF-08), resulting in *step-like* geometries on the cumulative distribution function (CDF) curves. As a result, the cumulative probability analysis may be interpreted either in terms of transportation effects or of distinct source areas for each sedimentary strata.

To test the hypothesis of different source areas, we performed a Kolmogorov-Smirnov (K-S) adhesion test, as shown in Table 3. When applied to sedimentary provenance studies, the K-S test compares the cumulative distribution of detrital

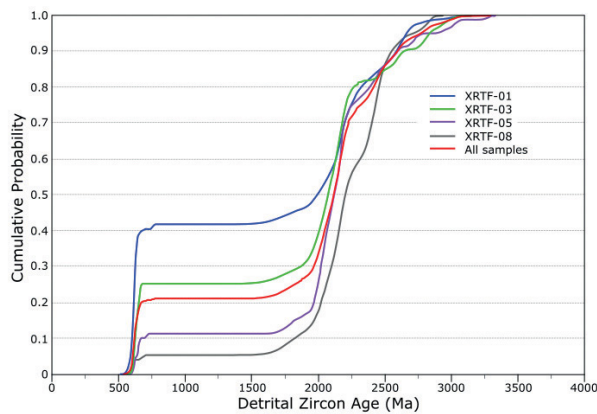


Figure 12. Cumulative probability curves from individual samples of the Bateias Formation, and for combined results. Note the similarities between samples in the Paleoproterozoic-Archean cluster, and the step-like behavior caused by variations in the Neoproterozoic range, from the most proximal to distal samples.

zircon ages between at least two samples, and if the CDFs are considered the same, it might indicate a common source for them. In short, the maximum distances (D) between two different CDFs are measured and their similarities or discrepancies estimated by P. In this sense, it is expressed the probability of a given D to represent a random sampling error, for 95% of confidence, if the obtained P are < 0.05 (Gynn and Gehrels 2010).

Our results suggest that the analyzed samples can represent varying populations of the same source areas. However, this correlation is noticeable only for the spatially closest pairs. The highlighted fields in the P from Table 3 strongly indicate that a given pair of samples might represent the same source area with 95% of confidence. As observed, samples registered an important contribution variation related to the proximity to the probable source area. In this sense, the samples can represent fragments from the same source area, and the presence of Neoproterozoic zircon grains is directly related to the preservation of volcanic clasts. The most susceptible fragments were transported, from the northwestern region of the Campo Alegre Basin to its southeast portion, and were progressively consumed.

Maximum depositional age of the Bateias Formation

Although the estimation of the maximum depositional age of a given sedimentary sequence are usually measured through the weighted mean age of the youngest cluster, or the peak age probability, the age of the youngest single grain can also provide time constraints for ca. 90% of the cases (Dickinson & Gehrels 2009). In the case of the Bateias Formation, it is possible to recognize rock fragments of igneous origin, possibly from the Piñ Magmatic Arc, or alternatively from early igneous manifestations related to the Campo Alegre Basin, as discussed above. Additionally, the range of obtained Neoproterozoic ages for all samples presents a wide distribution, which might result in a not representative mean age.

Considering all the analyzed samples, there is a wide variation of youngest zircon ages. For the sample XRTF-01, it was observed a 559 ± 14 Ma age, while the samples XRTF-03 and XRTF-08 exhibit similar results, 598 ± 5 and 594 ± 13 Ma, respectively, and for the sample XRTF-05 the youngest grain presents a 611 ± 8 Ma age. As observed, our results include zircon ages youngest than those representative of the main regional events for the sample XRTF-01. On the other hand, the youngest crystals for the XRTF-03 and XRTF-08 samples might correspond to the regional metamorphic peak, considering the uncertainties. Only one sample (XRTF-05) indicates a maximum depositional age based on the youngest zircon grain compatible with the observed stratigraphic

Table 3. Kolmogorov-Smirnov results for Bateias Formation samples*.

Sample	P (using uncertainties)				D (using uncertainties)			
	01	03	05	08	01	03	05	08
01		0.055	0.001	0.001		0.211	0.316	0.312
03	0.055		0.276	0.042	0.211		0.156	0.218
05	0.001	0.276		0.129	0.316	0.156		0.185
08	0.001	0.042	0.129		0.312	0.218	0.185	

*Note the spatial relationship between samples.

distribution at this basin, in which the sedimentary units represent the lowermost sequences, as evidenced by exploratory boreholes (Valiati 1974). Consequently, it might also suggest the volcanic rocks of Campo Alegre Basin and the A-type intrusions as late stage source areas, during some kind of reworking of these marginal occurrences of conglomeratic sequences.

Based on the discordance of the obtained youngest crystal's ages with the main regional geochronological framework, and the less expressive representativeness of these young grains in frequency, the maximum depositional age for the Bateias Formation was estimated by the weighted mean age of the Neoproterozoic age cluster. Figure 13A presents the weighted mean age for all Neoproterozoic detrital zircons of the measured samples, resulting in 630 ± 6 Ma, which may be not interpreted as their maximum depositional age. As predicted, given by the occurrence of a number of simultaneously Neoproterozoic events, this computed result is not a representative value and neither it is compatible with the main regional tectonic events. This result most probably of the great variability of the Neoproterozoic zircon population also reflected in the elevated mean-square weighted deviation value (MSWD). In this sense, if the different contributors can be distinguished, it should provide a better resolution of the different sources participation and thus provide a better age constraint for the deposition of the Bateias Formation.

To test this hypothesis, we plotted the age histogram presented in Figure 13B, which reveals an almost bimodal distribution, possibly resulting from the mixing of at least two overlapping age clusters. The division of age distributions occurs in ~ 620 Ma, which coincides with the oldest ages from the Piên Magmatic Arc (~ 620 Ma). Thus, the data was sectioned into two populations, in accordance with this age limit, resulting in two age clusters presented in Figures 13C and 13D. As expected, the MSWD values, though greater than the ideal threshold (~ 1.0), present a marked decrease (better precision), in particular for the youngest cluster. The resultant weighted mean is compatible with each peak at the histogram and strongly indicates that the Piên Magmatic Arc was an important source for the Bateias Formation. This result also indicates a possible volcanic activity during the earlier stages of Campo Alegre Basin formation due to the age variability, contemporaneous to the collisional process between the Luís Alves Terrane and Curitiba Terrane. Hence, our results suggest a maximum depositional age of 606 ± 4 Ma for the Bateias Formation.

TECTONIC SETTINGS OF CAMPO ALEGRE BASIN

Based on the mentioned results and interpretations, associated with the available regional data, we present a possible tectonic evolution for the region of the Campo Alegre Basin.

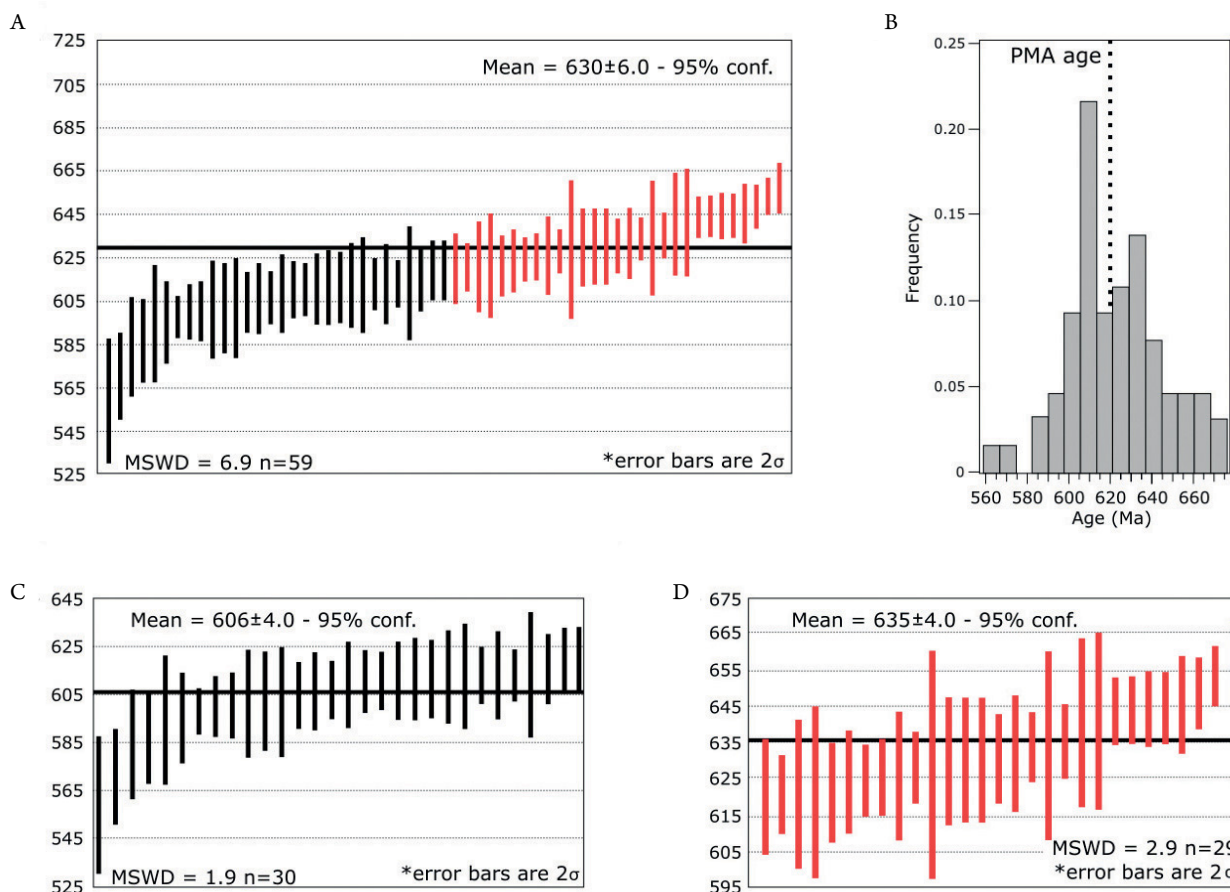


Figure 13. Results of the maximum depositional age estimation for Bateias Formation samples. (A) Weighted mean for all Neoproterozoic results. Note the mean-square weighted deviation value (MSWD) value and the mean age resultant. (B) Frequency analysis through histogram representation of all Neoproterozoic ages. Note the bimodal distribution divided at ~ 620 Ma. Weighted mean ages for zircon grains (C) youngest than 620 Ma, and (D) oldest than 620 Ma. Note the decrease in MSWD value.

Our model comprehends the final stages of the opening of the Adamastor Ocean and the late-stage emplacement process of the A-type granitic bodies of the Graciosa Province (Fig. 14). In this sense, the oldest ages of the Piên Magmatic Arc might indicate the minimum age for the beginning of the subduction process, which resulted in the Adamastor Ocean closure. Additionally, the Piên Ultramafic Suite, interpreted as an oceanic crust remaining, is suggestive of an oceanic environment in the interval of 630–618 Ma (Harara 2001, Harara *et al.* 2004) (Figs. 14A and 14B).

At this region, the collisional stage was estimated between 607–597 Ma, based on K-Ar cooling ages of the Piên Magmatic Arc (Harara 2001), while Faleiros *et al.* (2011) suggest a metamorphic peak age of ~590 Ma for the Turvo-Cajati metasedimentary rocks in the Curitiba Terrane. In this scenario, during the collisional stage, the main stress direction would be responsible for creating a perpendicular extensive field, which resulted in normal-faults and in the Campo Alegre Basin installation (Fig. 14C). The earlier sedimentary stages of the Bateias Formation are associated with minor volcanic manifestations. In this sense, the estimated maximum depositional age (~606 Ma) thus narrowly constraining the collision in the age interval after its deposition (606–590 Ma).

These tectonic dynamics was responsible for the development of a mountain ridge north of where the Campo Alegre Basin is presently preserved, conditioned by an over thrust front (Citroni *et al.* 2001). As a result, the paleogeography was responsible for creating a fan system that carried clasts from the Piên Magmatic Arc, the Luís Alves Terrane, and from early volcanic events. This sedimentary system is characterized by three different sequences, which include proximal sediments, composed by alluvial-fan conglomerates in the north, progressively grading to fluvial sandstones towards the southern portion of the basin. Then, the basement of the Campo Alegre Basin basement (Luís Alves Terrane) and the Piên Magmatic Arc represent important source areas for the sedimentary system. Finally, overlaying the sedimentary rocks of the Bateias Formation, there is a thick deposit resulted from the acid magmatic manifestation, from 604 to 598 Ma (Basei *et al.* 1998a). Finally, the late-stage mechanisms in this area are marked by the emplacement of the Graciosa Province (Vlach *et al.* 2011) (Fig. 13D).

CONCLUSIONS

- Detrital zircon grains record the important contribution of rocks from the Luís Alves Terrane and from the Piên Magmatic Arc, which acted as the main source areas for the Bateias Formation during the collisional stage of the Curitiba and Luís Alves terranes;
- Our U-Pb dataset also supports the interpretation of an early volcanic event during the initial stages of the Campo Alegre basin subsidence, particularly at the northwestern boundary, close to the thrust front;
- The transportation processes strongly affected the total proportion of the youngest zircon grains and the K-S test

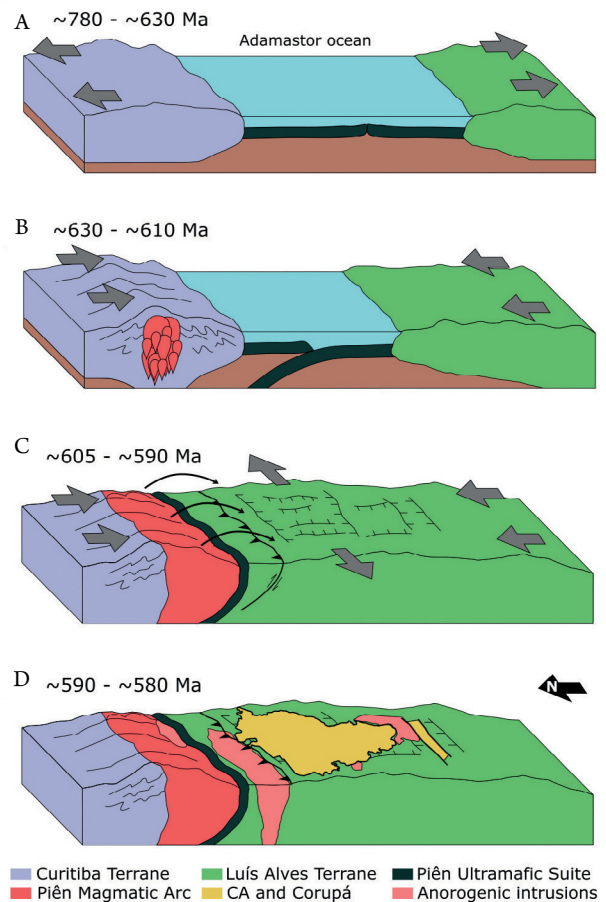


Figure 14. Proposed tectonic evolution model of the Campo Alegre Basin between 780–580 Ma based on available geological and geochronological models and new U-Pb detrital zircon data (Passarelli *et al.* 2018). See text for discussion.

results, as observed in our data. The large amount of zircon crystals youngest than 620 Ma and the observed increase in the Neoproterozoic mean ages from east to west suggest that the initial volcanic stage was concentrated at the eastern boundary of the basin;

- The Campo Alegre Basin is one of the most important volcano-sedimentary basin present at the Brazil southern region and registered the initial stages of the collisional process in this region. In this sense, the maximum depositional ages of Bateias Formation constraint the collisional stage to the interval ~590 to ~606 Ma.
- Our results open possible discussions about the relationship between the early volcanic manifestation and the main volcanic activity at the Campo Alegre Basin, which may lead to a better understanding of the geochronological evolution of this Precambrian volcano-sedimentary basin.

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F. R. Q.-V. acquired all geochronological and petrographic data set, interpreted the data, elaborated the figures, and wrote the manuscript. M. A. S. B. provided advisorship regarding the geochronological and tectonic approach, improved the manuscript through corrections and suggestions. L. M. L. supported data interpretation and discussion, revised and improved the manuscript, and drew all the figures. Competing interests: The authors declare no competing interests.

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