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Depositional systems, sequence stratigraphy, and sedimentary provenance of the Palaeoproterozoic Minas Supergroup and Itacolomi Group, Quadrilátero Ferrífero, Brazil

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Abstract

According to previous studies, the Palaeoproterozoic Minas-Itacolomi meta-sedimentary mega-sequence in the Quadrilátero Ferrífero metallogenic province records the transition of a continental rift to passive margin to foreland basin. From the perspective of sequence stratigraphy, this article identifies five sequences summarised in the Minas-Itacolomi Basin stratigraphic chart, providing information of the Palaeoproterozoic eustatic changes, such as the Great Oxidation Event. Interpretations were based on the systematic recognition of 41 facies and their associations, the identification of nine recurring depositional systems, nine system tracts, and five sequences (in that order). The Caraça and Itabira Groups comprise the first sequence, for which three system tracts were identified. The Piracicaba Group hosts two sequences and four system tracts. The Sabará and Itacolomi Groups are the two upper sequences, both related to a foreland basin, where the underfilled and overfilled system tracts were recognised. Sedimentary provenance was determined mainly from detrital zircon U-Pb age spectra of previous authors' databases, as well as on palaeocurrent field data and thickness variations. All of the units of the Minas-Itacolomi mega-sequence share detrital zircons from Archaean sources (Rio das Velhas Supergroup and crystalline basement). Only the Sabará and Itacolomi Groups exhibited bimodal U-Pb age histograms, thus indicating both Archaean and Palaeoproterozoic (Mineiro Belt) provenances.

KEYWORDS: sedimentary facies; Palaeoproterozoic Minas-Itacolomi Basin; sequence stratigraphy; sedimentary geology.

INTRODUCTION

Sedimentary basins are regions where sediment accumulates into successions of hundreds to thousands of metres thick over large areas. The sedimentary rocks in a basin provide a record of both the tectonic history of the area and the effects of other controls on deposition, such as climate, sea base level, and sediment supply (Catuneanu 2006, Nichols 2009).

The Palaeoproterozoic Minas-Itacolomi basins are a good example of several sedimentary successions controlled by tectonics. Their stratigraphic units are located within the Iron Quadrangle (acronyms: IQ or QF, for "Quadrilátero Ferrífero", in Portuguese), in the state of Minas Gerais, South East of Brazil. The QF is one of Brazil's most important metallogenic provinces, as it hosted many world-class Au deposits, as well as Lake Superior and Algoma type banded iron formations, and uranium palaeoplacers deposits, not to mention, its many similarities to the Transvaal Sequence, in South Africa (Villaça and Moura 1985, Minter *et al.* 1990, Renger *et al.* 1994, Lobato *et al.* 2000, Vial *et al.* 2007). There are few papers in the literature that focus on sedimentary facies description and depositional system identification in the Minas-Itacolomi basins. This article presents the sequence stratigraphy approach of Minas-Itacolomi sedimentation through the description of its sedimentary geology or, more specifically, through facies description, depositional systems interpretation, as well as system tracts and sequences correlations, in order to aid further in the geological evolution and time relationships of those basins.

The chronological relationships within Minas-Itacolomi are hard to be obtained precisely and accurately due to the lack of index fossils and the absence of cross-cutting and/or interlayered igneous rocks for isotope dating (Noce 2000, Dopico *et al.* 2017, Dutra *et al.* 2019). To overcome this major problem, sedimentary provenance geochronological studies regarding detrital zircons have been carried out to estimate the life span of the sedimentary basins (Renger *et al.* 1994, Machado *et al.* 1996, Hartmann *et al.* 2006, Koglin *et al.* 2014, Mendes *et al.* 2014, Nunes 2016, Dopico *et al.* 2017, Dutra *et al.* 2019). Furthermore, this article also presents a detrital zircon age data compilation (database from Machado *et al.* 1992, Machado *et al.* 1996, Hartmann *et al.* 2006, Koglin *et al.* 2014, Jordt-Evangelista *et al.* 2015, Nunes 2016, Dopico *et al.* 2017, Dutra 2017, Duque 2018, Dutra *et al.* 2019), in order to comprehend the provenance differences in the many geodynamic stages of the Minas-Itacolomi basins. In summary, this

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article presents, for the first time in the geological studies of the QF, a complete logging and description of sedimentary facies, depositional systems, and sequences (under the sequence stratigraphy approach), together with an U-Pb detrital zircon geochronological data compilation for provenance studies of the Minas-Itacolomi Palaeoproterozoic basins.

MATERIALS AND METHODS

The first stage of this article's workflow was the bibliographic research, aiming to collect both historical and recent Minas Supergroup sedimentology works. Afterwards, several field trips to the QF were carried out, with the purpose of profiling its upper units through facies recognition and samples collection (for macroscopic and transmitted light microscopy petrographic descriptions). In this stage of the workflow, special attention by the authors was required, in order to recognise and to distinguish in the field primary sedimentary structures from tectonic structures, such as folds, cleavages, lineations, and other tectonic driven rock fabrics. The next stage of the workflow was the second bibliographic research, now focused on both the compilation of U-Pb zircon age data for the Minas-Itacolomi stratigraphic units and the Minas Basin geodynamic evolution. After all of the previous steps were concluded, the sequence stratigraphy principles (Catuneanu *et al.* 2005, Catuneanu 2006) could be applied to the Minas-Itacolomi meta-sedimentary units, and the results were hereby presented.

The building block of sequence stratigraphy is the facies concept, which is defined as a particular combination of lithology, sedimentary structures, geometry, and textural attributes that allows to classify different sedimentary rock bodies. Therefore, facies is a product of sedimentary processes that exist in a specific depositional palaeoenvironment. Another important concept is the Walther's Law: the vertical shifts of facies reflect corresponding lateral shifts of facies as well. Based on this principle, the facies association (i.e., groups of facies genetically related to one another and which have some environmental significance) is a critical element for the interpretation of palaeo-depositional systems (Dalrymple 2010).

The lateral succession of the depositional systems deposited at the same time window, is the very definition of system tracts, the second-to-last sequence stratigraphic unit, also known as the association between contemporary depositional systems. At this level, the eustasy plays a major key role in a sequence stratigraphic framework, as it determines the formation of packages of strata with specific stacking patterns, as well as of sequence stratigraphic surfaces, such as unconfomities and correlative conformities. Finally, those surfaces, made by contemporary or genetically related strata, are the ones that mark the limits of the sequences, the ultimate chronostratigraphic unit.

According to Catuneanu *et al.* (2011), the stacking patterns of the strata form geometrical trends that include upstepping, forestepping, backstepping, and downstepping. These geometrical trends mark the three types of shoreline shift: forced regression (FR) (forestepping and downstepping at the shoreline), normal regression (NR) (forestepping and upstepping at the shoreline), and transgression (backstepping at the shoreline).

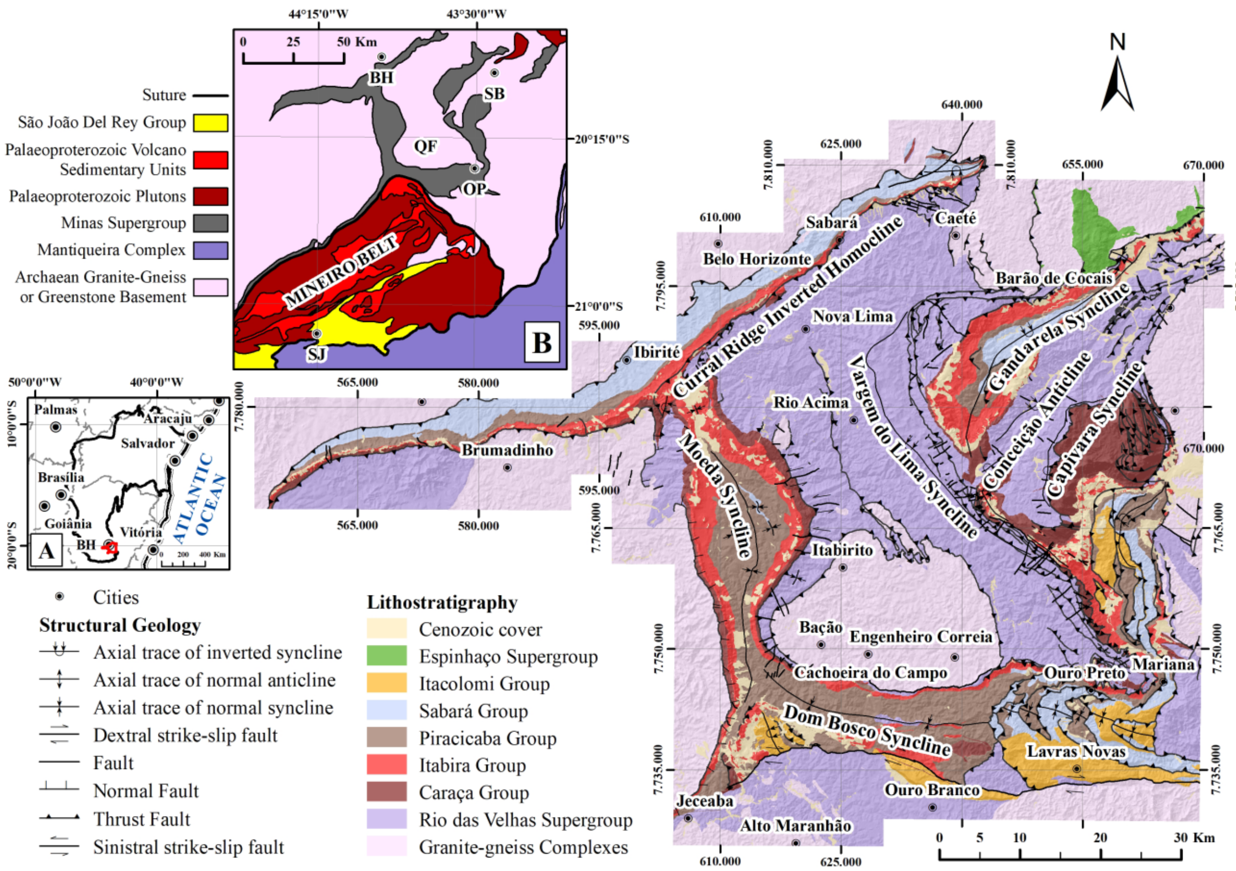
During an FR, a falling stage systems tract (FSST) takes place. During an NR, two system tracts are possible, depending on the base level at that time: if the sea level was originally falling, caused by a previous FR, then the lowstand system tract (LST) takes place; otherwise (if the sea level was high at that time), the highstand system tract (HST) occurs. In between those NR system tracts, when the base level is rising, i.e., during a transgression (T), the transgressive system tract (TST) is the one in place (Catuneanu *et al.* 2005, Catuneanu 2006, Catuneanu *et al.* 2011).

For the provenance studies, palaeocurrent data are of great importance and can be obtained through many field-related techniques: the most straightforward is the direct measurements with the compass in the field, mainly from cross-beds. Sedimentary provenance can also be interpreted from analytical methods, such as from U-Pb geochronological data (Cawood *et al.* 2003, Cawood *et al.* 2012): through the interpretation of the zircon ages frequency distribution and testing for multi-modality (i.e., if the rock has derived from more than one source), one can have information of provenance if nearby possible sources have distinct ages. Another geochronological dating method (e.g., Ar-Ar, Sm-Nd, and Re-Os of different minerals) is not recommended for this type of study, as zircons are more resistant to weathering and provide a well-constrained U-Pb isotopic clock, even if found within sedimentary rocks that underwent a multi-event geological history. Hence, a detrital zircon U-Pb database was assembled for this work in order to validate the interpretations within, based on many previous works in the literature. The statistics for the geochronology database was calculated using either the Java-based DensityPlotter software (Vermeesch 2012) or the software package within the statistical programming environment R, called Provenance (Vermeesch *et al.* 2016).

GEOLOGICAL SETTING

Located in the south-eastern region of the São Francisco Craton, the IQ is a metallogenic province of nearly 7,000 km^2 (Figure 1). The QF is composed of archaean and proterozoic geological units. The Archaean basement is made of tonalitic granite-gneiss complexes, followed by the Rio das Velhas Supergroup, and overlain by the Proterozoic Minas Supergroup and the Itacolomi Group. All of the aforementioned units have undergone at least two tectonic/metamorphic events (the Transamazonian — also known as Minas Accretionary Orogeny or Palaeoproterozoic Orogeny — and the Brasiliano Orogenies), responsible for their complex deformation and metamorphic evolution.

The Rio das Velhas Supergroup is a greenstone belt divided into the Nova Lima and Maquiné groups (from base to top), and they have an estimated thickness of 4 and 1.6 km, respectively. The Nova Lima Group hosts the largest orogenic gold deposits that made the QF famous for its world-class deposits, whose mineralisation is sulphide related, and can be a function of either hydrothermal alteration with high structural control (as most orogenic gold deposits are) or stratabound nature mineralisation, such as volcanogenic massive sulphides



QF: Quadrilátero Ferrífero; BH: Belo Horizonte; OP: Ouro Preto; SB: Santa Bárbara; SJ: São João Del Rey.
Source: modified from Dorr II (1969), Lobato *et al.* (2005), NASA LP DAAC (2016) and Alkmim and Teixeira (2017).
Figure 1. Geological map of the Iron Quadrangle, with São Francisco Craton location (A) and Mineiro Belt (B).

(Ladeira, 1980, 1988, Lobato *et al.* 2001, Lobato *et al.* 2016, Lobato and Costa 2018).

This greenstone belt supergroup is composed mainly of mafic, ultramafic, chemical volcano-sedimentary rocks, volcanoclastic (mainly greywackes) rocks, and sandstones formed in episodic (cycles of) sedimentation. They record a submarine fan system transitioning to continental sedimentation, with intense island arc volcanism (Noce *et al.* 1992, Baltazar and Zucchetti 2007, Angeli 2015).

The Minas Supergroup comprises the Caraça, Itabira, Piracicaba, and Sabará groups (base to top) that record a sedimentation from ca. 2580 to ca. 2050 Ma (Renger *et al.* 1994, Machado *et al.* 1996, Noce 2000, Hartmann *et al.* 2006, Farina *et al.* 2016). The basal Caraça Group is made of the Moeda and Batatal Formations, the first being mainly sandstones, with conglomerates and minor pelites, and the latter unit being pelitic (Dorr II 1969, Alkmim and Martins-Neto 2012).

The second group, Itabira, comprises the Cauê and Gandarela Formations, mainly made of itabirite (Lake Superior-type banded iron formations) and dolomite (dolostones), respectively (Dorr II 1969, Rosière and Chemale Jr. 2000). The third group, Piracicaba is made of four formations: Cercadinho (mainly pelitic with some ferruginous coarse-grained sandstones), Fecho do Funil (also pelitic, but with subordinate dolomite lenses), Taboões (fine-grained sandstones), and Barreiro (pelitic) (Dorr II 1969, Alkmim and Marshak 1998, Farina *et al.* 2016).

The fourth group (Sabará) and the overlying Itacolomi Group are both syn-orogenic. Sabará is a flysch sequence (pelites, diamictites, wackes), while Itacolomi is the molasse sequence (sandstones and conglomerates) (Dorr II 1969, Alkmim and Marshak 1998, Almeida *et al.* 2005, Alkmim and Martins-Neto 2012). All of the IQ lithostratigraphic units are summarised in Table 1.

The main tectono-magmatic events in the IQ region are several Archaean magmatic pulses/events (Santa Bárbara, Rio das Velhas I and II, Mamona I and II) related to the basement of Minas Supergroup (i.e., granite-gneiss complexes and Rio das Velhas Supergroup); Minas Rift (taphrogenesis); Minas Accretionary Orogeny (formerly named Transamazonian) — related to the Sabará-Itacolomi sedimentation; Espinhaço Rift (minor mafic dyke swarms); and Brasiliano Orogeny (Araçuaí Belt) (Machado *et al.* 1992, Silva *et al.* 1995, Alkmim and Marshak 1998, Lana *et al.* 2013, Farina *et al.* 2015, Teixeira *et al.* 2015, Farina *et al.* 2016, Albert 2017). These events are summarised in Table 2.

SEDIMENTARY FACIES

The sedimentary facies for the Minas-Itacolomi basins are described below, in each correspondent stratigraphic group sub-chapter. The name of the sedimentary rock was mainly used, rather than its metamorphic name, as the majority of the rocks of the Minas Supergroup within the QF, they have

Table 1. Iron Quadrangle lithostratigraphic summary.

Eon	Supergroup	Group	Formation	Thickness (m)	Lithology
Proterozoic		Itacolomi	Undivided	Up to 2000	Sandstones (ferruginous matrix), pelites, and conglomerates
	Minas	Sabará	Undivided	3000–3500	Sandstones (wackes), tuffs, conglomerates, diamictites, and turbidites
		Piracicaba	Barreiro	Up to 120	Pelites and carbonaceous mudstones
			Taboões	Up to 120 (thins out to S/SE)	Sandstones
			Fecho do Funil	100–300 (dolomite lenses over 30 m thick)	Pelites, dolomitic pelites, and siliceous dolomites
			Cercadinho	100–500	Ferruginous sandstones, sandstones, pelites, and dolomites
		Itabira	Gandarela	250–500	Dolomites, dolomitic pelites, and limestones
			Cauê	300–500 (over 1000 m in axial areas)	Itabirites (BIFs), dolomitic itabirite, and pelites
		Caraça	Batatal	200	Pelites, carbonaceous mudstones, cherts, and itabirites
			Moeda	30–300 (fine-grained sandstone can be up to 100 m thick)	Conglomerates, sandstones, and pelites
Archaean	Rio das Velhas	Maquiné	Undivided	Up to 1600	Sandstones, conglomerates, and pelites
		Nova Lima	Undivided	Over 4000	Mafic-ultramafic rocks, volcanoclastic rocks, cherts, banded iron formations, and pelites
	Granite-gneiss Complexes	Undivided	Undivided	(Basement)	Gneisses, migmatitic gneisses, augen-gneisses, and granites

Source: modified from Dorr II (1969), Alkmim and Marshak (1998), Almeida *et al.* (2005) and Alkmim and Martins-Neto (2012).

low-grade metamorphism and their sedimentary structures are well preserved, especially when then are located far from the main high strain zones. Some facies were not identified in the authors' fieldwork but are included in the text (with corresponding references), as they were previously described in the literature. The order in which the facies were catalogued in this work is according to their stratigraphic position, as observed in the field, from base to top. The lateral changes are frequent and are accounted for, since they represent the evolution of the depositional system.

Caraça Group

The seven sedimentary facies logged for the Moeda Formation, as well as the two facies of Batatal Formation are displayed in Table 3 and Figure 2. All of the authors' field catalogued Moeda facies were also previously described by Dorr II (1969), Villaça (1981), and Madeira *et al.* (2018), with the exception of a rare well-sorted fine-grained sandstone with hummocky cross-stratification identified by Canuto (2010). Two additional Batatal Formation rare facies are fine sandstone (or chert), and jaspilite (or BIF oxide facies), according to Dorr II (1969).

Itabira Group

The two sedimentary facies logged for the Cauê Formation, as well as the four facies of Gandarela Formation are displayed in Table 4 and Figure 3. Other Cauê Formation facies described in the literature are two types of itabirites (Mn-rich and amphibole-rich itabirites), and some other rare lithologies, such as volcaniclastic Mn-Fe-rich clay layers, carbonates, and mudstones (Dorr II 1969, Suckau *et al.* 2005, Cabral *et al.* 2012). For the Gandarela Formation, the two other sedimentary facies also described in the literature are some volcanic layers (greenschist made of up to 80% chlorite, and minor quartz, biotite, magnetite), and stromatolitic grey limestone (Dorr II 1969, Souza and Müller 1984). The depositional systems for these facies are shallow subtidal to intertidal environments for the carbonate and pelitic lithologies, Lake Superior-type sedimentation (continental shelf) for the itabirites, and volcanogenic for the greenschists and volcaniclastic layers.

Piracicaba Group

The six sedimentary facies logged for the Cercadinho Formation, the five facies of Fecho do Funil Formation, the two facies of Taboões Formation, and the three facies of Barreiro Formation are displayed in Table 5 and Figure 4. Dorr II (1969) also describes two rare sedimentary facies in the Cercadinho Formation: a basal pebble conglomerate (pebbles of itabirite, quartz, and quartzite), and dolomite lenses in the top of the unit. This work's Piracicaba-logged facies are conformable with the literature (Dorr II 1969, Dardenne and Campos Neto

Table 2. Main geological events in Quadrilátero Ferrífero.

Eon/Era		Event	Age (Ma)	Description	References
Phanerozoic		Laterisation, erosion, and recent sedimentation	60–0	Cenozoic geological events responsible for supergene processes and recent relief reshaping.	1
Proterozoic	Neo-	Brasiliano Orogeny	700–450	Orogeny responsible for both the west-verging fold and thrust belt that reactivates and superimposes/strains the prior Iron Quadrangle structures and the Gondwana agglutination.	6; 7; 22
	Meso-	-	-	-	-
	Palaeo-	Espinhaço Rift	~1700	Mafic dykes intrusions (related to the Espinhaço Rift) caused by an extensional tectonic regime.	4; 20
		Collapse of Minas Accretionary Orogen; Domes and keels II; Itacolomi Group sedimentation	~2050	Reactivation of the first archaean domes and keels at the final stages of the orogenesis (collapse), migmatisation, and subsequent structural remodelling. Followed by the Itacolomi Group sedimentation on newly formed intermontane regions.	21
		Minas Accretionary Orogeny (Transamazonian)	2260–1860	Accretionary orogeny due to the collision between the São Francisco proto-craton and the Congo proto-craton.	10; 13; 15; 16; 17; 20; 21
		Minas Supergroup sedimentation	2580–2100	Minas Supergroup sedimentation.	1; 3; 10; 19; 20; 22
Archaean		Minas Rift	~2600	Minas Supergroup related taphrogenesis (rifting).	9; 19
		Mamona II	2620–2580	High-K calc-alkaline granitoid and pegmatite intrusions.	12; 14; 18; 19
		Mamona I	2750–2700		
		Domes and keels I	2775–2730	Formation of first domes and keels in Iron Quadrangle during the collapse of Rio das Velhas greenstone belt orogen.	21
		Rio das Velhas Supergroup sedimentation	2803–2742	Sedimentation and volcanism associated to Rio das Velhas Supergroup.	1; 2; 5; 8; 9; 11; 14
		Rio das Velhas II	2800–2760	Medium-K granitogenesis from magma mixing of partial melts of both oceanic and continental crusts in orogenic regime (Bação, Belo Horizonte, Bonfim, Caeté Complexes)	11; 14; 16; 18
		Rio das Velhas I	2930–2850	TTG medium-K magmatic accretion to the continental crust and to mafic-ultramafic *greenstone belts* terrains: beginning of Meso-archaean orogenesis homonym to Event (Bação, Belo Horizonte, Bonfim Complexes, Mineiro Belt).	11; 14; 16
		Santa Bárbara	3220–3200	Santa Bárbara granite intrusion (Iron Quadrangle NE and Mineiro Belt).	11; 16
		Continental crust formation	3500–3200	Crystallisation of the first cratonic nuclei, i.e., continental crust.	11; 16; 18

References: [1] Dorr II (1969); [2] Machado *et al.* (1992); [3] Renger *et al.* (1994); [4] Silva *et al.* (1995); [5] Machado *et al.* (1996); [6] Alkmim and Marshak (1998); [7] Endo and Machado (2002); [8] Noce *et al.* (2005); [9] Hartmann *et al.* (2006); [10] Alkmim and Martins-Neto (2012); [11] Lana *et al.* (2013); [12] Romano *et al.* (2013); [13] Sanglard *et al.* (2014); [14] Farina *et al.* (2015); [15] Teixeira *et al.* (2015); [16] Farina *et al.* (2016); [17] Aguilar *et al.* (2017); [18] Albert (2017); [19] Dopico *et al.* (2017); [20] Dutra (2017); [21] Cutts *et al.* (2019); [22] Dutra *et al.* (2019).

1975, Cassedanne and Cassedanne 1976, Garcia *et al.* 1988, Kuchenbecker *et al.* 2015).

Sabará Group

The five sedimentary facies logged for the Sabará Group are displayed in Table 6 and Figure 5. All of the authors' field catalogued Sabará Group facies were also previously described by Dorr II (1969) and Reis *et al.* (2002).

Itacolomi Group

The six sedimentary facies logged for the Itacolomi Group are displayed in Table 7 and Figure 6. This paper's Itacolomi Group logged facies are conformable with the ones previously described by Alkmim (1987), Duque (2018), and Duque *et al.* (2020), but the first author also describes an extra sandstone facies (with ripple marks and interbedded mudstone/siltstone flaser beds) of a tidal flat depositional environment in the Serra de Ouro Branco locality.

FROM SEDIMENTARY FACIES TO DEPOSITIONAL SYSTEMS

At the base of the Caraça Group, the Moeda Formation contains layers and lenses of quartz arenites and quartz pebble-cobble conglomerates. The MOE1 and MOE2 facies (polymictic and oligomictic conglomerates) are found with erosional contact with the basement and record an important feature of the atmospheric conditions at the early stages of the Minas basins: detrital pyrite is the evidence for the then reducing atmospheric conditions; otherwise, it would have been oxidised to iron oxides and iron hydroxides. This facies, deposited by debris flow in an alluvial fan (Miall 2010), also has a certain degree of similarity with the Witwatersrand Au-U-bearing conglomerates (Villaça 1981, Minter *et al*. 1990, Pires 2005).

Table 3. Caraça Group facies and sedimentary processes.

Formation	Facies code	Facies description	Sedimentary processes
Batatal	BTT2	Carbonaceous mudstone	Marine transgression clay settling with organic input being preserved by reducing conditions
	BTT1	Mudstone	Marine transgression clay settling
Moeda	MOE7	Laminated mudstone and minor fine, well-sorted sandstones	Lacustrine facies
	MOE6	Laminated quartz-rich siltstone with minor very fine sand inputs in thin (<1 m thick) lenticular beds	Finer sedimentation in braided rivers
	MOE5	Poorly sorted sandstone with planar stratification	Plane-bed flow (upper flow regime)
	MOE4	Poorly sorted sandstone with trough cross-bedding	Sinuous-crested subaqueous dunes
	MOE3	Poorly sorted sandstone with tabular cross-bedding and tangential foresets	Cross-cutting sand bars in subaqueous dunes (straight crested sandy ripples)
	MOE2	Oligomictic quartz-rich conglomerate with detrital pyrite, rounded granules and pebbles of medium sphericity and coarse sand matrix; trough cross-bedding present	Longitudinal bars or minor channel fills in braided rivers
	MOE1	Polymictic (angular quartz, chert, phyllite, yellow felsic lava clasts, chlorite schists) conglomerate with detrital pyrite	Gravity-driven processes, such as debris flow

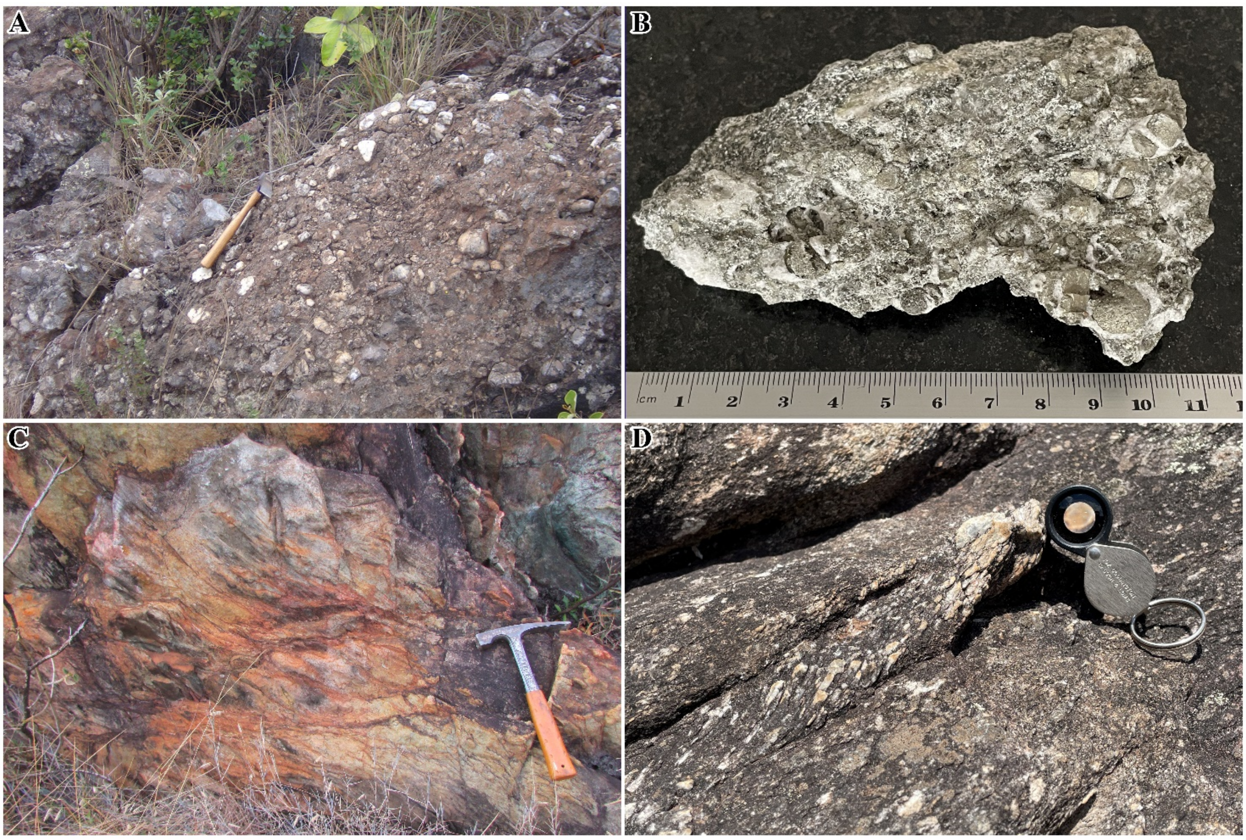


Figure 2. Caraça Group: (A) MOE1 facies — polymictic conglomerate — outcrop (X = 605,202; Y = 7,775,277; Z = 1,384 m); (B) MOE2 facies hand specimen — Au-bearing conglomerate with rounded detrital pyrites (Ouro Fino Mine — Jaguar Mining Inc.); (C) MOE4 facies — poorly sorted sandstone with trough cross-bedding — outcrop (X = 609,027.087; Y = 7,756,449.81; Z = 1,243.7 m); (D) MOE3 facies — poorly sorted sandstone with tabular cross-bedding and tangential foresets — outcrop (X = 604,540.709; Y = 7,779,506.869; Z = 1,343.9 m). Coordinates are in UTM and WGS84 datum.

The MOE2, MOE3, MOE4, and MOE5 facies (conglomerates and poorly sorted sandstones) comprise this unit's most abundant set of facies (both in thickness and lateral continuity). MOE2 (oligomictic conglomerate) is made of gravels deposited in longitudinal bars of braided rivers, whilst MOE3 and MOE4 (poorly sorted sandstones with trough or tabular bedding) are deposited by subaqueous dunes (sinuous and straight crested) in braided river environments. The

Table 4. Itabira Group facies and sedimentary processes.

Formation	Facies code	Facies description	Sedimentary processes
Gandarela	GDR4	Intraformational conglomerate (dolorudite with chert and dolomite clasts in dolomite matrix)	Tidal currents reworking of carbonate platforms
	GDR3	Dolomitic mudstone	Clay settling within carbonate platforms
	GDR2	Laminated algae mats in grey dolomite	Algae and bacterial growth in carbonate platforms
	GDR1	Fe-rich dolomite often interbedded with dolomitic itabirite	Chemical precipitation of iron oxides in shallow waters
Cauê	CAU2	Dolomitic itabirite	
	CAU1	Itabirite (jaspilite or BIFs)	Oxyatmoversion: oxidation of Fe^{2+} ions leading to the precipitation of iron oxide crystals

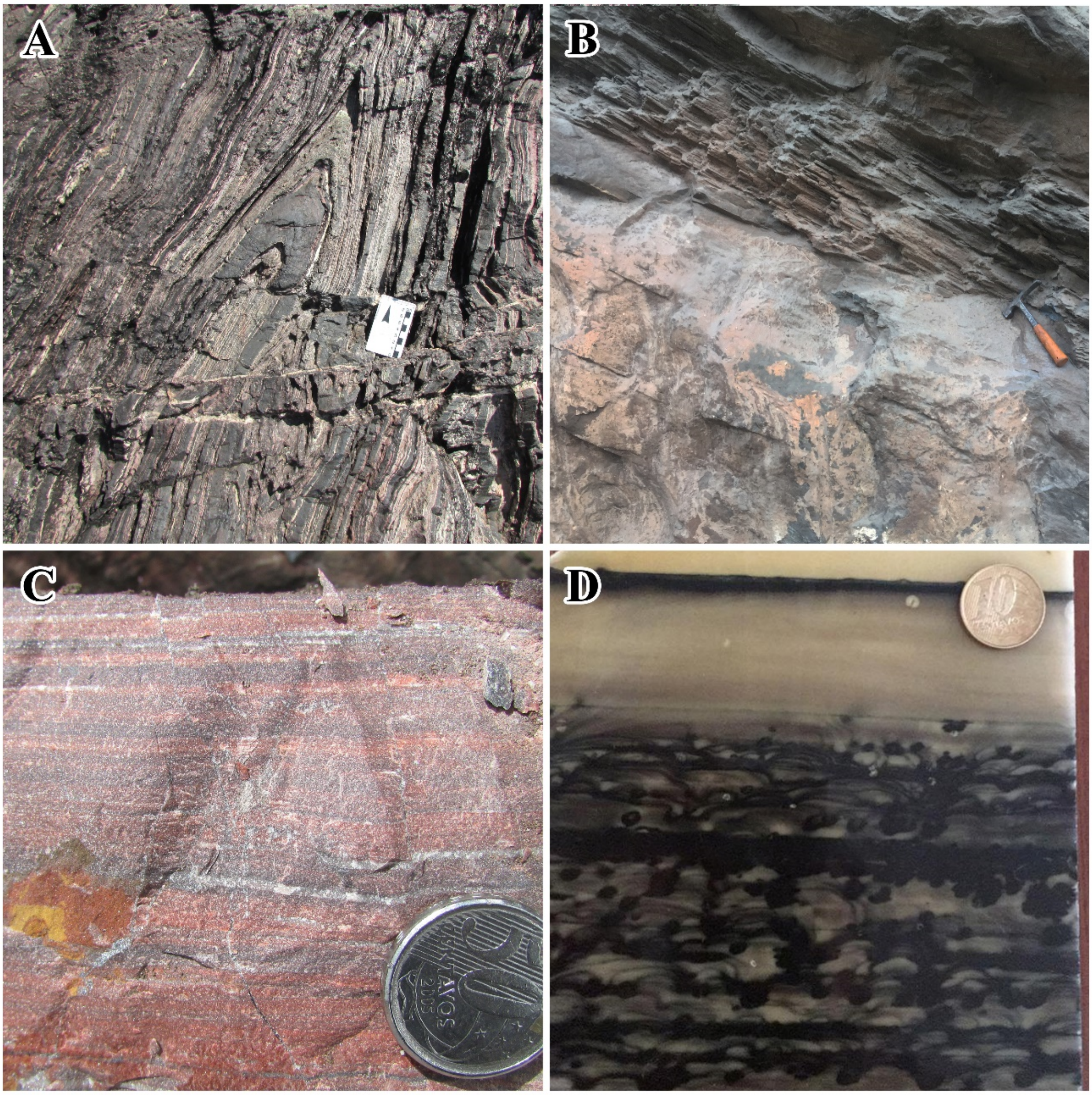


Figure 3. Itabira Group: (A) CAU1 facies — itabirite (X = 638,416.18; Y = 7,807,618.25; Z = 1,713 m); (B) GDR1 and GDR3 facies — dolomite and dolomitic mudstone (X = 643,411.603; Y = 7,746,329.701; Z = 1,081.6 m); (C) GDR1 facies — iron-rich dolomite (X = 638,900.029; Y = 7,781,831.391; Z = 1,383.2 m); (D) GDR2 facies — microbial mats dolomite hand specimen with well-preserved domal and laterally linked hemispheroids stromatolites and oncolites (X = 638,928.07; Y = 7,781,028.66; Z = 1,270 m). Coordinates are in UTM and WGS84 datum.

Table 5. Piracicaba Group facies and sedimentary processes.

Formation	Facies code	Facies description	Sedimentary processes
Barreiro	BRR3	Yellow rhythmite	Slightly coarser terrigenous input amidst clay settling within marine platform
	BRR2	Carbonaceous mudstone (grey or black)	Marine transgression clay settling with organic input being preserved by reducing conditions
	BRR1	Pink mudstone	Marine transgression and fair-weather clay settling
Taboões	TAB2	Laminated rhythmite (millimetric mudstone-siltstone and very fine sandstone in thin layers)	Subaqueous prodelta sand-silt-clay belt
	TAB1	Fine-grained, well-sorted, massive or thin laminated quartz sandstone	Deltaic progradation (delta front)
Fecho do Funil	FF5	Carbonaceous mudstones	Silt and clay (with organic input) settling in the continental platform
	FF4	Laminated rhythmite (alternating fine red sandstones and grey claystones with hummocky cross-stratification)	Storm-weather wave sedimentation of distal tempestites
	FF3	Fine- to medium-grained sandstone with low angle tabular cross-bedding	Wave action in upper or middle shoreface
	FF2	White-dark grey stromatolitic dolomite in lenses	Stromatolitic bioherms in the continental platform
	FF1	Laminated dolomitic mudstone	Silt and clay settling in the continental platform
Cercadinho	CCD6	Laminated rhythmite (alternating red silty sandstone and grey claystone with hummocky cross-stratification)	Storm-weather wave sedimentation of distal tempestites
	CCD5	Medium to coarse-grained quartz sandstone with cross-stratification	Storm-weather wave sedimentation of lenticular sand bars (proximal tempestites)
	CCD4	Rounded medium to coarse-grained lenticular ferruginous sandstone	
	CCD3	Chloritic shale	Fair-weather or storm wave weather in offshore marine settling
	CCD2	Sericitic ferruginous (very fine-grained plates of specularite, hence “silver”) shale	
	CCD1	Carbonaceous shale	

planar-bedded MOE5 sandstone represents the upper flow regime in this fluvial system.

The less common MOE6 and MOE7 facies, due to the fact that they are laminated siltstone (with minor fine sand inputs) and laminated mudstone, respectively, represent finer sedimentation (clays and silts settling) of river streams/abandoned channels and/or lake environments. Overall, the Moeda Formation is nearly 300 m thick and comprehends both alluvial fan and braided fluvial sedimentation (Miall 1978, 2010, Villaça 1981, Minter *et al.* 1990, Renger *et al.* 1994, Madeira 2018), as depicted in Figure 7. Fine-grained, well-sorted sandstones and mudstones that outcrop in the south-east of IQ most likely represent lacustrine sedimentation.

Each palaeocurrent data subset displayed in Figure 7 (from the authors' fieldworks, interpretations of facies lateral variations, and Villaça 1981) was collected in different geological domains of QF (i.e., Moeda Syncline, Curral Ridge, and Gandarela Syncline), and they were grouped accordingly. Overall, there were three main directions of sediment flow, from the NE, SE, and WSW.

The conformably and, locally, gradationally overlying Batatal Formation contains sericitic and graphitic mudstones, cherts, and banded iron formations. The BTT1 and BTT2 are alternated laminated mudstones facies, varying only in accessory mineral contents: organic content (carbonaceous mudstone) and its absence (sericitic mudstone). Both facies comprise a nearly 200 m thick sequence with great lateral continuity of marine sedimentation with sharp or gradational contact with the Moeda facies set. The less common BTT3 and BTT4 facies, as originally described by Dorr II (1969) made of rare quartzite/metachert and itabirites represent small pulses of chemical sedimentation in (as stated before) marine environments, prior to the onset of the environmental conditions responsible for the Itabira Group sedimentation. The Caraça Group thus records a rift to passive margin shift in the Minas Basin tectonic regime, being the Moeda Formation, the continental rift sedimentation in gradational contact with the Batatal marine transgression.

The Itabira Group contains the Cauê iron-rich Formation and the overlying Gandarela Formation. The mudstones in the upper few metres of the Batatal Formation are Fe-rich and they grade upwards into the overlying CAU1 facies, which is composed of banded iron formations (itabirite). This facies is parallel bedded and mostly homogeneous, which would imply shallow marine (passive margin) conditions for the iron oxides to precipitate and form such a rock fabric. Since it is a Lake

Figure 4. Piracicaba Group: (A) CCD1, CCD4, and CCD5 facies — carbonaceous shale, ferruginous sandstone, and quartz sandstone (X = 640,038.668; Y = 7,741,900.304; Z = 1,274.5 m); (B) CCD6 facies — rithmite with hummocky cross-stratification (X = 611,172.722; Y = 7,792,421.984; Z = 1,107.6 m); (C and D) FF2 facies hand specimen — stromatolite (X = 636,590.210; Y = 7,742,150.558; Z = 1,103.0 m); (E) FF4 facies — rhythmite with hummocky cross-stratification (X = 612,218.012; Y = 7,768,982.647; Z = 1,245.2 m); (F) FF2 and FF1 facies — dolomite lens within mudstones (X = 645,411.412; Y = 7,745,965.808; Z = 1,145.5 m). Coordinates are in UTM and WGS84 datum.

Superior-type BIF (Olivo *et al.* 1995), its depositional system is interpreted as a continental shelf. This facies, together with the CAU2, mark the oxyatmoversion (great oxidation event, also known as "GOE") in the Minas Basin, within a 500-m thick iron-rich succession, as the U-Pb zircon age of a metavolcanic layer within the Cauê BIF (Cabral *et al.* 2012) also matches the age of the GOE (Olejarz *et al.* 2021). The rare volcaniclastic facies (Dorr II 1969, Suckau *et al.* 2005, Cabral *et al.* 2012) suggests a small volcanism-related input to this marine sedimentation. Differences in the HREE signatures of itabirites suggest that dolomitic itabirites precipitated in shallower waters, receiving sediments from the continent, whilst quartz itabirite precipitated in deeper waters, with hydrothermal contribution (Spier *et al.* 2007).

The Gandarela Formation has gradational contact with the Cauê Formation and includes dolomites, limestones, dolomitic mudstones (GDR3), dolomitic iron formations (GDR1), and mudstones (Dorr II 1969). Carbonates (GDR2) in the middle part of the Gandarela Formation contain well-preserved domal and laterally linked hemispheroids stromatolites and oncolites (Souza and Müller 1984), indicating deposition in high-energy intertidal to shallow subtidal environments (Bekker *et al.* 2003). The GDR4 (dolorudite) is an intraformational reworking of the carbonates by waves or tides. All of the Gandarela Formation facies show a shallow marine depositional system (carbonate precipitation related). Similarly to the Cauê Formation, the Gandarela Formation also has volcanogenic facies (Dorr II 1969). In total, the estimated thickness for the Gandarela formation is 500 m.

The Cercadinho Formation has six facies and it lies at an erosional contact with the Itabira Group (Rossignol *et al.* 2020). The basal pebble conglomerate facies (described by Dorr II 1969) is found only at the Curral Ridge and is mainly a product of reworking of underlying units (pebbles of itabirites and sandstones). The Cercadinho main

Table 6. Sabará Group facies and sedimentary processes.

Group	Facies code	Facies description	Sedimentary processes
Sabará	SAB5	Mud-silt-sand rhythmite, often with high carbonaceous content or laminated fine sand/mudstone	Distal turbidites or low-density turbidite
	SAB4	Sandstone (wacke), often associated with rhythmites	Proximal turbidite: deposited by sand-silt-mud turbidity currents
	SAB3	Laminated mudstone	Distal turbidites or low-density turbidite
	SAB2	Diamictite – mainly granules and small pebbles up to 3 cm of quartzite and mudstone, rare quartzite cobbles or boulders	Subaqueous mud flow: Clasts suspended by cohesive forces provided by a matrix of fluid and fine-grained sediment (silty-clay mixture)
	SAB1	Pebble to cobble orthoconglomerate, with massive or graded bedding	Subaqueous debris flow

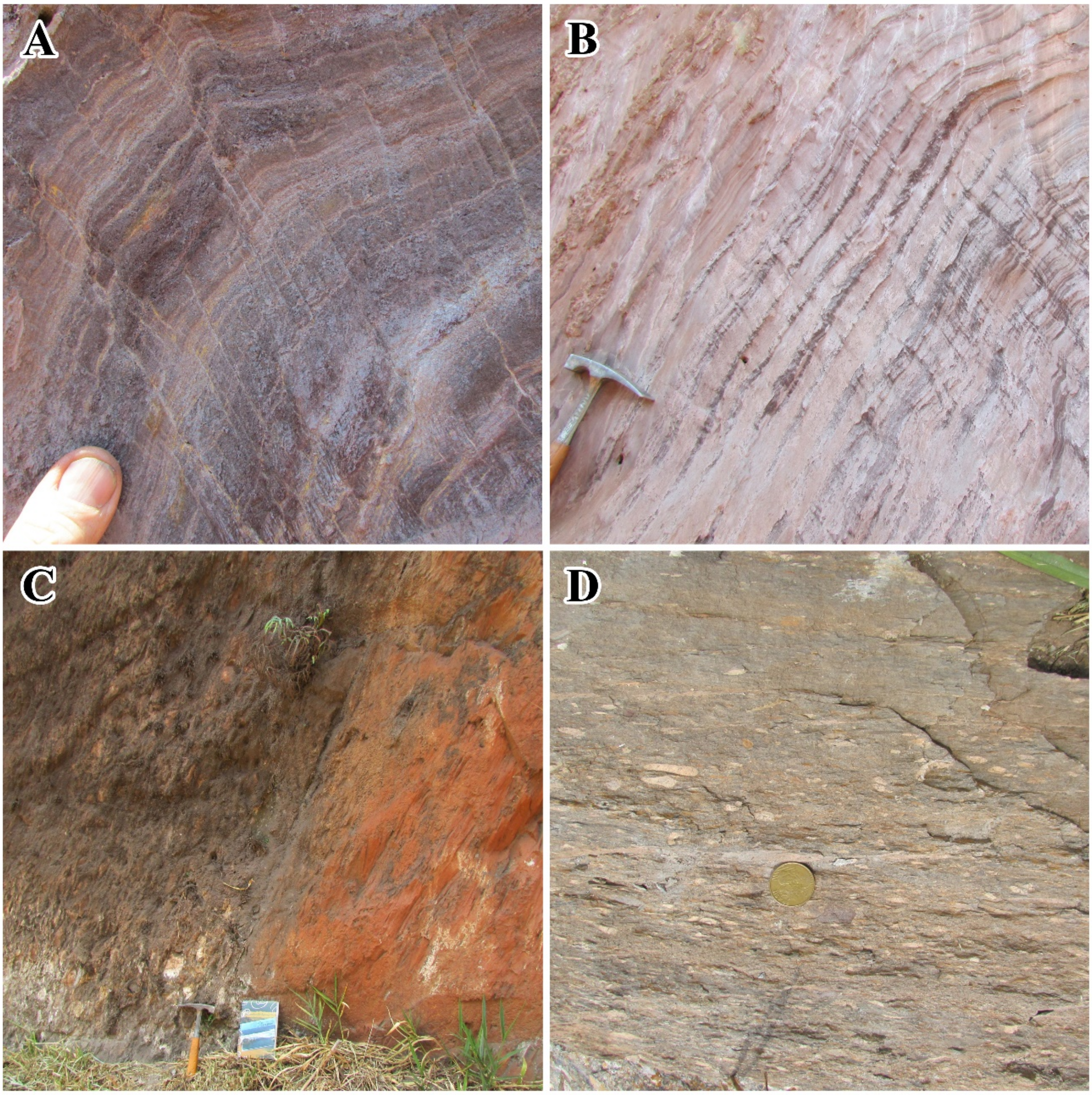


Figure 5. Sabará Group: (A) SAB5 facies — very crenulated rhythmite, or distal turbidite (X = 655,490.229; Y = 7,741,168.287; Z = 1,365.5 m); (B) SAB3 and SAB5 facies — laminated mudstone and rhythmite, or distal turbidites (X = 655,498.996; Y = 7,741,106.157; Z = 1,384.3 m); (C) SAB4 (sandstone / wacke) and SAB2 (diamictite) facies contact (X = 655,498.996; Y = 7,741,106.157; Z = 1,384.3 m); (D) SAB1 gravelly conglomerate with graded bedding, deposited by turbidity currents (X = 614,564.714; Y = 7,767,873.112; Z = 1,241.1 m). Coordinates are in UTM and WGS84 datum.

Table 7. Itacolomi Group facies and sedimentary processes.

Group	Facies code	Facies description	Sedimentary processes
Itacolomi	ITA5	Gravelly sandstone with trough cross-bedding	Sinuous-crested subaqueous dunes
	ITA4	Gravelly sandstone with low angle tabular cross-bedding and tangential foresets	Cross-cutting sand bars in subaqueous dunes (straight crested sandy ripples)
	ITA3	Gravelly sandstone with planar stratification	Plane-bed flow (upper flow regime)
	ITA2	Granule and pebble orthoconglomerate with coarse quartz sand matrix and trough cross-bedding	Longitudinal bars or minor channel fills in braided rivers
	ITA1	Rounded, high sphericity orthoconglomerate (pebbles and cobbles mainly of quartz and quartzite)	Gravitational (debris) flow sedimentation

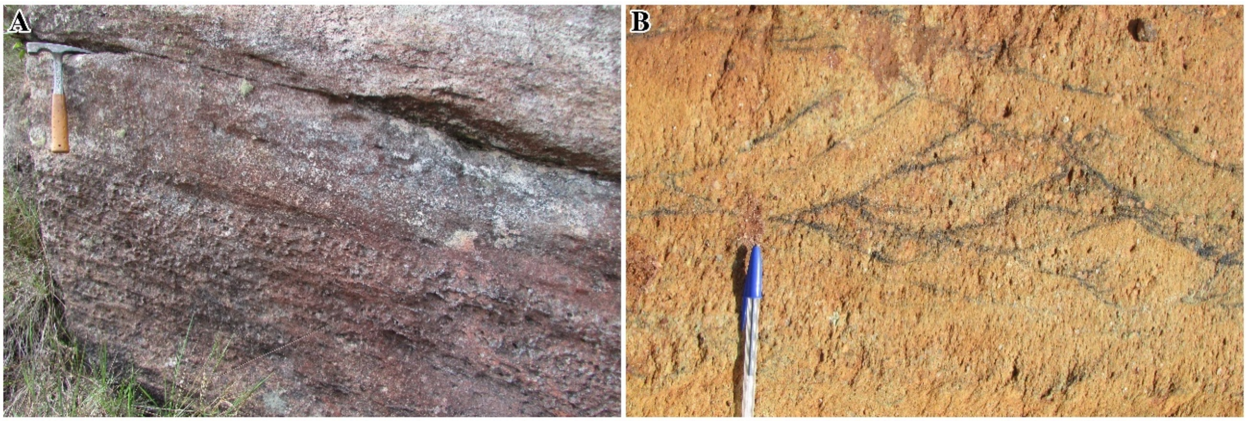


Figure 6. Itacolomi Group: (A) ITA3 facies — gravelly sandstone with planar stratification (X = 657,277.655; Y = 7,739,784.725; Z = 1,586.1 m); (B) ITA5 facies — gravelly sandstone with trough cross-bedding (X = 641,790.022; Y = 7,731,895.969; Z = 1,322.7 m). Coordinates are in UTM and WGS84 datum.

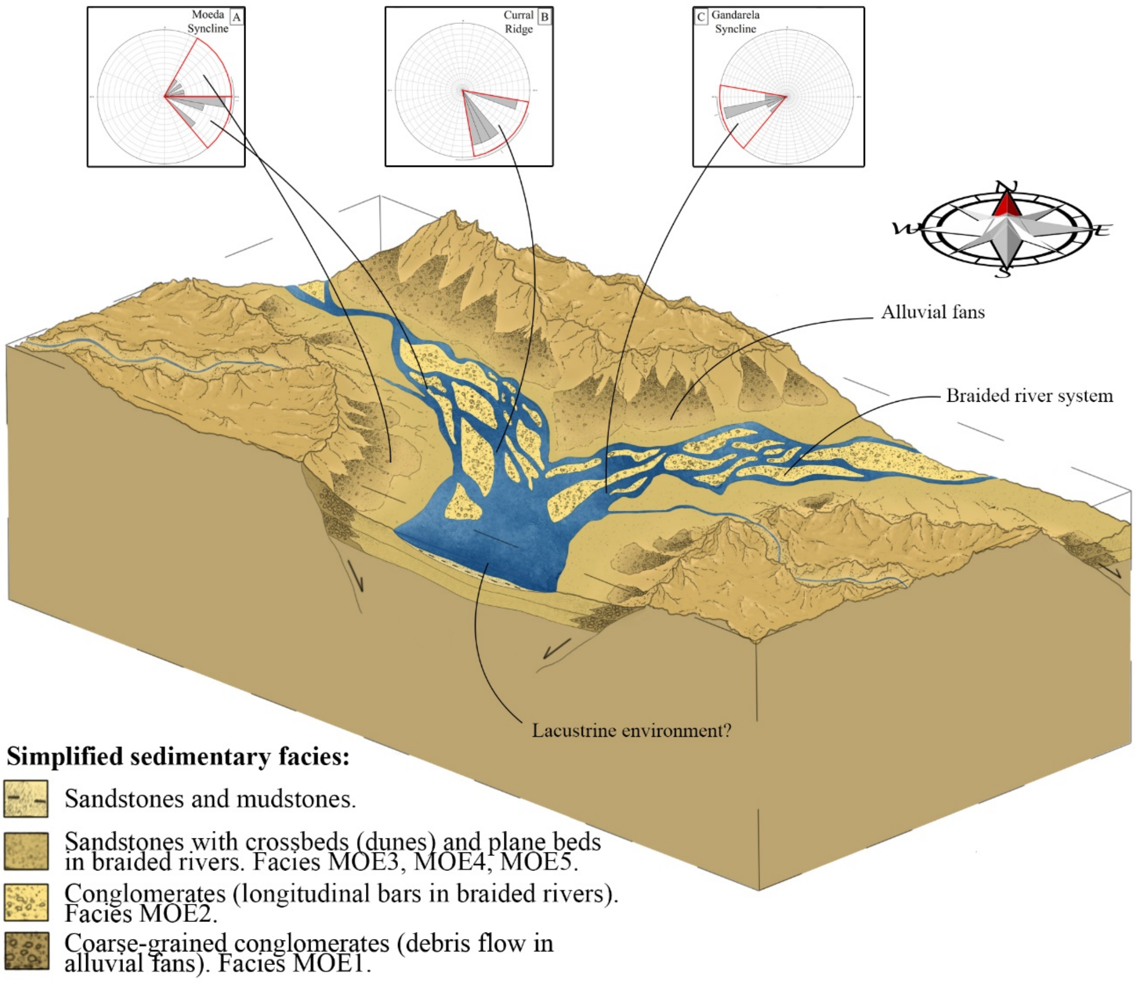


Figure 7. Palaeogeography of the rift stage of the Minas Basin: Moeda Formation. Compass and rose diagrams indicate sediment flow direction based on current day geographic coordinates (A is from Moeda Syncline; B is from Curral Ridge; C is from Gandarela Syncline). Palaeocurrent data are from the authors' fieldworks, interpretations of facies lateral variations, and Villaça (1981).

facies are the CCD1, CCD2, and CCD3 (carbonaceous, ferruginous, and chloritic shales, respectively). The CCD4 (rounded medium-grained ferruginous sandstone) is often found interbedded with the shales of CCD1, CCD2 or CCD3. In a similar geometry, the CCD5 (medium- to coarse-grained quartz sandstone) is found within the shales (in lenses), as well as the CCD6 facies (laminated rhythmite) does. The latter, found in the Curral Ridge, presents a hummocky cross-stratification, thus indicating a shallower marine environment to the NW of the QF with storm activity. A shallower marine sedimentation is also evidenced by the rare dolomite lenses facies (Dorr II 1969). All of the six facies of this formation are approximately 500 m thick and are interpreted as a result of marine shelf bars (Garcia *et al*. 1988) or shelf sand bars sedimentation in the offshore-shoreface transition zone, with lenticular sandstones intercalated with mudstones. Mud and fine sand deposits intercalation or mud beds record several episodes of distal storm or post-storm events. The thin conglomerate may be due to the erosion, as a result of storm waves on the shelf or the influence of deltas with greater erosive power in the coastal environment of the continental shelf.

The FF1 facies is the most common in the Fecho do Funil Formation, composed of laminated dolomitic mudstone. It is often in sharp contact with white/dark grey stromatolitic dolomite in lenses of the FF2 facies. Less commonly, there are a few up to 40 cm beds of FF3 fine- to medium-grained sandstone with low angle tabular cross-bedding within the FF1 facies. To the top of the formation, there is a layer of FF4 facies (laminated rhythmite: alternating red silty sandstone and grey claystone), a few dozen metres thick, with a hummocky cross-stratification pattern, indicating storm activity in shallow marine context. Another common sedimentary facies of this unit is the FF5, made of thin beds of carbonaceous mudstones, preserved in reducing environments. Overall, the total thickness for Fecho do Funil Formation is estimated at approximately 300 m and its depositional system is interpreted as a coastal environment, subtidal, with carbonaceous and carbonatic pelites and microbial reefs (bioherms) made up by stromatolites that have a wide variety of morphologies (Dardenne and Campos Neto 1975). It possibly had a low relief source area, with coastal sedimentation of carbonaceous and carbonatic pelites and bioherms in a shallow marine ramp. The whole formation likely represents a regressive cycle with the deeper water facies at the base (pelites) and upward shallowing (stromatolite dolomite lenses) trend towards the top (Bekker *et al*. 2003).

The overlying Taboões Formation (maximum thickness of 120 m) presents the TAB1 facies and is made of fine-grained, very well-sorted, laminated quartz sandstone. The other sedimentary facies for this stratigraphic unit is the TAB2, which is also made of a fine-grained terrigenous rock: a rhythmite (alternating siltstone and fine sandstone layers). Both facies can be interpreted as a result of a delta depositional system. To the north, in Curral Ridge, the TAB1 sandstones outcrop, with thicknesses that range from 70 to 150 m, possibly representing delta front facies. In the central region of the QF (Moeda Syncline), the rhythmites and pelites (TAB2) are more representative, approximately 30 m thick, representing the prodelta facies.

The Barreiro Formation is a fairly homogeneous unit, concerning its constituting rock type, with a maximum thickness of 120 m and made of three alternating BRR1, BRR2, and BRR3 facies: pink mudstone, carbonaceous (grey) mudstone, and yellow rhythmite. The depositional systems interpreted for this unit are the continental shelf (below the wave base).

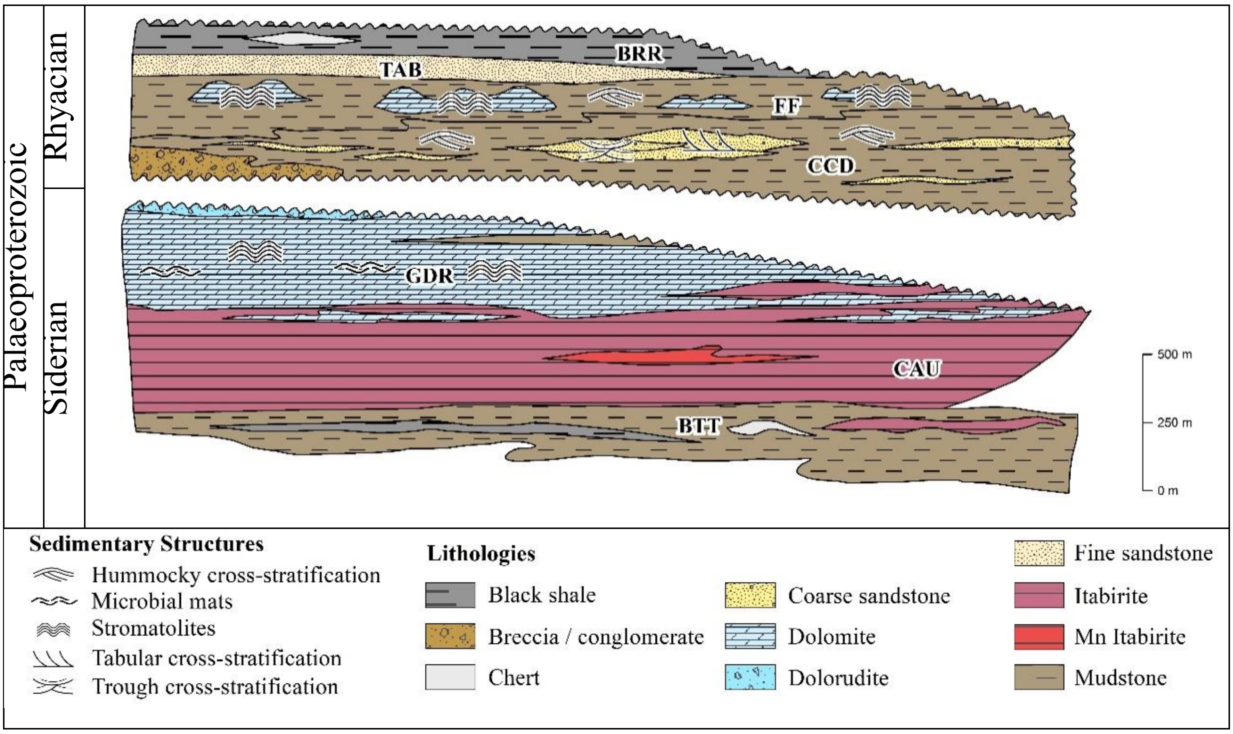
The depositional systems identified for the sedimentary facies from the Batatal Formation to the Barreiro Formation are all related to a passive margin tectonic regime, as depicted in Figure 8.

The overlying Sabará Group, approximately 3,500 m thick, has five facies: conglomerates (orthoconglomerate and diamictite), sandstones, laminated, and massive pelites. The SAB1 (conglomerate facies) overlies the Piracicaba Group with an erosional contact (unconformity) and was deposited by subaqueous debris flow. This facies often gradates towards the SAB2 facies, the diamictite, deposited also by the same sedimentary process (subaqueous debris flow). The SAB3, SAB4, and SAB5 facies were deposited by mass flow and turbidity currents of high and low density, thus representing proximal and distal turbidites. The debris flow facies are thicker at the base of the group, but they still exist in thinner beds (up to a few metres thick) towards the top. The most abundant facies is the SAB3, the laminated mudstone, deposited by distal turbidity currents, as the interbedded SAB5 (rhythmite, often with high carbonaceous content) facies also was. The SAB4 (wacke) facies was deposited by mass flow/high-density turbidity currents and, therefore, interpreted as a part of the proximal turbidites. All of the five facies make the submarine fan, with gravitational subaqueous debris flow and turbidite currents depositional system (Reis *et al*. 2002, Arnott 2010). Since it lies within a foreland basin (in the foredeep), close to a building orogen, the term *flysch* applies (as previously interpreted by Dorr II 1969) (Figure 9).

Finally, the Itacolomi Group (approximately 2,000 m thick) is made of six facies. The ITA1 and ITA2, made of orthoconglomerates most likely were made by proximal alluvial fans sedimentation and by gravel-filled longitudinal bars in braided rivers (Miall, 1978, 2010). The facies ITA3, ITA4, and ITA5, since they are made of gravelly sandstones, a poorly sorted sedimentary rock with both cross and planar bedding, the facies association allows the interpretation of medial to distal alluvial fans and/or braided stream channels sedimentation (upper flow regime for the planar beds, as well as lower flow regime for the subaqueous dunes and cross-beds). Within the Ouro Branco Ridge, two finer grained facies (one of which suggesting flaser beds, according to Alkmim 1987) were identified (ITA6 and ITA7) and are interpreted as the result of tidal flat sedimentation. In summary, this entire succession is related to alluvial and fluvial (braided stream channels) molasse, with subordinate tidal flat depositional systems (Figure 10).

SYSTEM TRACTS AND SEQUENCES

The system tracts are defined as the lateral succession of the depositional systems deposited at the same time, which tend to form specific stratigraphic frameworks as the geological history evolves (Catuneanu *et al.* 2005, Catuneanu 2006). Those frameworks are the stratigraphic surfaces themselves, made by



Stratigraphic units: BTT: Batatal Formation; CAU: Cauê Formation; GDR: Gandarela Formation; CCD: Cercadinho Formation; FF: Fecho do Funil Formation; TAB: Taboões Formation; BRR: Barreiro Formation.

Figure 8. Passive margin sedimentation within Minas Basin.

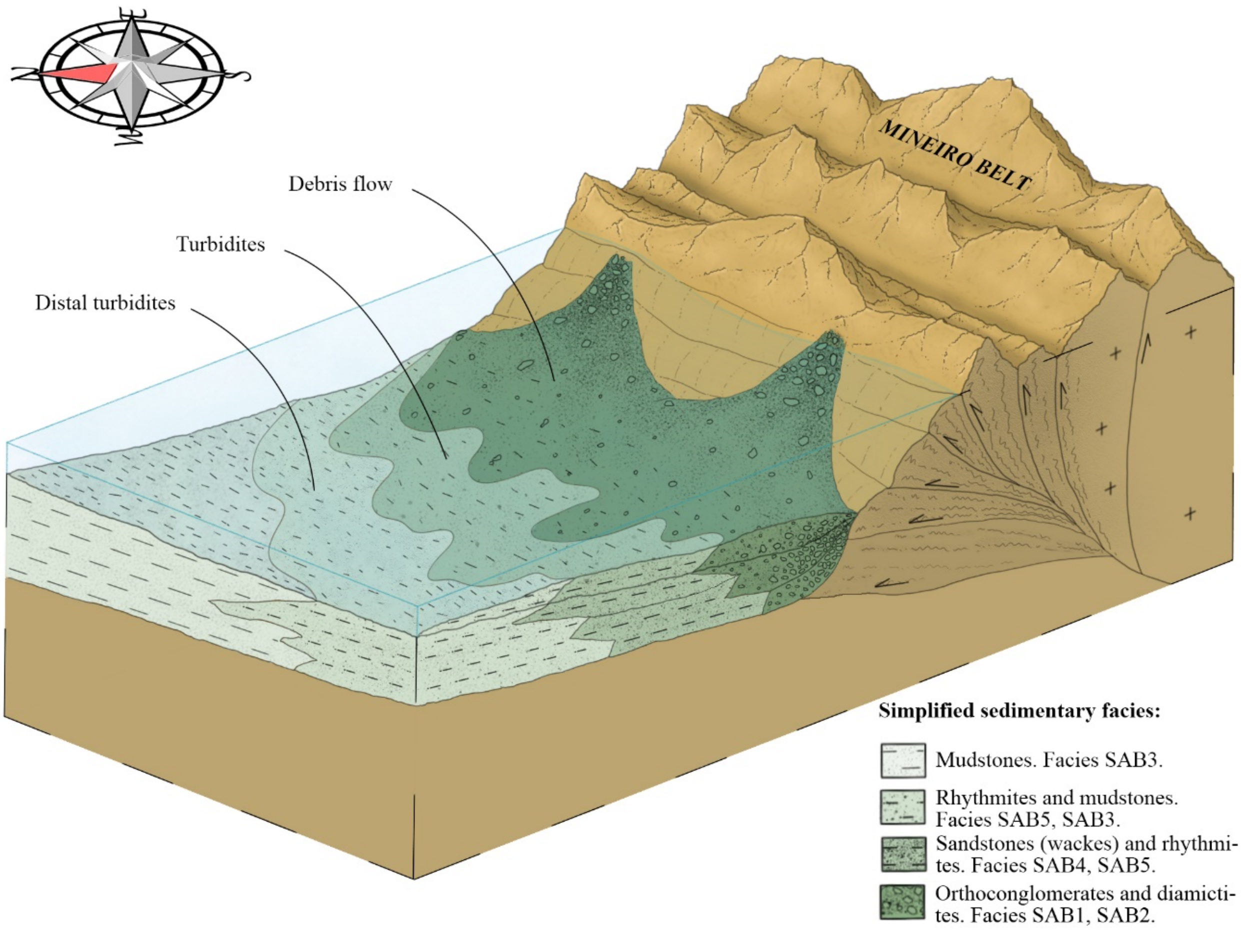
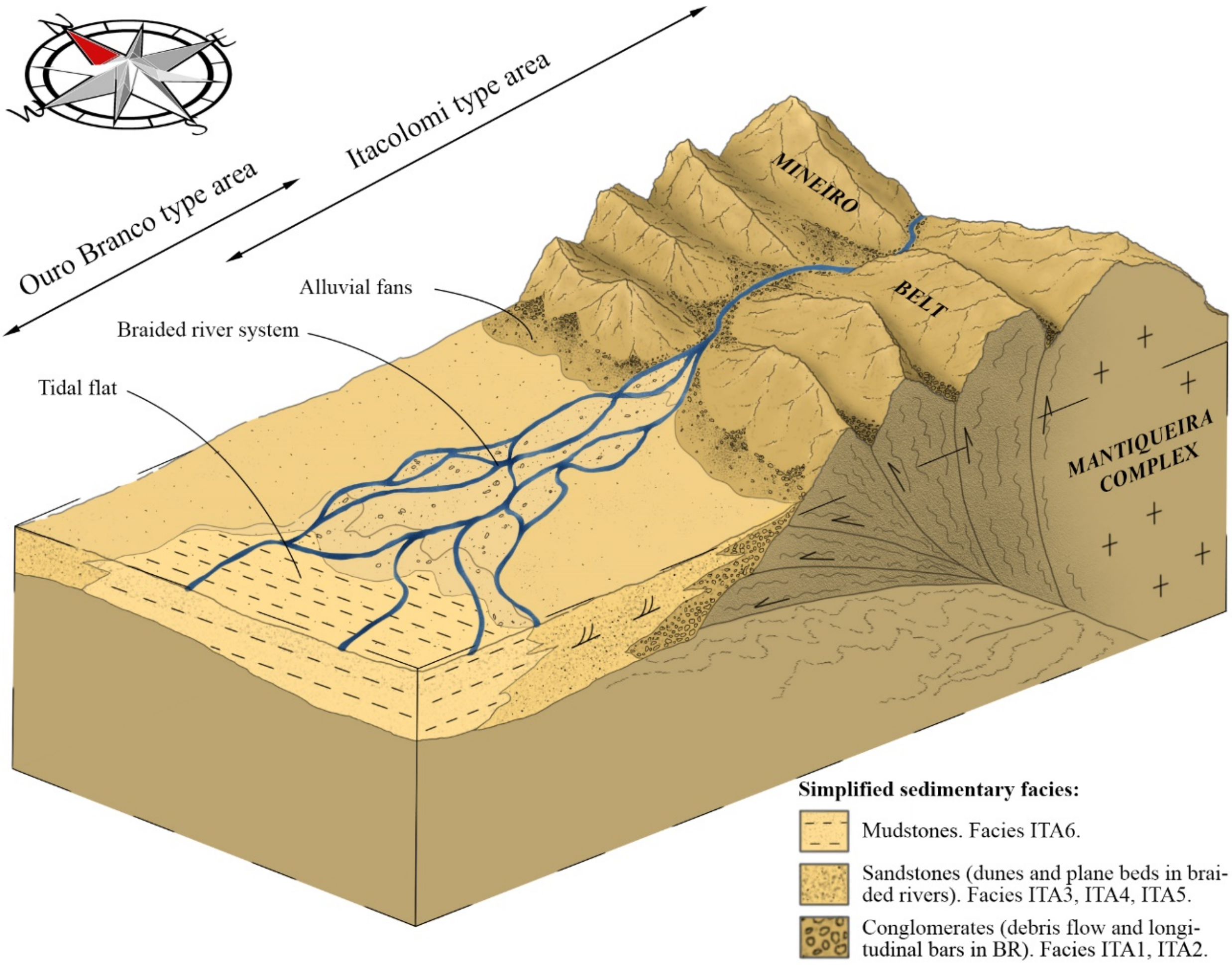


Figure 9. Sabará Group foreland (flysch) sedimentation. São Francisco palaeo-craton lies to NW and orogenic belt to SE. Compass indicates sediment flow direction based on current day geographic coordinates.



BR: Braided Rivers.

Figure 10. Itacolomi Group foreland (molasse) sedimentation. Reverse faults represent the Mineiro Belt orogenesis. Compass indicates sediment flow direction based on current day geographic coordinates.

contemporary or genetically related strata, and some of them mark the limits of the sequences, driven by both the sea-level change and sedimentation rates. The goal of this section is to provide an interpretation of the sequence stratigraphic framework of the Minas-Itacolomi Basins.

The Moeda Formation has many alluvial fans and high-energy braided river facies (Villaça 1981, Madeira *et al.* 2018) (Figure 7). Fine-grained, well-sorted sandstones and mudstones that outcrop in the central and south-eastern areas of IQ are interpreted as a lacustrine environment (Madeira *et al.* 2018). Normal faults are inferred, considering the occurrence of thick alluvial fans, and they represent the rift phase (with mechanic subsidence) of the Minas Basin geological evolution. This depositional context is considered LST, as continental sedimentation predominates within the basin at this time.

The Batatal Formation hosts pelitic facies, and locally, cherts, and banded iron formations. It comprises the beginning of a TST, as the sea level rises, leading the Minas Basin towards a marine platform development. This interpretation makes possible to classify the contact between Moeda and Batatal Formations as the maximum regressive surface (MRS) stratigraphic surface. Sediment input is lessened with the sea-level rise, allowing large-scale clay settling (and occasionally, chemical and organic matter precipitation/deposition) in the basin. This Formation has a gradational contact with the overlying Cauê Formation, which is mostly homogeneous, with thick itabirite beds and minor mudstones and carbonate-rich iron formations. Cauê Formation is the continuity of the TST, with further lower rates of terrigenous inputs and chemical precipitation dominance, where large amounts of Fe^{2+} ions were being oxidised to Fe^{3+}. Hydrothermal submarine contribution was responsible for higher concentrations of Fe^{2+}, as the geochemical studies of Spier *et al.* (2007) suggest.

A maximum flooding surface (MFS) is inferred at the mid-portion of Cauê Formation, possibly where the clay/mud and the volcaniclastic beds lie (Dorr II 1969, Suckau *et al.* 2005, Cabral *et al.* 2012), prior to the carbonate-rich iron formations and carbonate beds that represent the transition to Gandarela Formation. Above the MFS, there is a gradual increase of terrigenous input, shifting towards a progradational pattern, with the onset of a slow marine regression, and further shallowing of marine facies. This sedimentary setting comprises the HST, which takes place throughout the entire Gandarela Formation. This stratigraphic unit's facies indicate the existence of both shallow water carbonates (stromatolites and oncolites, Souza and Müller 1984, Bekker *et al.* 2003) and deep-water carbonates and pelites, thus making a palaeoproterozoic carbonate platform. The first depositional sequence (Sequence 1) of Minas Basin is made by all the four basal formations (i.e., Moeda, Batatal, Cauê, and Gandarela), and the three aforementioned system tracts (i.e., LST, TST, and HST).

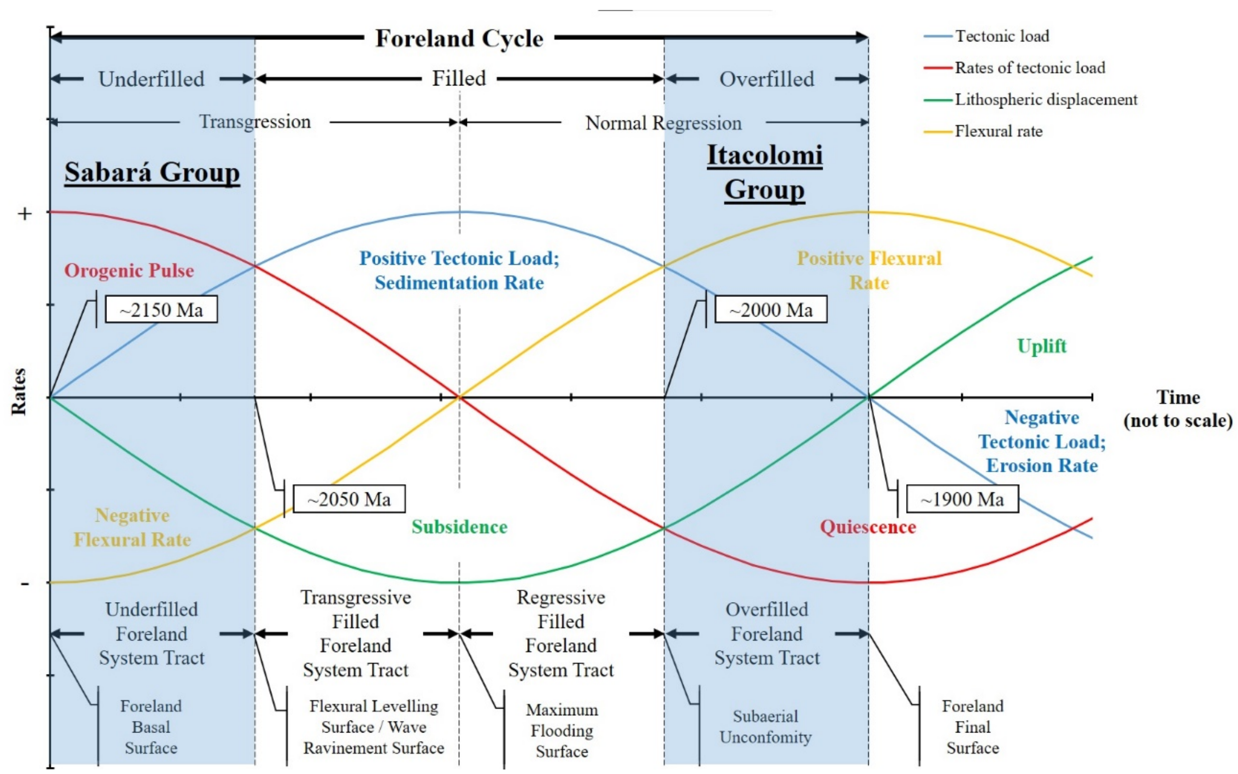
Between the Itabira and Piracicaba Groups, there is an important discordance in the Minas Basin evolution, which probably represents a hiatus of ca. 60 Ma (Rossignol *et al.* 2020). This event is still little understood, but can be explained by a sea-level fall and consequent erosion of Itabira Group, on the late stages of the HST. According to Rossignol *et al.* (2020), the discordance is due to the onset of Mineiro Belt Palaeoproterozoic tectonics.

The Piracicaba Group's basal Cercadinho Formation hosts sandstone lenses amidst mudstones, as platform sandbars in the marine environment. They are either amalgamated sandbars (shoreface) or isolated within the pelites of the platform (offshore). Such depositional environment belongs to a TST, with progressive supply reduction. At the base, it is possible to infer a transgressive ravinement surface (TRS), as the sea level rises. Towards the top, the Cercadinho Formation transitions to the Fecho do Funil Formation, with the reduction of sand lenses, and further onset of dolomitic lenses. An MFS can be inferred at the base of Fecho do Funil Formation prior to the carbonate lenses, where thick (sometimes discontinuous) carbonaceous mudstone beds lie. The upper Fecho do Funil Formation represents a shallowing HST that enabled stromatolitic dolomite lenses and fine-grained shoreface sandstones to be formed.

The Taboões Formation's delta front and prodelta facies lie directly over the platform mudstones of Fecho do Funil, which imply an abrupt change in sediment input (progradation increases and the sea level is even lower, as shoreline moves basinward), characteristic of an LST. This geological contact can be interpreted as a correlative conformity (therefore, an interpreted discordance, since the system tracts shift from a Highstand to a Lowstand), which marks the end of the Sequence 2 (that started in the base of Piracicaba Group). Taboões and Barreiro's contacts are sharp, and as Taboões thins out, Barreiro Formation sometimes overlies directly the Fecho do Funil Formation (another evidence for the correlative conformity interpretation). Barreiro's carbonaceous mudstones and rhythmites are deposited onlapping the Minas Basin, at a TST, and the unit's upper contact is as erosive one that ends the Sequence 3.

Sequences 4 and 5 (to be described next) are deposited in a foreland basin (Alkmim and Marshak 1998, Reis *et al.* 2002), which requires a different system tracts classification, if compared to the rift/passive margin (classic) sequence stratigraphy, where base-level changes and sedimentation rates are the main drivers of the stratigraphic framework. In this type of basin (Foreland), the tectonic load and flexural behaviour of the lithosphere play the major roles in stratigraphic control, making the eustasy a secondary agent, or merely a consequence. For that purpose, different system tract classification is hereby proposed (Figure 11), based on its Underfilled, Filled, and Overfilled stages (Sinclair and Allen 1992, Crampton and Allen 1995, Catuneanu 2004).

The main driver for the stratigraphic framework of a foreland basin is the tectonic load and its flexural consequences in the lithosphere. The derivative of this property (i.e., the tectonic load rate) defines orogenic pulses and periods of quiescence.



Source: based on Sinclair and Allen (1992), Crampton and Allen (1995) and Catuneanu (2004).

Figure 11. Foreland Basin Sequence Stratigraphy proposition and its application in Sabará and Itacolomi Groups within Minas Basin (Underfilled and Overfilled Foreland, respectively).

In addition, the tectonic load is the cause of the lithospheric displacement (function of both orogenic load mass and flexural rigidity of lithosphere), resulting in subsidence when it is positive and uplift when it is negative. The derivative of the lithospheric displacement is the flexural rate, which is directly involved in the accommodation space generation in the basin. Finally, the sedimentation rate increases with the gradual uplift of the fold-thrust belt and decreases with its erosion. All of these properties and how they correlate with each other over time create specific geological conditions for the strata to be arranged. See Figure 11 for better comprehension.

The Sabará Group, whose depositional system is composed of submarine fans, along with debris flow, mass flow, and frequent turbidite sedimentation (facies SAB1 to SAB5), the system tract identified is the Underfilled Foreland System Tract (UFST), since it correlates to the period of time when the orogenic pulse was greater than the sedimentation rate. The Itacolomi Group, in its turn, records an Overfilled Foreland System Tract (OFST), since it is mainly composed of alluvial and fluvial molasse sediments (Alkmim 1987, Alkmim and Martins-Neto 2012). These sediments were deposited when both the tectonic load and the sedimentation rate were smaller than the flexural rate (i.e., when the accommodation space generation was in its decline, as the orogenic belt carried on being eroded away and the basin, being overfilled). The Filled phase of the foreland cycle was probably eroded away by the onset of the Overfilled stage, as the contact between Sabará and Itacolomi Groups is of erosive nature. Moreover, it is in this late stage's nature to rework some (if not all) of the final marine sediments of the basin, as the initial subsidence gradually diminishes by the isostatic compensation of the fold-thrust belt erosion.

The chronostratigraphic chart for the Minas-Itacolomi basins (Figure 12) summarises all the results and interpretations from the facies logging.

SEDIMENTARY PROVENANCE

A statistical analysis (Figure 13) of the detrital zircon U-Pb database (compiled from Machado *et al.* 1992, Machado *et al.* 1996, Hartmann *et al.* 2006, Koglin *et al.* 2014, Jordt-Evangelista *et al.* 2015, Nunes 2016, Dopico *et al.* 2017, Dutra 2017, Duque 2018, Dutra *et al.* 2019) for the Minas-Itacolomi stratigraphic units was carried out, through histograms, Probability Density Plots (PDPs), and adaptive Kernel Density Estimates (KDEs) from the Java-based DensityPlotter software (Vermeesch 2012). The PDP and histogram from the compilation of all the available Moeda Formation zircon U-Pb data were not carried out due to the large amount of spots/zircons, (therefore, large $^{207}Pb/^{206}Pb$ ages data set, N = 1,980), which tend to over smooth the probability density function (Vermeesch 2012). The KDE was carried out instead, which lead to more reliable results through Provenance R software package (Vermeesch *et al.* 2016). Only the zircon ages with 95% or greater degree of concordance were accounted in the plots, with the exception of the ones from Machado *et al.* (1996), whose concordance degrees were not mentioned in their study (they still were accounted for in the plots).

Figure 13A shows the Moeda Formation's detrital zircon U-Pb ages histogram, with a large amount of spots/zircons (N = 1,980, compiled from Machado *et al.* 1996, Hartmann

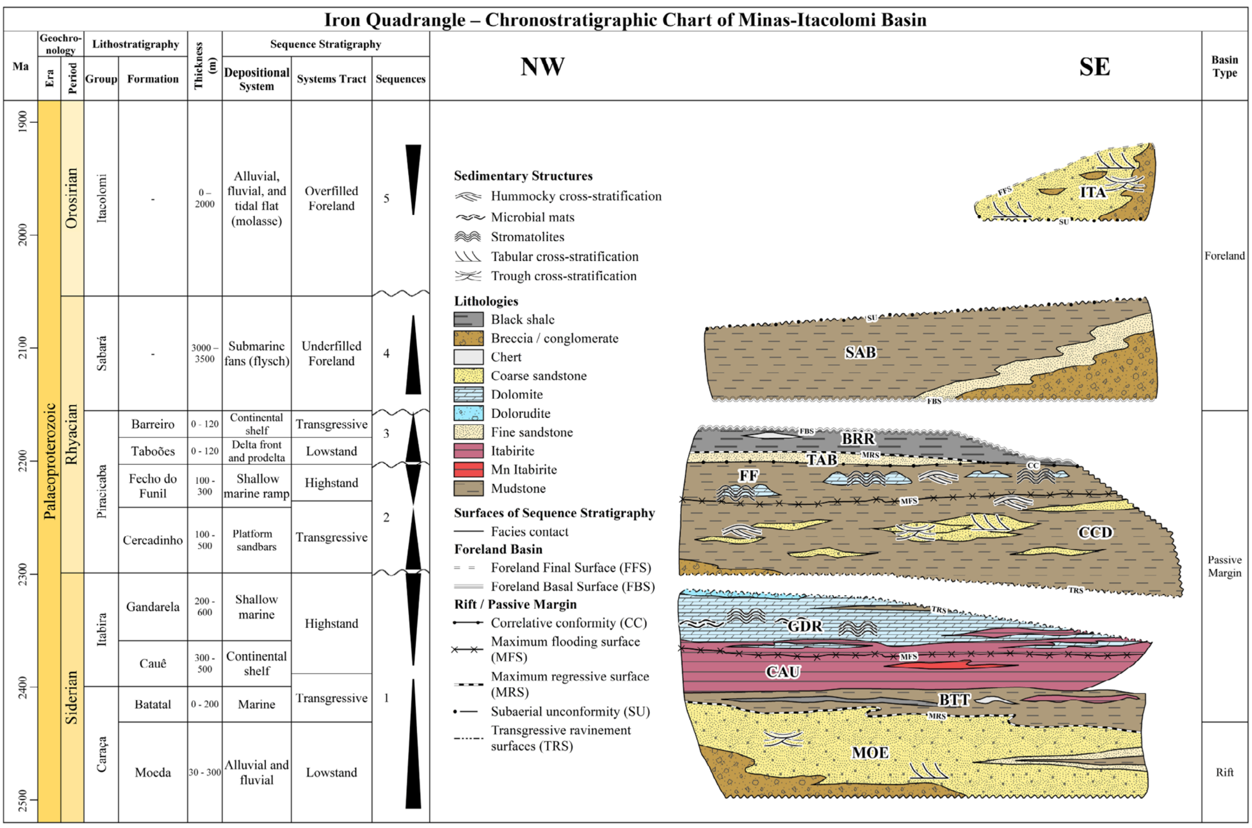
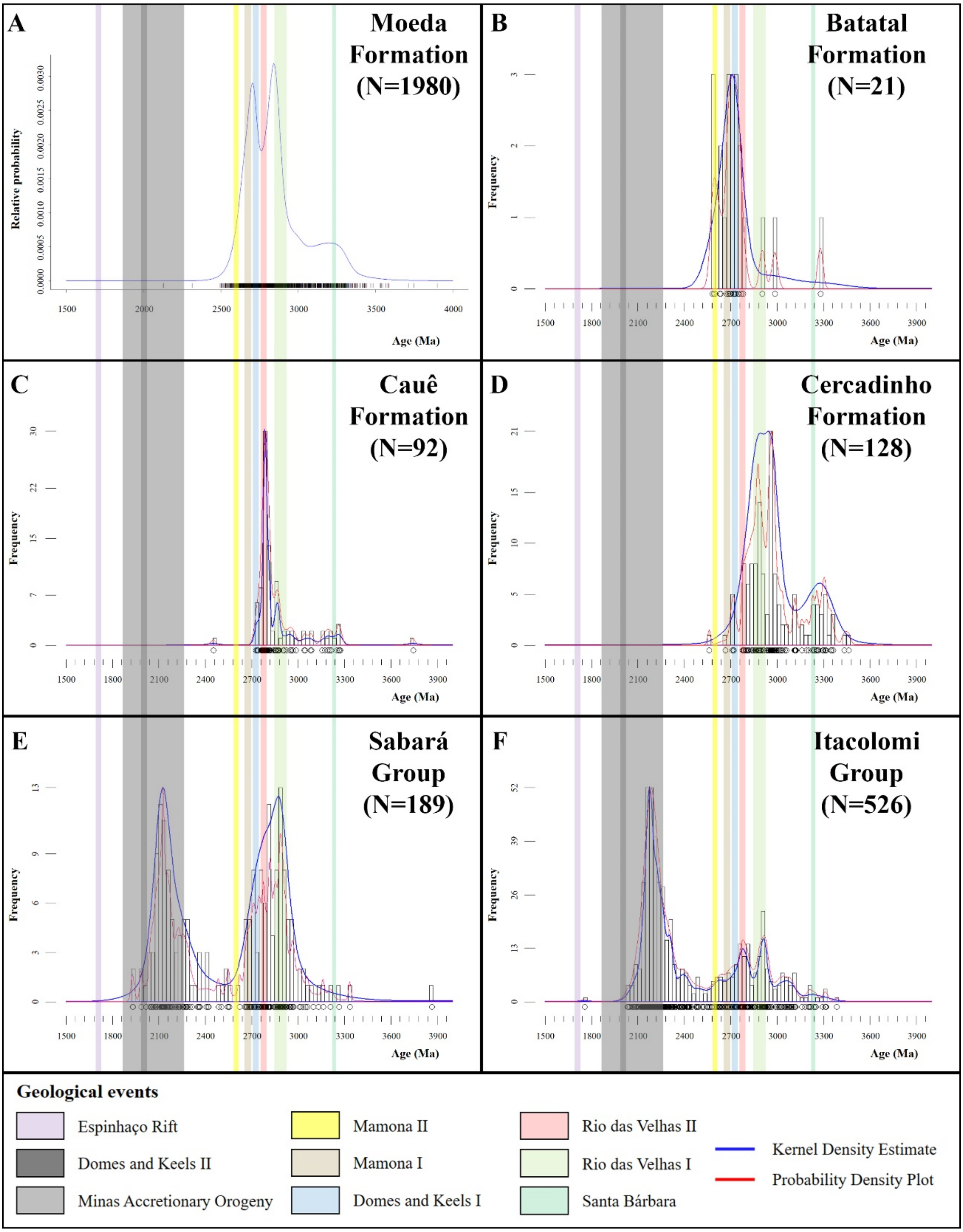


Figure 12. Chronostratigraphic chart of Minas-Itacolomi Basins. Ages for the stratigraphic units are according to Alkmim and Martins-Neto (2012). Black triangles indicate sea-level rise (triangle pointing upwards) and fall (pointing downwards).



Source: data from Machado *et al.* (1992), Machado *et al.* (1996), Hartmann *et al.* (2006), Koglin *et al.* (2014), Jordt-Evangelista et al. (2015); Nunes (2016), Dopico *et al.* (2017), Dutra, (2017), Duque (2018), Dutra *et al.* (2019).

Figure 13. Detrital zircon U-Pb ages statistics: histograms, adaptive Kernel Density Estimates (KDEs), and Probability Density Plots (PDPs). (A) Moeda Formation. (B) Batatal Formation. (C) Cauê Formation. (D) Cercadinho Formation. (E) Sabará Group. (F) Itacolomi Group.

et al. 2006, Koglin *et al.* 2014, Nunes 2016 and Dopico *et al.* 2017), mainly due to its sedimentary rock-type abundance (in this stratigraphic unit, there are fewer pelitic or chemical sedimentary rock types, which tend to present less detrital zircons, as different sedimentary processes or energy levels are involved, than coarser terrigenous sedimentary rocks). The Moeda Formation shows at least three modes in its detrital zircon age distribution: the first, and of lesser importance, being simultaneous with Santa Bárbara pluton emplacement; the second and of larger relative probability, probably related to the Rio das Velhas I event; and the last mode lies within the first domes and keels pulse or the Mamona I event.

Figure 13B shows the Batatal Formation's detrital zircon U-Pb ages histogram, with a small amount of spots/zircons (N = 21, compiled from Dopico *et al.* 2017). This small statistical population can be explained by the predominance of pelitic rocks in this stratigraphic unit. The Batatal Formation showed one KDE mode coeval with both Domes and Keels II and the Mamona I events, and it also showed five PDP modes, as it follows: the first related to Santa Bárbara event; the second and third related to Rio das Velhas I; the fourth and of greater relative probability concordant to the KDE, and the fifth mode coeval with the Mamona II event.

Figure 13C shows the Cauê Formation's detrital zircon U-Pb ages histogram, with a small amount of spots/zircons (N = 92, compiled from Dopico *et al.* 2017). This small statistical population can be explained by the predominance of chemical sedimentary rocks in this stratigraphic unit. The Cauê Formation showed two main modes (both KDE and PDP alike) coeval with Rio das Velhas I and II events.

Figure 13D shows the Cercadinho Formation's detrital zircon U-Pb ages histogram, with a small amount of spots/zircons (N = 128, compiled from Machado *et al.* 1996, Dopico *et al.* 2017, and Dutra 2017). This slightly greater statistical population can be explained by the occurrence of sandstone lenses within the pelites in this stratigraphic unit. The Cercadinho Formation showed two main modes (both KDE and PDP alike) coeval with Santa Bárbara and Rio das Velhas I events.

Sabará Group (Figure 13E, N = 189, compiled from Machado *et al.* 1992, Machado *et al.* 1996, Hartmann *et al.* 2006, Dopico *et al.* 2017 and Dutra *et al.* 2019) zircon U-Pb age distribution showed a bimodal behaviour, with the first peak along Archaean events (specially coeval with Rio das Velhas I) and the second peak lying within the Minas Accretionary Orogeny (Transamazonian, i.e., Mantiqueira Complex — Cutts *et al.* 2020) age range. Both modes show similar relative probability.

The Itacolomi Group (Figure 13F, N = 526, compiled from Machado *et al.* 1996, Hartmann *et al.* 2006, Jordt-Evangelista *et al.* 2015 and Duque 2018) shows a similar distribution (bimodal, with the same age ranges), but with different relative probabilities: the Minas Accretionary Orogeny peak is significantly greater than the Archaean age peak.

The sedimentary provenance for the three stages in the geological evolution of the Minas-Itacolomi Basin is represented in Figure 14. The rift stage (Figure 14A, N = 1,980, Moeda Formation), as stated before, shows at least three modes in its detrital zircon age distribution: one coeval with Santa Bárbara pluton emplacement; the second and of larger relative probability, related to the Rio das Velhas I event; and the last one lies within either the first domes and keels pulse or the Mamona I event. Additionally, as Figure 7 previously introduced, this Formation showed three main directions of sediment flow, from the NE, SE, and WSW that also support these geochronological provenances. This zircon age distribution is concordant to Cawood *et al.*'s (2012) study that states that extensional settings contain greater proportions of zircons with older ages (than the depositional age of sediment) that reflect the history of the underlying basement (in this case, both the Rio das Velhas Supergroup and the granitic-gneissic complexes).

The passive margin stage (Figure 14B, N = 241) has similar pattern, since it is a logical evolution from the rift stage. The KDE shows a peak at each geological main event of QF from 3 to 2.4 Ga: Rio das Velhas I and II, domes and keels I, Mamona I, and Mamona II. This zircon age distribution is also concordant to Cawood *et al.* (2012) regarding extensional settings.

The foreland stage (Figure 14C, N = 715) shows the reworking of the underlying Minas Supergroup sedimentary rocks, with the Archaean detrital zircon age peak, and introduces the Minas Accretionary Orogeny detrital zircon age peak. The younger mode marks the inversion of the Minas-Itacolomi Basin, as this new sediment input, from the adjacent orogeny begins to overprint the detrital zircon age pattern with its own age signature (Palaeoproterozoic), thus developing its higher frequency in the histograms. The Sabará-Itacolomi foreland basin lies within the collisional settings of Cawood *et al.* (2012), where it is usual to present a bimodal behaviour in detrital zircon spectra: one mode with ages close to the depositional age of the sediment and the other mode that reflect the history of the underlying basement.

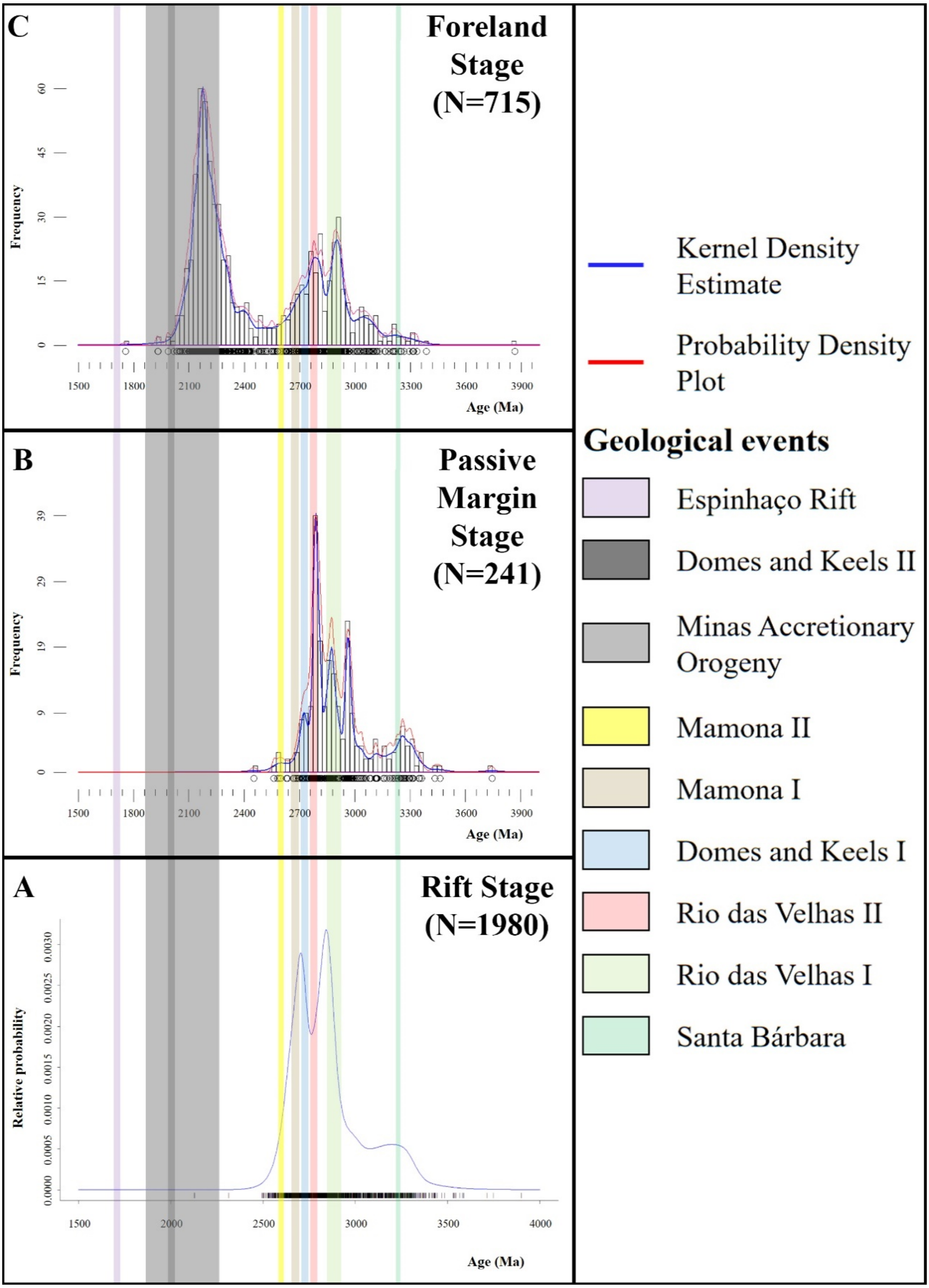
CONCLUSIONS

Within the Minas-Itacolomi Proterozoic basins, there are 41 sedimentary facies identified, which supported the interpretations of 9 (in a broader sense) depositional systems that repeat over time (e.g., Moeda Formation vs. Itacolomi Group alluvial fans and braided rivers). These depositional systems, in their turn, supported the interpretation of nine system tracts. From these building blocks of sequence stratigraphy, it was possible to interpret that the ca. 8.2 km thick Minas-Itacolomi succession of meta-sedimentary units records at least seven cycles of marine transgressions and regressions within five sequences (*strictu sensu,* separated by discordances and/or correlative conformities).

The first sequence showed an overall increase in oxidising atmospheric conditions from base to top, as the MOE1 facies showed detrital pyrite, evidencing more reducing conditions, and the banded iron formations of the Cauê Formation can be linked to the Great Oxidation Event (Cabral *et al.* 2012, Olejarz *et al.* 2021). This sequence began with continental sedimentation of Moeda Formation. Above, the Batatal transgression marks the first marine sedimentation. The transgression carried on until an MFS within Cauê Formation, prior to its gradational contact with Gandarela Formation, where the first carbonate beds appeared, evidencing an episode of shallowing of the marine environment.

The second sequence began at the erosive contact (TRS) of Itabira and Piracicaba Groups and ended at the interpreted correlative conformity between Taboões and Fecho do Funil

Formations. The Cercadinho Formation up to 500 m thick and mostly pelitic unit is the record of a second transgressive trend, which was followed by the Fecho do Funil HST with its carbonate lenses, thus indicating another regression. The contact between these two units is an MFS as well, similar to Cauê and Gandarela.



Source: data from Machado *et al.* (1992), Machado *et al.* (1996), Hartmann *et al.* (2006), Koglin *et al.* (2014), Jordt-Evangelista *et al.* (2015), Nunes (2016), Dopico *et al.* (2017), Dutra (2017), Duque (2018) and Dutra *et al.* (2019).

Figure 14. Detrital zircon U-Pb ages statistics: histograms, adaptive Kernel Density Estimates (KDEs), and Probability Density Plots (PDPs). (A) Rift stage. (B) Passive margin stage. (C) Foreland stage.

The third sequence began with prograding deltas of the Taboões Formation and transgressive systems tract of the Barreiro Formation, with an MRS indicating their contacts.

The fourth sequence originated when two cratonic nuclei collided, giving birth to the Minas Accretionary Orogeny. The orogen was responsible for the flexural subsidence (isostatic response) of one of the cratonic nuclei due to its lithostatic load. This basin (Sabará Group) is a good example of a flysch sequence formed in an underfilled foreland (when the orogenic pulse was greater than the sedimentation rate). The Itacolomi sequence (Sequence 5) formed when the accommodation space generation was in its decline, and the orogenic belt carried on being eroded away overfilling the foreland basin with continental sediments.

Sedimentary provenance shifted according to the basin evolution of the Minas-Itacolomi mega-sequence. The rift stage has many palaeovectors with three modes that could suggest a triple junction continental rift. The passive margin shows facies lateral shifts suggesting a depocentre to the SE. All of detrital zircon age spectra for both the rift and passive margin stages show Archaean peaks, coincident with basement magmatic events. From Sabará Group onwards, evidences show the inversion of the basin, probably flowing from SE to NW as the Minas Accretionary Orogeny had a NE-SW trend. This orogeny contributed greatly for the high frequency of Palaeoproterozoic zircon U-Pb ages in the foreland basin sediments.

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G.F.G.: Conceptualisation, data curation, formal analysis, investigation, methodology, software, writing – original draft, writing – review & editing.
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