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KOMATIITE LAVAS FROM THE QUEBRA OSSO GROUP (RIO DAS VELHAS GREENSTONE BELT, SOUTHEAST BRAZIL): A FIELD GUIDE TO AN ARCHEAN FLOW FIELD

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Abstract

The Quebra Osso Group encompasses one of the best preserved Archean komatiite flows in the Quadrilátero Ferrífero region, southern São Francisco craton (Brazil). It is commonly associated with the base of the Rio das Velhas greenstone belt within the Santa Bárbara tectonostratigraphic block. The Quebra Osso rocks are well exposed along the valley of the homonymous river, near the Catas Altas city (Minas Gerais state), and in inactive serpentine quarries. In this field guide, we provide the descriptions of the key outcrops in this area, including a variety of komatiite flows, sedimentary rocks and pyroclastic rocks. Despite the pervasive alteration of primary mineral assemblages due to greenschist to amphibolite facies metamorphism, the ultramafic rocks exhibit diverse igneous textures and structures. Volcanic textures are recognizable due to the morphology of the original igneous olivine and pyroxene, which underwent pseudomorphosis by hydrous minerals – serpentine and chlorite. These features include distinctive spinifex and cumulate textures that provide clues of the conditions operating during emplacement and crystallization of the ultrabasic liquids. The predominance of thick-packages of massive flows suggests channelized lava flows, with subordinate thin marginal layered (spinifex-textured), pillowed, brecciated and pyroclastic flows. Volcanic breccias, pillow lavas and chemical sedimentary rocks indicate that these rocks erupted underwater. These multiple volcanic products characterize a unique komatiite flow field and their remarkable preservation distinguishes the Quebra Osso Group from the other ultramafic associations within the São Francisco Craton.

Keywords: Komatiite, Quebra Osso Group, Rio das Velhas greenstone belt, Quadrilátero Ferrífero.

1. Introduction

The Quebra Osso Group, located in the Quadrilátero Ferrífero region (South-eastern São Francisco craton; Fig. 1A), comprises preserved komatiite flows of the Rio das Velhas greenstone belt. It outcrops in the eastern portion of the Santa Bárbara tectonostratigraphic block (Araújo et al., 2020; Fig. 1B), defining a 0.5-1.5 km wide NNE-SSW trending package, which extends through approximately 15 km along strike (Fig. 1C). The metaultramafic rocks are well exposed along the Quebra Ossos River – its type locality, and in inactive serpentinite quarries of the Pedreira Um Valemix, especially within the Catas Altas quadrangle (Ferreira et al., 2020a).

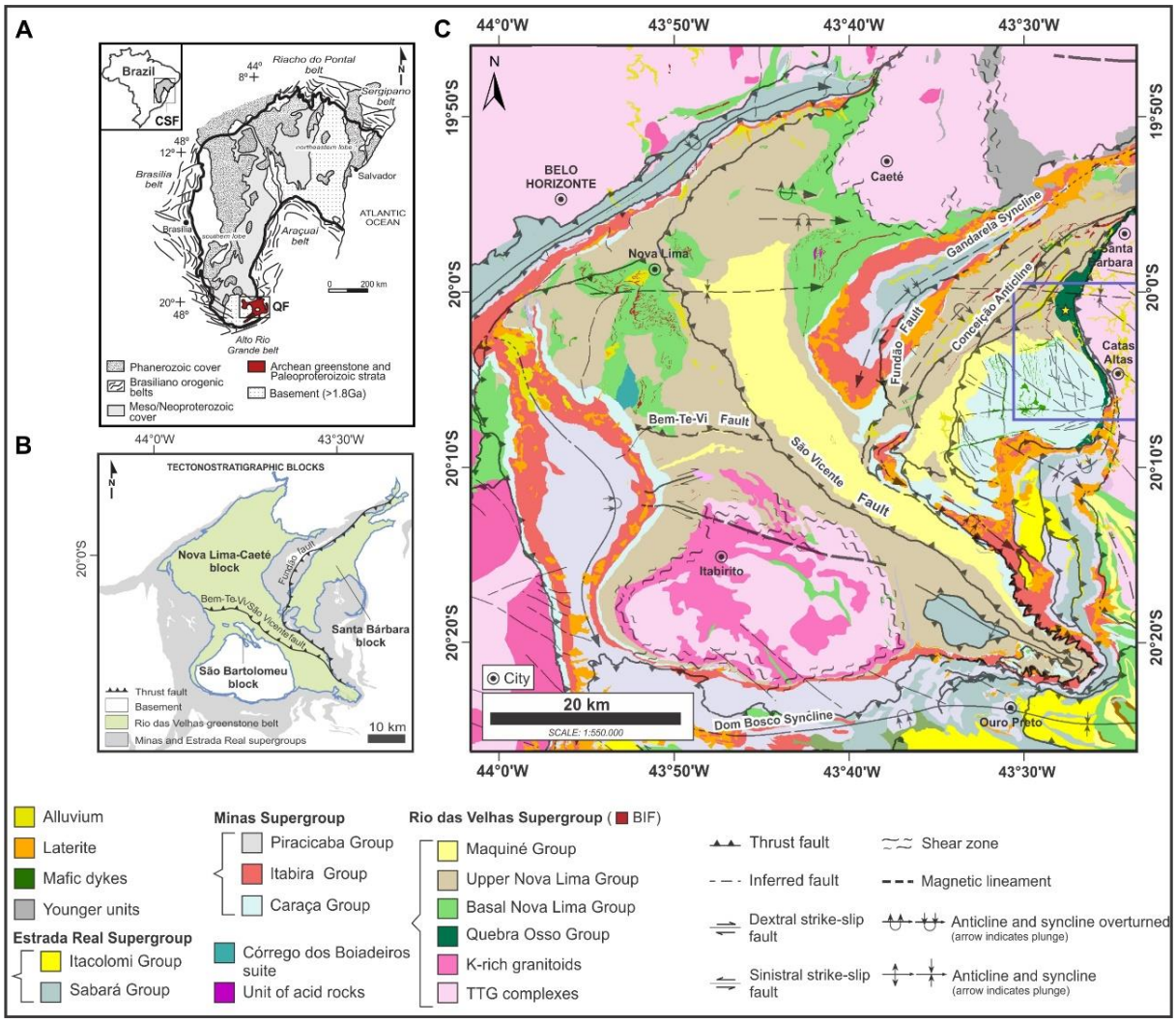

Figure 1: A) Regional map of the São Francisco craton, highlighting the location of the Quadrilátero Ferrífero region (QF) (modified from Alkmim and Marshak, 1998); B) tectonostratigraphic blocks of the Rio das Velhas greenstone belt; C) geological map of the central QF (compiled from Endo et al., 2020; Silva et al., 2020a,b; Araújo et al., 2020). The blue square represents the Catas Altas quadrangle.

The Quebra Osso rocks have been interpreted either as an intrusive ultramafic body (Simmons, 1968; Maxwell, 1972) or as peridotitic komatiites (Schorscher, 1978, 1979, 1992; Baltazar and Zucchetti, 2007; Acken et al., 2016; Verma et al., 2017; Ferreira et al., 2020b). The presence of distinctive spinifex texture and high MgO values (>18 wt%) – considered a fundamental criteria for komatiites (Arndt et al., 2008), support the latter interpretation (Ferreira et al. 2020b and references therein).

Its stratigraphic position was also been subjected to two diverging interpretations, such as: (1) the Quebra Osso Group has been considered an independent unit (Schorscher, 1979; Ferreira et al., 2020b), and (2) related to the base of the Nova Lima Group (Dorr II, 1969; Baltazar and Raposo, 1993; Zucchetti and Baltazar, 2000). Recently, Araújo et al. (2020) have supported the formalization of the Quebra Osso Group as metaultramafic unit, including komatiites, due to its unique characteristics, such as presence of relict spinifex texture and the absence of associated basalts (differently from the Nova Lima Group).

The first descriptions of Quebra Osso rocks were presented by Schorscher (1978), followed by numerous works (Sichel, 1983; Sichel and Valença, 1983; Schrank et al., 1984, 1990; Schorscher et al., 1992; Santos 2011; Acken et al., 2016; Verma et al. 2017; Ferreira et al., 2020b). Based on geochemical aspects, these ultramafic rocks were classified as high-Al Commondale-type (Acken et al., 2016) or Al-undepleted Munro-type komatiites (Verma et al., 2017). On the other hand, Ferreira et al. (2020b) suggested that all three types of komatiites (Al-depleted, Al-undepleted and Al-enriched) coexist in the area.

Based on textural characteristics, Ferreira et al. (2020b) subdivided the Quebra Osso rock into different volcanic facies and established the spatial and temporal relationship between them. This study furnished new insights concerning the volcanic architecture and emplacement of these lavas, which could have flowed through channels within the Santa Bárbara Complex.

Overall, the study of the Quebra Osso komatiites contributed to understanding the early evolution of the Southern São Francisco craton. The observation of its preserved lithotypes gives many clues to unravel the volcanic process that operated during the Archean. In this field guide, we present the major characteristics of the Quebra Osso Group, primarily obtained during detailed geological mapping by Ferreira et al. (2020b). We also hope to make the geological community aware of the importance of these rocks and the need for preservation of their remarkable exhibitions for future generations.

2. Geological Setting

The Rio das Velhas greenstone belt comprises Archean metavolcano-sedimentary sequences of the Rio das Velhas Supergroup (Baltazar and Zucchetti, 2007), including ultramafic-mafic volcanic and acid to intermediate volcanic/volcaniclastic rocks, along with chemical and clastic metasedimentary rocks (Araújo et al., 2020 and references therein).

Numerous stratigraphic subdivisions have been proposed for this Supergroup (Dorr II, 1969; Schorscher, 1979; Zucchetti and Baltazar, 2000; Baltazar and Zucchetti, 2007; Araújo et el., 2020). From base to top, it can be

subdivided into the Quebra Osso, Nova Lima and Maquiné groups. These rocks are distributed along three tectono-stratigraphic blocks (Nova Lima-Caeté, Santa Bárbara and São Bartolomeu, Fig. 1B), which were juxtaposed by tectonic amalgamation and separated by large regional faults (Baltazar and Zucchetti, 2007; Araújo et al., 2020).

The Quebra Osso Group is restricted to the Santa Bárbara block and represents an important ultramafic segment of the São Francisco Craton (Araújo et al., 2020). It displays tectonic contacts with Archean TTG (tonalite-trondhjemite-granodiorite) rocks of the Santa Bárbara Complex and the metasedimentary rocks of Minas Supergroup, to the east, and with metavolcano-sedimentary rocks of the Nova Lima Group, to the west (Fig. 1C). The contacts between this unit and the TTG are marked by alteration zones represented by chloritites ("blackwall"), tourmaline-chlorite schists and phlogopitites (Ferreira et al., 2020b and references therein).

This group encompasses komatiites with rare lenses of clasto-chemical sedimentary rocks (banded iron formation, chert, carbonaceous phyllite and fuchsite-quartz schist) and ultramafic tuffs. The lavas were metamorphosed under green schist to amphibolite facies conditions and correspond to green to dark grey, fine- to medium-grained serpentinites. Mineral assemblages are mostly secondary and include serpentine, chlorite, tremolite and talc in variable proportions. Magnetite, chromite, pyrite, chalcopyrite, ilmenite, carbonate and rutile occur as accessory phases (Ferreira et al., 2020b and references therein).

Despite the metamorphic alteration, igneous textures (mostly expressed by olivine morphologies) were retained by pseudomorphic serpentine and/or chlorite. Preserved igneous features include spinifex and cumulate textures, pillow lavas and volcanic breccias. Considering that the Rio das Velhas greenstone belt experienced polyphase deformation (Baltazar and Zucchetti, 2007), the igneous features of these lava flows are completely obliterated in several locations, where the Quebra Osso Group is represented by tremolitites and ultramafic schists (Ferreira et al., 2020b and references therein).

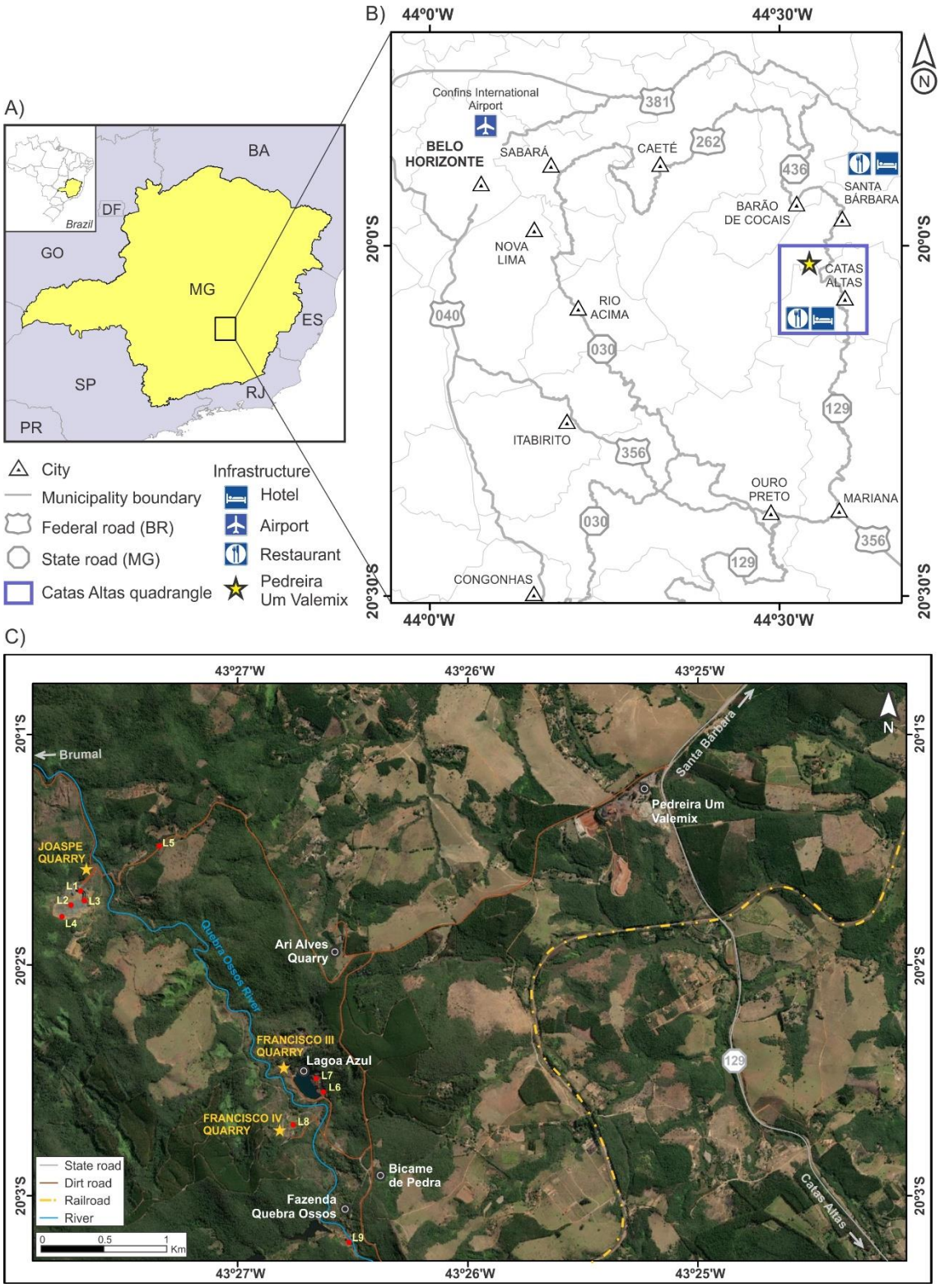

Figure 2: A) Geographic location of the study area in the Minas Gerais state, southeastern Brazil. B) Main access roads, departing from the capital Belo Horizonte, and available infrastructure (airport, hotels and restaurant). The blue square represents the Catas Altas quadrangle. C) Satellite view of the study area (extracted from Google Earth). Symbols - black dots: key points, touristic locations; yellow stars: serpentinite quarries; red dots: location of outcrops.

3. Field trip logistics

The area covered by this field guide is located approximately 7 km north and 15 km south of the Catas Altas and Santa Bárbara cities, respectively, in the south-central region of the Minas Gerais state (Fig. 2A, B). From Belo Horizonte (capital of Minas Gerais), the main access roads to the spots of interest are BR-381 to MG-436, or BR-040 and BR-356, followed by the MG-129 to the headquarters of Pedreira Um Valemix. Dirt roads link the Pedreira Um Valemix entrance to the Joaspe, Francisco III and Francisco IV quarries (Fig. 2C), which contain the best outcrops of the Quebra Osso ultramafic rocks.

These quarries are located in the area of the Fazenda Quebra Ossos ("Quebra Ossos Farm"), nearby the touristic location named "Bicame de Pedra" (also known as Aqueduct "Quebra Ossos"; Table 1), easily found on Google Maps (Fig. 3A). This aqueduct was built in the end of 18th century, and used to provide water to villages, farms and gold mines near the Caraça Ridge (Veiga et al., 2004).

Other points of interest in the area include the Lagoa Azul ("Blue Lagoon"), a pit lake in the Francisco III quarry (Fig. 3B), which was filled with rain and/or groundwater when mining operations ceased. In the Ari Alves quarry, located northeast of the Francisco III quarry (Fig. 2C), there are great exposures of the basement rocks of the Santa Bárbara Complex (Fig. 3C, D). In this inactive quarry, grey gneisses used to be extracted for production of building materials.

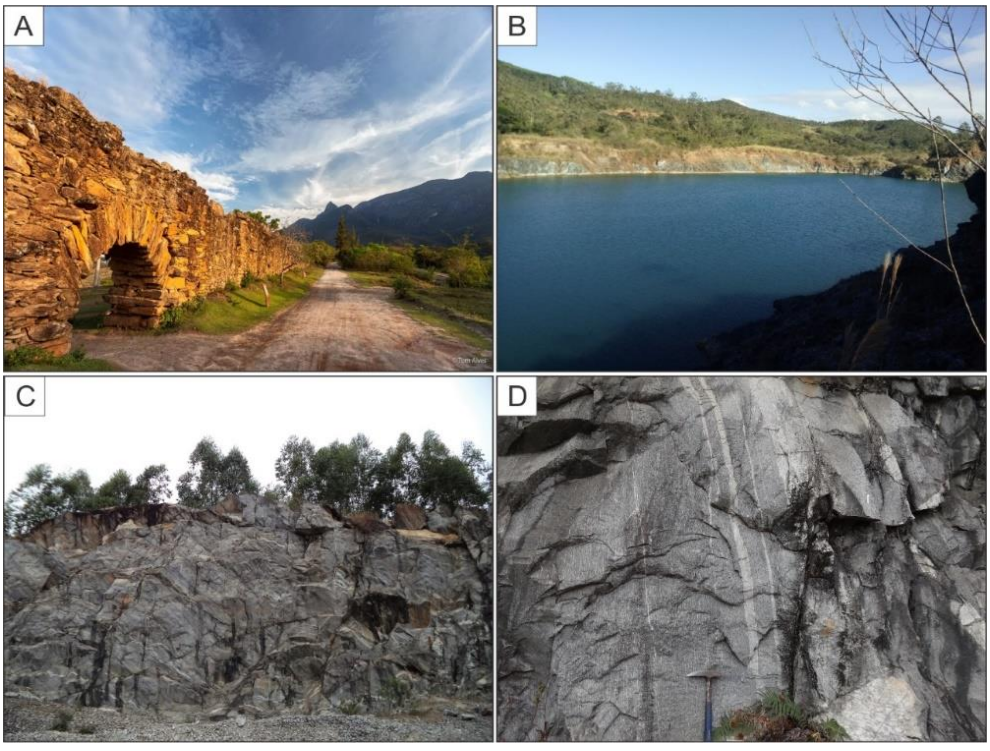

Figure 3: Key points within the study area. Touristic locations include A) Bicame de Pedra, also known as "Aqueduct Quebra Ossos" (photograph by Alves, 2021); and b) Lagoa Azul ("Blue Lagoon"), a pit lake in the Francisco III quarry. C) Ari Alves quarry and D) exposures of grey gneisses of the Santa Bárbara Complex.

4. Outcrops

Komatiites are believed to have crystallized from high temperature and low viscous ultrabasic magmas, conventionally related to mantle plumes (Arndt et al., 2008 and references therein). They are restricted to the Archean and Paleoproterozoic, with a rare exception in the Gorgona Island that erupted 90 Ma ago (e.g., Arndt et al., 2008). Considering that they are extinct, the study of preserved flows allows inferences concerning the characteristics and extrusion site of these magmas.

These highly fluid ultrabasic liquids erupted along fissures and channels through long distances, and a great variety of volcanic facies are observed within the komatiite flow fields (Arndt et al., 2008 and references therein). In the Quebra Osso Group, the komatiite flows are subdivided into i) coherent (massive, layered, and pillowed flows), ii) autoclastic (autobreccias and hyaloclastites), and iii) pyroclastic facies (ultramafic tuffs and lapilli-tuffs) (Ferreira et al., 2020b). The coherent facies originate from cooling and solidification of molten lava, while autoclastic facies are the result of fragmentation of non-explosive lava (quenching, auto-brecciation). On its turn, the pyroclastic facies are made of particles generated by explosive eruptions (McPhie et al., 1993).

These metakomatiites exhibit distinctive igneous textures and structures, which were recognized during fieldwork and petrographic analysis. In the following sections, the key outcrops are described and their main characteristics are summarized (see Table 1 for coordinates).

Table 1: Touristic locations' and key outcrops' coordinates of the Quebra Osso lithotypes (locations 1 to 9).

	Location	*Coordinate System*	*Longitude*	*Latitude*	*Altitude (m)*
-	Bicame de Pedra ("Quebra Ossos Aqueduct")	GCS Sirgas 2000	-43.440213	-20.047690	809
-	Lagoa Azul ("Blue Lagoon")	GCS Sirgas 2000	-43.445151	-20.042264	720
-	Ari Alves Quarry	GCS Sirgas 2000	-43.442603	-20.031343	802
L1	Joaspe Quarry viewpoint	GCS Sirgas 2000	-43.461304	-20.027998	745
L2	Joaspe Quarry (massive flows)	GCS Sirgas 2000	-43.461539	-20.028920	746
L3	Joaspe Quarry (brecciated flows)	GCS Sirgas 2000	-43.461209	-20.028479	745
L4	Joaspe Quarry (layered flows)	GCS Sirgas 2000	-43.461886	-20.029854	809
L5	Road to Joaspe Quarry (metasedimentary rocks)	GCS Sirgas 2000	-43.455913	-20.025138	796
L6	Francisco III Quarry (pillowed flows)	GCS Sirgas 2000	-43.443944	-20.042356	749
L7	Francisco III Quarry (spinifex-textured flow)	GCS Sirgas 2000	-43.444483	-20.041646	763
L8	Francisco IV Quarry (brecciated flows)	GCS Sirgas 2000	-43.446700	-20.044905	785
L9	Fazenda Quebra Ossos (volcaniclastic rocks)	GCS Sirgas 2000	-43.441642	-20.052900	766

Location 1: Quarry Viewpoint, Joaspe Quarry, Catas Altas (MG).

What can be seen: landscape viewpoint

The Joaspe quarry (Fig. 4A) contains a variety of ultramafic rocks, including lava flows with spinifex, cumulate textures and volcanic breccias. However, due to deformation processes, the degree of preservation of igneous features is variable. In several locations, the metakomatiites are highly foliated and do not show relict textures.

Igneous textures are commonly preserved within metric to decametric-scale sigmoidal pods (Fig. 4B), with dips of 50° to E-SE, with local variations to NE

and SW. The contacts between them may be marked by shear zones, and it is difficult to estimate the precise thickness of each flow.

From base to top, this quarry contains seven benches, with approximate heights of 10 m each (Fig. 4A). The first point of interest is located at the base level (location 2), with an altitude of 740 m, followed by locations 3 and 4, described in the second (750 m) and last benches (800 m), respectively.

Location 2: Joaspe Quarry, Catas Altas (MG).

What can be seen: Massive flows

The massive flows are predominant in this area and comprise thick-packages of fine to medium-grained serpentinites with cumulate textures (Fig. 4C). Cumulates are characterized by the presence of sub-rounded phenocrysts (up to 2 mm in size), originally of olivine but now replaced by serpentine. Joints and millimeter- to centimeter-scale carbonate veins commonly cross-cut the massive rocks (Fig. 4D).

The formation of these cumulates is attributed to gravitational settling and accumulation of phenocrysts in major lava pathways, which were carved in the Santa Bárbara sialic crust (Ferreira et al, 2020b and references therein).

Location 3: Joaspe Quarry, Catas Altas (MG).

What can be seen: Autoclastic flows (volcanic breccias)

The autoclastic flows (Fig. 4E) encompasses hyaloclastites and autobreccias, which were formed by fragmentation of hot lava in contact with water or dynamic stress during turbulent lava flow (Ferreira et al., 2020b and references therein). The monomitic breccias are composed of angular fragments of komatiites, with jigsaw-fit textures (Fig. 4F). The clasts may retain igneous features, such as cumulate and spinifex textures, suggesting fragmentation of solidified lava.

Location 4: Joaspe Quarry, Catas Altas (MG).

What can be seen: Layered flows

Layered flows are composed of an upper spinifex-textured zone and a lower cumulate zone (Fig. 5). The spinifex texture comprises randomly oriented tabular to dendritic crystals of pseudomorphic serpentine (after olivine), which dimensions vary between 1.5-10 mm in length and 0.2-1.5 mm in width (Fig. 5-1). The texture is formed during relatively rapid, in-situ crystallization of ultramafic liquids (Arndt et al., 2008).

In the lower zone of cumulate-textured rocks it is possible to observe granular to polyhedral grains of pseudomorphic serpentine (Fig. 5-3). The transition zone is marked by the decrease in size of the tabular crystals and the appearance of cumulate grains.

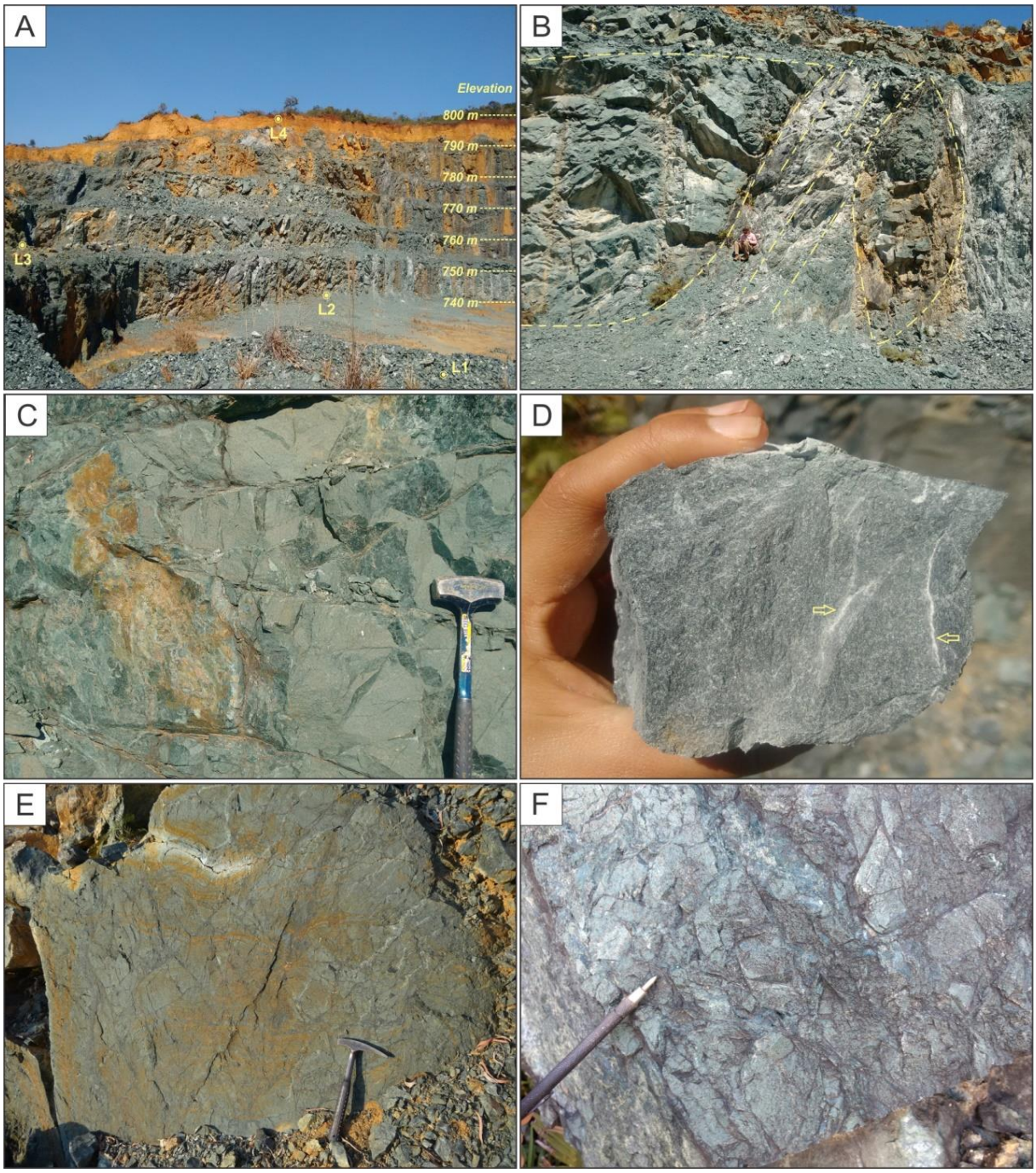

Figure 4: A) Joaspe quarry, landscape view (location 1) and position of locations L2, L3 and L4. Elevations in the right corner mark the limits of each bench; B) metric to decametric sigmoidal pods of metakomatiites, bordered by ultramafic schists and shear zones; C) jointed massive flow in location 2; and D) hand-sample of fine-grained serpentinite cross-cut by millimeter-scale carbonate veins (see arrows); E) brecciated flow in location 3, and F) detail of volcanic breccia with jigsaw-fit texture.

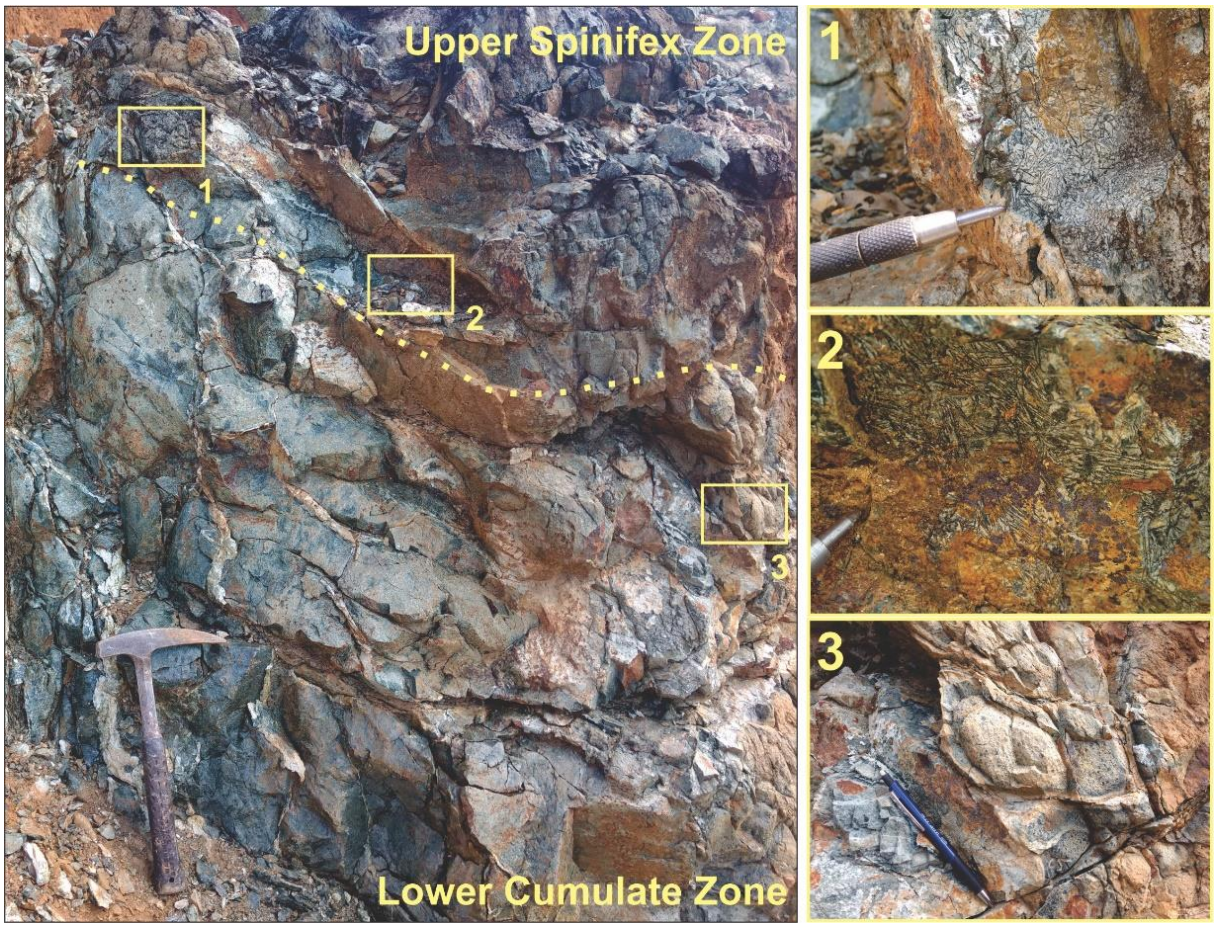

Figure 5: Layered komatiite flow in location 4. 1- Upper spinifex-textured flow; 2- transitional zone; and 3- lower cumulate zone.

Location 5: Dirt road between Pedreira Um Valemix and Joaspe Quarry (towards Brumal district).

What can be seen: Metasedimentary rocks

Thin lenses of clasto-chemical metasedimentary rocks are interbedded with the ultramafic schists (Fig. 6A). In this particular location, the sedimentary sequence begins with centimetric layers of white to beige metachert that grades to banded iron formations, ending with thin a thin layer of carbonaceous phyllite (Fig. 6B). Approximately 15 m northeast of this location, fuchsite-quartz schist shows alternating layers of green mica and quartz, and is strongly folded and crenulated (Fig. 6C, D).

Location 6: Francisco III Quarry, Catas Altas (MG).

What can be seen: Pillowed ultrabasic lavas

The rocks in Francisco III Quarry are exposed in the margins of the lake called Lagoa Azul (Fig. 3B). On the southeastern side of the lake, 60 m away from the access road, there are good exposures of ultramafic pillowed flows (Fig. 7A). They are characterized by juxtaposed circular to ellipsoidal masses of lava (serpentinites) (Fig. 7B), with variable dimensions, having pedunculated cross-sections (Fig. 7C). The interpillow spaces are filled with

carbonate-rich aggregates and hyaloclastites. The pillows exhibit concentric textural zoning, defined by an inner cumulate zone bordered by a thin fine-grained to aphanitic crust. Concentric radial contraction cracks are also observed (Fig. 7D).

Pillow lavas are believed to have formed from the cooling of lava in contact with water and represent interconnected lava tubes (McPhie et al., 1993 and reference therein), indicating that the Quebra Osso lavas reached an underwater environment (Ferreira et al., 2020b).

Figure 6: Location 5. A) Outcrop with layers of metasedimentary rocks, following exhibitions of ultramafic schists; B) lamination of the metachert layers and gradual transition to thin layers of banded iron formations and carbonaceous phyllites; C) fuchsite-quartz schists; D) detail of crenulation.

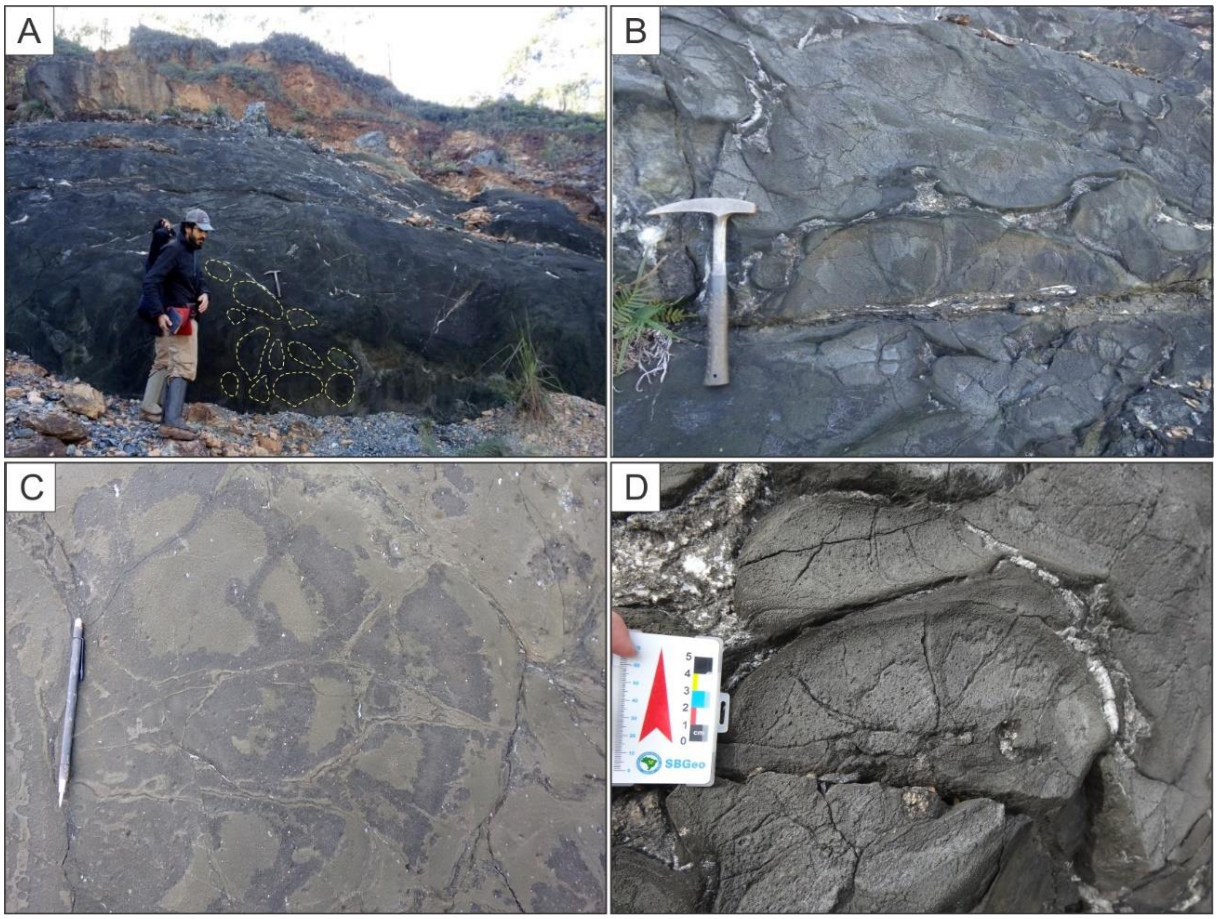

Figure 7: A) Outcrop of Quebra Osso pillowed ultrabasic flows (some pillows are highlighted in yellow), characterized by B) juxtaposed circular to ellipsoidal masses; C) detail of pedunculated pillows; D) concentric textural zoning, dark-colored to light-gray aphanitic crust (altered-glass rind) and concentric radial contraction cracks.

Location 7: Francisco III Quarry, Catas Altas (MG).

What can be seen: Spinifex-textured flow

On the southeastern side of the pit lake in the Francisco Quarry, approximately 150 m away from the access road and 90 m away from location 6, there is an outcrop with distinctive spinifex texture (Fig. 8A). Coarse-grained tabular crystals of pseudomorphic serpentine are randomly oriented and widespread in the lower portion of the exhibition (Fig. 8B). The spinifex domain show irregular contacts with surrounding massive to foliated rock (Fig. 8C) and marks the upper portion of the komatiite flow that rapidly cooled in contact with water.

Location 8: Francisco IV quarry, Catas Altas (MG).

What can be seen: Brecciated and highly foliated rocks

The Francisco IV quarry, approximately 350 m southwest of the Francisco III quarry, contains outcrops of brecciated and massive flows (Fig. 9A). As observed in the Joaspe Quarry, the komatiites usually preserve igneous features within tectonic pods (also observed in centimeter-scale), which are

bordered by highly foliated and sheared ultramafic rocks (Fig. 9B).

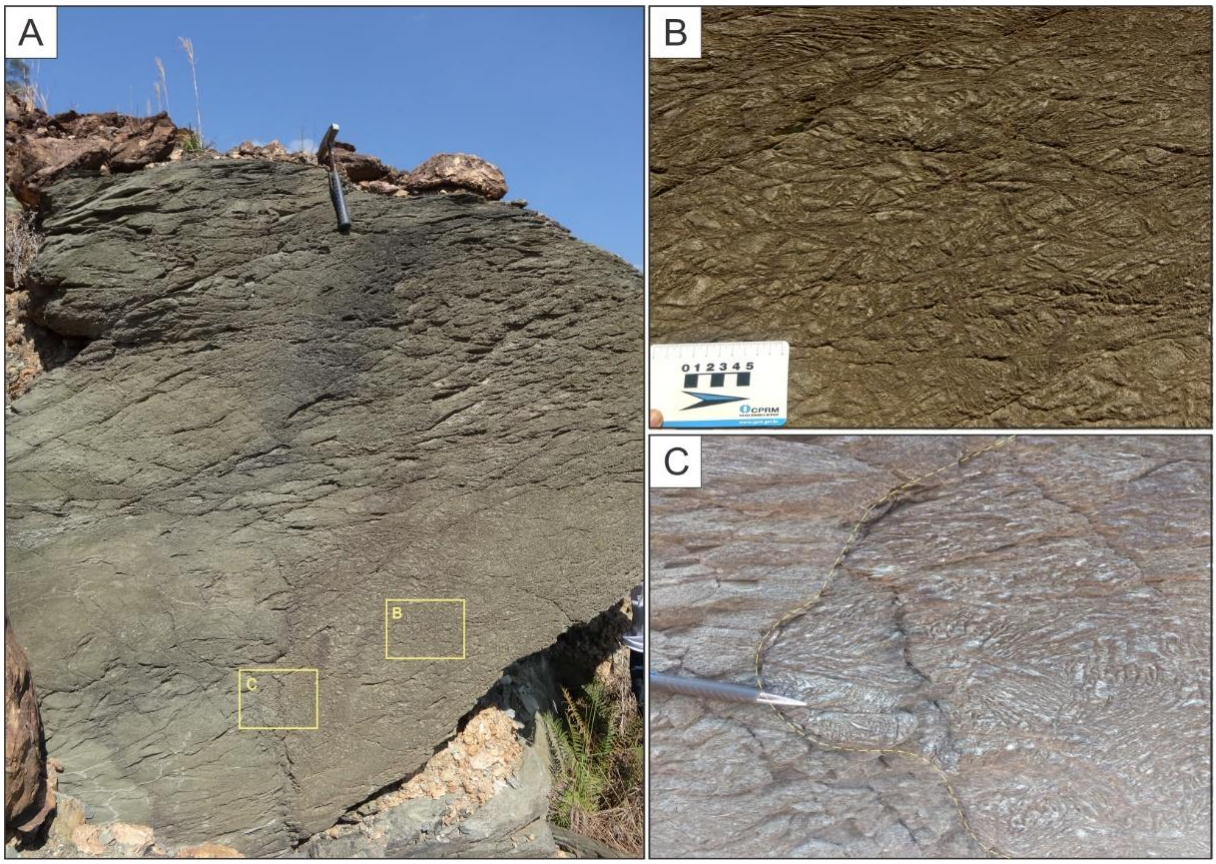

Figure 8: A) Spinifex-textured flow of Quebra Osso Group; B) random disposition of tabular crystals and C) irregular contacts with adjacent flows.

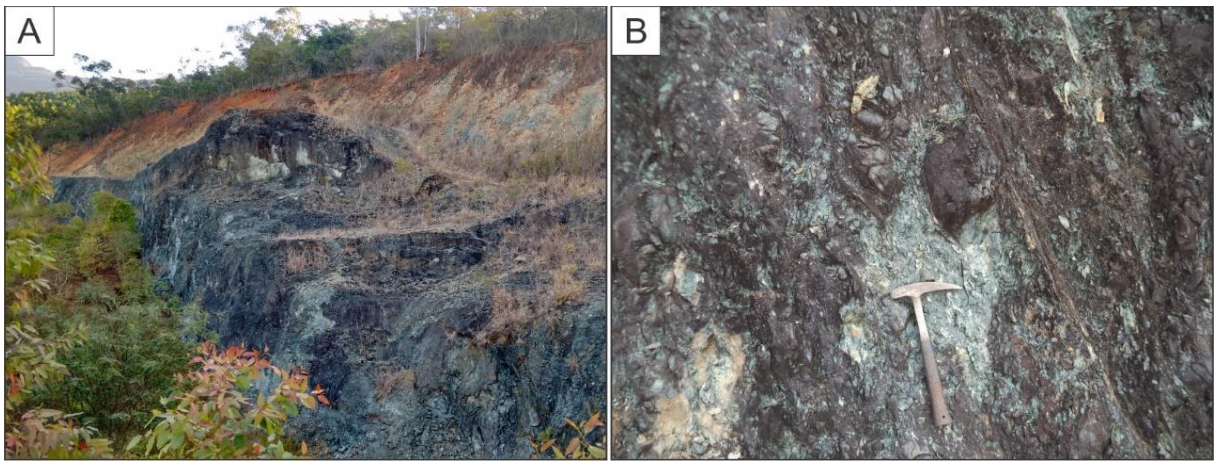

Figure 9: A) Landscape view of the Francisco IV quarry. B) Brecciated and highly foliated ultramafic rocks of the Quebra Osso Group.

Location 9: Fazenda Quebra Ossos, Catas Altas (MG).

What can be seen: Volcaniclastic rocks

The type area of the Quebra Osso Group is located nearby the headquarters of the Fazenda Quebra Ossos. The ultramafic rocks are exposed along the stream bed of the Quebra Ossos River, close to a small bridge (Fig. 10A). This location includes good exposures of the pyroclastic facies, including lapilli tuffs and agglomerates (Fig. 10B). Agglomerates are characterized by the presence of coarse fragments of rocks, whose interior retains milimetric granules in a phyllosilicate matrix.

Small pillow lavas are also observed, characterized by contiguous circular masses of ultrabasic lava, with concentric textural variation (Fig. 10C). Serpentine veins are also present (Fig. 10D).

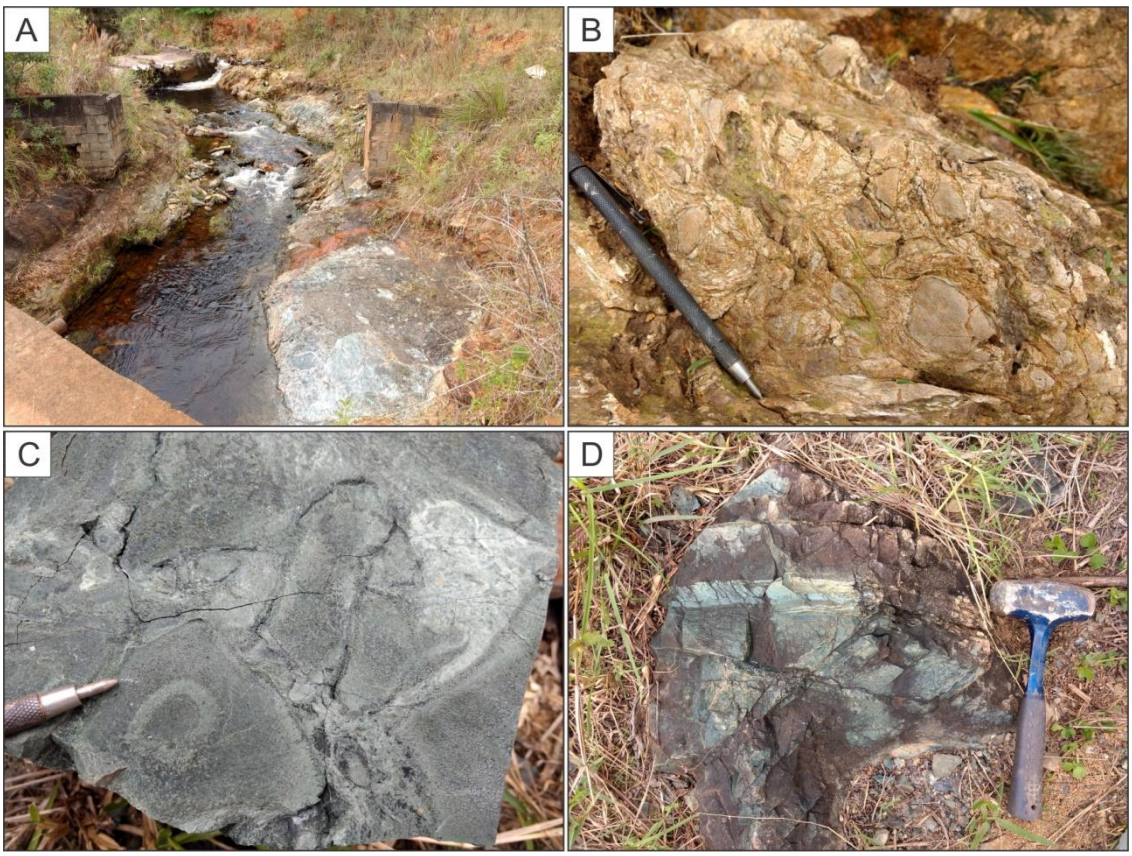

Figure 10: A) Expositions of the Quebra Osso rocks along the homonymous river; B) pyroclastic facies, represented by agglomerates and lapilli-tuffs; C) Pillow lava; D) Serpentine veins.

5. Final comments

The Quebra Osso Group stands as a unique geological unity in the São Francisco craton and brings significant implications to the comprehension of the early history of the Quadrilátero Ferrífero. It encompasses diverse facies of komatiite lava flows, formed by multiple physical processes that operated during

its emplacement onto the sialic crust of the Santa Bárbara Complex. Thick-packages of massive flows with cumulate textures indicate that ultrabasic liquids flowed through channels within the sialic crust, allowing gravitational deposition and accumulation of phenocrysts. The spinifex-textured flows, restricted to marginal zones, points to localized extravasation from the lava pathway. The volcanic breccias suggest that the komatiite flows were fragmented by thermal shock upon contact with water and/or by new influxes of lava, coherent with a dynamic environment. The presence of pillows lavas, hyaloclastites and chemical metasedimentary rocks indicate that these rocks erupted underwater.

Finally, the primary mineralogy (olivine and pyroxene) was altered by hydrothermal fluids and low to medium-grade metamorphism, resulting in mineral assemblages rich in hydrous minerals (serpentine, chlorite, tremolite and talc). However, serpentine pseudomorphs formed after igneous crystals retained the original volcanic textures, allowing their recognition despite the secondary alteration. These textural characteristics distinguish the Quebra Osso Group from the other ultramafic associations within the Rio das Velhas greenstone belt and endorse the singularity of these rocks.

Acknowledgements

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