



Tectonometamorphic evolution of the Anicuns-Itaberaí Sequence, Southern Brasília Orogen: Evidence of deep burial and syn-collisional exhumation

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ABSTRACT

Metamorphic pressure–temperature (P–T) conditions in the Southern Brasília Orogen are relatively well constrained, particularly in its southernmost segments. However, the central and northern portions need further attention, especially regarding the metamorphism affecting the volcano-sedimentary sequences of the Arenópolis Magmatic Arc (AMA). The Anicuns-Itaberaí Sequence (AIS), located in the southern segment of the AMA, comprises a well-exposed metavolcano-sedimentary succession of mafic to ultramafic metavolcanic rocks, metachert, metarhytmite, marble lenses and quartzite. Well-preserved outcrops in the lowlands surrounding the Serra da Jiboia region, located in the central portion of the study area, were used to investigate the structural features and deformation recorded in metasedimentary rocks of the AIS and two samples of metagreywackes were selected for metamorphic modelling. The analyzed rocks correspond to garnet–chlorite–biotite–muscovite schists and were selected for microstructural analysis, quantitative mineral mapping, and thermodynamic modelling based on electron microprobe analyses. The results indicate that the peak metamorphic assemblage (garnet + biotite + plagioclase + muscovite + rutile + ilmenite) was stable at temperatures above 600 °C and pressures exceeding 0.95 GPa. The metamorphic evolution, inferred from compositional zoning in garnet, defines a clockwise P–T path, with initial garnet growth at 525–555 °C and 0.67–0.77 GPa, a metamorphic peak at 660 °C and 1.16–1.30 GPa, followed by decompression between 550 and 585 °C and 0.65–0.79 GPa. These results indicate that the AIS schists reached high-pressure amphibolite-facies conditions, exceeding those typical of the Barrovian metamorphism, and point to a collisional tectonic regime characterized by deep crustal burial and subsequent exhumation. Deformation structures were chronologically classified into four distinct phases (D₁ to D₄). The main deformation event (D₂) is characterized by asymmetric folding, while subsequent reverse faulting and shearing (D₃) are associated with post-burial exhumation during syn-collisional processes. Microstructural evidence suggests that the metamorphic peak likely occurred between the end of D₁ and the onset of D₂, indicating that peak mineral growth was broadly synchronous with early stages of the main deformation phase and burial.

1. Introduction

Characterizing the pressure (P), temperature (T), and ages of metamorphic events is fundamental to understand tectonic evolution in orogens. Approaches including the reconstruction of the P–T path, dating

of metamorphic events, detailed microstructural and petrographic analyses provide the foundation of this study. Building on these approaches, metamorphism in the Brasília Orogen has been widely studied in the southernmost domains, which describe rocks formed under high-pressure conditions (Motta and Moraes, 2017). In contrast, the northern

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and central portions of the Southern Brasília Orogen have provided constrains on detrital zircon ages, provenance pattern and geochemistry (e.g., Pimentel & Fuck, 199, [Laux et al., 2005](#); [Laux et al., 2010](#); [Carneiro et al., 2021](#)) while the tectonic-metamorphic conditions are still not well understood, particularly due to a lack of studies involving the domains of the Arenópolis Magmatic Arc (AMA), which are delimited by the Anicuns-Itaberaí metavolcanic-sedimentary sequence.

The Anicuns-Itaberaí Sequence (AIS) represents the easternmost volcano-sedimentary unit of the southern Arenópolis Arc. This sequence includes mafic to ultramafic metavolcanic rocks with an island-arc signature, metachert, metarhytmite, and marble lenses, formed around 880 Ma ([Laux et al., 2004](#)). It has been interpreted as an arc/-forearc basin setting, marking the tectonic boundary between the

magmatic arc and the high-grade core of the Brasília Orogen, represented by the Anápolis-Itaçu Complex ([Laux et al., 2010](#)). However, evidence in the literature suggests that metamorphic conditions might have reached high-pressure amphibolite conditions. This includes the presence of diopside in blasto-subophitic metabasalts (e.g., [Lacerda-Filho et al., 2021](#)) composed by hornblende and plagioclase (oligoclase) ([Nunes, 1990](#)), as well as localized occurrences of kyanite-bearing schists ([Baêta Junior, 1994](#); [Lacerda-Filho et al., 2021](#)).

Despite its significance for understanding the geological evolution and economic potential of the Brasília Orogen, information on the metamorphism of these rocks remains limited, since most published studies have been only at reconnaissance level (e.g. [Nunes, 1990](#); [Baêta Junior, 1994](#); [Lacerda-Filho et al., 2021](#)). In this study, we investigated

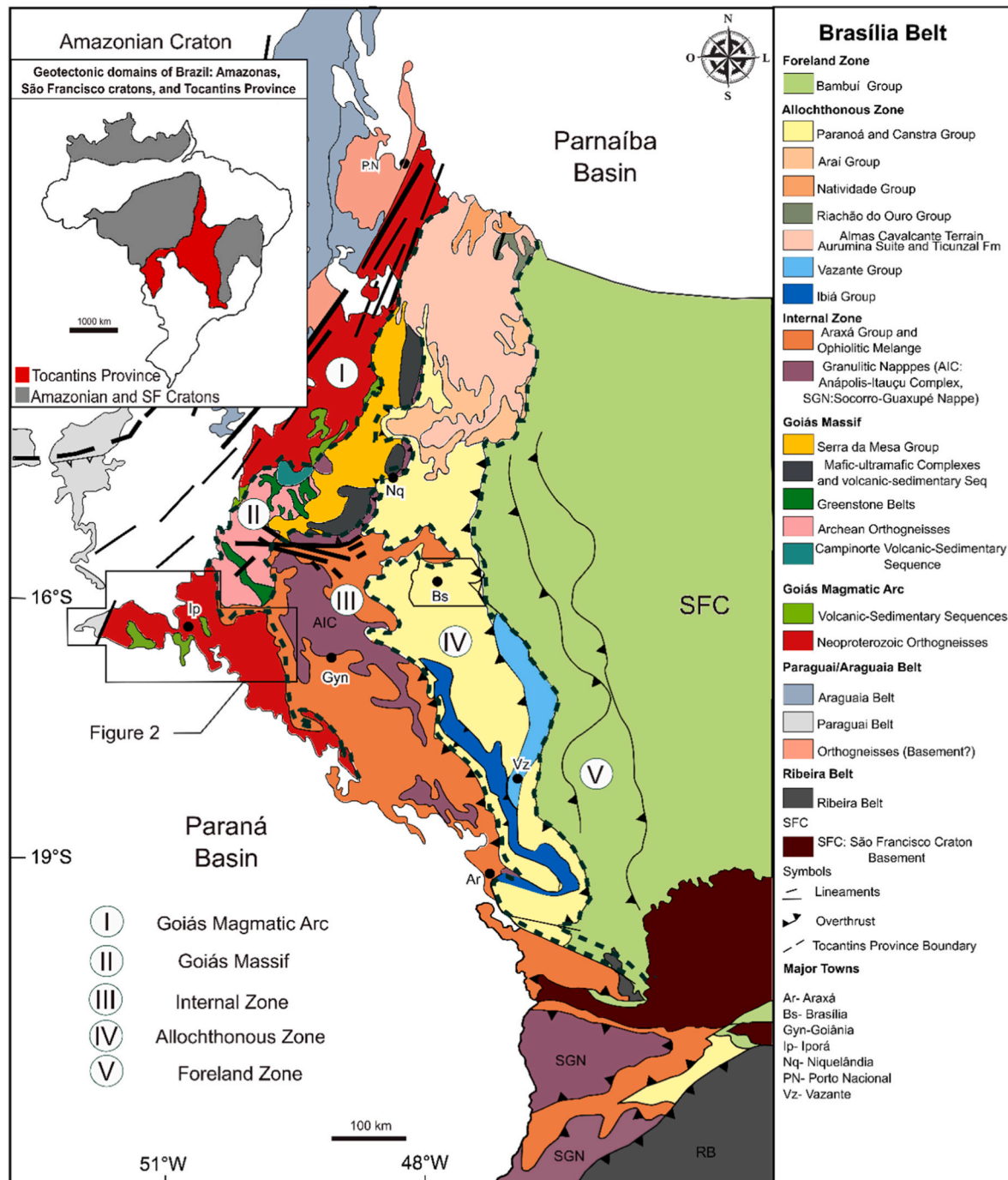


Fig. 1. Geological map of the tectonic units from the Brasília Orogen. Modified from [Pimentel et al. \(2004\)](#); [Valeriano et al. \(2008\)](#).

paraderived garnet-chlorite-biotite-muscovite schists from the AIS, outcropping in the Serra da Jiboia region (Fig. 3), to characterize the local metamorphism. Our analysis included petrographic studies of the lithotypes, microprobe mapping, and metamorphic modelling. The results, combined with structural data, indicate that these rocks were buried in deep crustal levels before undergoing extensive exhumation through reverse faulting and thrusting. These findings provide new insights into the exhumation and erosion of the arc-related supracrustal sequences during the evolution and accretion of Brasília Orogen and may contribute to future research on potential for mineral resource preservation in environmentally favorable areas.

2. Geological setting

2.1. Brasília orogen

The Brasília Orogen (Fig. 1) is the easternmost sector of the Tocantins Province (Almeida, 1967; Brito Neves et al., 2021), a Neoproterozoic to early Paleozoic orogenic system that developed during the assembly of the West Gondwana Supercontinent, as result of the convergence between Paranapanema, Amazonia and São Francisco cratons (Dias et al., 2025).

The Brasília Orogen is the largest of the three fold-and-thrust belts of the Tocantins Province. It is located in the central portion of Brazil, has a curved shape with two distinct branches: a NE-trend in the north and a SE-trend in the south, and has been defined as an orogen with accretionary and collisional events, structured in a series of tectonic slices (Valeriano et al., 2008). Its initial evolution begins with: (1) the development of intra-oceanic magmatic arcs (Pimentel and Fuck, 1992; Laux et al., 2005; Cordani et al., 2013); followed by (2) the amalgamation of cratonic blocks against the western portion of the Congo-São Francisco Craton (Cordani et al., 2003; Oriolo et al., 2017); simultaneously with (3) the development of syn-collisional continental magmatism (Pimentel, 2016); followed by (4) post-collisional relaxation

accompanied by crustal extension and late-to post-collisional magmatism (Piuzeana et al., 2003).

Orogeny was preceded by multiple episodes of Proterozoic rifting that evolved into an ocean-floored and passive margin basin in the Neoproterozoic (Valeriano et al., 2008; Dias et al., 2025). In terms of orogenic evolution two major tectonic components have been identified: (1) pre-orogenic sedimentary basins, which include a Paleoproterozoic rift basin, a Mesoproterozoic rift-SAG basin, and a Mesoproterozoic to Neoproterozoic rift-SAG basin that developed in a passive margin setting; and (2) Ediacaran to Cambrian syn-orogenic basins, which are subdivided into forearc and syn-collisional basins (Dias et al., 2025, Fig. 1). The convergence of Paranapanema and Amazonia paleocontinents to the western margin of São Francisco converted the passive margins into a complex accretionary system and later, into orogen (Valeriano et al., 2008; Valeriano, 2017; Dias et al., 2025).

The Brasília Orogen has been geologically divided into five zones (Fuck, 1994; Valeriano et al., 2008; Pimentel, 2016). The zonation, as proposed by Valeriano et al. (2008), consists of the following, from east to west: (1) foreland zone; (2) external allochthonous zone; (3) internal zone; (4) Goiás Massif; and (5) Goiás Magmatic Arc.

2.2. Arenópolis Magmatic Arc (AMA)

The AMA (Fig. 2) is primarily characterized by extensive exposures of orthogneisses, including the Arenópolis, Matrinxã, and Sanclerlândia gneisses (Pimentel and Fuck, 1992), interspersed with a series of metavolcano-sedimentary sequences (Carneiro et al., 2021) and late-to post-kinematic intrusions with compositions ranging from felsic to mafic-ultramafic (e.g., Lacerda-Filho et al., 2021). The arc rocks underwent greenschist facies metamorphism related to the development of strike-slip faults (Marques, 2009).

The orthogneisses, primarily composed of hornblende-bearing metadiorites, metatonalites, and metagranodiorites, exhibit positive $\epsilon_{\text{Nd}}(\text{T})$ values and Nd model ages mostly ranging between 800 and 1100 Ma

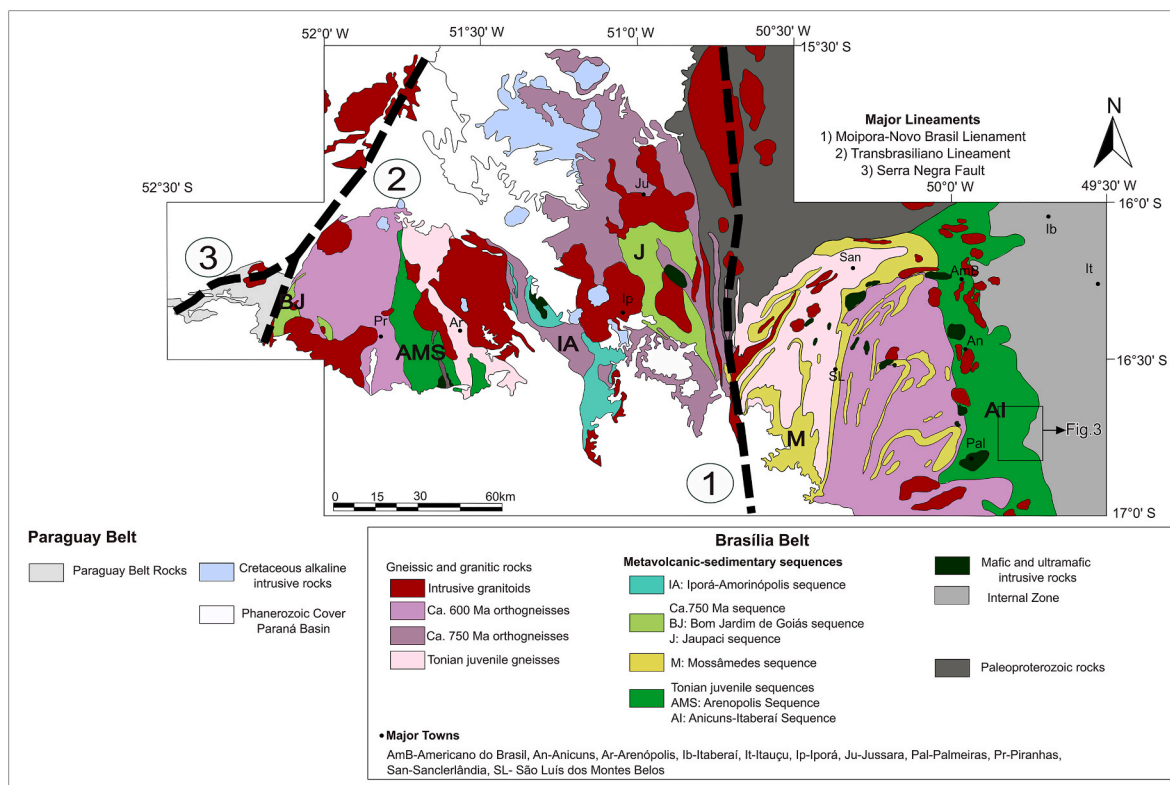


Fig. 2. Simplified geological map of the northern portion of the Arenópolis Arc. The study area is represented in the black square. Modified from Carneiro et al. (2021); Lacerda-Filho et al. (2021).

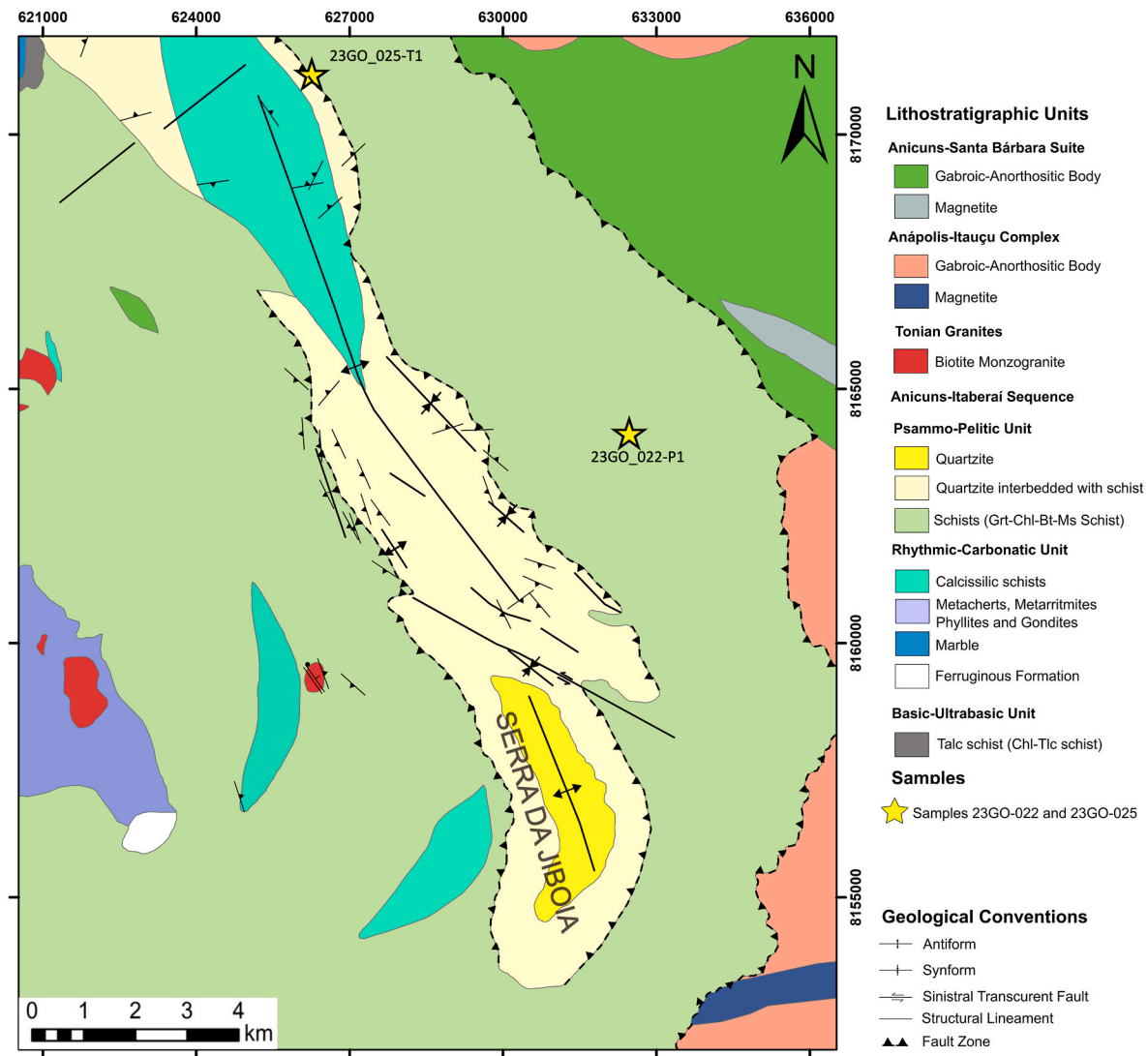


Fig. 3. Geological map of the study area, emphasizing the Serra da Jiboia and the samples 23GO-022 (UTM 632469/8164133) and 23GO-025 (UTM 626263/8171194) location, used for metamorphic modelling.

(Pimentel and Fuck, 1992; Pimentel, 2016). At least three magmatic crystallization events have been reported for the orthogneisses of the Arenópolis Arc: (1) the Sanclerlândia gneiss is interpreted as M-type granitoids formed in an intra-oceanic island arcs setting, with ages varying from 828 to 822 Ma; (2) the deformed peraluminous muscovite-bearing granitoid intruded in the eastern part of the Arenópolis Arc, represented by the Creoulos Granite, with crystallization age between 790 and 786 Ma; and (3) the metaluminous gneisses with crystallization ages between 669 and 630 Ma are represented by Matrinxã, Turvânia, Palminópolis and Firminópolis gneisses (Laux et al., 2005; see Pimentel, 2016 and references therein).

The metavolcano-sedimentary sequences, interpreted as arc-related basins, are exposed in two structural domains separated by the NNW-SSE Moiporá-Novo Brasil Lineament (Carneiro et al., 2021). To the west of this lineament, the Bom Jardim, Arenópolis, Iporá-Amorinópolis, and Jaupaci sequences are exposed within erosional windows of the Paraná Basin, where the supracrustal sequences occur as N-S strips interspersed between orthogneiss bodies (Fig. 2) (Carneiro et al., 2021; Lacerda-Filho et al., 2021). Immediately to the east, several thin strips of the Mossamedes sequence are exposed within Sanclerlândia gneisses, while the Anicuns-Itaberaí volcano-sedimentary Sequence appear as a single irregularly shaped strip along the easternmost portion of the arc, where it is in contact with the high grade metamorphic rocks of

Anápolis-Itaúçu Complex (Fig. 2) (Lacerda-Filho et al., 2021).

The late to post-kinematic intrusions have crystallization ages ranging from 630 to 540 Ma (Pimentel, 2016). These intrusions include high-K calc alkaline to alkaline (A-type) granite (Pimentel, 2016; Pimentel et al., 1996) and mafic-ultramafic intrusions such as Córrego-Seco (Lacerda-Filho et al., 2021), Americano do Brasil (Silva et al., 2011), Santa Bárbara Intrusive Suite (Lacerda Filho et al., 2021) and Mangabal (Augustin and Della Giustina, 2019; Augustin et al., 2023).

2.3. Anicuns-Itaberaí Sequence (AIS)

The AIS comprises a complex assemblage of igneous and supracrustal rocks, including calc-alkaline meta-basalts, andesitic to dacitic meta-tuffs, metapelites, iron formations, mafic-ultramafic rocks, metacherts, metarhythmites, and marble lenses, formed in an island arc setting (Baêta Junior, 1994; Lacerda Filho et al., 2021), within an arc to fore-arc basin (Laux et al., 2010). Geological mapping by Lacerda-Filho et al. (2021) subdivided the sequence into five minor geological units, in which the rocks were grouped according to their lithological and structural affinities, as follows: (1) the basic-ultrabasic unit, composed primarily of amphibolite layers with variable amounts of talc schists and tremolitites, and also including gabbroic intrusions; (2) the

rhythmic-carbonatic unit, mainly characterized by intercalations of metacherts, gondite, and Fe-rich sediments, with marbles occurring at the top of the unit; (3) the psammo-pelitic unit, represented by quartzites and mica-rich schists with nearly rhythmic intercalations; (4) the kyanite-muscovite gneiss unit, comprising localized occurrences of sericitic kyanite-bearing rocks and kyanite-bearing quartzites; and (5) the epidote gneiss unit, represented by epidote-rich amphibolites and gneisses.

Contacts with the gneisses of the Anápolis-Itaúçu Complex to the east are tectonic, marked by NNW-SSE-oriented dextral transpressional shear zones, while contacts with the metagranitoids of the Sanclerlândia Gneiss to the west are characterized by thrust faulting (Lacerda-Filho et al., 2021). Crystallization ages of the metagabbro (metagabbro and metadiorite) interbedded with the metasedimentary sequences range from 886 ± 5 Ma to 815 ± 10 Ma, based on U-Pb zircon dating, whereas the $\epsilon\text{Nd}(T)$ values range from +4.4 to +4.1, and the TDM model ages are approximately 1.0 Ga (Laux et al., 2004).

The AIS has been described as having undergone low-grade metamorphism, with peak conditions ranging from upper greenschist facies (Nunes, 1990) to low amphibolite facies (Baêta Junior, 1994). Many of the rock types, including chemical sediments, acidic volcanic rocks, quartzites, and marbles, exhibit mineral associations unsuitable for metamorphic inferences. Therefore, evidence of metamorphism is primarily derived from the mineral assemblages present in pelitic schists and mafic rocks. In the metabasalts and metagabbros of the basic-ultrabasic unit, the mineral assemblage includes hornblende, oligoclase, albite, quartz (e.g., Nunes, 1990; Baêta Junior, 1994), epidote, and diopside (Lacerda-Filho et al., 2021). The mineral assemblage in pelitic schists of the psammo-pelitic unit includes biotite, muscovite, chlorite, and garnet porphyroblasts that are occasionally replaced by chlorite. Additionally, kyanite-bearing muscovite schists are described in the kyanite-muscovite gneiss unit (Lacerda-Filho et al., 2021).

The regional structural framework in the western portion of Brasília Orogen resulted from adjustments of a mosaic of crustal segments or blocks of distinct ages, which were assembled during Neoproterozoic through accretionary processes, according to Lacerda-Filho et al. (2021). The authors also observed that these events were characterized by deformational mechanisms that facilitated the amalgamation of these segments, leading to substantial crustal shortening, followed by the development of shear zones and thrust slices that accommodated the regional deformation. Regarding the AIS, the same work shows that it is structurally situated within the Itaberaí-Campestre structural domain, which is characterized by a belt of imbricated folds and the development of oblique ramps with eastward vergence. The main structure in this domain is a NNW-trending S_2 foliation, interpreted as the limb of asymmetrical folds, with limb orientations ranging from $N005^\circ\text{W}/25^\circ\text{SW}$ to $N015^\circ\text{E}/35^\circ\text{SE}$, and fold axes varying from $010^\circ/125^\circ-010^\circ/270^\circ$.

3. Materials and methods

3.1. Structural analysis

The structural geology analysis was based on standardized procedures for the identification, classification and interpretation of tectonic structures at outcrop scale (e.g., Faleiros et al., 2016). Structural data were collected using a geological compass (Pocket Geotransit – Brunton) and the structures were organized according to the strain intensity observed. The stereographic representation of structural orientation was performed using Stereonet v.11.3.0 software (Allmendinger et al., 2013). Microtectonic analysis was conducted on approximately four thin sections, using the terminology and descriptive criteria established by Passchier and Trouw (2005) and Vernon (2018).

3.2. Petrography and scanning electron microscope analysis

Four samples of garnet-chlorite-biotite-muscovite schist thin section were selected for petrography and microstructural analysis under transmitted light petrography two perpendicular to the schistosity and two transverse to main schistosity in order to analyse microstructural variations associated to the deformational events. The thin sections 23GO_022-P1 and 23GO_025T1 were analyzed with a polarizing optical microscope and after were coated with a thin layer of graphite to assure electrical conductivity for subsequent analysis using a scanning electron microscope JEOL JSM 6010LA (SEM), using 15–20 kV at the Department of Geology of São Paulo State University (UNESP), Brazil.

3.3. Chemical analysis

The microprobe analysis was performed using a JEOL JXA-8230 Electron Probe Micro Analyzer (EPMA) equipped with five wavelengths dispersive spectrometry (WDS) at the Department of Geology of UNESP. WDS quantitative analyses of garnet, biotite, chlorite, plagioclase and muscovite were conducted using a current of 20 nA and an accelerating voltage of 15 kV with a dwell time of 80 ms. The compositional maps were made to generate mineral distribution maps, recognize internal composition variation in the minerals, and determine the local bulk composition for the metamorphic modelling. The maps were generated with 15 kV and 100 nA with the beam size varying from 4 to 5 μm , and a pixel size of 4 μm (e.g., Fumes et al., 2021).

The microprobe data (maps and quantitative analyses) were then processed using the XmapTools 4.4 software (Lanari et al., 2014). The minerals were identified based on the different concentrations of elements obtained for garnet, biotite, muscovite, chlorite and plagioclase. Next the spot analyses were integrated and standardized manually for all elements for the mineral phases. From this procedure the semi-quantitative mineral maps were converted into quantitative maps, used to extract the local bulk composition (Lanari et al., 2014; Lanari and Duesterhoeft, 2019). The mineral chemistry data interpreted in this work and the thermodynamic modelling were based on these quantitative maps.

3.4. Thermodynamic modelling

Thermodynamic modelling was performed using the Local Bulk Composition of the samples obtained by the standardized XmapTools quantitative maps which were input into the Theriak-Domino v2023.06.06 (de Capitani and Brown, 1987; de Capitani and Petrakakis, 2010) software with the thermodynamic database tcds55_p07_rb (Holland and Powell, 1998) and solution models for garnet (White et al., 2005), biotite (White et al., 2005), chlorite (Mahar et al., 1997), muscovite (Coggon and Holland, 2002), and ilmenite (White et al., 2000). The pseudosections were based on the chemical system. $\text{MnO} - \text{Na}_2\text{O} - \text{CaO} - \text{K}_2\text{O} - \text{FeO} - \text{MgO} - \text{Al}_2\text{O}_3 - \text{SiO}_2 - \text{H}_2\text{O} - \text{TiO}_2 - \text{O}_2$ (MnNCKFMASHTO), with pressure and temperature ranges varying from 0.4 to 1.4 GPa and 400–680 $^\circ\text{C}$, respectively, and with excess water in the system. Detailed diagrams for Fe^{3+} estimation using T-X(Fe^{3+}) are provided in the supplementary material (Appendix S1; Fig. S1 and Fig. S2). Although the isochemical diagrams results are internally consistent, it is important to note that these modelling inherently carry uncertainties related to the thermodynamic dataset, the adopted solidus solution and the definition of the local bulk composition.

4. Results

4.1. Study area

Detailed geological mapping of the Serra da Jiboia region (Fig. 3), indicates that the AIS in the study area consists predominantly of metasedimentary rocks of siliciclastic origin, primarily pelite-derived schists

and quartzites, interbedded with marbles, calc-silicate schists, and localized occurrences of talc schist and granite intrusion.

Quartzite predominates at the higher elevations of the Serra da Jiboia, whereas pelitic schists are the dominant lithotype in the surrounding flatlands. These rocks have been deformed into asymmetrical folds, with limbs dipping NNE–SSW at angles between 20° and 35° . The pelitic schists commonly exhibit crenulation cleavage. It is composed of muscovite (30 %), quartz (20 %), plagioclase (15 %), biotite (15 %), and chlorite (10 %), with garnet porphyroblasts (8 %) ranging from millimetric to centimetric in size and displaying a sieve texture.

Hornblende-bearing garnet-mica schists are frequently associated with the pelitic schists. These rocks crop as slabs and boulders and are mapped as lenses within the schist-dominated units (Fig. 3). Due to the presence of Ca-amphibole (hornblende), they were classified as calc-silicate schists. Their mineral assemblage includes quartz (30 %), muscovite (20 %), plagioclase (10 %), biotite (10 %), chlorite (10 %),

garnet (10 %), and hornblende (8 %).

Quartzite layers of variable thickness also occur within the pelitic schists in the flatland areas. When exposed, they form elongated, ridge-like lineaments as a result of asymmetrical folding, producing prominent topographic features, as shown in the block diagram of Fig. 4. Toward the Serra da Jiboia, schist intercalations become less frequent, and the quartzite becomes increasingly pure and dominant, with only rare interbedded schist layers.

In the northwestern part of the area, calcitic marbles are finely interlayered with quartzite, and in this zone, the marbles – composed mainly of calcite and dolomite – predominate over quartzite. Localized talc schists are occasionally found within the pelitic schists, although they are generally not mappable except in the northwestern sector. These appear as fine-grained whitish to greenish schists, composed of approximately 95 % talc and 5 % chlorite.

In the southwestern portion of the study area, a small outcrop of

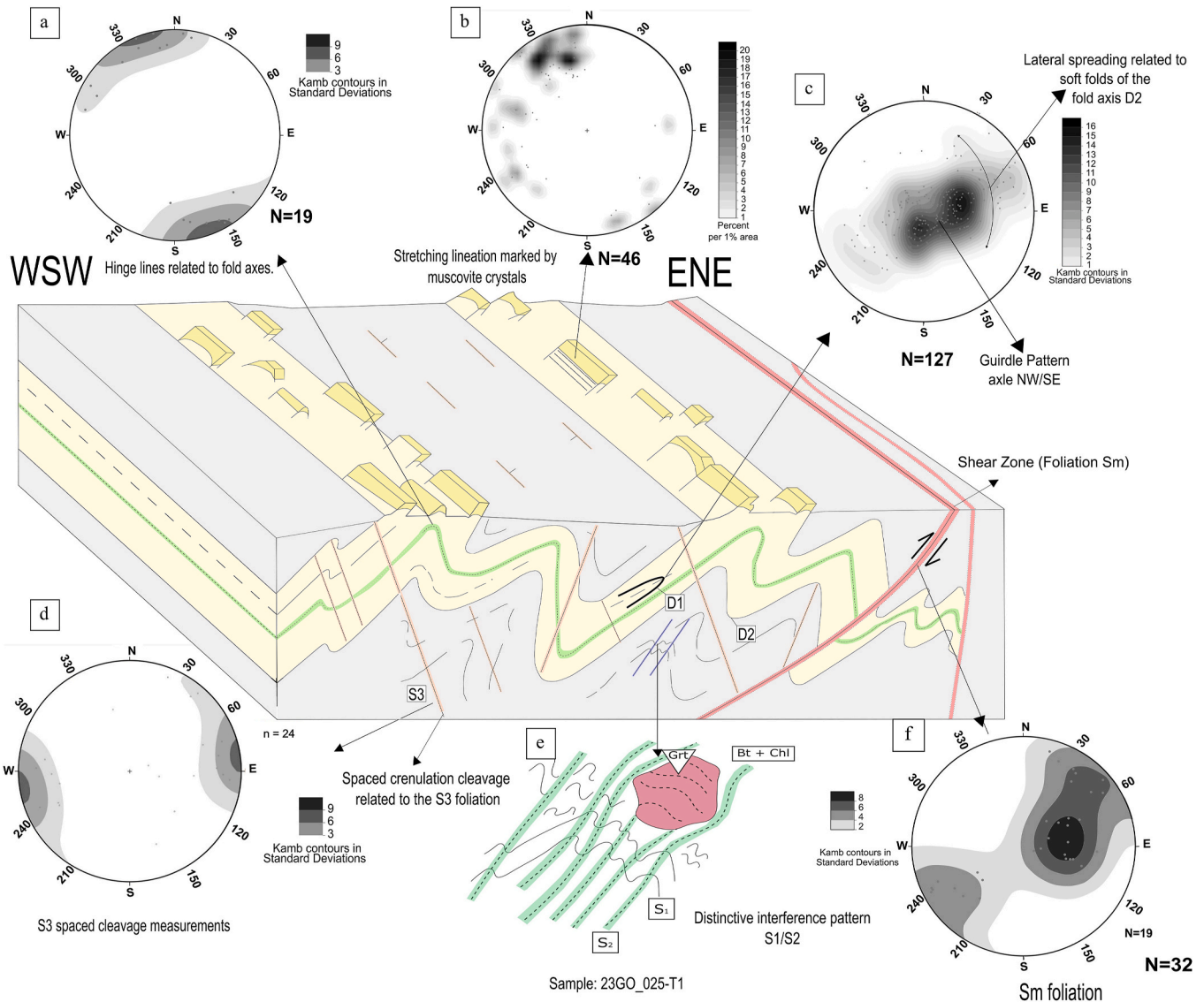


Fig. 4. Schematic geological cross-section showing the studied samples within the structural framework observed in the study area supported by stereograms of the main structures which were plotted in lower hemisphere using an equal-area projection (Schmidt Net). The block diagram highlights the association between D₁ isoclinal folds, D₂ asymmetrical folds, and D₃ reverse fault-related shear zones with eastward vergence. It also shows the associated mylonitic foliation (S_m) and spaced cleavage (S₃), both developed under brittle–ductile transitional conditions. The diagram further illustrates the disruption of earlier D₂ fold hinges by D₃ shear zones, as well as the inferred oblique ramp geometry a) Poles of the S₁ foliation plane, indicating folds with a NW–SE axis. b) Muscovite mineral lineation within S₂ schistosity plane, showing a preferred orientation towards NNW. c) S₁ foliation, forming a girdle pattern defined by the distribution of pole points with a N–S orientation. d) Poles to S₃ spaced cleavage planes, showing a preferred N–S orientation and steep dips towards the WSW and ENE. e) Schematic illustration of sample 23GO-025 highlights the distinct relationship between the garnet porphyroblast internal foliation trails with matrix foliation. f) Poles to S_m mylonitic foliation planes.

biotite–muscovite granite, belonging to the Creoulos Suite, has been identified. It crops out as slabs and boulders associated with a modest topographic high. The margins of the intrusion exhibit a mylonitic C-type shear bands (Passchier and Trouw, 2005), and the rock is characterized by euhedral phenocrysts of potassium feldspar (~34 %) and plagioclase (~32 %) up to 2 cm in length, with a whitish-gray color and porphyritic texture.

4.2. Structural settings and microtectonics

In the Serra da Jiboia region, the rocks of the AIS are structured into a series of asymmetrical folds associated with reverse faulting. The structures identified in the area have been chronologically divided into four distinct deformation phases, all developed during a single,

prolonged compressional event linked to the accretion of magmatic arc segments onto the metamorphic core of the Brasília Orogen during the Neoproterozoic. The structural relationships among these phases are schematically illustrated in the block diagram of Fig. 4, and the outcrop images are shown in Fig. 5. The deformation phases are described as follows.

The D_1 phase is characterized by the folding of the original S_0 compositional layering into discontinuous intrafolial isoclinal folds (Fig. 4). These structures are not widely exposed in the AIS within the study area, and their preservation is generally limited to isolated outcrops. The preserved D_1 folds (Fig. 5a) range from centimeter-to meter-scale and are commonly refolded by later asymmetric folding events. At the thin-section scale, evidence of D_1 deformation is preserved as inclusion trails within garnet porphyroblasts (Fig. 6b), believed to

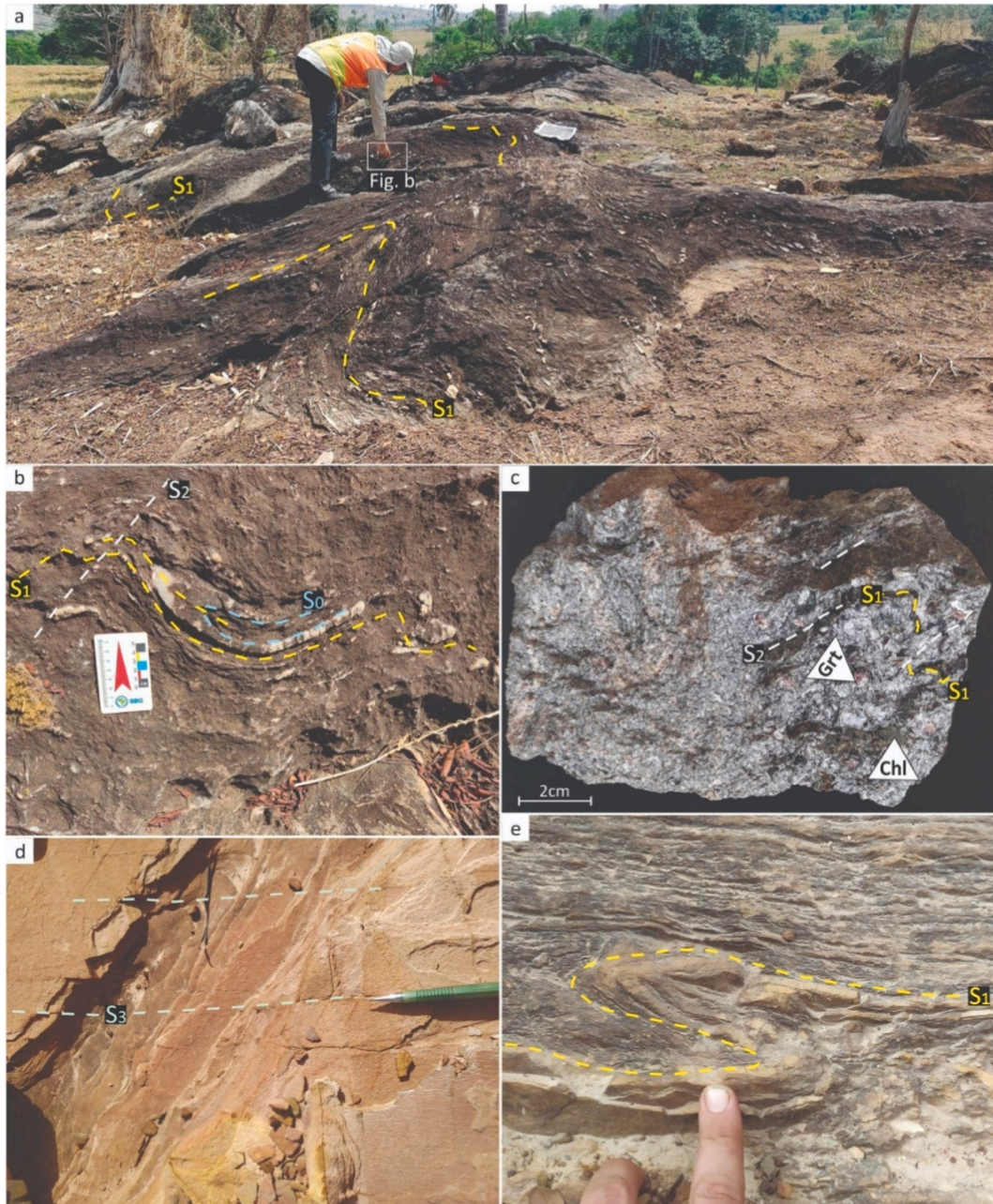


Fig. 5. Photographs illustrating the structural relationships in outcrops and hand samples. (a) Schist outcrop photo showing asymmetrical D_2 folds that deform the S_1 schistosity. (b) Detail from the same outcrop showing isoclinal folding of S_0 and the relationship between S_0 , S_1 , and S_2 . (c) Hand sample photo displaying crenulated S_1 schistosity and crenulation cleavage of S_2 , aligned with the axial plane of the crenulation. (d) Detailed outcrop photo showing S_3 spaced cleavage in quartzites. (e) Tight folding of S_1 schistosity, which is parallel to S_0 in this outcrop.

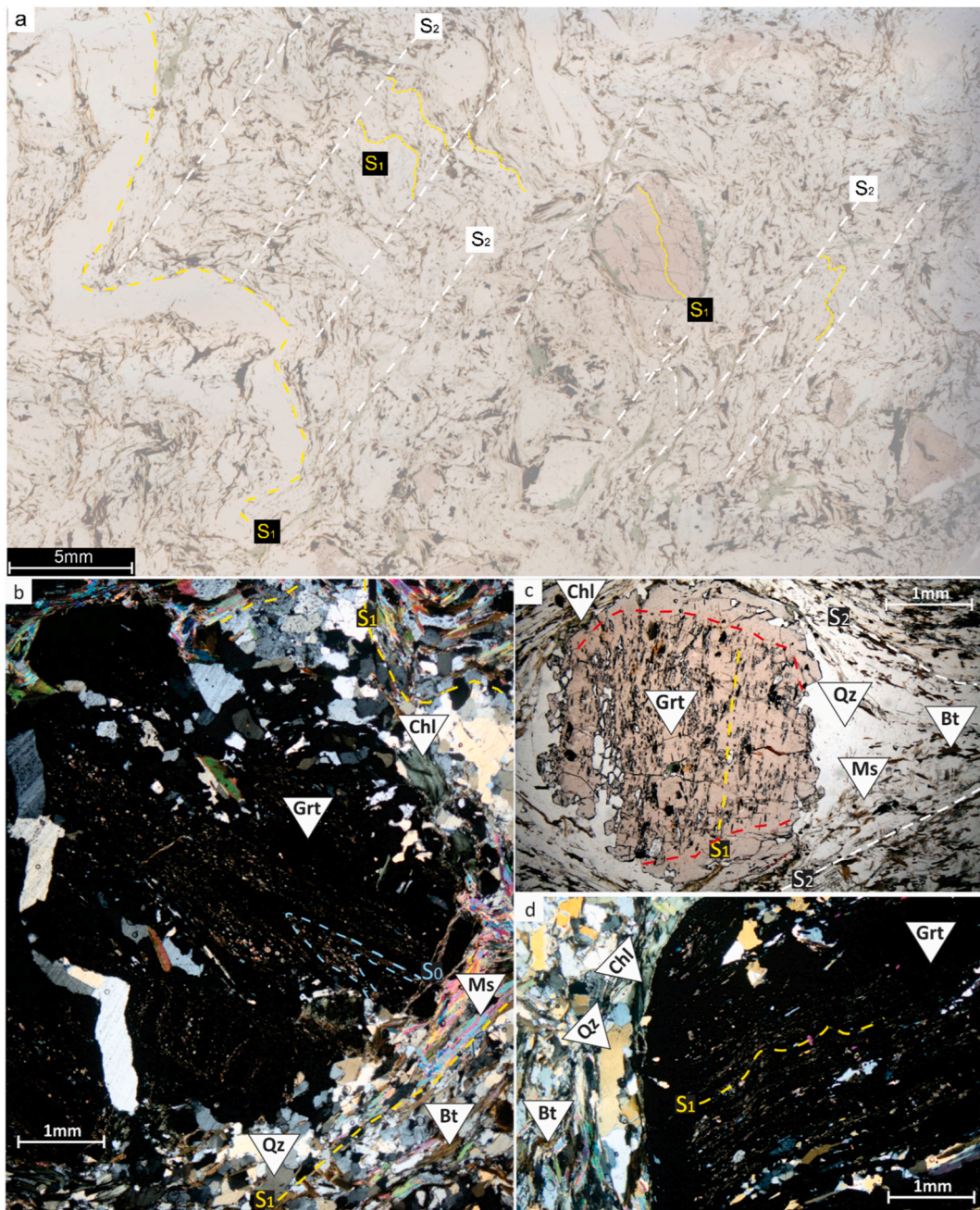


Fig. 6. Microtectonic features observed in thin sections. (a) Scan of a thin section illustrating the relationship between S₁ and S₂ foliations. (b) Photomicrograph showing a garnet porphyroblast containing inclusions that preserve isoclinal D₁ folding, interpreted to have grown between the D₁ and D₂ deformation phases - cross-polarized light. (c) Texturally zoned garnet porphyroblast characterized by an inclusion-rich core, where inclusions are aligned along a folding-free S₁ foliation, and a latter-formed, massive, inclusion-free rim. (d) Garnet porphyroblast exhibiting inclusions arranged in an open-fold crenulation pattern, interpreted as having crystallized during the early stages of D₂ deformation - cross-polarized light. Mineral abbreviations according to [Whitney and Evans \(2010\)](#).

represent early isoclinal folding.

The S₁ foliation, a well-developed schistosity, is parallel to the axial planes of the D₁ folds. Its orientation defines a girdle pattern ([Fig. 4](#)), consistent with interference from the subsequent D₂ deformation phase, which is marked by asymmetric folding and crenulation.

The D₂ phase represents the main folding event and is defined by asymmetrical folds ranging from millimeter to decameter scale, with ENE vergence and variably oriented fold limbs. These folds define a girdle pattern, with the maximum concentration of poles ranging from 01 to 16 reflecting preferred orientation of the main foliation. In other words, these concentrations quantify the intensity of directional fabric in orientation space. The D₂ fold axes are cylindrical and nearly

horizontal, plunging gently (~0°–10°) toward either 340° or 160° ([Fig. 4](#)). Due to the intrafolial nature of the D₁ folds – where fold limbs are tightly appressed and parallel – many outcrops lacking visible D₁ structures instead exhibit D₂ folds that affect both the S₁ schistosity and the S₀ compositional layering, which are typically parallel.

The S₂ foliation locally overprints the earlier crenulations and the S₁ foliation, forming a penetrative schistosity. In these cases, evidence of the earlier S₁ fabric is preserved as inclusion trails within pre-D₂ garnet porphyroblasts, which retain relics of S₁ even in high-strain zones ([Fig. 5c](#)). In certain instances, these trails define small-amplitude crenulations, indicating that garnet growth continued into the early stages of the D₂ deformation phase ([Fig. 5d](#)).

In most outcrops, the S_2 foliation is only weakly developed, typically appearing as a crenulation cleavage subparallel to the axial planes of D_2 folds. However, in zones of more intense deformation, the folds become tighter and may evolve into closed geometries (Fig. 5e). In such areas, the distinction between S_1 and S_2 foliations becomes challenging due to their subparallel orientation, even in thin sections cut perpendicular to the mineral lineation.

The D_3 phase is characterized by high-angle thrust shear zones with eastward vergence and an associated spaced cleavage (Fig. 4). This phase is marked by the development of a mylonitic foliation (S_m) along fault planes, as well as a spaced cleavage (S_3), which is interpreted as the manifestation of D_3 deformation outside the main shear zones, formed under brittle–ductile transitional conditions. These shear zones, associated with reverse faulting, commonly disrupt the hinge zones of earlier D_2 asymmetric folds, reflecting progressive deformation toward a more brittle regime.

Although only a limited number of D_3 shear zones were clearly identified in the field, they are interpreted as oblique ramps, as suggested by Lacerda-Filho et al. (2021). The S_3 spaced cleavage (Fig. 5d) displays a dominant NNW–SSE strike and steep dips, variably oriented toward the WSW and ENE.

The D_4 structures exhibit a more regional character, as evidenced by the broad bending of large-scale geomorphological features, including the hilltops of the Serra da Jiboia and its surroundings. This deformation phase gently folds earlier structures, producing a systematic shift in the orientation of the main foliation traces – from NNW–SSE in the northern portion of the range to NNE–SSW in the southern portion. This pattern defines a broad, open fold, with its hinge zone centered within the Serra da Jiboia.

The effects of this deformation are also recorded in the S_1 foliation stereogram, where the girdle of S_1 poles displays a dispersion of concentrations toward both the north and south (Fig. 4c), consistent with large-scale warping of earlier planar structures. This geometry is interpreted as the result of a late-stage deformation phase, likely related to E–W-trending shear zones mapped regionally outside the study area. The D_4 phase is thought to have occurred under relatively brittle conditions, which may explain the lack of corresponding structures at the outcrop scale despite the pronounced curvature observed in regional structural trends.

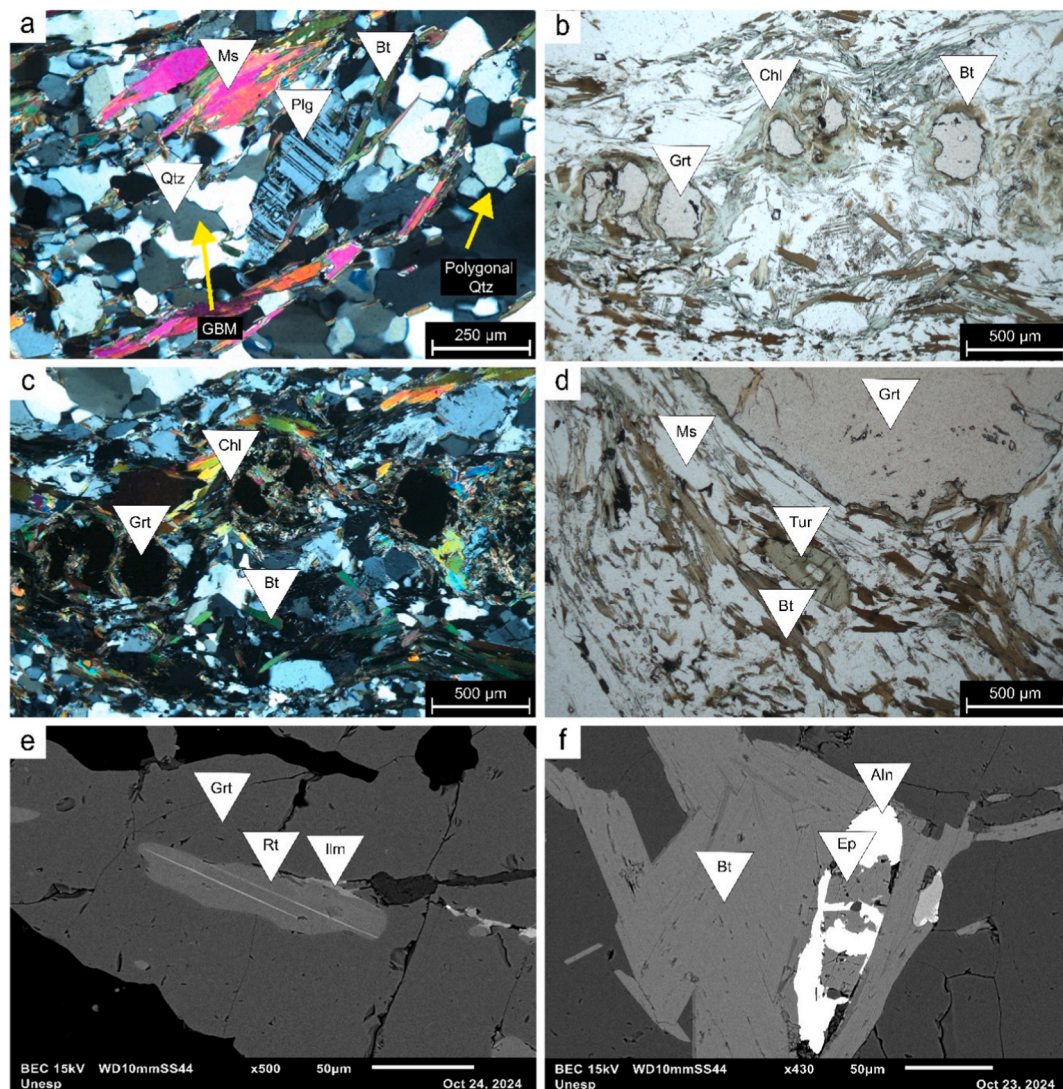


Fig. 7. Photomicrograph of pelitic schists from the AIS. a) Granoblastic domains marked by quartz with grain boundary migration recrystallization features and polygonal quartz. b) Garnet porphyroblast replaced by chlorite and biotite in polarized light and c) crossed-polarized light. d) Garnet porphyroblast with zoned tourmaline in polarized light. e) Rutile crystal with ilmenite exsolution lamellae under scanning electron microscope. f) Allanite in the matrix associated with epidote crystal. Mineral abbreviations according to Whitney and Evans (2010).

4.3. Petrography

The studied samples are medium-to coarse-grained pelitic schists characterized by a crenulated schistosity and a lepidoblastic texture. The main mineral assemblage comprises muscovite (30 %), quartz (20 %), plagioclase (15 %), biotite (15 %), chlorite (10 %), and garnet porphyroblasts (8 %). Microtectonic features are displayed in Fig. 6. Garnet porphyroblasts are euhedral to subhedral, reaching up to 5 mm in diameter, and exhibit a sieve-like poikiloblastic texture. Inclusions within the garnet consist of quartz, plagioclase, rutile, titanite, apatite, epidote, tourmaline, and zircon. These inclusions are aligned in trails that preserve earlier structural fabrics, indicating garnet growth occurred between the post-D₁ isoclinal folding event and the early stages of D₂ crenulation of the S₁ schistosity in some porphyroblast as sample 23GO-022 (Fig. 6c) the garnet rim represents a Syn-D₂ estage. This suggests that the garnet porphyroblasts are of intertectonic origin with rims in some porphyroblast syntectonic. Garnet is commonly partially replaced by chlorite and/or biotite as a result of retrograde metamorphic reactions, and in some cases, it is completely pseudomorphed by these minerals.

Muscovite and biotite occur as aggregates of oriented lamellar crystals that define the schistosity of the rock, as noted in Fig. 7. Individual crystals reach up to 0.5 mm in length, while aggregates may attain sizes of up to 1.5 mm (Fig. 7a). Biotite shows strong pleochroism from light to dark brown (Fig. 7b). Some biotite crystals are partially replaced by chlorite due to retrograde metamorphism, forming chlorite films developed parallel to the {001} cleavage planes within the biotite.

Chlorite crystals predominantly occur as aggregates of platy minerals. They appear as secondary phases replacing garnet and biotite, as well as in aligned clusters along the schistosity, preferably along the S₂ foliation (Fig. 7b, c and 7d). These aggregates can reach up to 1 mm in size. From a genetic perspective, chlorite crystallization is interpreted to have occurred either contemporaneously with or subsequent to the D₂ deformation phase, as evidenced by their common retrograde metamorphic texture. Individual crystals are typically around 0.1 mm in length, light green in color, and display pleochroism ranging from light green to colorless.

The plagioclase composition is oligoclase, and it is relatively abundant for pelitic rocks. Some crystals display polysynthetic twinning (Fig. 7a). Associated with quartz, oligoclase forms the granoblastic domains within the rock. In these domains, both minerals occur as inequigranular crystals with lobate grain boundaries, indicative of recrystallization dominated by grain boundary migration (GBM) (Fig. 7a). Additionally, some quartz crystals display polygonal grain boundaries, suggesting static recrystallization or post-deformational annealing (Fig. 7a).

Accessory phases include rutile, ilmenite, titanite, apatite, zircon, tourmaline, epidote, and allanite. These minerals generally exhibit euhedral shapes and are typically smaller than 100 µm. Ilmenite occurs as thin intergrowths within rutile (Fig. 7e), while allanite appears as an exsolution-like texture within euhedral epidote crystals (Fig. 7f). Tourmaline is the most common accessory mineral, with some crystals reaching up to 150 µm in length (Fig. 7d).

4.4. Mineral chemistry

The mineral composition maps were made for samples 23GO_022-P1 (Fig. 8) and 23GO_025-T1 (Fig. 9). The garnet porphyroblasts show a distinct chemical zoning pattern, since the core is depleted in almandine as the concentration gradually increases moving to the rims $X_{alm} = 0.6-0.74$ (Fig. 8b) and $X_{alm} = 0.62-0.74$ (Fig. 9b). The grossular content shows relatively constant concentration in the core and the mantle with a decrease towards the rims $X_{Grs} = 0.28-0.14$ (Fig. 8c) and $X_{Grs} = 0.29-0.19$ (Fig. 9c), while the pyrope end-member exhibits the opposite behavior $X_{Pyr} = 0.05-0.14$ (Fig. 8d), $X_{Pyr} = 0.04-0.14$ (Fig. 9d). In spessartine, the core is enriched and a progressive decrease

is noted heading to the rims ($X_{spss} = 0.8-0.02$ (Fig. 8e) and $X_{spss} = 0.03-0.01$ (Fig. 9e), characterizing a bell-shaped pattern.

The plagioclase crystals are predominantly sodic with composition varying between albite and oligoclase $X_{Ab} = 0.8-1.0$ (Figs. 8g and 9g). Although the composition of the plagioclase is similar in both samples, in samples 23GO_022-P2 there are rims enriched in albite ($X_{Ab} = 0.9-1.0$; Fig. 8g). In contrast, in Sample 23GO_025-T1, the pattern is reversed, with cores enriched in albite ($X_{Ab} = 1.0$) and rims varying between $X_{Ab} = 0.8-0.9$ (Fig. 9g).

The biotite crystals show relatively constant concentration of X_{Mg} ranging from 0.5 to 0.6 (Figs. 8f and 9f). Muscovite crystals show a pattern variation in Al content (apfu), ranging from 2.8 to 2.6 in sample 23GO_022-P1 (Fig. 8i) and from 2.75 to 2.5 in sample 23GO_025-T1 (Fig. 9i).

The chlorite crystals in sample 23GO_022-P1 show no significant variation in the X_{Mg} (Mg/Mg + Fe) ratio, maintaining constant values around 0.7 (Fig. 8h). On the other hand, the chlorite crystals located near the garnet porphyroblast show lower X_{Mg} values, around 0.59 while the crystals at the matrix have higher concentration around 0.62 to 0.7 (Fig. 9h).

4.5. Thermodynamic modelling - isochemical P-T phase diagrams

Two pairs of isochemical phase diagrams for samples 23GO_022-P1 (Fig. 10) and 23GO_025-T1 (Fig. 11) were made to delimit the metamorphic trajectory, due the well-defined chemical zoning in the garnet porphyroblasts between core, outer core and rim, considering that the core was not in thermodynamic equilibrium with the matrix during the peak and retrometamorphism. Therefore, one isochemical phase diagram for each sample considers the total bulk composition of the samples to delimit the trajectory of prograde metamorphism (Figs. 10a and 11a) and the other bulk composition subtracts the composition of the core of garnets to delimit the metamorphic peak and retrograde metamorphism.

Samples 23GO_022-P1 and 23GO_25-T1 exhibit similar chemical composition and mineralogy, so the phases obtained were the same in both pairs of isochemical diagrams: garnet, chlorite, plagioclase, kyanite, sillimanite, zoisite, muscovite, paragonite, quartz, staurolite, ilmenite, rutile, titanite and water as an excess phase. In the isochemical analyzed, the stability of the mineral phases is quite similar, with quartz and water being in excess. Garnet is stable in most diagrams, restricted to conditions of temperatures below 450 °C and pressure below 0.85 GPa. Biotite is unstable at temperatures below 450 °C and in a pressure range of 0.4–0.85 GPa, varying according to the composition of the diagram. Muscovite is stable in most isochemical diagrams; however, it becomes unstable at pressures exceeding 0.7 GPa and within a temperature range of 500–600 °C. Paragonite occurs at pressures above 0.7 GPa, but at a temperature range between 400 and 650 °C.

Plagioclase defines a broad stability domain of P-T range, generally above 470 °C. However, in the diagrams for sample 23GO_025-T1, stability occurs over a wider temperature range between 450 and 680 °C (Fig. 11a and c). Albite is stable under conditions below 450–530 °C; 0.5–0.7 GPa, though it is found in fields with pressures greater than 1.05 GPa. Potassium feldspar is restricted to a narrow P-T field at the diagrams from sample 23GO-025 T1, occurring only at ~660 °C and pressures of 0.4–0.5 GPa (Fig. 11a and c). Staurolite is stable under P-T conditions between 550 and 650 °C and 0.4–0.8 GPa. Titanite is stable at temperatures below 500 °C and over a broad pressure range of 0.4–1.4 GPa, except in the diagram of sample 23GO_025-T1 (Fig. 11a) where this phase is stable above 0.75 GPa. Ilmenite is observed in a broad stability field, but is unstable at pressures greater than 1.05 GPa (Fig. 10c). In sample 23GO_025-T1, ilmenite is not stable between 500 and 600 °C. Rutile is observed in all diagrams under P-T conditions greater than 500 °C and 0.9 GPa, which indicates replacement of ilmenite under higher pressure conditions.

The Al₂SiO₅ phases are found in a temperature range varying from

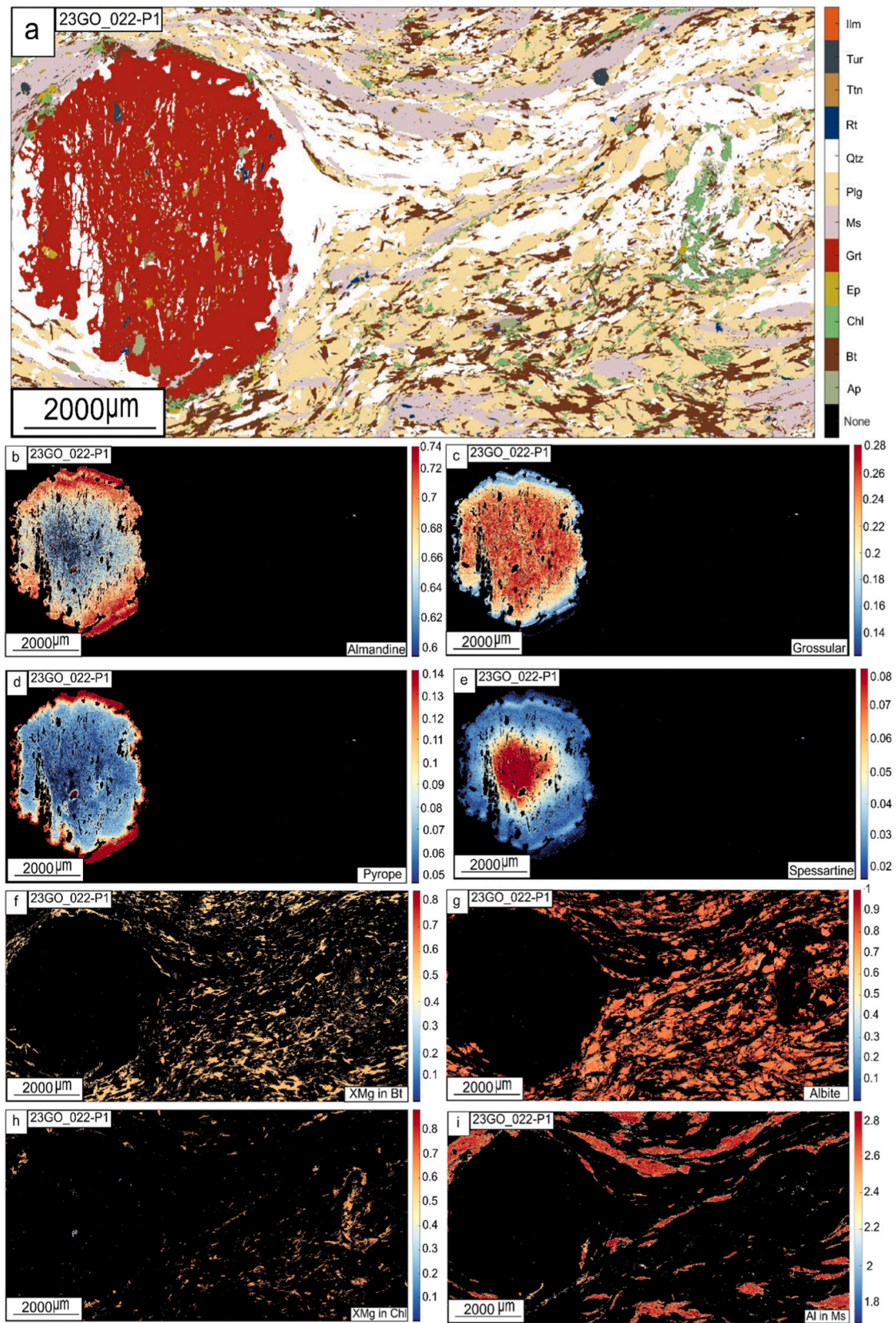


Fig. 8. Mineral composition maps for sample 23GO_022-P1. a) Mineral distribution. b) Almandine ($X_{\text{Alm}} = \text{Fe}/[\text{Fe} + \text{Ca} + \text{Mg} + \text{Mn}]$). c) Grossular ($X_{\text{Grs}} = \text{Ca}/[\text{Fe} + \text{Ca} + \text{Mg} + \text{Mn}]$). d) Pyrope ($X_{\text{Pyr}} = \text{Mg}/[\text{Fe} + \text{Ca} + \text{Mg} + \text{Mn}]$). e) Spessartine ($X_{\text{Sps}} = \text{Mn}/[\text{Fe} + \text{Ca} + \text{Mg} + \text{Mn}]$). f) XMg content in biotite crystals g) Albite content. h) XMg content in chlorite crystals. i) Al content apfu in muscovite crystals.

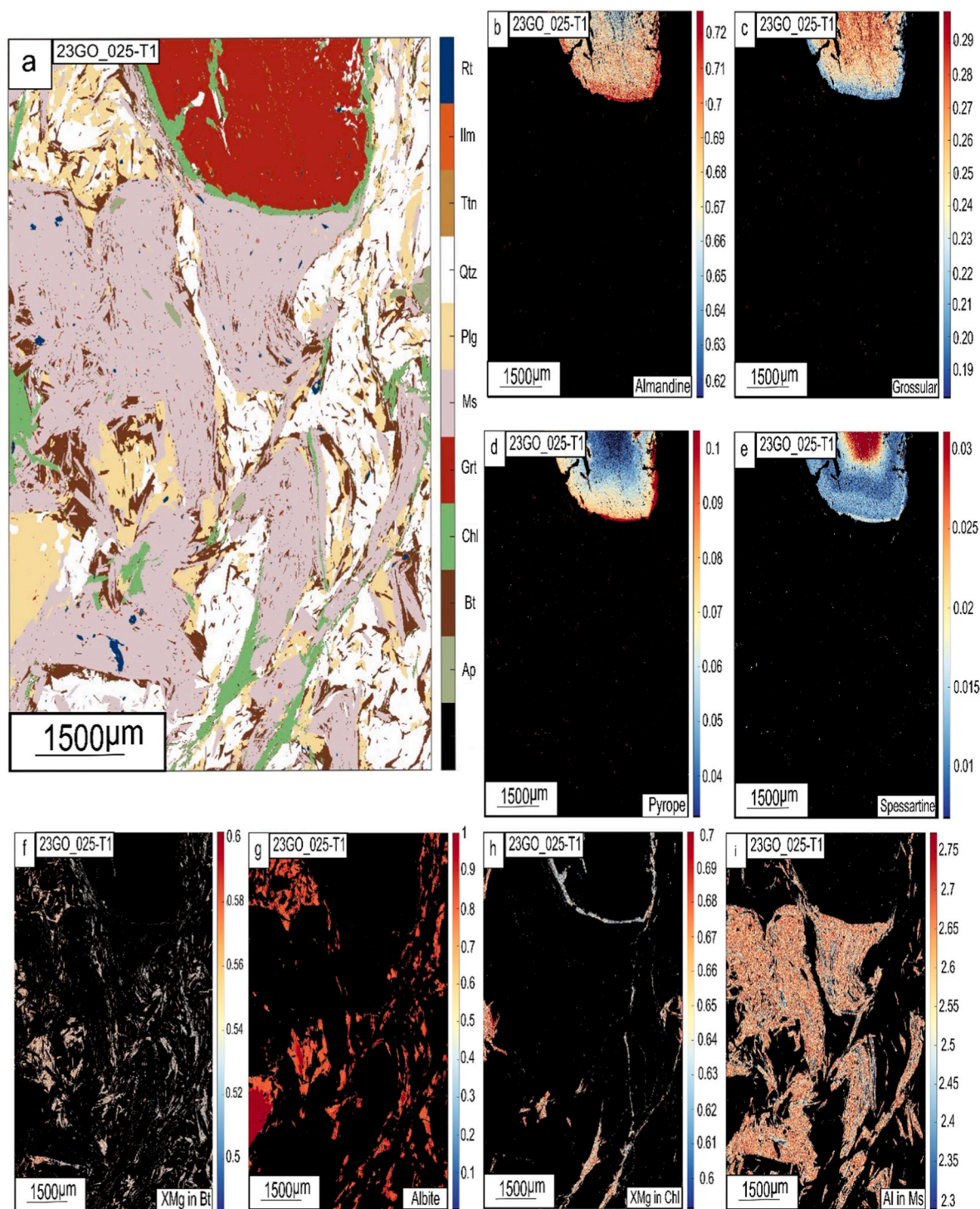


Fig. 9. Mineral composition map for sample 23GO_025-T1. a) Mineral distribution. b) Almandine ($X_{Alm} = Fe/[Fe + Ca + Mg + Mn]$). c) Grossular ($X_{Grs} = Ca/[Fe + Ca + Mg + Mn]$). d) Pyrope ($X_{Pyr} = Mg/[Fe + Ca + Mg + Mn]$). e) Spessartine ($X_{Sps} = Mn/[Fe + Ca + Mg + Mn]$). f) XMg content in biotite crystals. g) Albite content. h) XMg content in chlorite crystals. i) Al content apfu in muscovite crystals.

580 to 600 °C, where sillimanite is dominant at pressures lower than 1 GPa. At the same time, Kyanite is observed in a more limited range between 0.65 and 1 GPa, except for the diagram of sample 23GO_022-P1 (Fig. 10c). Zoisite is stable under moderate P-T conditions below 600 °C and in the range of 0.4–1.4 GPa, with slight variations.

In both isochemical diagrams, the mineral paragenesis metamorphic peak is composed by plagioclase + garnet + biotite + muscovite + quartz + rutile + ilmenite, which is stable at temperatures above 620 °C and pressures above 0.95 GPa (Figs. 10d and 11d).

With the well-defined zoning of the garnet porphyroblasts, it was possible to define the P-T path using the isopleths of the end-members of the spessartine and grossular (Fig. 10b–d). In sample 23GO_022-P1, the intersection of the spessartine isopleths of 0.08 and grossular of 0.28 marks the start of garnet crystallization under conditions of 525 °C and 0.67 GPa (Fig. 10b). The spessartine-depleted mantle corresponding to the 0.02 isopleth crosses the 0.16 grossular isopleth, marking the peak of metamorphism at 660 °C and 1.25 GPa (Fig. 10d). For the retrometamorphism path the isopleth of the XMg of the chlorite and grossular

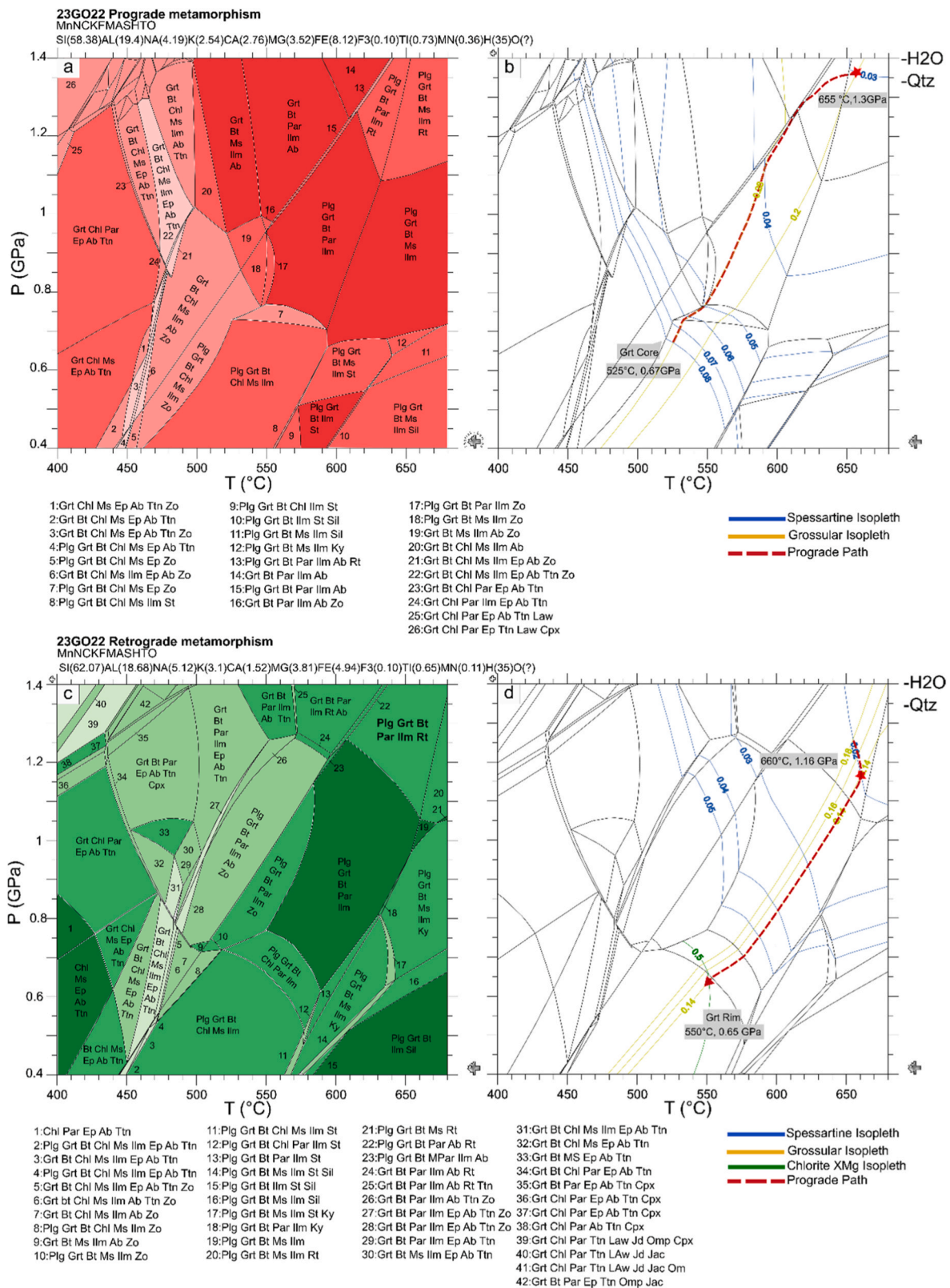


Fig. 10. Pressure–temperature (P–T) isochemical phase diagram in the MnNCKFMASHTO system for sample 23GO_022-P1. a) Isochemical phase diagram using the whole rock composition, including the garnet core composition, defining the prograde stage. b) Phase diagram showing the garnet isopleths of spessartine and grossular, defining the prograde path. c) Isochemical phase diagram without the garnet core, used to characterize the retrograde path. d) Isochemical diagram based on garnet composition (grossular and spessartine), and the XMg Chlorite composition indicating the conditions of the retrograde path.

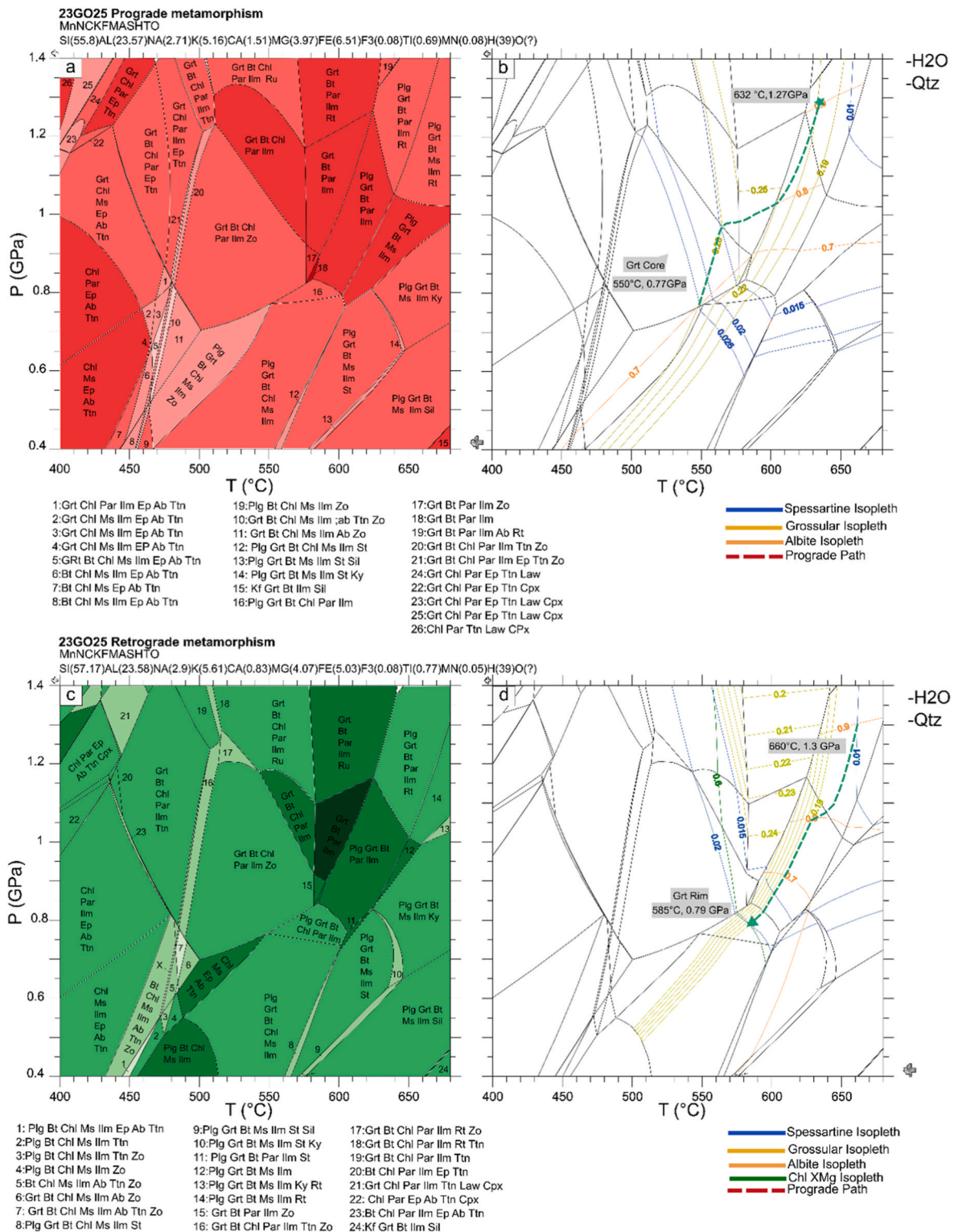


Fig. 11. Pressure–temperature (P–T) isochemical phase diagram in the MnNCKFMASHTO system for sample 23GO_025-T1. a) Isochemical phase diagram using the whole rock composition, including the garnet core composition, defining the prograde path. b) Phase diagram showing the garnet isopleths of spessartine, grossular and the composition of albite to define the prograde path. c) Isochemical phase diagram excluding the garnet core, used to characterize the retrograde path. d) Isochemical diagram based on garnet composition (grossular and spessartine) and the albite and XMg of chlorite, indicating the conditions of the retrograde path.

were used, in which the isopleth intersects with the 0.16 grossular isopleths, registering the 550 °C and 0.65 GPa conditions of retrograde metamorphism.

In sample 23GO_25-T1, the intersection of the grossular isopleth of 0.26, spessartine isopleth of 0.025 marked the beginning of garnet

crystallization at 550 °C and 0.8 GPa during the prograde path (Fig. 11b). The metamorphic peak is constrained by the intersection of spessartine 0.01 and albite 0.9 isopleth yielding estimates of 660 °C and 1.3 GPa for the metamorphic peak. While the isopleths of XMg Chlorite, grossular and spessartine mark the pressure and temperature of the

retrometamorphism at 585 °C and 0.79 GPa (Fig. 11d).

5. Discussion

5.1. Protolith composition

Samples 23GO_022-P1 and 23GO_025-T1 exhibit a mineral assemblage composed of muscovite, quartz, plagioclase, biotite garnet, and chlorite, in addition to accessory minerals such as rutile, zircon, apatite, ilmenite, tourmaline, epidote, and allanite. Thermodynamic modelling indicates that the paragenesis of the metamorphic peak is formed by garnet-plagioclase-muscovite-biotite-rutile-ilmenite (Figs. 10c and 11c), stable at conditions above 600 °C and 1 GPa, with an estimated metamorphic peak at 660 °C and between 1.16 and 1.3 GPa (Fig. 10d).

In a preliminary analysis, these rocks exhibit mineralogy typical of metapelites that reached amphibolite facies and were exhumed in greenschist facies during metamorphism, as evidenced by the reaction of garnet breaking down into biotite and chlorite which was described by Nunes (1990), Baêta Junior (1994) and Lacerda-Filho et al. (2021) for the rocks in the region. However, the estimated conditions for the metamorphic peak in the samples in this study are compatible with high-pressure amphibolite facies (Fig. 12), in which kyanite and staurolite would be stable in metapelites (Spear and Cheney, 1989). The lack of these minerals may be associated with the lower availability of aluminum in the system, in which these phases are stable at lower temperatures and pressures than those recorded (Fig. 10a, c and 11a, 11c).

The mineral assemblage and the pressure and temperature conditions obtained in this study are similar to those described by Fumes et al. (2021), who investigated the metamorphism of metagreywackes in the southernmost portion of the Brasília Orogen. According to Johnson et al. (2008) and Yakymchuk et al. (2017), greywackes are immature sediments, rich in feldspar and lithic fragments, more abundant than pelites in orogenic contexts where the metamorphism of such sediments gives rise to more restricted mineral associations compared to metapelites, greywackes are often composed of plagioclase, quartz, and biotite, with subordinate phases such as garnet, cordierite aluminosilicates, or potassium feldspar (Johnson et al., 2008).

Considering the geotectonic context and the geochemistry of the samples, the formation of the AIS in a forearc basin associated with the activity of the Arenópolis Magmatic Arc (Laux et al., 2010), as well as the mineral assemblage and stability conditions of the paragenesis identified in this work, it is proposed that the protolith of the schists studied here corresponds to metagreywackes (Fig. 13). This interpretation is corroborated by the similarity with the results of similar studies with P-T conditions close to those observed, such as Fumes et al. (2021), who describe parageneses under similar metamorphic conditions.

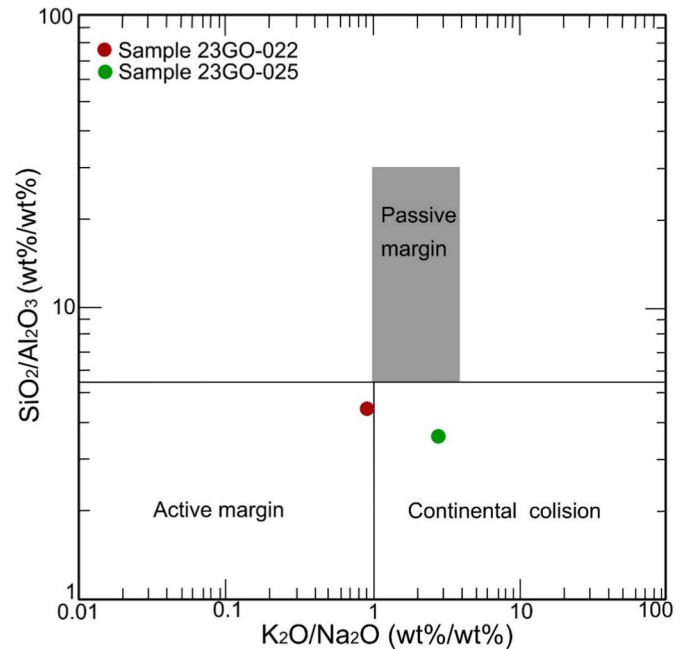


Fig. 13. $\text{SiO}_2/\text{Al}_2\text{O}_3$ versus $\text{K}_2\text{O}/\text{Na}_2\text{O}$ plot showing bulk rock composition trends used to infer the tectonic setting based from Fumes et al. (2021).

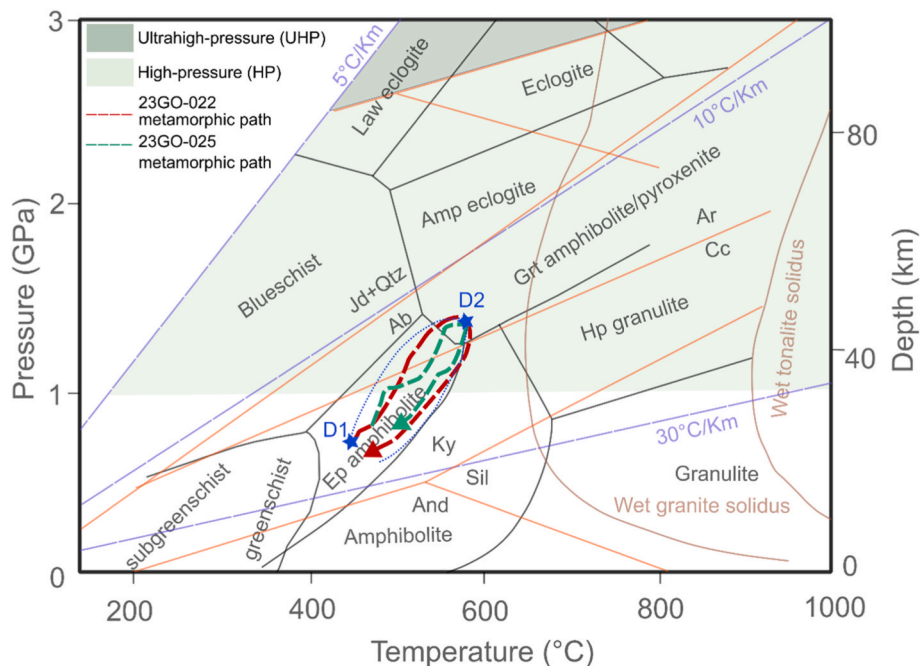


Fig. 12. Metamorphic P-T path of samples 23GO_022 and 23GO_025 of Anicuns-Itaberai Sequence, containing deformation stages. Metamorphic facies boundaries based from Zheng and Chen (2017).

5.2. Metamorphic conditions and P-T paths

The combination of garnet compositional isopleths in the isochemical diagrams (Figs. 10 and 11) defines a clockwise metamorphic path (Fig. 12). Garnet core crystallization began at approximately 525–550 °C and 0.65–0.77 GPa. The rock was then progressively buried, reaching a baric peak of 1.3 GPa (Fig. 10d). The metamorphic peak occurred subsequently at 660 °C and 1.16–1.3 GPa, within the high amphibolite facies, characterized by the stable paragenesis of plagioclase–garnet–biotite–muscovite–quartz–rutile–ilmenite, within a stability field exceeding 600 °C and 1 GPa. The metamorphic peak conditions indicate that these rocks were buried at > 40 km, and were subsequently exhumed in amphibolite facies under conditions of 530 °C and 0.72 GPa >20 km depth.

Few studies in the literature have addressed the metamorphism of the AIS, and those that do rely primarily on petrographic descriptions of mineral assemblages with a lack of thermodynamic modelling. These works generally suggest low-grade metamorphic conditions, with peak assemblages corresponding to the upper greenschist to low amphibolite facies (Nunes, 1990; Baêta Junior, 1994). However, the presence of kyanite-bearing rocks in the region challenges this interpretation. For instance, Lacerda-Filho et al. (2021) documented localized occurrences of kyanite-bearing schists and gneisses within the AIS, which imply a high-pressure metamorphic component that is incompatible with the previously proposed low-grade conditions.

Recent studies of the adjacent Americano do Brasil and Mangabal ultramafic complexes provide further evidence for higher-grade metamorphism in the region. Augustin et al. (2025) reported peak metamorphic conditions of 670–710 °C and pressures up to 0.75 GPa in these rocks. The recorded temperatures are broadly comparable with the results obtained at this work. The pressures are somewhat lower than those determined in the present study, however those authors modeled metamorphism based on retrogressed ultramafic rocks, in which the paragenesis and thermodynamic calculations did not constrain the metamorphic peak due to a latter open system behavior and strong alteration associated with metasomatism. Thus, pressure values presented by Augustin et al. (2025) are underestimated and may not represent the peak conditions. Additionally, the intense retrogressed parageneses and metasomatism processes observed in the ultramafic rocks in their study are not observed in our samples.

Such high-pressure metamorphism, involving deep burial followed by significant exhumation, is well documented in several other units in the southernmost of the Brasília Orogen. However, the P-T conditions of the metamorphic peak are compatible with high-pressure metamorphism (Zheng and Chen, 2017) since the metamorphic peak exceed the reaction line between calcite and aragonite (Fig. 12). These rocks may have reached these pressures because they are located within the accretionary prism domains of the Arenópolis Magmatic Arc (Dias et al., 2025). This interpretation is consistent with the description of a gravimetric anomaly between the SAI and the Anápolis-Itaçu Complex described as suture zone (Marangoni et al., 1995; Laux et al., 2005).

5.3. Tectonic and geodynamic interpretations

Metamorphic modelling coupled with structural architecture preserved in the AIS records a complex tectonometamorphic evolution linked to the accretionary and collisional dynamics between the Goiás Magmatic Arc and the southern segment of the Brasília Belt. This evolution reflects deep crustal burial followed by syn-orogenic exhumation.

As previously discussed, the AIS comprises a metavolcano-sedimentary package interpreted as deposited within a fore-arc basin setting (Laux et al., 2010). The studied samples consist of paraderived schists located near the concealed contact with the Anápolis-Itaçu Complex, that is a granulite basement unit that exhibits widespread partial melting features (Fig. 3). Although direct field exposure of this contact is limited by a thick soil cover, multiple evidence supports its

regional significance. Geophysical data reveal a marked gravity gradient across the boundary, and regional mapping consistently indicates a reverse shear zone at this interface (Marangoni et al., 1995; Laux et al., 2005). Taken together, these observations suggest the presence of a major crustal discontinuity that may correspond to the suture between the Neoproterozoic magmatic arc and the reworked core of the Brasília Belt.

The earliest penetrative deformation phase (D₁) is characterized by tight to isoclinal folding of the primary bedding (S₀), producing an S₁ foliation. Preserved isoclinal folding as inclusion trails within garnet porphyroblasts (Fig. 6b) indicate that garnet growth might have occurred post-D₁, extending into the early stages of D₂. This suggests that D₁ predated the metamorphic climax and may be related to initial crustal loading and burial during early arc–continent convergence.

The D₂ phase corresponds to the main deformation event recorded in the study area and is responsible for the development of asymmetric folds and a pervasive crenulation cleavage. These structures overprint both the S₀ bedding and the earlier S₁ foliation and are interpreted to have developed shortly after the peak of metamorphism.

D₃ structures—manifested as high-angle reverse shear zones with associated mylonitic foliations (S_m) and spaced cleavages (S₃)—indicate a shift to a more localized, brittle–ductile regime. These shear zones overprint earlier folds and disrupt hinge zones of D₂ structures, implying continued deformation during the retrograde path. Stereographic projections of the S_m foliation show a dominant N013°W/30°SW orientation (Fig. 4e), consistent with oblique ramp geometries and reverse faulting. Although relatively sparse in the field, these structures are significant, marking the transition from distributed shortening to localized strain partitioning.

Finally, the D₄ phase reflects a more regional, brittle deformation overprint. It is recognized by the gentle bending of foliation traces and geomorphological features, particularly in the Serra da Jiboia region. This broad, open folding reorients earlier structures from NNW–SSE in the north to NNE–SSW in the south, with its hinge centered over the range. The geometry of this folding is evident in the stereographic distribution of S₁ poles, which display a girdle pattern with north–south dispersion (Fig. 4c). Although no clear D₄ structures are observed at the outcrop scale, the regional expression suggests a late-stage change of the stress field. This phase is likely related to E–W trending shear zones present in regional maps in the surrounding areas and is interpreted as a product of post-collisional transpressional or strike-slip tectonics.

The D₁–D₄ deformation history reveals a comprehensive tectonic evolution: from magmatic arc–continent convergence and crustal thickening (D₁–D₂), through exhumation and strain localization (D₃), to post-orogenic reactivation and final structural stabilization (D₄).

6. Conclusions

The set of information obtained from the structural, microstructural, mineral chemical, and metamorphic modelling analysis of the supracrustal rocks of the AIS indicates a clockwise metamorphic trajectory in which the garnet core began to crystallize between the D₁ and D₂ stages at 525 °C, and 0.67 GPa, 570 °C and 0.77 GPa for samples 23GO_022-P1 and 23GO_025-T1, respectively. The D₂ stage responsible for asymmetric folds and crenulation cleavage is characterized by the depletion of spessartine and the absence of mineral inclusion at the rim of garnet porphyroblast where the pressure increased progressively to 1.3 GPa and a metamorphic peak of 660 °C, and between 1.16 and 1.3 GPa in high amphibolite facies at depths greater than 40 km and exhumed at 550 °C, 0.65 GPa and 585 °C, 0.79 GPa at depths greater than 20 km. It is suggested that stages D₃ and D₄ are related to the final exhumation events observed on a regional scale. The pressures observed in these rocks are higher than those in metapelites in Barrovian metamorphism, indicating that the metamorphic trajectory defined in this study is consistent with the tectonics of collisional environments, similar to other areas in the Southern Brasília Orogen.

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CRediT authorship contribution statement

Otávio Passo-Vieira: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Rodrigo Prudente Melo:** Conceptualization, Supervision, Validation, Visualization, Writing – review & editing. **Regiane Andrade Fumes:** Conceptualization, Supervision, Validation, Writing – review & editing. **Gabriel Silveira Brod:** Investigation, Visualization. **Filipe Altoé Temporim:** Funding acquisition, Investigation, Resources, Writing – review & editing. **Sergio Willians de Oliveira Rodrigues:** Investigation, Writing – review & editing. **George Luiz Luvizotto:** Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jsames.2026.105974>.

Data availability

Data will be made available on request.

References

- Allmendinger, R.W., Cardozo, N.C., Fisher, D., 2013. *Structural Geology Algorithms: Vectors & Tensors*. Cambridge University Press, Cambridge, England, p. 289.
- Almeida, F.F.M., 1967. Origem e Evolução da Plataforma Brasileira. *Boletim Da Divisão de Geologia e Mineralogia (Departamento Nacional Da Produção Mineral)* 241, 35.
- Augustin, C.T., Mungall, J.E., Schutesky, M.E., Chamberlain, K.R., Ernst, R., Garcia, V.B., 2023. U-Pb in-situ SIMS baddeleyite and zircon dates and thermodynamic modelling of the Mangabal Complex: indications of asthenospheric mantle influence in the formation of layered intrusions of the Brasília orogen. *Gondwana Res.* 122, 93–111. <https://doi.org/10.1016/j.jgr.2023.06.007>.
- Augustin, C.T., Mungall, J.E., Schutesky, M.E., Ernst, R.E., 2025. Metamorphism overprint in mafic-ultramafic cumulates in the Mangabal and Americano do Brasil complexes, Brasília Belt, Brazil. *J. Geol. soc.* 182, jgs20024–j20238. <https://doi.org/10.1144/jgs2024-238>.
- Augustin, C.T., Della Giustina, M.E.S., 2019. Geology and metamorphism of the neoproterozoic Mangabal complex: an example of Ni–Cu–PGE mineralized intrusion in the Goiás Magmatic Arc, central Brazil. *J. S. Am. Earth Sci.* 90, 504–519. <https://doi.org/10.1016/j.jsames.2018.12.013>.
- Baêta Junior, J.D.A., 1994. Programa de Levantamentos Geológicos Básicos do Brasil: carta geológica, carta metalogenética-previsional - escala 1:100.000 (Folha SE-22-X-A-VI - nazário). Estado De Goiás. DNPM/CPRM, p. 108.
- Brito Neves, B.B., Fuck, R.A., Campanha, G.A.C., 2021. Basement inliers of the Brasiliano structural provinces of South America. *J. S. Am. Earth Sci.* 110, 103392.
- Carneiro, J., Fuck, R., Dantas, E.L., 2021. Arenópolis sequence, evolution of a marginal basin in the Neoproterozoic Goiás magmatic arc, central Brazil. *J. S. Am. Earth Sci.* 106 (November 2020). <https://doi.org/10.1016/j.jsames.2020.103033>.
- Coggon, R., Holland, T.J.B., 2002. Mixing properties of phengitic micas and revised garnet–phengite thermobarometers. *J. Metamorph. Geol.* 20, 683–696.
- Cordani, U.G., Brito-Neves, B.B., D'Agrella, M.S., 2003. From Rodinia to Gondwana: a review of the available evidence from South America. *Gondwana Res.* 6 (2), 275–283. [https://doi.org/10.1016/S1342-937X\(05\)70976-X](https://doi.org/10.1016/S1342-937X(05)70976-X).
- Cordani, U.G., Pimentel, M.M., De Araujo, C.E.G., Basei, M.A.S., Fuck, R.A., Girardi, V.A.V., 2013. Was there an ediacaran clymene ocean in central South America? *American journal of science. Am. J. Sci.* 313 (6), 517–539. <https://doi.org/10.2475/06.2013.01>.
- De Capitani, C., Brown, T.H., 1987. The computation of chemical equilibrium in complex systems containing non ideal solutions. *Geochim. Cosmochim. Acta* 52, 639–2652.
- De Capitani, C., Petrakakis, K., 2010. The computation of equilibrium assemblage diagrams with Theriak/Domino software. *Am. Mineral.* 95 (7), 1006–1016. <https://doi.org/10.2138/am.2010.3354>.
- Dias, P.H.A., Reis, L.H.S., Valeriano, C.M., Rodrigues, J.B., Silva, M.A., Leite, M.M., Matos, C.A., 2025. Revisiting the geological evolution of the Brasília orogenic belt (Central Brazil) through the integration of tectonic and provenance studies. *Precamb. Res.* 418. <https://doi.org/10.1016/j.precamres.2025.107693>.
- Faleiros, F.M., Campanha, G.A.C., Pavan, M., Almeida, V., Rodrigues, S.W.O., Araújo, B. P., 2016. Short-lived polyphase deformation during crustal thickening and exhumation of a collisional orogen (Ribeira Belt, Brazil). *J. Struct. Geo.* 93, 106–130. <https://doi.org/10.1016/j.jsg.2016.10.006>.
- Fuck, R.A., 1994. A Faixa Brasília e a compartimentação tectônica na Província Tocantins. IV Simpósio de Geologia Do Centro-Oeste 184–187. <https://www.researchgate.net/publication/284305146>.
- Fumes, R.A., Luvizotto, G.L., Moraes, R., Patto, L.A., 2021. The potential for using metagreywacke to study metamorphism of amphibolite facies conditions: a comparison study within the Luminárias Nappe, Southern Brasília Orogen (Southeastern Brazil). *Mineral. Petrol.* 115 (5), 519–534. <https://doi.org/10.1007/s00710-021-00758-8>.
- Holland, T.J.B., Powell, R., 1998. An internally consistent thermodynamic data set for phases of petrological interest. *J. Metamorph. Geol.* 16, 309–343. <https://doi.org/10.1111/J.1525-1314.1998.00140.X>.
- Johnson, T.E., White, R.W., Powell, R., 2008. Partial melting of meta greywacke: a calculated mineral equilibria study. *J. Metamorph. Geol.* 26, 837–853.
- Lacerda Filho, J.V., Gollmann, K., Santos, D.R.V., Martins, F.R., Souza, J.O., Carneiro, J. S.M., Meneghini, P.F.V.B., Hattingh, K., Silva, E.R., Eberhardt, D.B., 2021. Projeto geologia e metalogenia da porção oeste de Goiás. Serviço Geológico Do Brasil. CPRM.
- Lanari, P., Vidal, O., De Andrade, V., Dubacq, B., Lewin, E., Grosch, E.G., Schartz, S., 2014. XMapTools: a MATLAB®-based program for electron microprobe X-ray image processing and geothermobarometry. *Comput. Geosci.* 62, 227–240. <https://doi.org/10.1016/j.cageo.2013.08.010>.
- Lanari, P., Duisterhoeft, E., 2019. Modeling metamorphic rocks using equilibrium thermodynamics and internally consistent databases: past achievements, problems and perspectives. *J. Petrol.* 60, 19–56.
- Laux, J.H., Pimentel, M.M., Dantas, E.L., Armstrong, R., Armele, A., Nilson, A.A., 2004. Mafic magmatism associated with the Goiás magmatic arc in the Anicuns region, Goiás central Brazil: sm - nd isotopes and new ID-TIMS and SHIMP U-Pb data. *J. S. Am. Earth Sci.* 16 (7), 599–614. <https://doi.org/10.1016/j.jsames.2003.11.001>.
- Laux, J.H., Pimentel, M.M., Dantas, E.L., Armstrong, R., Junges, S.L., 2005. Two neoproterozoic crustal accretion events in the Brasília belt, central Brazil. *J. S. Am. Earth Sci.* 18 (2), 183–198. <https://doi.org/10.1016/j.jsames.2004.09.003>.
- Laux, J.H., Pimentel, M.M., Gioia, S.M.C.L., Ferreira, V.P., 2010. The Anicuns-Itaberai volcano-sedimentary sequence, Goiás Magmatic Arc: new geochemical and Nd-S isotopic data. *Geochim. Bras.* 24 (1), 13–28.
- Mahar, E.M., Baker, J.M., Powell, R., Holland, T.J.B., Howell, N., 1997. The effect of Mn on mineral stability in metapelites. *J. Metamorph. Geol.* 15, 223–238.
- Marangoni, Y.R., Assumpção, M., Fernandes, E.P., 1995. Gravimetria do norte de Goiás, Brasil. *Rev. Bras. Geofis.* 13, 205–219. <https://doi.org/10.22564/rbfg.v13i3.1196>.
- Marques, C.G., 2009. Geologia Dos Grupos Araf e Serra Da Mesa E Seu Embasamento No Sul Do Tocantins [Master Thesis]. Universidade de Brasília.
- Motta, R.G., Moraes, R., 2017. Pseudo- and real-inverted metamorphism caused by the superposition and extrusion of a stack of nappes: a case study of the Southern Brasília Orogen, Brazil. *Int. J. Earth Sci.* 106, 2407–2427. <https://doi.org/10.1007/s00531-016-1436-7>.
- Nunes, N.S.V., 1990. Geologia E Potencial Mineral Da Região De Anicuns, Goiás. [Master Thesis]. Universidade de Brasília.
- Oriolo, S., Oyhantçabal, P., Wemmer, K., Siegesmund, S., 2017. Contemporaneous assembly of Western Gondwana and final Rodinia break-up implications for the supercontinent cycle. *Geosci. Front.* 8 (6), 1431–1445. <https://doi.org/10.1016/j.gsf.2017.01.009>.
- Passchier, C.W., Trouw, R.A.J., 2005. *Microtectonics*, 2 ed. Springer, p. 260.
- Pimentel, M.M., 2016. The tectonic evolution of the Neoproterozoic Brasília Belt, central Brazil: a geochronological and isotopic approach. *Braz. J. Genet.* 46 (June), 67–82. <https://doi.org/10.1590/2317-4889201620150004>.
- Pimentel, M.M., Fuck, R.A., Alvarenga, J.C.S., 1996. Post-Brasiliano (Pan-African) high-K granitic magmatism in Central Brazil: the role of late Precambrian-early Palaeozoic extension. *Precamb. Res.* 80, 217–238.
- Pimentel, M.M., Jost, H., Fuck, R.A., 2004. O embasamento da Faixa Brasília e o Arco Magmático de Goiás. In: Mantesso-Neto, V., Bartorelli, A., Carneiro, C.D.R., Brito-Neves, B.B. (Eds.), *Geologia Do Continente Sul Americano*. Beca, pp. 355–369.
- Pimentel, M.M., Fuck, R.A., 1992. Neoproterozoic crustal accretion in central Brazil. *Geology* 20 (4), 375. [https://doi.org/10.1130/0091-7613\(1992\)020<0375: NCAICB>2.3.CO](https://doi.org/10.1130/0091-7613(1992)020<0375: NCAICB>2.3.CO).
- Piuzana, D., Pimentel, M.M., Fuck, R.A., Armstrong, R., 2003. SHRIMP U-Pb and Sm-Nd data for the Araxá group and associated magmatic rocks: constraints for the age of sedimentation and geodynamic context of the southern Brasília Belt, central Brazil. *Precamb. Res.* 125 (1–2), 139–160. [https://doi.org/10.1016/S0301-9268\(03\)00107-4](https://doi.org/10.1016/S0301-9268(03)00107-4).

- Silva, J.M., Filho, C.F.F., Bühn, B., Dantas, E.L., 2011. Geology, petrology and geochemistry of the “Americano do Brasil” layered intrusion, central Brazil, and its Ni-Cu sulfide deposits. *Miner. Deposita* 46 (1), 57–90. <https://doi.org/10.1007/s00126-010-0312-9>.
- Spear, F.S., Cheney, J.T., 1989. A petrogenetic grid for pelitic schist in the system $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-FeO-MgO-K}_2\text{O-H}_2\text{O}$. *Contrib. Mineral. Petrol.* 101, 149–164.
- Valeriano, C.M., 2017. The Southern Brasília Belt. In: Heilbron, M., Cordani, H.G., Alkmim, F.F. (Eds.), *São Francisco Craton, Eastern Brazil Tectonic Genealogy of a Miniature Continent. Regional Geology Reviews*. Springer, pp. 189–203.
- Valeriano, C.M., Pimentel, M.M., Heilbron, M., Almeida, J.C.H., Trouw, R.A.J., 2008. Tectonic evolution of the Brasília Belt. *Central Brazil Assembly Gondwana* 294, 197–210. <https://doi.org/10.1144/SP294.11>.
- Vernon, R.H., 2018. *Practical Guide to Rock Microstructures*. Cambridge Press, p. 474.
- White, R.W., Pomroy, N.E., Powell, R., 2005. An in-situ metatexite–diatexite transition in upper amphibolite facies rocks from Broken Hill, Australia. *J. Metamorph. Geol.* 23, 579–602.
- White, R.W., Powell, R., Holland, T.J.B., Worley, B., 2000. The effect of TiO_2 and Fe_2O_3 on metapelitic assemblages at greenschist and amphibolite facies conditions: mineral equilibria calculations in the system $\text{K}_2\text{O-FeO-MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O-TiO}_2\text{-Fe}_2\text{O}_3$. *J. Metamorph. Geol.* 18, 497–511.
- Whitney, D.L., Evans, B.W., 2010. Abbreviations for names of rock-forming minerals. *Am. Mineral.* 95 (1), 185–187. <https://doi.org/10.2138/am.2010.3371>.
- Yakymchuk, C., Clark, C., White, R.W., 2017. Phase relations, reactions sequences and petrochronology. In: Kohn, M.J., Engi, M., Lanari, P. (Eds.), *Petrochronology: Methods and Applications*, 83, pp. 13–48.
- Zheng, Y.-F., Chen, R.-X., 2017. Regional metamorphism at extreme conditions: implications for orogeny at convergent plate margins. *J. Asian Earth Sci.* 145, 46–73. <https://doi.org/10.1016/j.jseas.2017.03.006>.