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Structural context of Ambatovarahina copper deposit, Central Madagascar

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Abstract: This study presents a comprehensive structural analysis of a copper skarnoid deposit hosted in dolomitic marble within Itremo subdomain, central part of Madagascar. The deposit exhibits two distinct styles of mineralization: stratabound replacement-type (i) and vein-type (ii), both controlled by structural features. The first type is related to D1 deformation and the second with a transpressional shearing associated with transversal fractures syn to post deformation. Primary ore minerals formed by chalcopyrite, cubanite, and bornite followed hydrothermal fluid circulation. And cataclastic textures within the ore confirm the presence of D2 deformation which promoted the remobilisation and reconcentration of primary copper ore along syn to post fracture to form secondary copper ore appearing as "copper vein type" deposit.

The result of stereonet analysis reveals the presence of D1 deformation with S1 cleavage and its axial planes-oriented Northeast-Southwest, while D2 deformation represented by crenulation cleavage and asymmetric boudinage.

Keywords: Madagascar ; Ambatovarahina ; structural ; deformation ; copper ; stratabound ; vein-type ; mineralization ; skarnoid.

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1. Introduction

Madagascar exhibits an exceptionally favourable geological environment for copper mineralization, with several hundred occurrences distributed throughout the island. However, despite this considerable potential, none of these deposits is currently considered economically viable. This paradoxical situation can be primarily attributed to the lack of geological data regarding the structural characterization and mineralization's genesis. The copper deposits within the Itremo Group have distinctive characteristics that bear witness to a complex geological history. The Ambatovarahina copper deposit represents one of these occurrences and constitutes the focus of this study. Previous studies of this mineralization have been limited to petrographic description of the ore and its host rock (Besairie, 1968; Lacroix, 1922) which show that it is a mineralization contained in diopsidites skarnoids formed from metadolomites (Fournié, 1970). Most skarn literature are found in lithologies containing at least some carbonate as a result of a variety of metasomatic processes (Meinert, 1992; Meinert et al., 2005), and are found adjacent to plutons, however they can also occur along faults and major shear zones (Li et al., 2014; Meinert et al., 2005). The tectono-metamorphic evolution of Itremo metasedimentary rocks played a decisive role in the concentration and redistribution of copper mineralization. Deformation processes, including folding and shearing, created structural traps favourable to the precipitation of copper-bearing minerals. The aim of this work was to provide information about structural control that led to the concentration of copper deposit.

2. Methodologies

During fieldwork, systematic structural measurements using a geological compass were conducted. Foliation planes (S1, S2) and fractures were measured at multiple stations across the mine site, with GPS coordinates recorded for each location.
Structural data were compiled in Microsoft Excel spreadsheets, including strike/dip values, station coordinates, and field observations. Data were subsequently processed by stereographic projection method on lower-hemisphere equal-area projections using stereonet software v.11.6 (Allmendinger, 2025).
Stereographic analysis included plotting poles to planes, statistical assessment of structural orientations, and determination of intersection geometries between foliations and fractures. This approach enabled quantitative characterization of structural controls on copper mineralization and interpretation of polyphase deformation history.

3. Geological setting

3.1 Regional geology

The Itremo Group is a distinctive Proterozoic metasedimentary sequence unconformably overlying the Archean Antananarivo domain (figure 1a). These formations are located within granulite to upper amphibolite facies orthogneisses and paragneisses of the Betsiboka Suite dated around 2550-2500 Ma (Tucker et al., 1999). The metasedimentary rocks are formed by detrital sources from continental or cratonic provinces (Cox et al., 1998). These metasediments are interpreted as a passive margin sequence deposited on a shallow continental shelf. The sequence consists predominantly of quartzites, metapelites, and metadolomites, with the latter hosting the copper mineralization described in this study. Detrital zircon populations show significant age peaks at approximately 2500 Ma and 1800 Ma (Cox et al., 2004; Fitzsimons & Hulscher, 2005), constraining the maximum depositional age to younger than 1800 Ma.
Two major magmatic episodes affected the Itremo Group. The Tonian-aged (ca. 850-750 Ma) Imorona-Itsindro Suite comprises calc-alkaline granitoids and gabbros formed in a convergent margin setting (Handke, 2001; Tucker et al., 1999), with U-Pb zircon ages of 800-820 Ma contemporaneous with D1 deformation. The Pan-African Ambalavao Suite consists of granitic intrusions dated at approximately 550 Ma (Tucker et al., 2014).
The metamorphic gradient increases from East to West across the Itremo Group (figure 1b):

- Eastern rocks preserve greenschist to sub-greenschist facies assemblages (T <500°C),
- Central and Western portions exhibit kyanite- and sillimanite-bearing assemblages indicative of upper amphibolite facies conditions with a temperature around T° 600-700°C (Raoelison, 1997).

The copper mineralization occurs in the eastern, lower-grade portion where peak metamorphic conditions (greenschist to lower amphibolite facies, ~400-550°C) during D2 deformation.

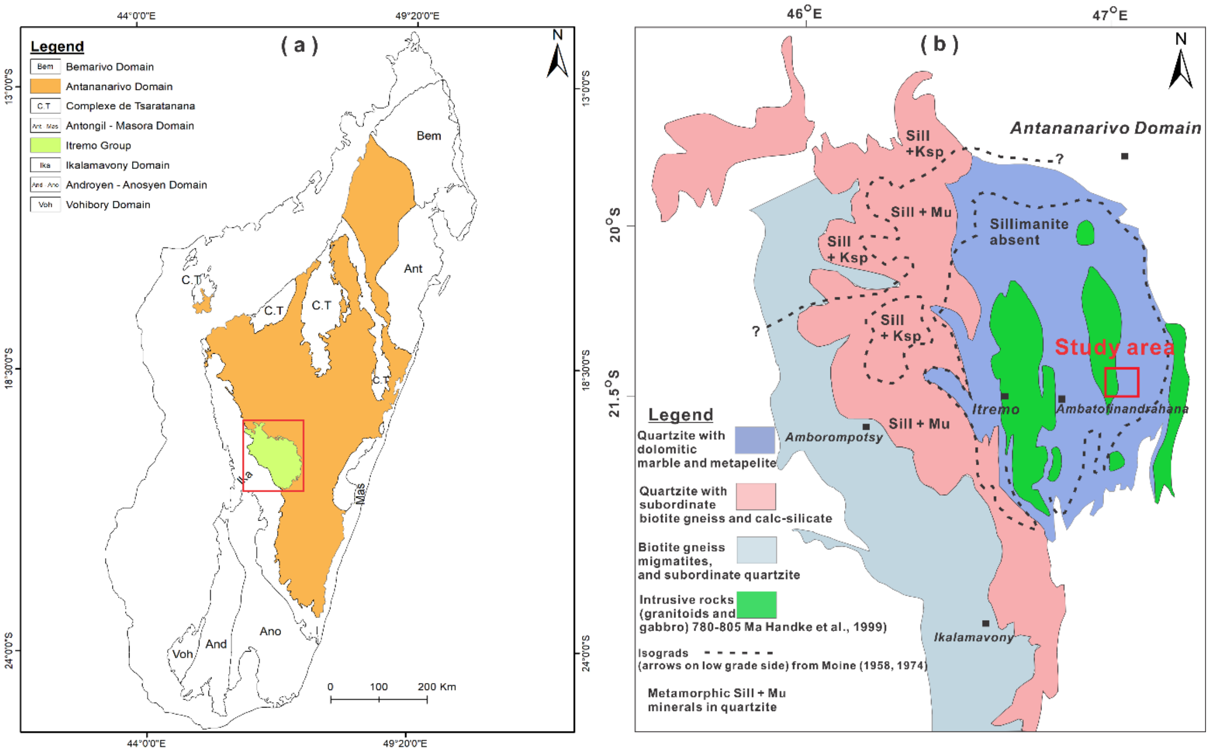

Figure 1. Simplified geological map
(a): Tectono-metamorphic subdivision of Madagascar
(b): Itremo Group showing the different formation and metamorphic isograde. (Modified from Moine, 1974).

3.2 Regional structure

Regional structure evolution records two principals' deformation phases:

- The first phase (D1, ~800 Ma) deformed the metasedimentary sequence into an East- to Northeast vergent fold and reverse fault belt, with the Itremo Group. This Group was overthrusted eastward over the migmatitic gneisses of the Antananarivo block (Cox et al., 1998; Tucker et al., 2012). During this tectonic movement, copper element followed hydrothermal fluid and formed primary copper ore deposit (chalcopyrite, cubanite, bornite).
- The second phase (D2, ~560-530 Ma) generate large-scale North-South trending folds with steeply dipping axial planes and mylonitic shear zones (figure 2). The assemblage of Gondwana resulting from East-West shortening marked by fold boundaries in Itremo Group (Fernandez et al., 2001, 2003; Nédélec et al., 2003).

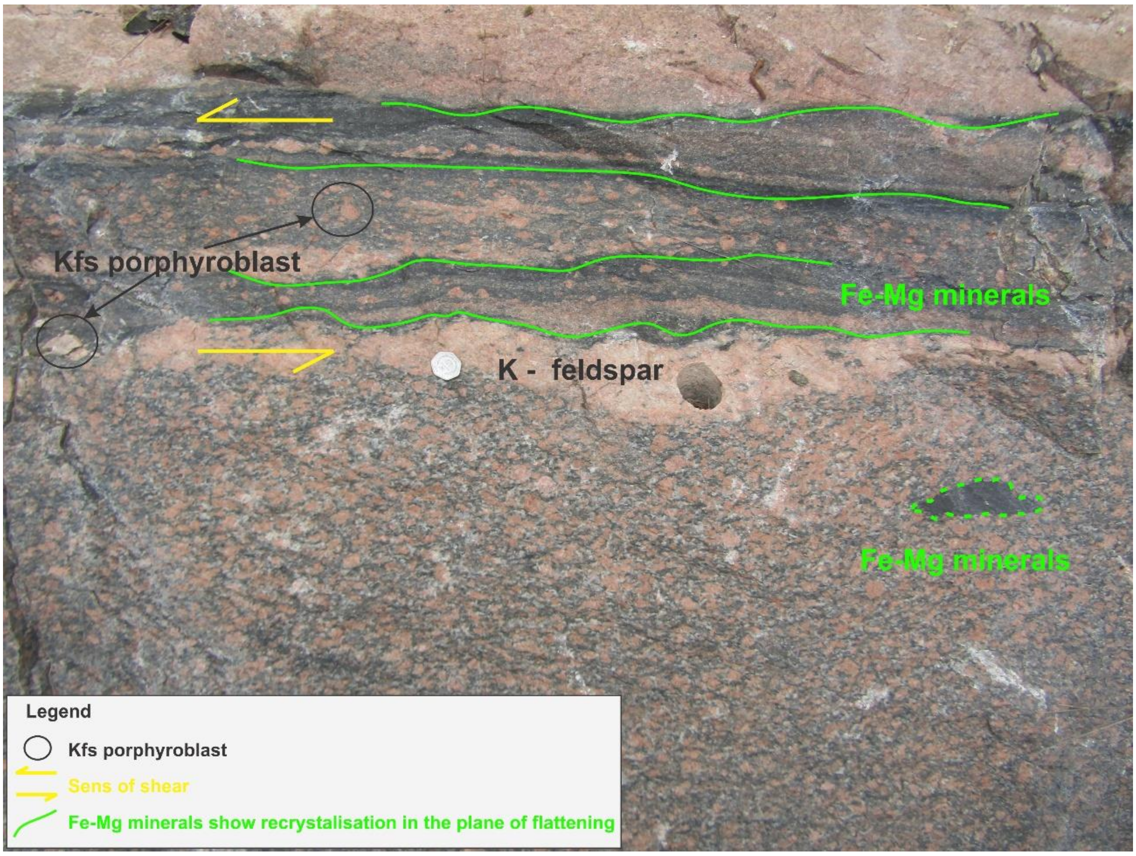

Figure 2. Outcrop of mylonized shear zone X: 456793 Y: 617472 (m)

3.3 Copper mineralization in the study area

Two critical structural features appear within the study area indicating polyphase deformation relating to D1 and D2 Ediacaran tectonics.

Google earth (figure 3a) shows that the copper mine is located on the western limb of Tsiahazahoana hinge antiform (figure 3b) related to the D1 deformation phase with the hinge oriented toward N50. The copper mineralization in the study area is controlled by a transpressional shear zone and transversal fractures.

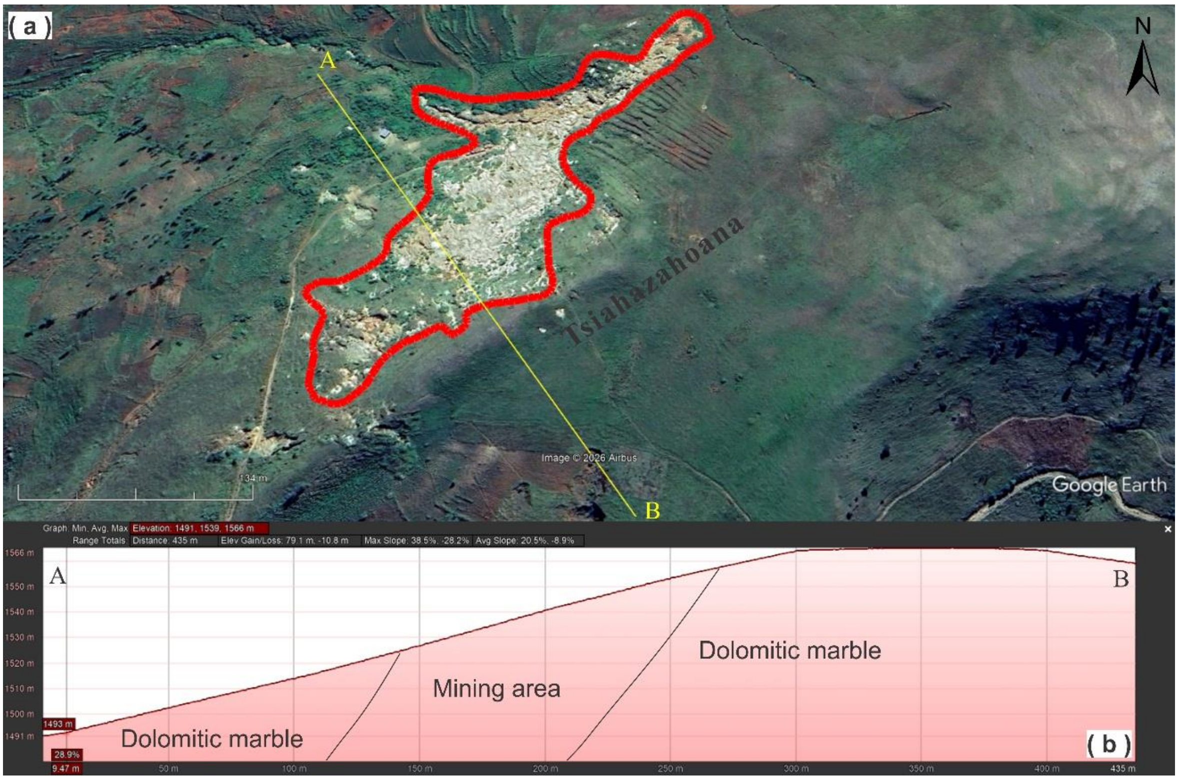

Figure 3. Copper mine
(a): Google earth image delineating the limit of the copper mine and show the orientation of Tsiahazahoana hinge,
(b): Topographic profile along A-B showing an antiform and host rock of the mine

Cleavages:

Two distinct cleavages can be observed in the mining area (figure 4a):

- S1 transposes the S0 stratification and is roughly oriented N045-N070°E with an average dip of 50°NW which correspond to the axial planes of the folds that represent the first phase of deformation (D1).
- A second deformation phase (D2), associated with S2 folding, affects these planes. Within the deposits, this S2 fabric is expressed as a crenulation cleavage, and asymmetric boudinage (figure 4b) which are associated with multi-directional fracture networks.

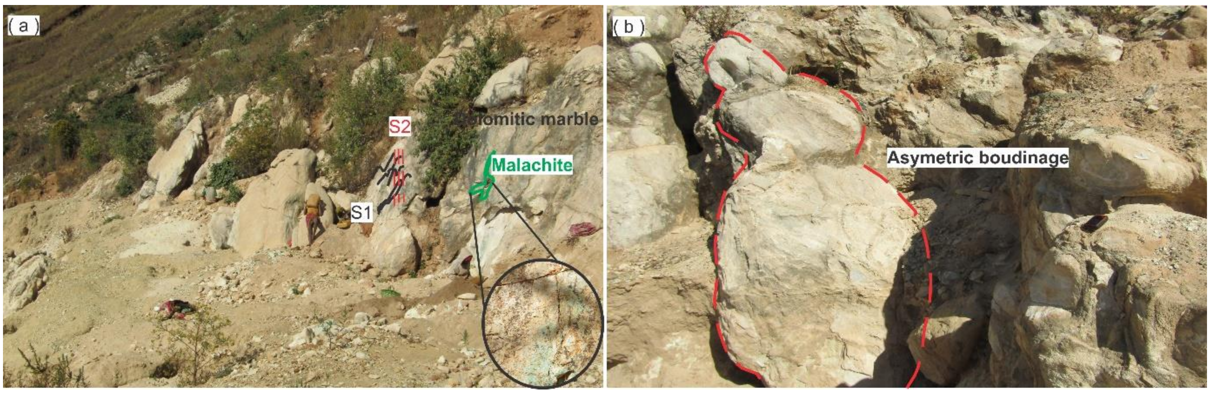

Figure 4. Outcrop of dolomitic marble
(a): S1 and S2 cleavages outcropping in the mine site with malachite staining
(b): Asymmetric boudinage

Many shafts mine appears within the dolomitic marble (figure 5a). Polyphases deformation marked by well-developed crenulation cleavage on the wall followed by a sinistral shear kinematics and faulting (figure 5b).

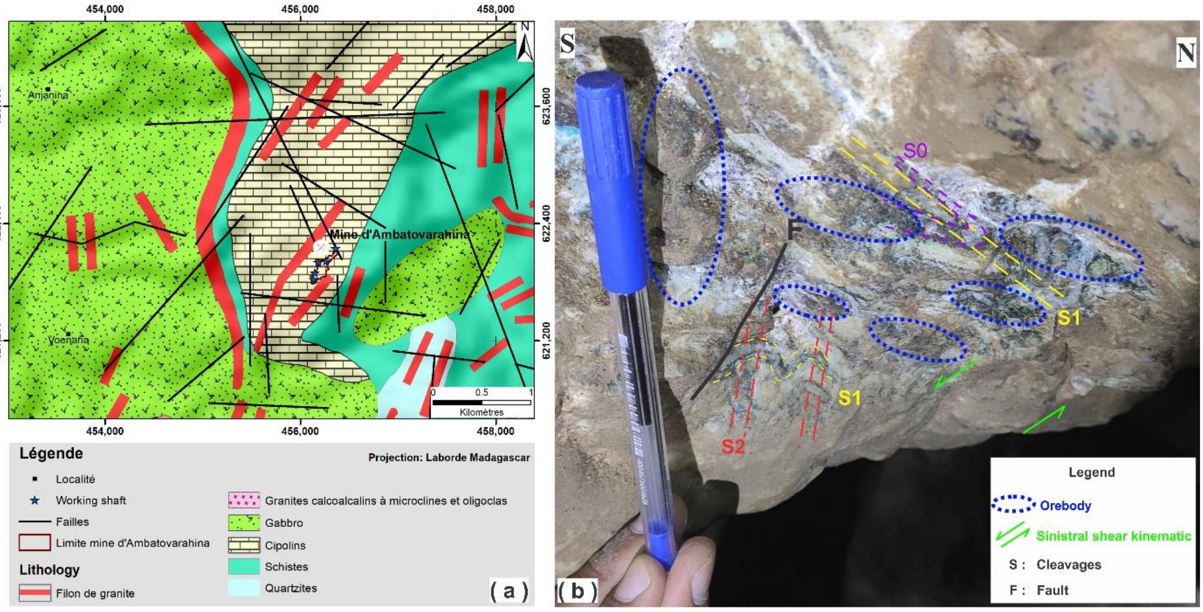

Figure 5. (a) : Simplified geological map of Ambatovarahina copper deposit
(b) : Shaft copper mine showing: (i) juxtaposition of S1-S2 cleavages, (ii) sinistral shear kinematics, and (iii) faulting

This crenulation represents microscopic to mesoscopic folding of the primary S1 foliation, producing a closely-spaced axial planar cleavage (S2) that formed during D2 shortening. The crenulation geometry indicates compression perpendicular to the earlier foliation plane. The asymmetric boudinage formed through extension of competent dolomitic marble within shear zone. The coexistence of crenulation cleavage close to sinistral shear fabrics indicates that D2 deformation involved both pure shear and simple shear components, characteristic of transpressional deformation regimes.

Stereonet analysis (figure 6) of seven S1 cleavage measurements from the dolomitic marble reveals a moderate dispersion of orientations (strikes ranging from 029° to 110°, dips 30-70°) with a statistical best-fit great circle oriented 270.6°/39.9° N. Bingham analysis yields a dominant eigenvector (eigenvalue = 0.8672) trending 331.1° and plunging 36.0°. The significant spread in strike orientations, coupled with the note trend = 065, plunge = 19 representing the calculated fold axis, indicates that S1 has been folded during D2 deformation (~560-530 Ma). Pole concentration in the NW quadrant (eigenvalue = 0.8672) indicates S1 cleavage dips predominantly 30-70° NW, defining the steep limb of an ENE-plunging asymmetric antiform.

This fold geometry demonstrates that S1, originally formed as a penetrative tectonic foliation during D1 (~800 Ma), was subsequently deformed by D2. The E-W fold axes are perpendicular to the D2 compression direction, consistent with regional structural patterns. The folding of S1 creates a complex 3D geometry for copper mineralization.

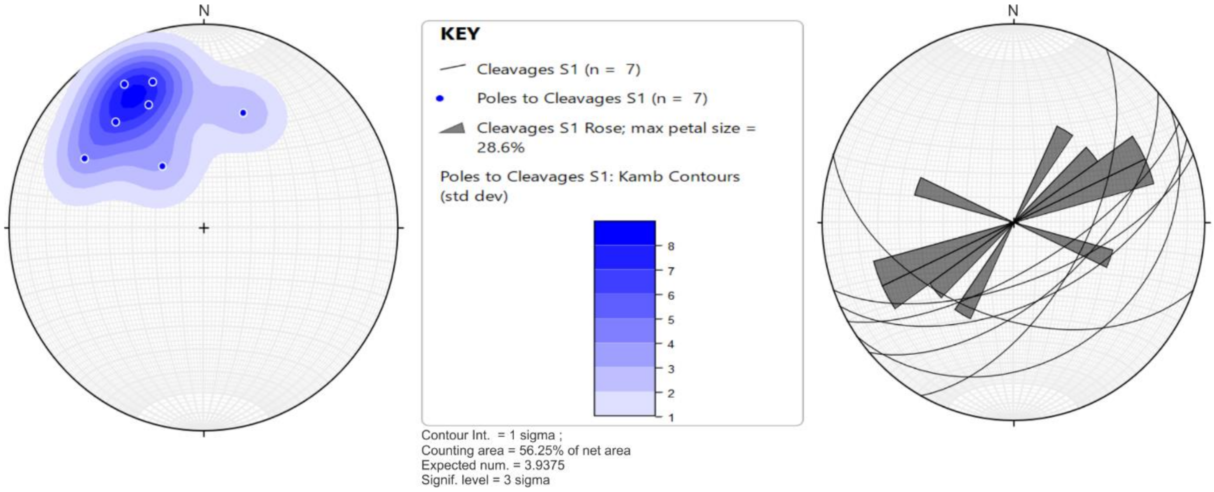

Figure 6. Lower-hemisphere Schmidt stereonet and rose diagrams of the measured foliation data of the host rocks

Fractures and joints

Four distinct fracture sets with varying orientations indicating multiple deformation events appears (figure 7):

- Vertical to sub-vertical fractures indicate a strike. They are evenly distributed across the exposure and represent extensional or tension fractures that likely formed during uplift and/or late-stage brittle deformation;
- Horizontal fractures likely represent bedding planes or foliation surfaces within the dolomitic marble;
- Oblique fractures which dip moderately (40-60°) toward the Northeast, suggesting a conjugate shear fractures or structural discontinuities formed during compressional deformation;
- Transversal fractures that cut obliquely across all other structures, they likely represent the transversal fractures described in previous structural studies. These fractures served as major fluid conduits during D1 mineralization (~800 Ma) and were reactivated during D2 deformation (~560-530 Ma).

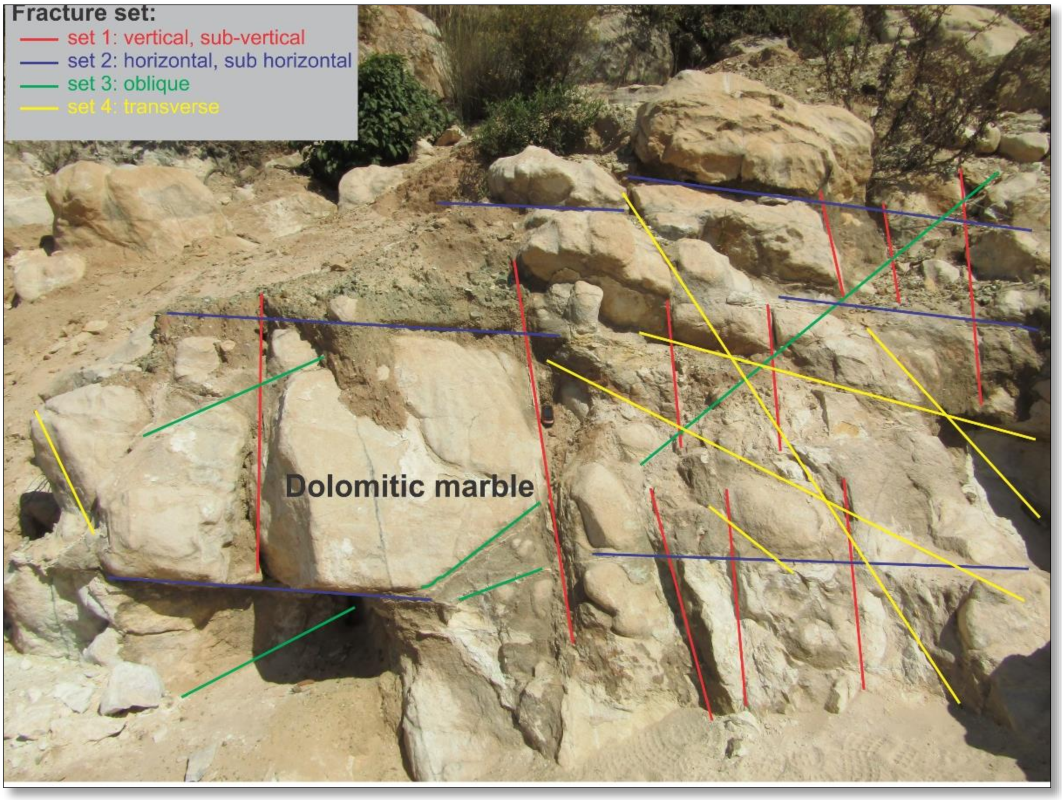

Figure 7. Outcrop of dolomitic marble showing polyphase fracture network

Structural analysis using stereonet (figure 8) projections of 7 fractures measurements within the copper mine reveals a dominant sub-horizontal to moderately-dipping fracture set striking NE-SW (mean orientation: 223.5°/24.1°SE). Bingham analysis yields a best-fit great circle with strike 223.5° and dip 24.1° (RHR), with the principal eigenvector (eigenvalue = 0.6548) trending 341.0° and plunging 21.7°. This orientation is consistent with the regional foliation (S1 or transposed S2) formed perpendicular to the E-W shortening direction during D2 deformation. The moderate dip angles (10-31°) and NNW-NNE trends indicate that these fractures represent either preserved bedding planes or tectonic foliation, rather than late-stage extensional fractures.

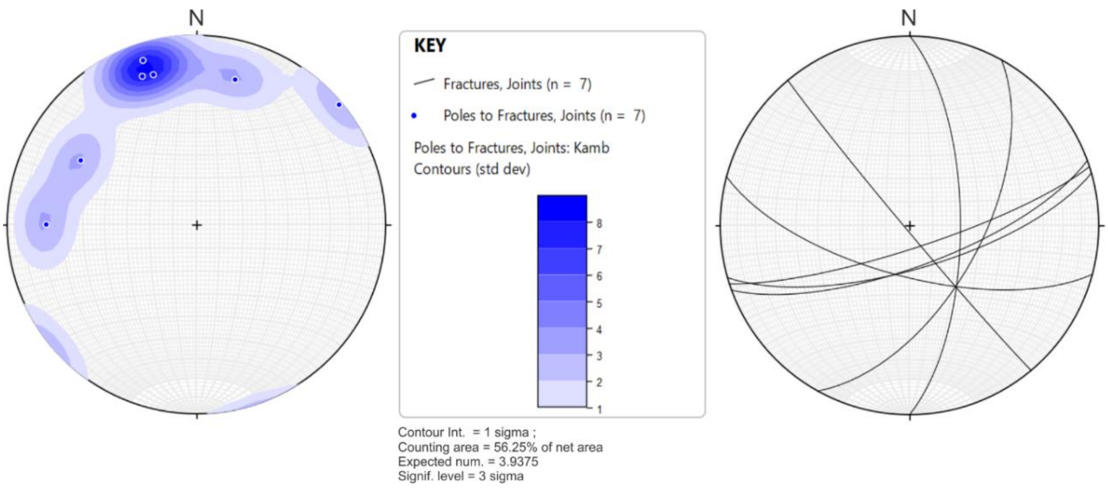

Figure 8. Equal-area azimuthal projection and statistical analysis of main fractures and joints data of the host rocks

4. Discussions

S1 and S2 foliations, associated with fold, fracture networks and transpressional shear zones, played fundamentally different roles in controlling copper ore distribution throughout the Ambatovarahina copper mine. This transpressional deformation is marked by the coexistence of crenulation cleavage with sinistral shear fabrics, characteristic of oblique convergence (Sanderson & Marchini, 1984; Tikoff & Teyssier, 1994). The occurrence of transpressional shear fabrics in this deposit provides independent confirmation of the transpressional deformation affecting Itremo Group (Tedy et al., 2025).

The genetic origin of copper mineralization in the Ambatovarahina deposit has been debated. Despite the stratabound appearance of mineralization within dolomitic marble, and the presence of hydrothermal gangue minerals are inconsistent with syngenetic formation. Also, the complexity of the mineral paragenesis, and the high copper grades cannot be explained by syn-sedimentary processes, and concluded that mineralization is epigenetic, resulting from hydrothermal fluid circulation related to magmatic intrusions (Fournié, 1970). In 1985, BRGM interpreted this deposit as syngenetic based on the stratabound geometry of ore bodies, and suggest that copper ore was deposited contemporaneously with carbonate sedimentation.

Our structural analysis provides compelling evidence supporting Fournié's, (1970) original epigenetic interpretation. The apparent paradox of stratabound geometry in epigenetic system is resolved by recognizing that S1 cleavage, developed parallel to bedding during D1 deformation, provided bedding-parallel permeability. This structure and characteristic of host rock facilitated hydrothermal fluids circulation through S1 and reactive dolomitic marble horizons. This processus produced ore bodies conformable to bedding. The intersection of S1 with transversal fractures created optimal permeability zones where epigenetic fluids efficiently replaced carbonate host rocks, producing ore bodies that follow stratigraphic control despite their undeniably hydrothermal origin, a common feature of carbonate-replacement deposits worldwide (Einaudi et al., 1981; Meinert et al., 2005).

And S2 crenulation cleavage, developed during D2 deformation, remobilized and reconcentrated existing mineralization. During D2, pre-existing fractures were selectively reactivated and created secondary copper ore mineralization into crosscutting vein systems. The dominant sub-horizontal corresponds to either preserved bedding planes or tectonic foliation (S0/S1). These structures served as hydrothermal fluid pathways during the D1 mineralization event (~800 Ma) to moderately-dipping fracture set (strike 223.5°/24.1°SE). Stereonet analysis confirm the primary structural control for the stratabound-style copper mineralization. The consistency of fracture orientations (dominant eigenvalue = 0.6548) indicates systematic structural preparation of the host rocks for mineralization, rather than random fracturing, enhancing the predictability of ore distribution.

5. Conclusion

The Ambatovarahina copper deposit is among the largest copper deposits in Madagascar. Mineralization's are contained in metasedimentary dolomitic marble to form a skarnoid type deposit. It is characterized by two distinct mineralization styles: stratabound replacement-type and vein-type mineralization. The mine is located on the western limb of the Tsiahazahoana antiform and the copper ore accessed via shafts and galleries. The results of this study show that this deposit is of epigenetic origin with stratabound geometry ore bodies. Its distribution is controlled by sequential structural events involving S1 cleavage confirmed by Stereonet analysis. Transversal fractures, and transpressional deformation D2 (~560-530 Ma) justified by crenulation cleavage and asymmetric boudinage remobilize the primary stratabound copper mineralization and form secondary vein type ore deposit along fracture and fault.

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