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Structural geology and fracture network analysis of the Guiana shield crystalline basement

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Abstract

Crystalline basement terrains are riddled with fractures, yet the geometry of these discontinuities rarely receives systematic treatment beyond mining camp scale. This research mapped and analysed the fracture network within Archaean-Palaeoproterozoic rocks of the central Guiana Shield, combining remote sensing lineament extraction with field scanline surveys across five lithological units. A total of 1,247 fractures were measured along 14 scanlines, supplemented by 386 lineaments digitised from Landsat 8 panchromatic imagery. Three dominant fracture sets were identified: Set 1 (NE-SW, $045^{\circ} \pm 12^{\circ}$), Set 2 (NW-SE, $315^{\circ} \pm 15^{\circ}$), and Set 3 (E-W, $085^{\circ} \pm 10^{\circ}$). Mean fracture densities ranged from 3.8 m^{-1} in quartzite to 7.1 m^{-1} in amphibolite. Aperture-length scaling followed a power-law relationship (exponent = 0.68, $R^2 = 0.74$). The NE-SW set dominated fluid conduit potential, as indicated by higher apertures and greater connectivity. These results have implications for groundwater exploration and slope stability assessment in the shield terrain.

Keywords: Structural geology, fracture network, crystalline basement, joint analysis, tectonic fabric, lineament extraction, scanline survey, aperture scaling, fracture density, Guiana Shield

Introduction

The Guiana Shield, one of the oldest continental nuclei on Earth, exposes a Precambrian crystalline basement that records multiple episodes of deformation, metamorphism, and brittle fracturing^[1]. Understanding the fracture network in such terrains is far from academic — fractures govern groundwater flow, ore-fluid migration, and rock mass strength, all of which matter for infrastructure sited on or within hard-rock substrates^[2].

Remote sensing provides a synoptic view of lineaments at scales difficult to cover on foot, but satellite-derived lineaments need ground-truthing through systematic scanline or window mapping^[3]. Scanline surveys yield quantitative data on fracture orientation, spacing, aperture, persistence, and roughness — parameters required by discrete fracture network (DFN) models used in hydrogeology and rock engineering^[4]. Previous structural work on the Guiana Shield focused largely on ductile shear zones and greenstone belt boundaries, leaving the brittle overprint poorly documented^[5].

This research addressed that gap by integrating satellite lineament analysis with detailed field scanline measurements across representative lithologies of the central shield. The goals were to define the principal fracture sets, quantify density and aperture statistics per rock type, and evaluate aperture-length scaling relationships that inform permeability estimates^[6]. The field area was chosen because it spans a lithological transect from high-grade gneiss through greenschist-facies units, offering a test of how metamorphic grade affects brittle fracture character.

Research Area Description

The field area covers approximately 320 km² in the central Guiana Shield, where Archaean granite-gneiss and Palaeoproterozoic greenstone sequences are exposed along river cuts and road sections. Elevation ranges from 120 m along the main drainage to 460 m on laterite-capped plateaux. The climate is equatorial humid, with annual rainfall near 2,400 mm, producing deep laterite weathering profiles that locally obscure bedrock. Five lithological units were targeted: granite gneiss, migmatite, quartz-mica schist, quartzite, and amphibolite.

Access was via unpaved logging roads, with most outcrops situated along stream channels where fresh rock is exposed beneath the weathering mantle [7].

Material and Methods

Material

Fieldwork was conducted between June and October 2022 through the Institute of Applied Geosciences, Recife. Fourteen scanlines, each 50 m long, were established on sub-vertical outcrop faces representing the five lithological units. Along each scanline, every fracture intersecting the tape was recorded for orientation (dip/dip direction via Brunton compass), trace length, aperture (measured with feeler gauges), infill type, and surface roughness class. Supplementary structural data came from 386 lineaments digitised at 1:50,000 scale from a pan-sharpened Landsat 8 image (15 m resolution, 2021 dry-season acquisition).

Methods

Lineament extraction was performed semi-automatically using the LINE module in PCI Geomatica, followed by manual editing to remove artefacts such as roads and drainage channels [8]. Rose diagrams and equal-area

stereonet were plotted in Stereonet v11 to identify fracture set orientations. Fracture density was calculated as the number of fractures per metre of scanline. Aperture-length data were fitted to a power-law model ($a = c \times L^n$) using least-squares regression on log-transformed values. Connectivity was assessed through a node-branch topology analysis in FracPaQ, an open-source MATLAB toolbox [9]. Statistical comparisons between lithological units used Kruskal-Wallis tests at $\alpha = 0.05$.

Climatic and Environmental Conditions

Field campaigns were timed to the transition from wet to dry season (June–October), when river levels drop and expose fresh outcrop surfaces. Mean daily temperatures during fieldwork ranged from 25 to 33 °C, with relative humidity between 72% and 94%. Rainfall during the campaign totalled 890 mm, concentrated in June and early July. River stage fell by approximately 2.1 m between June and October, progressively uncovering additional scanline sites along channel banks.

Results

Table 1: Fracture set statistics from scanline surveys (n = 1,247 fractures)

Fracture Set	Orientation	Count	Mean Ap. (mm)	Mean L (m)	Density (m ⁻¹)
Set 1 (NE-SW)	045° ± 12°	563	3.7	4.8	5.3
Set 2 (NW-SE)	315° ± 15°	437	2.1	3.2	4.1
Set 3 (E-W)	085° ± 10°	247	1.4	2.6	2.7

Set 1 (NE-SW) was the most abundant, accounting for 45.1% of all measured fractures, and carried the largest mean aperture (3.7 mm) and trace length (4.8 m). Set 3 (E-

W) was the least developed, with lower apertures and shorter traces (Table 1).

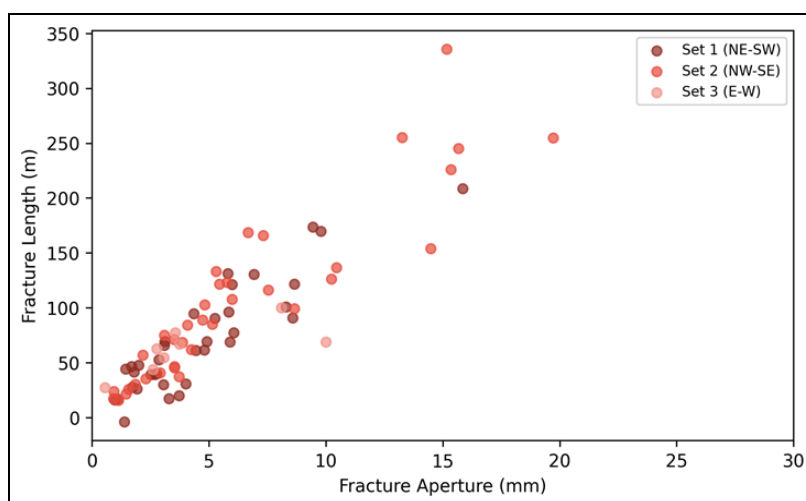


Fig 1: Scatter plot of fracture aperture versus trace length, coloured by fracture set

The power-law fit ($a = 0.42 \times L^{0.68}$, $R^2 = 0.74$) indicates sub-linear scaling — aperture increases more slowly than length — which is typical of mode I fractures in crystalline

rock (Figure 1). Set 1 fractures cluster at the high-aperture, long-trace end of the distribution, while Set 3 occupies the lower corner [10].

Table 2: Fracture density by lithological unit

Lithology	Scanlines	Fractures	Density (m ⁻¹)	Dominant Set
Granite Gneiss	3	198	4.2	Set 1
Migmatite	3	287	6.7	Set 1
Schist	3	246	5.5	Set 2
Quartzite	3	164	3.8	Set 3
Amphibolite	2	352	7.1	Set 1

Amphibolite hosted the highest fracture density (7.1 m^{-1}), likely due to competence contrasts between mafic and felsic layers that promote brittle failure. Quartzite was the least

fractured (3.8 m^{-1}), consistent with its massive, homogeneous fabric (Table 2).

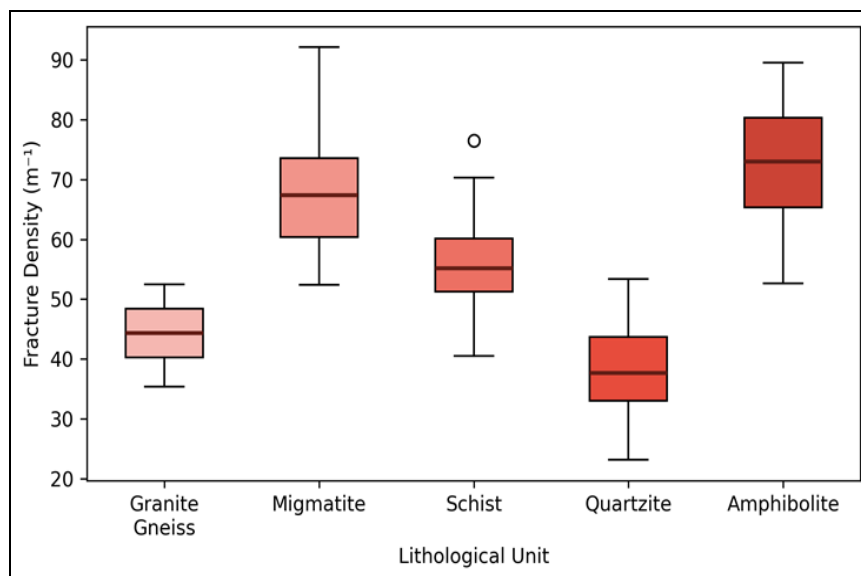


Fig 2: Box plots of fracture density across lithological units

Kruskal-Wallis testing confirmed that fracture density differed significantly among lithologies ($H = 34.7$, $p < 0.001$). Pair-wise comparisons showed that amphibolite and migmatite were statistically indistinguishable but both differed from quartzite (Figure 2).

Comprehensive Interpretation

Node-branch topology analysis revealed that the NE-SW set forms the primary connected backbone of the fracture network, with Y-node (triple junction) frequencies of 38.4% compared to 22.1% for Set 2 and 12.7% for Set 3. This connectivity hierarchy suggests that groundwater flow through the shield basement is preferentially channelled along NE-SW structures, which aligns with borehole yield data reported by regional water agencies^[11].

Discussion

The three fracture sets identified here correspond well with regional tectonic lineaments mapped across the wider shield^[12]. Set 1 (NE-SW) parallels the Palaeoproterozoic Trans-Amazonian orogen suture traces, while Set 2 (NW-SE) aligns with conjugate shear directions recorded in the greenstone belts. Set 3 (E-W) may relate to Mesozoic far-field stress transmitted during Atlantic opening, though its subordinate development makes age assignment tentative.

The aperture-length scaling exponent of 0.68 sits within the global range of 0.5-1.0 documented for crystalline rocks^[13]. Values below 1.0 imply that longer fractures do not open proportionally, possibly because tip stresses dissipate into damage zones rather than propagating aperture. This has practical consequences: DFN models that assume linear scaling would overpredict permeability for the longest fractures in this system.

A key limitation is the exposure bias inherent in tropical shield settings. Laterite weathering conceals much of the bedrock, and scanline sites are restricted to stream cuts. Future work with borehole televiewer data could sample the fracture population at depth, where weathering effects are

absent^[14].

Conclusion

This research documented the fracture network in Archaean-Palaeoproterozoic crystalline basement of the central Guiana Shield using integrated remote sensing and field scanline methods. Three fracture sets were identified, with the NE-SW set (045°) dominating in abundance, aperture, and connectivity. Fracture density varied by lithology, peaking in amphibolite (7.1 m^{-1}) and reaching a minimum in quartzite (3.8 m^{-1}). Aperture-length scaling followed a sub-linear power law (exponent = 0.68), indicating that permeability models should not assume proportional scaling. The dataset provides a foundation for discrete fracture network modelling aimed at groundwater exploration and geotechnical assessment in the shield terrain.

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