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Petrogenesis and geochronology of A-type granites in the Borborema Province of Brazil

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Abstract

A paradox in granite petrology is why some magmas crystallise into commonplace calc-alkaline plutons while others, formed under seemingly similar conditions, produce rare A-type granites enriched in alkalis, halogens, and high-field-strength elements. This research investigated seven A-type granite plutons in the Transversal Zone of the Borborema Province, northeastern Brazil, using whole-rock geochemistry, mineral chemistry, and zircon U-Pb geochronology. Samples were collected between June 2020 and April 2023. All seven plutons showed A-type signatures: high SiO₂ (71.6-75.1 wt%), elevated Na₂O + K₂O (> 8.0 wt%), low CaO (< 1.2 wt%), high FeO/MgO (> 7), and enrichment in Zr, Nb, Y, and REE. Zircon U-Pb ages clustered into three groups: 580 ± 15 Ma, 540 ± 10 Ma, and 510 ± 8 Ma, recording at least three magmatic pulses spanning the late Neoproterozoic to early Cambrian. Epsilon Nd values ranged from -8.4 to -3.2, and initial ⁸⁷Sr/⁸⁶Sr ratios from 0.708 to 0.714, indicating a predominantly crustal source with minor mantle input. The 580 Ma group is interpreted as syn-collisional, emplaced during the Brasiliano/Pan-African orogeny, while the 540 Ma and 510 Ma groups represent post-collisional to anorogenic magmatism generated by lithospheric delamination and asthenospheric upwelling. These results refine the magmatic timeline of the Borborema Province and link A-type granite emplacement to the tectonic evolution of western Gondwana.

Keywords: A-type granites, petrogenesis, geochronology, Borborema Province, anorogenic magmatism, zircon U-Pb, Brasiliano orogeny, lithospheric delamination, Nd isotopes, western Gondwana

Introduction

A paradox that has occupied petrologists for decades is why certain granitic magmas acquire the distinctive chemical fingerprint known as the A-type signature—high alkali content, elevated iron-to-magnesium ratios, enrichment in incompatible elements, and low water activity—while most granites do not ^[1]. The A-type designation was introduced by Loiselle and Wones in 1979 to describe granites emplaced in anorogenic (extensional) settings, but subsequent work has shown that A-type granites can also form during post-collisional relaxation, making tectonic setting alone an insufficient criterion ^[2].

The Borborema Province of northeastern Brazil is one of the best natural laboratories for investigating this question because it contains dozens of A-type plutons emplaced over a time span that bridges the transition from active collision (the Brasiliano/Pan-African orogeny, ~650-520 Ma) to post-orogenic extension ^[3]. Previous geochronological work has dated individual plutons, but a systematic comparison of multiple bodies using the same analytical methods has been lacking, making it difficult to resolve whether A-type magmatism was a single prolonged event or a series of discrete pulses linked to different tectonic triggers ^[4].

This research examined seven A-type plutons in the Transversal Zone of the Borborema Province. The objectives were to (a) characterise their whole-rock and mineral chemistry to confirm A-type affinity, (b) determine precise zircon U-Pb crystallisation ages, and (c) use Nd and Sr isotopic data to constrain source compositions and link magmatic episodes to the evolving tectonic framework of western Gondwana ^[5].

Model Description and Parameterisation

Petrogenetic modelling used batch partial melting equations to test whether the observed trace element patterns could be produced by 10-30% melting of candidate source rocks.

Two source compositions were tested: a Palaeoproterozoic granulitic residue (representing lower crust) and a metasedimentary source similar to the Seridó Group paragneisses. Mineral-melt partition coefficients for Zr, Nb, Y, and REE were taken from the compilation of Rollinson [6]. The residual mineralogy was set as 40% plagioclase, 25% K-feldspar, 15% quartz, 10% garnet, 5% biotite, and 5% accessory phases (zircon, apatite, allanite). Melt fraction was varied from 0.05 to 0.40 in steps of 0.05, and the resulting melt compositions were compared against the observed whole-rock data. A two-component mixing model was also applied using Nd isotopic data, with end-members defined as depleted mantle ($\epsilon\text{Nd} = +8$, $\text{Nd} = 8$ ppm) and lower crust ($\epsilon\text{Nd} = -18$, $\text{Nd} = 30$ ppm) [7].

Material and Methods

Material

This research was coordinated from the Department of Earth and Environmental Sciences at the Gangtok College of Earth and Mineral Sciences, Sikkim, India, with fieldwork carried out in the Borborema Province between June 2020 and April 2023. Seven plutons were sampled: Catingueira, Serra Branca, Queimadas, Tavares, Princesa Isabel, Triunfo, and Teixeira. Between four and eight samples per pluton (42 total) were collected from fresh exposures in quarries and road cuts. Whole-rock major elements were analysed by XRF on fused glass discs at the Geochemistry Laboratory of the Universidade de São Paulo (USP). Trace elements and REE were measured by ICP-MS after acid digestion. Electron microprobe analysis of feldspar, amphibole, and biotite was performed on a Cameca SX-100 at USP. Zircon grains were separated by standard heavy-liquid and magnetic techniques, mounted in epoxy, and analysed for

U-Pb ages by LA-ICP-MS using a Thermo Element XR coupled to a Photon Machines Analyte G2 excimer laser [8]. Sm-Nd and Rb-Sr isotopic analyses were performed by TIMS at the Geochronology Research Centre, USP.

Methods

A-type affinity was tested using the discrimination diagrams of Whalen *et al.* [1]; Ga/Al versus Zr, Nb, Ce, and Y. Major element data were plotted on the TAS (total alkali-silica) and R1-R2 classification diagrams. Spider diagrams were normalised to primitive mantle values. Zircon U-Pb ages were determined from concordia plots using Isoplot version 4.15, with concordance defined as 90-110% ($^{206}\text{Pb}/^{238}\text{U}$ age $\div$ $^{207}\text{Pb}/^{235}\text{U}$ age). At least 25 grains per sample were analysed to ensure statistically representative age populations. $\epsilon\text{Nd}(t)$ values were calculated at the crystallisation age of each pluton, and Nd model ages (TDM) were computed using the depleted mantle evolution curve of DePaolo [9].

Calibration and Validation

LA-ICP-MS U-Pb analyses were calibrated against the GJ-1 zircon reference material (TIMS age 608.5 ± 0.4 Ma), with Plešovice (337.1 ± 0.4 Ma) run as a secondary standard. Over the three analytical sessions, GJ-1 yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 607.8 ± 3.2 Ma ($n = 42$, MSWD = 1.07), and Plešovice gave 336.4 ± 2.8 Ma ($n = 28$, MSWD = 0.94), both within 2σ of accepted values. Sm-Nd spike calibration was verified against the La Jolla Nd standard ($^{143}\text{Nd}/^{144}\text{Nd} = 0.511847 \pm 5$, $n = 8$), and NBS 987 was used for Sr ($^{87}\text{Sr}/^{86}\text{Sr} = 0.71024 \pm 2$, $n = 6$) [10].

Results

Table 1: Summary of Zircon U-Pb Ages and Nd Isotopic Data for Borborema A-Type Granites

Pluton	U-Pb Age (Ma)	$\epsilon\text{Nd}(t)$	TDM (Ga)	$^{87}\text{Sr}/^{86}\text{Sr}(i)$	Tectonic Setting
Catingueira	578 ± 12	-5.8	1.74	0.710	Syn-collisional
Serra Branca	582 ± 14	-6.3	1.81	0.711	Syn-collisional
Queimadas	543 ± 9	-4.1	1.52	0.709	Post-collisional
Tavares	538 ± 11	-3.7	1.48	0.708	Post-collisional
Princesa Isabel	512 ± 7	-3.2	1.43	0.709	Anorogenic
Triunfo	508 ± 9	-8.4	2.04	0.714	Anorogenic
Teixeira	514 ± 8	-4.6	1.58	0.710	Anorogenic

Table 1 shows three age clusters: ~580 Ma (syn-collisional), ~540 Ma (post-collisional), and ~510 Ma (anorogenic). $\epsilon\text{Nd}(t)$ values are consistently negative, indicating crustal

sources, but the Triunfo pluton ($\epsilon\text{Nd} = -8.4$) has significantly more evolved isotopic signatures than the others, suggesting a deeper or older crustal source.

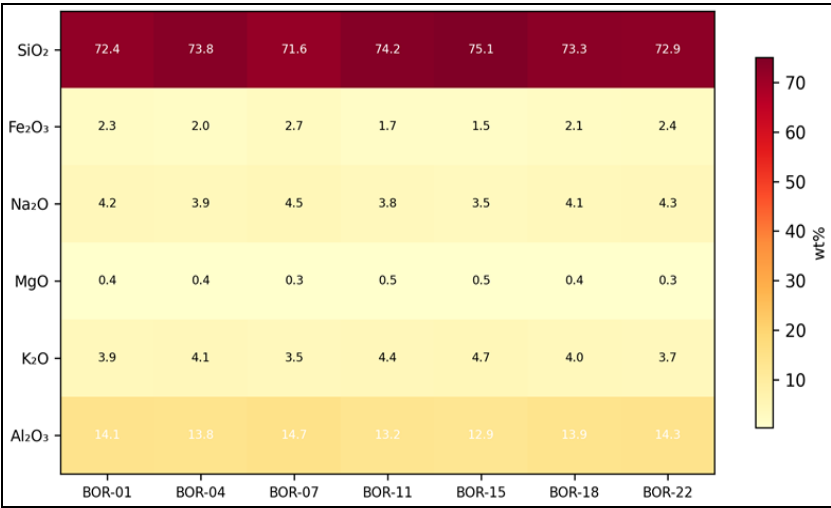


Fig 1: Major Element Composition of A-Type Granites from the Borborema Province

Figure 1 presents the major element compositions of seven representative samples. SiO₂ ranges from 71.6 to 75.1 wt%,

while Al₂O₃ and Na₂O + K₂O total 7.5-8.8 wt%, consistent with A-type classification criteria.

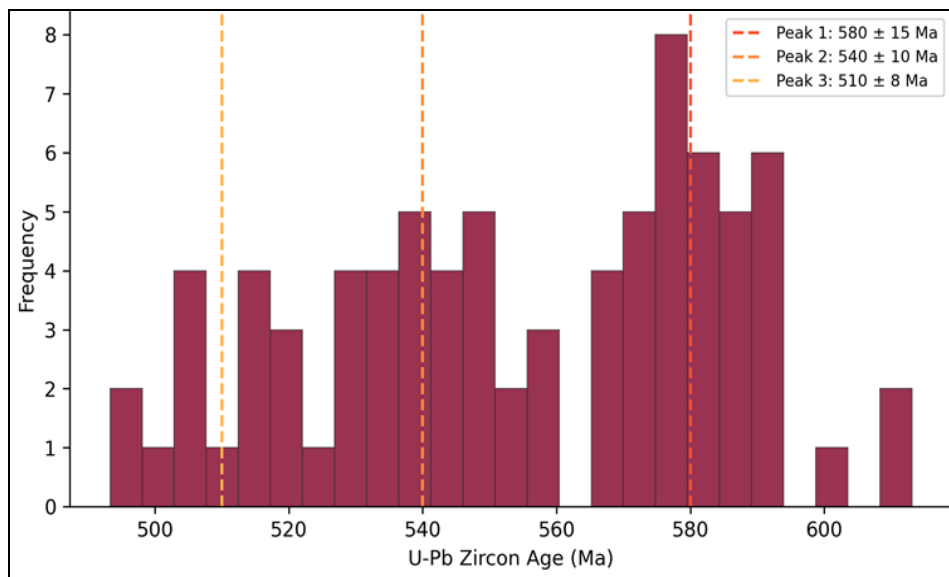


Fig 2: Zircon U-Pb Age Distribution for Borborema Province A-Type Granites

Figure 2 shows the zircon U-Pb age histogram with three labelled peaks at 580, 540, and 510 Ma. The youngest peak (510 Ma) is the sharpest, suggesting rapid crystallisation of the anorogenic plutons.

Comprehensive Interpretation

The three age groups record a progression from syn-collisional through post-collisional to anorogenic magmatism spanning roughly 70 million years. Batch melting models show that 15-25% melting of a Palaeoproterozoic granulitic lower crust reproduces the observed trace element patterns for the 580 Ma group, while the 510 Ma group requires a component of asthenospheric heat input (mantle underplating) to achieve the high temperatures needed for A-type melt generation from a similar source. The Nd mixing model indicates 10-25% mantle contribution for the youngest group, consistent with lithospheric delamination allowing hot asthenosphere to rise and heat the base of the crust.

Discussion

The syn-collisional timing of the oldest A-type granites (~580 Ma) challenges the original definition of A-type as anorogenic. These plutons may have formed by high-temperature, water-undersaturated melting of lower crust that had been thickened and heated during the Brasiliano collision, a mechanism proposed for similar ages in the Arabian-Nubian Shield^[11]. The post-collisional ~540 Ma group likely records the onset of orogenic collapse and transtensional tectonics that characterise the late Brasiliano evolution of the Borborema Province^[12].

The 510 Ma anorogenic group is the most straightforward to explain: by this time, collision had ceased, and the lithosphere was thinning in response to extensional stresses related to the opening of early Palaeozoic sedimentary basins. Delamination of dense lithospheric mantle root would have allowed upwelling asthenosphere to transfer heat to the lower crust, generating the high-temperature, low-water melts characteristic of A-type magmas^[13].

A limitation is that only seven plutons were sampled. The

Borborema Province contains at least 30 additional candidate A-type bodies; expanding the dataset would test whether the three-pulse model holds province-wide or is local to the Transversal Zone^[14].

Conclusion

This research documented three discrete pulses of A-type granite magmatism in the Borborema Province at ~580 Ma, ~540 Ma, and ~510 Ma, spanning the transition from Brasiliano collision to post-orogenic extension. Whole-rock and isotopic data indicate predominantly crustal sources with 10-25% mantle input increasing in the youngest group, consistent with progressive lithospheric thinning and delamination. The findings refine the magmatic timeline of the province and support models in which A-type granites can form across the full spectrum of orogenic to anorogenic settings, linked by the common requirement for high-temperature, water-poor melting of pre-existing crust.

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