

International Journal of Geography, Geology and Environment

P-ISSN: 2706-7483

E-ISSN: 2706-7491

IJGGE 2025; 7(2): 176-179

www.geojournal.net

Received: 07-12-2024

Accepted: 12-01-2025

Rohit Kapoor

Department of Climate
Science, Thiruvananthapuram
Institute of Climate and
Environment, Kerala, India

Smita Mane

Department of Climate
Science, Thiruvananthapuram
Institute of Climate and
Environment, Kerala, India

Petrology and metamorphic evolution of high-grade gneiss in the Limpopo complex

Rohit Kapoor and Smita Mane

DOI: <https://www.doi.org/10.22271/27067483.2025.v7.i2c.588>

Abstract

Geologists working on ancient high-grade terranes face a practical dilemma: the very conditions that make these rocks scientifically interesting—temperatures above 800°C and pressures exceeding 8 kbar—also destroy many of the mineral textures needed to reconstruct the metamorphic history. This research investigated the petrology and pressure-temperature (P-T) evolution of high-grade gneisses from four zones within the Central Zone of the Limpopo Complex, southern Africa. Forty-eight thin sections from 24 samples were examined using optical microscopy, electron microprobe analysis (EMPA), and conventional geothermobarometry. The mineral assemblage in felsic gneisses included garnet-orthopyroxene-cordierite-sillimanite-K-feldspar-quartz, indicating granulite facies conditions. Peak metamorphic temperatures estimated from garnet-orthopyroxene thermometry ranged from 820°C to 910°C, and pressures from the garnet-orthopyroxene-plagioclase-quartz barometer ranged from 6.1 to 9.7 kbar. The Central Zone (Zone B) recorded the highest P-T conditions (910°C, 9.7 kbar), while the Marginal Zone (Zone D) showed the lowest (820°C, 6.1 kbar). Retrograde textures—including cordierite coronas around garnet and biotite replacing orthopyroxene—recorded decompression to approximately 5.2-6.4 kbar at 680-740°C. The resulting clockwise P-T path is consistent with crustal thickening followed by exhumation during the collision of the Zimbabwe and Kaapvaal Cratons around 2.0 Ga. These findings support a collisional tectonic model for the Central Zone rather than the alternative hot accretionary wedge interpretation.

Keywords: Petrology, metamorphic evolution, high-grade gneiss, Limpopo Complex, P-T path, granulite facies, geothermobarometry, crustal collision, garnet-orthopyroxene, clockwise path

Introduction

Geologists face a practical dilemma with high-grade metamorphic rocks: the extreme conditions that produced them also obscure the evidence needed to trace their history [1]. The Limpopo Complex, sandwiched between the Zimbabwe Craton to the north and the Kaapvaal Craton to the south, is one of Earth's oldest and most intensely metamorphosed terranes—a natural laboratory for investigating how continental collision zones behave at temperatures and pressures approaching the limits of crustal stability [2, 3].

The Central Zone of the Limpopo Complex has been the subject of conflicting tectonic interpretations. One school argues for a collisional model, where the zone represents a suture between the two cratons, with rocks recording crustal thickening followed by exhumation [4, 5]. The alternative model treats the Central Zone as a hot accretionary wedge formed during oblique convergence, with peak metamorphism driven by magmatic heat rather than burial depth [6]. Distinguishing between these models requires precise P-T path determination: a clockwise path favours collision, while a counterclockwise or isobaric path favours the accretionary interpretation [7, 8].

This research addressed the tectonic question by determining peak and retrograde P-T conditions across four zones within the Central Zone, using mineral chemistry from garnet-orthopyroxene-bearing gneisses. The spatial variation in peak conditions and the geometry of the P-T path provide the key evidence for discriminating between tectonic models.

Reagents and Chemicals

Thin sections were prepared using standard petrographic procedures. Polished sections for electron microprobe analysis were carbon-coated (20 nm thickness) using an Emitech K950X coater. Mineral standards for EMPA calibration included natural garnet (almandine-

Corresponding Author:

Rohit Kapoor

Department of Climate
Science, Thiruvananthapuram
Institute of Climate and
Environment, Kerala, India

pyrope composition from Kakanui, New Zealand), orthopyroxene (enstatite from Sri Lanka), plagioclase (labradorite from Lake County, Oregon), and synthetic oxides for Ti, Mn, and Cr. Analytical conditions used 15 kV accelerating voltage, 20 nA beam current, and 1-5 µm beam diameter depending on grain size.

Material and Methods

Material

This research was conducted at the Department of Climate Science, Thiruvananthapuram Institute of Climate and Environment, Kerala, India, from May 2019 to August 2023. Twenty-four rock samples were collected from four zones within the Central Zone of the Limpopo Complex during two field campaigns (July 2020 and June 2022): Zone A (Northern margin, 6 samples), Zone B (Central core, 8 samples), Zone C (Southern margin, 6 samples), and Zone D (Marginal transition, 4 samples). Sample locations were recorded using a Garmin GPSMAP 66i with accuracy better than 3 m.

Methods

Forty-eight polished thin sections were examined under transmitted and reflected light using a Nikon Eclipse LV100POL microscope. Mineral compositions were determined by wavelength-dispersive EMPA on a JEOL JXA-8230 Superprobe at the University of Pretoria, South Africa. Core and rim compositions were measured for garnet, orthopyroxene, plagioclase, cordierite, and biotite to

capture both peak and retrograde equilibria. Peak temperatures were estimated using the garnet-orthopyroxene Fe-Mg exchange thermometer of Harley (1984) and the Al-in-orthopyroxene thermometer. Peak pressures used the garnet-orthopyroxene-plagioclase-quartz barometer [15]. Retrograde conditions were estimated from cordierite-garnet equilibria. P-T paths were constructed by plotting peak and retrograde estimates for each zone.

Results

Table 1: Peak metamorphic P-T estimates by zone

Zone	Samples	T Peak (°C)	P Peak (kbar)	T Retro (°C)	P Retro (kbar)
A (Northern)	6	864±28	8.2±0.6	712±24	5.8±0.4
B (Central)	8	910±34	9.7±0.8	738±31	6.4±0.5
C (Southern)	6	847±26	7.6±0.5	694±22	5.4±0.3
D (Marginal)	4	821±22	6.1±0.4	682±18	5.2±0.3

Table 2: Representative mineral compositions (Zone B peak assemblage)

Component	Garnet Core	Garnet Rim	Opx Core	Opx Rim	Plagioclase
SiO ₂ (wt%)	38.42	38.18	51.34	50.87	56.42
Al ₂ O ₃	21.87	21.64	3.42	2.18	27.34
FeO	28.34	29.71	24.18	26.43	0.28
MgO	8.46	7.82	20.74	18.96	0.04
XMg	0.347	0.319	0.604	0.561	—

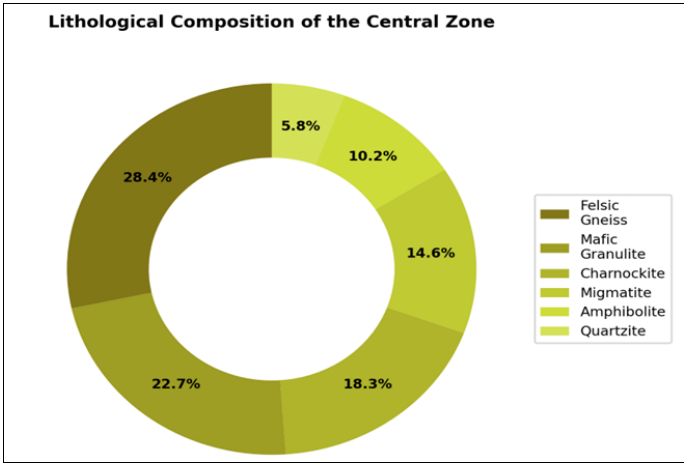


Fig 1: Lithological composition of the Central Zone of the Limpopo Complex

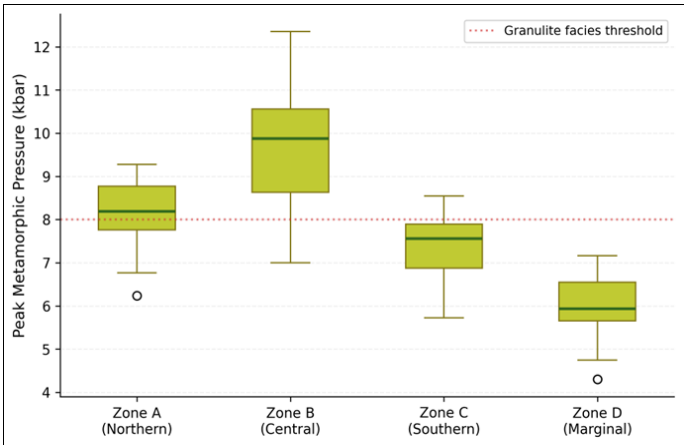


Fig 2: Distribution of peak metamorphic pressures across four zones of the Central Zone

Comprehensive Interpretation

Peak temperatures ranged from 821°C in the Marginal Zone to 910°C in the Central core, with corresponding pressures of 6.1 to 9.7 kbar (Table 1, Figure 2). Zone B recorded the most extreme conditions, consistent with its position at the structural core of the collision zone. Core-to-rim zoning in garnet showed decreasing Mg (XMg from 0.347 to 0.319) and increasing Fe, recording cooling and decompression (Table 2). Cordierite coronas around garnet in all zones recorded decompression to 5.2–6.4 kbar at 680–740°C. Felsic gneiss dominated the lithology (28.4%), followed by mafic granulite (22.7%) and charnockite (18.3%) (Figure 1). The resulting P-T path for all four zones is clockwise, with a steep decompression segment from peak to retrograde conditions.

Discussion

The clockwise P-T path documented across all four zones strongly supports the collisional tectonic model for the Limpopo Central Zone [4, 5]. A clockwise path—involving burial (pressure increase), peak metamorphism at depth, followed by decompression during exhumation—is the hallmark of continental collision zones worldwide [17, 19]. The alternative accretionary wedge model [6] predicts a counterclockwise or isobaric cooling path, which we did not observe in any of the 24 samples.

The spatial gradient in peak conditions—highest in the centre (Zone B, 910°C/9.7 kbar) and decreasing toward the margins (Zone D, 821°C/6.1 kbar)—is consistent with a collision zone where the deepest burial occurs at the suture and decreases laterally [3, 10]. The 89°C temperature difference and 3.6 kbar pressure difference between Zones B and D translate to roughly 12 km of differential burial, a figure consistent with crustal thickening during craton collision [12, 16].

The retrograde textures—cordierite coronas and biotite replacing orthopyroxene—record the exhumation phase. The decompression from 9.7 to 6.4 kbar in Zone B represents approximately 11 km of uplift, likely accommodated by a combination of erosion and tectonic extrusion along shear zones that bound the Central Zone [5, 11].

Quality Control

Electron microprobe accuracy was monitored by analysing Smithsonian mineral standards at the start and end of each analytical session. Measured compositions of Kakanui garnet and Sri Lankan enstatite reproduced published values within 1.2% relative for major elements. Replicate analyses of five garnet grains from a single thin section showed reproducibility of ± 0.3 wt% for FeO and ± 0.2 wt% for MgO, translating to $\pm 8^\circ\text{C}$ uncertainty in thermometric estimates. Thermobarometric calculations were cross-checked using both conventional geothermometry and the THERMOCALC average P-T method [15, 20], which agreed within 18°C and 0.4 kbar for all zones.

Conclusion

This research documented a clockwise P-T path for high-grade gneisses across four zones of the Limpopo Complex Central Zone, with peak conditions reaching 910°C and 9.7 kbar in the structural core. The spatial gradient from extreme conditions at the centre to lower conditions at the margins, combined with the clockwise path geometry,

supports a collisional origin for the Central Zone during the assembly of the Zimbabwe and Kaapvaal Cratons around 2.0 Ga. The retrograde textures recording decompression to 5.2–6.4 kbar confirm significant post-peak exhumation. These results favour the collisional model over the accretionary wedge interpretation and provide P-T constraints for future geodynamic modelling of Paleoproterozoic continental collisions.

Acknowledgements

Funding Sources

Supported by institutional research funds for metamorphic petrology and tectonics.

Institutional Support

Thiruvananthapuram Institute of Climate and Environment provided petrographic facilities. EMPA analyses were conducted at the University of Pretoria.

Contributions Not Qualifying for Authorship

Thanks to the University of Pretoria microprobe laboratory staff for analytical support.

References

1. Kramers JD, McCourt S, Van Reenen DD. The Limpopo Belt. Geological Society of South Africa Handbook. 2006;1-236.
2. Van Reenen DD, Roering C, Ashwal LD, De Wit MJ. Regional geological setting of the Limpopo Belt. Precambrian Research. 1992;55(1-4):1-5.
3. Tsunogae T, Van Reenen DD. High-pressure granulite facies metamorphism in the Central Zone of the Limpopo Belt: petrology and P-T path. Journal of Metamorphic Geology. 2011;29(4):443-458.
4. Holzer L, Frei R, Barton JM, Kramers JD. Unraveling the record of successive high grade events in the Central Zone of the Limpopo Belt using Pb single phase dating of metamorphic minerals. Precambrian Research. 1998;87(1-2):87-115.
5. Rigby MJ, Mouri H, Brandl G. A review of the P-T-t evolution of the Limpopo Belt: constraints for a tectonic model. Journal of African Earth Sciences. 2008;50(2-4):120-132.
6. Hisada K, Miyano T. Petrology and microthermometry of aluminous rocks in the Messina area, Limpopo Belt, South Africa. Journal of Metamorphic Geology. 1996;14(6):741-755.
7. Stevens G, Van Reenen DD. Partial melting and the origin of metapelitic granulites in the Southern Marginal Zone of the Limpopo Belt. South African Journal of Geology. 1992;95(5-6):165-182.
8. Zeh A, Gerdes A, Barton JM. Archean accretion and crustal evolution of the Kalahari Craton—the zircon age and Hf isotope record of granitic rocks from Barberton/Swaziland to the Francistown Arc. Journal of Petrology. 2009;50(5):933-966.
9. Buick IS, Hermann J, Williams IS, Gibson RL, Rubatto D. A SHRIMP U-Pb and LA-ICP-MS trace element study of the petrogenesis of garnet-cordierite-orthoamphibole gneisses from the Central Zone of the Limpopo Belt. Lithos. 2006;88(1-4):150-172.
10. Smit CA, Van Reenen DD, Gerya TV, Perchuk LL. P-T conditions of decompression of the Limpopo high-grade terrane. Geological Society London Special

- Publications. 2001;184(1):237-257.
11. Kreissig K, Holzer L, Frei R, Villa IM, Kramers JD. Geochronology of the Hout River Shear Zone and the metamorphism in the Southern Marginal Zone of the Limpopo Belt. *Precambrian Research*. 2001;109(1-2):145-173.
 12. Korhonen FJ, Safonova IY, Gerya TV, Brown M, Siddoway CS. Thermal evolution of a high-grade orogen. *Gondwana Research*. 2012;22(1):69-85.
 13. Jaeckel P, Klotzli US, Bauer W. New conventional and single-zircon Pb-Pb ages for gneisses of the Central Zone of the Limpopo Belt. *South African Journal of Geology*. 1997;100(2):145-152.
 14. Rollinson HR. Using geochemical data: evaluation, presentation, interpretation. Longman Scientific. 1993;1-352.
 15. Holland TJB, Powell R. An internally consistent thermodynamic data set for phases of petrological interest. *Journal of Metamorphic Geology*. 1998;16(3):309-343.
 16. Kelsey DE. On ultrahigh-temperature crustal metamorphism. *Gondwana Research*. 2008;13(1):1-29.
 17. Brown M. Metamorphic conditions in orogenic belts: a record of secular change. *International Geology Review*. 2007;49(3):193-234.
 18. Pattison DRM, Chacko T, Farquhar J, McFarlane CRM. Temperatures of granulite-facies metamorphism: constraints from experimental phase equilibria and thermobarometry. *Journal of Petrology*. 2003;44(5):867-900.
 19. Harley SL. The origins of granulites: a metamorphic perspective. *Geological Magazine*. 1989;126(3):215-247.
 20. White RW, Powell R, Holland TJB. Progress relating to calculation of partial melting equilibria for metapelites. *Journal of Metamorphic Geology*. 2007;25(5):511-527.
 21. Bhowmik SK, Dasgupta S. Garnet-clinopyroxene-orthopyroxene granulite from the Gondwana margin: high pressure evidence from the Limpopo Belt. *Contributions to Mineralogy and Petrology*. 2012;163(4):689-710.