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Petrogenesis and Geodynamic Setting of Archaean Granitoids around Salaiya, Panna District: Constraints from Trace Element Geochemistry

Anju Mishra
Department of Geology
Dr. Hari Singh Gour Vishwavidyalaya Sagar, Madhya Pradesh
Email - anjusonu40@gmail.com

Abstract

Salaiya area possesses granitoids of Archean age belonging to the Bundelkhand Craton, Panna district, records a historical event of crustal evolution from the Palaeoarchaean to the Palaeoproterozoic (~3.55 Ga to ~2.13 Ga). This review synthesizes existing geochemical, geochronological, and petrological data to deduce the petrogenesis and geodynamic setting of these granitoids. Three distinct magmatic suites are identified: (1) Tonalite-Trondhjemite-Granodiorite (TTG) gneisses (3551–3382 Ma), (2) sanukitoids (2644 Ma), and (3) biotite and hornblende granites (2521–2130 Ma). The TTG suites exhibit high SiO_2 (65–72 wt%), high Al_2O_3, lower MgO ratios, without any Eu anomalies which indicates it is derived from a basaltic crust which was partially melted with ample amount of water in a subduction zone along with garnet-amphibolite or eclogite residual facies. The sanukitoids composed of SiO_2 (55–62 wt%), high MgO (4–8 wt%), high Cr and Ni, along with elevated Mg# (60–70) which indicates that there was a contact and reaction between slab-derived melts and mantle peridotite. Granites having biotite and hornblende of younger age display Eu anomalies with negative values (Eu/Eu*=0.5–0.8) along with horizontal HREE patterns. Tectonic discrimination consistently supports a subduction-related arc setting for all suites. Regional correlation suggests these granitoids formed during three major tectono-thermal events culminating in the amalgamation of the North and South Indian blocks at ~2250 Ma. Future research should focus on high-precision U-Pb geochronology, Lu-Hf isotopes, and experimental petrology to better constrain magma sources and P-T conditions.

Keywords: Archaean granitoids, Bundelkhand Craton, TTG suite, petrogenesis, geodynamic setting, Panna district.

1. Introduction

Archean continental crust is source of earth geodynamics. It includes granitoids, mainly Tonallite-Trondhjite-Granodiorite (TTG) suites and their younger counterparts, that formed during early crustal growth and differentiation. They play an important role in understanding how magma was generated and what kind of tectonic regime existing at that time, especially when modern style of plate tectonics is concerned (Martin et al., 2005). The Bundelkhand Craton is considered to be one of the oldest Archaean cratonic blocks of the Indian shield that witnessed crustal development through the age from 3.6 to 2.1 Ga ago (Mohanty, 2021).

The research attempts to bridge the aforementioned lacunae through a synthesis of the existing geochemical, geochronological, and petrological information on the Salaiya granitoids to (i) establish distinct signatures of the trace elements of various granitoid series, (ii) determine their possible sources and conditions of partial melting, and (iii) ascertain their geodynamic settings based on discrimination techniques. Three distinctive aspects contribute to the novelty of this research project: (a) a comprehensive petrogenesis scenario that accounts for the magmatic evolution of TTGs, sanukitoids, and younger granitoids in terms of an integrated evolutionary process (Kaur et al., 2016) (b) careful reconsideration of the subduction-related versus other geodynamic models in the light of Archaean crust development (Martin et al., 2005; Moyen and Martin, 2012), and (c) establishment of a time-controlled geodynamic evolution model of the Salaiya region, covering crust development, interaction between crust and mantle, and further re-working stages (Mohanty, 2021).

2. Geological Setting

2.1 Regional Geology of Bundelkhand Craton

The Bundelkhand Craton is surrounded by the Satpura Orogenic Belt on its southern side and by the Indo-Gangetic Alluvium on its northern side (Mohanty, 2021). The Bundelkhand Craton is made up of a semi-circular exposure of granite gneiss complex containing multiple generations of intrusive rocks (Basu, 1986). Figure 1 shows the regional map of Bundelkhand craton. Craton from Bundelkhand belonging to ~3700 Ma to 400 Ma which denotes the earth's evolution (Mohanty, 2021). In total, intrusive granitoids has shown 3 episodes first from 3551Ma to 3190 Ma, second 2780Ma to 2550 Ma, and third from 2450–2250 Ma (Mohanty, 2021). A thermal episode having tectonic disturbances corresponding to an unconformity period of ~400 Ma separates Episodes I and II (Mohanty, 2021).

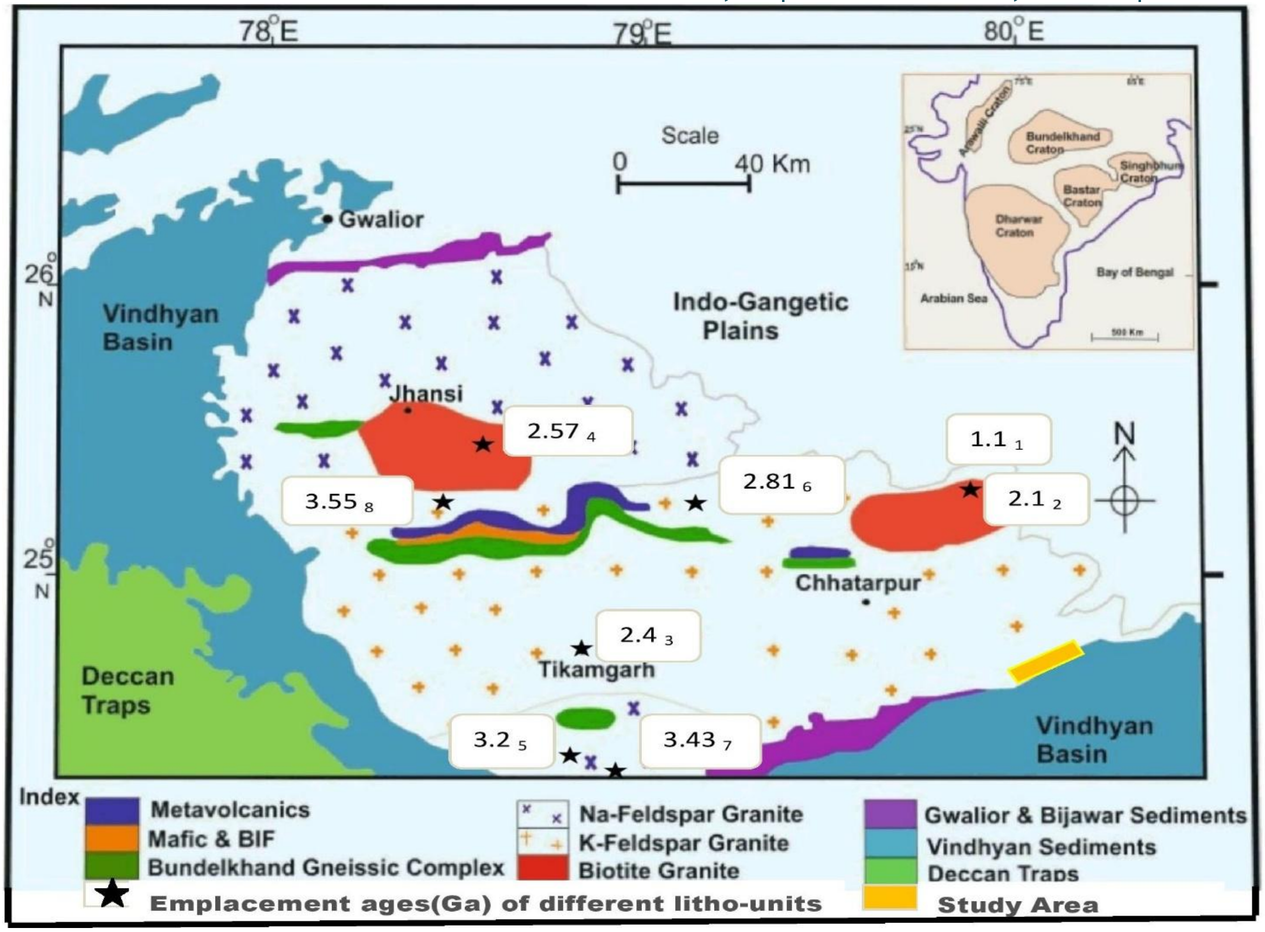

Fig. 1: Showing regional geological map of Bundelkhand Craton (after Thomas et al., 2019). Also showing the study area and emplacement ages (Ga) of different litho-units: 1. Mafic dykes,D1(Pradhan et al. (2012)) 2. Mafic dykes, D2 (Pradhan et al. (2012)) 3. Quartz veins (Bhattacharya and Singh (2013); Pati et al. (2007)) 4. Bundelkhand granitoids (Joshi et al., 2016; Kaur et al. (2014); Mondal et al. (2002)) 5. Madawara Ultramafic Complex(Singh et al., 2010) 6. Central Bundelkhand Greenstone Complex (Singh and Slabunov (2015, 2016)) 7. Southern Bundelkhand Greenstone Complex (Singh and Slabunov (2015, 2016)) 8. Bundelkhand Gneissic Complex (Kaur et al. (2016, 2014); Saha et al. (2016); Mondal et al. (1998, 2002)

2.2 Geology of Salaiya Area

Salaiya area, located in Panna district, has rocks that belong to the Bundelkhand Granite Complex. Linear ridges oriented in the NE-SW direction, gentle rolling topography and low relief pediplains characterize the area (Bagchi et al., 2021). The studied area lies between N $24^{0}45'57''$ to N $24^{0}54'10''$ and E $80^{0}01'00''$ to E $80^{0}08'18''$. TTG gneissic rocks, biotite granite, hornblende granite, leucogranite, sanukitoid plutons, different generation mafic dykes occur in the area around Salaiya (Mondal et al., 2002). The oldest rocks in this region include TTG gneisses whereas sanukitoids and leucogranites have relatively young age (Joshi and Slabunov, 2019) (Table 1). The greenstone belts of the area comprise metavolcanic rocks, metasedimentary rocks, and Banded Iron Formations (BIFs), which are intruded by different types of granitoids. Figure 2 shows the lithological map of the study area. The structural setting reveals that there have been several episodes of deformation, with the earliest structures being characterized by upright folds having ENE-oriented axes (Mohanty, 2021) (Table 1).

Table 1: Summary of lithostratigraphic units in the Salaiya area, Panna district

Lithounit	**Rock Type**	**Age (Ma)**	**Analytical Method**	**Reference**
Kuraicha TTG suite	Tonalite-trondhjemite-granodiorite	3551 ± 6	Pb-Pb zircon	Kaur et al. (2016)
Kuraicha Granite	Granite	3382 ± 20		Mondal et al. (2002)
Sanukitoid	Granodiorite	2644 ± 25		(Joshi and Slabunov, 2019)
Biotite granite	Granite	2521 ± 7		Mondal et al. (2002)
Leucogranite	Leucogranite	2492 ± 10		
Hornblende granite	Granite	2482 ± 7		
Pink granite	Granite	2291 ± 71	Rb-Sr WR	Bishui et al. (1989)

WR = Whole Rock; TTG = Tonalite-Trondhjemite-Granodiorite

3. Geochronological Framework

The geochronology of the Bundelkhand Craton shows that there are two significant spike in the rocks of Archean group, which include ~2546 Ma and ~3254 Ma (Mohanty, 2021). There are examples of both the mentioned ages present in the Salaiya zone. The oldest material in the Salaiya zone is the Kuraicha TTG Group belonging to an age of 3551±6 Ma (Pb-Pb zircon; Kaur et al., 2016). The detrital zircon age in the Chorhat sandstone suggests a much older age of 3707 ± 56 Ma for the source rocks of the region, indicating the presence of Eoarchaean materials (Lan et al., 2021). Age of the Kuraicha Granite intrusion into the older greenstone belt is dated to be 3382 ± 20 Ma (Mondal et al., 2002). Mafic dykes were subsequently intruded at 3254±3 Ma (Pradhan et al., 2012) and are categorized as Bundelkhand mafic dykes-A. The Bundelkhand Granite-I experienced a deformation and metamorphism from 3200Ma upto 2700 Ma, based on zircons' metamorphic rims (3185 ± 9 Ma; Kaur et al., 2016) and high-Mg and Al bearing schist of age 2785±49 Ma. Extensional tectonics occurred around 2700 Ma, evident from mafic dyke emplacement (2686–2777 Ma; Pradhan et al., 2012). The second stage in the history of granitoid rock formation is marked by the formation of sanukitoids (2644 ± 25 Ma) and other granites – biotite granite (2521 ± 7 Ma), leucogranite (2492 ± 10 Ma), and hornblende granite (2482 ± 7 Ma) (Mondal et al., 2002). Felsic volcanics from the upper greenstone belt give an age of

2542 ± 17 Ma according to the U-Pb zircon geochronology method. In the third stage, the representatives of granitoids are hornblende granite (2328 ± 35 Ma), pink granite (2291 ± 71 Ma), migmatitic gneiss (about 2130 Ma), and leucogranite (2108 ± 36 Ma; Mondal et al., 2002). These are interpreted to represent the Satpura Orogeny IA (Mohanty, 2021).

4. Geochemistry of Granitoids

4.1 Major Element Geochemistry

The TTG suite rocks from Salaiya formation are defined by higher SiO_2 (65-72 wt%), higher Al_2O_3 (15-18 wt%), lower MgO (1-3 wt%) and lower K_2O/Na_2O ratio (<0.5) (Kaur et al., 2016). This is indicative of the Archaean TTG suites that originate from hydrated basaltic source rocks globally (Moyen and Martin, 2012). The sanukitoid rocks have intermediate SiO_2 (55-62 wt%), higher MgO (4-8 wt%), higher Cr and Ni concentrations as well as higher LILE contents (Joshi and Slabunov, 2019). These features suggest that they have interacted with peridotite of the mantle peridotite (Smithies and Champion, 2000). Granites with biotite and hornblende contain higher SiO_2 (70-75 wt%) and K_2O, with the ratio K_2O/Na_2O greater than 1, implying evolution and crust origin (Mondal et al., 2002). They contain high incompatible elements with low Sr and Eu, which implies plagioclase fractionation.

4.2 Trace Element Geochemistry

The trace elements in the TTG suites of Salaiya have distinct characteristics of having higher abundances of LILE (Rb, Ba, and Th) than HFSE, presence of a positive Sr anomaly, and a negative Nb-Ti anomaly (Kaur et al., 2016). All these features point to a subduction setting. The REE chondrite patterns of TTGs reveal fractionation patterns, where $(La/Yb)_n$ values vary between 15 and 45, without any Eu anomaly (Kaur et al., 2016) (Table 2). The above pattern shows that the source material is of the type of garnet-amphibolite or eclogite, which involves garnet residue (Rapp and Watson, 1995). Sanukitoids have low degrees of REE fractionation with $(La/Yb)_n$ = 10-20 and positive Eu anomalies for some samples (Joshi and Slabunov, 2019). They have higher levels of compatible elements (Cr, Ni) and Mg# = 60-70, suggesting a metasomatic origin from mantle interactions (Smithies & Champion, 2000).

Granites containing biotite and hornblende of younger age are characterized by higher levels of evolution in their trace elements: low ratios of Sr/Y, negative Eu anomalies, and a flat HREE pattern (Mondal et al., 2002) (Table 2). This shows plagioclase fractionation along with shallower source depths in comparison with TTGs.

Table 2: Trace element compositions of granitoids from the Salaiya area Kaur et al. (2016), (Joshi and Slabunov, 2019), and Mondal et al. (2002)

Element (ppm)	TTG Gneiss (n=12)	Sanukitoid (n=8)	Biotite Granite (n=10)	Hornblende Granite (n=6)
Rb	45–85	65–110	120–180	95–150
Sr	350–550	450–600	150–250	200–300
Ba	400–700	550–850	650–900	500–750
Th	5–15	8–20	15–25	10–20
U	1–3	1.5–4	3–6	2–5
Nb	5–12	8–15	12–18	10–15
Ta	0.5–1.5	0.8–2	1.5–2.5	1–2
Zr	120–200	150–250	180–280	150–220
Hf	3–6	4–7	5–8	4–6
Y	8–18	12–22	20–30	15–25
La	20–45	25–55	40–65	35–50
Yb	1–2.5	1.5–3	2.5–4	2–3.5
Cr	30–80	150–300	20–50	25–55
Ni	20–50	80–180	15–35	20–40

Table 3: REE characteristics and key trace element ratios of Salaiya granitoids Kaur et al. (2016), (Joshi and Slabunov, 2019) and Mondal et al. (2002)

Parameter	TTG Gneiss	Sanukitoid	Biotite Granite	Hornblende Granite
$(La/Yb)_n$	25–45	12–20	8–15	10–18
$(Gd/Yb)_n$	2.5–4	1.8–2.5	1.2–2	1.5–2.2
Eu/Eu*	0.9–1.1	1.0–1.3	0.5–0.7	0.6–0.8
Sr/Y	35–60	30–45	7–12	12–18
La/Sm	4–6	3.5–5	3–4.5	3.5–5
Nb/Ta	8–12	8–10	7–9	8–10
Zr/Hf	35–45	35–40	30–38	32–40
Th/U	4–6	4.5–6.5	3–5	3.5–5

5. Petrogenesis

5.1 Source Characteristics

The TTG suites produced by Salaiya have higher ratios of La/Yb and Sr/Y, lower amounts of Y and heavy REE, and lack Eu anomalies (Kaur et al., 2016). This is an indication that they were derived through the melting of hydrated basaltic crust from depths greater than 40 kilometers (Rapp and Watson, 1995). The negative Nb-Ti anomalies imply a subduction environment characterized by metasomatism of the mantle wedge fluids derived from the slab. The sanukitoids possess higher concentrations of MgO, Cr, and Ni with radiogenic

Nd isotopes (Joshi and Slabunov, 2019). These attributes shows that sanukitoids is evolved from magma formed by mixing of TTG melts and the mantle wedge. High Mg# (60-70) indicates that the melts interacted with peridotitic mantle after being derived from the subducted lithospheric slab (Smithies and Champion, 2000). More evolved isotopes of biotite/hornblende granites are those which have higher initial Sr concentrations and negative Nd values (Mondal et al., 2002). This implies a substantial input of older continental crust due to recycling of TTG basement in subsequent tectono-thermal events.

5.2 Partial Melting Conditions

Petrological experimental results have shown that TTG melts develop from the partial melting of hydrated basalt under pressure between 1.5 to 2.5 GPa (50 to 80 km deep), with temperatures of 950 to 1050 °C (Rapp and Watson, 1995). Garnet in the residue accounts for the depleted heavy rare earth elements, while plagioclase absence accounts for the positive Sr anomaly. (Moyen and Martin, 2012). This shift in magma type from TTG to sanukitoids around 2.65 Ga could be due to changes in subduction parameters or higher temperatures of the mantle (Smithies & Champion, 2000). Sanukitoids depend on interaction with the mantle wedge, suggesting that the slab melts must have penetrated the mantle wedge before being emplaced (Martin et al., 2005). The biotite and hornblende granites of the younger age have a record of crustal anatexis because their chemistry suggests a melt of the earlier TTG crust at shallow depths of 30-40 km (Mondal et al., 2002). The negative Eu anomaly observed in these rocks shows plagioclase in a residual phase.

6. Geodynamic Setting

6.1 Subduction Zone Model

It can be inferred that Salaiya granitoids were formed under the conditions of subduction-based arc. This conclusion is drawn based on several geochemical properties of TTG suites: enrichment of these rocks in LILE in comparison with HFSE, negative Nb-Ti anomalies, and highly fractionated REE patterns (Kaur et al., 2016). Such features of rock composition resemble modern arc magmas, thus, confirming the similarity between subduction processes in the Archaean period and the present time (Martin et al., 2005). Moreover, the existence of sanukitoids with elevated content of Mg# and compatible elements proves the occurrence of slab-mantle interactions – a process peculiar for contemporary subduction systems (Smithies and Champion, 2000). The transition from TTG to sanukitoid magmatism at ~2.65 Ga may record a change from flat-slab to steep-slab subduction (Martin et al., 2005).

6.2 Tectonic Discrimination

Based on tectonic discrimination charts, the Salaiya TTG series lie mostly in the volcanic arc granite domain. The Salaiya TTG suite lies in the syn-collisional and volcanic arc domains according to Rb versus Y+Nb diagram (Kaur et al., 2016). Sanukitoid rocks possess transitional nature between volcanic arc environment and post-collisional environment due to their occurrence at the last stage of subduction (Joshi and Slabunov, 2019). Younger biotite and hornblende granites have been placed in the within plate granite category in some studies, but their arc-like geochemical signatures (negative Nb-Ti anomalies) indicate that they cannot be considered to have originated from within plate tectonics (Mondal et al., 2002). These conflicting results may reflect crustal contamination or post-emplacement modification.

6.3 Regional Implications

Bundelkhand Craton belonging to ~3.5 Ga and ~2.1 Ga has several events which involves subduction, arc magmatism, and crustal recycling (Mohanty, 2021). The Salaiya granitoids as a part of Bundelkhand craton shows plate tectonic activity during the Archean era. The Palaeoarchean TTG assemblages (~3.55 Ga) represent an early stage of crust formation through subduction-driven activities (Kaur et al., 2016). The Neoarchean sanukitoid rocks (~2.64 Ga) reflect the emergence of matured arcs involving extensive mantle participation (Joshi and Slabunov, 2019). The Palaeoproterozoic granites (~2.5–2.1 Ga) represent crustal reworking during the amalgamation of the North and South Indian blocks along the Satpura Orogen (Mohanty, 2021).

7. Conclusions

Archaean granitoids of the area of Salaiya, Panna District shows a part of geological evolution of the region through different periods of time from ~3551 Ma to ~2130 Ma. Different type of granitoids have been distinguished in this region: TTG gneisses (3551-3382 Ma), sanukitoids (2644 Ma), and biotite hornblende granites (2521-2130 Ma). The geochemical features of the TTG type granitoids (high La/Yb, Sr/Y, low HREE, no Eu anomaly) point towards the formation through partial melting of hydrated basaltic crust in a subduction zone setting with garnet amphibolite/eclogite residua. Sanukitoids (MgO, Cr, Ni, Mg# high) reflect the interaction of melts from subduction slab setting with peridotite in the wedge shape mantle during subduction. The younger granites have the evidence of reworking of the crust with a negative Eu anomaly, suggesting shallow melting levels and fractional crystallization of plagioclase. The results of the tectonic discrimination method suggest the development of the rocks under the influence of regimes of subduction zone and indicate the action derived from tectonic movement of plates in the Archaean age. The regional correlation implies that the granitoids of the Salaiya were formed due to three main tectono-thermal events resulting in the coalescing of North and South Indian blocks (~2250 Ma). The future study on the Salaiya granitoids would be best focused on precise U-Pb dating of zircons and Lu-Hf isotopic analysis, along with mapping and experimental petrology, to better determine the magma pulses and the sources involved. Regional correlations with other portions of the Bundelkhand Craton are important for understanding the tectonics of the area.

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