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Geochemistry of Alirajpur Granitoids (Gujarat, India) and Their Genetic Relationship to the Precambrian Basement Underlying the Deccan Traps

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Abstract—The granitic basement rocks of central and western India, which are overlain by the Deccan Traps, are important for understanding early Earth processes and crustal evolution. The Alirajpur region presents a unique opportunity to study the complete sequence of basement granites, overlain by the marine Turonian Bagh beds. These granitic basement rocks are mainly composed of orthoclase, quartz, plagioclase, and biotite as rock-forming minerals. Abundant zoned zircons are hosted within biotite and hornblende. The whole rock geochemistry is calc-alkaline with a prevalence of potassium over sodium. The Alirajpur granitoids exhibit low REE with positive Eu anomaly exhibiting typical lower crust signatures. A detailed petrological-geochemical comparison of the granitic basement rocks from the Koyna and Alirajpur basement, separated by ~500 km, indicates that they are genetically related and provide important clues about the extent of the Precambrian basement underlying the ~500000 km^2 of Deccan Traps.

Keywords: granitic basement, Alirajpur granites, Deccan volcanics, Koyna basement granitoids, Peninsular gneissic complex

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INTRODUCTION

Basement rocks, particularly those of Precambrian origin, play a critical role in understanding early Earth processes and crustal evolution (Yan et al., 2010). However, the Precambrian granites of central and western India, which are entirely covered by the ~65 Ma Deccan Traps (Schoene et al., 2015; U-Pb of basalts), remain poorly characterized due to a lack of exposed outcrops (Weber et al., 2003; Shuaibu et al., 2015). In most parts of the Deccan Igneous Province (DIP), the subtrappean basement has been typically inaccessible, generating interest in better understanding the age and composition of the basement. The understanding of the basement rocks at DIP has been largely from indirect sources such as: (i) scattered occurrences of crustal/mantle xenoliths (Dessai et al., 2004; Ranjini Ray et al., 2008); (ii) drill cores at a few localities, mainly along the peripheral parts of the DVP and (iii) geophysical data (e.g., Sain et al., 2002; Praveen Kumar and Mohan, 2014; Rao et al., 2015; Deshpande and Mohan, 2016). Recently, samples obtained from a scientific drilling expedition under the Deccan traps at the Koyna-Warna region reported the major and trace element geochemistry and Zircon U-Pb age and Hf-isotope of these granitic basement rocks (Bhaskar Rao et al., 2017; Shukla et al., 2022). Alirajpur (Fig. 1a) lies in the northern extremity of Deccan traps where the lithology is quite distinct with a thin cover of the Deccan basalts. This region is unique in that it records a complete sequence of basement granites, overlain by the marine Turonian Bagh beds, which are considered to be infratrappean to the overlying Deccan Traps.

A previous study on the granitic basement rocks from Koyna (Shukla et al., 2022) reported fractionated REE patterns with enriched light REE and depleted heavy REE. Further, the Koyna granitoids display a geochemical pattern with close proximity to the peninsular gneisses (PGC) of the Dharwar supergroup and may be considered as it's continuation. In close proximity to the Alirajpur region, Banerjee et al. (2022a) have reported detailed geochronology of the area where the authors report 2544 ± 82 Ma for the coarse-grained granitoid comprising majorly of Quartz, K-feldspar, Plagioclase and Biotite. Such age suites bring out a need for cross-examinations regarding the existence of older rock sequences in and around the Alirajpur region which has demonstrated very prominent exposures of granitioids and granitic basement.

This study attempts to understand the geochemical characteristics of Alirajpur granitoids (Fig. 1b) and aims to compare the geochemical affinity of the Alira-

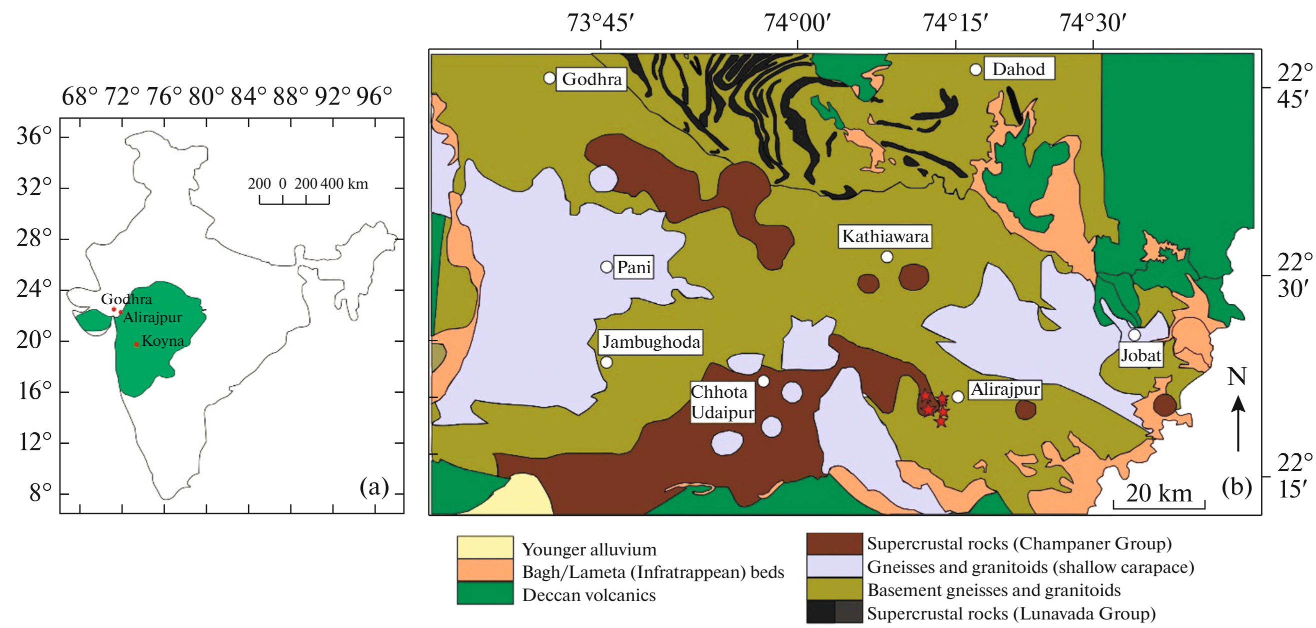

Fig. 1. (a) India map with locations of Alirajpur, Godhra and Koyna marked with red circles and the green patch showing the spatial distribution of Deccan basalts. (b) Geological map of Alirajpur modified from Banerjee et al. (2022a) showing locations of studied samples (red circles).

jpur granitoids with both Koyna and Dharwar granitoids. The study also explores the possibility of the northern extent of the Dharwar granitoids which is engulfed by the large extent of Deccan volcanism extending all the way to Alirajpur.

GEOLOGICAL SETTING OF ALIRAJPUR GRANITES AND KOYNA BASEMENT

The Alirajpur basement rocks (Fig. 2) are exposed in the Panwad-Kawant corridor of the Chhota Udaipur Alkaline Complex and exposed in small hillocks on the roadside. The basement rocks are exposed at lower elevation as compared to the granites. The Alirajpur rocks are lacking any kind of structural deformity as compared to the Godhra litho-units where multiple deformation events have been recorded (Banerjee et al., 2022b). The granites are fresh with prominent presence of biotite laths and feldspars which characteristically give the buff red color to these rocks. The basement gneisses are overlain by granits, however, a strict boundary is not observed in the field.

The Alirajpur rocks lie very close (30–40 km) to the Precambrian crystalline rocks of the Godhra-Chhota Udaipur sector (Fig. 1b) which are divided into four lithogenic units (Geological Survey of India, 1968): (a) a group of blastoporphyritic granitoids with varying degrees of deformation (massive, foliated, and mylonitic), collectively known as the Godhra granite; (b) mesoscale outcrops of anatectic quartzo-feldspathic gneisses that have been intruded by the granite body and contains biotite hornblende; (c) the Champaner Group, which consists of amphibolites, meta-arenites, deformed intraformational conglomerates, mica schists, calc-schists, greenschist/epidote-amphibolite facies, quartzites, and micaceous quartzites; and (d) the Lunavada group consisting of quartzite, phyllite, schist, and minor carbonates metamorphosed at greenschist facies conditions. In the Champaner Group, the abundances of meta-carbonate and Mn-rich horizons decrease, and mafic-ultramafic rocks increase from south to north. The Upper Cretaceous Deccan volcanics, the infra-trappean Lameta Formation, and the inter-trappean Bagh beds partially obstruct the southern lithogenic units.

The Koyna region, which is geochemically similar to the Alirajpur granites, is located in the western part of the Deccan Volcanic Province (DVP) in Maharashtra, India (Fig. 1a). The rocks primarily consist of several basaltic lava flows that constitute the main surface lithology of the region (Geological Survey of India, 1968). The region is dissected by several prominent lineaments, e.g., the West Coast lineament, the Koyna lineament, Chiplun lineament, Warna lineament, etc. (Talwani, 1997). Geographically, the DVP is bound by the Bastar, Aravalli–Bundelkhand, and Dharwar Cratons in the east, north, and south, respectively. The basement rocks explored in the Koyna region, as well as in the other parts of the DVP (e.g., south of Son–Narmada–Tapti lineament zone), are mainly granite gneiss/granitoids. Further, preliminary petrological characteristics and age estimates suggest that these basement sections are equivalent to the Archaean Peninsular gneisses and Closepet granites of the Peninsular Indian Shield (Gupta et al., 2003; Bhaskar Rao et al., 2017 and Misra et al., 2017).

Fig. 2. Rocks samples from Alirajpur. Granitoids (a–d). Biotite rich granite (d). Alirajpur basement gneiss (e) and pink granite (f).

ANALYTICAL TECHNIQUES

Megascopically fresh samples were collected from in and around the Alirajpur city stationed at Alirajpur district of Madhya Pradesh, India. These samples (~5 kg each) were first crushed to a coarse size and then coned and quartered. The thin sections were prepared from the rock chips which were mounted on a glass slide and then ground smooth using progressively finer abrasive grit until ~30 μm thickness was achieved. The sections were then polished and the interference colours of the minerals were compared to the Michel-Lévy interference colour chart. The thin sections are studied under LEICA DM 2700 P microscope. The minerals were identified by their optical properties and composition of heavy minerals are determined in Zeiss ULTRA Plus High-resolution field emission scanning electron microscopy (HR-FESEM) with EDS at Central Instrumentation Facility at IISER Bhopal.

Approximately 5 g of rock chips were powdered for major and trace element analyses. To avoid metal contamination, the materials were crushed in plastic sheets, and 50 g of hand-picked chips were powdered using an alumina ball mill (SPEX) at IISER Bhopal. Fusion glass beads were made by heating a combination of powdered materials to flux in a 1 : 10 ratio. The flux was made up of pure-grade lithium tetraborate (66.67%), lithium metaborate (32.83%), and lithium iodide (0.50%). X-ray Fluorescence analysis was done at in-house PANalytical Epsilon 4 spectrometer under vacuum at the Central Instrumentation Facility, IISER Bhopal. The source of X-rays was a ceramic side window X-ray tube, for maximum stability along with a 15 W, 50 kV Ag anode. Calibration was prepared using eight international rock standards from the United States Geological Survey (USGS). BHVO-2 and BCR-2 were analyzed as control standards along with the samples to determine the accuracy and precision of analyses. The uncertainties associated with most of the major oxides are <2%, except 2.5 to 3.5% for K_2O and TiO_2, and 5% for Na_2O. The major element data has been reported in Table 1.

For trace element analyses 25 mg aliquots of the powdered samples were dissolved in 15 mL screw-cap Teflon vials from Savillex, USA, using a mixture of concentrated HF and HNO_3 in the proportion of 2 : 3 following standard digestion protocol from Ghatak et al. (2013). The final solution was a 4000 times dilute solution in 2 wt % nitric acid (v/v) with a 10 ppb internal standard of In, Cs, Re, and Bi. Laboratory blanks were also made parallelly to check of blank corrections. The USGS rock standards BIR-1a (Reykjavik Iceland Basalt), BCR-2 (Columbia River Basalt), BHVO-2 (Hawaiian Basalt), RGM-2 (Rhyolite, Glass Mountain) and AGV-2 (Guano-valley Andesite) were analyzed as standards for calibration whereas, AGV-2 and BCR-2 are analyzed as control standards and sample CH-1 was used to test the repeatability for the experiment. For all elements, internal precision (wt % RSD) based on three repeat observations is better than 5%. Based on multiple analyses of AGV-2 and BCR-2, the external consistency for most elements is better than 5%. The USGS standards and laboratory blanks were processed in a similar manner to the rock samples. Element concentrations were measured using a Thermo Scientific iCAP-Q quadrupole inductively coupled plasma mass spectrometer (ICPMS) at the in-house facility at IISER Bhopal. Trace element data are reported in Table 2.

RESULTS

Petrography

There are several texturally and compositionally distinct subtypes of Alirajpur granites: (a) white-gray, very coarse-grained granite; (b) pinkish-gray, medium-grained granite; (c) fine- to medium-grained biotite granite (Fig. 2). The Alirajpur granites exhibit zonation in texture of minerals, color, and mineral composition. However, the mineralogy is generally uniform quartz, plagioclase (An1-11), K-feldspar, biotite, muscovite, and opaques (Fig. 3a). The phenocrysts and groundmass are made up of K-feldspars, plagioclase, and quartz. Minor phases include zircon, apatite, sphene, monazite, xenotime, opaques, and thorite, the majority of which are biotite inclusions. K-feldspar is found to be anhedral and typically shares a close grain boundary with quartz grains accompanied by biotite (Fig. 3b). The biotite-rich granites host monazite within the biotite grains (Fig. 3c). In most of the cases the zircons are being hosted by K-feldspar (Figs. 3b, 3d, 3e). The majority of the phenocrysts are up to 6 cm in length and made up of K-feldspar, which includes microcline-perthites with zircons and biotite (Fig. 3e). K-feldspars are typically cloudy or altered (Figs. 3b, 3e).

Quartz grains ranging up to 2 cm in length, exhibit recrystallization as anhedral isolated grains or aggregates. Quartz intergrowths with K-feldspar and plagioclase result in micrographic and/or granophyric textures, accompanied by prominent myrmekites in thin sections. Large phenocrysts of quartz often display wavy extinction, while intergrowths and smaller grains show uniform extinction. Magnetite is the common opaque phase and contains ilmenite lamellae in some instances. Magnetite (Fig. 3f) occurs as anhedral crystals within or in close proximity to pyroxene. Ilmenite crystals exhibit a range of shapes from prismatic to anhedral, with the majority of them intergrown with titanite and rutile (Fig. 3f). Apatite, the most common accessory mineral, appears as inclusions in biotite in various sizes, ranging from medium-sized anhedral crystals to small hexagonal crystals. Zircon grains are prismatic (Figs. 3b, 3e). Heavy minerals from Alirajpur granitoids and SEM images are provided in the supplementary data (SM 1-3).

Geochemistry

Major and trace element concentrations of the Alirajpur granites are reported in Tables 1 and 2 respectively and plotted in Figs. 4–15. Chemical analyses of granitic samples show that SiO_2 varies from 58.22 to 70.61 wt % (avg. 66.65 wt %) whereas, Al_2O_3 varies moderately from 7.65 to 14.84 wt % (avg. 11.75 wt %). The total alkali content of these granitic rocks varies from 12.21 to 22.99 wt % (avg. 16.52 wt %). The Predominance of K_2O (avg. 6.6 wt %) over Na_2O (avg. 2.06 wt %) is observed. TiO_2 (0.02–0.048 wt %), $Fe_2O_3^T$ (0.11–

Table 1. Major elements data for Alirajpur suite of rocks from XRF analysis (*all concentrations in wt % oxide*)

Rock type	Basement gneiss		Granites				
Sample Name/Oxides	BASE	CH-01	CH-02	CH-03	CH-04	CH-05	CH-06
SiO_2	59.1	58.2	70.6	70.6	69.7	69.1	69.3
Na_2O	1.66	1.55	2.32	0.66	4.36	3.24	0.66
MgO	6.78	6.37	0.04	2.08	0.12	1.01	5.08
Al_2O_3	8.08	7.65	14.37	14.85	14.32	14.65	8.39
P_2O_5	0.12	0.2	0.05	0.13	0.01	0.04	0.04
K_2O	7.07	7.89	9.56	3.68	7.58	5.29	5.16
CaO	13.1	13.6	0.4	7.9	3.4	5.5	11.3
TiO_2	0.04	0.05	0.07	0.05	0.01	0.02	0.05
MnO	0.05	0.08	0.01	0.02	0.02	0.01	0.04
$Fe_2O_3^T$	2.57	2.5	0.16	0.27	0.49	0.12	0.47
Total	**98.6**	**98.1**	**98.9**	**100.2**	**99.9**	**97.5**	**100.5**
K_2O/Na_2O	4.26	5.11	4.12	5.58	1.74	1.63	7.77
K_2O/CaO	0.54	0.58	25.97	0.47	2.26	0.97	0.46
$(Na_2O + K_2O)/CaO$	0.67	0.7	32.27	0.55	3.56	1.57	0.51
$Al_2O_3/(CaO + Na_2O + K_2O)$	0.37	0.33	1.17	1.22	0.94	1.05	0.49
$Al_2O_3/(Na_2O + K_2O)$	0.92	0.81	1.21	3.42	1.2	1.72	1.44
Agpaitic index	–4.46	–5.39	–4.27	3.52	–4.36	–0.78	–1.38
CIPW							
Quartz	3.0	3.2	20.4	35.3	14.3	20.7	24.6
Anorthite	–	–	0.56	26.6	–	9.9	4.7
Albite	2.2	–	20.1	5.6	31.5	27.8	5.6
Orthoclase	42.4	42.6	57.9	21.7	44.8	31.6	30.3
Diopside	44.7	42.6	0.5	9.0	2.1	5.8	28.4
Hypenthene	–	–	–	1.33	–	–	–
Wollastonite	3.7	5.8	0.2	–	5.9	4.1	6.1
Acmite	1.2	1.2	–	–	0.2	–	–
K_2SiO_3	–	1.37	–	–	–	–	–
Na_2SiO_3	2.5	2.8	–	–	1.2	–	–
Ilmenite	0.08	0.09	0.13	0.09	0.02	0.04	0.09
Magnetite	–	–	0.04	0.06	–	0.03	0.10
Apatite	0.28	0.46	0.12	0.30	0.02	0.09	0.09
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

2.56 wt %), MgO (0.11–6.78 wt %), MnO (0.01–0.08 wt %), and P_2O_5 (0.07–0.19 wt %) shows a conspicuous antipathetic relation with silica. The content of CaO is low to moderate and has a wide range (0.36–13.56 wt %) (avg. 7.85 wt %).

In the TAS plot (Middlemost, 1994; Fig. 4) as well as in other relevant figures (Figs. 4, 8, 10–12) the Alirajpur samples are also compared to Koyna, Dharwar, and Godhra Sector rocks. Chemically, the Alirajpur granites varies from granodioritic-quartz

Table 2. Trace elements data for the Alirajpur suite of rocks (*all the concentrations in parts per million*)

Rock Type	Basement Gneiss		Granites				
Sample No.	CH-01	BASE	CH-02	CH-03	CH-04	CH-05	CH-06
			Trace Elements				
Sc	0.9	1.2	0.2	1.0	1.2	1.6	2.8
Ti	2.3	1.7	0.1	1.5	0.7	0.6	1.5
V	70	37	1	20	2	2	17
Cr	95.2	7.0	63.5	5.5	8.1	60.9	91.8
Co	2.6	1.9	0.6	1.9	0.9	0.7	2.0
Ni	43.1	9.8	29.1	17.1	6.0	27.5	41.0
Cu	2.5	0.4	2.9	0.1	1.1	9.3	2.8
Ga	1.4	1.2	20.4	1.3	16.7	11.8	3.8
Rb	1.0	1.8	666	1.0	17.9	140	8.7
Sr	116	149	38	105	330	98	68
Y	4.3	4.1	5.3	1.4	2.3	6.0	6.1
Zr	6.9	7.1	7.1	4.5	105.8	42.9	17.4
Nb	0.8	0.7	2.9	0.4	3.7	11.3	2.7
Ba	115	95	125	22	67	802	78
Hf	0.2	0.2	0.5	0.1	3.2	2.3	0.6
Ta	0.1	0.1	1.5	0.1	0.4	1.9	0.2
Pb	3.4	6.6	131	1.1	18	19	1.9
Th	0.5	1.2	2.7	0.9	2.5	19.6	3.3
U	1.7	5.6	2.6	2.4	1.0	3.2	0.7
			Ratios				
Rb/Sr	0.01	0.01	17.5	0.01	0.05	1.43	0.13
Rb/Ba	0.01	0.02	5.33	0.05	0.27	0.17	0.11
Sr/Ba	1.01	1.57	0.31	4.75	4.96	0.12	0.87
U/Th	3.28	4.64	0.98	2.59	0.41	0.16	0.22
			REE				
La	2.68	2.94	3.2	2.51	2.91	6.6	8.0
Ce	3.52	4.12	2.71	3.65	3.68	12.7	13.1
Pr	0.58	0.67	0.27	0.57	0.45	1.61	1.95
Nd	2.19	2.58	0.73	2.01	1.73	5.74	7.05
Sm	0.38	0.51	0.21	0.36	0.31	1.29	1.33
Eu	0.14	0.16	0.25	0.09	0.54	0.54	0.21
Gd	0.46	0.5	0.34	0.32	0.37	1.27	1.23
Tb	0.07	0.08	0.09	0.04	0.05	0.21	0.17
Dy	0.51	0.53	0.76	0.24	0.34	1.18	0.97
Er	0.3	0.31	0.57	0.12	0.25	0.74	0.6
Tm	0.05	0.04	0.11	0.02	0.05	0.11	0.09
Yb	0.27	0.27	0.84	0.11	0.37	0.89	0.56
Lu	0.04	0.04	0.13	0.02	0.07	0.14	0.1
			Ratios				
$(Ce/Yb)_{CN}$	3.4	4.0	0.9	8.5	2.6	3.8	6.2
$(La/Lu)_{CN}$	7.5	8.5	2.5	16.3	4.4	5.0	8.7
$(La/Sm)_{CN}$	4.4	3.6	9.4	4.3	5.9	3.2	3.8
Eu/Eu*	1.0	1.0	2.8	0.8	4.9	1.3	0.5
$(Gd/Lu)_{CN}$	1.5	1.7	0.3	2.4	0.7	1.2	1.6
$(La/Yb)_{CN}$	6.7	7.3	2.6	15.1	5.4	5.0	9.7

$Eu/Eu^* = (Eu)_{CN}/[(Sm)_{CN} \times (Gd)_{CN}]^{0.5}$, McLennan, (1989). Abbreviations: CN—Chondrite Normalised.

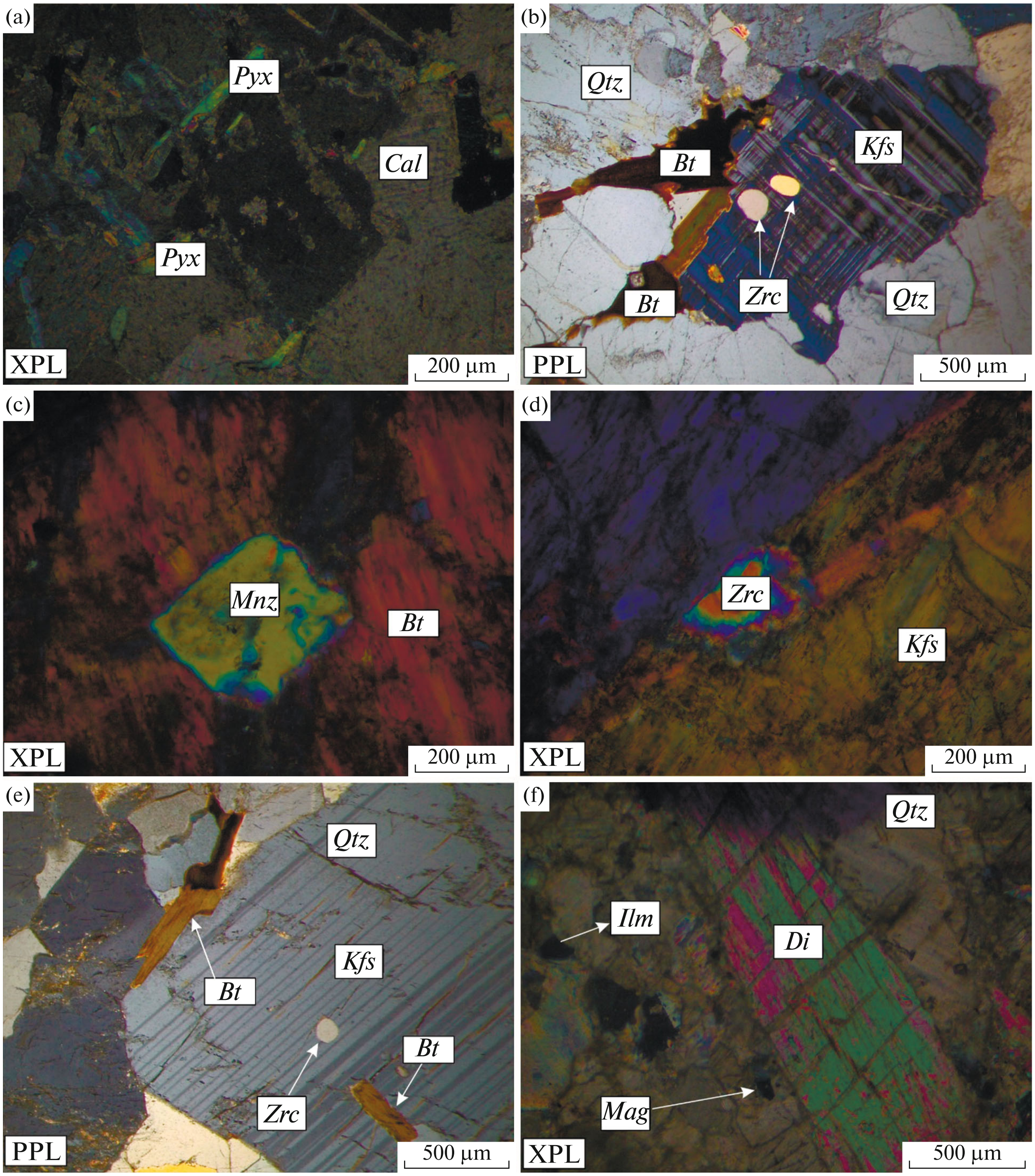

Fig. 3. Photomicrograph of Alirajpur granites depicting the close association of heavy minerals with the rock-forming minerals. The Zircon is hosted by K-feldspar. Monazite is exclusively being hosted by Biotite. Abbreviations: *Bt*—Biotite, *Cal*—Calcite, *Di*—Diopside, *Ilm*—Ilmenite *Kfs*—K-feldspar, *Mag*—Magnetite, *Q*—Quartz, *Mnz*—Monazite, *Zrc*—Zircon, *Pyx*—Pyroxene. PPL—Plane polarized light, XPL—Cross Polarized light.

monzonite field. The Harker variation plots SiO_2 vs. Al_2O_3, CaO, $Fe_2O_3^T$, MgO, and MnO wt % show an overall decreasing trend that indicates progressive evolution of a granitic magma (Figs. 5b–d, 5f, 5h), which has calc-alkaline parentage with ferroan to magnesian nature along with fractionation of plagioclase and ferromagnesian (Fe–Mg) minerals. The SiO_2 versus P_2O_5 and TiO_2 wt % plots (Figs. 5g, 5i) show a negative correlation with increasing silica content, which indicates the formation of titanomagnetite and apatite phases during crystallization, which are

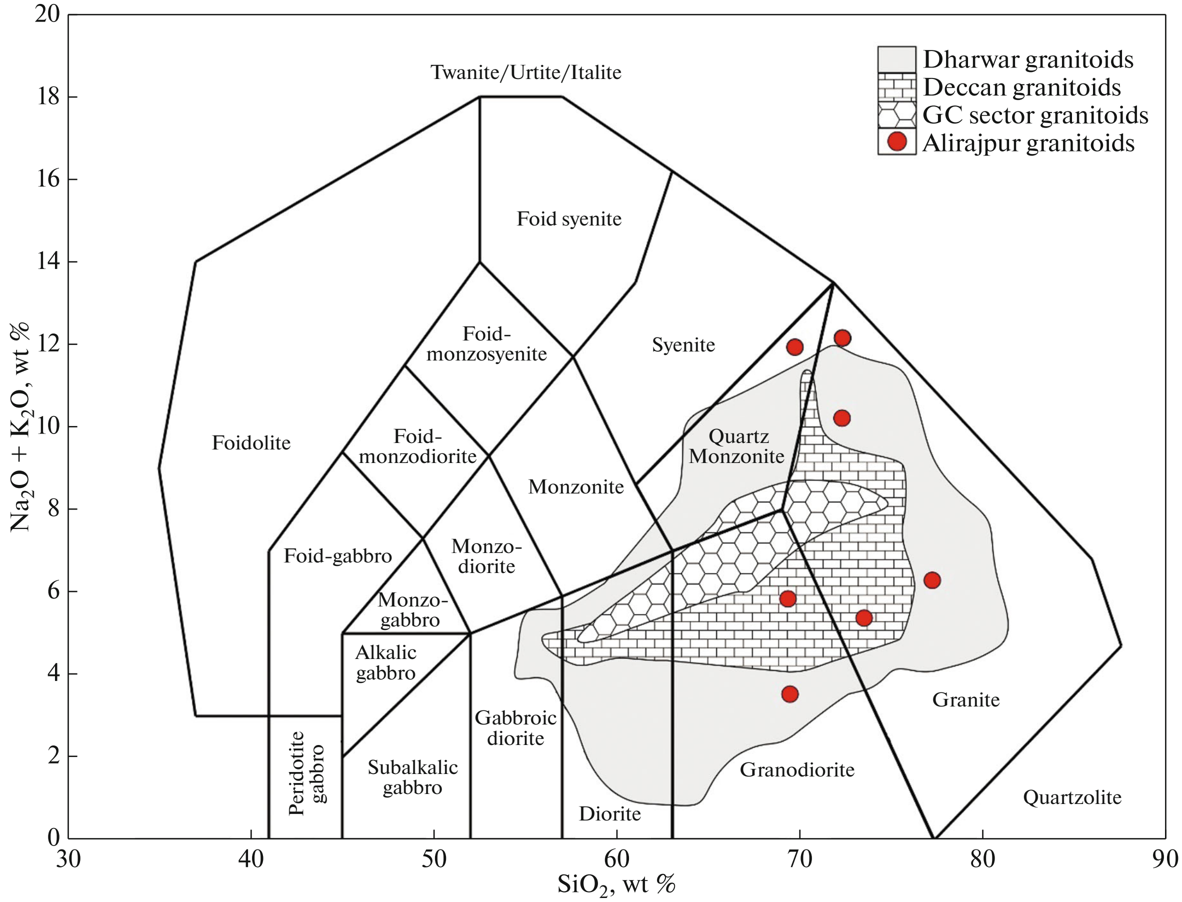

Fig. 4. Total Alkali–Silica classification of Middlemost (1994). The samples for Alirajpur, Koyna basement and Dharwars (DIGIS Team, 2023, "GEOROC Compilation: Rock Types", https://doi.org/10.25625/2JETOA, Goettingen Research Online/Data, V1; Lehnert et al., 2000) are plotted to understand the range of compositional variation within the rock types.

confirmed by the petrographic studies. SiO_2 wt % versus Na_2O wt % plot (Fig. 5a) show scatter indicating mobility of Na_2O during secondary processes. These rocks when translated to QAPF diagram fall largely in the silica oversaturated bracket of quartz rich granitoids (Fig. 6a). The composition of Alirajpur granitoids ranges from granitic to monzograntic suite with a calc-alkaline parentage (Figs. 6b, 7a and 7b). These rocks evolved in a low-pressure environment where these rocks evolved below 0.1 Gpa (Fig. 6c). K_2O wt % shows a positive correlation with SiO_2 wt % with shoshonitic trends which is consistent with Archean granitoids (Fig. 9a). Trace element data reflects\strong variation in LILEs and moderately enriched HFSEs (Arth, 1976). Rb/Sr, Rb/Ba, and Sr/Ba ratios are low with an average value of 2.38, 0.74, and 1.82 respectively. The overall distribution of trace elements shows low to moderate abundance of V, Cr, Co, Y, and U. Elements such as Cu, Ga, and Nb show low concentrations and Pb and Th have moderate concentrations. All the samples have low to moderate concentrations of REE (Fig. 11a) and are enriched in light rare earth elements (LREE) relative to the heavy rare earth elements (HREE), as indicated by LREE/HREE ratio, which ranges from 2.68 to 11.06 (average 6.75).

The primitive mantle normalized trace elements pattern (Fig. 8b) of the basement granitic rocks of Alirajpur, depicts that Th, U, and Sr are enriched, whereas Nb, Nd, and Y are depleted in accordance with the normal calc-alkaline continental arc granitoids (Brown, 1984). High Rb, Th, U, and low Zr and Ti values are compatible with typical crustal melts (Carr et al., 1986; Chappell and White, 1992) and suggest crustal contamination during magmatic evolution. Negative Ba, Nb, and Ti anomalies are typical characteristics of subduction-related magmas (Pearce, 1984). The Nb-Ta trough is typical for calc-alkaline magmas formed above subduction zones and reveals an arc signature in the evolution of magmas (Khalaji et al., 2007; Arsalan and Aslan, 2006). The chondrite normalized REE pattern for the basement granitic rocks of Alirajpur shows enrichment in LREEs relative to the HREEs. Strong fractionation of LREE from HREEs is a distinct feature of the Archean gneissic complex (Martin, 1994) as represented by moderate ratios of $(La/Lu)_{CN}$: 2.49–8.71, $(La/Yb)_{CN}$: 2.59–15.1

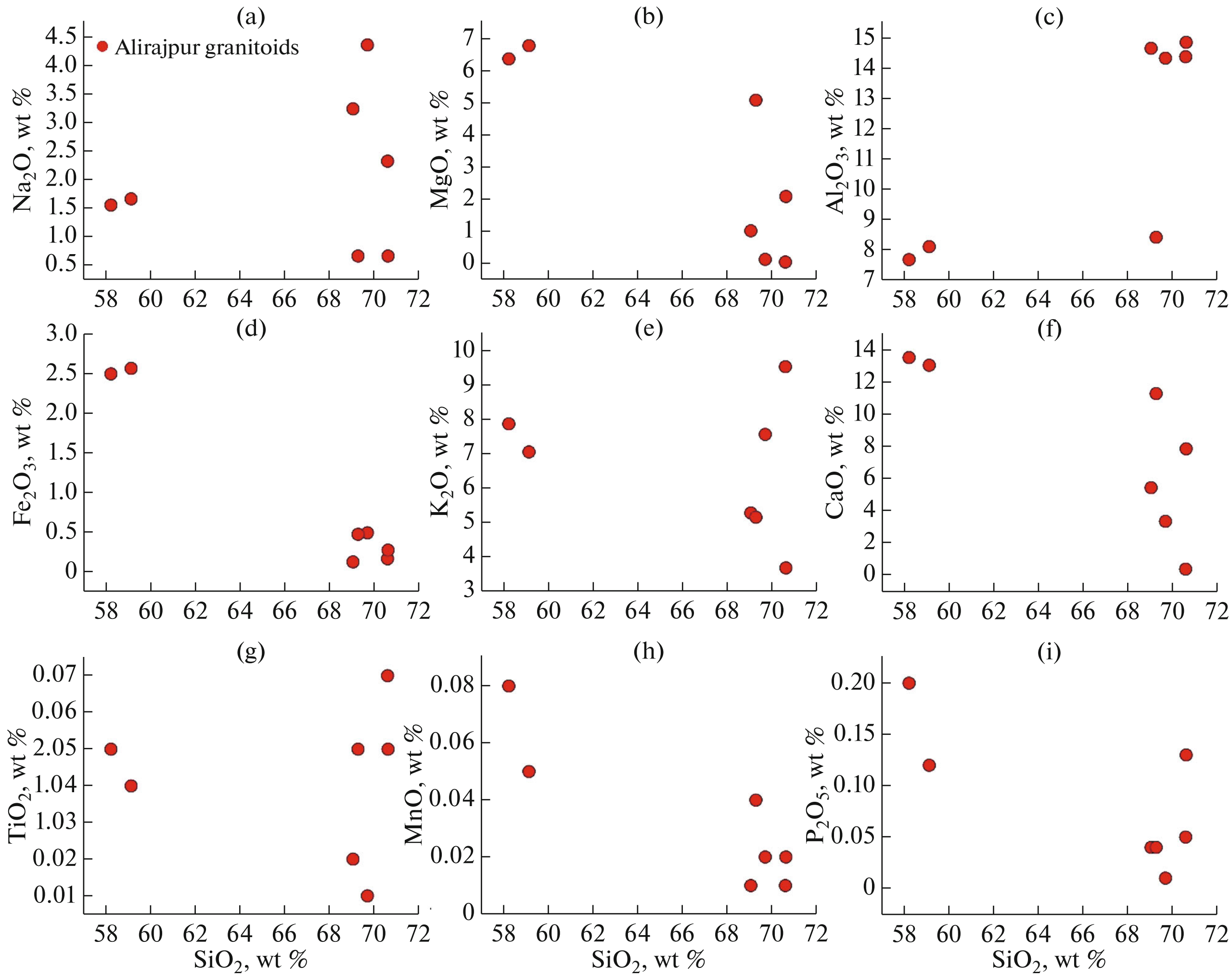

Fig. 5. Harker diagram for Alirajpur granitoids (Harker, 1909).

and $(Ce/Yb)_{CN}$: 0.85–6.14. This can be attributed to the presence of zircon, ilmenorutile, and apatite as accessory phases in felsic liquids causing the depletion of HREE. Fractionation among the HREEs is weak $(Gd/Lu)_{CN}$: 0.31 to 1.66. Positive Eu anomaly is related to Eu/Eu* ratio ($Eu/Eu^* = (Eu)_{CN}/[(Sm)_{CN} \times (Gd)_{CN}]^{1/2}$; McLennan, 1989): 0.49–4.86 and plagioclase fractionation. The possible tectonic environment that prevailed at the time of the evolution of the granitic rocks of Alirajpur were volcanic arc + syn-collisional and post-orogenic (POG) settings (Fig. 10). These granitic rocks were most likely derived from mafic to tonalitic sources through continental arc magmatism in post-continental collision tectonic settings.

DISCUSSION

Low REE Granitic Basement with Lower Crust Signature

The use of REE in studying granites is more challenging compared to mafic igneous rocks as they occur in the accessory minerals in felsic rocks and their abundances are influenced by the complicated physical and chemical factors that define accessory mineral assemblages (Guo et al., 2005). However, as previously stated, the REEs are useful in differentiating between highly fractionated I- and S-type granites (Figs. 11a–11d). They may also be able to distinguish between I-type granites produced at various temperatures (Chappell et al., 1998). The rare earth pattern in Alirajpur granites exhibits low REEs with Eu positive anomaly which is a characteristic lower crust signature (Fig. 8a). This typically occurs due to accumulation of igneous plagioclase during fractionation of a magma in the lower crust (Rudnick, 1992). This pattern also resembles the Dharwar granites and the granitic basement reported from Dharwar sequences (Moyen et al., 2001; Jayananda et al., 2008, 2018). It has been noticed worldwide that the emplacement of younger granites has significant REE contents as compared to the older granites (Rino et al., 2008; Hu et al., 2020). However, from petrographic and SEM studies it is observed that there is the presence of Zircon, Monazite and Xenotime which are potential hosts for REEs but

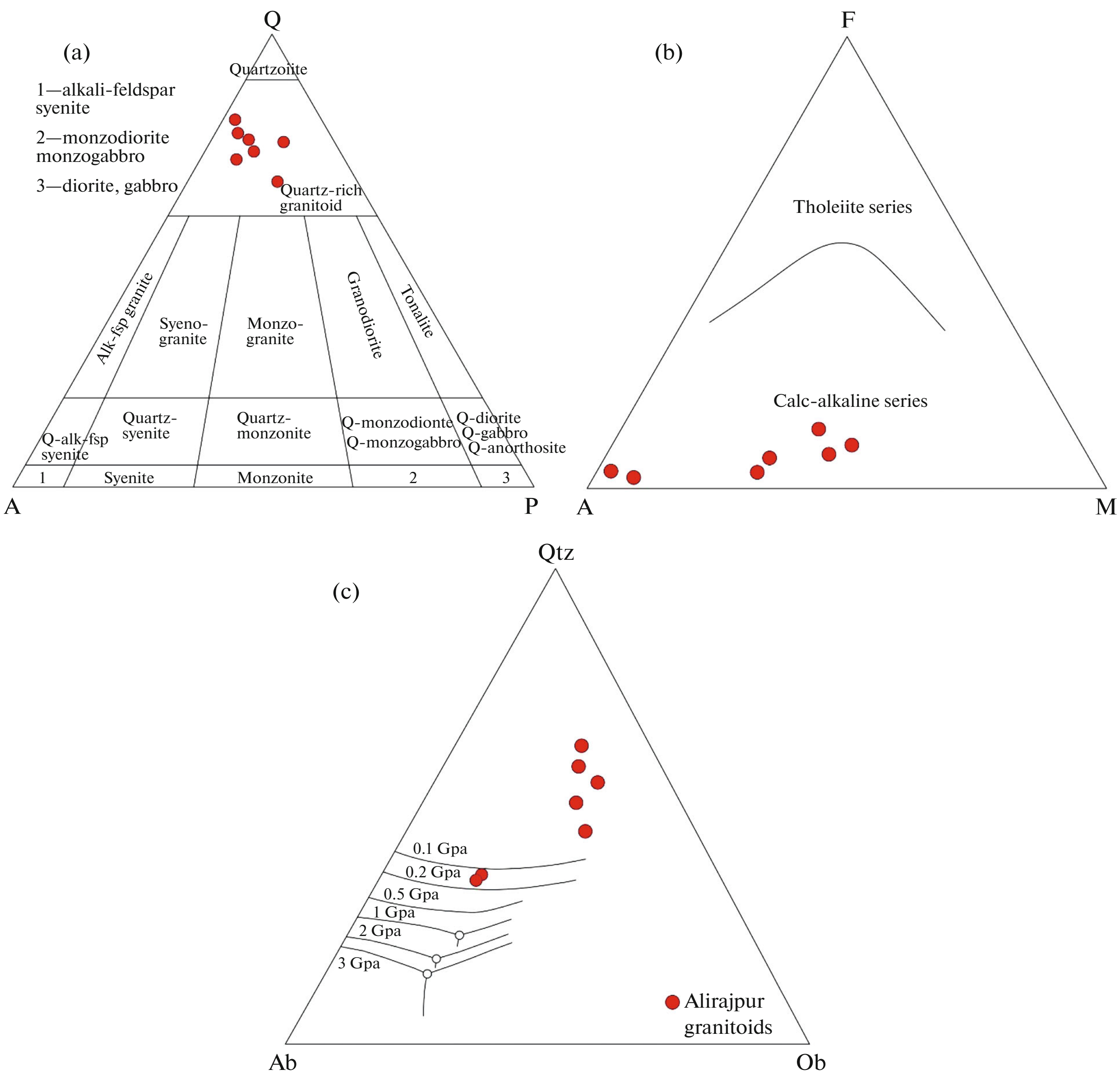

Fig. 6. (a) QAPF (Silica Oversaturated) classification for Alirajpur granitoids (b) AFM diagram (Irvine and Baragar, 1971) and (c) Q–Ab–Or for depiction of depth for Alirajpur granitoids(most samples falls within <0.1 Gpa) (Wyllie, 1983).

it is not reflected in the whole rock chemistry since the dominant phase in the granites is morphed by quartz and feldspar which are low REE hosts. These granites display no evidence of hydrothermal alteration that could have influenced the REE pattern.

Koyna Basement Rocks and a Strong Geochemical Affinity with the Alirajpur Granitoids

The data from scientific drilling down to 3 km depth provide fresh perspectives into the petrographic and geochemical details of a deep section of the crystalline basement underlying the Deccan Traps in western India's Koyna region (Shukla et al., 2022). The Koyna basement granitoids' whole rock geochemical analyses reveal a wide range of whole-rock chemistry. Based on preliminary composition and age studies, basement granitoids are possibly an extension of the Dharwar Craton's peninsular gneiss. The geochemistry of Alirajpur granitoids shows a strong correlation with Koyna which has a close association with Dharwar. Further, the presence of Dharwar rocks as a basement in the Chhota-Udaipur has been reported by Gwalani et al. (1993) and points towards a possibility of the Alirajpur granitoids rocks belonging to the Dharwar system. However, extensive work done by Banerjee et al. (2022a, b) gives a 934 ± 7 Ma and 1610 ± 9 Ma of monazite and zircon ages respectively

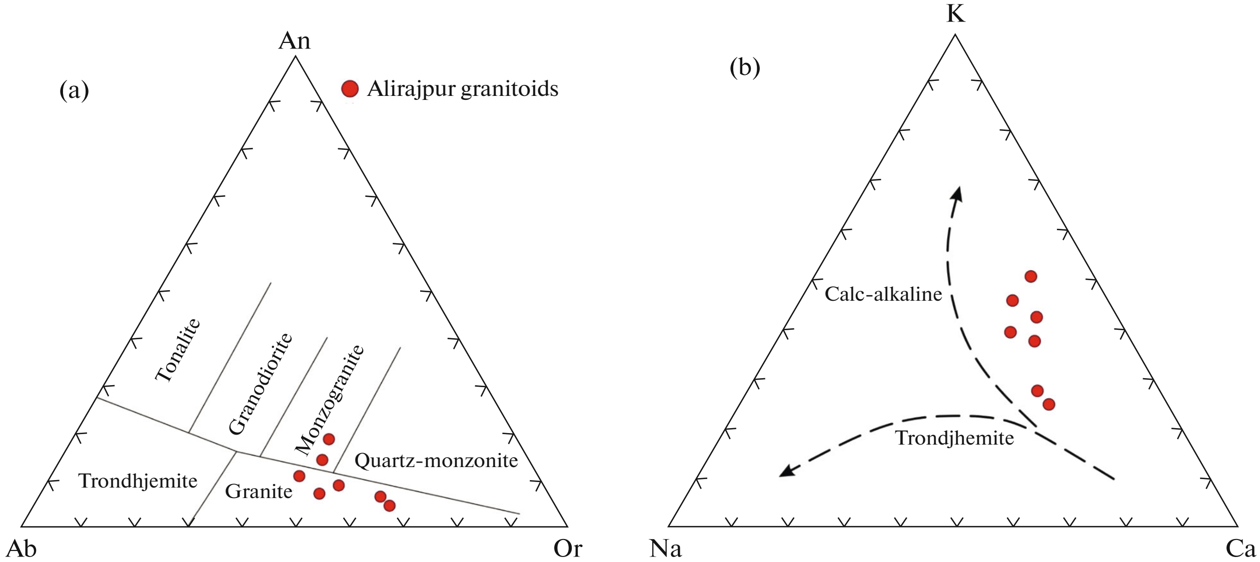

Fig. 7. (a) Ab–An–Or ternary diagram after Barker (1976); (b) K–Na–Ca plot (trends from Baraker and Arth, 1976).

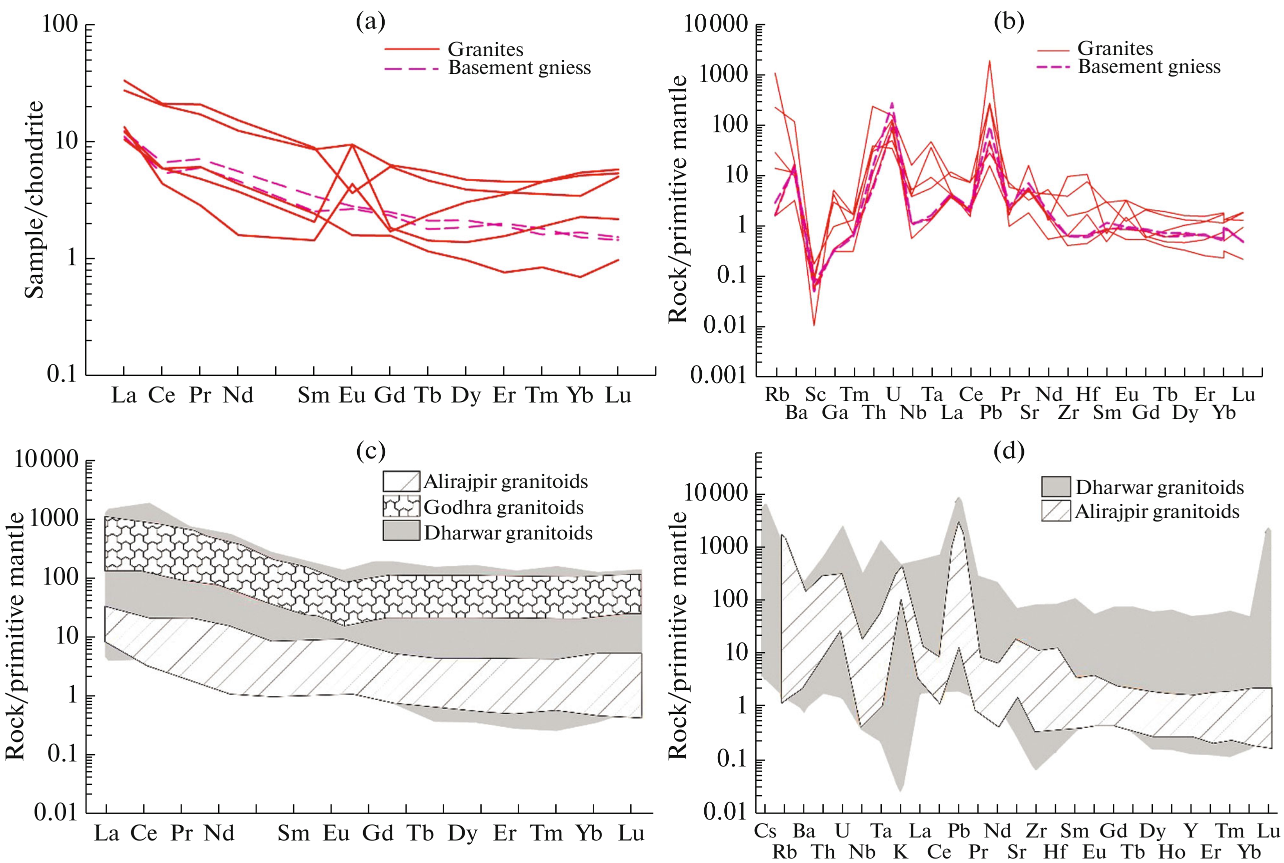

Fig. 8. Chondrite normalized REE and Primitive mantle of granites of Alirajpur (a, b). The dataset is also compared to Dharwars granitoids and GC-sector granitoids (Banerjee et al., 2022a) (normalizing values after Sun and McDonough, 1989; McDonough and Sun, 1995).

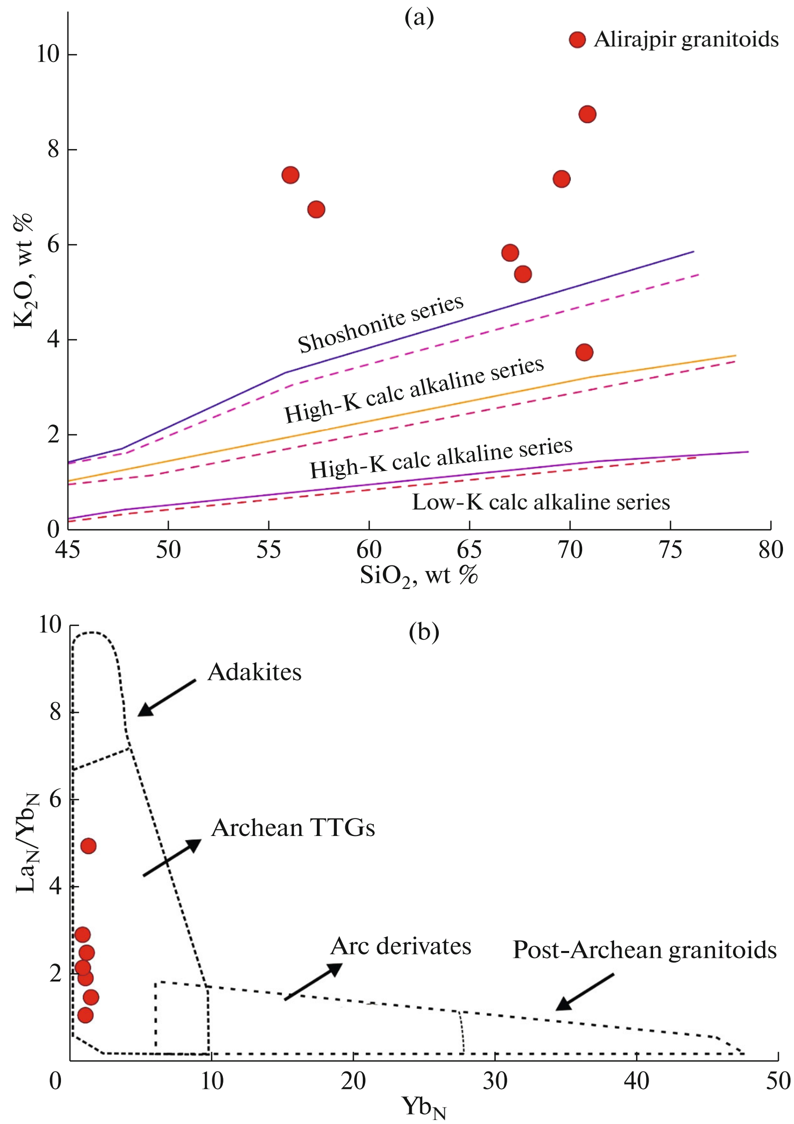

Fig. 9. (a) SiO_2 and K_2O correlation diagram (Peccerillo and Taylor, 1976). (b) Characterization diagram for the Archean rock suites.

with a strong correlation with the Godhra granites of the Lunawada group. Geochronology of the Alirajpur granites can shed further light on its genetic association with Koyna and Dharwar, as opposed to the Godhra granites.

Comparison of Alirajpur Granitoids with Dharwar Granitic Rock Suites

In order to better understand the geochemical affinity of Alirajpur with the Dharwar granitic suites few discrimination diagrams proved helpful to understand the trends and mineral fractionations (Fig. 12). A comprehensive geochemical evaluation was made among the Dharwar granitic gneiss, Closepet granite and Alirajpur granitoids to understand the variation among the rock suites which are separated over 500 km apart. It is noted that Alirajpur granitoids follow the I-type trends in accordance with the Dharwar suites of rocks (Figs. 12a, 12b). The mobile elements like P and Rb proves to be a good indicator element to study such trends since these elements are sensitive to secondary processes and are key elements to discriminate between I and S type granites (Chappell and White, 1992). Further, the trends defined in Sr versus Ba and Sr versus Rb/Ba plots (Figs. 12c, 12d) suggest that K-feldspar and plagioclase were being removed in sequence from the melt leading to enrichment of feldspars in the Alirajpur granitoids.

However, the geochronological studies of Alirajpur granitoid is still pending but from previous studies (Banerjee et al., 2022a) the authors report series of geochronological ages for the rock suites from adjacent area around Alirajpur. The upper intercept of

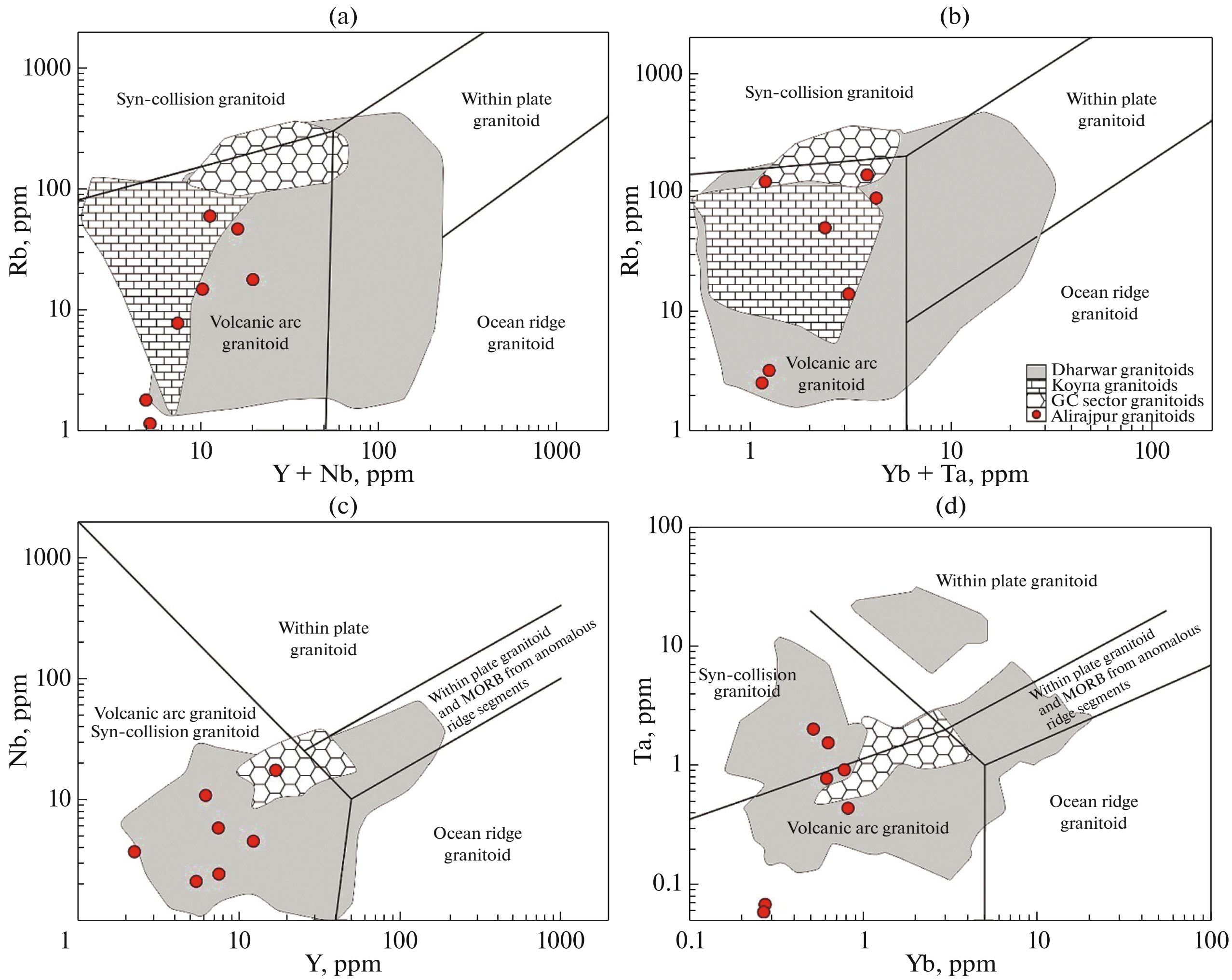

Fig. 10. Discrimination diagram for granitoid characterization where all Alirajpur granitoids fall into Volcanic Arc granitoids.

Table 3. The geological formations from the Archean to Neoproterozoic formation of the Indian subcontinent

Geological Formations	Events (Time)	References
Peninsular Gneissic Complex (PGC)	3000–3400 Ma	Pichamuthu (1976); Rao et al. (1991a, b); Naha et al. (1993)
Dharwar Supergroup	2500–2700 Ma	Patra et al. (2020); Jayananda et al. (2000, 2006, 2013)
Aravalli Supergroup	2500–3300 Ma	Gopalan et al. (1990); Roy and Kröner (1996); Wiedenbeck and Goswami (1994); Wiedenbeck et al. (1996); Roy et al. (2001)
Godhra	965 ± 40 Ma (Whole Rock Sr) and 921–1657 Ma (U-Pb Zircon)	Gopalan et al. (1979) and Banerjee et al. (2022a)
Koyna	2710 ± 63 Ma and 2700 ± 49 Ma (U-Pb Zircon)	Bhaskar Rao et al. (2017), Shukla et al. (2022)
Alirajpur	*Geochemical signatures corroborate PGC and Dharwar rocks*	*This Study*

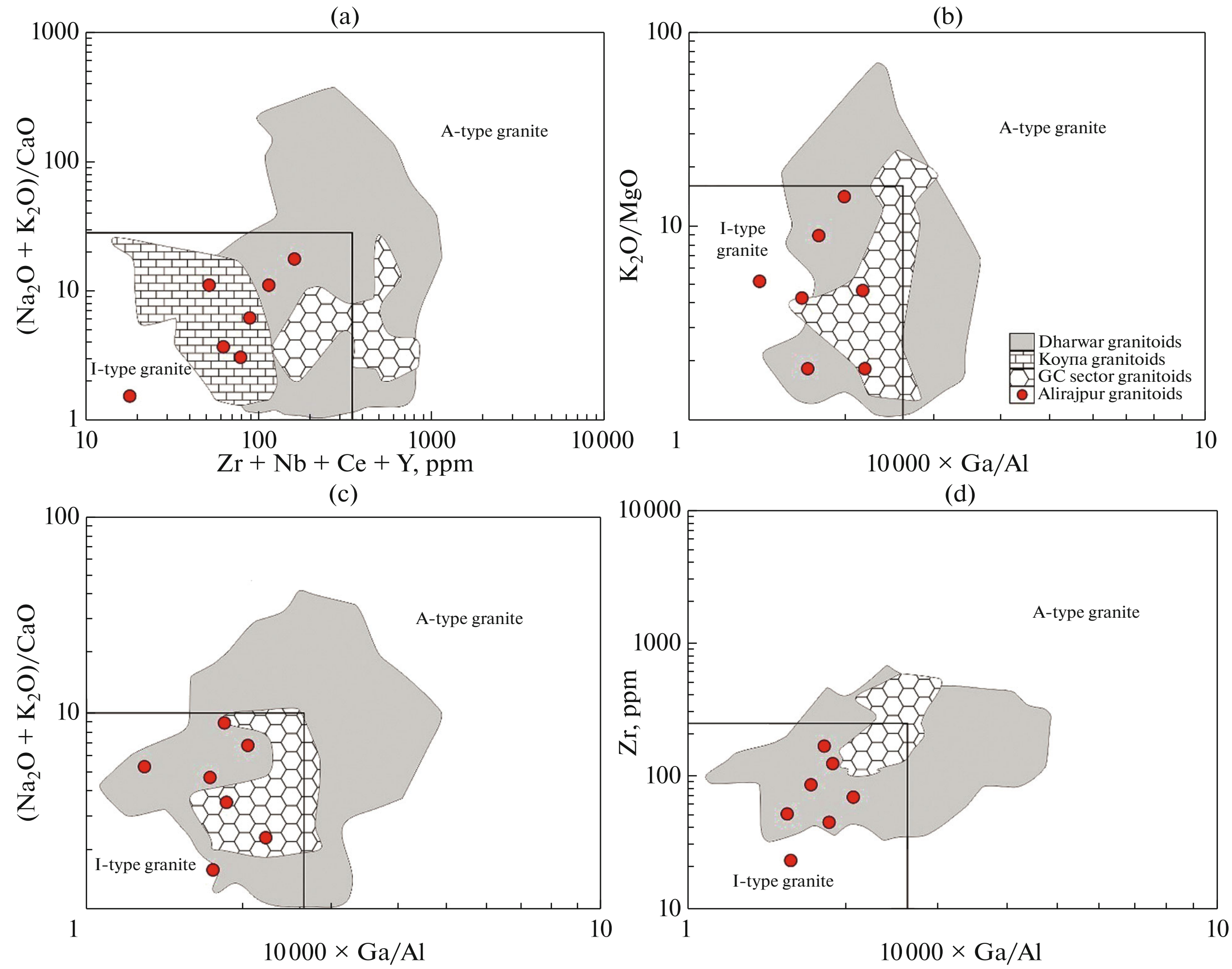

Fig. 11. Granitic classification diagram showing Alirajpur granitoid is exclusively I-type.

U-Pb dating for quartzo-feldspathic gneiss is reported to be 2485 ± 15 Ma whereas, for coarse grained granites it was found to be 2544 ± 82 Ma. As far as Koyna basement rocks are concerned, these rocks yield consistent U–Pb ages of 2710 ± 63 and 2700 ± 49 Ma (Bhaskar Rao et al., 2017) equivalent to the Kushtagi granitoids that occurs in the central part of the Neoarchean eastern Dharwar Craton (Mohan et al., 2013). The age bracket reported for the peninsular gneisses from various exposures of the Dharwar supergroup ranges from 2500 to 3400 Ma (Taylor et al., 1984; Pichamuthu and Srinivasan, 1984; Rao et al., 1991a, b). While comparing the upper intercepts of the quartzo-feldspathic gneiss and coarse-grained granites (Banerjee et al., 2022a) it comes under the close age ranges of the lower intercepts of the Neoarchean peninsular gniesses from Dharwar supergroup. In congruence to such close age brackets, we presume that the age of the Alirajpur granitoids may fall within the same age suites. A geological correlation has been made with all the Precambrian formations of the Indian subcontinent and its comparison with Alirajpur granitoids to bring forth a greater understanding of the geochemical similarities (Table 3, Fig. 13).

In summary, this study attempts to compare the rock suites from Neoarchean Era and bring out inferences regarding the geochemical fit between these rock types. Since, the Alirajpur granitoid share a close geochemical affinity with the Dharwar granitic suites, in this regard we assume a possibility of close genetic relationship of Alirajpur granitoids with the Koyna basement rocks which is reported to be the continuation of the Peninsular gneissic complex (Shukla et al., 2022). In this regard, such geochemical fit of the Alirajpur granitoids with the Koyna basement rocks and the Dharwar granitic suites with dissimilar REE pattern with Godhra granites (Figs. 11c, 11d) can be protracted with the similar age brackets as that of Peninsular gneissic complex of the Dharwar supergroup.

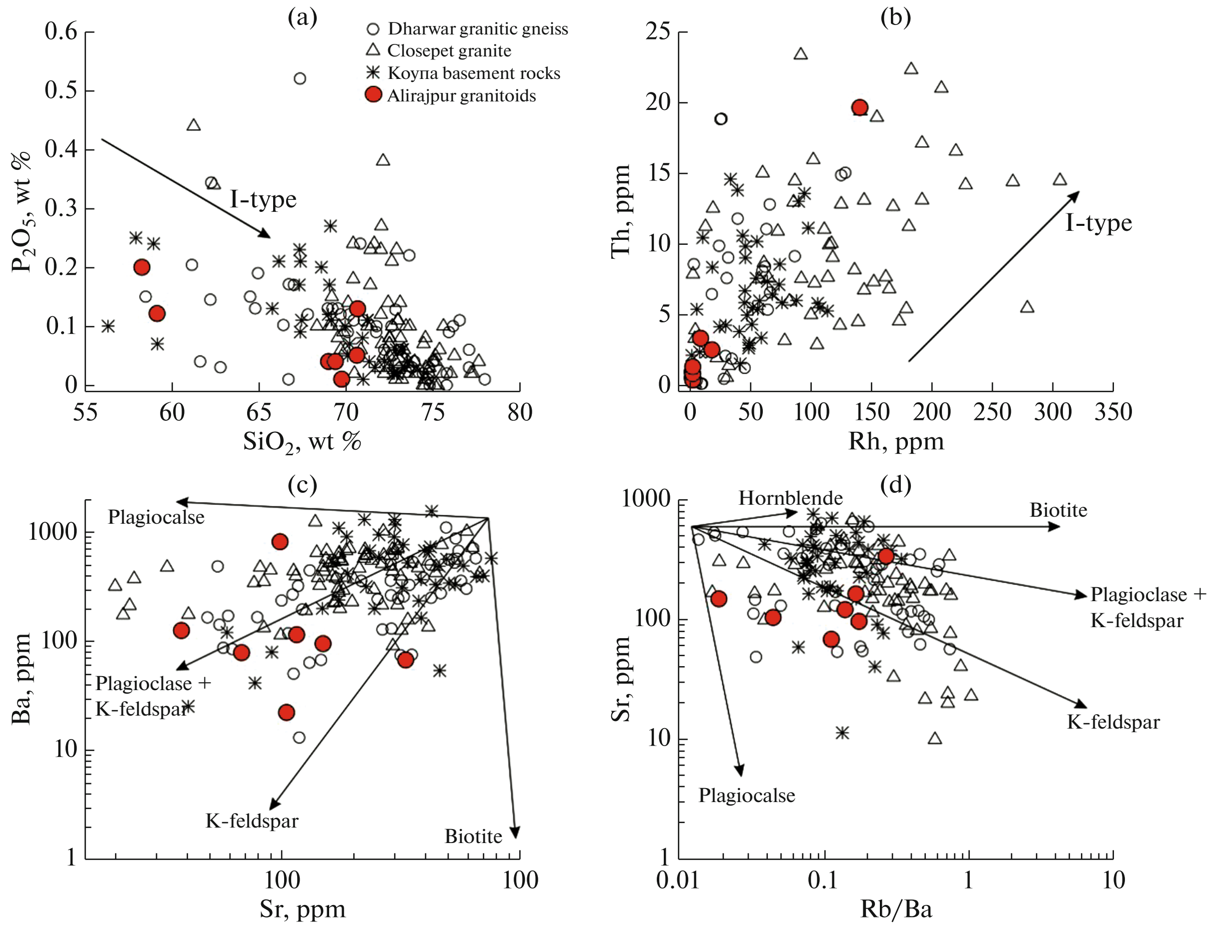

Fig. 12. Geochemical affinity of Alirajpur granitoids with Dharwar granitic suites: (a) SiO_2 vs. P_2O_5 (wt %) showing I-type trend. (b) Rb (ppm) vs. Th (ppm) showing positive correlation indicating I-type trend from all rock types. Binary relation between Ba vs Sr (c) and Sr vs. Rb/Ba (d) showing that fractional crystallization of K-feldspar and plagioclase played a significant role during the formation of the Alirajpur granitoids. The arrow mark indicates the Rayleigh fractionation vectors. The dataset for Dharwar is compiled from DIGIS Team, 2024, "GEOROC Compilation: Rock Types," https://doi.org/10.25625/2JETOA, Goettingen Research Online/Data, V1; Lehnert et al. (2000).

Present Status and Perspective of Alirajpur Granitoids

The Alirajpur granitoids in this study comprise of shallow carapace granitoids and the basement granitoids which have a very clear demarcation when observed in the field. The age constraints as manifested by Banerjee et al. (2022a) gives a demonstration of early Neoproterozoic orogenic welding where the authors have clearly mentioned the Late Neoarchean granitoids are unlikely to represent the basement for the younger Late Paleoproterozoic gneisses because the Neoarchean granitoids would be unable to escape the ubiquitous 1.65–1.60 Ga metamorphism-anatexis at T ≥ 750°C (Banerjee et al., 2022b). Given the wide range of ages of the granitoids, the term "Godhra granite" was coined by Gopalan et al. (1979) and subsequently used by later workers for the sector's felsic intrusives (Shivkumar et al., 1993; Srimal and Das, 1998; Goyal et al., 2001). However, this study has made a detail comparison of the Alirajpur granites with the Koyna basement granitoids and Dharwar granitoids and show the genetic similarity of these two groups. This raises the question of the extension of the Dharwar Group further the north beyond the Central India Suture Zone (CITZ). The Chhota Udaipur alkaline complex which is stationed adjacent to the Godhra-Chhota Udaipur sector have reported the presence of Precambrian gneiss and schists as the basement (Gwalani et al., 1993). In this regard, the notion of the presence of older granitoids as the basement cannot be ruled out. A strong correlation in this study brings a necessity to constrain the age of Alirajpur granitoids to make it allocate the exact age suite.

CONCLUSIONS

The geological and geochemical characterization of Alirajpur basement granitic rocks was carried out in this study. Field and petrographic observations reveal a close relation with the basement rocks of Koyna.

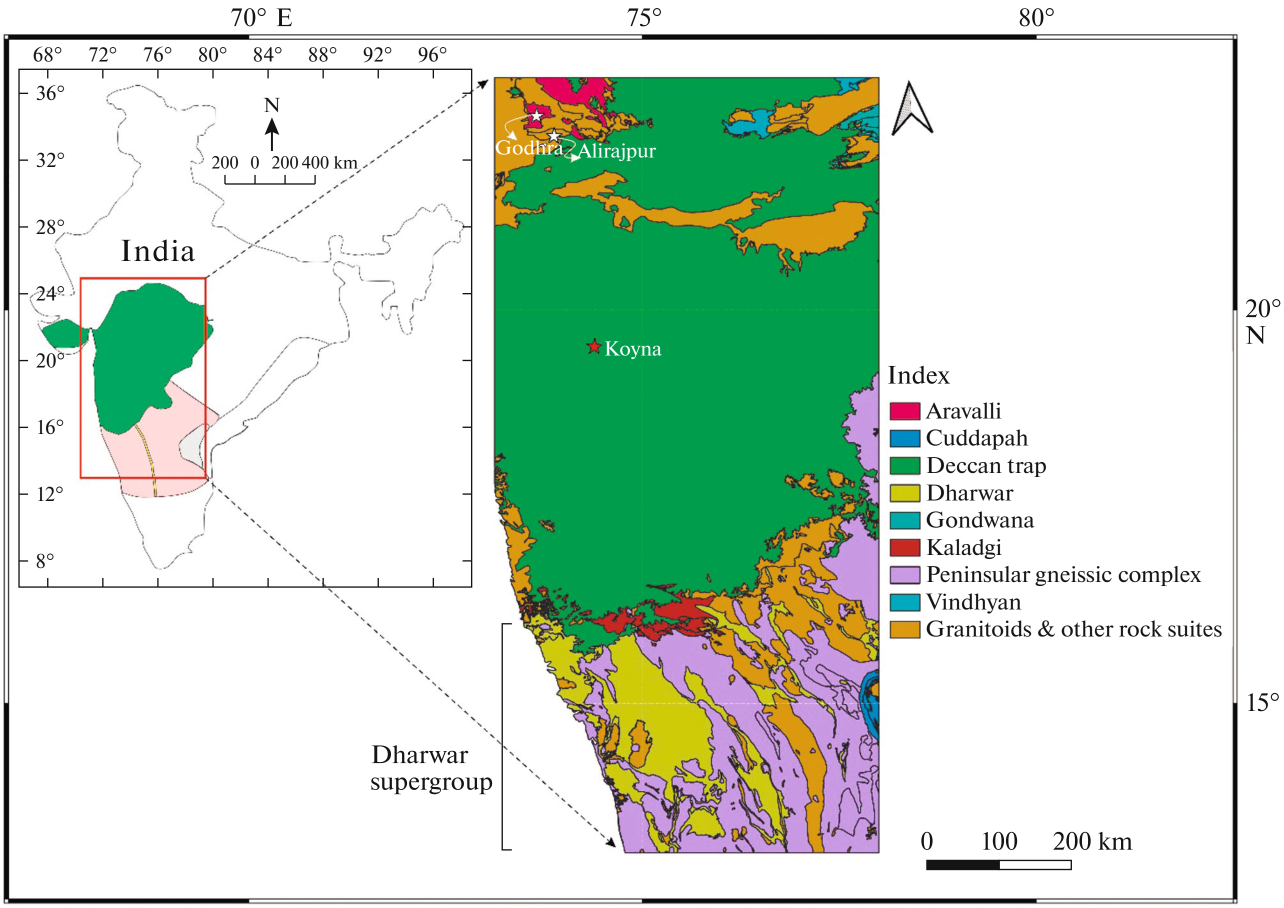

Fig. 13. The aerial rock distribution from Alirajpur region. The figure demonstrates the location of Alirajpur, Godhra, Koyna and Dharwar along with Peninsular gneissic complex from central to southern region of Indian subcontinent. *Source: Geological Survey of India, 2024. Bhukosh. Geological Survey of India. https://bhukosh.gsi.gov.in/Bhukosh/Public (accessed April 20, 2024).*

These granitoids are composed primarily of feldspar, quartz, biotite, and minor plagioclase which are medium to coarse-grained holocrystalline and hypidiomorphic. As an accessory constituent, opaque minerals (magnetite and ilmenite), zircon, apatite, and xenotime grains are present. Geochemical studies of granitic rocks show that the sub-alkaline granitic magma evolved progressively during its extrusion from calc-alkaline parentage. These granitic rocks have magnesian to ferroan, calcic to calc-alkalic, and metaaluminous to peraluminous parentage. The trace and REEs concentration show that the magmatic differentiation process was active during the evolution of these rocks. HREE depletion versus LREEs indicates incorporation in fractionating accessory phases such as zircon, apatite, and xenotime. Overall, the petrology, mineralogy, and geochemistry of the Alirajpur granitoids' granites are comparable to I-type granites, which exhibit characteristics of typical volcanic arc granites related to the active continental margin. The close geochemical proximity with the Koyna granitic basement indicates correlation of these rocks with the Dharwar granitoids which raises the question of the extent of Dharwar suites of rocks below the Deccan in the northern part of the subcontinent. In this regard, geochronological studies are necessary to understand the genesis of these rocks with proper correlation to other granitic rocks of the subcontinent.

SUPPLEMENTARY INFORMATION

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AUTHOR CONTRIBUTION

Sunit Mohanty: Conceptualization (Lead), Methodology (Supporting), Writing—Original Draft (Lead)

Vishal Nareda: Methodology (Supporting), Writing—Original Draft (Supporting)

Arundhuti Ghatak: Writing—Review and Editing (Lead), Validation (Lead), Investigation (Lead), Funding acquisition (Lead), Project administration (Lead).

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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