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9. Attributes and Significance of the A-Type Malani Magmatism, Northwestern Peninsular India

Naresh Kochhar

Department of Geology, Panjab University
Chandigarh, 160014, India

Abstract

The Malani Igneous Suite in northwestern peninsular India represents the third largest felsic magmatism in the world. The Malani magmatism has typical A-type geochemical characteristics. The granites and the co-magmatic acid volcanics are low in CaO, MgO, Sc, Cr, Co, Ni, Ba, Sr and Eu abundances, and high in silica, total alkalis, Fe/Mg, Zr, Hf, Nb, Ta, REEs (except Eu), and Ga/Al. The high heat producing Malani magmatism is characterized by subvolcanic setting and volcano-plutonic ring structures, and is indicative of extensional tectonic environment in the Trans-Aravalli block of the Indian shield.

The Malani granites in the southwest (Siwana and Jalor) are characterized by low whole rock $\delta^{18}O$ values (-10 to +1.8 ‰) whereas the Tusham and Jhunjhunu granites in the northeast are characterized by higher whole rock $\delta^{18}O$ values (5.9 to 8.9 ‰). The significance of low oxygen isotope values is discussed in the light of synplutonic, rift-related hydrothermal system.

Combined Sr, Pb and Nd isotope data indicate that the emplacement of Malani granites and the acid volcanics was coeval at 732 Ma. This time period marks a major Pan-African event of widespread intraplate, anorogenic magmatism represented by alkali granites and coeval rhyolites of central Iran, Nubian-Arabian shield, Somalia, Seychelles and the Trans-Aravalli block of the Indian shield. All these microcontinents constitute a Neoproterozoic supercontinent – the Malani supercontinent.

Keywords: A-type magmatism, Rajasthan, Mantle plume, Ring structure, Isotopic data, Supercontinent.

Introduction

The Trans-Aravalli block (TAB) is unique in the geological evolution of the Indian shield as it is characterized by a major period of anorogenic (A-type), 'Within Plate' magmatism represented by the Malani Igneous Suite (MIS) of rocks. This Neoproterozoic (732 Ma) suite, covering 55,000 sq. km and comprising peralkaline (Siwana), meta-aluminous to mildly peralkaline (Jalor) and peraluminous (Tusham and Jhunjhunu) granites with cogenetic carapace of acid volcanics (welded tuff, rhyolite, trachyte, explosion breccia and perlite), displays distinctive ring structures and radial dykes. The suite is bimodal in nature with minor amounts of basalt, gabbro, and dolerite dykes. The Siwana ring structure (30 km in E-W and 25 km in N-S directions) is the most spectacular feature of the Thar desert. Representatives of the MIS also occur in the Kirana Hills, Pakistan (Fig. 1). The Malani magmatism is controlled by NE—SW trending lineaments (zones of extension and high heat flow) of fundamental nature and owes its origin to hot-spot (mantle?) magmatism and related tectonics (Kochhar, 1973, 1983, 1984, 1989a, 1999a; Pareek, 1981; Basu, 1982; Bhushan, 1991; Bhushan and Chittora, 1999).

The present contribution describes the field relationships of all the four major complexes of MIS. The geochemical characterization of granites and comagmatic acid volcanics and their petrogenesis is presented. Based on Sr, Pb and Nd isotopic data, oxygen isotope and paleomagnetic studies, crustal evolution of the Trans-Aravalli block and the assembly of a late Proterozoic supercontinent—the Malani supercontinent is also discussed.

Regional Geology and Tectonic Framework

To give an idea of the geological position of the MIS rocks, the Precambrian sequence of northwestern peninsular India is presented in Table 1. The lower boundary of the Malani rocks is exposed near Miniari, Pali district, Rajasthan,

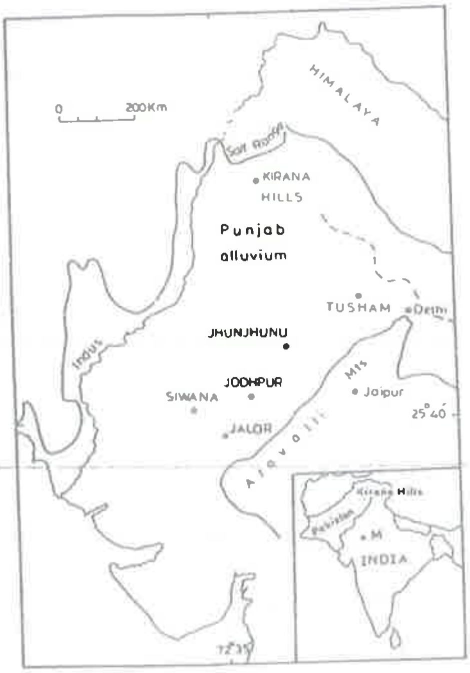

Fig. 1 Location map showing the occurrence of Malani rocks.

Table 1 Precambrian sequence in northwestern peninsular India

Jodhpur sandstone (Sonia sandstone)		Vindhyan Supergroup (1400–500 Ma)
Malani igneous suite	Siwana Jalor, Tusham, Jhunjhunu (India)	732 Ma
	Kirana Hills (Pakistan)	870 Ma?
Erinpura Granite		850 Ma
Mafic and ultramafic intrusions in the Delhi fold belt.		
Champaner group		
Sirohi Group (?)		
Delhi Supergroup		1650 Ma
— — — — — — — — — — Unconformity — — — — — — — — — —		
Aravalli Supergroup		
— — — — — — — — — — Unconformity — — — — — — — — — —		
Mewar gneiss, Pre-Aravalli granite, gneiss, amphibolite, metasediments, granitic rocks		2500–3000 Ma

N.B. Stratigraphy after Roy, 1988; Radiometric ages after Crawford, 1970, Crawford and Compston, 1970, Davis and Crawford, 1971, Gopalan and Choudhary, 1984, Kochhar et al., 1985, Dhar et al., 1986.

where the Malani volcanics are underlain by the slates of Aravalli Supergroup, and in the Tusham area, Bhiwani district, Haryana, where the Malani volcanics are underlain by the Delhi quartzites. The upper boundary is observed at Radar hill, near Jodhpur Fort, where the Malani rhyolites are overlain by Jodhpur sandstone of Vindhyan age.

The Malani acid volcanics and the contemporaneous granites are much younger than the Aravalli-Delhi geosynclinal deposits with which they are associated at places. The time gap between the Delhi orogeny and the emplacement of the MIS is 700 Ma (Table1), which is much more than the average span of an orogeny (Condie, 1976). No direct relationship of the MIS with the Aravalli-Delhi orogenic cycles are observed in the field. The MIS is thus non-orogenic.

The Siwana ring structure, a spectacular feature, is visible on Landsat imagery (Fig.2) because of its size and absence of soil cover. It is a continuous ring of 30 km from west to east and 25 km from north to south. The continuous exposure of granite on the southern periphery of the ring indicates an apparent thickness of about 8 km from the outer to inner contact of the rhyolite. The northern periphery is essentially composed of acid volcanics. The Tusham area is also characterized by volcano-plutonic ring structures and radial dykes have been mapped in the Jhunjhunu complex. The volcano-plutonic ring structures, radial dykes and the Mandli volcanic cone (near Jodhpur) are all indicative of tensional tectonic environment.

Geophysical Features

Gravity, Magnetic, Radiometric and Heat flow data

The exposed suite of Malani granites and rhyolites in Rajasthan lie within the regional gravity high, but is within the zone of relatively low gravity field. The Siwana and Jalor granites are not characterized by prominent lows. A considerable part of gravity highs is caused by uplift of dense lower crustal or upper mantle material (Krishna Brahamam, 1993). The Tusham area (Fig. 3) however lies on triple gravity junction and a considerable portion of gravity low is caused by arcuate granitic intrusions (240 km long and 6 km wide), thus confirming the ring structure in the area. Further the Aravalli strike turns northwest from Tusham (Krishna Brahmam and Kochhar, 1989). According to Mishra and Laxman (1997) there is a trifurcation of gravity trends from Tusham marked by the extension of Aravalli basement towards Himalayas in the form of Delhi-Hardwar ridge; Delhi-Moradabad ridge in the eastward direction and Delhi-Lahore ridge in the northwest direction.

An arcuate pattern of magnetic anomaly is observed in the western part of Tusham suggesting the presence of intrusive rocks of acid and basic nature. However, in the eastern part a low gradient anomaly is seen suggesting a number of parallel fracture zones. Thus gravity and magnetic survey confirm the presence of arcuate structure in the area. Radiometric survey also indicated the presence of acid intrusions in the Tusham area (Anand et al., 1996).

The Tusham area is also associated with a high heat flow of around 96 mWm^{-2}. This is the highest of all the heat flow values from the Meso- to Neoproterozoic terrains in India and more than double that of the nearby regions in Aravalli-Bundelkhand craton. The heat flow values obtained 100 km south of Tusham, in and around Khetri and Jhunjhunu is 74 mWm^{-2} with an average value of $60 mWm^{-2}$ for the Delhi mobile belt. It has been inferred that both the high crustal heat generation as evidenced by the presence of HHP granites and the upper mantle heat flow are responsible for the high surface heat flow observed around Tusham and Jhunjhunu (Sunder et al., 1990; Kochhar, 1996; Verma, 1994). The thickened basaltic crust as indicated by positive isostatic anomaly and the geoelectric model and induction pattern of Trans-Aravalli conductor and high heat flow are suggestive of transition type (oceanic to continental) crust beneath the Marwar terrain of the TAB (Arora, 1993).

Geologic Setting

Sketches of the geologic setting of Malani magmatism in the four major areas of its occurrence is given below in terms of the extrusive, intrusive and dyke phases as well as the host rocks.

Siwana area (district Barmer, Rajasthan)

Various lithological units exposed in the area include (Fig.4):

Extrusive phase: Basalt, trachyte, rhyolite and minor welded tuff.

Intrusive phase: Granites and gabbro with marginal facies variation.

Dyke phase: Trachyandesite, trachydacite, rhyolite and microgranite.

Country rocks: not exposed.

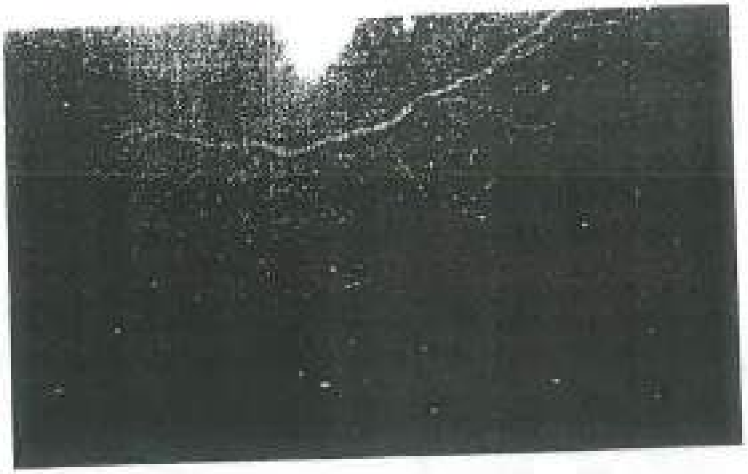

Fig. 2 Landsat imagery of Siwana ring structure.

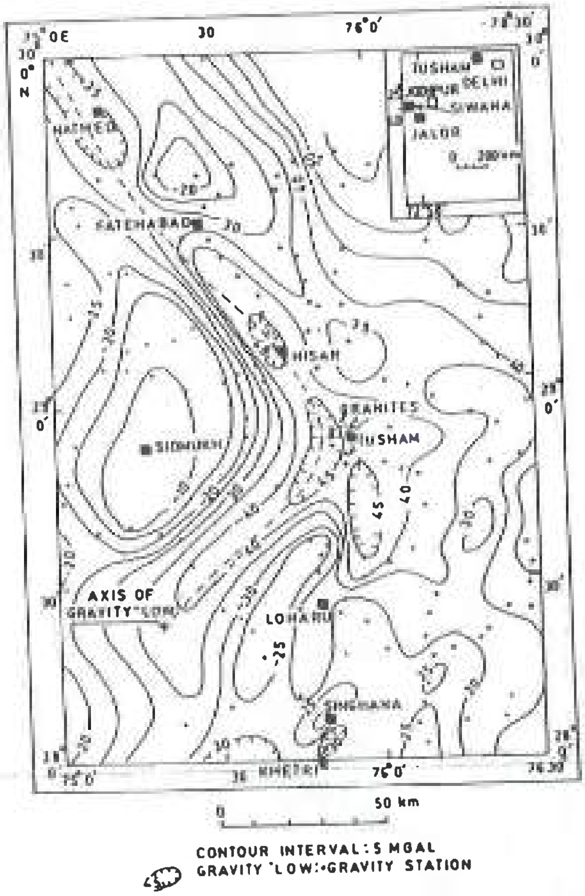

Fig. 3 Bouger gravity anomaly map of Tusham and surrounding areas , Haryana.

Jalor area (district Jalor, Rajasthan)
Various lithological units exposed in the Jalor area include (Fig.5):
Extrusive phase: Rhyolite, welded tuff. Arcuate rhyolite dyke.

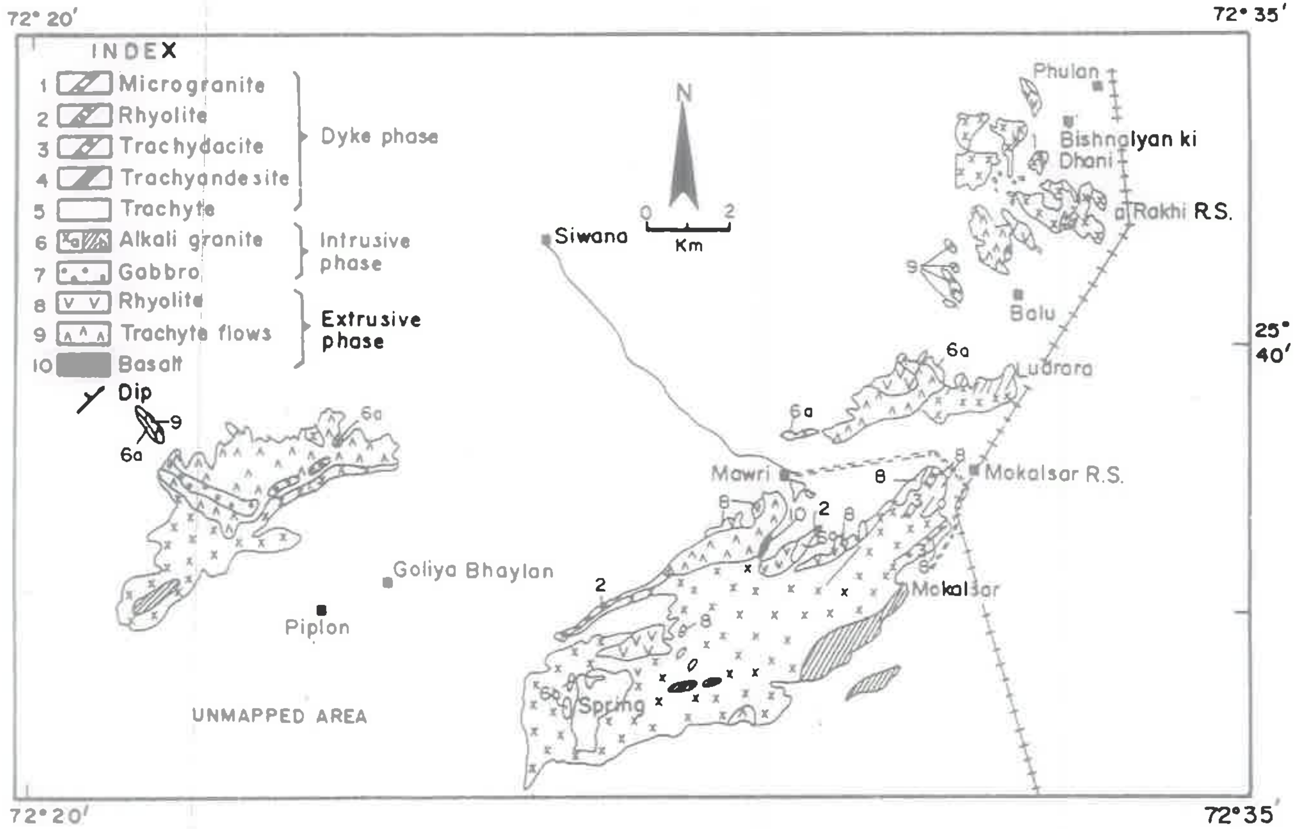

Fig. 4 Geological map of the eastern and southern flank of the Siwana ring structure.

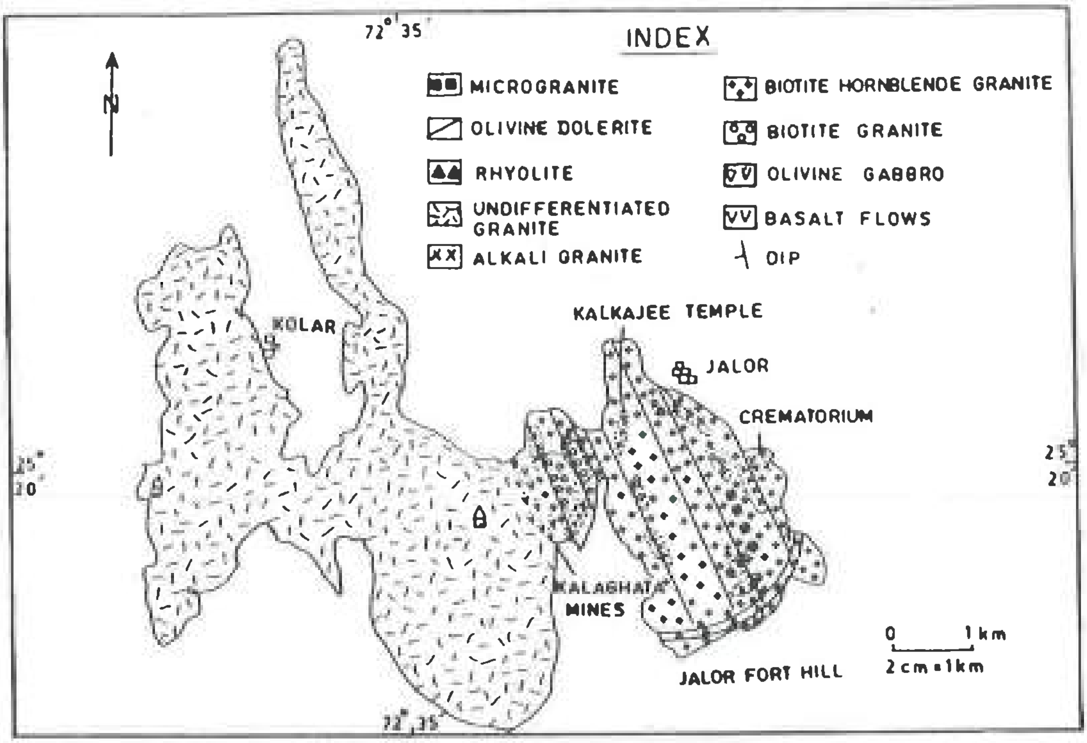

Fig. 5 Geological map of the Jalor ring structure.

Intrusive phase: Olivine gabbro, biotite hornblende granite, biotite granite and alkali granite.
Dyke phase: Rhyolite and olivine dolerite.
Country rocks: not exposed.

Jhunjhunu area (district Jhunjhunu, Rajasthan)
The lithological units exposed in the area (Fig.6) are:
Extrusive phase: Rhyolite/ welded tuff (radial dykes).
Intrusive phase: Granite/ granite porphyry.
Dyke phase: Rhyolite/felsite.
Country rocks: Delhi quartzites.

Tusham area (district Bhiwani, Haryana)
The disposition of the various lithological units encountered in this area is presented in Fig.7.
Extrusive phase: Felsite, welded tuff, explosion breccia.
Intrusive phase: Granite/granite porphyry.
Dyke phase: Ring dyke of quartz porphyry.
Country rocks: Delhi quartzite, quartz mica schist.

Geochemical and Mineralogical Characteristics

Malani granites

The granites of the MIS have the following characteristics typical of A-type granites (cf. Collins et al., 1982; Whalen et al., 1987; Eby, 1990):

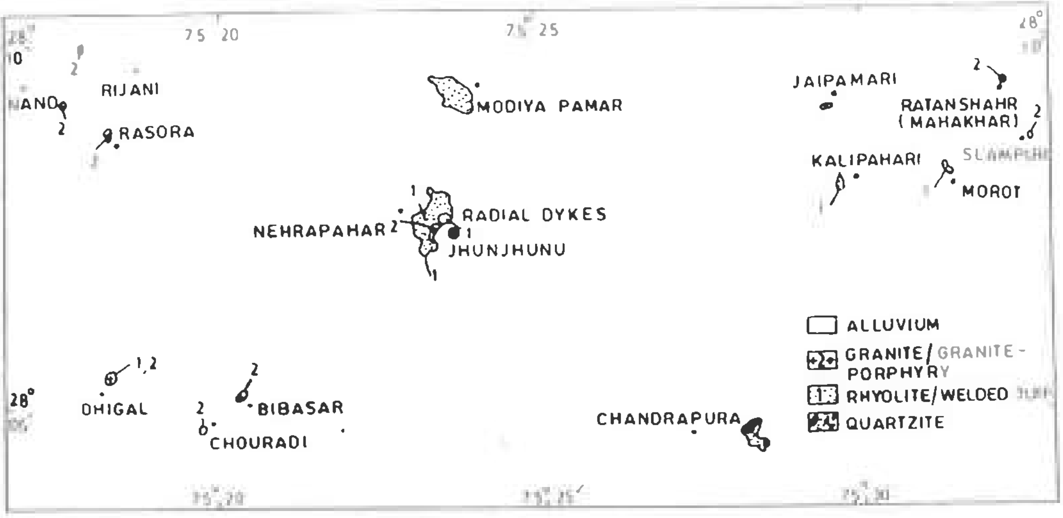

Fig. 6 Geological map of the Jhunjhunu igneous complex.

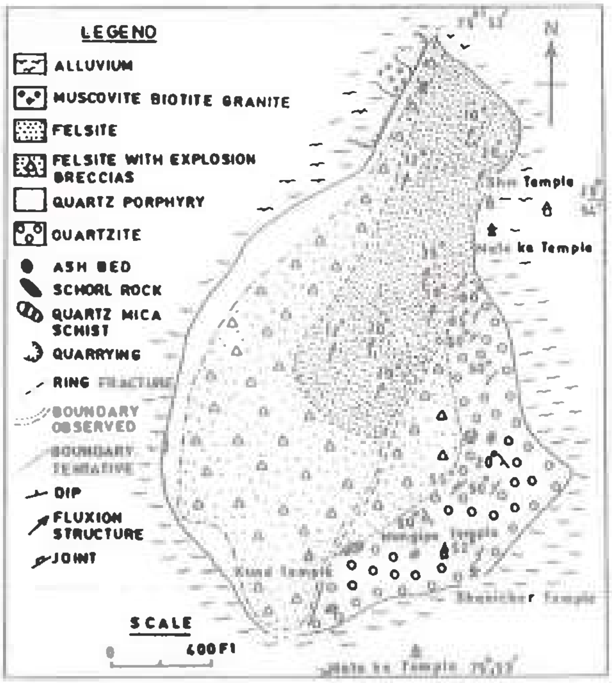

Fig. 7 Geological map of the Tusham ring complex.

1. The granites are high level, subvolcanic and intrude their own ejecta.
2. Volcano-plutonic ring structures and radial dykes characterize them. They occur in anorogenic setting, i.e., in 'Within-Plate' tectonic environment.

3. The Siwana and Jalor magmatism show bimodal suites of granites, trachyte, rhyolite and basalt (gabbro).
4. They are felsic, peralkaline (Siwana), meta-aluminous (Jalor) or peraluminous (Tusham and Jhunjhunu). The Malani granites plot in the alkali granite field of QAP diagram.
5. The Siwana granites are hypersolvus, whereas thee Tusham and Jhunjhunu granites are peraluminous. The Jalor granites are mainly subsolvus but have a hypersolvus component associated with them in space and time (Kochhar and Dhar, 1993).
6. These granites are low in CaO, MgO, high in silica, $Na_2O + K_2O$, Fe/Mg, Zr, Hf, Nb, Ta, high REE (except Eu) and low in Sc, Cr, Co, Ni, Ba, Sr and Eu abundances.

According to Whalen et al. (1987) high Ga/Al ratio is an effective discriminator of A-type granitoids and other granitoid types. Fig. 8 shows the Ga/Al vs Zr plot for the Malani granites. The Siwana, Jalor and Tusham granites form distinct clusters outside M-, I- and S-type granites. They fall in the A-type field. This diagram is best suited for alkaline granitic compositions. For discriminating highly fractionated I-type granites, Whalen et al. (1987) suggested a plot of Ga/Al vs Zr+Nb+Ce+Y. In this plot (Fig.9), the Jhunjhunu granites grade from highly fractionated I-type granites to A-type granites. Ga/Al ratio increases with the total abundance of Zr+Nb+Ce+Y suggesting that Ga behaves as incompatible element in A-type suite (Eby, 1990). Similar relationships can be seen in a plot of FeO_T/MgO vs Zr+Nb+Ce+Y (Fig.10). The FeO_T/MgO ratio is a measure of the degree of fractionation.

Mineral Chemistry

The Siwana granites have aegirine, riebeckite and arfvedsonite, in addition to alkali feldspar (perthite, orthoclase) and quartz. Apatite, sphene, hematite and

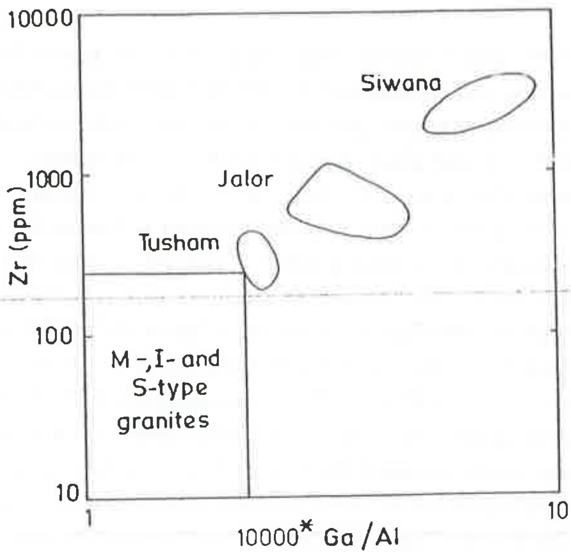

Fig. 8 Ga/Al vs Zr plot for Siwana, Jalor and Tusham granites.

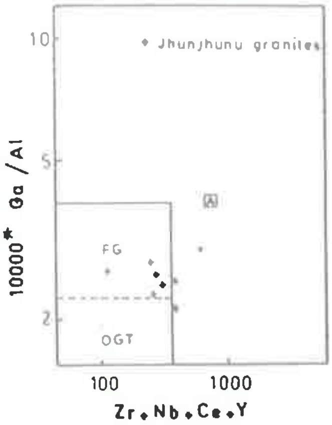

Fig. 9 **Ga/Al vs Zr+Nb+Ce+Y plot for Jhunjhunu granites. FG = Fractionated granite; OGT = unfractionated M-, S-, I-type granites.**

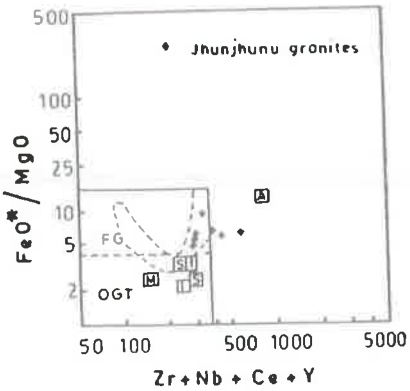

Fig. 10 Zr+Nb+Ce+Y vs FeO_T/MgO plot for Jhunjhunu granites. FG, OGT same as in Fig. 9.

zircon are accessory minerals. The Tusham, Jhunjhunu and the sub-solvus component of Jalor granite contain alkali feldspars (perthite, orthoclase), biotite and quartz as essential minerals; zircon sphene, apatite, fayalite occur as accessory minerals. The amphiboles in the Siwana alkali granites evolve from richterite to arfvedsonite (magmatic subsolidus trend), in trachyte from arfvedsonite to riebeckite (oxidizing), and in rhyolite from richterite through arfvedsonite to riebeckite (magmatic subsoliduous to oxidizing trend). The pyroxenes in the Siwana alkali granites evolve from hedenbergite to aegirine through aegirine augite, (acmite-hedenbergite trend), whereas in the felsic volcanic rocks they are represented by the aegirine (acmite trend). Arfvedsonite and aegirine also occurs as needles in gabbro (Baskar and Kochhar, 1995, Vallinayagam, 1997). The hypersolvus component of Jalor granites has ferro-hornblende and ferro-edenitic compositions of the amphiboles (Dhar and Kochhar, 1997). The Jalor ring complex forms a classical example of hypersolvus-subsolvus (volcanic-plutonic) association (Kochhar and Dhar, 1993; Garhia and Ravi, 1995).

Zircons

Trace element studies along with morphological observations indicate that the

Tusham zircons belong to hydrothermal and late magmatic type. The high content of UO_2 in the Tusham zircons is a reflection of high abundance of UO_2 in the host rocks. Jalor zircons are magmatic (elongation ratio = 2.5-3.0). The Siwana granites though high in Zr values have very poor zircon yield due to peralkalinity of Siwana magma (Kochhar et al., 1991).

Acid volcanics

The Acid volcanics of the MIS when plotted on H_2O-and-CO_2 free basis in SiO_2 vs Zr/TiO_2 plot (Winchester and Floyd, 1977) show that the Siwana volcanics are mainly rhyodacite and trachyte. Jalor acid volcanics fall mainly in the rhyolite and rhyodacite fields. The Tusham and Jhunjhunu acid volcanics are mainly rhyolite. Some of the Tusham samples plot in the comendite field (Fig.11).

The acid volcanics have similar major and trace elements including REEs, but the abundances of trace elements and REEs are less, as compared to the comagmatic granites. One notable feature of the acid volcanics is the depletion of Na_2O due to post emplacement hydrothermal alteration (Kochhar, 1977; Pareek, 1981; Gupta and Elsdon, 1994).

The Siwana rhyolite and trachyte consist of alkali feldspar (perthite), orthoclase, quartz, arfvedsonite, aegirine, riebeckite, along with haematite, sphene, zircon as accessory minerals. The groundmass consists of quartz, alkali feldspar and needles of arfvedsonite. The peraluminous varieties have the same mineralogy but lack in sodic pyroxene and alkali amphibole.

The Jalor rhyolites are essentially composed of alkali feldspar, quartz, hornblende; a few specks of biotite, zircon, fluorite, apatite and iron oxides occur as accessory minerals.

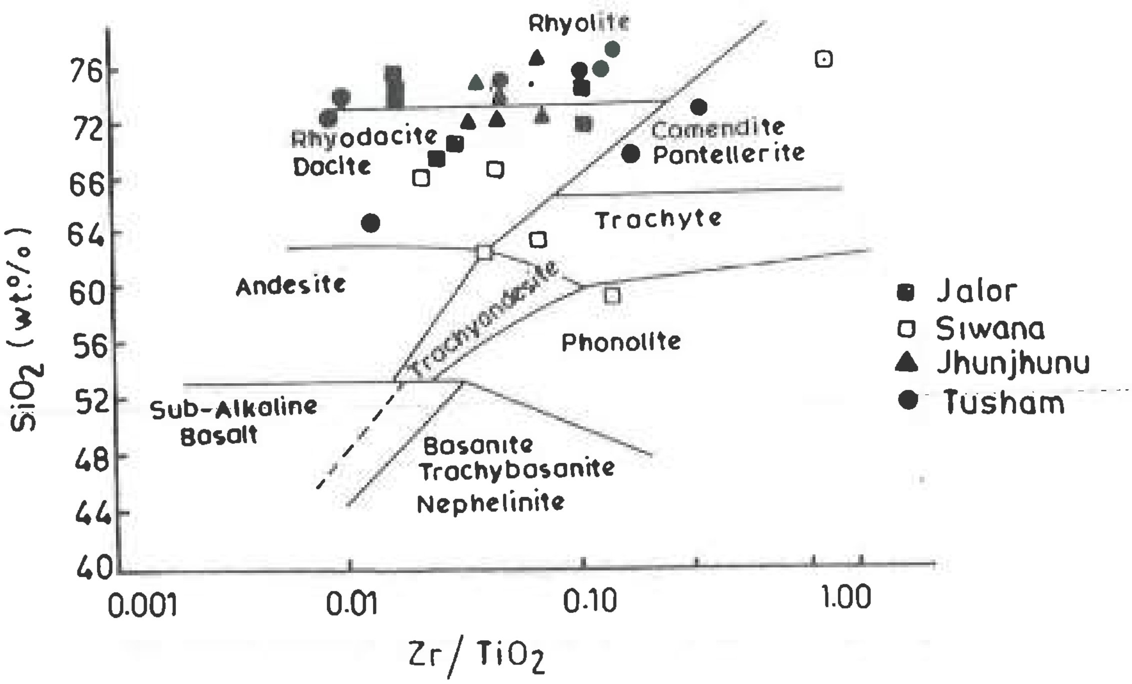

Fig. 11 SiO_2 vs Zr/TiO_2 plot for the Malani acid volcanics.

The Tusham and Jhunjhunu felsite, welded tuff and rhyolite consist mainly of quartz, potash feldspar, biotite, and chlorite. The accessory minerals are zircon, apatite, specularite, sphene and tourmaline.

Rare earth elements in the Malani granites

Siwana granite is characterized by high total REE content and relatively flat chondrite normalized pattern with little fractionation between LREE and HREE (La/Yb=2.3), with marked Eu anomaly (Eu/Eu* = 0.34)(Fig.12). They develop a relative enrichment in middle REE group (Sm, Gd and Dy) with corresponding Eu depletion characteristic REE pattern of peralkaline granites. The relative enrichment of MREE may be related to the precipitation of early formed perthitic feldspar and late crystallization of alkali amphiboles from low temperature liquid enriched in volatiles (Bowden and Whitley, 1974).

Tusham granites fall in a very restricted range of REE abundances and the LREE are enriched with respect to HREE (La/Yb = 17) and show moderate Eu anomaly (Fig.12), with Eu/Eu* = 0.44.

Jalor granites have the lowest REE abundances with La/Yb ratios of 5. The REE pattern of subsolvus granites (biotite granite) is quite different from that of hypersolvus (alkali) granite. The La/Yb ratios for subsolvus granites and hypersolvus granites are 1.52 to 2.55 and 2.61 to 4.27 respectively. Moderate LREE enrichment and a mild upward curvature of HREE portion of the chondrite-normalized plot can be seen in Fig.13. The hypersolvus granites show enrichment of LREE as compared to subsolvus granites (Fig.14). In the subsolvus granites,

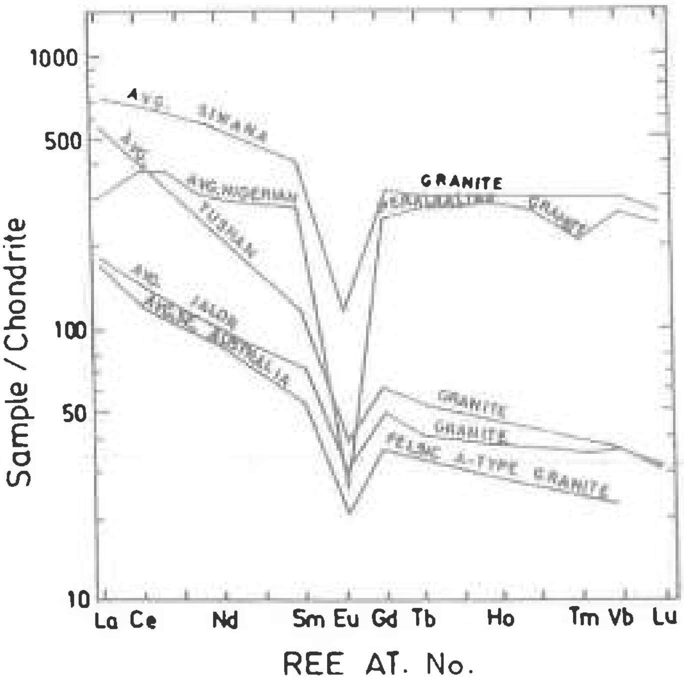

Fig. 12 **Chondrite normalized rare earth pattern of the Malani granites compared with the average felsic A- type granites from SE Australia and the Nigerian peralkaline granites.**

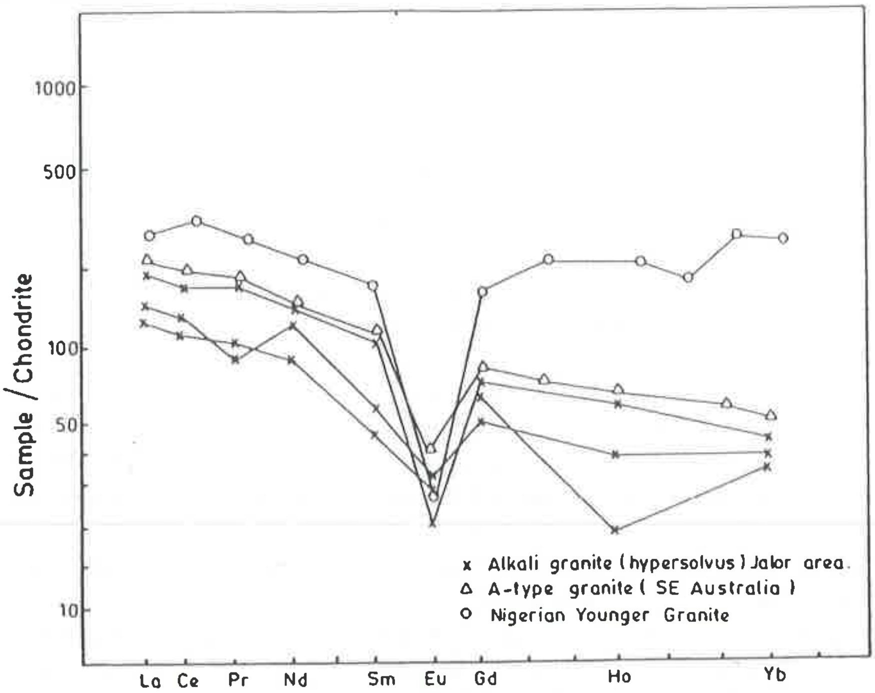

Fig. 13 **Chondrite-normalized REE plot for Jalor hypersolvus granites. The average A-type granite (SE Australia) and Nigerian younger granite are shown for reference; also in Fig. 14.**

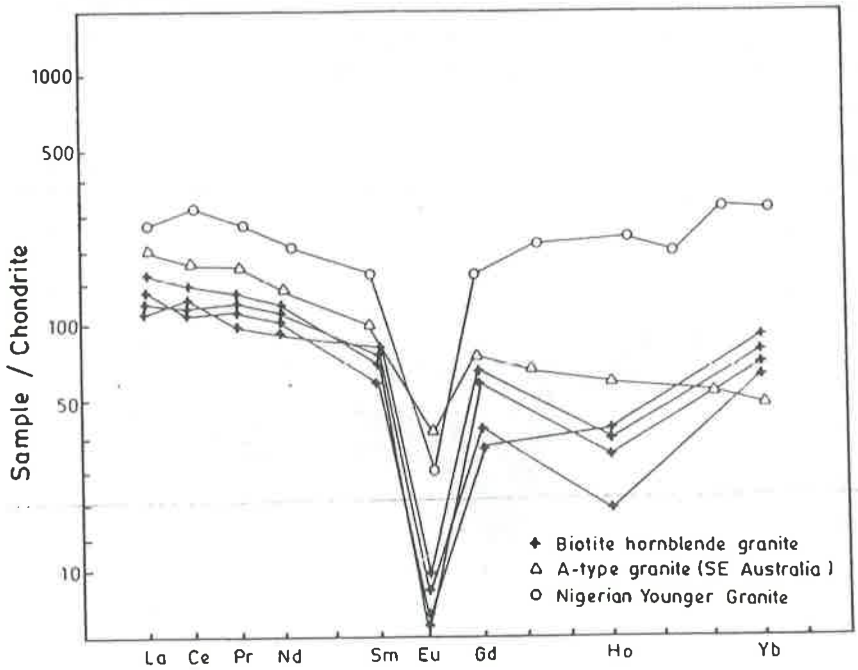

Fig. 14 **Chondrite-normalized REE plot for Jalor subsolvus granite.**

Eu anomaly is more pronounced (Eu/Eu* = 0.15) as compared to hypersolvus granites (Eu/Eu* = 0.41). Normally peralkaline (hypersolvus) granites show more pronounced Eu anomaly (cf. Bowden and Kinnaird, 1984; Vallinayagam and Kochhar, 1998) as compared to the subsolvus granites. The more pronounced Eu anomaly in the subsolvus granites could be due to the interaction with a fluid phase and also due to fractionation of plagioclase (Kochhar and Dhar, 1993). Like the Jalor granites, the peralkaline granites of the Median Mountains, Saudi Arabia (Harris and Mariner, 1980) also show enrichment of LREE with less marked Eu anomaly as compared to peraluminous granites.

Jhunjhunu granites are also characterized by a relatively flat chondrite-normalized pattern with slight enrichment of LREE (La/Yb = 9) and with marked Eu anomaly (Eu/Eu* = 0.25) (Fig.15) (Kochhar and Sharma, 1992).

Rare earth abundances in the acid volcanics

Siwana rhyolites and trachytes. Fig.16 shows the chondrite-normalized REE plot of the acid volcanics of the Siwana area. The rhyolites and trachytes show similar REE contents and patterns but with less marked Eu anomalies as compared to the granites. One rhyolite sample does not show negative Eu anomaly. This could probably represent a primitive sample, which did not have enough time before eruption to undergo fractionation.

Jalor rhyolites. Two trends are seen in the chondrite-normalized REE plot. One trend shows rhyolite with negative Eu anomaly (Fig.17a) and a second trend without any negative anomaly (Fig.17b). The samples without any anomaly could represent pristine compositions.

Jhunjhunu rhyolites show enrichment of LREE as compared to HREE (La/Yb = 9) with marked Eu anomaly. (Eu/Eu* = 0.21). Rhyolite samples, which have undergone tourmalinization, show depletion of all the REEs and the original Eu anomaly has been obliterated (Fig.18). This can be partly explained by the

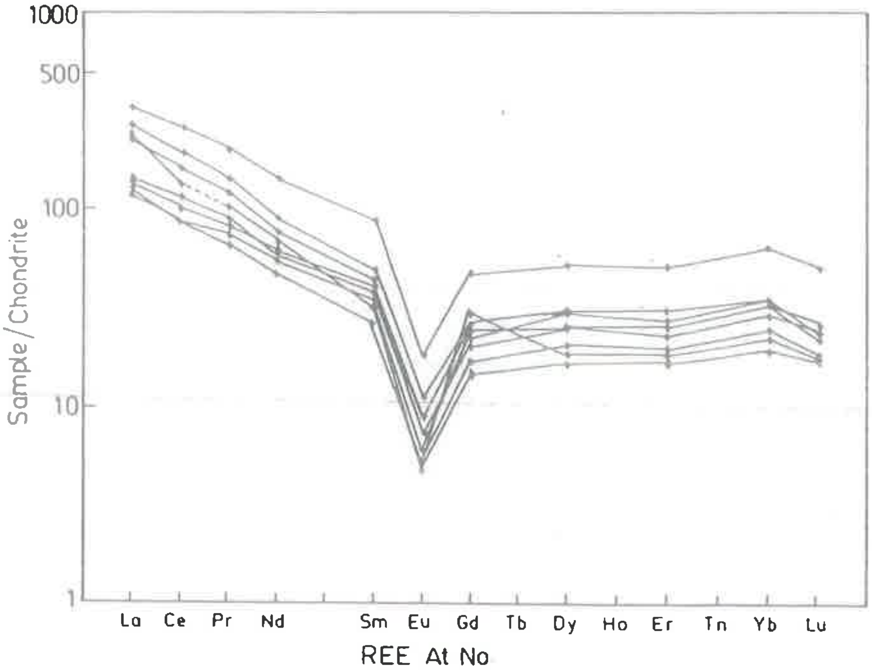

Fig. 15 Chondrite normalized REE plot for Jhunjhunu alkali-feldspar granites.

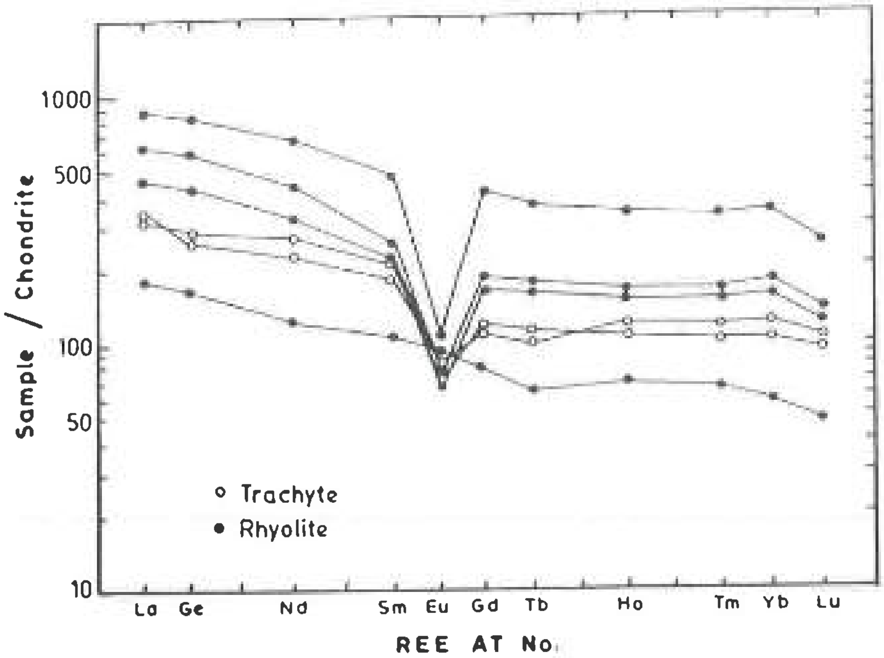

Fig. 16 Chondrite-normalized REE plot for Siwana rhyolites and trachytes.

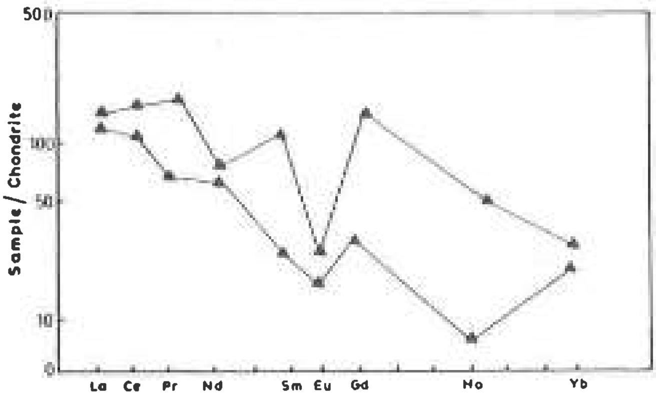

Fig. 17(a) Chondrite-normalized plots for Jalor rhyolites, showing negative Eu anomaly.

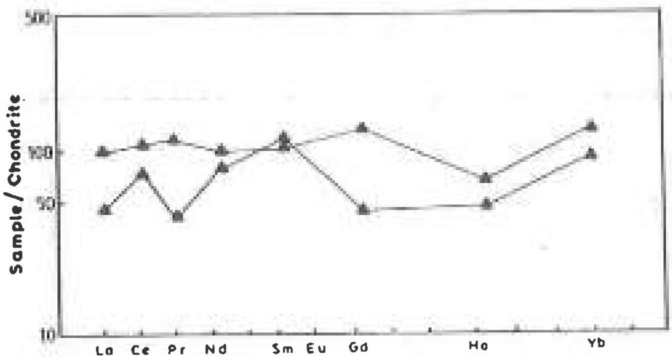

Fig. 17(b) Chondrite-normalized plots for Jalor rhyolites, without negative Eu anomaly.

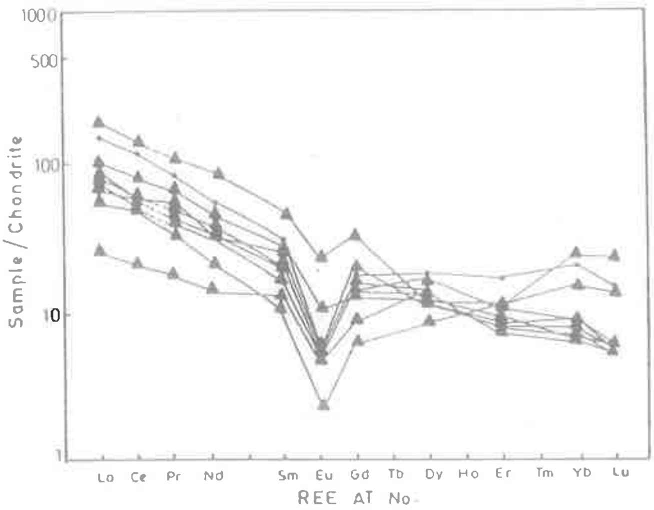

Fig. 18 Chondrite-normalized plot for Jhunjhunu rhyolites.

dilution effect of new (recrystallized) quartz. Both quartz and tourmaline are unable to accommodate all the light REEs released from feldspar and mica. However, tourmaline has sites which could accommodate Eu^{+2}. Hence Eu suffers less depletion as compared to other REEs (Alderton et al., 1980).

Petrogenesis

Feldspar fractionation plays an important role in the evolution of A-type granites. Plots of Eu/Eu* vs Ba, and Y/Nb vs Ba/Lb are important petrogenetic indicators (Eby, 1990). While Eu/Eu* ratios less than 1 can be due to feldspar fractionation, residual feldspar in the source region and /or source region with a negative Eu anomaly. Eu/Eu* ratios greater than 1 are usually ascribed to the presence of cumulus feldspar. The relative importance of plagioclase versus alkali feldspar in a fractionation trend can be assessed using Eu/Eu* versus Ba diagram. Variation in Ba/La is almost totally controlled by alkali feldspar fractionation. The Ba vs Eu/Eu* plots for Siwana, Jalor and Tusham granites are presented in Fig.19. Evolution of Siwana granite is largely controlled by alkali feldspar fractionation, which is in agreement with its peralkaline character. For the Jalor granites, the linear trend is indicative of both plagioclase and alkali feldspar. The variation in Ba concentration in Tusham granites can be explained by the crystallization of both alkali feldspar and plagioclase. For Tusham granites the ratio is 55AF: 45PL while for Jalor granites the ratio is 33AF: 65PL (Eby and Kochhar, 1990). The Jhunjhunu granites when plotted in Y/Nb vs Ba/La diagram (Fig. 20) show trend subparallel to alkali feldspar indicating the importance of alkali feldspar in their evolution. This is in agreement with the pronounced negative Eu anomaly (Eu/Eu* = 0.15 – 0.28) (Sharma, 1992).

The trace element including REE data show that the Siwana granites are likely to be derived as a high temperature melt from anhydrous granulite source from which a previous melt has been extracted. The Jalor granites are more primitive and have a more fractionated REE pattern, but may have been derived from a similar source. The Tusham granites show chemical characteristics typical

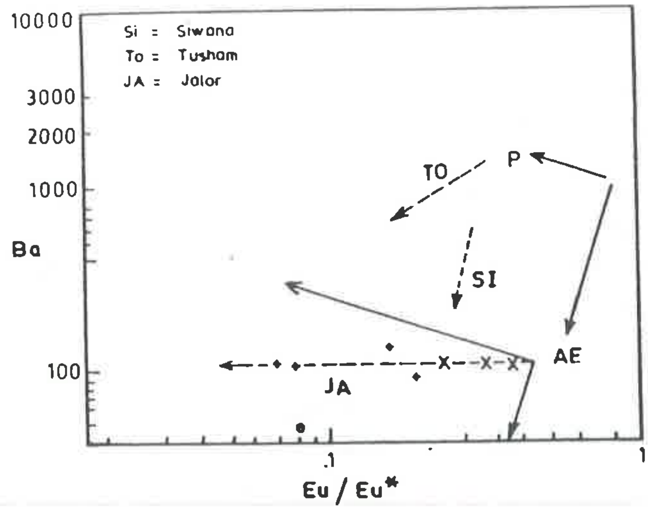

Fig.19 **Eu/Eu* vs Ba plot for Siwana, Jalor and Tusham granites. AF and PL are Raleigh fractionation trends calculated for removal of alkali feldspar (AF) and plagioclase feldspar (PL).**

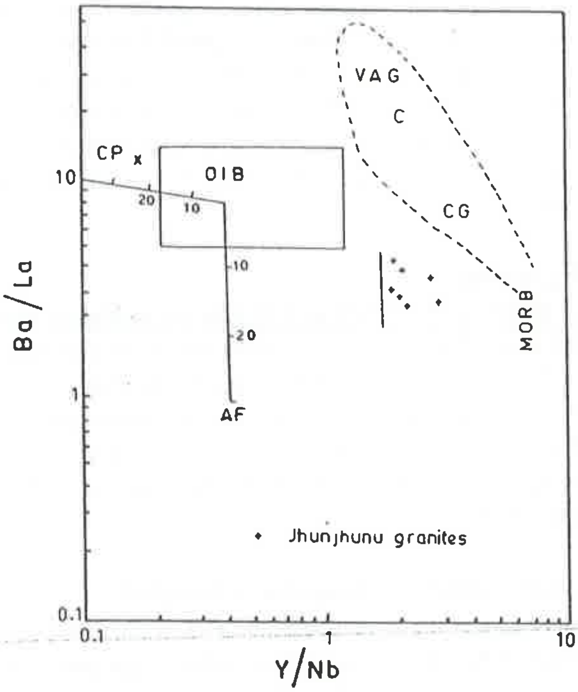

Fig. 20 **Y/Nb vs Ba/La plot for Jhunjhunu granites. Clinopyroxene (cpx) and alkali feldspar (AF) fractionation trends, after Eby (1990). OIB = ocean island basalt; VAG = volcanic arc granite; CG = syn-collision granite; C = Average crustal ratios.**

of magma derived from a high grade metasedimantary source (Eby and Kochhar, 1990). The Jhunjhunu granites appear to have been derived from a source of granodioritic composition (Sharma, 1992). Pb and Nd isotopic compositions show that Siwana magma is mantle derived, and for the Jalor complex, the combined Sr, Pb and Nd data indicate primary mantle derivation with a variable degree of crustal contamination, with the assimilated crust being most likely of Archean age. The data also document the presence of Archean age in the region (Dhar et al., 1996).

The commonality between widely separated Tusham, Jhunjhunu, Siwana and Jalor complexes is anorogenic, 'Within-Plate' magmatism, characterized by ring structures and extensional tectonic environment during the same thermal regime in the TAB of the Indian shield some 732 Ma ago.

HHP Granites

The Malani granites are of high heat production (HHP) type (Table 2). Their average heat productivities are as follows (Kochhar, 1989b, Sharma, 1994):

Jhunjhunu granites	:	12.06 uWm^{-3}
Tusham granites	:	7.68 uWm^{-3}
Siwana granites	:	5.90 uWm^{-3}
Jalor granites	:	2.80 uWm^{-3}

The Malani granites are quite unique in terms of heat production. The Jhunjhunu granites have the highest heat productivity values amongst the Malani granites followed by the Sn-bearing Tusham granites. Selected trace element abundances in some of these granites (Tusham and Jhunjhunu), which are typical of HHP granites, have been normalized to the premordial (undepleted) mantle and shown in Fig. 21. The Tusham granites show marked Ti depletion whereas the Jhunjhunu granites show Ta and Sr depletion.

Significance of the HHP granites

The A-type, HHP Malani granites have the potential of rare metal mineralization. The Siwana, Jalor, Jhunjhunu and Tusham granites have Nb>Ta and correspond to NYF (Niobium-Yittrium-Fluorine) association whereas the Jalor granites have Ta>Nb and may correspond to LCT (Lithium-Cesium-Tantalum) association (Kochhar, 1992; 1999b). Bidwai and Krishnamurthy (1996) have also suggested that stratabound and vein-type uranium mineralization may occur in the rocks of MIS of southwestern Rajasthan.

Subvolcanic Setting and Shallow Magma Chamber

Volcano-plutonic ring structures and subvolcanic setting in an extensional tectonic regime characterize the A-type Malani magmatism. The typical A-type geochemical signatures are manifestation of shallow crustal residency. The shallow origin of A-type granites is in turn, a consequence of their emplacement in a non-compressive tectonic regime where the crust tends to be thin and magmatic advection of heat can approach the Earth's surface. Pitcher (1997) has also emphasized the role of the hot plumes, crustal extension and rifting in the evolution of silicic, subvolcanic magma chamber.

According to the experimental work of Douce Patina (1997), profuse crystallization of plagioclase + orthopyroxene during low pressure ($P \leq 4$ kbar)

Table 2 Radioactive elements and heat productivity of the Malani rocks.

Sample No.	Rock Type	U (ppm)	Th (ppm)	K (%)	Th/U	HPU (uWm^{-3})
Malani Igneeous Suite						
(Siwana)						
M1	Mokalsar alkali-granite	10.5	58.1	3.76	5.53	7.09
L6	"	6.8	29.8	3.59	4.38	4.16
100	"	6.4	43.0	3.99	6.72	5.01
B14	"	17.1	95.1	3.50	5.56	11.31
R8	"	11.2	33.3	3.67	2.97	5.53
190	"	11.0	60.8	3.65	5.53	7.39
P1	"	15.3	50.6	3.59	3.31	7.78
144	"	5.93	26.3	2.15	4.44	3.55
157	"	10.84	38.8	3.74	3.38	5.83
184	"	9.87	52.0	3.32	5.27	6.45
85	Mokalsar alkali-rhyolite	14.0	59.9	3.90	4.28	8.33
M12	"	5.38	29.5	3.32	5.48	3.84
132	"	4.61	30.5	4.23	6.62	3.80
R1	"	1.21	5.29	3.67	4.37	1.06
M11	Mokalsar alkali-trachyte	3.72	12.10	2.29	3.25	2.08
101	"	1.4	9.23	2.91	6.59	1.32
R9	"	1.14	8.14	3.84	7.74	1.26
(Jalor)						
K01	Kolar biotite-granite	5.8	29.3	4.19	5.05	3.92
K02	"	6.9	31.0	3.67	4.49	4.27
K05	"	2.6	13.3	3.16	5.12	1.89
K06	"	3.8	17.8	3.41	4.68	2.54
K08	"	2.0	8.4	3.01	4.20	1.38
(Tusham)						
B3	Tusham microcline-granite	9.3	94.0	4.32	10.05	9.32
C4	"	11.3	74.0	3.74	0.51	8.39
D3	"	7.9	57.7	3.74	7.30	6.39
M5	"	11.0	88.4	4.57	8.04	9.39
KH1	Tusham granite-porphyry	10.5	96.5	4.57	9.19	9.83
TG2	Tusham muscovite-biotite-granite	4.1	21.6	2.49	5.27	2.79
(Jhunjhunu) Choul	Jhunjhunu alkali feldspar-granite	28.39	126.08	4.84	101.11	16.75
Bib2	"	20.91	135.07	4.77	97.89	15.42
Rs2	"	14.80	75.72	4.56	61.78	9.62
IPI	"	23.39	112.59	4.64	88.96	14.48
NN3	"	12.67	79.54	4.56	61.56	9.32
RNI	"	18.66	69.77	4.56	62.66	10.22
NP34	"	13.66	66.00	4.40	55.46	8.63
Md5	Jhunjhunu rhyolite	7.34	38.66	3.87	34.41	4.95
Md4	"	14.98	32.66	4.00	39.41	5.12
Md7	"	3.58	42.49	0.38	25.58	6.59
MR5	"	4.92	84.86	3.10	53.55	3.95
NP7	"	7.73	36.39	4.00	33.92	7.53
B1	"	5.92	25.36	2.99	24.58	3.61
CH5	"	4.08	18.36	1.57	16.41	2.50
NP23	Jhujhunu rhyolite dyke	17.52	78.71	4.56	65.99	8.63

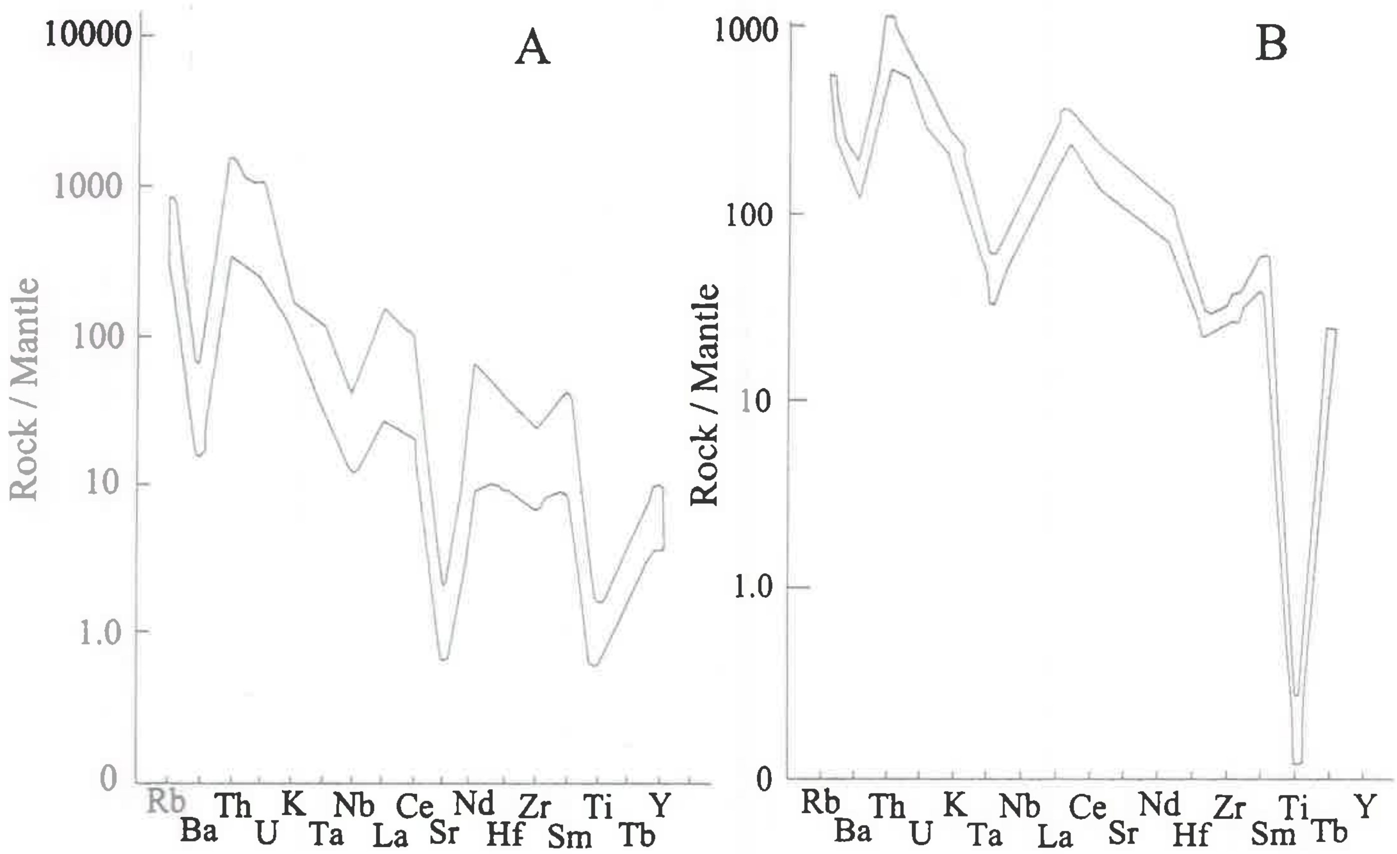

Fig. 21 **Primordial mantle-normalized trace element diagrams for Jhunjhunu (A) and Tusham (B) granites. The bands represent the trend of several analyzed samples.**

incongruent dehydration melting of hornblende and biotite-bearing assemblages, is the key factor in the generation of A-type granite melt with its typical chemical characteristics. With increase in pressure ($P \geq 8$ kbr) clinopyroxene becomes the dominant residual phase, and thus A-type chemical characters are lost. A compressive tectonic environment, which causes thickening of crust, is not conducive to the generation of A-type granite melt.

It is pertinent to mention here that the concept of subvolcanic setting originated here in India in the Malani terrane. It was McMahon (1886) who first suggested that the Tusham granites represent roots or deep seated portions of ancient volcanoes. La Touche (1902) also observed that the "Siwana granites mark the approximate sites of vents or fissures from which the volcanic rocks poured out". This idea was subsequently developed by British geologists (for a review see Reynolds, 1956). It was Buddington (1959) who first coined the term epizonal (subvolcanic) setting for the granites. All the ring complexes of the world are characterized by subvolcanic setting.

Sr, Pb, and Nd Isotope Studies

Crawford and Compston (1970) dated Malani granites and rhyolites at 745 ± 5 Ma. Kochhar et al. (1985) determined a Rb/Sr age of 770 Ma for Tusham rocks. Eby and Kochher (1990) re-evaluated both data sets, using the revised Rb decay constant ($l = 1.42 \times 10^{-11}$ years) and the standard York regression, and obtained an age of 727 ± 5 Ma for the Siwana rocks and an age of 732 ± 41 Ma for the Tusham rocks. Dhar et al. (1996) obtained a Rb/Sr age of 725 ± 7 Ma for the Jalor granites and rhyolites, and 723 ± 6 Ma for Siwana granites. Thus, 732 Ma appears to be an authentic and well-documented age for the Siwana, Jalor and Tusham rocks. Pb and Nd isotope compositions of the Siwana granites show that the magma is mantle derived, and for the Jalor granites, the combined Sr, Nd and Pb data (Tables 3 and 4) indicate a primary mantle derivation with a variable degree of crustal contamination, the assimilated crust being of Archean age (Dhar et al., 1996). Fig.22 depicts the Pb isotope composition of granite and gabbro from Jalor and granite from Siwana. The Siwana data plot close to the Earth's Pb isotope composition (Doe and Zartman, 1979) and when corrected for 730 Ma, will be in the upper mantle composition range for $^{207}Pb/^{204}Pb$ as well as for $^{208}Pb/^{204}Pb$ ratios. The average crustal evolution curve of Stacey and Kramer (1975) is shown as reference. Basic rocks from Jalor show Pb isotope composition similar to that of Siwana granite. More radiogenic Pb, especially higher $^{207}Pb/^{204}Pb$ value characterize the Jalor granite. The 736 Ma reference line shows that the initial $^{207}Pb/^{204}Pb$ values of Jalor granites must have been well above the common Pb growth curve indicating possibly strong contamination of the Jalor magma by Archean rocks. Fig. 23 shows $\varepsilon Nd(T)$ of Siwana and Jalor samples vs age (in Ma). Evolution lines of Siwana samples converge towards the age of Rb/Sr isochron supporting its interpretation as intrusion age. The 'probable age' of the contaminated crust refers to the Nd contribution to Jalor granites from the wall rocks. Ages in Ga indicate the respective Nd model ages of such crust, calculated with an average crustal $^{147}Sm/^{144}Nd$ (0.12) value(Dhar et al., 1996).

Table 3 Whole rock lead isotope data of Jalor and Siwana rocks.

Sample	Rock type	Locality	$^{206}Pb/^{204}Pb$	+/-2σ (abs.)	$^{207}Pb/^{204}Pb$	+/-2σ (abs.)	$^{208}Pb/^{204}Pb$	+/-2σ (abs.)
JL-12	granite	Jalor	20.170	0.088	15.842	0.093	40.418	0.302
JL-9	granite	Jalor	19.548	0.076	15.842	0.087	40.375	0.290
JL-8	granite	Jalor	19.742	0.085	15.838	0.092	40.798	0.303
JL-10	granite	Jalor	19.782	0.075	15.807	0.086	40.462	0.289
JL-7	granite	Jalor	21.282	0.079	15.978	0.086	39.986	0.284
Int.KG	granite	Jalor	20.503	0.087	15.874	0.092	40.666	0.302
B-1	gabbro	Jalor	18.539	0.243	15.577	0.215	38.533	0.557
M-1	granite	Siwana	18.517	0.071	15.618	0.085	38.957	0.279
M-2	granite	Siwana	18.635	0.069	15.621	0.084	38.831	0.275
M-3	granite	Siwana	18.607	0.127	15.600	0.123	38.646	0.353

Table 4 Whole rock Samarium-Neodymium data of Jalor and Siwana rocks

Sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\pm 2\sigma m^{*}$	εNd(O)	εNd (730 Ma)
J17	8.73	26.3	0.1320	0.512255	+ 18	-7.5	-1.4
J18	13.87	66.5	0.1260	0.512364	+ 20	-5.3	1.3
J19	16.5	71.5	0.1315	0.512228	+ 14	-8.0	-2.7
M1	62.4	287	0.1315	0.512538	+ 14	-2.0	4.2
M2	76.4	297	0.1557	0.512668	+ 13	0.59	4.4
M3	63.1	248	0.1538	0.512680	+ 08	0.82	4.8

Oxygen Isotope Studies and Crustal Evolution

Preliminary oxygen isotope data ($\delta^{18}O$ ‰ with respect to SMOW) from the Malani granites is presented below in Table 5.

Table 5 Oxygen isotope data for Malani granites.

Locality	$\delta^{18}O$‰ SMOW	No. of Sample
Siwana granites:	–0.10 to +1.8 ‰	(n = 10)
Jalor granites:	–4.60 to +1.2 ‰	(n = 3)
	5.70 to 6.2 ‰	(n = 6)
Tusham granites:	10.4 to 11.6 ‰	(n = 7)
Jhunjhunu granites:	5.9 to 8.9 ‰	(n = 7)
	one sample gave a value of 4‰	

Siwana data

The Siwana samples show ubiquitous low ^{18}O. This is very significant. The low values can be interpreted in terms of interaction with a low ^{18}O rift-related meteoric/hydrothermal system, generated by cylindrically-shaped Siwana granites of HHP nature which acted as 'heat engines'. Overall, it seems that low whole rock ^{18}O is much more common for the Malani granites to the southwest compared to those further north and east. The oxygen isotope data do indicate synplutonic rift developed during the emplacement of the Siwana and Jalor granites in the southwest, and Jhunjhunu and Tusham granites in the northeast (cf. Taylor et al., 1991).

Jalor data

High values encountered in six samples indicate a very primitive protolith with no recycled mature crustal component, whereas samples with low values indicate the effect of low ^{18}O fluids in Siwana granite (hypersolvus-subsolvus association) (Kochhar and Dhar, 1993).

Tusham and Jhunjhunu data

Suggest no significant hydrothermal interaction with low ^{18}O fluids, and a protolith with a substantially high ^{18}O (crustal) component. The low value found in one of the Jhunjhunu samples indicates hydrothermal interaction with low ^{18}O fluids.

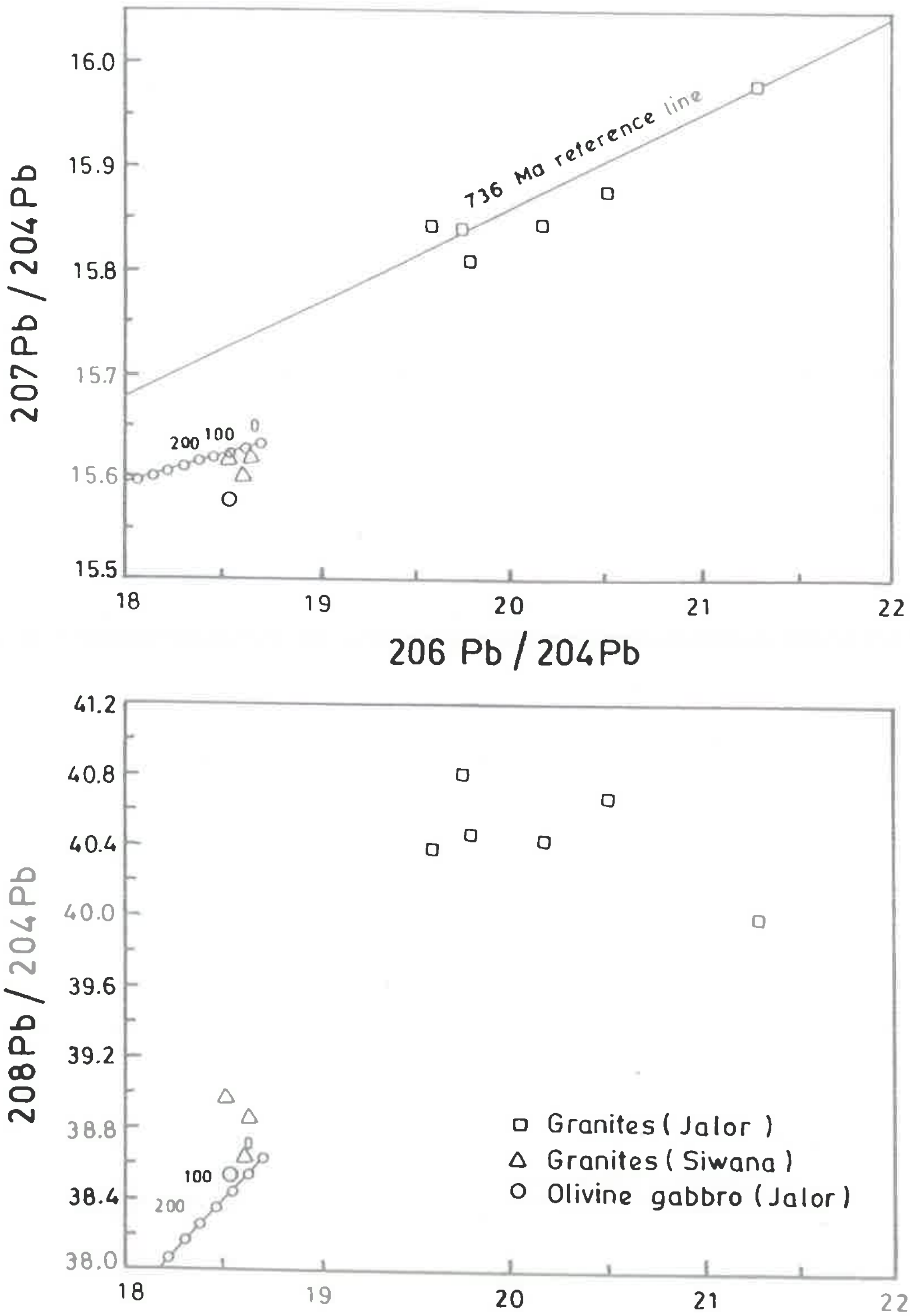

Fig. 22 $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagrams for Siwana and Jalor granites.

Taylor et al. (1991) have also attributed extremely low $\delta^{18}O$ values (-2 to +4‰) of Rand granite pluton which lie along Badenweiler-Lenzkirch (B-L) tectonic line in southern Schwarzwald, Germany to a large meteoric-hydrothermal system. The B-L line is interpreted as a fossil syn-plutonic rift because all the giant hydrothermal systems on Earth (both fossil and present) are known to be rift-related or associated with extensional tectonics e.g., the Tertiary ring dykes of Scottish Hebrides, the Yellowstone Park caldera line on the eastward extension of the Snake River rift zone, and Jurassic igneous activity in California (Solomon and Taylor, 1991). During the development of B-L hydrothermal system, a humid, sub-tropical climate existed as indicated by the presence of evaporites and carbonate platform sediments in southern Schwarzwald (Taylor et al., 1991). It is pertinent to mention here that when the Malani magmatism related hydrothermal system developed, humid sub-tropical climate also prevailed in the TAB of the Indian shield as indicated by paleomagnetic data and the presence of evaporites.

Thus 'Within-Plate' anorogenic Malani magmatism, low oxygen isotope values, the presence of evaporites, evidence of Precambrian glaciation (see below) are indicative of rift-related tectonic environment in the TAB of the Indian shield some 732 Ma ago.

Significance of Age and Assembly of the Malani Supercontinent

The unique A-type chemistry and 'within plate' setting of the Malani magmatism which is characterized by volcano-plutonic ring structures owe their origin to hot-spot activity in the TAB of the Indian shield, and is indicative of a tensional tectonic environment. There has been practically no movement of the Indian plate between 1.5 Ga and 750 Ma BP, as is indicated by the ring-shaped alkaline intrusions of syenite, kimberlite and carbonatite in the northwestern part of the Indian shield. After the accretion and stabilization of the Aravalli-Delhi mobile belt, there was intense build-up of stress fields, which gave rise to areas of extension, and high heat flow along which the alkaline magmatism was triggered by hot-spot activity. There has been at least two abortive attempts by the Indian lithosphere to rift, one related to the Aravalli-Delhi belt at 1500–1100 Ma BP, and the other at 732 Ma BP related to the Malani magmatism. The basic dykes of continental tholeiitic affinity of the Jalor area, and the ponding of the crust by basaltic magma in the Malani terrane (Jalor and Siwana) further substantiates the abortive attempts by the Indian lithosphere to rift some 732 Ma ago. The Malani magmatism marks the cratonization of the northwestern part of the Indian shield (Kochhar, 1984; Kochhar et al., 1995).

India has been a part of the Asian supercontinent since Precambrian time. On the basis of paleomagnetic data, Klootwijk (1979) suggested that the Gondwana existed as a major continent from atleast 750 Ma. Around 750 Ma BP, the southern shores of the Proto-Tethys lay between 40° to 45°N latitude (Powell et al., 1993). However, around 700 Ma, the margin started drifting to the tropical latitudes and around 600 Ma, it lay near the equator. During this period of time, the northern margins of the Gondwana were subjected to dessication, particularly in regions where tidal, estuarine and lagoonal environments prevailed. Thus there are evaporites in Arabia, Iran, Salt Range (Pakistan) and the Trans-Aravalli block (Nagaur-Bikaner basin)(Banerjee and Mazumdar, 1999). Interestingly, Förster (1987) compared the Infracambrian rhyolites and the associated granites of central Iran with the Malani rhyolites and the Pan-African granites of the Arabian shield. This similarity has been attributed to the Gondwana connection based on paleomagnetic data. Central Iran held a position south of the equator in Infracambrian and Cambrian times, and later drifted from the southern margin of the Gondwanaland to its present position as a microplate. According to Ilyin (1990), the continental margins of Vendian-Early Paleozoic supercontinent comprising, southern China, India, Kazakhstan and Mongolia were also the sites of near-equatorial sedimentation in the form of shallow water carbonate and phosphorites. The apparent polar wander paths show that there was no palaeomagnetic separation between Laurentia and the East Gondwana at about 725 Ma and that widespread glacial deposits were formed in active rift environment in tropical latitudes. The Sturtian glacial strata in Australia and Coastes Lake Group underlying the Rapitan glacial deposits in Laurentia are carbonates and shales with evaporitic fabrics suggesting that there must have been some remarkable climatic changes to account for wide spread low latitude glaciation. In the TAB of the Indian shield, the Malani rhyolites are also overlain by evaporites (Marwar Supergroup) in India and Salt Range Formation in Pakisthan. The Vendian glaciation represented by the Pokhran boulder bed also records the cobbles and pebbles of the Malani volcano-plutonic rocks (Valdiya, 1995; Virdi, 1998). According to Poornachandra Rao et al.(1997), the Indian sub-continent migrated to steep northern latitudes during the Malani rhyolite period (732 Ma) before drifting to southern hemisphere during Rewa and Bhander (Vindhyan Supergroup) periods. This steep northern latitude migration could be the cause of climatic changes and glaciation.

732 Ma is not a mere number. It has a bearing on the assembly of the Neoproterozoic supercontinent. Windley (1993) has recognized two periods of anorogenic magmatism (rapakivi granites, rhyolites, peraluminous granites, anorthosites, gabbros, basic dykes, and alkaline rocks) in North America and Europe at 1.76-1.55 Ga and at 1.45-1.40 Ga. In the Aravalli-Delhi craton of the

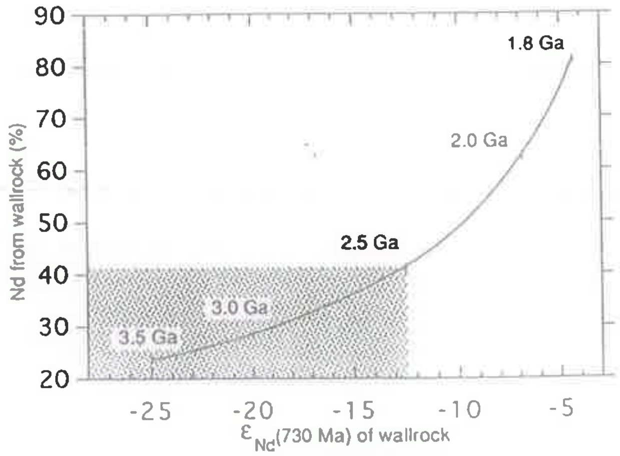

Fig. 23 ε_{Nd} (T) of Siwana and Jalor samples versus age in Ma.

northwestern peninsular India, the 1.75-1.55 Ga event is represented by the A-type Ajitgarh granites, Dadikar, Harsora and Chapoli granites (Pandit and Khataneh, 1998; Gopalan and Choudhary, 1984). The 732 Ma age marked a major Pan-African event of widespread, intraplate, anorogenic magmatism represented by alkali granites and coevel rhyolites (ring intrusions) in central Iran (Förster, 1987), the Nubian-Arabian shield, Somalia (Kroner et al., 1989; Hoshimo, 1986), Seychelles, Tuva-Mongolia massif, Siberia (Nur and Ben-Avraham, 1988) and the trans-Aravalli blocks of the Indian Shield. In view of a common crustal stress pattern (extensional tectonic regime), Pan-African tectono-magmatic thermal event of widespread anorogenic (A-type) character, all these microcontinents are considered to constitute a Neoproterozoic supercontinent – the Malani supercontinent (Kochhar, 1996). If the Owen fracture is adjusted and the Arabian sea is closed, the TAB of the Indian Shield becomes proximate to Somalia, the Nubian-Arabian shield, and all the continental islands, i.e., Sri Lanka, Seychelles and Madagascar, form a linear zone (Fig. 24) (cf., Chatterjee and Hotton, 1986). The migration of the Indian subcontinent during the Malani magmatism to high northern latitudes (75° across the equator) may be due to mantle plume activity some 750 Ma BP, which gave rise to the MIS.

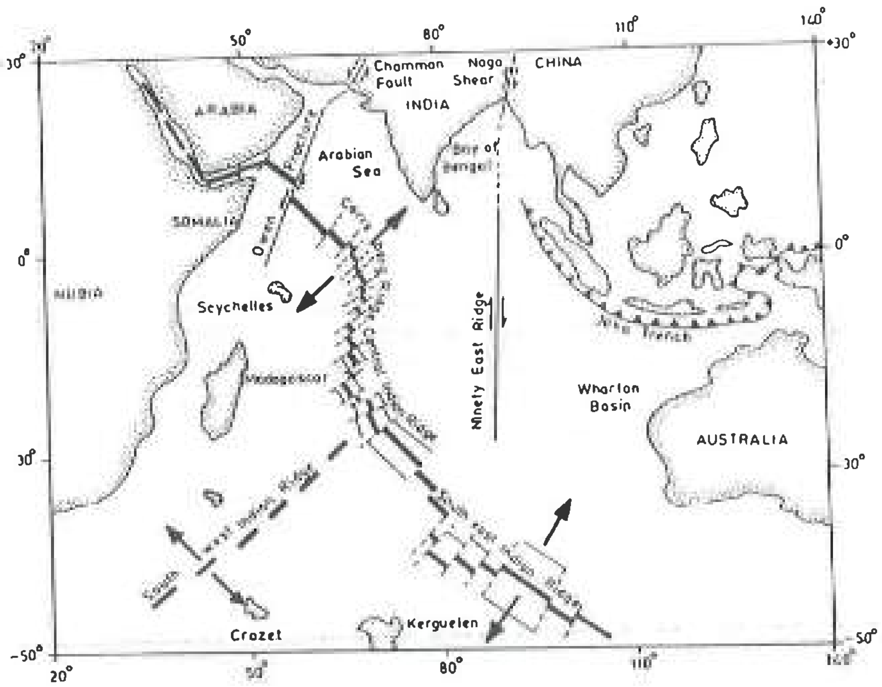

Fig. 24 Map showing the major tectonic features of the Indian ocean and the position of India, Arabia, Nubia, Seychelles, Madgascar with respect to the Owen fracture.

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