A-Type Malani Magmatism, NW Peninsular India

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INTRODUCTION

The Indian subcontinent comprises three geotectonically discrete blocks or terranes, the South Indian Block (SIB), the Bundelkhand Block (BB) and the Trans–Aravalli Block (TAB). These were juxtaposed and sutured during different periods of Earth's history (Radhakrishna, 1989). The TAB and BB are geologically unrelated to each other and are separated by NE-SW-trending, 700-km-long Proterozoic Aravalli-Delhi mobile belt.

TRANS-ARAVALLI BLOCK

The TAB is unique in the geological evolution of the Indian shield as it marks a major period of anorogenic (A-type), 'Within Plate', high heat producing (HHP) magmatism represented by the Malani igneous suite of rocks (MIS). The Neoproterozoic Malani igneous suite (55,000 km^2; 732 Ma) comprising peralkaline (Siwana), metaluminous to mildly peralkaline (Jalor), and peraluminous (Tusham and Jhunjhunu) granites with cogenetic carapace of acid volcanics (welded tuff, trachyte, explosion breccia and perlite) are characterized by volcano-plutonic 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, 25 km in N-S direction) is the most spectacular feature of the Thar desert. The representatives of Malani suite also occur at Kirana Hills, and at Nagar Parkar, Sindh, Pakistan. The Malani magmatism is controlled by NE–SW- trending linaments (zones of extension and high heat flow) of fundamental nature (mantle?) and owes its origin to hot-spot and related tectonics (for a review, Kochhar, 2000a).

SEISMIC, THERMAL AND CHEMICAL ANISOTROPY IN THE TAB

1. ***Low-velocity anomaly*:** Based on P-wave arrival times, Kennette and Widiwantoro (1999) delineated a low-velocity anomaly to the north of Cambay Gulf. This feature is 120 km across and is in marked contrast to high seismic velocities that characterize the lithosphere beneath the peninsular India. This anomaly extends from shallow depth to contact with a more extensive low-velocity zone below 200 km beneath the Indian lithosphere. The anomaly coincides with the Siwana ring structure, and the low velocity possibly represents the conduit of the fossil plume, the Malani plume (Kochhar, 2001a).
2. ***Gravity and heat-flow data*:** The Marwar terrain of the TAB is characterized by high heat flow and basement high (Krishna Brahmam., 1993; Mishra & Laxman, 1997). The Tusham area is associated with high heat flow of around 96 mWm^{-2}. Heat flow in and around Khetri and Jhunjhunu is 75 mWm^{-2}, with an average value of 60 mWm^{-2} for the Delhi fold belt (Sunder et al., 1990).
3. ***Chemcial and thermal anisotropy*:** The chemical and thermal anisotropy in the TAB is manifested in the anorogenic magmatism represented by high heat producing, A-type, 'Within Plate' Malani magmatism indicative of extensional tectonic environment, high crustal thickness and high heat flow. The generation of A-type is controlled by thick crust, crustal extension with high heat flow (Pitcher, 1997). The bimodal nature of Malani magmatism, as exemplified by the occurrence of basalt, gabbro and dolerite dykes of continental alkaline affinity, the trace-element pattern of granite and the associated volcanic rocks of granite (high abundance of HFS-Zr, NB, Ga, Zn, Y, REEs except Eu) emphasizes the role of halogens in fluxing these elements from the mantle magma (Kochhar et al., 1995, 2000a). The seismic, gravity, thermal and chemical anomaly in the TAB are symptomatic of plume activity in the region (Kochhar, 2000b).

REGIONAL GEOLOGY AND THE AGE OF MIS

The lower boundary of the Malani rocks is exposed near Miniari, Pali district, Rajasthan. Here the Malani volcanics are underlain by slates of Aravalli Supergroup. In the Tusham area, Bhiwani district, Haryana, 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 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, which is much more than the average span of an orogency (Condie, 1976). No direct relationship of the MIS with the Aravalli-Delhi cycles are observed in the field. Thus MIS is anorogenic and cannot be related to any subduction process (Sinha-Roy, 1988).

Crawford and Compston (1970), determined an age of 745±10Ma (Rb-Sr method) for the Malani granites and rhyolites. Dhar et al. (1996) determined an age of 723±6Ma for the Malani granites and rhyolites. However, Crawford and Compston (1970) obtained a much younger age (428 Ma) for a museum sample mistakenly attributed as Jalor granite (GA 1711). A rhyolite sample (GA 1734) also gave a young age of 526 Ma, but the specimen is slightly weathered and results may not be reliable (op. cit., p. 164).

These two doubtful specimens which gave younger ages were used by Srivastava (1988) to propose that Siwana and Jalor granites are much younger than the rhyolites and mark a thermal event at 500Ma related to a period of crustal

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upwarping and rejuvenation before the commencement of Gondwana rifting. Sinha-Roy and Mohanty (1998) also supported this view. On the basis of argon –argon dating of two Jalor granite samples, Rathore et al. (1999) made a far-fetched conclusion of a 500-550Ma thermal event. According to the authors (op. cit., p. 277, sample JR-15 is an altered sample and Jr-17 also appears to be more radiogenic than other related samples. This was questioned by Kochhar (2001b), Kochhar and Dhar, 2000 Torsvik et al. (2001b) who opined that 500-550Ma age spectra were of poor quality with no statistically valid plateau. The dating of the Diri, Gurpratap Singh rocks of doubtful Malani affinity (Kochhar, 1998), at 779±10Ma by Rathore et al. (1996) led Roy (2001) to erroneously suggest that the span of Malani rocks is about 100 Ma from 779 to 680 Ma. New U/Pb ages for Malani rhyolites range between 771 ± 2 and 571 ± 3Ma (unpublished data of Tucker et al.,2001 cited by Torsvic et al., 2001b). The location of Tucker et al.'s samples are not known.

GEOCHEMICAL CHARACTERISTICS OF THE MIS

The geochemistry (major-, trace- including rare-earth elements) of the four complexes viz. Siwana, Jalor, Tusham and Jhunjhunu was described by Kochhar (1983, 1989a, 2000 a and b), Vallinayagam and Kochhar (1998), Kochhar and Dhar (1993), Eby and Kochhar (1990), Sharma (1994), Pareek (1981, 1984) Bhushan (1995, 2000). Geochemical signatures of Malani magmatismas given below indicate an A-type nature of MIS.

1. The granite are high level, subvolcanic and intrude their own ejecta.

2. These are characterized by volcano-plutonic ring structures and radial dykes and occur in anorogenic setting i.e. 'Within Plate' tectonic environment.

3. The Siwana and Jalor magmatism show biomodal suite of granites, trachytes, rhyolites and basalt (gabbro, dolerite).

4. These are felsic, peralkaline (Siwana), metaluminous (Jalor) and peraluminous (Tusham and Jhunjhunu). The Malani granites plot in the alkali granite field of QAP diagram.

5. The Siwana granite is hypersolvus whereas the Tusham and Jhunjhunu granites are peraluminous. The Jalor granite is mainly subsolvus but has a hypersolvus component closely associated with it in space and time (Kochhar and Dhar, 1993; Garhia and Ravi, 1995).

6. These granites are low in CaO, MgO, high in silica, $Na_2O + K_2O$, Fe/Mg, Zr, Hf, Nb, Ta, high REEs (except Eu) and low in Sc, Cr, Co, Ni, Ba, Sr and Eu abundance.

7. According to Whalen et al. (1987), high Ga/Al ratio is an effective discriminator of A-type granitoids and other granite types. The Ga/Al versus Zr plot for the Malani Siwana, Jalor and Tusham granites from distinct clusters put aside M–, I–, and S-type granites. They fall in the A-type field. The field of Seychelles granites overlaps with that of Jalor and Tusham granites. For discriminating highly fractionated I-type granites, similar relationship can be seen in a plot of Ga/Al versus Zr+Nb+Ce+Y. The Jhunjhunu granites grade from highly fractioned I-type granites to A-type granites, Ga behaves as incompatible element in A-type suites (Eby, 1990). Eby (1992) has classified A-type granites into two subdividions: Al granites which have Y/Nb and Yb/Ta ratios less than 1.2, and the A2 granites which have this ratio between 1.2 – 7. The A1-type granites have generally low initial Sr ratios, and these are differentiates of basaltic magma directly derived from oceanic-island basalt (OIB) like the mantle source. This may have undergone some crustal interaction. These granites are emplaced during intraplate rifting or as the result of inferred plume or hot-spot activity. Type A2 granites have highly variable initial Sr ratios and exhibit complex petrogenetic history. Some suites have significant mantle component, whereas the others may be of crustal origin. The A2 group granites represent magmas derived from continental crust or underplated crust that has been through a cycle of continent-continent collision or island-arc magmatism. These granites were emplaced at the end of a long period of apparently high heat flow and granitic magmatism. The Y/Nb and Yb/Ta plots of Siwana, Tusham and Jhunjhunu granites indicate that the Jhunjhunu plots cluster around OIB, whereas the Siwana and Tusham plot between the average crust and IAB. The dispersion of measured values away from the source towards continental crustal and IAB. The dispersion of measured values away from the source towards continental crust may be indicative of crustal interaction in their petrogenesis. It is important to mention here that Y/Nb and Yb/Ta ratios are measure of amphibole and pyroxene fractionation in the evolution of magma and can change if the crust interacts with the magma. The crustal involvement (Y/Nb and Yb/Ta ratios: 2 or more) can push A1 granite to A2 granite field.

8. Siwana granites are characterized by high total REE content, relatively flat chondrite-normalized pattern with little fraction between LREE and HREE (La/Yb=2.3), with marked Eu anomaly (Eu/Eu*=0.34). They develop a relative enrichment in middle REE group (Sm, Gd and Dy) with corresponding Eu depleted characteristic REE pattern of peralkaline granites (Kochhar, 1989a). 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 restricted range of REE abundances and the LREE are enriched with respect to HREE (LA/Yb=17) and show moderate Eu anomaly 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 different from that of hypersolvus granites (biotite granite) and 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. A moderate LREE enrichment and a upward curvature of HREE portion of the chondrite-normalized plot is seen. The hypersolvus granites show enrichment of LREE as compared to subsolvus granites. In the subsolvus granites, Eu anomaly is more pronounced (Eu/Eu*=0.15) as compared to hypersolvus granites (Eu/Eu*.41). Normally peralkaline (hypersolvus) granites show more prounced Eu anomaly (cf. Bowden and Kinnaird, 1984; Vallinayagam and Kochhar, 1998) as

compared to the subsolvus granites. More prounced 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, perlkaline granites of the Median Mountains, Saudi Arabia (Harris and Mariner, 1980), Jalor granites also show enrichment of LREE with less marked Eu anomaly as compared to peraluminous granites.

9. 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) (Kochhar and Sharma, 1992).

10. The Malani granites are of high heat production type (Kochhar, 1989b). These granites have potential of Sn-W-rare metal mineralization (Kochhar, 1985, 1989c). The average heat productivities are as follows: Jhunjhunu granites: 13.06 mWm^{-3}, Tusham granites: 7.68 $mWm^{-3,}$ Siwana granites : 5.90 mWm-^{3}, Jalor granites : 2.80 mWm^{-3}.

11. *Amphiboles and Pyroxenes*: The amphiboles in the 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 subsolidious to oxidizing trend). The pyroxenes in the alkali granites evolve from hedenbergite to aegirine through aegirine augite (acmite-hedenbergite trend) whereas in the acid volcanics they are represented by aegirine (acmite trend). Arfvedsonite and aegirine also occur as needles in gabbro (Baskar and Kochhar, 1995; Vallinayagam, 1997; Mukherjee and Roy, 1981, Bhushan, 1991) have also shown erichment of Ti, Fe, Na and depletion of Ca, Mg and K in aegirine of Siwana granite. The trace-element studies along with morphological studies indicate that the Tusham zircons belong to hydrothermal and late magmatic type. The high content of UO_2 in the Se zircons is a reflection of high abundances of UO_2 in the host rocks, Jalor zircons are magmatic. The Siwana granites though high in Zr values have very poor zircons yield due to peralkalinity of the Siwana magama (Kochhar et al., 1991).

12. Biotites: The biotites from Jalor, Tusham and Jhunjhunu granites show iron-enrichment trend. FeO^+/MgO ratio is the highest (6.72) in Jalor granites, whereas lower values of (4.08) and (3.72) have been observed in Tusham and Jhunjhjunu samples respectively. Mg Fe and 2AI $3Fe^{+2}$ substitution is dominant in Jalor samples, whereas influence of 3Mg Al is deciphered in the Tusham and Jhunjhunu samples (Dhar et al., 2002).

13. Basic Rocks : EPMA studies indicate that augite and aegirine are the main pyroxenes in the basalts and gabbros, whereas arfvedsonite is the dominant amphibole in these rocks. The chemistry of amphiboles and pyroxenes indicate that they have high contents of Na and Fe and low contents of Mg and Ca thereby indicating alkalic nature of Siwana parental magma (Vallinayagam, 1997).

14. The Siwana granites (10 samples) show an ubiquitous low $^{18}\delta O$ values (-0.10 to + 1.8%o) with respect to SMOW, whereas the Jalor granites (10 samples) also show low values (-4.60 to + 1.2%0). The low values are indicative of interaction with low $\delta^{18}O$ rift-related meteoric/hydrothermal systems generated by cylindrical shaped Siwana granites of HHP nature which acted as 'steam engines'. The Tusham and Jhunjhunu granite show values which range from 16.4 to 11.6_{oo} and 5.9 to $8.9_{\ oo}$ respectively indicating no significant hydrothermal interaction with low 18^{o} find (Kochhar, 2000a).

15. Pb-and Nd-isotopic composition of the Siwana granites show that the Siwana magma is mantle derived, and for Jalor complex, the combined Sr and Nd data indicate primary mantle derivation with a valuable degree of contamination of crust of Archaean age (Dhar et al., 1996).

Mantle Plume vs. Andean –type arc model for the MIS, and its position in the late Proterozoic supercontinent.

Malani Super Continent

Kochhar (1996) proposed that 730Ma marked a major tectonmagmatic event of widespread intraplate, anorogenic magmatism (alkali granites and cogenetic acid volcanics in the northwestern Indian shield, the Trans-Aravalli block (Malani Igneous Suite), central Iran, Nubian-Arabian shield, Somalia and Seychelles. In view of the commonality of crustal stress pattern, rifting and thermal regime which gave rise to this anorgenic magmatism, it has been proposed that all these microcontinents formed a supercontinent termed here the Malani supercontinent. Paleomagnetic data also support the existence of such a supercontinent around c. 750 Ma. This is in view of the occurrence of near-equatorial sedimentation in the form of shallow-water carbonate, phosphorite and evaporates (Kochhar, 2000 a and b, 2001a and b). The centre of low velocity anomaly depth beneath Sarnu-Dandali coinciding with the Siwana ring structure marks the expression of a fossil plume head the Malani plume. This plume activity some 732 Ma caused the separation of TAB of the Indian shield from Eastern Gondwana and subsequent amalgamation of the Malani sueprcontient (Kochhar, 2004a and b).

During the past five years a serious debate centered around the role of mantle plume vs. Andean-type arc model for the tectono-magmatic evolution of the MIS and its position in the assembly of a late Proterozoic supercontinent (Sankaran, 2003). According to Torsvic et al. (2001) India, Seychelles and northern. Madagascar formed a tectonic-trio atleast since the assembly of Gondwana (~550 Ma) but their pre-Gondwanan history is less constrained. Ashwal et al. (2002) have proposed an eastward directed (present-day coordinates) subduction beneath and associated magmatism into and onto western margin of Rodinia at 750 Ma with the product of magmatism (MIS), represented in India, Madagascar. Torsvic et al. (2001) and Pandit et al. (2001) have also suggested an Andean – type arc on the western margin of Rodinia. Paleomagnetic data from Seychelles and MIS yield local paleolatitude of 30°N and 40°N, and a new MIS-Seychelles fit place Seychelles only 600 km apart from MIS during the Mid-Proterozoic. Two scenarios are possible. If MIS is representative of India (i.e. not a separate terrain), than India was located at latitudes comparable with those of Australia. But if MIS, Madagascar and Seychelles was a separate terrain, and seprated from the rest of India, then it is possible to keep eastern India as a conjugate margin with Antartica (Tucker et al., 1999).

Recently Kochhar (2004 a,b) has shown that the Mahe, Ste. Anne and Praslin granites of Seychelles have close resemblance to the Siwana and Jalor granites of MIS in terms of age, paleopositions, hypersolvus-subsolvus associations, Sr, Pb, Nd and oxygen isotopic compositions and the role of 3.2-Ga Archaean crust of BGC, Rajasthan,. The Ga/Al vs. Zr plot of Seychelles granites overlap with those of Jalor and Tusham granites. These geochemical characteristics suggest that like MIS, the Seychelles granites are also 'WPG', anorogenic, A-type and do not represent Andean-type arc on the western margin of Rodinia. Based on commonalitites between Arabian-Nubian shield and the Trans-Aravalli block of the NW Indian shield in terms of anorogenic magmatism with A-type geochemical signatures, ring structures, presence of Archaean crust of BGC (3.2 Ga) as protolith, and evidence of Strutian glaciation and subsequent desiccation, it has been suggested by Kochhar (2006; 2008) that the Arabian-Nubian shield was attached to the TAB of the NW Indian shield around 600-700 Ma in the configuration of the Malani supercontinent.

Similarly there are similarities between the Yangtze craton of South China and the TAB of the NW Indian shield in terms of bimodal plume related syn-rift Chengijan magmatism (780-745 Ma) (Li et al., 2003) paleopoles (55-70° N of both YC and TAB at 750 Ma), Liantua and Nantua deposits (748 Ma) of glaciogenetic origin, corresponding to the Pokhran boulder bed and subsequent desiccation exemplified by carbonate mainly delomite and phosphate deposits correlatable with Hanseran evaporites of Marwar basin. All these similarities have led Kochhar (2007, 2008) to suggest that the YC of south China was attached to the TAB of NW Indian shield in the assembly of the Malani supercontinent. It has been suggested by Kochhar (2001 a and b) that the position of Indian subcontinent in the assembly of a Late Proterozoic supercontinent should be viewed in terms of three major blocks with different magmatic, metamorphic and tectonic histories, and not a single entity.

Future Possibilities

1. The significance and role of mantle plume (low-velocity anomaly, north of Gulf of Cambay), and the crust-mantle interaction in the genesis of MIS should be studied.
2. The position of Indian plate, and its suspect terrains i.e. South India block, the Bundelkhand block and the Trans-Aravalli block in the assembly of a Late Proterozoic supercontinent in the light of magmatism, metamorphism and tectonic environment and paleomagnetism needs to be further studied.

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