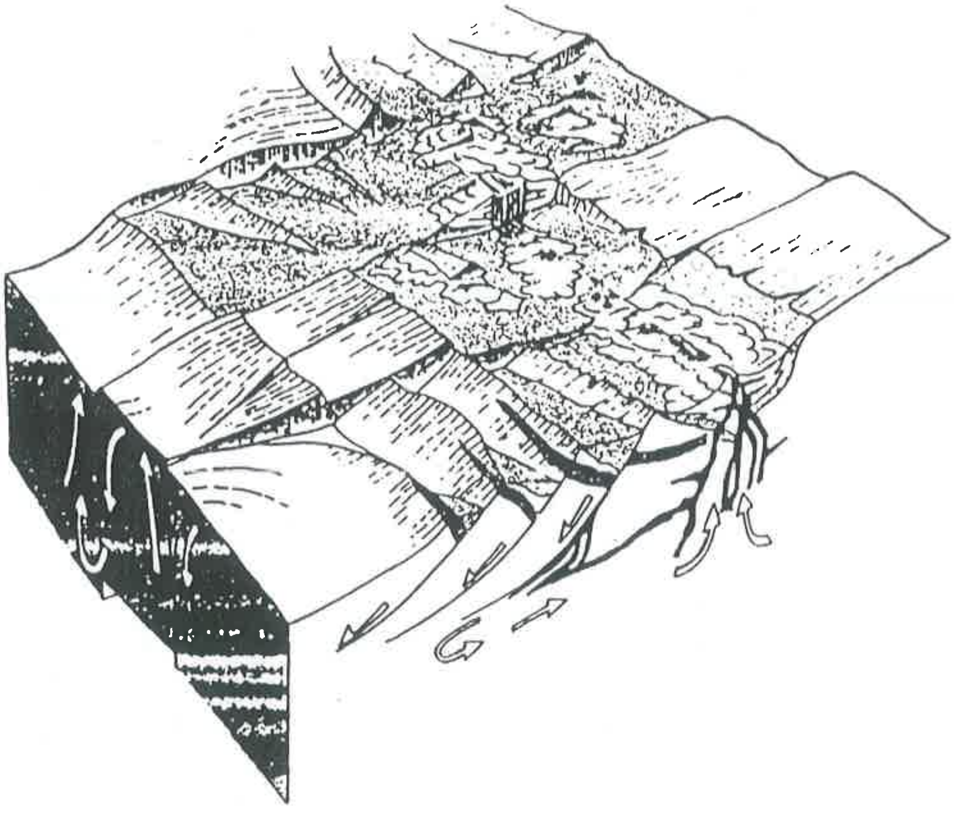
METALLOGENY RELATED TO TECTONICS OF THE PROTEROZOIC MOBILE BELTS



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Editor

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Mineralization Associated with A-type Malani Magmatism, Northwest Peninsular India

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ABSTRACT

Late Proterozoic Malani igneous suite of NW Rajasthan comprises peralkaline to peraluminous granites and co-genetic acid volcanics, related apparently to hot-spot tectonics. They are low in CaO, MgO and Ba, high in SiO_2, $Na_2O + K_2O$, Fe/Mg, Zr, Hf, Ta, U, Th, REE (except Eu) and very low in Sc, Co and Cr and may be referred to the A-type, HHP magmatism. Malani magmatism has already revealed Sn and W mineralization at places, and holds out prospect for new finds of Sn, W, Nb, U, Th and REE mineralization.

INTRODUCTION

Chappel and White (1974) proposed a genetic subdivision of granitic rocks into those extracted from a sedimentary protolith (S-type) and those extracted from an igneous protolith (I-type). Another distinctive group of granitic rock has been designated 'A-type' by Loisellé and Wones (1979), who used the term to emphasize the anorogenic tectonic setting and relatively alkaline composition of the magmas. A-type designation (unlike the S-or I-type) does not imply a specific source or mode of origin. A-type granites represent both the rift-associated magmatism of the shield areas and the final plutonic event in orogenic belts.

A-type granites are characterized by high SiO_2, $Na_2O + K_2O$, Fe/Mg, F, Zr, Nb, Ga, Sn, Y, and REE (except Eu) and low CaO, Ba and Sr (Loisellé and Wones, 1979; Collins *et al.*, 1982; White and Chappel, 1983; Whalen *et al.*, 1987). Mineralization associated with A-type granites includes Sn, Mo, B, Nb, W, Ta, F, Be, Li and REE (Collins *et al.*, 1982; Pitcher, 1983). The A-type granites correspond to the 'within plate granites' (anorogenic magmatism) of Pearce and colleagues (1984). Based on a study of pathfinder elements such as Rb, U, Th, Zr, Hf, Ta and K/Rb, TiO_2, Zr/Hf and U/Th ratios, it is proposed here that like the Tusham granite, the Siwana and Jalor granites have the potential for Sn W, Nb, U, Th, REE mineralization.

MALANI MAGMATISM

The Late Proterozoic, trans-Aravalli Malani igneous suite (55,000 km^2; 750 Ma) (Fig. 1) comprises peralkaline (Siwana), peraluminous to mildly peralkaline (Jalor) and peraluminous (Tusham) granites with a co-genetic carapace of acid volcanics (welded tuffs, rhyolite, trachyte flows, explosion breccias, perlite etc.) and is characterized by ring structures. The magmatism is controlled by NE-SW-trending lineaments of fundamental nature and owes its origin to hot-spot tectonics (Kochhar, 1983, 1984; Kochhar and Dhar, 1988).

The granites of the Malani igneous suite have the following characteristics typical of A-type granites:

1. The granites are subvolcanic and intrude their own ejecta. They were emplaced at a high level in the earth's crust.
2. They are felsic, peralkaline (Siwana) and peraluminous (Tusham) according to the agpaitic index. They plot in the alkali granite field of a QAP diagram.
3. They occur in an anorogenic setting i.e., an 'within plate' tectonic environment.
4. The Siwana granites are hypersolvus, whereas the Tusham granites are subsolvus. The Jalor granites are mainly subsolvus but have a hypersolvus phase associated with them in space and time (Kochhar and Dhar, 1988).
5. These granites are low in CaO, MgO and Ba, high in SiO_2, Na_2O + K_2O, Fe/Mg, Zr, Hf, Ta, Th, REE (except Eu) and very low in Sc, Co and Cr (Table I) (Fig. 2a). The Siwana granites are characterized by a high total REE content and relatively flat chondrite-normalized pattern (La/Yb: 2.3). The Tusham granites fall in a very restricted range of REE abundances and the LREE are significantly enriched with respect to HREE (La/Yb: 17). The chondrite-normalized La/Yb

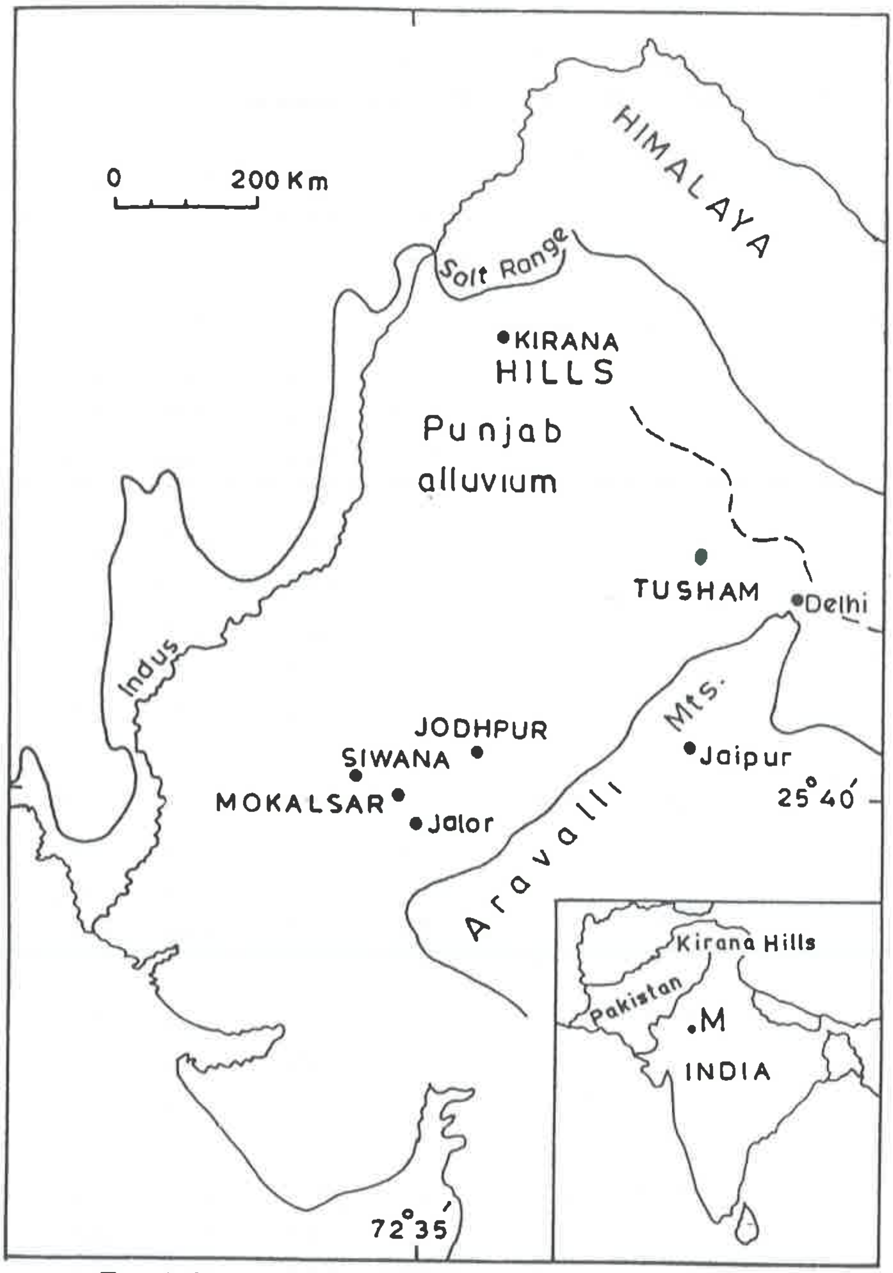

Fig. 1. Location map of the Malani igneous suite, Rajasthan.

ratios for the Jalor granites (La/Yb: 5) are intermediate between the Siwana and Tusham granites. The Jalor granites have the lowest total REE abundances, with Eu/Eu*: 0.56 (Eby and Kochhar, 1990).

Anorogenic magmatism is attributed to hot-spot activity and is due to thermal process in the asthenosphere. According to Burke and Dewey (1973), many anorogenic granites were emplaced above the mantle plume prior to development of intracontinental rifts. Sillitoe (1974) pointed out that economic deposits of tin are associated with these granites e.g., Jos Plateau, Nigeria, Upper Proterozoic tin mineralization in St. Francis, Missouri, and the Late

Table 1: Radioactive element abundance and heat productivites for alkali granite, rhyolite, trachyte of Malani igneous suite

Sample No.	Rock Type			U (ppm)	Th (ppm)	K (%)	Th/U	HPU (uWm^{-3})
Malani Igneous Suite								
M1 (Siwana)	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	95.0	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
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
B3 (Tusham)	Tusham	microcline oligoclase	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

Proterozoic deposits of Rondonia in Brazil. Piper (1984) has concluded from the palaeomagmatic evidence that a large continent must have existed over much of the Proterozoic. Alkali magma generated by emplacement of basaltic magmas into the continental crust could collect and concentrate Mo, W or Sn, depending upon the redox levels imparted by the rocks that were subjected to melting. Anorogenic magmatism, which marks the stabilization of the continental crust, might have been the major mechanism for the heat dissipation before the break-up of proto-Pangaea. It is interesting to mention here that the Malani magmatism also marks the cratonization of the northern part of the Indian shield some 750 Ma B.P. (Kochhar, 1984).

The Malani granites are of the high-heat production (HHP) type (Table 1) (Kochhar, 1988). There is no precise definition of a high-heat production granite; a level of 10 ppm of U (the dominant heat-producing member amongst the natural radioelements) is accepted as a lower limit (Simpson in Parslow 1985). This is about 2.5 times the mean value for granites (Rogers and Adams, 1969). Taking into consideration the decay of U over time, this minimum (10 ppm) has been lowered to about 7.5 ppm for 'present-day' U in granitic rocks over 1.75 Ga in age (see Parslow, 1985). In view of the lack of a precise definition for HHP granites, Plant and colleagues (1985) have suggested that the geochemical characteristics which could be used for identifying alkaline and subalkaline HHP granites include (a) exceptionally high contents of these radioelements: Rb, Th, U, K and of Cs, Ta, Nb, Y, Sc, and Li together with low Nb/Ta, Th/U, Zn/Sn, K/Rb, Sr/Y, and Mg/Li, with low to very low contents of Ba, Sr, Ti, Zr, and basic elements such as Ni, Cr, Mg, Co, V and Ni; (b) high total REE content, pronounced negative Eu anomalies and heavy REE enrichment at higher silica contents.

A perusal of Table 1 shows that the Tusham granites have uniformly high HPU values followed by the Siwana and Jalor granites. The low value in sample TG_2 (Tusham) is due to potash metasomatism. The tin mineralization in the Tusham area is related to this two-mica granite (Kochhar, 1985). The lower values of some rhyolites and trachytes are also due to potash metasomatism and hydrothermal alteration (Kochhar *et al.*, 1988). In heat production, the Malani granites are quite similar to the Nigerian Younger Granites (see Kinnarid *et al.*, 1985) The Siwana granites have higher contents of U, Th, La, Ce, Zr, Hf and Sm compared to the Nigerian Younger Granites, whereas Tusham granites have a marked Ti depletion and Jalor granites have a Ta depletion (Fig. 2a-d).

MINERALIZATION IN THE TUSHAM AREA

The occurrence of cassiterite from the Tusham area was first reported by Kochhar (1982) where it is associated with two-mica granite (musocvite-biotitie granite). Kochhar (1985) described the porphyry-type copper and tin

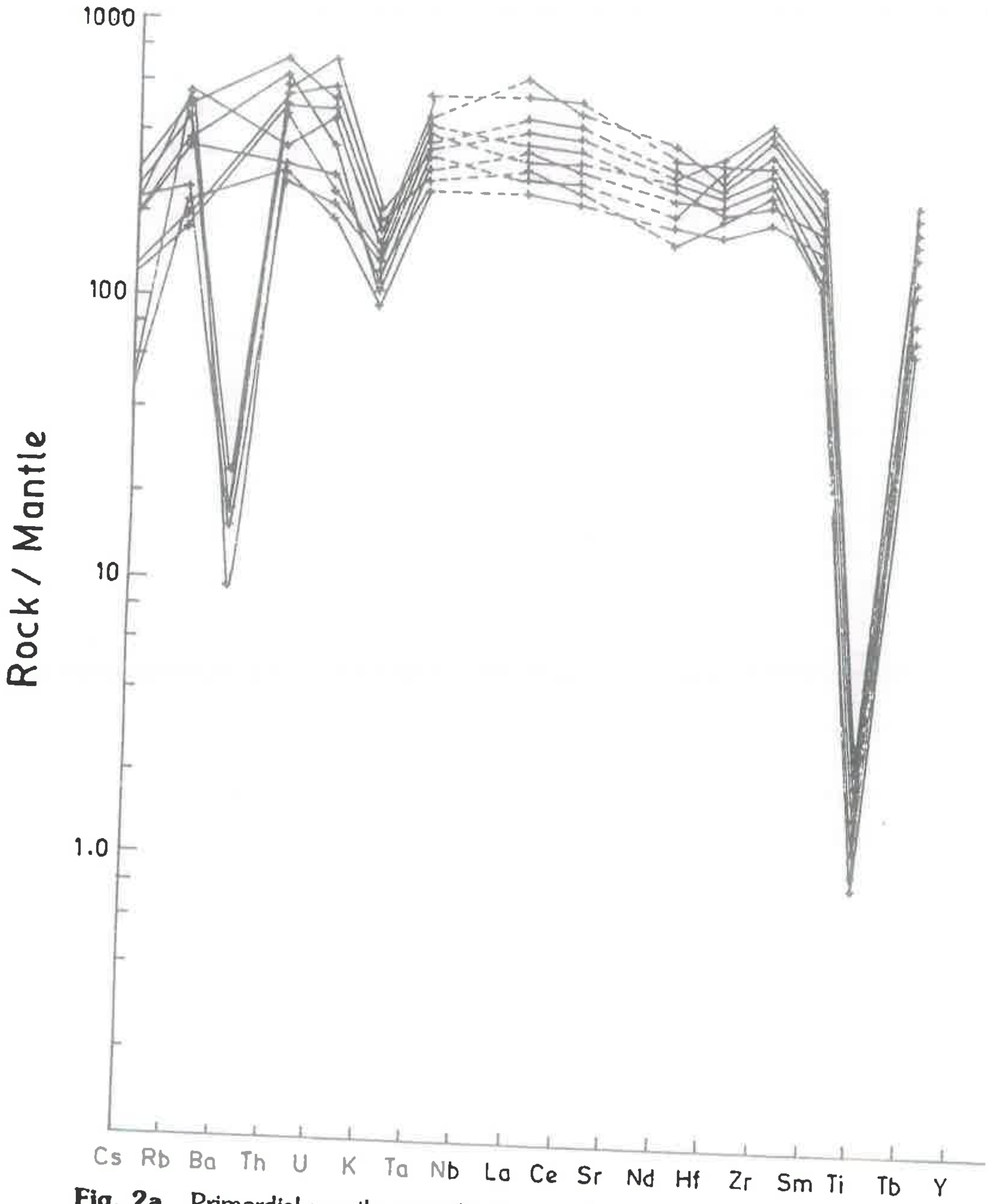

Fig. 2a. Primordial mantle normalized trace element diagram for the Siwana granites (absent data indicated by dotted line).

deposits from the Tusham area and proposed an orthomagmatic model of subvolcanic alteration for their genesis. The Tusham ring complex consists of various co-genetic members, viz., felsite (welded tuff), quartz porphyry, explosion breccia and the subsolvus granites. The concentration of Sn in quartz porphyry is 30 ppm, B 1 and Li 0.3, whereas in the ash bed (occurring as pockets in felsite) the concentration of Sn is 45, B 5, Li 0.3 and Nb 15 ppm.

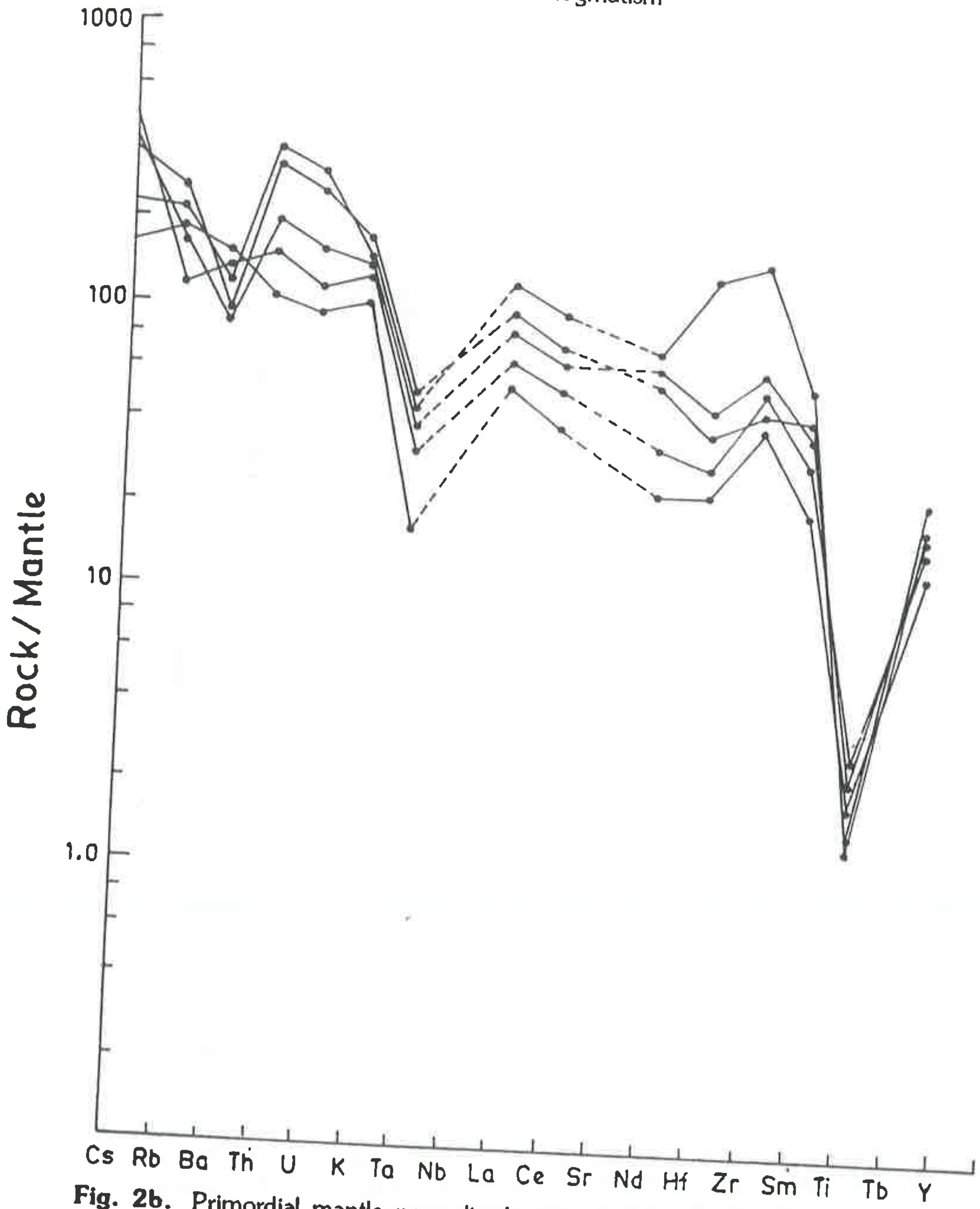

Fig. 2b. Primordial mantle normalized trace element diagram for the Jalor granites (absent data indicated by dotted line).

According to Pareek (1986), the mean concentrations (9 samples) in the Tusham acid volcanics of the various trace elements (in ppm) are as follows: Nb 103, Sn 80, B 85, Zr 106. The Mineral Exploration Corporation of India is currently exploring these deposits. Since the Jalor and Siwana granites and the associated acid volcanics belong to the same suite and represent the same tectonic (anorogenic) environment including age (750 Ma) as that of the Tusham rocks, Kochhar (1984) has suggested that these granites should also be explored for tin and related mineralization.

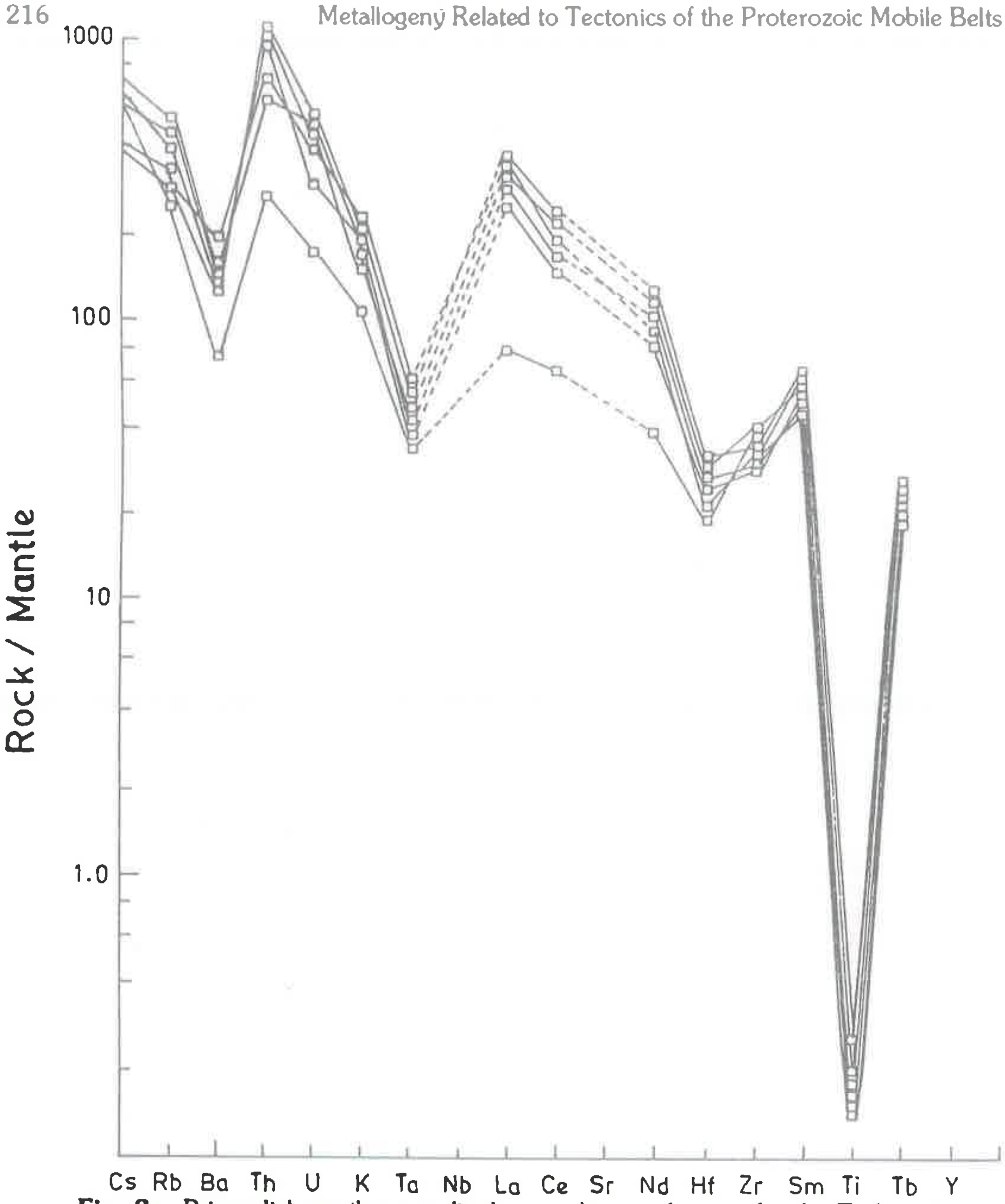

Fig. 2c. Primordial mantle normalized trace element diagram for the Tusham granites (absent data indicated by dotted line).

MINERALIZATION POTENTIAL OF THE MALANI ROCKS

Ring complexes containing alkali granites associated with tin deposits are enrriched in some elements, which include Sn, Nb, Ta, Zn, W, U, Th, REE Zr, Y, Rb, Li and F. This enrichment is at the expense of Ca, Mg, Sr and Ba. The complexes associated with mineralization are characterized by low K/Rb, Ba/Rb and Rb/Zr and high Rb/Sr ratios (Olade, 1980; Imeokparia, 1984; Ekwere, 1985; Kinnaird *et al.*, 1985). Imeokpria (1985) has shown that Li, F, Rb, Sn, Nb, Th, U and Zn are enriched in the 'specialized' granites of the Tongolo anorogenic complex of northern Nigeria.

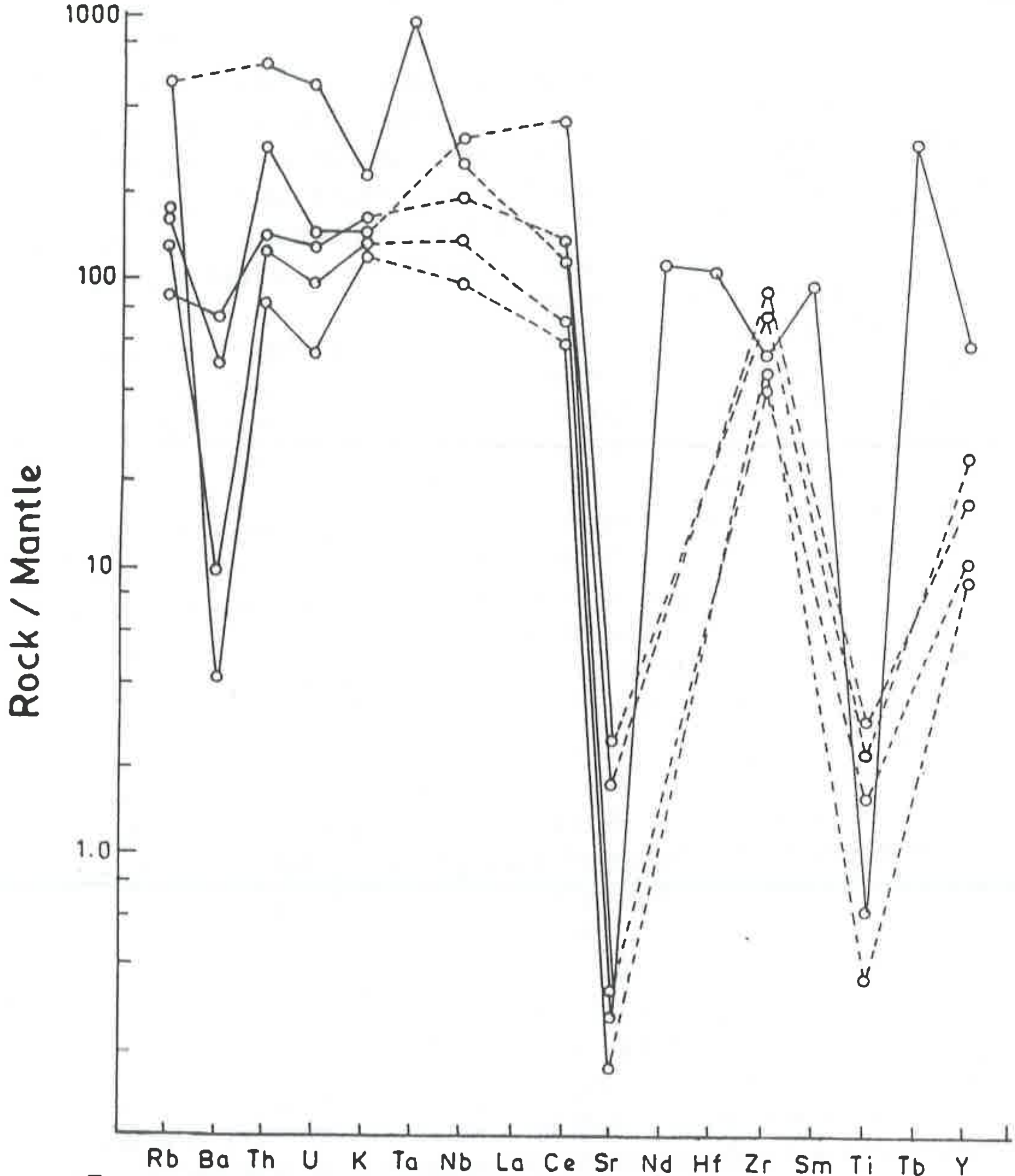

Fig. 2d. Primordial mantle normalized trace element diagram for the Nigerian younger granites (absent data indicated by dotted line).

Table 2 gives the means and ranges of selected trace elements in the Malani granites. A perusal of the Table shows that the Malani granites are also enriched in Rb, Th, U, compared to the low Ca granite. The Siwana granites are very much depleted in Ba. In the Tusham rocks, the concentration of U is three times higher than the average low Ca granite. The higher values of Th in these rocks (Fig. 3) might reflect the presence of thorite, which accompanies columbite and cassiterite in albitized biotite granites (see Bowden and Kinnaird, 1978). The Th-U plot of the Malani granites falls within the field of the Nigerian syenites and peralkaline granites (Fig. 4). This association is reflected in the significant positive correlation between Sn, Nb and Th. According to Bhushan and Mohanty (1988), the average trace element abundances (ppm) for Siwana granites is as follows: Nb 220, Zr 2984, Sn 37 and Be 18. The zirconium enrichment trend is accompanied by enhanced U and Nb. According to Imeokparia (1985), the Zr enrichment trend is associated with Nb-Sn mineralization, whereas the Zr-depleted trend indicates Sn-W mineralization. Thus, the Siwana granites may be expected to contain Nb-Sn mineralization, whereas the Jalor and Tusham granites may be associated with Sn-W mineralization.

According to Ekwere (1985), low Ba/Rb ratios and high Rb/Sr ratios of the Banke and Ririwai ring complexes of Northern Nigeria are indicative of post-magmatic alteration and Sn-Nb mineralization in these rocks. Fig. 5 shows that the Tusham and Jalor granites plot in the 'barren' field. This is anomalous with the above.

It has also been demonstrated that the low K/Rb (100) ratio in the Nigerian Younger Granites indicates highly fractionated and mineralized granites. Rb is considerably enriched relative to Ba and K during post-magmatic processes related to mineralization. The K/Rb ratios of the Tusham and Siwana granites lie between 50 and the main trend (150) line, whereas the Jalor rock lies between the 150–200 line (Fig. 6). Low Zr/Rb ratios characterize the Sn-W-bearing granites, while higher Zr/Rb ratios dominate the Nb/Sn-bearing granites. The Malani granites also form two separate clusters corresponding to the Northern Nigerian granites (Fig. 7) but are comparatively lower in Rb. Boissavy-Vinau and Roger (1980) have suggested that the TiO_2/Ta ratio is a good indicator of magmatic differentiation in tin granites. This ratio varies from 4900 in the earliest granites facies to 1 in the final tin mineralized albitic granites of the Marche granitic complex, Massif Central, France. For the Malani granites the ratio is as follows: Siwana 219, Jalor 4387 and Tusham 578 (Fig. 8).

Pollard and colleagues (1987) have recognized two types of tin environments: boron-rich environment and fluorine-rich environment. The boron-rich environment is characteristic of peraluminous granites and the mineralization style is hydrothermal intrusive breccia, stockworks and vein deposits. Tourmaline is the characteristic mineral. The principal metals are Sn and W. The fluorine-rich granites are characterized by the presence of fluorite and/or topaz and include peraluminous and peralkaline non-orogenic varieties. Mineralization is controlled by brittle fractures, and stockwork systems in massive/fractured granite systems. The principal metals are Sn, W, Nb and Tb. It is suggested that in view of the abundance of boron in the Tusham magmas (Kochhar, 1985), the Tusham deposit may represent a boron-rich environment, whereas the Jalor and Siwana deposits may represent a fluorine-rich enviroment. The identification of HHP granites is important not only in locating magmatogenous mineral deposits, but also in locating ore fluids in carbonate and other sedimentary cover sequences over

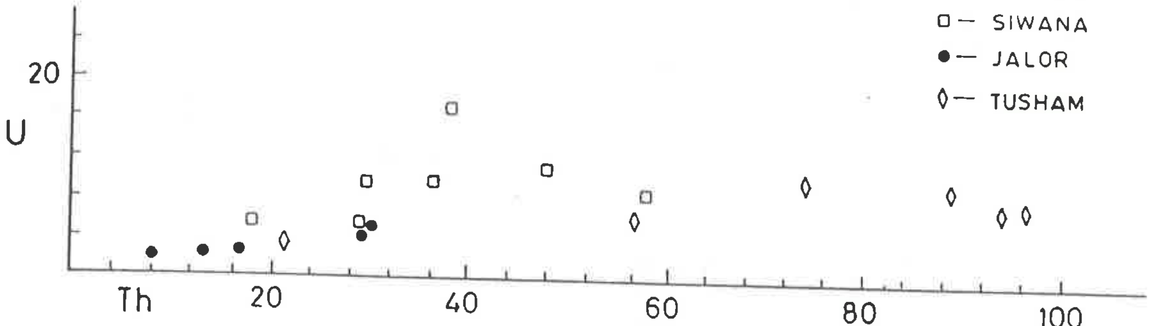

Fig. 3. U-Th Plot.

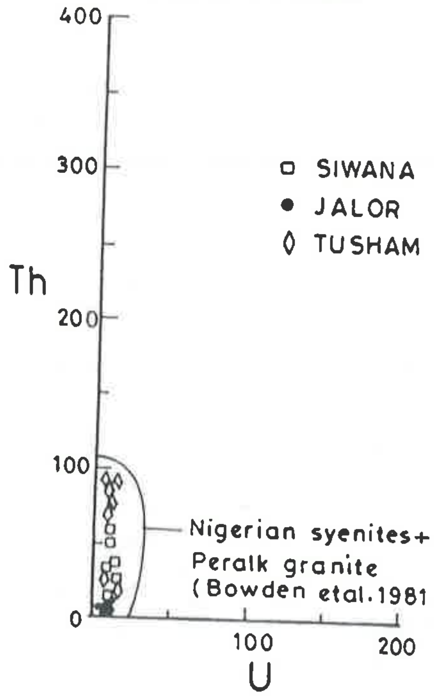

Fig. 4. Th-U Plot.

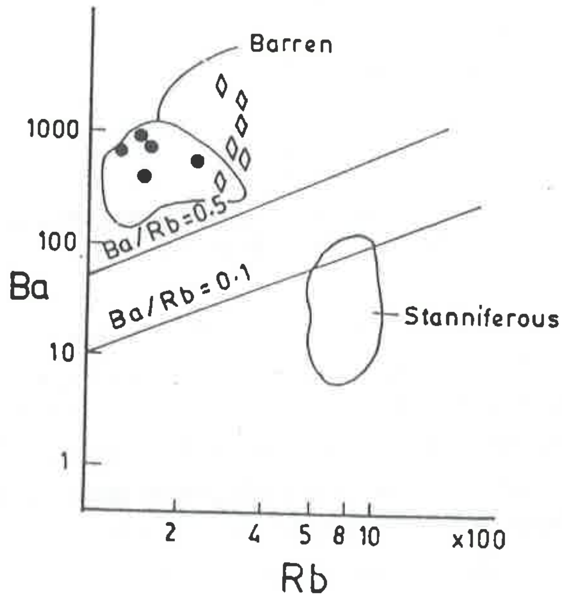

Fig. 5. Barren and stanniferous fields in the Northern Nigerian granites (Jos-Bukuru) (after Olade, 1980).

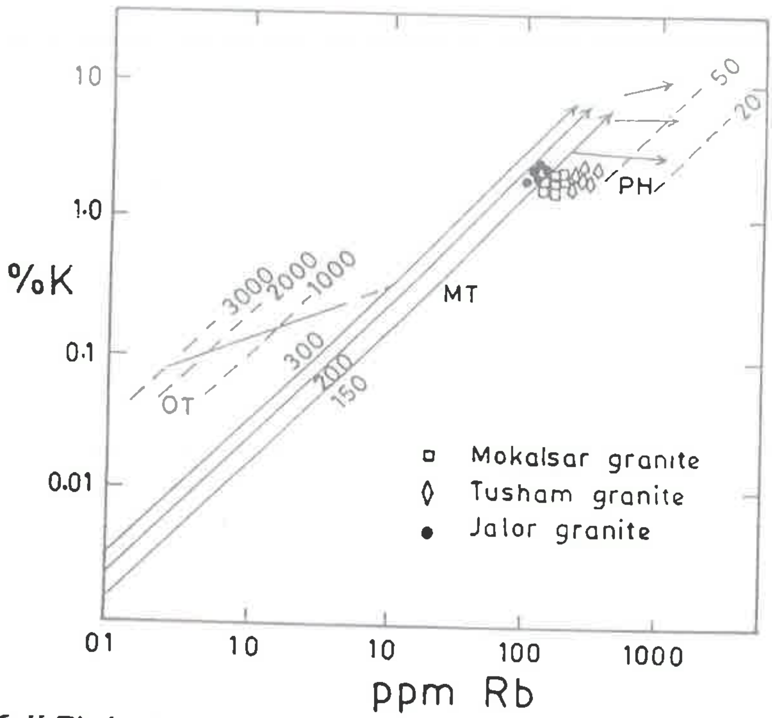

Fig. 6. K/Rb: fractionation trends in igneous rocks; OT: oceanic tholeiitic basalt; MT: main trend; PH: pegmatite hydrothermal.

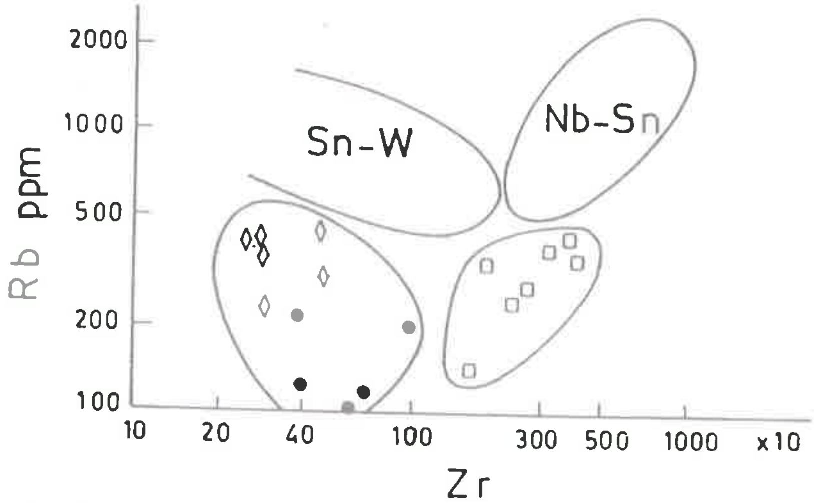

Fig. 7. Nb-Sn and Sn-W fields of the Tonglo complex, Northern Nigeria (Imeokparia, 1985); Rb-Zr plot.

such HHP granites. The HHP granites act as 'heat engines' which prolong the circulation or ore-bearing fluids which concentrate the metals.

Kinnaird and co-author (1985) have recognized the following types of subsolidus hydrothermal alteration processes in the Nigerian HHP granites. These processes are similar to those of the prophyry-type copper formation.

Sodic metasomatism: Mineralogically, this involves the conversion of original perthitic feldsper into albite and the grwoth or new micas in the compositional range protolithionite to zinnwaldite. Chemically, sodic

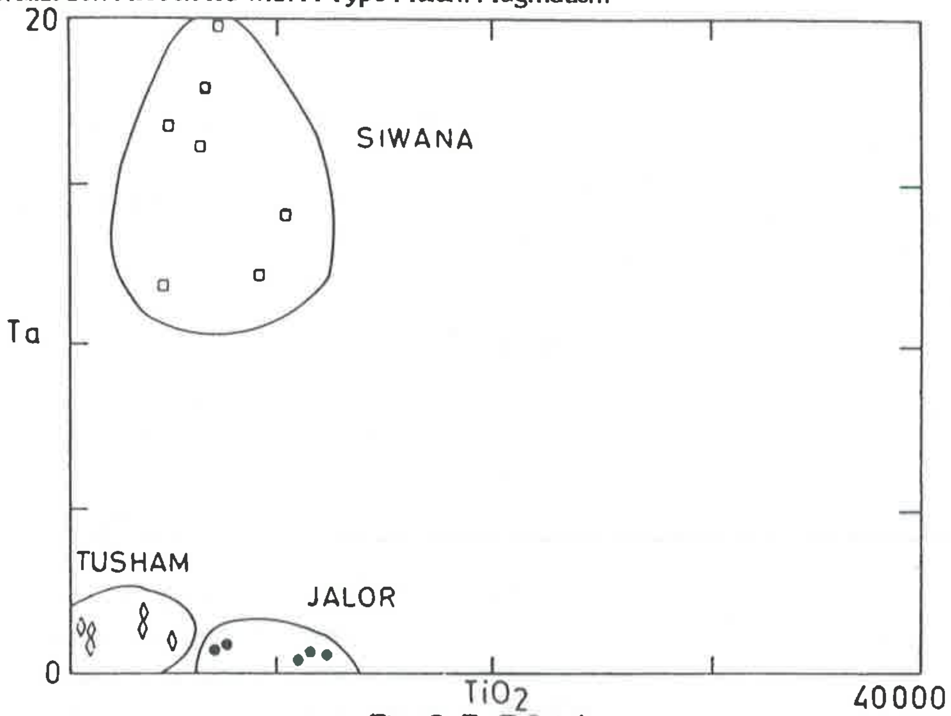

Fig. 8. Ta-TiO_2 plot.

metasomatism shows an increase in Na and Fe and a decrease in K. There is a substantial enrichment of all REEs, particularly in the peralkaline facies, which display an increase in all trace elements including high field strength Nb, Zr and Hf. The biotite granites show a substantial enrichment in Rb, Th, Nb, La, Ce, and Hf but sometimes depletions in Zn and Y. Sodic metasomatism is economically important for the formation of niobium-bearing ore minerals, pyrochlore and columbite. These are accompanied by uranium-enriched thorite, xenotime, Th-rich monzanite, Hf-rich zircon and cassiterite in biotite granites.

Potash metasomatism: Mineralogically, this is characterized by microclinization of feldspar due to the partial or complete replacement of sodium by potassium in the feldspars, often accompanied by haematitic reddening. There is development of new mica in the compositional range annite to ferrous siderophyllite. Chemically, there is an increase in K and a concomitant loss of Na. There is depletion in the whole rare earth spectrum combined with a similar decrease in most of the trace element although Sn and Zn are enhanced. Potash metasomatism is characterized by an assemblage of oxidic ores dominated by casiterite and wolframite with accessory molybdenite, and sphalerite.

Acid (hydrogen ions) metasomatism: There is a progressive breakdown of granitic minerals in response to changing K^+/H^+ ratios in the fluids. Perthite or microcline feldspar is destroyed and replaced by mica in the composition range siderophyllite/zinnwaldite and may be accompanied by sericite/chlorite/topaz/fluorite/cryolite. This mica-quartz assemblage corresponds to the process of greisenization.

Chemically, hydrogen ion metasomatism is characterized by a marked decrease in potash and alumina due to to feldspar breakdown and sometimes by an increase in Fe_2O_3 and SiO_2.

Silica metasomatism: Quartz may be deposited into vugs or may replace earlier formed minerals. The process of silicification shows an increased in silica balanced by a decrease in all the other major elements except iron. Sphalerite is the main ore.

Argillic alteration: This invloves formation of clays at the expense of fledspars. In the Tusham tin deposits the potassic zone (potash metasomatism) is very well developed (Kochhar, 1985). The muscovite-biotite granite (sample TG2) with which tin mineralization is associated in the area shows a marked depletion in all these. There is also a depletion in other trace elements (Fig. 2) compared to the Jalor and Siwana granites .

In fact, the acid volcanics of the north-eastern part of the Malani suite are potassic and those of the northern and north-western parts are mainly sodic. The loss of soda in potassic rocks has been attributed to hydrothermal alteration and devitrification (Kochhar *et al*., 1988; Pareek, 1981, 1986). The sodic acid volcanics may indicate the prevalence of sodic metasomatism.

Since the Malani rocks are interpreted as the Precambrian analogues to those of the Nigerian Younger Granite province, it is suggested that based on the above-mentioned pathfinder elements and alteration patterns, a systematic geochemical exploration for Sn, Nb, U, Th, W, Mo, Be, Li, and REE in the Malani HHP rocks be carried out. The Tusham area has already shown a potential for tin and related mineralization. It may be mentioned here that Kochhar (1973) had earlier suggested that the Tusham and Jalor granites should be explored for tin and related mineralization.

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