CHAPTER - V

PETROGENESIS

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PETROGENESIS OF THE GRANITOIDS

The evolutionary path of a magma is controlled by a number of factors including temperature, pressure, water fugacity and oxygen fugacity. Although exact estimation of these variables at magmatic conditions is often difficult because of changes imposed by late magmatic processes, several approaches have been evolved to approximate the values and effect of these variables on evolutionary paths.

There are problems in assessing the relative roles of different processes such as partial melting, fractional crystallization, crustal assimilation, mixing of magma etc. in the generation of granite liquid. White and Chappell (1977) proposed a restite unmixing model as the main process of evolution of some granitoids. Mathematical models suffer from inherent limitations in a way that they depend on geological variables like estimation of exact composition of source rocks, identification and establishment of residual mineral assemblages, bulk partition coefficients etc., specially for felsic rocks which are not yet well understood and their exact estimation is often very difficult. For this reason mathematical models have not been taken into account, instead qualitative models have been employed.

Normative composition, plotted on the Qz-Ab-Or diagram (Fig. 45) shows the cluster of plots away from Or-apex. Any clear trend, either calc-alkaline or gabbro-trondhjemite (Arth *et al.*, 1978) can not be deciphered from the diagram. Majority of the biotite granitoid and leucogranitoids plot between cotectic 1 and 4 kb water vapour pressure,

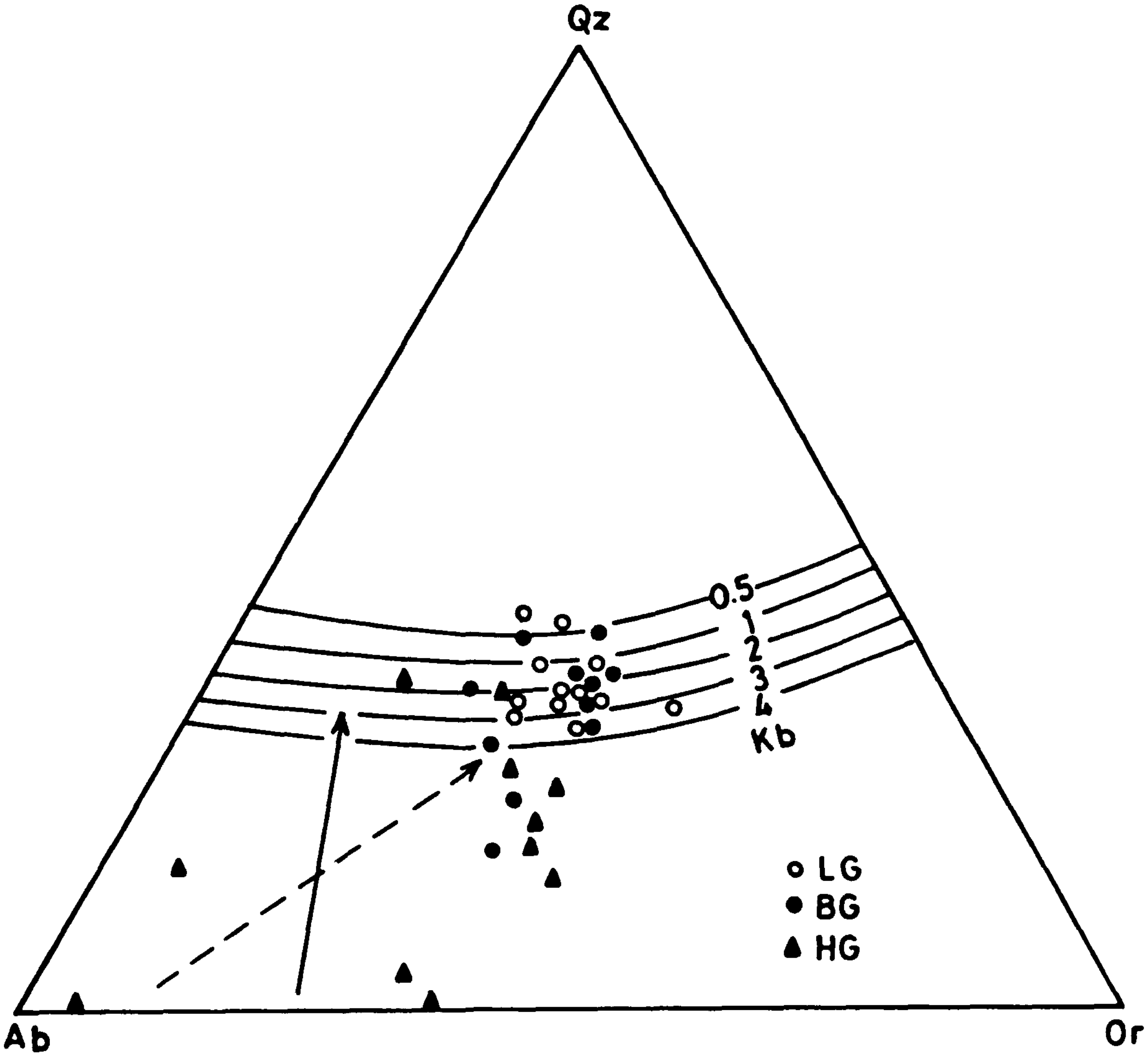


Fig. 45 : Normative Qz - Ab - Or plots of Bundelkhand granitoids. Co-tectic curves for the Qz - Ab - Or-H_2O system are from Tuttle and Bowen (1958). Trends : dashed arrow calc-alkaline, solid arrow gabbro - trondhjemite (Arth et al., 1978). Symbols : HG hornblende granitoid, BG biotite granitoid, LG leucogranitoid.

whereas the hornblende granitoids mostly plot well below 4 kb cotectic curve. The Bundelkhand granitoid samples define a path which is very close to the experimentally determined path followed by a trachytic liquid fractionating a single feldspar and evolving towards a quarternary minimum (Tuttle and Bowen, 1958).

The presence of alkali-feldspar phenocrysts in the younger phases of granitoids may point to moderate water content of the melts because at intermediate water contents below saturation levels, alkali-feldspars will grow at a faster rate than the plagioclase or quartz (Swanson, 1977). Early crystallization of hornblende and biotite and lack of pyroxenes have been interpreted to be suggestive of water content greater than 4 or 5% in the melt (Noyes *et al.*, 1983). The strongly perthitic nature of the K-feldspars may indicate the emplacement of the granitoids at a medium crustal level of 10-12 km (Poli and Tommasini, 1991). Plots of granitoids of M parameter against Zr, where M=cationic (Na+K+2Ca)/(Si. Al), are shown in Fig. 46 (after Watson and Harrison, 1984). Isotherms of magmas saturated with zircon are also displayed in the figure. The plots of granitoids cluster within 800°C and 930°C isotherms. The higher M values (>1) of the hornblende granitoids are consistent with complete solubility of zircon in the melt at magmatic temperatures (Watson and Harrison, 1984).

Fractional Crystallization

The variation of major elements against SiO_2 (Fig. 40) display smooth trends broadly consistent with evolution of magma by fractional crystallization process. Crystal fractionation produces curved trends as a consequence of systematic adjustment of compositions of the phases which form solid solutions. Rayleigh fractional crystallization

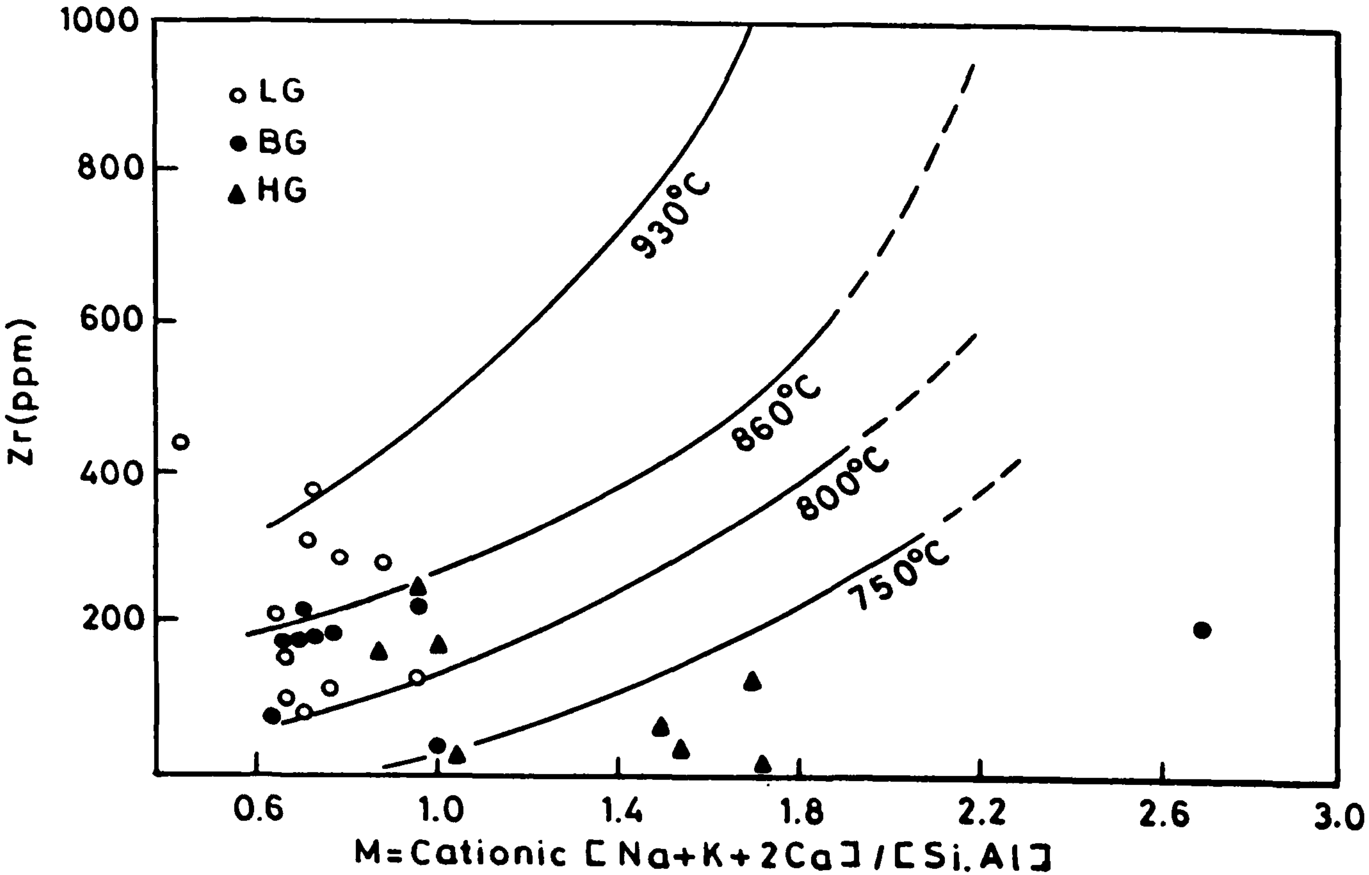


Fig. 46: Plot of M value (Watson and Harrison, 1984) against Zr showing isotherms for temperatures in the range of 750 °C-930 °C for the Bundelkhand granitoids. Symbols : as in Fig. 45.

can produce straight line trends on bivariate diagrams only if the bulk distribution coefficient of the two elements involved are same and if there is no change in the fractionating mineral phases (Poli and Tommasini, 1991). Although some curved as well as straight line trends in major elements vs. SiO_2 diagram (Fig. 40) can be discerned, a fractional crystallization process may not be considerd to be dominant process for the evolution of the massif because the trace elements do not show continuous and smooth variation trends (Fig 41) which is expected for a composite massif evolved by fractional crystallization process from a common parent magma. The evolution of the granitoids by fractional crystallization process is also discarded from other observations which include the predominance of monzogranite in association with minor quartz diorite and absence of syn-plutonic basaltic rocks. The long geological time span (2.5-2.2 Ga) for different granitoid phases does not favour a fractional crystallization process involving same parental magma.

On Zr vs. TiO_2 diagram (Fig. 42), the trend of plots of hornblende granitoids is not similar to the trends shown by the rest of the granitoids. This indicates that the whole massif could not have evolved from a common parental magma. Perhaps the hornblende granitoids like the mafic magmatic enclaves represent unrelated magma type and are derived by partial fusion of upper mantle. The broad gentle slopes on Co vs. Th, Rb, Ta diagram (Fig. 47) and Rb vs. Sr diagram (Fig 43) are inconsistent with fractional crystallization as a process for the evolution of granitoids. The REE patterns are also not suggestive of a model of fractional crystallization involving a common parental magma for the evolution of the massif. However, fractional crystallization may have played an important role within an individual

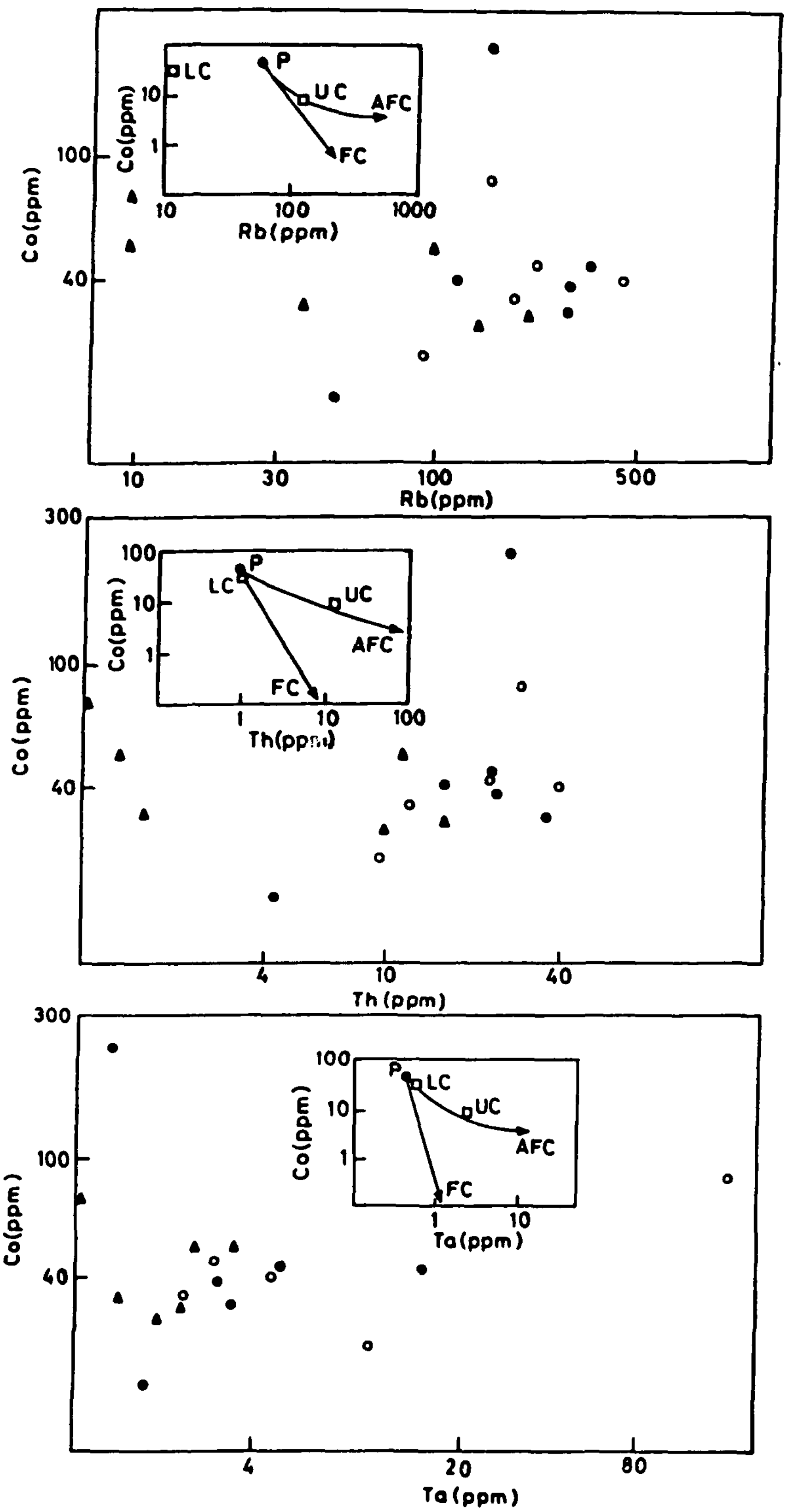


Fig. 47 : Plots of Co vs. Ta, Th and Rb for Bundelkhand granitoids. Explanations of insets are given in the text. Symbols : as in Fig. 45.

granitoid phase as evident from TiO_2 vs. Zr (Fig. 42), Sr vs. Rb and Ba (Fig. 43) plots.

Two End-Member Mixing

The linear to near-linear trends of the major elements of the Bundelkhand massif on element-element diagram (Fig. 48) may be indicative of magma mixing. Following the simple two end-member mixing model of Langmuir *et al.* (1978), a set of diagrams (Fig. 48) have been utilized. These diagrams are based on trace element ratios vs. trace element concentration e. g. Rb/Sr vs. Sr and Co/Th vs. Sr; corresponding "companion" plots e.g. Rb/Sr vs. 1/Sr and Co/Th vs. 1/ Th have also been constructed (Fig. 49). Although plots of Rb/Sr vs. Sr display hyperbolic trend consistent with simple two end-member mixing, such trends for other parameters are not observed. Neither any hyperbolic trend for Co/Th vs. Sr plots nor the straight line trend for companion plots (Rb/Sr vs. 1/Sr and Co/Th vs. 1/Th) can be distinctly discerned from Fig. 48. As such a simple two end- member mixing model does not seem to be the main process of the evolution of massif. Trace element ratio vs. trace element plots are useful for assessing the concentration of an element from the asymptote to the hyperbola if the curvature of the hyperbola is not very large. Thus, from the asymptote of Rb/Sr vs. Sr plots (Fig. 48), it is estimated that Sr concentration in the liquid end -member may be about 50 ppm.

Although hyperbolic trend in Rb/Sr vs. Sr diagram (Fig. 48) is indicative of simple two end-member mixing, such hyperbolic trends and straight line trend in "companion" plot are not observed for other elements e.g. Co/Th vs. Sr, Rb/Sr vs. 1/Sr and Co/Th vs. 1/Th (Fig. 48).

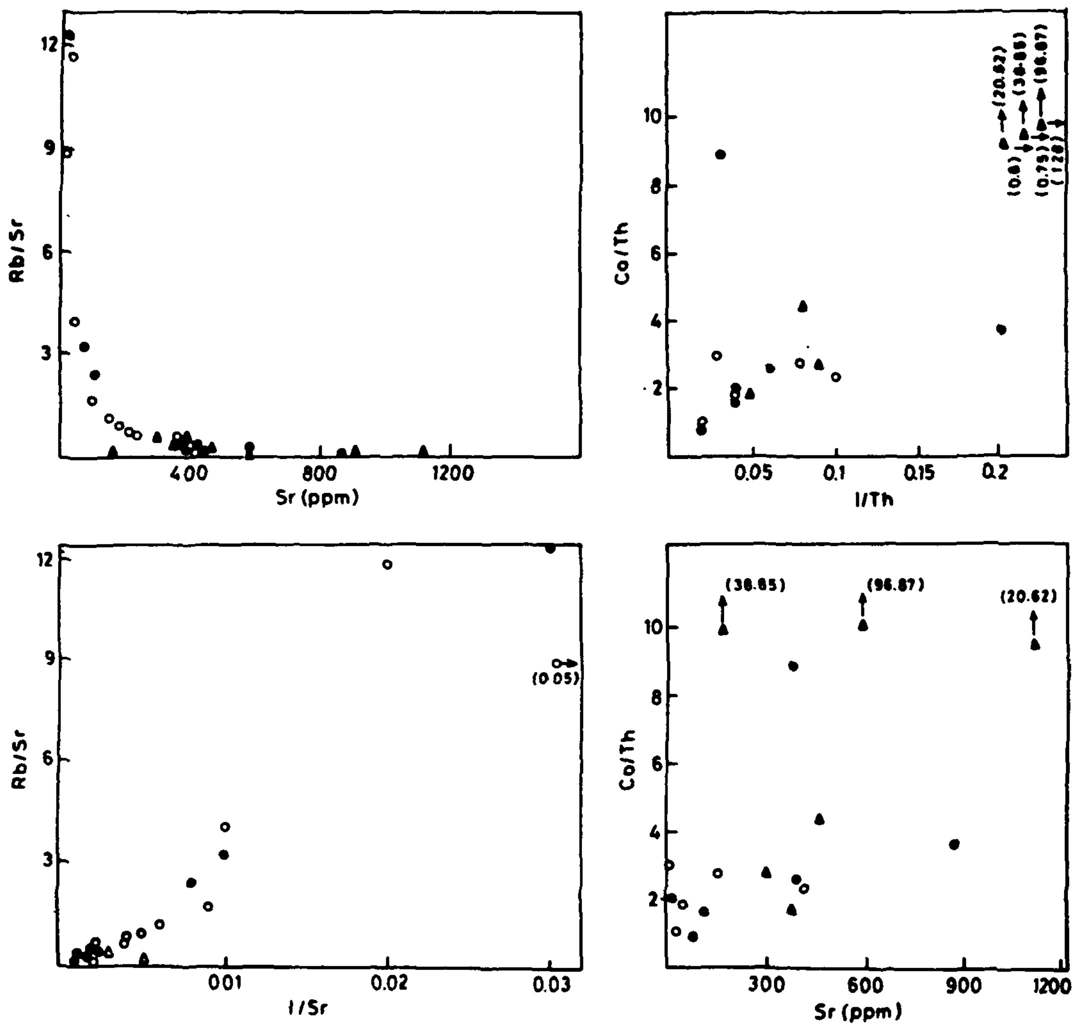


Fig. 48 : Diagrams of trace element ratios vs. trace element and companion plots of Bundelkhand granitoids. Symbols : as in Fig. 45.

Further, Langmuir *et al.* (1978) point out that even though samples may plot on the apparent mixing path, this does not prove that such process occurred. The simple two end-member mixing model is inconsistent with the great scattering of data, particularly of the trace elements on element-element plots (Fig. 41).

Restite Unmixing

The straight to near-straight line trends on bivariate diagram (Fig. 40) may be indicative of restite unmixing. A strong linear correlation for every element is implicit in restite model. White and Chappell (1977) have described a number of textural features of a number of phases which are thought to be restites. The best single evidence of the presence of restite is the irregular patchilly zoned and corroded plagioclase cores. They argue that other primary restite phases like clinopyroxene, hornblende, garnet, cordierite and orthopyroxene are most likely to be destroyed during slow cooling of a granitic pluton, whereas the restite plagioclase in all probability be preserved as cores since the plagioclase core is shelled from the system by zoning. Chappell *et al.* (1987) suggested that restite plagioclase tend to be unzoned because of slow and prograde metamorphism of the source rocks. However, the criteria for recognition of restite has been controversial. Wall *et al.* (1987) found that criteria for the recognition of restite phases are not unequivocal.

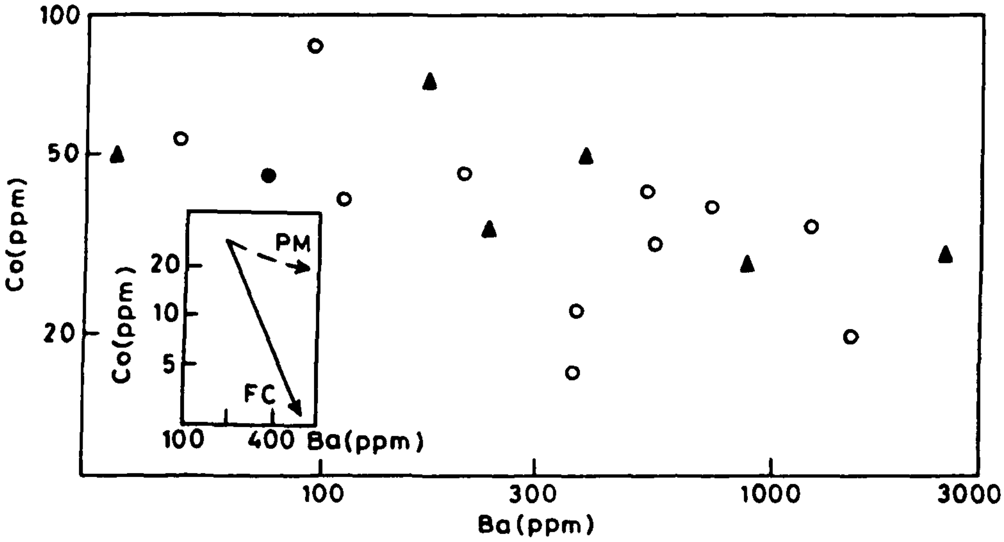
Petrographically, no restite phase including restitic plagioclase have been observed in the granitoids; the plagioclase in the granitoids are typically zoned. Large departures from linear correlation on element-element plot are observed. The scattering of majority of the elements on covariate diagrams coupled with typical zoned plagiocle is not consistent with restite unmixing model.

Partial melting, Assimilation-Fractional Crystallization

Diagrams involving compatible-incompatible elements have widely been utilized to assess the relative importance of fractional crystallization and partial melting. Plots of compatible (Co) vs. incompatible elements (Th, Rb, Ta) for Bundelkhand granitoids are shown in Fig. 47 with the generalised fractional crystallization (FC) and assimilation-fractional crystallization (AFC) trends (insets) of Ayuso and Arth (1992). The elemental abundances of average lower crust (LC) and upper crust (UC) are also shown (Taylor and Mc Lennan, 1985) in Fig. 47. The plots on Fig. 47 define a broad gentle slope inconsistent with fractional crystallization and follow the trend of assimilation-fractional crystallization (AFC) with quartz gabbro as parent assimilating with rocks similar in composition of upper crust. From the gentle slope on Rb vs. Sr diagram (Fig. 43), partial melting (PM) trend can be deciphered. Ba vs. Ni and Co plots (Fig. 49) for Bundelkhand granitoids correspondence to partial melting trend (Martin, 1987).

PETROGENESIS OF THE MAFIC MAGMATIC ENCLAVES

The nature and origin of the enclaves in general and the mafic magmatic enclaves (MME) in particular has been a subject of great enigma. Different hypotheses have been put forward to account for the MME or microgranular enclaves as referred by Didier (1973). Chappell *et al.* (1987) suggested that microgranular enclaves may represent restite or unmelted part of the source rock, whereas Vernon (1984)



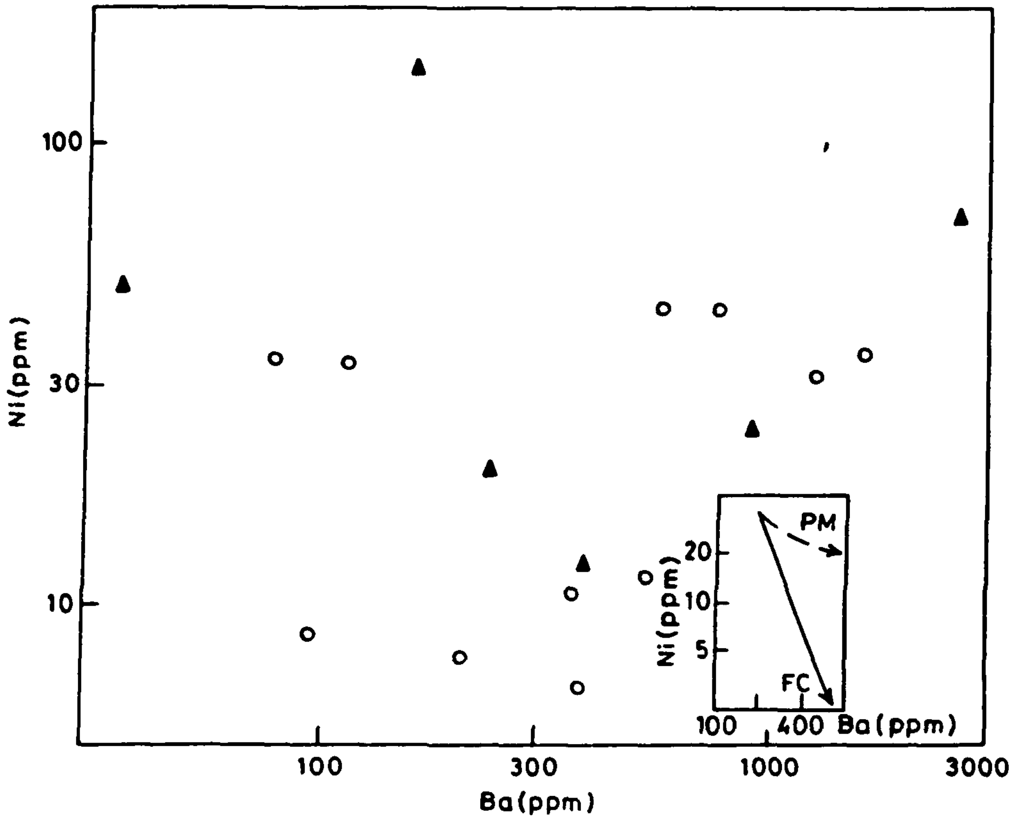


Fig. 49 : Ba vs. Ni and Co plots for Bundelkhand granitoids. Generalised trends (insets) for fractional crystallization (FC) and partial melting (PM) are from Martin (1987). Symbols : as in Fig. 45.

considered them to be blobs of basic magma derived from the mantle. Any mechanism to account for the origin of the mafic magmatic enclaves should incorporate field, petrographic and geochemical observations.

The chondrite normalised (Sun and Mc Donough, 1989) multi-element plots of the representative granitoids have been compared with those of the MME in Fig. 50. The enclaves are enriched in Ba, Rb, Sr, K and P. They are also enriched in LREE and contain higher amount of HREE (Fig. 44) than do their host granitoids. These features coupled with enrichment of Ba, Rb, Sr, K and P can be explained by metasomatic enrichment of mantle source by large ion lithophile elements, LREE and P_2O_5.

From field and petrographical observations, a restite origin of the enclaves is discarded. The enclaves have ellipsoidal shapes and exhibit fine grained textures. Extreme degree of fragmentation of the enclaves is observed. The enclaves display magmatic texture. Restite phase including restitic plagioclase cores has not been observed in enclaves. The zoned plagioclase alongwith other textural features including fine grain size, quench-like textures of the enclaves is inconsistent with a restite origin. The presence of acicular apatite in the enclaves may indicate undercooling (Reid *et al.*, 1983; Vernon, 1983). These features favour a melt derived origin of the enclaves.

Strong linear correlation for every element on bivariate diagrams which is implicit in the restite model is not observed. On Harker's variation diagrams (Figs. 40 & 41), large departures of the plots of enclaves from linear trends are observed. The scattering of majority of the elements in covariate diagrams can not be explained by the restite

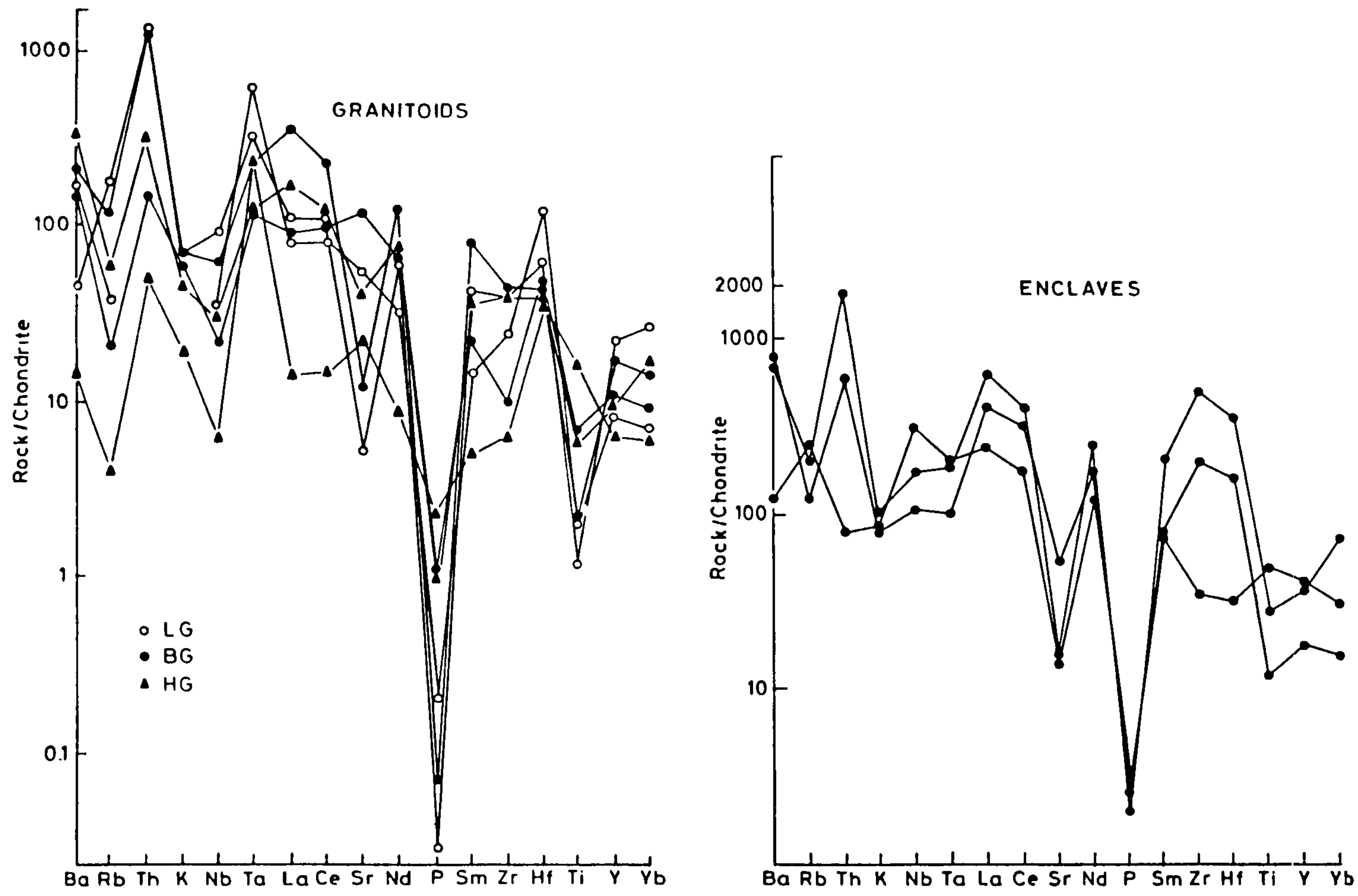


Fig. 50 : Chondrite normalised (Sun and Mc Donough, 1989) major and trace elements spidergram. Symbols : HG hornblende granitoid, BG biotite granitoid, LG leucogranitoid.

unmixing model. The scattering shown by the enclaves and the hosts may be due to the chemical potential gradients of the enclaves and the host magma interface; the extent of attainment of chemical potential, in turn, depends on the size of the enclaves and the compositional difference of the host and the enclaves (Dorais *et al.*, 1990). A non-restite origin of the MME of Bundelkhand granitoids have been proposed by Mondal and Zainuddin (in press) from field, petrographic and geochemical observations.

It is suggested that basic rock produced by partial melting of mantle wedge which was enriched by subduction zone components was ripped off and carried by granitic magma. The caught up basic rock represents mafic magmatic enclaves within the batholith.The properties and distribution of the enclaves can be understood by applying fractal geometry (Mandelbort, 1982) and chaotic theory (Ottino, 1989).

POSSIBLE SOURCE REGION

A number of samples of hornblende granitoid have very low values of Rb/Sr indicative of derivation from mantle source. Some of the hornblende granitoids and biotite granitoids are metaluminous and have I-type characteristics and have probably formed by partial fusion of an igneous protolith. These granitoids also exhibit cafemic magmatic associations. The cafemic magmatic associations are believed to have been produced exclusively from mantle source or hybrid source of the mantle and crust with major contributions coming from the mantle (Debon and Le Fort, 1982). Thus it seems that the hornblende granitoids are produced either from mantle or from a hybrid source with major contributions from mantle.

A few samples of the biotite granitoids and leucogranitoids exhibit peraluminous geochemistry. The peraluminous nature of the granitoids is probably not due to derivation from sedimentary protolith as the mineral assemblages of the granitoids do not support a sedimentary parentage. The peraluminous nature is explained by greater degree of assimilation of crustal rocks during late stage. Early crystallization of hornblende, which is a crucial mineral in Bundelkhand batholith may explain the peraluminous nature of the later phases of the granitoids.

The Y/Nb ratio of the granitoids of Bundelkhand massif is in general greater than 1.2 which is a characteristic geochemical feature of magmas derived from sources chemically similar to island arc or continental margin basalts (Eby, 1990). The depleted nature of the granitoids in terms of high field strength elements (HFSE) may suggest refractory Ti-bearing residual phase in the source (Briqueu *et al.*, 1984; Arculus and Powell, 1986). Lower concentration of Nb can be accounted for by retaining hornblende and garnet in the source during partial melting.