SUMMARY
AND
CONCLUSION

SUMMARY AND CONCLUSION

The Bundelkhand massif of late Archean to Paleoproterozoic age occupies an area of about 26,000 sq km in the central part of Indian peninsula. The massif is a composite body composed mainly of granitoid rocks. It is overlain by the younger rocks of Bijawar and Vindhyan groups and Indo-Gangetic alluvium. The massif is traversed by a number of quartz veins and basic dykes. Previous investigations on the massif have mainly been restricted to the determination of the petrological diversity of the massif. Very little work has been undertaken to understand the petrogenesis of the granitoids. The basement into which the granitoids were emplaced has remained poorly defined. Significant effort has not been undertaken to elucidate the geodynamic setting of this region.

The present work involves studies to determine the nature and origin of the granitoids and the basement complex. An attempt has been made to decipher the tectonic evolution of the massif. Geochemical characteristics of temporally and spatially distributed granitoids of the massif were correlated. Nature and possible origin of the mafic magmatic enclaves which are very wide spread within the massif have also been studied.

The geology of the Bundelkhand region is complex because the massif represents a protracted history of evolution with contrasting petrological units. The dominant petrological episode has been the series of granitoid magmatism which in all probability has obliterated the earlier events. On the bases of field relations, three genetically and compositionally distinct granitoid phases have been deciphered and delineated, they are hornblende granitoid, biotite granitoid and leucogranitoid, in order of age.

The granitoids were emplaced into a basement consisting of gneisses, migmatites, banded iron formations with other metasediments, basic to felsic volcanics etc. which probably constituted an Archean greenstone belt. In the southern margin of the massif, ultramafic rocks are exposed. The banded iron formations are unevenly distributed, whereas the gneissic rocks are mainly exposed in the northern parts of the massif. The banded iron formations as well as the gneissic rocks are intensely deformed. The intruding granitoids are generally undeformed which indicates that the granitoids were emplaced in an already deformed basement.

Field evidence support an igneous origin of the granitoids; any evidence favouring metasomatic or metamorphic origin of the granitoids has not been observed. Although the granitoid plutons are mostly underformed, at places they have suffered shearing and have acquired foliation.

Hornblende granitoid, a dark coloured hornblende bearing rock, is the oldest granitoid unit of the massif. The granitoid is very massive and compact, the grain size is coarse and uniform. The high concentration of ferromagnesian phases imparts dark colour to the rock. The biotite granitoid, a medium to coarse grained pink coloured rock, is intrusive into hornblende granitoid. The main ferromagnesian phase of biotite granitoid is biotite. The rock exhibits porphyritic texture; the phenocrysts are mainly feldspars. The leucogranitoid is the youngest granitoid phase of the massif, it is greyish white to greyish pink in colour. The grain size of the granitoid phase varies from fine to coarse and contain minor amount of ferromagnesian constituents.

The Bundelkhand massif hosts a number of mafic magmatic enclaves which vary greatly in terms of shape, size, orientation and composition. The mafic magmatic enclaves (MME) are always finer than their host granitoids and are mostly ellipsoidal in shape; they range widely in size from few millimetres to few metres. Contact of MME with the host granitoids is mostly sharp. Interaction between the enclaves and the host granitic magma is exhibited by diffuse contacts of the enclaves with the host granitoids at some places. Extreme degree of fragmentation of the enclaves is also observed. The MME does not appear to be part of disrupted basic dykes.

The Bundelkhand granitoids are all one-mica granitoids containing biotite only in addition to quartz, plagioclase and K-feldspars. Hornblende is present only in the two older varieties, i.e. hornblende granitoid and biotite granitoid. Apatite, zircon, sphene and magnetite are common accessories. The secondary minerals are represented by chlorite, epidote and sericite. There is petrographic evidence of limited grain-boundary-controlled alteration.

The different types of granitoid have generally similar mineralogy; however, the difference in relative proportion of various phases is observed. The older hornblende granitoid and biotite granitoid have higher modal proportion of ferromagnesian minerals and plagioclase. In younger leucogranitoid, ferromagnesian constituents are negligible; hornblende is totally absent, whereas biotite is rare or occurs as traces. The content of K-feldspars and quartz concomitantly increases in leucogranitoid. Magnetite when present occurs in general in association with hornblende and biotite.

The mafic magmatic enclaves (MME) are composed of pyroxene, hornblende, plagioclase and magnetite; K-feldspars are rare. MME have higher content of ferromagnesian phases and plagioclase and lower content of quartz and K-feldspars than do their host granitoids. Apatite, in general is acicular in MME, but is stubby in host granitoids The enclaves display magmatic texture. The restite phase has not been observed either in granitoids or in MME.

The granitoids cover large compositional spectrum on the IUGS (modal) classification scheme. The hornblende granitioids are restricted to quartz diorite and quartz monzodiorite fields, whereas biotite granitoids are concentrated within tonalite and monzogranite fields; the leucogranitoids are clustered within monzogranite and syenogranite fields. The granitoids as a whole define a calc-alkaline granodiorite (medium-k) trend on quartz-alkali feldspar and plagioclase diagram.

Bundelkhand granitoids closely correspond to I-type in terms of the concentrations of highly charged cations e.g. Zr, Ce, Nb, Y, Ga and Al with affinities towards A-type. From A/CNK values of the granitoids which range from 0.4 to 1.4, it may be inferred that the granitoids have both I- and S-type affinity. Other I-type features of the granitoids include presence of CIPW normative diopside or <1% CIPW normative corundum and absence of muscovite, whereas the S-type characters include > 1% CIPW normative corundum. It may be concluded that the Bundelkhand granitoids have I-, S- and A-type characteristics; a number of hornblende granitoids have very low values of Rb/Sr indicative of M-type granites. One plausible explanation for the apparently contradictory I- and S-type characters of Bundelkhand granitoids may be that the granitoids seem to have formed by partial fusion of an igneous protolith and as a consequence the granitoids acquired I-type features. At a later stage the magma may have undergone assimilation of country rocks thereby masking the I-type characters with S-type. A-type characters may be due to increasing mantle contributions at the later stage of granitoid formation

Majority of the granitoids plot in the calc-alkaline field on AFM diagram and on the ternary diagram based on the cation per cent of Al, Fe + Ti and Mg Calc-alkaline trend of the granitoids is also evident from K-Na-Ca diagram. Mafic magmatic enclaves show alkaline affinity on AFM diagram. On R1-R2 multicationic diagram, the majority of the samples are alkali-calcic. However, different granitoid types of the massif range from calcic through calc-alkaline to alkali-calcic On "characteristic minerals" or "A-B" diagram, the Bundelkhand granitoids correspond to cafemic to alumino-cafemic magmatic associations.

Almost all major elements exhibit linear to near-linear trends against SiO_2 A wide scattering is observed for all the trace elements on Harker's diagram The curved trend on CaO vs. SiO_2 and positive correlation on CaO vs Sr may indicate plagioclase fractionation Negative correlation of elements like CaO, MgO, Fe_2O_3(T), TiO_2 and Cr with SiO_2 and positive correlation of K_2O and Rb with SiO_2 are indicative of hornblende fractionation. Further, the decreasing Sc content with increasing SiO_2 is also indicative of amphibole fractionation The inter-elemental relationship of Rb and Sr contents of the granitoids may be correlated with biotite and plagioclase fractionation The variation trends of Sr vs Ba reflect biotite and K-feldspar fractionation. Two distinct trends can be discerned from TiO_2 vs. Zr diagram. The trend shown by hornblende granitoids is consistent with biotite fractionation, whereas the rest of the granitoids correspond to fractionation trends produced by plagioclase plus biotite and/or hornblende. K/Rb values for different phases of Bundelkhand granitoids range from 95 to 373 which, in general, is compatible with calc-alkaline suites elsewhere.

The granitoids as well as the enclaves display greater variability in REE fractionation; both of them exhibit LREE enrichment. The Yb contents of the hornblende granitoids are similar to the classical Archean tonalite, trondhjemite, granodiorite suites having low Yb content ($Yb_N<8.5$), whereas the biotite granitoids and the leucogranitoids, in respect of Yb content are more similar to post-2.5 Ga granitoids emplaced in subduction zone environment where Yb content is high $4.5<Yb_N<20$. Almost all the samples have negative Eu anomalies except for a few which have either no anomaly or slight positive Eu anomaly. The fractionated REE patterns and HREE depletion may point to the retention of garnet and/or hornblende in residue. The REE patterns of the biotite granitoids and leucogranitoids, in general, closely correspond to those of calc-alkaline intermediate volcanic rocks of continental margin geodynamic setting.

Plots of normative composition on the Qz-Ab-Or diagram are concentrated away from Or-apex. Majority of the biotite granitoids and leucogranitoids plot between cotectic 1 and 4 Kb water vapour pressure, wheras the hornblende granitoids mostly plot well below 4 Kb cotectic curve. The granitoids 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. Early crystallization of hornblende and biotite, lack of pyroxenes and presence of alkali-feldspar phenocrysts may point to greater than 4 or 5% water content in the melt. The M parameter of Watson and Harrison (1984) indicate 800°C to 930°C temperature for the formation of the granitoids.

Although smooth variation trends of major elements against SiO_2 are broadly consistent with the evolution of magma by fractional crystallization process, it may not be considered to be the dominant process for the evolution of the massif because the trace elements do not show continuous and smooth variation trends expected for a composite massif evolved by fractional crystallization from a common parent magma. The fractional crystallization process is also discarded from other observations which include the predominance of monzogranite in association with minor quartz diorite. 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, the trend of plots of hornblende granitoids does not coincide with the trend shown by the rest of the granitoids thereby indicating that all the granitoid types are not comagmatic. Further, the broad gentle slopes on Co vs. Th, Rb and Ta diagrams, on Ba vs. Ni and Co plots and on Rb vs. Sr diagram are inconsistent with fractional crystallization. However, fractional crystallization may have played an important role within an individual granitoid phase.

Although the samples sometimes plot along the predicted trends, the granitoids do not always follow the mixing model. Moreover, the simple two end-member mixing model is hard to reconcile with the great scattering of data, particularly of the trace elements on element-

element plots Restite unmixing model also does not seem to be a viable mechanism since the strong linear correlation for every element on element-element diagrams which is implicit in restite model is not observed for the granitoids No restite phase has also been observed

Plots of compatible (Co) vs incompatible elements (Th, Rb, Ta) of Bundelkhand granitoids define a broad gentle slope closely following the assimilation-fractional crystallization trends From the gentle slope of Rb vs Sr, partial melting trend can be deciphered It may be concluded that the dominant process for the evolution of the granitoid massif is partial melting, the magma at a later stage may have undergone assimilation-fractional crystallization

The mafic magmatic enclaves are enriched in Ba, Rb, Sr, K and P They are also enriched in LREE and contain higher amount of HREE 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 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 melt represents mafic magmatic enclaves within the massif From field, petrographic and geochemical observations, a restite origin of the enclaves is discarded

Samples of different types of granitoids were plotted on a number of tectonic discrimination diagrams based on Rb vs Y + Nb, Yb + Ta and Nb vs Y Majority of the samples plot in the volcanic arc granite field on these diagrams On SiO_2 vs Rb diagram, the granitoids plot in the fields of volcanic arc and syn-collision granites On SiO_2 vs Rb/Zr diagram, the Bundelkhand granitoids plot in the combined field of volcanic arc granite and late or post-collision granite. The ocean ridge granite normalised spidergrams of the granitoids exhibit close resemblance with the patterns of volcanic arc granitoids. The patterns are marked by enrichment of K_2O, Rb, Ba, Th relative to Ta, Nb, Hf, Zr with significant low values of Y and Yb.

The granitoids of the Bundelkhand massif show a progressive change in composition from calc-alkaline to alkali-calcic from southern region to northern part. This change in composition may reflect increase in arc maturity. Granitoids from northern region which are predominantly alkali-calcic show marked depletion in Ba, Sr, P and Ti compared to those from southern region which are predominantly calc-alkaline in nature. Such trends are compatible with increasing arc maturity. The Bundelkhand granitoids show a selective enrichment of Th compared to Ta and follow the trend of subduction related source variation.

On the bases of field and geochemical features akin to volcanic arc granitoids, it is proposed that the granitoids of Bundelkhand massif represent an arc-related tectonic setting associated with subduction of an oceanic plate under a continental margin. The gravity high along the southern margin of the massif which possibly indicates obduction of ophiolite and mafic-ultramafic suites in the southern margin of the massif which possibly indicate the existence of an ocean and consequent subduction of the ocean from the southern side of the massif. The apparent lack of typical ophiolite, blue schist facies metamorphic rocks and continental margin sedimentary rocks can alternatively be accounted for by involving "A-subduction" in which subcontinental lithosphere sinks in an ensialic environment. The mafic dyke swarms may also be related with A-subduction, where the source of the dykes is thought to be mafic material emplaced into a rheological weak zone in the lithosphere and later transforms to eclogite to initiate A-subduction. The abundance of mafic dyke swarms in the southern portion of the massif may point to possible A-subduction environment in the southern portion of the massif.