A bimodal LIP and the plume debate: The Palaeoproterozoic Dongargarh Group, central India

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ABSTRACT

A bimodal LIP with sub-equal volumes of near-coeval felsic-mafic volcanic rocks occurs in the ~2500 Ma Dongargarh Group, central India – perhaps the only LIP of this kind known to date. Although some of its features match the predictions of the plume model, the longer eruption times (~≤30-73 Ma) and bimodal distribution of lava types do not. Melting of crust and mantle, driven by a common thermal perturbation in an extensional tectonic setting, and interactions of the crustal and mantle melts, gave rise to the province. This contrasts with contemporary mantle-melting or crust-melting models for LIP genesis.

Keywords: rhyolite, high-Mg basalts, crust-mantle, large igneous province (LIP), plume, Palaeoproterozoic, India

INTRODUCTION

Large igneous provinces (LIPs) are generally considered to comprise two types:

1. Mafic LIPs (MLIPs; Bryan and Ernst, 2006), also called Large Basaltic Provinces (LBPs; Sheth, 2007), as typified by Continental Flood Basalts (CFB), which are short-duration eruptive events of mantle melts with volumetrically insignificant felsic lavas erupting late in the history of volcanism (e.g., the Deccan Traps; Melluso et al., 2006 and references therein).

2. Silicic-dominated igneous provinces (SLIPs) with <10% basalts, e.g., the Early Cretaceous volcanic rifted margin, eastern Australia (e.g., Bryan et al., 2002), the Jurassic Chon Aike Province, South America, the Antarctic Peninsula (e.g., Riley and Leat, 1999; Pankhurst et al., 1998) and the Neoproterozoic Malani igneous province in NW India (e.g., Sharma, 2004). These are thought to be the products of crustal melting, the mantle providing the heat. SLIPs may have comparable eruptive volumes to CFBs, but their duration of emplacement may be up to 40-60 Ma (e.g., Bryan et al., 2002; Ernst and Buchan, 2001).

Here, I describe a third type of LIP from central India – a bimodal LIP with sub-equal proportions of felsic and mafic volcanic rocks, the Palaeoproterozoic Dongargarh province (Sensarma, 2005; Sensarma et al., 2004). It is perhaps the only bimodal LIP known to date (e.g., Foulger, *this volume*), hitherto considered absent from the geological record (Bryan et al., 2002). This province has felsic rocks early in the sequence, something not commonly reported.

Contemporary models for LIP genesis consider thermal anomalies in the form of mantle plumes rising from deep within the mantle (e.g., Ernst et al., 2005; Campbell. 2005; Courtillot et al., 1999; Morgan, 1971), compositional heterogeneity and enhanced fertility in the upper mantle coupled with processes consequential to plate tectonics (e.g., Foulger and Anderson, 2005; Foulger et al., 2005), and lower-crustal delamination that recycles continental mantle lithosphere into the asthenosphere and triggers eruptions of flood basalts (e.g., Lustrino, 2005; Tanton and Hager, 2000). The purpose of the present contribution is to highlight the uniqueness of the Dongargarh province where substantial melting of both the crust and mantle was apparently driven by a common thermal perturbation.

I first critically appraise stratigraphic, geochronological, petrographic and geochemical constraints to illustrate how different source regions were involved and interacted over a period of ~30-73 Ma at ca. 2500 Ma. I then evaluate features of the Dongargarh LIP in terms of the predictions of the plume model, and briefly discuss the implications. The major conclusions are that LIPs are more diverse than previously thought, and that large-scale crust-mantle interactions could be a plausible mechanism for LIP genesis that has not, to date, been considered in contemporary models.

GEOLOGIC SETTING

The Dongargarh volcanic-sedimentary succession in the central Indian Craton, called the Dongargarh Group (DG) (Figure 1), is 10-12 km thick, 80-100 km wide, and extends southerly for ~300 km into Kotri area (Bastar). The DG is folded into the regional 'Sitagota Syncline' and is metamorphosed to low-grade greenschist facies. Magmatism in the belt took place in an extensional setting (e.g., Sensarma et al., 2004, 2000; Krishnamurthy et al., 1990), and is presumably related to global Neoarchaean-Palaeoproterozoic rifting (e.g., Blake and Groves, 1987).

The litho-stratigraphic units within the DG (Table 1) form a structurally concordant sequence without any regional unconformity (Sensarma and Mukhopadhyay, 2003). The volcanics (Figure 2) comprise sub-equal volumes of felsic pyroclastic rocks (average SiO_2 ~75 wt %, ≤ 4 km thick) and mafic lava flows which together constitute about two-thirds of the preserved stratigraphy. The basal felsic volcanic rocks (the Bijli Rhyolite) are followed by three mafic volcanic rock formations, interspersed with volcanogenic wacke and quartz arenite respectively. Two mafic volcanic formations, the Pitepani Volcanics (PV, ~1 km thick), and the more voluminous younger Sitagota Volcanics (SV, >3 km thick) (Table 1), have inter-layered high-Mg basalts (MgO ~7.5-12 wt %) and low-Mg basalts (MgO ~6 wt %). Volumetrically minor andesite (Sensarma, 2001) to basaltic andesite (Neogi et al., 1996) (<1 km thick) constitutes the youngest unit. Granitic plutons (the Dongargarh Granite) intrude the DG. The felsic volcanic rocks underlie the mafic lava flows in Kotri area also. The Amgaon Gneissic Complex with vestiges of TTG suite of rocks (U-Pb zircon date 3562 ± 2 Ma) are unconformably overlain by the volcanics in Kotri area, and thus possibly constitute the Archaean basement to the Kotri-Dongargarh rocks (Ghosh, 2004). However, our field mapping in the northern part of the belt could not confirm this observation (Sensarma, 2001; Sensarma and Mukhopadhyay, 2003).

Although the Dongargarh Granite intruded the DG, the rhyolites and Dongargarh Granite have close geochemical similarities, and are products of the same tectono-thermal event (see Roy et al., 2000 and references therein). Hence, the felsic volcanic-plutonic activity in the belt is approximately coeval - the Dongargarh Granite represents a continuation of the magmatic event that initially produced the rhyolites. The high- and low-

Mg basalts are compositionally distinct (e.g., Figures 3a, c). A genetic connection exists between the felsic volcanic rocks and the basalts in both the PV and the SV, as the compositions of all of these either vary within close range or show smooth trends on immobile refractory-element-ratio plots such as e.g. Ta/Th, La/Sm, Sm/Nd, Zr/Y, Ta/La (Figures 3b, d, e). The mafic rocks are more tholeiitic than komatiitic, and the relationship between the PV and the SV is discussed in the next section.

COMPOSITIONS OF THE VOLCANIC ROCKS

The geochemical data discussed here include those of Neogi et al. (1996), Asthana et al. (1996) and Sensarma, (2001). In the last of these, concentrations of major oxides and trace elements such as Rb, Ba, Sr, Zr, Y, Ni, Cr were determined using XRF, whereas other trace and rare earth elements were determined using INAA at the Institüt für Mineralogie und Geochemie, Köln (Germany).

The geochemical details of high-silica rhyolite are provided in Sensarma (2001) and Sensarma et al. (2004). These are characterized by high contents of silica ($SiO_2 \geq 74$ wt %), LILE (Rb >100 ppm, Cs >1 ppm, K >2.4 wt %), HFSE (Zr >270 ppm, Nb >18 ppm, Ta >1.5 ppm, Hf >4.1 ppm, Y >28 ppm) and REE (La >31.9 ppm, Sm >6.1 ppm, Eu >0.17 ppm, Lu >0.36 ppm). In addition, they have $Na_2O + K_2O > 6.8$ wt %, $FeO_t/MgO > 8$. Combined with low contents of CaO (≤ 1 wt %), Ba (<1000 ppm) and Sr (<80 ppm), these characteristics point to an 'A-type' granitic composition. A high eruption temperature (900-950ºC) is indicated for the melts (Sensarma et al., 2004). The Bijli Rhyolite is the only preserved felsic volcanic unit in the area.

The mafic volcanics in the PV and SV, separated by volcanogenic wacke of Chandsuraj Formation (Table 1), are intrinsically similar in composition. The high-Mg basalts are generally characterized by MgO ~7.5 -12 wt % at SiO_2 ~50-52 wt %, the maximum MgO measured is 15.3 wt % (sample no. 8, Neogi et al., 1996). These rocks have Na_2O + K_2O >2 wt %, FeOt ~9.5 wt %, TiO_2 ~0.5 wt %, Al_2O_3/TiO_2 (~22; Figure 3a), CaO/Al_2O_3 ~0.8, Mg# ≥60, Ni up to 250 ppm, and are sub-alkaline basalts to basaltic andesites (Figure 2). On the basis of IUGS classification for high-Mg volcanic rocks, the rocks can be classified as basalts, with few samples as picrite (samples with MgO >12 wt %).

The high-Mg basalts in the PV have higher SiO_2 (~54 wt %; Figure 3c), LILE (e.g. Rb, Ba, Sr) and LREE at a given Mg#. These rocks differ from other common volcanic rocks, including boninite, and are designated Siliceous High Magnesian Basalts (SHMB) following Sensarma et al., (2002, and references therein). The mantle-derived Koolau and Lanai tholeiitic basalts in Hawaii are known to have high SiO_2 contents (SiO_2 >51 wt %). When compared with high-silica Koolau (Frey et al., 1994) and Lanai (West et al., 1992) lavas, the SHMB in the Dongargarh province have higher SiO_2 (≥54 wt % vs. 51-53 wt %), higher alkali (Na_2O + K_2O: ~3.5 wt % vs. ≤3.5 wt %), but lower FeO (~9.5 wt % vs. 10-12 wt %) and Al_2O_3 (≤13 wt % vs. ≥13 wt %), and significantly low TiO_2 (~0.5 wt % vs. ~2 wt %) values at comparable MgO contents. Generally lower SiO_2, LILE and LREE contents, but higher MgO, Mg#, Ni and Cr values, indicate a more primitive character for the SV high-Mg basalts.

The low-Mg basalts in PV and SV have MgO 6-8 wt % at SiO_2 ~48-50 wt %, FeOt ~12 wt %, TiO_2 ~1 wt %, Mg# ≤52, Ni <150 ppm, Al_2O_3/TiO_2 (≤16; Figure 3a) and CaO/Al_2O_3 (≤0.7) and are compositionally similar to Continental Flood Basalts (CFB). Thus, it seems that two batches of basalt, one with high Mg and the other low Mg, erupted in pulses, first to form the PV, and then the thicker SV within the DG. The larger volume in the younger pulse (the SV) may be attributed to a higher magma supply rate with increasing extension of the lithosphere.

The high-Mg basalts are related to a parental more Mg-rich magma by olivine fractionation (Sensarma et al., 2002). On the basis of the thermometer of Niu (2005: $T^{\circ}C = 1026e^{0.01894 \times MgO\ wt\%}$), and taking the picrite sample so far known to have maximum MgO in the province (MgO = 15.3 wt %; Neogi et al., 1996) as parental melt, a temperature of 1370˚C is-estimated. The primary liquid with higher MgO would have higher temperature. The ol-normative low-Mg tholeiites (MgO ~6-8 wt %), on the other hand, may have been crystallized from a lower temperature (1149ºC -1193ºC; Niu, 2005) magma.

SIZE OF THE PROVINCE

The volumes of erupted melts and their original areal extent are difficult to estimate because the rocks are deformed and have been subjected to prolonged erosion. The present areal extent of the felsic and mafic volcanic rocks is roughly estimated at ~30,000 sq. km. The size of the near-coeval Dongargarh Granite further adds to the volume, perhaps to a major extent. The relationship between the mafic volcanics of comparable age in the southern part of the craton (i.e., the sub-alkaline basalts, basaltic andesite, high-Mg basalts; Srivastava et al., 2005 and references therein), and the Dongargarh mafic volcanic rocks in the northern part is unknown. Thus, although the estimated area of the DG is smaller than the minimum size suggested for a LIP (≥ 50000 sq km; Sheth, 2007, in press; Coffin and Eldholm, 1994), the original size of the province may have been much larger. In any case, the appropriate lower size limit for a LIP is controversial, and the size of igneous provinces may form a continuous spectrum (see http://www.mantleplumes.org/TopPages/LIPClassTop.html)

DURATION OF MAGMATIC ACTIVITY

The age data in the province are sparse, and mainly from the felsic rocks. Nevertheless some important constraints may be derived from the available U-Pb data. The U-Pb single-crystal zircon dating of the oldest and youngest rhyolite yielded emplacement ages of 2525 ± 15 Ma and 2506 ± 4 Ma respectively (Ghosh, 2004) indicating a span of ≤38 Ma for felsic volcanism in the area. The intrusive Dongargarh Granite is correlated to the well-known Cu-Mo-Au-bearing Malanjkhand Granite, located about 120 km north of the DG in the craton. The U-Pb zircon ages of the Malanjkhand granite yield 2478 ± 9 Ma and 2477 ± 10 Ma (Panigrahi et al., 2002). An age of ~2500 Ma is also obtained by Re-Os geochronology in molybdenite from the Malanjkhand deposits (Stein et al., 2004). So the Dongargarh Granite is possibly of similar age. Although there are no isotopic age data for the mafic rocks, the U-Pb zircon age constraints for the rhyolites, and the granitic activity in the province together suggests that the DG (including sedimentary components) may have been formed between ~2540 Ma and ~2467 Ma i.e. within a period of ~73 Ma, but surely longer than ~38 Ma. The total duration of formation of the DG is thus reasonably similar to the age range (40-60 Ma) suggested for SLIPs (e.g., Bryan et al., 2002; Ernst and Buchan, 2001).

CONTEMPORANEITY OF FELSIC AND MAFIC VOLCANISM

The Dongargarh belt is characterized by eruptions of separate, but in part coeval, felsic and mafic magmas. The evidence for near-contemporaneous rhyolitic and basaltic magmas is as follows.

Petrographic evidence

Many rounded enclaves of plagioclase-phyric basalt are found in the Bijli Rhyolite. Several basaltic enclaves contain quartz xenocrysts with rounded embayed margins and sharp extinction, similar to those present in rhyolites. Also, pumice in felsic rocks from several localities has vesicles filled with devitrified basaltic glass. The textural relations, including rounded margins of the enclaves, imply that the basaltic melts were incorporated into rhyolite while both were in a molten state. This is suggestive of mingling of felsic-mafic melts in the area, and argues for near-contemporaneity of both melts.

Chemical evidence

In the basaltic fractionation model, a large amount of basalt is needed, and it would produce only a small amount of derivative felsic melt. Also, continuous ranges of differentiated product of a basaltic magma like andesite, dacite and rhyodacite should occur in spatial proximity. The presence of a 'Daly Gap' (Figure 2) and a large volume of rhyolite in the province therefore do not support such an origin for the Bijli rocks. The spread in the concentration of elements compatible in feldspar and Fe-Ti oxides in the samples (e.g., Sr, Ba Eu, Ti) (Figure 4) may then indicate fractional crystallization of feldspar and Fe-Ti oxides, presumably from crust-derived melts.

Evidence for crustal involvement in rhyolite genesis includes the presence of a silica gap (Figure 2), the similarity of initial $^{87}Sr/^{86}Sr$ ratios of the rhyolites to the crustal value (~0.703) at ~2500 Ma (0.70305 ± 0.0017; Krishnamurthy et al., 1990; 0.7057 ± 0.0015; Sarkar et al., 1981), high alkali and HFSE contents. Low Ta/Th (0.06-0.08) as obtained in many Bijli samples (Figures 3b, d), in comparison to bulk continental crust (BCC: Ta/Th = 0.19; McLennan, 2001), are encountered in granulites (Rudnick and Presper, 1990). Combined with high eruption temperature (900-950ºC), and lower than expected values of LILE (e.g., Rb, U) in some samples (Figure 4) these observations could indicate contribution of a deeper crustal material into the Bijli Rhyolite. On the other hand, shallow melting of a possible calc-alkaline granitic source may also be responsible for generation of these rhyolites with depressed Al, Ca and Sr contents, as demonstrated by Patiño Douce (1997) for the generation of metaluminous A-type liquids. Large variations in incompatible element concentrations in high-silica rhyolites are often caused by crystallization of accessory phases with high concentrations in these elements. This may also partly be attributed to source heterogeneity at different crustal depths. So, partial melting of the regional crust at various depths seems reasonable for the origin of the Bijli rhyolite. Subsequent fractional crystallization may have magnified the variation particularly in trace element chemistry.

A La/Sm diagram is an efficient method for constraining magmatic processes, crustal- and mantle-melts interactions. On a La/Sm vs. Ta/Th plot (Figure 3b), La/Sm (~3-6.5) ratios in the high-Mg basalts (PV and SV), particularly in the PV, overlap with some of the rhyolites (5-11) at similar Ta/Th values. The Sm/Nd and Zr/Y values in the PV (Figures 3d, e) also overlap or plot close to those of rhyolites.

Olivine fractionation, by which the high-Mg basalts are related to a more MgO-rich parental picritic melt, cannot increase the La/Sm ratios in the melts, because both elements are highly incompatible in olivine. We have shown earlier that an enriched, depleted or hydrous mantle source is unsuitable, because such melts are not consistent with high-Mg basalts in PV i.e. SHMB composition (see Sensarma et al., 2002). The comparison of these SHMB with high-SiO_2 Hawaiian tholeiites, considered to have recycled subducted materials in their source (West et al., 1992) provides further evidence that an enriched mantle source cannot give rise to SHMB composition. So, the elevated La/Sm in high-Mg basalts in PV (Figure 3b) must have resulted from assimilation of rhyolite compositions. The overlapping Sm/Nd and Zr/Y values in the rhyolites, and high-Mg basalts in PV (Figures 3d, e) support the model. The higher SiO_2 contents in high-Mg basalts in PV compared to many high-Mg basalt samples in SV at comparable Mg# (Figure 3c) further suggests additional silica supply into high-Mg basalts in PV. 15-20 % input of rhyolitic melts into a parental high-Mg melt is suggested for the origin of the high-Mg basalts in PV (Sensarma et al., 2002). A lesser extent of assimilation may explain the lower La/Sm ratios (~3-4) and lower SiO_2 contents in the younger high-Mg basalts. The increase in high-Mg basalt volumes concomitant with decline in rhyolite input upwards in SV may suggest higher rates of magma supply with drop in pressure in a widening rift, as mentioned earlier.

The low-Mg basalts, on the other hand, maintain typical tholeiitic basalt compositions, and have La/Sm values (~2-4.5) much lower than the rhyolites and not far from primitive mantle (PM) (~2; Figure 3b). In other plots also (Figures 3d, e), the low-Mg basalts move away from rhyolites and plot closer to the PM signifying that they may be relatively uncontaminated. The inability of low-Mg basalts to assimilate rhyolite may be attributed to lower temperatures (~1150ºC), i.e. lower heat content.

In summary, crustal melts and mantle-derived high-Mg basalts interacted closely to form geochemically hybrid rhyolites and basalts, especially in the older mafic volcanic pulse (PV). This undoubtedly suggests a coeval nature for the rhyolites and basalts.

TESTING A PLUME ORIGIN

The predictions of the plume model include eruption of high-temperature magmas with high MgO content in the range of 18-22 wt %, a high rate of melt production and increase in the eruptive volume in later, syn- or post - rift pulses. There may be precursory or syn-eruption uplift, and emplacement of lavas within typically 1-5 Ma (Ernst et al., 2005; Campbell, 2005).

The picture that emerges from the discussion above is that (i) major felsic-mafic magmatism in Dongargarh is related in time and space, and duration of emplacement of the lavas took ~30-73 Ma, reasonably comparable to durations found for silicic LIPs (40-60 Ma; e.g., Bryan et al., 2002; Ernst and Buchan, 2001), (ii) eruptions of ~1350ºC picritic magma erupted as part of the igneous activity, (iii) pulsatory mafic volcanism occurred, with melt volumes in the second pulse (the SV) exceeding those of the first (the PV), (iv) felsic-mafic melt interactions probably decreased with time in the SV. Some of these features match the predictions of the plume model.

However, there are certain discrepancies also, particularly concerning duration of emplacement of the lavas. Total emplacement duration was not as short as 1-5 Ma, as suggested by Campbell (2005). On the other hand, SLIPs, though they have comparable emplacement duration to that of the Dongargarh volcanics, do not characteristically include the large volumes of mafic lavas that occur in the Dongargarh province. The MgO content (15.3 wt %) of the presumed parental picritic magma is less than the suggested MgO values for parental melts in the plume model.

Thus, the Dongargarh LIP does not unequivocally exhibit all the characteristics predicted by the plume model. At the same time, large-scale near-coeval genesis of mafic-felsic melts and their interactions, leading to the generation of a wide range of melt compositions, are not part of contemporary non-plume models either.

IMPLICATIONS AND CONCLUSIONS

Studies of LIP genesis have either considered mantle melting or crustal anatexis. It is of great significance that a common process of crust-mantle interaction is primarily responsible for building the bimodal LIP in Dongargarh. The major conclusions of this study are:

(1) Bimodal LIPs exist, in addition to mafic and silicic LIPs.

(2) Melting of both crust and mantle below Dongargarh, driven by a common thermal perturbation, along with interactions of the melts, gave rise to the province. The thermal perturbation existed for longer (~60 Ma) than the few million years generally reported for LIPs.

(3) This kind of close interactions between crustal and mantle melts over a longer duration contrasts with contemporary models for LIP genesis.

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References

Asthana, D., Dash, M. R., Pophare, A. N., and Khare, S. K., 1996, Interstratified low-Ti and high-Ti volcanics in arc-related Khairagarh Group of Central India, Current Science, v.71, no. 4, p. 304- 306.

Blake, T. S. and Groves, D. I., 1987, Continental rifting and the Archean-Proterozoic transition, Geology, v. 15, p. 229-232.

Bryan, S. E. and Ernst R. E., 2006, Proposed revision to large igneous province classification, www. mantleplumes.org/LIPClass2.html.

Bryan, S. E., Riley, T. R., Jerram, D. A., Stephens, C.J. and Leat, P. T, 2002, Silicic volcanism: an undervalued component of large igneous provinces and volcanic rifted margin. In: Menzies, M. A., Klemperer, S. L., Ebinger, C. J., and Baker, J., eds., Volcanic Rifted Margins, Geol. Soc. Amer. Spec. Paper, v. 362, p. 99-120.

Campbell, I. H., 2005, Large Igneous Provinces and the Mantle Plume Hypothesis, Elements, v. 1, p. 265-269.

Coffin, M. F. and Eldholm, O., 1994, Large igneous provinces: crustal structure, dimensions, and external consequences, Review of Geophysics, v. 32, p. 1-36.

Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P., and Besse, J., 1999, On causal links between flood basalts and continental breakup, Earth Planet. Sci. Lett., v. 166, p. 177-195.

Ernst, R. E., and Buchan, K. L., 2001, Large mafic magmatic events through time and links to mantle-plume heads. In: Ernst, R. E. and Buchan, K. L., eds., Mantle Plumes: Their Identification Through Time, Geological Society of America Special Paper, v. 352, p. 483- 575.

Ernst, R. E., Buchan, K., and Campbell, I. H., 2005, Frontiers in Large Igneous Province research, Lithos, v. 79, p. 271-297.

Foulger, G. R. and Anderson, D. L., 2005, A cool model for the Iceland hotspot, Journal of Volcanology and Geothermal Research, v. 141, p. 1-22.

Foulger, G. R., Natland, J. H., and Anderson, D. L., 2005, A source for Icelandic magmas in remelted Iapetus crust, Journal of Volcanology and Geothermal Research., v. 141, p. 23-44.

Foulger, G. R., this volume, The “Plate” model for the genesis of melting anomalies, in Foulger, G. R., and Jurdy, D. M., eds., Plates, Plumes and Planetary Processes, Volume Special Paper ####, Geological Society of America, p. 000-000.

Frey, F. A., Garcia, M. O., and Roden, M. F., 1994. Geochemical characteristics of Koolau Volcanics: Implications of intershield geochemical differences among Hawaiian volcanoes. Geochimica et Cosmochimica Acta, v. 58. no. 5, 1441-1462.

Ghosh, J. G., 2004. Geochronological constraints on the evolution of the Kotri linear Belt and its basement. Records of the Geological Survey of India, v.136, part 2, p. 24-26.

Krishnamurthy, P., Sinha, D. K., Rai, A. K., Seth, D. K., and Singh, S. N., 1990, Magmatic rocks of the Dongargarh Supergroup, Central India-Their Petrological evolution and Implications on Mettallogeny, Geological Survey of India Special Publication, v. 28, p. 303-319.

Le Bas, M. J., Maitre, Le, Streckeisen, A and Zanettin, B., 1986, A chemical classification of volcanic rocks based on total alkali-silica diagram, Journal of Petrology, v. 27, p. 747-750.

Lustrino, M., 2005, How the delamination and detachment of lower crust can influence basaltic magmatism? Earth-Science Reviews, v. 72, p. 21-38.

McLennan, S. M., 2001, Relationships between the trace element composition of sedimentary rocks and upper continental crust, Geochemistry, Geophysics, Geosystems, v. 2, p. 2000GC000109, ISSN: 1525-2027

Melluso, L., Mahoney, J. J. and Dallai, L., 2006, Mantle sources and crustal input as recorded in high-Mg Deccan Traps basalts of Gujrat (India), Lithos, v. 89, p. 259-274.

Morgan, W. J., 1971, Convection plume in the lower mantle, Nature, v. 230, p. 42-43.

Münker, C., Pfänder, Jörg A., Weyer, Stefan., Büchl, Anette., Kleine, Thorsten., and Mezger, Klaus., 2003, Evolution of Planetary Cores and the Earth-Moon System from Nb/Ta Systematics, Science, v. 301, p. 84-87.

Neogi, S., Miura, H. and Hariya, Y., 1996, Geochemistry of Dongargarh volcanic rocks, Central India: Implications for the Precambrian mantle, Precambrian Research, v. 76, p.77-91.

Niu, Y., 2005, Generation and evolution of basaltic magma: Some basic concepts and new view on the origin of Mesozoic-Cenozoic basaltic volcanism in eastern China, Geol. J. China Univ., v. 11, p. 9-46

Palme, H. and O'Neill, H St. C., 2003, Cosmochemical estimates of mantle composition, Treatise On Geochemistry, v. 2; (ISBN: 0-08-044337-0); pp. 1-38.

Panigrahi, M.K., Misra, K. C., Brteam, B. and Naik, R. K., 2002, Genesis of the granitoid affiliated copper-molybdenum mineralization at Malajkhand, central India: facts and problems. Extended Abstract, In Proc. 11th Quadrennial IAGOD symposium and Geocongress, Windhoek, Namibia.

Pankhurst, R. J., Leat, P. T., Sruoga, P., Rapela, C. W., Márquez, M., Storey, B. C., and Riley, T. R., 1998, The Chon Aike silicic igneous province of Patagonia and related rocks in Antarctica: a silicic large igneous province, Journal of Volcanology and Geothermal Research, v. 81, p. 113-136.

Patiño Douce, A. E., 1997. Generation of metaluminous A-type granites by low-pressure melting of calc-alkaline granitoids, Geology, v. 25, no.8, p. 743-746.

Riley, T. R. and Leat, P. T., 1999, Large volume silicic volcanism along the proto-Pacific margin of Gondwana: lithological and stratigraphical investigations from the Antarctic Peninsula, Geological Magazine, v. 136, p. 1-16.

Roy, A., Ramachandra, H. M. and Bandopadhyay, B. K., 2000, Supracrustal belts and their significance in the crustal evolution of central India, Geological Survey of India Special Publication, v. 55, p. 361-380.

Rudnick, R. L. and Presper, T., 1990, Geochemistry of intermediate/- to high pressure granulites. In Vielzeuf, D and Vidal, Ph., eds, Granulites and Crustal Evolution, Kluwer Academic Publishers, Netherlands.

Sarkar, S. N., Gopalan, K. and Trivedi, J.R., 1981, New data on the geochronology of the Precambrians of Bhandara-Durg, Central India, Ind. J. Earth. Sci., v. 8, p. 131-151.

Sensarma, S. and Mukhopadhyay, D., 2003, New Insight on the stratigraphy and volcanic history of the Dongargarh Belt, central India, Gond. Geol. Magz. Spl. Vol.., v. 7, p. 129-136.

Sensarma, S., 2001, Volcanic Stratigraphy and Petrology of the Dongargarh belt near Salekasa-Darekasa, Bhandara district, Maharashtra., Unpublished Ph. D thesis, Jadavpur University, Calcutta.

Sensarma, S., 2005, The Dongargarh Group: A Large Igneous Province at the Archean-Proterozoic Transition in India. AGU Chapman Conference, The Great Plume Debate: The origin and impact of LIPs and hot spots, p. 87.

Sensarma, S., Hoernes, S., and Mukhopadhyay, D., 2004, Relative contributions of crust and mantle to the origin of Bijli Rhyolite in a palaeoproterozoic bimodal volcanic sequence (Dongargarh Group), central India, Proc. Indian. Acad. Sci. (Earth Planet. Sci.), v. 113, no.4, p. 619-648.

Sensarma, S., Palme, H. and Mukhopadhyay, D., 2002, Crust-Mantle interaction in the Genesis of Siliceous High Magnesian Basalts (SHMB): Evidence from the Early Proterozoic Dongargarh Supergroup, India. Chemical Geology, v. 187, p. 21-37.

Sensarma, S., Palme, H., Deloule, E. and Mukhopadhyay, D., 2000, Evidence of Liquid Immiscibility in the Early Proterozoic Andesitic rocks, Dongargarh Supergroup, Central India and Possible Tectonic Implication, Goldschmidt Conference, Oxford, p.101-102.

Sharma, K. K., 2004, The Neoproterozoic Malani magmatism of the northwestern Indian Shield: Implications for crust-building processes, Proc. Indian Acad. Sci. (Earth Planet Sci.), v. 113, no. 4, p. 795-807.

Sheth, H. C., 2007, Large Igneous Provinces (LIPs): Definition and recommended terminology, Journal of Volcanology and Geothermal Reserach (in press).

Srivastava, R. K., Singh, R. K. and Verma, Surendra P., 2004, Neoarchean mafic volcanic rocks from the southern Bastar greenstone belt, Central India: petrological and tectonic significance, Precambrian Research, v. 131, p. 305-322.

Stein, H. J., Hannah, J. L., Zimmerman, A., Markey, R. J., Sarkar, S. C. and Pal, A. B., 2004, A 2.5 Ga porphyry Cu-Mo-Au deposit at Malanjkhand, Central India: Implications for Late Archaean continental assembly, Precambrian Research, v. 134, p. 189-226.

Tanton, L. T. E. and Hager, B. H., 2000, Melt intrusion as a trigger for lithospheric foundering and the eruption of the Siberian flood basalts, Geophysical Research Letters, v. 27, p. 3937-3940.

West, H. B., Garcia, M. O., Gerlach, D. C., and Romano, J., 1992. Geochemistry of tholeiites from Lanai, Hawaii. Contributions to Mineralogy and Petrology, v. 112, p. 520-542.

Figure Captions

Figure 1:

Regional map of the Dongargarh province, central India. Map of India is shown in inset.

Figure 2:

Figure (after Le Bas et al., 1986) showing bimodal compositions of the volcanic rocks in the Dongargarh province. PV: Pitepani Volcanics, SV: Sitagota Volcanics, MV: Mangikhuta Volcanics. Stratigraphic positions for the volcanic formations are given in Table 1.

Figure 3:

(a) The high-Mg basalts in PV and SV (Mg# ≥60) have Al_2O_3/TiO_2 values ~22, whereas low-Mg basalts (Mg# ≤52) have Al_2O_3/TiO_2 ratios ≤16. Mg-numbers (Mg#): 100 x (Mg/(Mg + Fe^{2+})).

(b) A La/Sm vs. Ta/Th plot illustrating overlapping La/Sm values for the Bijli rhyolites and high-Mg basalts, particularly for high-Mg basalts (the PV), at Ta/Th (0.06-0.08), common in granulites. Low-Mg basalts, however, have lower La/Sm values and higher Ta/Th (0.1-0.2) values.

(c) The high- and low-Mg basalts are compositionally distinct on a SiO_2 wt% vs. Mg# plot. The high-Mg basalts in PV have higher SiO_2 concentrations (~54 wt %) compared to that of high-Mg basalts (SiO_2 ~50-52 wt %) in SV at comparable Mg# (60-64). Low-Mg basalts are compositionally similar to CFB.

(d) Several high-Mg basalt (PV) samples cluster with rhyolites (Sm/Nd ~0.15) implying close genetic relations. Sm/Nd (0.2-0.4) in low-Mg basalts is comparable to primitive mantle (PM: 0.32); for high-Mg basalts, Sm/Nd (0.2-0.6) show a larger spread.

(e) Zr/Y values in rhyolites, high-Mg basalts, low-Mg basalts and PM plot along a smooth curve suggesting genetic relationships. Note that high-Mg basalts (PV) plot closer to rhyolites, whereas low-Mg basalts (SV) lie at the other end, closer to PM. Primitive mantle

(PM) taken from Palme and O'Neill, 2003) and bulk continental crust from (McLennan, 2001). PV and SV: same as in Figure 2.

Footnote to Figure 3

The concentrations of major and trace elements (e.g., Rb, Sr, Zr, Y, Ni, Cr) were determined by XRF using fused glass discs. The analyses were made with a Philips PW 2400 XRF spectrometer, equipped with an automatic sample changer. Based on extensive comparison with standard rocks, XRF data accuracy is estimated to be <3%. For INAA data, about 100 mg powdered samples were irradiated in the carousel of the TRIGA reactor of the Institüt für Kernchemie, Universität Mainz (Germany), and subsequently counted on large Ge-detectors at the Institut für Geologie und Mineralogie, Universität zu Köln (Germany). INAA data precision is within 10%. Details of analytical techniques and accuracies obtained from inter-laboratory comparison are given in Sensarma et al. (2002) and references therein.

The Ta values are calculated from given Nb values for few selected mafic volcanic rock samples in Neogi et al. (1996) taking chondritic Nb/Ta = 19.9 (Münker et al., 2003)

Figure 4:

Primitive mantle (PM)-normalized incompatible elements plots of the Bijli Rhyolite. Negative Sr-, Eu-and Ti-anomalies are characteristic of the rocks. The plots show lower than expected Rb and U values in few samples. Primitive mantle data taken from Palme and O'Neill (2003).

Table 1. Litho- stratigraphic succession in the Dongargarh Province, central India (Sensarma and Mukhopadhyay, 2003).

The principal lithology of the stratigraphic units are given in corresponding parentheses.

Bijepar Formation (*arkosic wacke*)	
Unconformity	
Dongargarh Granite (*granite, granophyre, aplite*)	
Intrusive contact	
Mangikhuta Volcanics (*andesite / basaltic andesite*)	**Dongargarh Group**
Karutola Formation (*quartz arenite*)	
Sitagota Volcanics (*high-Mg basalts – low-Mg basalts*)	
Chandsuraj Formation (*pebbly volcanogenic wacke*)	
Pitepani Volcanics (*high-Mg basalts – low-Mg basalts*)	
Bijli Rhyolite (*felsic pyroclastic rocks*) (with Halbitola Rhyolitic breccio-conglomerate Member)	
Basement ? ?	

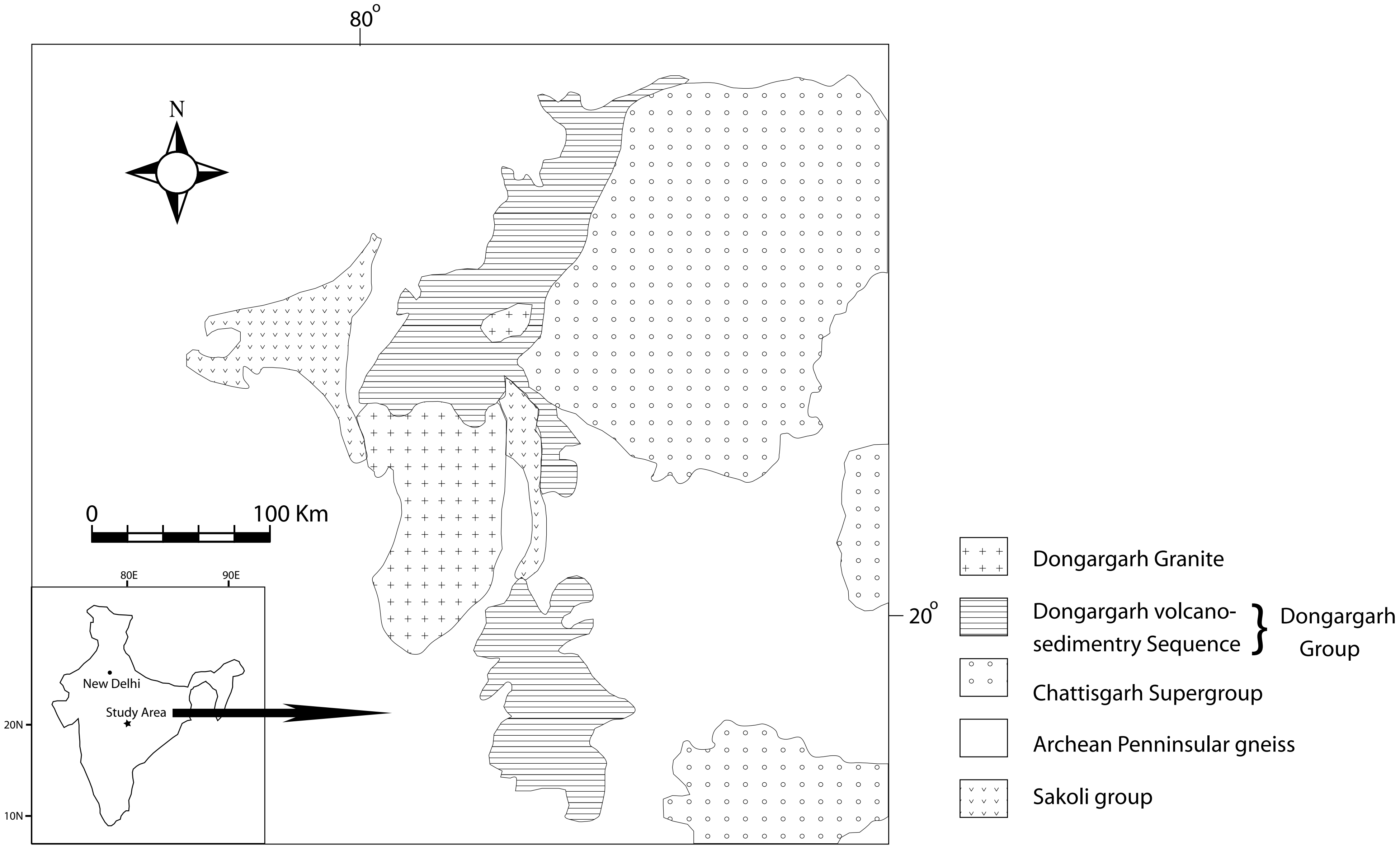
80°
N
0
100 Km
80E
90E
New Delhi
Study Area
20N
10N
20°
Dongargarh Granite
Dongargarh volcano-sedimentry Sequence
Dongargarh Group
Chattisgarh Supergroup
Archean Penninsular gneiss
Sakoli group

Figure 1

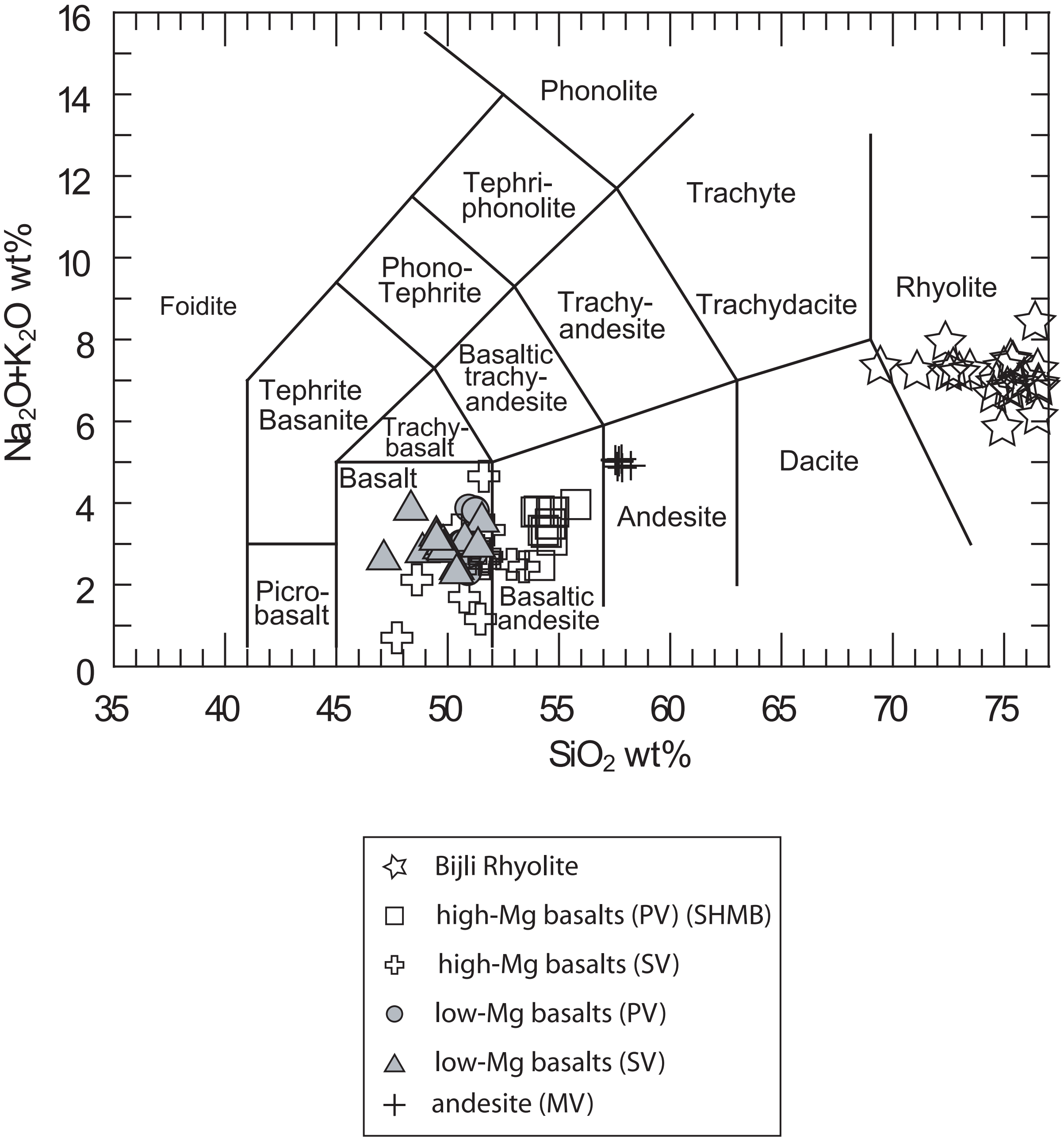
16
14
12
10
8
6
4
2
0
Na$_2$O+K$_2$O wt%
35
40
45
50
55
60
65
70
75
SiO$_2$ wt%
Phonolite
Tephri-phonolite
Trachyte
Phono-Tephrite
Foidite
Trachy-andesite
Trachydacite
Rhyolite
Basaltic trachy-andesite
Tephrite Basanite
Trachy-basalt
Basalt
Dacite
Andesite
Picro-basalt
Basaltic andesite
☆ Bijli Rhyolite
□ high-Mg basalts (PV) (SHMB)
✣ high-Mg basalts (SV)
● low-Mg basalts (PV)
▲ low-Mg basalts (SV)
+ andesite (MV)

Figure 2

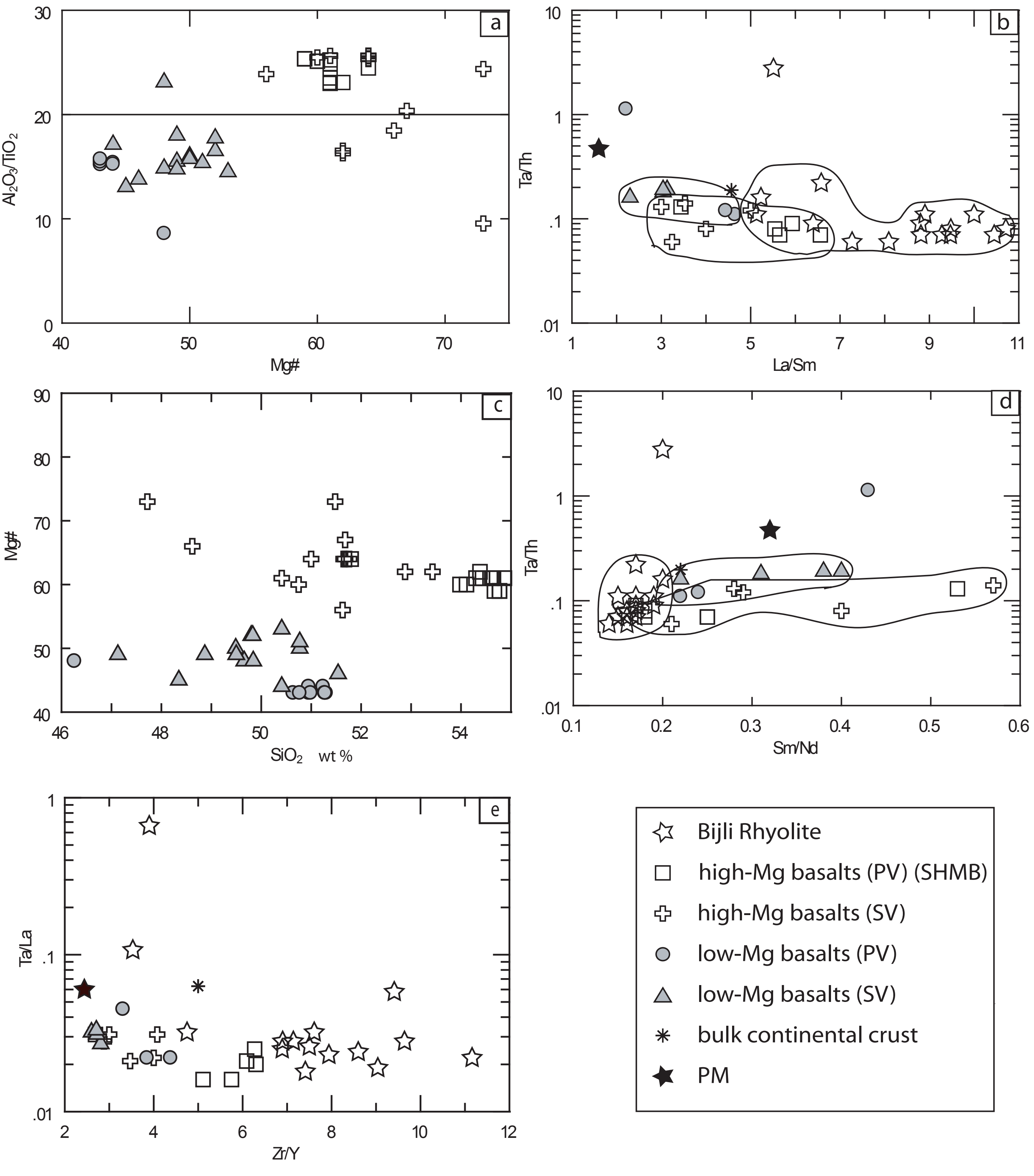
a
Al2O3/TiO2
30
20
10
0
40
50
60
70
Mg#
b
Ta/Th
10
1
.1
.01
1
3
5
7
9
11
La/Sm
c
Mg#
90
80
70
60
50
40
46
48
50
52
54
SiO2 wt %
d
Ta/Th
10
1
.1
.01
0.1
0.2
0.3
0.4
0.5
0.6
Sm/Nd
e
Ta/La
1
.1
.01
2
4
6
8
10
12
Zr/Y
☆ Bijli Rhyolite
□ high-Mg basalts (PV) (SHMB)
✙ high-Mg basalts (SV)
● low-Mg basalts (PV)
▲ low-Mg basalts (SV)
✳ bulk continental crust
★ PM

Figure 3

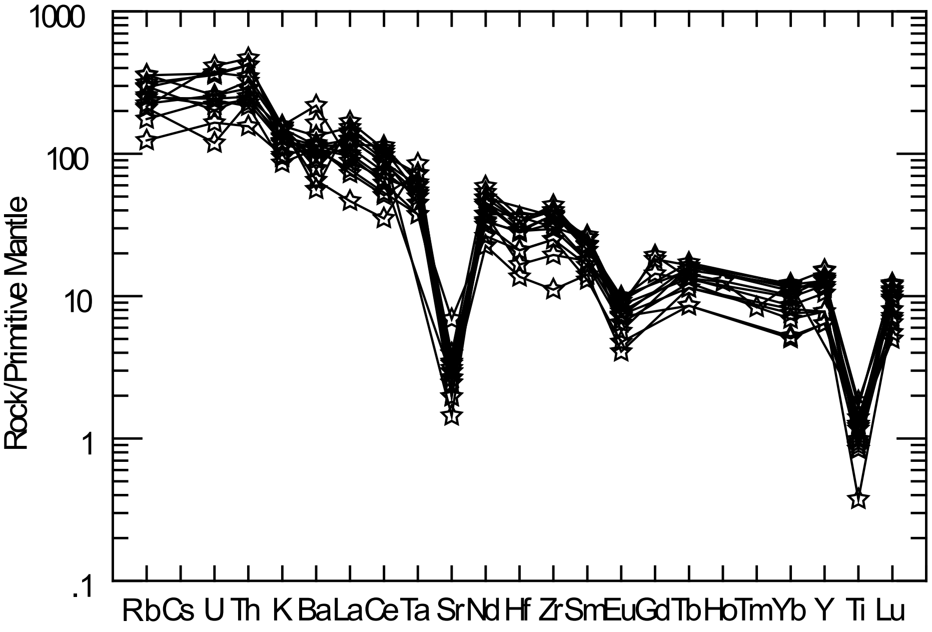
1000
100
10
1
.1
Rock/Primitive Mantle
Rb Cs U Th K Ba La Ce Ta Sr Nd Hf Zr Sm Eu Gd Tb Ho Tm Yb Y Ti Lu

Figure 4