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A review of research on Late Cretaceous volcanic-sedimentary sequences of the Mandla Lobe: implications for Deccan volcanism and the Cretaceous/Palaeogene boundary

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Abstract

Regional mapping and detailed petrographic studies of the volcanic-sedimentary sequences of the Mandla Lobe, coupled with lateral tracing has enabled the recognition of 37 physically distinct lava flows, and major oxide chemistry grouped them into eight chemical types. The lava pile becomes structurally complex to the east of Jabalpur where the juxtaposition of distinct groups of lava flows is observed near the Deori (flows 1–4 abutting flows 5–14) and Dindori areas. At Dindori, distinct lava packages (flows 15–27 and 28–37) are juxtaposed along the course of Narmada River, indicating the presence of four post-Deccan faults in the Nagapahar, Kundam, Deori and Dindori areas, and arguing against the idea of a small regional dip. Major geochemical breaks, when traced from section to section, exhibit shifts in height of approximately 150 m near Nagapahar and 300 m near Deori and Dindori. These findings, when considered in conjunction with magnetic chron reversal heights, support the presence of four NE–SW-trending faults. Major and trace element abundances in 15 lava flows in the Jabalpur area are similar to those of the south-western Deccan flows. The Ambenali Formation and a few flows of the Khandala and Bushe formations are present in north-eastern Deccan. Improved stratigraphic correlation is needed to define the lateral continuity and spatial distribution of the western-defined formations in regions to the east. The dominance of smectites in the detrital assemblage of the Lameta Formation suggests their derivation from a volcanogenic source rock. IR spectra support the commonality of the mineralogical attributes of the Lameta Formation and the Deccan basalt in their mutual resemblance of absorption bands. Structural formulae indicate that smectites of the Lameta deposits are rich in octahedral Mg and Fe. The abundance of Fe together with Mg further favours derivation from the Deccan basalt as do similarities in the concentrations of immobile trace elements, REE patterns, and the negative Ce anomalies observed. These findings correlate the smectite-dominant detrital clays with the Deccan basalt, implying the availability of the latter during deposition of the Lameta Formation in the Maastrichtian. These findings do not match models suggesting an extremely short period of Deccan volcanism (<0.5 myr) at the Cretaceous/Palaeogene transition; it is congruent with the models advocating a more prolonged volcanism.

Keywords: Major oxides; Deccan volcanic province; Lava flow stratigraphy; N-R-N chrons; Cretaceous/Palaeogene boundary

1. Introduction

The Deccan traps are continental flood basalts that record immense accumulations of tholeiitic basaltic eruptions over a relatively short time span (ca. 0.5 myr according to Courtillot, 1990) straddling the Cretaceous/Palaeogene boundary (KPg, age ca. 65 Ma). This is one of the largest igneous provinces in the world and a wealth of data are available on its stratigraphy, structure, geochemistry, petrogenesis, and the age and duration of volcanism. Flows of variable thickness (1–100 m) are

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superimposed to form a lava pile that attains its maximum thickness (1.5 km) in the south-west of the Deccan Volcanic Province. Most of the traps at outcrop are horizontal or gently dipping and show no lateral or vertical compositional variations for almost 100 km along strike (Lightfoot and Hawkesworth, 1988).

The thickest accumulation of Deccan basalt in western India (Pattanayak, 1999, fig. 1) is stratigraphically and geochemically well-characterised (Krishnamurthy and Cox, 1977; Najafi et al., 1981; Mahoney et al., 1982; Cox and Hawkesworth, 1984, 1985; Lightfoot, 1985; Beane et al., 1986; Devey and Lightfoot, 1986; Sen, 1986; Beane, 1988; Bodas et al., 1988; Khadri et al., 1988a,b; Lightfoot and Hawkesworth, 1988; Mahoney, 1988; Mitchell and Cox, 1988; Subbarao et al., 1988a,b; Lightfoot et al., 1990; Melluso et al., 1995; Khadri et al., 1999a). In this region, 12 basalt formations were recognized and grouped into three subgroups by Subbarao and Hooper (1988). More recently, Peng et al. (1994) grouped these accumulations into lower (Jawhar to Khandala) and upper (Bushe to Desur) formations on the basis of the geochemistry of the flows, but these divisions appear to have no stratigraphic significance (Mahoney, pers. comm. 1998). Similar studies have been extended up to the Mhow (e.g., Sreenivasa Rao et al., 1985) and Mograba (e.g., Khadri et al., 1999b) regions of northern Deccan; Jawhar to Kondaibar in the north and Buldana in the east of central Deccan (Subbarao et al., 1994); Medha-Mahabaleshwar, Kumbharli, Kolhapur and Phonda in southern Deccan (Mitchell and Widdowson, 1991); several sections in central and eastern Deccan (Deshmukh et al., 1996); and the Bidar-Nagpur section (Bilgrami, 1999) of eastern Deccan (Pattanayak, 1999).

Deep seismic sounding (DSS) studies by Kaila (1988) have revealed that the thickness of the Deccan Trap gradually decreases from 1.5 km (with the thickness of the flows varying between 1 and 100 m) along the west coast of India to about 100 m on the north-eastern margin, at the village of Khajuria Kalan near Bhopal. After a small gap the thickness again increases eastwards, with an isolated lava pile some 900 m thick cropping out around Mandla (Kaila, 1988, fig. 1). The great thickness of this lava pile and its separation from the western Deccan Province indicate that it originated from another source of basaltic lava located within the region bounded by Chindwara in the west, Amarkantak in the east, Kundam in the north and Seoni in the south.

This basaltic outlier is commonly known as the Mandla Lobe (Fig. 1), and provides important data on the associated Narmada-Tapti rift system (Hooper, 1990). Recent studies (Pattanayak and Shrivastava, 1996a,b; Solanki et al., 1996; Yedekar et al., 1996; Pattanayak, 1999; Pattanayak and Shrivastava, 1999)

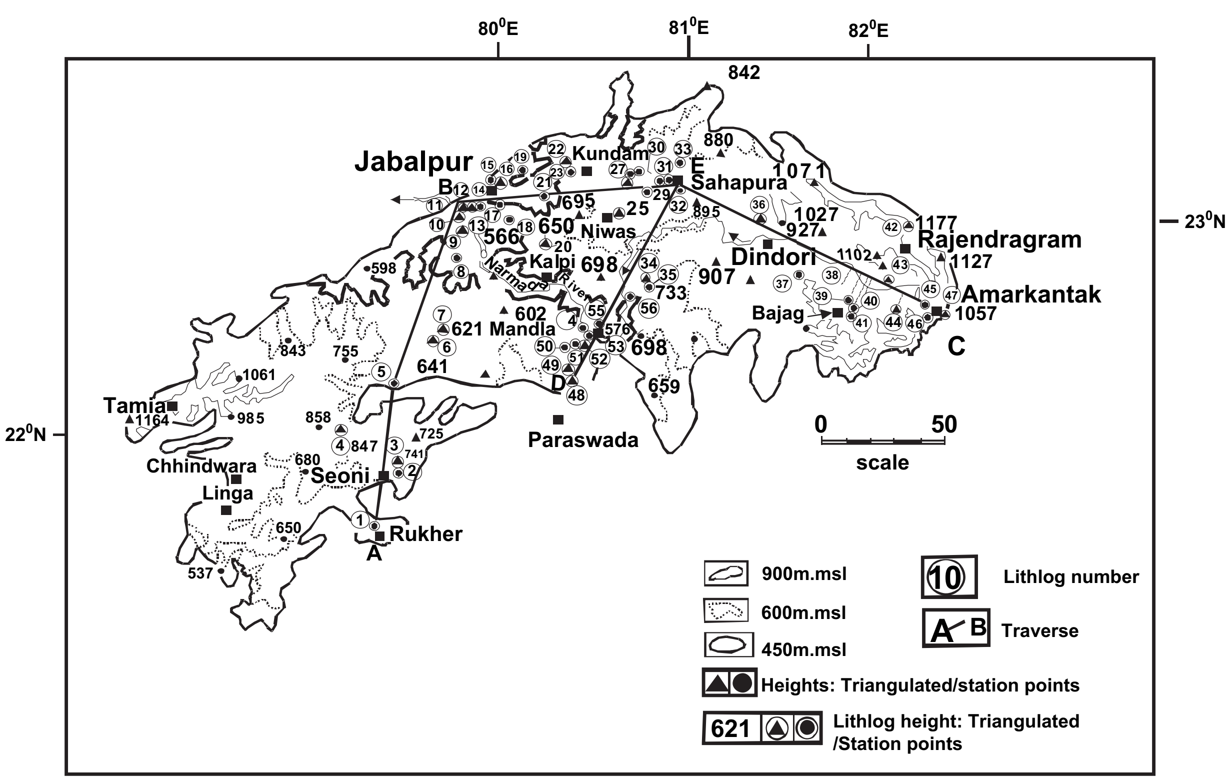

Fig. 1. Detailed topographic map of the Mandla Lobe in the Eastern Deccan Volcanic Province showing layout of traverses (A–N, B–C and C–D) and 56 measured sections, studied by Pattanayak and Shrivastava (1996a,b and 1999), and Pattanayak (1999).

have defined a stratigraphic framework for this lava pile. Nevertheless, long-distance stratigraphic correlation of lava flows or formations (a package of lava flows) over the Deccan Province remains problematic. Deshmukh et al. (1996) stated that the Eastern Ambenali Formation (analogous to the Ambenali Formation of the Western Ghats area) and Eastern Low-Ti Formation (may correspond to the Panhala Formation of the Western Ghats) have a large areal extent in central and eastern areas. Peng et al. (1998) reported isotopic and elemental geochemistry of lava flow samples from a 690-m-thick lava pile at Mhow, a 620-m-thick pile at Chikaldhara and a 230-m-thick pile at Jabalpur, and suggested that the Ambenali Formation and a few flows of the Bushe and Khandala formations may be present in north-east Deccan (Mandla Lobe). However, Subbarao et al. (1999) concluded that direct correlations are made difficult by a confusing stratigraphic order of flows, the available isotopic composition and, in some areas, different magnetic polarities.

Our review herein takes into account various studies in the Eastern Deccan Volcanic Province (EDVP), which are dispersed through the literature, and addresses issues related to geochemistry, geophysics, flow stratigraphy, structure, palaeomagnetism, and the age and duration of Deccan volcanism.

2. Lava flow stratigraphy

On the basis of the regional mapping and detailed petrographic studies of the lava flows, coupled with the lateral tracing, Pattanayak and Shrivastava (1996a) first reported a comprehensive framework of lava-flow stratigraphy on the Mandla Lobe comprising 37 petrochemically distinct flows grouped into eight chemical types (Pattanayak and Shrivastava, 1999; Pattanayak, 1999). Four ordered combinations of chemical types with three major chemical breaks intervening suggested that four distinct sets of lava flows were laid down during separate eruptive cycles, and that these correspond to four distinct basalts, as at Jabalpur, Seoni, Dindori and the mountain of Badargarh. It was found that the major chemical breaks correlate with the palaeomagnetic reversals corresponding to the 30N, 29R and 29N chrons of the well-established magnetostratigraphy of the Deccan. Pattanayak and Shrivastava (1999) and Pattanayak (1999) found that the geographical distribution and order of superposition of the flows in the Mandla Lobe indicates that the older flows are in the west, in the Seoni-Jabalpur-Sahapura sector, whereas the younger flows are confined to the Dindori-Amarkantak sector in the east. Furthermore, based upon megascopic characters and microscopic textural and mineralogical characters observed at the best exposed localities, they proposed a petrologic nomenclature for the flows (Table 1). The Dhanwahi plagiophyric (flow 4), Kahani giant clinopyroxene basalt (flow 8), Surjitolla columnar (flow 11), Rehtapakri columnar (flow 17), Sahapura plagiophyric (flow 21) and Murgatolla coarse grained (flow 23) flows exhibit a wide spatial distribution (50–100 km along two traverses). Together with megascopic- and micro-petrography this wide geographic spread makes them useful as marker horizons in Mandla Lobe. The major oxide chemistry of the flows sampled supports the recognition of 37 flows as well as their physical correlation across the sections measured.

The eight chemical types of flows (Pattanayak and Shrivastava, 1999, figs. 4, 6–8; Table 2 herein) are: high alumina quartz normative tholeiite (flows 4, 7–9, 11, 12, 14, 21, 22, 26, 27, 29, 30, 32–37); low alumina quartz normative tholeiite (flows 2, 3, 5, 6, 16, 24); high hypersthene normative tholeiite (flow 19); diopside and olivine normative tholeiite (flows 10, 17); olivine normative tholeiite (flows 18, 28); tholeiite (flows 1, 13, 15, 20, 23); high olivine normative tholeiite (flow 11) and high diopside and olivine normative tholeiite (flow 31). These groupings are based upon major oxide data and employ stepwise discriminant analysis (Pattanayak, 1999; Pattanayak and Shrivastava, 1999). The data provide a basis for future interpretations and discussions that will improve our understanding of lava flows of the Mandla Lobe.

Deshmukh et al. (1996) proposed a possible stratigraphic configuration of the lava pile in the central and eastern area. Yedekar et al. (1996, fig. 1) studied three sections at Chindwara, Jabalpur-Seoni and Jabalpur-Piparia, and, based on element ratio variations, grouped the lava pile into four informal formations that have similarities with the south-western formations. They noted that use of only chemical signatures of the basalt flows of the Mandla Lobe does not permit correlation with those of the western Deccan. Solanki et al. (1996) divided the 500-m lava sequence around Mandla into four formations and reported on the geochemistry of these basalts. Neither of these stratigraphic papers improves on earlier work owing to poor documentation of the sections studied (e.g., sampling sites, flow boundaries and location of measured sections).

3. Isotopic studies

Alexander and Paul (1977) argued that the high Sr-isotopic composition and variations in the chemistry of Sagar basalts were a result of some selective additions from the crust, such as Sr through wall-rock reactions. Mahoney (1984) and Macdougall (1986) discussed the Nd-Sr isotopic variations in the Jabalpur-Chindwara, Rajpipla-Narmada, Igatpuri-Kalsubai and Mahabaleshwar areas (Macdougall, 1986, fig. 3). The

Table 1
Nomenclature and petrographic characters of 37 recognized lava flows (after Pattanayak and Shrivastava, 1999)

Flow#	Nomenclature	Petrographic characters
Flow 37	Badargarh bauxitised	Lateritised and bauxitised
Flow 36	Badargarh saccharoidal clinopyroxene	Pitch black with saccharoidal clinopyroxene
Flow 35	Daldallapahar plagiophyric	Light grey, fine-grained, plagiophyric
Flow 34	Badargarh phyric	Steel grey, phyric and lateritised
Flow 33	Barkhera maphyric	Black with euhedral clinopyroxene
Flow 32	Mohtara aphyric	Aphyric and vesicular
Flow 31	Sonebhadra aphyric	Grey with tiny black magnetite
Flow 30	Rehtapakri fine-grained	Black, fine-grained with plagioclase laths
Flow 29	Badargarh zeolitised	Tough, black, magnetite phyric and zeolitised
Flow 28	Bhartolla aphyric	Aphyric, silica filled vesicles, lateritised
Flow 27	Banki plagiophyric compound	Compound, medium-grained with metallic sound
Flow 26	Mohgaon amygdular compound	Compound, medium-grained, amygdaloidal
Flow 25	Sonebhadra plagiophyric compound	Compound, columnar and plagiophyric
Flow 24	Karanjia vesicular	Plagiophyric (∼6 mm), vesicular
Flow 23	Murgatolla coarse-grained	Coarse-grained, euhedral clinopyroxene (4–6 mm)
Flow 22	Mohtara doleritic	Tough and doleritic
Flow 21	Sahapura plagiophyric	Columnar with acicular plagioclase (∼8 mm)
Flow 20	Karopanipahar plagiophyric	Plagiophyric with lateritised top
Flow 19	Keonchi plagiophyric	Plagiophyric with spheroidal weathering
Flow 18	Devgaon maphyric	Jet black, columnar, phyric clinopyroxene
Flow 17	Rehtapakri columnar	Black, columnar, vesicular and lateritised
Flow 16	Bikrampur acicular plagiophyric	Phyric with acicular plagioclase
Flow 15	Mohtara grey	Grey-black with chlorophaeite
Flow 14	Jatlapur amygdular	Amygdular and vesicular
Flow 13	Jatlapur amygdular	Amygdular and vesicular
Flow 12	Bandol plagiophyric	Plagioclase
Flow 11	Surjitola columnar	Columnar, plagiophyric (∼4 mm)
Flow 10	Lakhnadon doleritic	Black, doleritic with phyric clinopyroxene
Flow 9	Surjitola amygdular amygdules	Aphyric to plagiophyric with pipe
Flow 8	Kahani giant clionopyroxene basalt	Giant pyroxene (0.5–1 cm)
Flow 7	Nanhakhera giant plagioclase basalt	Giant plagioclase (∼1 cm)
Flow 6	Jodhpur aphyric	Aphyric with metallic lustre
Flow 5	Nagapahar pitchblack	Pitch black, phyric clinopyroxene (∼3 mm)
Flow 4	Dhanwahi plagiophyric	Plagiophyric, entablatured
Flow 3	Matka plagiophyric	Spotted (altered magnetite), plagiophyric
Flow 2	Matka maphyric	Phyric clinopyroxene (∼4 mm) with green alteration
Flow 1	Deori glassy basalts	Glassy, pitch black with metallic sound

Table 2
Eight chemical types with their major oxide values (wt %) and calculated parameters in the lava sequence of 37 lava flows in the Mandla Lobe of the Eastern Deccan Volcanic Province (after Pattanayak and Shrivastava, 1999)

Chemical types	A(19*)	B(8**)	C(1)	D(2)	E(2)	F(5)	G(1)	H(1)
Oxides								
SiO_2	48.40–50.60	47.92–49.05	49.50	47.20–47.70	47.89–48.46	46.87–48.01	46.29	44.80
TiO_2	1.67–3.06	2.47–2.76	1.47	1.56–2.24	2.36–2.45	1.21–2.30	2.31	1.56
Al_2O_3	13.48–14.71	12.48–13.41	14.10	3.12–14.09	14.34–15.25	13.80–14.63	15.16	12.72
Fe_2O_3*	14.12–15.66	14.22–16.00	15.93	14.05–15.40	15.19–15.60	14.22–15.03	14.82	13.14
MnO	0.24–0.64	0.24–0.39	0.47	0.20–0.23	0.45	0.14–0.28	0.28	0.68
MgO	4.08–5.77	4.80–5.62	5.89	6.98–7.72	5.91–6.16	5.38–6.69	5.85	4.26
CaO	8.73–10.06	9.68–10.48	10.09	10.72–11.28	10.23–11.21	9.78–10.57	12.27	15.98
$Na_2O + K_2O$	2.150–3.25	2.39–3.25	2.48	2.15–2.80	3.11–3.43	2.81–3.28	3.00	2.72
P_2O_5	0.18–0.32	0.19–0.27	0.30	0.12–0.16	0.29–0.35	0.17–0.28	0.24	0.22
Mg#	38.42–48.06	41.35–46.46	46.28	51.35–54.61	47.54–47.92	42.82–51.76	49.80	43.03
DI	24.70–31.70	23.07–28.03	21.78	17.60–23.10	25.17–27.87	21.59–23.42	27.56	22.20

A, high alumina quartz normative tholeiite (HAQNT) [flows 4, 7, 8, 9, 11, 12, 14, 21, 22, 26, 27, 29, 30, 32, 33, 34, 35, 36 and 37]; B, low alumina quartz normative tholeiites (LAQNT) [flows 2, 3, 5, 6, 16, and 24]; C, high hypersthene normative tholeiite (HHNT) [flow 19]; D, diopside olivine normative tholeiite (DONT) [flows 10 and 17]; E, olivine normative tholeiite (ONT) [flows 18 and 28]; F, tholeiite (T) [flows 1, 13, 15, 20 and 23]; G, high olivine normative tholeiite (ONT) [flow 11]; H, high diopside olivine normative tholeiite (HDONT) [flow 31]; *, ** = 5 and 2 cluster groups show similarity after DA defining the chemical types A and B, respectively; values significant in CA and DA are underlined.

two Mahabaleshwar mixing trends intersect at an isotopic composition not far removed from the field of ocean ridge basalts and data from all areas form trends that project towards this region of intersection (Mahoney, 1984; Mahoney et al., 1985). Samples from north-eastern Deccan plot closest to the end-member compositions, i.e., high ϵ_{Nd} and low $^{87}Sr/^{86}Sr$ values. The plots of samples from Jabalpur-Chindwara basalts cluster together, forming a distinct field that indicates simple mixing trends involving only one end-member in contrast to the Mahabaleshwar basalts, which show two enriched endmembers. The Jabalpur-Chindwara area forms a part of the EDVP where the lava-pile thickness is comparatively less than that of the Amarkantak, Mandla and Seoni regions. More recently, Nd-Pb-Sr isotopic (and chemical) similarities between the north-eastern and western Deccan lavas (Peng et al., 1998) have suggested that Ambenali-type magma may have travelled over great distances from the south-west Deccan where the type section is located. In Nd-Pb-Sr isotopic space (Peng et al., 1998, fig. 7) many north-eastern lavas define an array characterised by a negative correlation of $^{206}Pb/^{204}Pb$ with $\epsilon^{(t)}_{Nd}$ and a positive correlation of $^{206}Pb/^{204}Pb$ with $(^{87}Sr/^{86}Sr)^{(t)}$, which is distinct from any of the isotopic fields calculated from sections in south-west Deccan formations (Peng et al., 1998). This array overlaps the Ambenali Formation field and runs towards that of the Bhimashankar Formation or more generally towards the "common-signature lavas" (Peng et al., 1994). The work of Peng et al. (1998) contains isotope analyses of eight samples from the south-west of Jabalpur. The enormous thickness to the east of Jabalpur and the large areal spread, from Chindwara to Amarkantak, requires similar studies in order to construct a well-constrained stratigraphic framework.

4. Mineral chemistry

Geothermometry based upon Fe-Ti oxide of basalt samples from Bhopal, Sagar, Jabalpur, Mandla, Linga and Nagpur in the eastern Deccan, and the Poladpur-Mahabaleshwar and Bhiwandi-Igatpuri-Kalsubai sections in the west, indicates that the liquidus curves of the Sagar-Nagpur are similar to those of Hawaii (Sethna et al., 1987). Furthermore, the Sagar-Nagpur samples have higher liquidus temperatures (mean T, 1088 °C; n, 13) as compared to the Igatpuri samples (mean T, 1017 °C; n, 12) even though the latter are petrographically picritic with excess accumulative olivine and thus were expected to give higher liquidus temperatures. The range of liquidus temperatures observed for Mahabaleshwar samples is 950–1150 °C (mean T, 1072 °C; n, 5). These observations reflect petrogenetic differences for the basalts from different corners of the Deccan Province.

Recent mineral chemistry studies of Ahmad (2003) have revealed the presence of calcium-rich (Ca:Mg:Fe = 50:36:14) and calcium-poor varieties of pyroxenes (Ca:Mg:Fe = 11:50:39) in Mandala lavas, indicating a wide range of crystallization temperatures (750–1120 °C). The iron-titanium oxide geothermometric studies of Ahmad and Shrivastava (2004) on the lavas yielded high values of equilibration temperature, namely 974–1172 °C, for high alumina quartz normative tholeiitic flows; 1129–1229 °C for low alumina quartz normative tholeiitic flows; 1124–1283 °C for tholeiitic flows; and 990 °C and 1243 °C for diopside olivine normative tholeiitic flows. High olivine normative flows yielded 1092 °C and 1095 °C whereas high hypersthene normative tholeiite gave a temperature of 1187 °C. Data plots of iron-titanium oxide equilibration temperature vs. $\log fo_2$ (Ahmad and Shrivastava, 2004, figs. 3, 4) for Mandla lavas and other parts of the Deccan (Igatpuri, Mahabaleshwer, Nagpur and Sagar areas) revealed that tholeiitic (evolved) basalt of the eastern Deccan volcanic province formed at high temperatures whereas picritic (primitive) lavas of the Igatpuri and tholeiitic basalt of the Mahabaleshwar areas were formed at low temperatures. Mahabaleshwer basalts follow a FMQ (fayalite-magnetite-quartz) buffer curve but plots of the Mandla basalts lie above this curve (Ahmad and Shrivastava, 2004, figs. 3, 4), indicating higher temperatures of crystallization for ilmenite-titanomagnetite than that of the lava flows from other parts of the Deccan. The eastern Deccan traps are the most evolved types of lavas, as characterised by their low Mg-number and Ni content whereas the Igatpuri lava flows are picritic (primitive) in having a high Mg-number and Ni content. Temperature vs. $FeO + Fe_2O_3/FeO + Fe_2O_3 + MgO$ ratio data plots for Mandla and other Deccan lava flows and liquidus data for Hawaiian tholeiites, indicate that the Igatpuri basalts lie parallel to the liquidus line of Hawaiian tholeiite but at lower temperatures (Ahmad and Shrivastava, 2004, fig. 5). The large data plots of the Mandla lavas lie along the liquidus line of the Hawaiian lava. The highly vesicular nature of compound lava flows having large amounts of volatile material is considered to be responsible for low temperature values whereas lava flows represented by high temperatures show high modal values for glass and opaque minerals.

5. Structural complexity in the area

5.1. Geophysical aspects

Attempts have been made to map the thickness of Deccan Trap flows in India based upon Deep Seismic Sounding (DSS) studies (Kaila et al., 1987, 1989; Kaila, 1988). Of these, the Harper-Mandla DSS profile (Kaila, 1988) has unveiled the structural configuration across the Narmada rift system. The high gravity anomaly between Jabalpur and Mandla has been attributed to igneous intrusion in the upper crust or density anomalies in the upper mantle (Verma and Banerjee, 1992). The gravity high observed around Jabalpur can be explained as a massive high-density intrusive body in the upper crust, with a density contrast of $+0.1$ g/cm^3 (Verma and Banerjee, 1992) compared to the normal crustal density, and appears to be related to the tectonic framework of the Narmada-Son Lineament. The DSS crustal profile does not provide any evidence for this gravity high. However, it suggests that the Jabalpur-Mandla crustal block is a horst-type structure (Kaila, 1988, fig. 6; Kaila et al., 1989). Geomagnetic depth-sounding studies (Arora, 1993) have revealed the existence of an elongated geoelectrical conducting zone (0.2 Ohm/m) of asymmetric anticlinal geometry, extending between Jabalpur and Paraswada, with a lateral axis passing beneath Kalpi (Pattanayak and Shrivastava, 1999, fig. 1). The top of the structure is at a depth of about 10–12 km. It represents a zone of fluids or partial melt and is supported by geophysical signatures such as positive density contrast, an anomalously high velocity zone embedded between the lower crust and upper mantle, and the high reflectivity of the mid-crust. The Narmada-Son Lineament appears to represent a weak zone in the Indian continental crust. Two deep-seated faults that run from the surface, cutting the Moho, are evident from the Hirapur-Mandla DSS profile to the north of Jabalpur (Kaila, 1988). South of Jabalpur, a near-surface fault was inferred through the study of reduced DSS travel-times (Kaila et al., 1989, fig. 8) with an undulating Moho at a depth of about 40 km (Kaila, 1988).

5.2. Palaeomagnetic aspects

Sahashrabudhe (1963) observed reversed polarity in four flows near Linga. Athavale (1970) pointed out that in the Mandla region the boundary between the main "reversed basaltic sequence" and the overlying "normal sequence" is located at about 350 m above the average altitude of 600–625 m above sea level (m a.s.l.) at which it was observed in the west. A possible explanation for this is the existence of another polarity reversal during relatively rapid accumulation of an additional 350 m of lava flows at Amarkantak. However, because the thickness of the lava package between the Lameta beds and the reversal at Amarkantak is very similar to that observed near Jabalpur, the most plausible explanation is uplift of the Amarkantak region. Verma and Pullaiah (1971) and Verma et al. (1973) confirmed the existence of a polarity reversal in a section near Kundam and recognized that much of the Deccan volcanism had probably occurred in two relatively long periods of reversed and normal polarity. Assuming that the lava flows are flat-lying, and taking into account events of shorter duration with those of the main eruptive events, then based upon the altitude of the reversals, a sequence of six polarity intervals is indicated. Verma and Pullaiah (1971) found a normal sequence at an altitude of between 605 and 685 m to the north of Dindori, whereas Athavale (1970) observed a reversed one between 701 and 953 m along the road from Dindori to Amarkantak. Horizontal correlations are particularly difficult in the west of the traverse, especially between Jabalpur and Kundam. Vandamme and Courtillot (1992) undertook palaeomagnetic measurements of flows near Jabalpur, Kundam and Lakhnadon and from the data accumulated suggested either the existence of two major faults with vertical offsets of about 100 m or the presence of a synform structure of smooth cylindrical symmetry that reconciles the entire dataset with the proposed 30N-29R-29N reversal sequence (Vandamme et al., 1991) of the well-established magnetostratigraphy of south-west Deccan, and stressed the latter. Vandamme and Courtillot (1992, fig. 6) concluded that a cylindrical synform structure is most likely.

5.3. Geological aspects and seismotectonic model

Crookshank (1936) speculated that emplacement of the intrusive complex, with contemporaneous domal warping, uplift and rifting, may have resulted in faulting of lava flows along the Satpura mountain range, whereas Cox (1988) attributed the post-Deccan faulting to post-eruptive isostatic adjustments. The magnetic polarity bias might be the result of conjugate effects of erosion, altitude and undetected faults; additional work within a stratigraphic framework is required for a successful reappraisal. Some detailed work followed the Jabalpur earthquake of 22 May 1997. Shrivastava et al. (1999, fig. 1) revealed a vertical shifting of the fifth lava flow in adjacent sections, suggesting a NE–SW trending normal fault at Nagapahar. This fault coincides with a fault to the south of Jabalpur that was revealed through reduced travel time of DSS (Kaila et al., 1989, fig. 8). Rajendran and Rajendran (1999) presented a schematic model that included "rift pillows" i.e., excess mass at the crust-mantle boundary in the Narmada Fault System (NFS). These rift pillows may have acted as a "stress concentrator" that led to the Jabalpur earthquake. Mahadevan and Subbarao (1999), on the other hand, stressed that "rift cushions" or "rift pillows" are absent below the Narmada South Lineament, and that rather "lower crystal underplating" caused by Precambrian faults and numerous feeder dykes provided the tectonic conditions for the stress concentration. The seismotectonic model of Kayal (2000, fig. 9) clearly indicated that the NSF (F–F′: fault located between the Jabalpur and Tikaria areas in the NSF system inferred from aftershock study) to the south of Jabalpur was activated at the crust-mantle depth by a compressional stress, i.e., by a reversal stress system. The focal depths of the Jabalpur (35 km; Kayal, 2000) and Satpura (M 6.3, 40 km; Mukherjee, 1942) earthquakes suggest that the events are associated with Narmada rift systems because numerous earthquakes of greater focal depths have been recorded in ancient rift systems (e.g., Assumpcao and Suarez, 1988; Stein et al., 1989). Based upon this present state of knowledge of the EDVP, Kayal (2000) concluded that: (1) the NSF developed as an ENE–WSW-trending normal fault that experienced reactivation in the past, and failed as a reverse fault with left lateral strike-slip movement under the present-day compressive regime; the "stationary model" (the concept of old faults controlling centres of rock failure, especially in palaeorifts), is applicable to Jabalpur earthquake.

6. Search for equivalents within the Deccan Province

Mapping of individual flows is less advanced in the Deccan Province but some conspicuous flows have been traced for tens of kilometres (Devey and Lightfoot, 1986) and most formations have been traced for hundreds of kilometres (Mitchell and Cox, 1988; Subbarao et al., 1988b). The chemical and Nd-Sr isotopic data have resolved that some lavas in far north-eastern Deccan have strong affinities with the Ambenali and Poladpur formations (Mahoney, 1984, 1988). Sen and Cohen (1994) studied limited data on the chemical compositions (Rb/Y, Nb/Y and Sr) and radiometric ages of the Chakla-Delakhari sill and a flow west of Jabalpur in the Satpura mountain range, and noted chemical similarity to the Mahabaleshwar Formation, which overlies the Ambenali Formation in south-west Deccan. On this basis, they proposed synchronous volcanism in the Western Ghats and Satpura Range and vertical magma pathways from the head of the asthenospheric Reunion Plume 800 km in diameter. An alternative would be lateral migration of magmas through the lithosphere to the Satpura Range. This hypothesis draws support from the opinion of White and McKenzie (1995) that during major flood basalt eruptions, large quantities of basaltic melt can move considerable distances rapidly, either as flows on the surface or as dykes at midcrustal levels. However, Sheth and Chandrasekharam (1997) contended that in order to have simultaneous volcanism in the Western Ghats and Satpura Range the continental lithospheric mantle probably played a role in magma production beneath the NFS.

Sen and Cohen (1994) theorised that the lavas of the Bushe, Poladpur and Ambenali formations in western Deccan are distinct from the eastern flows and sills. On the basis of age, geochemical signatures and magnetic polarity, Baksi et al. (1994) observed that lava beds indicative of intracanyon flow remnants near the east coast of the Rajahmundri area correlate over a distance of more than 800 km with the Kolhapur Member of the Mahabaleshwar Formation. A high incidence of low-K flows (K_2O less than 0.5%) in this region constitutes almost 75% of the total lava pile and is similar to the western pile that comprises the accumulations above the Bushe Formation (Deshmukh et al., 1996). High K_2O ($>1.0\%$) flows usually exhibit Rb, Sr, Ba, Y and Zr enrichment, although Rb is somewhat inconsistent. Four aphyric to plagiophyric flows (flows 3–6 of Deshmukh et al., 1996) are capped by marker GPB in the Nagpur-Jabalpur section. These are characterised by high TiO_2, P_2O_5, Zr and Y abundances and are considered equivalent to the Ambenali Formation. Eight porphyritic flows (8–15) with plagioclase, minor olivine and augite are also similar to the Ambenali flows. Six flows (1–6) in the Jabalpur-Mandla section that contain plagioclase and augite are transitional between the Poladpur and Mahabaleshwar flows. Five GPB flows (7–11) and four others (12–15) are also considered to be Ambenali-type. Two key groups emerged from this study: the Eastern Ambenali Formation at the base of the section and overlying it, the low-Ti Panhala and Desur formations with an areal distribution from Toranmal in the west to Jabalpur in the east. The Panhala and Desur formations overlie the Eastern Ambenali Formation in the Chikaldara section, and indirectly in the Shahada-Toranmal section in central Deccan and the Akot-Harisal section.

Peng et al. (1998) carried out a detailed investigation to understand the relationship between the north-east and south-west Deccan basalts using: (1) bivariate plots of elemental abundances and ratios; (2) mantle-normalised multielement patterns; (3) discriminant function analysis of chemical data; (4) stratigraphic similarities and dissimilarities between the geochemical variation of the two regions; and (5) Nd-Pb-Sr isotopic data. Their study revealed that flows akin to the Ambenali chemical-type of the south-west overlie the Chikaldhara and Jabalpur sections, which in turn overlie lava flows of Poladpur-type. However, they further observed that: (1) interspersed at lower levels are several flows in the Chikaldhara section and one in the Jabalpur section that are very close to Khandala-type flows; and (2) in the Ambenali-like part of the Chikaldhara sequence two flows show Bushe-like chemical composition. On an isotopic diagram (Peng et al., 1998), the latter type of flow is seen to represent a type of basalt not seen in south-western Deccan. If true. these results indicate that the Ambenali Formation is one of the most widespread of the Deccan formations.

The search for geochemical equivalents within the Deccan has been greatly facilitated by the findings of Subbarao et al. (1999). Their study has shown that, despite the fact that a similar chemical composition is exhibited by the flows of Narmada and the Western Ghats, simple flow-by-flow or formation-by-formation correlation between the two areas is not feasible. The lower flows at Narmada erupted in a normal chron whereas those at the base of the Western Ghats succession occurred in a reversed chron, and the isotopic signatures of these two groups of flows are different (Peng et al., 1998; Khadri et al., 1999a,b; Subbarao et al., 1999). In the Nb/Y vs. Rb/Y diagram of Peng et al. (1994) the dykes and flows with Bushe-like compositions plot well outside the Bushe field (Subbarao et al., 1999, fig. 4) providing evidence in support of the above "disparities".

All of the studies of the eastern Deccan Volcanic Province that have been published so far provide insufficient details to enable the development of a plausible model defining the lateral continuity and geographic distribution of formations across the province.

7. Age and duration

Three lava flows at 705, 975 and 999 m a.s.l. in the Amarkantak hills have K-Ar ages of 45.9 ± 1.7, 48.1 ± 1.5 and 55.0 ± 1.5 Ma, respectively (Agrawal and Rama, 1976). Lava flows near Chindwara were dated at 47.2 ± 1.3 Ma, which is similar to the age of the lower two Amarkantak samples. More recently, $^{40}Ar/^{39}Ar$ dating of Takli lava flow I (near Nagpur) gave an age of 63.6 ± 0.2 Ma (Shukla et al., 1988). K-Ar dating indicated an age for the Sagar basalts of 47 Ma (Alexander, 1981). This date is similar to that of the Chindwara and Amarkantak basalts. On the basis of K-Ar dating of basalts from Manpur, those of the Malwa Plateau in north-central Deccan erupted between 62.5 and 50.6 Ma (Karkare and Singh, 1977), which provides support for age calibrations of around 50 Ma and younger that possibly reflect a second phase of volcanic extrusion. Available K-Ar ages date most of the succession at between 60 and 65 Ma, although ages as high as 80 Ma and as low as 40 Ma have been reported (Rama, 1968; Kaneoka and Haramura, 1973; Agrawal and Rama, 1976; Kaneoka, 1980; Alexander, 1981). Most of these early dates are based on the conventional K-Ar method, except for eight samples dated by the $^{40}Ar/^{39}Ar$ method (Kaneoka, 1980). Therefore, the Deccan basalts indicate a twofold volcanic history (Alexander, 1981) in which the first episode (60–65 Ma) was the most violent and built the major portion of the Deccan Province, especially in western India. Alexander (1981) described a second major episode from 50–42 Ma, during which flows of northeastern and other peripheral areas, such as Sagar, Jabalpur, Amarkantak and Malwa, erupted. However, Mahoney (1988, p. 162) has critically evaluated the dates (both K-Ar and $^{40}Ar/^{39}Ar$) from the traps and emphasized that "the statements of certain workers to the effect that their samples are free from alteration must be treated with a great deal of suspicion". Similarly, Courtillot et al. (1986b) noted that the ages for the less altered samples ranging from 55 to 66 Ma (with 1σ error bars between 2 and 4 myr) and the more altered samples correspond to non-magnetic fractions with younger apparent ages and greater uncertainties. Such observations point to the need for careful, detailed chronological investigations of the Mandla Lobe. Palaeontological data, particularly the remains of the ray *Igdabatis* found by H. Cappetta in the Lameta beds near Jabalpur (in Courtillot et al., 1986b), indicate that Deccan volcanism began in the late Campanian after 70.3 Ma and possibly as late as the deposition of the *Abathomphalus mayaroensis* Zone at around 67.5 Ma. It probably ended before 60.5 Ma (Vandamme et al., 1991, fig. 9). Duncan and Pyle (1988) reported $^{40}Ar/^{39}Ar$ dates from a stratigraphically controlled, geochemically well-characterised, ca. 2000-m-thick lava sequence in the Western Ghats. They observed no significant difference in age from the stratigraphically oldest to youngest rocks and concluded that the lavas erupted rapidly. Courtillot et al. (1988) observed that the $^{40}Ar/^{39}Ar$ dates suggest that the bulk of Deccan volcanism occurred over less than 4 myr, possibly as little as 2 myr, whereas the magnetostratigraphy (Courtillot et al., 1986b) indicates an even shorter duration of less than 1 myr.

These constraints indicate that major eruptive phases before 75 Ma (Alexander, 1981; Sreenivasa Rao et al., 1985) and after 60 Ma (Pal, 1969; Pal and Bhimashankaram, 1971; Alexander, 1981) are not valid and prompted Vandamme et al. (1991) to propose that Deccan volcanism lasted only for a about 5 myr, as first suspected by McElhinny in 1968. The small number of reversals in the Deccan lavas have been considered compatible with most of the volcanism being concentrated within a period of about 1 myr (Vandamme et al., 1991, fig. 9) straddling the Cretaceous/Palaeogene boundary in chron 29R (Courtillot et al., 1986a,b; Gallet et al., 1989; Jaeger et al., 1989). In the context of a short duration of major eruption in the Deccan Province, Vandamme et al. (1991) opined that the K-Ar age histogram should be interpreted as a convolution between a narrow true age distribution and a "filter" characterizing alteration and argon loss. Jaeger et al. (1989) pointed out that the overall mean of the best $^{40}Ar/^{39}Ar$ ages of the Deccan lavas centre around the K/Pg transition at 65.7 ± 2.0 Ma, which Vandamme et al. (1991) corrected to 65.5 ± 2.5 Ma. The $^{40}Ar/^{39}Ar$ plateau ages of 65.2 ± 0.1 Ma and 64.98 ± 0.10 Ma (relative to an age of 520.4 ± 1.7 Ma for Minnesota Hornblende MMhb-1) for microtektites discovered in marine sedimentary rocks around the K/Pg boundary in Haiti (Izett et al., 1991) and in melt glasses from the

Chicxulub crater (Swisher et al., 1992) respectively, indicate a link between an impact event and the boundary. Venkatesan et al. (1993) measured the age of Deccan basalts relative to the same standard (MMhb-1) and pointed out that the time interval between voluminous eruption in the reversed magnetic chron and the K/Pg boundary is not less than 1.5 myr. They suggested the possibility of inclusion of these two events in polarity chron 31R. Baksi (1994) integrated the age data with the magnetic polarity of different lava formations in western Deccan and concluded that over 80% of the exposed material was extruded in about 1 myr in chron 29R. However, he suspected that an undetected loss of about 3% of Ar would shift whole-rock basalt and plagioclase crystallization ages to ca. 67.5 Ma, indicating that the bulk of the Deccan traps were extruded during chron 31R. As also stated by Venkatesan et al. (1993, p. 186) "translating the chronostratigraphy of a single section from the Western Ghats into time variation of eruptive volumes would be premature due to the difficulties of assessing the amount of eroded material, the volume of basalt below the surface and in the offshore extrusions of the Deccan Province, and the aerial extent of individual flows". Added to this is the opinion of Tandon (in Venkatesan et al., 1993) that the volcanic quartz fragments in the basal green sandstone of the Lameta deposits near Jabalpur suggest the initiation of volcanism prior to sedimentation. Furthermore, recent observations on mineralogical and chemical similarities between smectite-dominated detrital clays of the Lameta beds and degraded Deccan basalt (Salil et al., 1996, 1997) point towards the availability of Deccan basalt during the Maastrichtian when the Lameta Formation was deposited. This contradicts the model suggesting an extremely short period of Deccan volcanism of less than 0.5 myr near the K/Pg transition (Courtillot, 1990), supporting instead models advocating a prolonged duration (Basu et al., 1993; Venkatesan et al., 1993; Baksi, 1994). To understand the eruptive events over the Deccan Province more clearly, such studies need to be extended towards the east, north and south of the main exposure in the Western Ghats.

8. Future directions

The inflation process (Hon et al., 1994; Self et al., 1996; Keszthelyi et al., 1999) suggesting lobe-by-lobe emplacement of basaltic lava flows in continental flood basalt provinces appears to be the most appropriate model for understanding the lavas of the Mandla Lobe. This model has been applied satisfactorily to the Roza flow field of the Columbia River Basalt Province (Hon et al., 1994; Self et al., 1996). As suggested by Keszthelyi et al. (1999) it is now important to determine the volume erupted as a function of time in order to determine the timing of maximum Deccan volcanism. Such a detailed study on flows based on the inflation model is essential. We suggest the following areas for future research: (1) group the lava flows in the eastern Deccan Volcanic Province into different formations and study the petrogenesis based on a large dataset on trace elements and isotopes; (2) use these data to test whether flows of the western Deccan magma-type(s) at a high altitude between Jabalpur and Amarkantak are present further east of Jabalpur; (3) compare both vertical and lateral regional variations in magmatic character in order to relate any changes in magma supply to a single magma chamber or more than one; (4) aim to understand better the nature and kind of contaminant(s) that may account for heterogeneities in the EDVP magma-types; (5) use variations in Nd, Sr and Pb-isotopic compositions within suites and correlate isotopic ratios with SiO_2 contents to determine whether contamination has accompanied fractionation in some or all cases; (6) study the chemistry of mineral phases for lava flow minerals (e.g., pyroxene, calcic plagioclases, magnetite and ilmenite) to estimate the temperature and pressure of crystallization, thus improving our understanding of petrogenesis by reinterpreting existing modal data in the light of these results; (7) determine the ages of rock and mineral separates using the high precision $^{40}Ar/^{39}Ar$ laser fusion technique, which, when combined with results of point 6 within a stratigraphic framework, will define the temporal history of magma emplacement in the outlier; (8) interpret flow-by-flow measurements of palaeomagnetism in the trap sequence in the EDVP with palaeontological evidence to provide better estimates of both the volume and timing (e.g., 30N–29R–29N) of basalt eruptions in the Deccan.

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