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Records of the influence of Deccan volcanism on contemporary sedimentary environments in Central India

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Abstract

Deccan volcanism, with a duration of ~5 Myr, represents a major continental flood basalt province in which ~2 million km^3 of lavas were formed. Such voluminous and rapid volcanism in Phanerozoic earth history has commonly been advanced as a cause for mass extinctions. Despite this significance, few studies have attempted to understand the influence of continental flood basalt volcanism on contemporary sedimentary environments. Thin sedimentary sequences associated with the Deccan volcanics, i.e. the infra- and inter-trappean sequences, offer an opportunity to assess the influence of Deccan volcanism on contemporary sedimentary environments in Central India. The Lameta Formation mainly constitutes a well-characterised regolith, regionally consisting of calcretes and palustrine facies, which may, in places, be associated with ephemeral sandy braided river and sheetflood facies. An assessment of the influence of Deccan volcanism on contemporary surficial environments reveals: (a) an input of basaltic degradational products in the basal fluvial facies of the Lameta Formation; (b) upward changes in facies assemblages from lacustrine/palustrine to subaerial dominated, followed eventually by burial by the first lavas locally; (c) significant changes in the palaeoflow characteristics of fluvial channel facies, respectively under and overlying the main calcareous regolith of the Lameta Formation; (d) that most freshwater lacustrine taxa survived the initial effects of the Deccan volcanism without undergoing any drastic change. In addition to the role of constructional topography resulting from lava emplacement and associated surface uplift, the mode of preservation of sedimentary packets significantly affects changes in the vertical motifs of coeval sedimentary sequences. Because of the problems of time-resolution on 10^5–10^6-year time scales in the continental infra- and inter-trappean sequences, detailed cause (volcanism)–effect (surficial environments) relationships at the event level are not well understood. Also, the lack of data from multiple stratigraphic levels of the inter-trappean beds precludes any serious assessment of the directions and rates of changes that took place in CO_2 concentrations of the palaeoatmospheres of that period (65 ± 3 Myr). © 2002 Published by Elsevier Science B.V.

Keywords: Deccan volcanism; Infra- and inter-trappean beds; Sedimentary environments; Atmosphere; Clay mineral and palaeocurrent shifts; Cretaceous; India

1. Introduction

Volcanism is known to affect contemporary sedimentary environments in many ways (Cox, 1988). Close to the end of the Cretaceous, India witnessed a huge outpouring of lava flows, which resulted in the formation of the Deccan Traps volcanic province (Subba Rao, 1999). A tholeiitic lava pile, in excess of 2 km at its thickest, covered a major part of Western and Central India. The traps cover large areas of Madhya Pradesh, Kutch, Saurashtra, Mainland

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Gujarat, Maharashtra, Andhra Pradesh and Karnataka adding up to a total area of half a million square kilometres. The present distribution of this lava pile is only a part of their original extent, as a considerable volume has been eroded in the Cenozoic. Also, the traps are found in the offshore off Mumbai, and as part of the Seychelles microcontinent (Devey and Stephen, 1991).

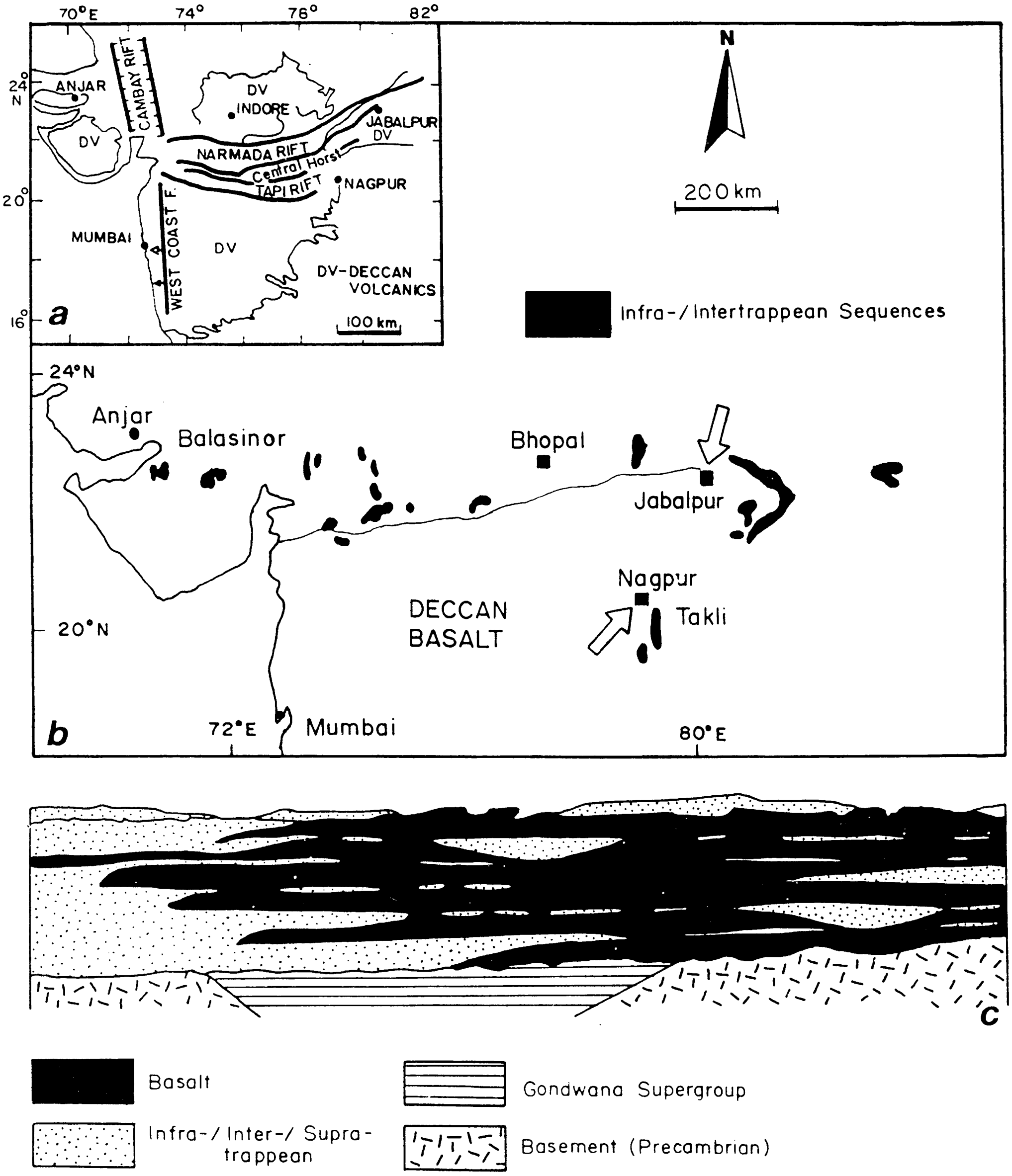


Fig. 1. Location map of Central and parts of Western India showing the location of the major rift structures of the region (a). Locations (in black) showing some of the important outcrops of patchily distributed infra- and inter-trappean beds of the Deccan volcanic province in Central India (b). Schematic representation of possible relationships between infra-/inter-trappean sequences and the associated lava flows, and the rifted basement lithologies (after Sahni et al., 1994) (c).

Major rifts—the E–W trending Narmada and Tapti rifts—occur in the Central Indian region. These E–W rifts in their western extremity link in with the NNE–SSW trending Cambay rift (Fig. 1a). The patchily distributed outcrops of the Lameta Formation (Fig. 1b), consisting of regionally developed regolithic, lacustrine, fluvial, and sheetwash facies, represent a late stage event in rift history following long-term major filling of the Gondwana basins by thick alluvial sequences. Later, the rift–Reunion hotspot interaction resulted in the eventual burial of the rift fills by a thick pile of lava flows.

The importance of this volcanic episode stands emphasised as it occurred around the Cretaceous–Tertiary boundary (Sahni and Bajpai, 1988). Deccan volcanism undoubtedly straddles the KTB (Venkatesan et al., 1993; Widdowson et al., 2000), and has often been linked to the KTB mass extinction (Mclean, 1985).

The duration of the Deccan volcanic episode has been a matter of some debate. The acme of volcanism may have had a duration of 1 Myr (Courtillot et al., 1986; Hoffmann et al., 2000); however, from the beginning to its final phases, a longer duration of > 5 Myr is generally accepted (Jaiprakash et al., 1993; Venkatesan et al., 1993; Krishnamurthy, 2000).

The Deccan volcanism is associated with the rifting and rapid movement of the Indian plate over the Reunion Island hotspot. Hotspots are considered to be the surface expression of mantle plumes. Plumes, in addition to rapid and high volumes of magmatism, may result in topographic doming (Cox, 1989). Cox (1989) also showed that plume-related surface uplift is the cause of new-river systems draining away from the new continental edge (dome–flank system). As the continental areas uplifted by plume activity remain topographically high, the courses established during plume-related surface uplift continue to evolve over considerable lengths of geologic time, for example ~ 70 Myr in the case of the Deccan volcanic province.

Among other factors that affect the topography of the Deccan volcanic province, surface uplift due to emplacement of the lavas, or in other words, the constructional topography of the lava sequence, is also important (Widdowson and Cox, 1996). Menzies (2000) has suggested that pre-volcanic surface uplift may be of the order of metres only, and that kilometre scale uplift is synchronous with magmatism; thus, uplift does not predate magmatism in all instances.

Yet another aspect of continental flood volcanism that would affect contemporary sedimentary environments is the rates of emission of basaltic lavas and atmospheric contaminants. For instance, in the fissure vent system of Laki, Iceland, the rate of emission was of the order of 5000 m^3/s. Besides, "considerable quantities of water vapour and significant amounts of other gases, such as SO_2, CO_2, Cl and F, are also inferred to have been emitted" (Sigurdsson, 1982) during such volcanic episodes.

From the above account, it follows that the topographic and atmospheric changes driven by mantle plume-related volcanism result in significant landscape and environmental changes. These changes, in turn, result in drainage adjustments, changes in sediment supply and distribution, and in the biotas. They may manifest themselves as short-term effects related to individual eruptive events, or groups of eruptive events, or long-term and cumulative effects integrated over substantial periods spanning the duration of volcanism. In principle, records of the influence of volcanism on landscape, sediment systems, and biotas should be preserved in the stratigraphic records of sedimentary sequences contemporary to volcanism (cf. White, 2000).

In the present work, which is largely derived from the previous work of the author, his co-workers, and others, stratigraphic records of infra- and inter-trappean sequences, associated with the basal lavas of the Deccan volcanics of parts of Central India, are examined to assess the influence of Deccan volcanism on contemporary sedimentary environments and stratigraphic development. The data are mainly from the Jabalpur area on the southern side of the Narmada rift—a failed rift that had been receiving sediments since the Early Cretaceous. The comparative sedimentology of areas in the margin of the Tapi rift, such as the Nagpur area, is also investigated as it provides information on the development of the Deccan volcanic edifice, its syn- and post-rift uplift and evolution of the subsequent drainage patterns.

2. Physical setting and age

Thin sedimentary sequences, commonly referred to as infra- and inter-trappean beds, are intimately associated with the basal Deccan lavas. They are distributed as discontinuous patches of a few square kilometres to tens of square kilometres in the region of the Narmada lineament, as well as in other areas of Central India (Fig. 1a). These sequences either underlie a flow (infra-trappean = Lameta Formation) or are intercalated within them and are termed inter-trappean (Fig. 1b). These terms describe the physical position of the associated sedimentary sequences regardless of chronology.

The infra-trappean beds were originally assigned a Turonian age based on the dinosaurian faunas (Huene and Matley, 1933). Re-assessment of the bio-chronology of the dinosaurian faunas of the Lameta Beds (Chatterjee, 1978; Colbert, 1984), the presence of *Igdabatis* (Besse et al., 1988), *Aquillapollenites* sp. (Dogra et al., 1988), and pelobatid frogs (Sahni et al., 1994) are used to infer a Maastrichtian age.

The grouping of the Lameta Formation, as being coeval with the basal Deccan flows and related inter-trappean beds, is consistent with biochronological, radiometric, and mineralogical data (Colbert, 1984; Buffetaut, 1987; Kohli, 1990; Venkatesan et al., 1993; Salil et al., 1997; Krishnamurthy, 2000). The Deccan volcanics and associated infra- and inter-trappean sedimentary sequences are generally assigned to an interval bracketed by $\sim 65 \pm 3$ Myr and includes the KTB.

3. Stratigraphic records

Before the influence of volcanism on lithological records, mineralogical variations, drainage adjustments, biotas, and climates can be understood, the stratigraphic records that contain evidence of this influence require description. As pointed out earlier, the record is spatially widespread. However, most previous works (references in Tandon, 2000; Tandon et al., 1995) have focussed mainly on the Lameta Beds of Jabalpur region and Maharashtra (Nagpur region, e.g. Dongargaon) (Mohabey, 1996; Mohabey et al., 1993). In recent years, the inter-trappean beds at Anjar (Kutch) have received considerable attention (Bhandari et al., 1995, 1996; Khadkikar et al., 1999; Shrivastava et al., 2000). The stratigraphic records at Jabalpur, Dongargaon area, and Anjar are summarised below.

3.1. Jabalpur

The stratigraphy of the Jabalpur area is summarised in Table 1. The Lameta Formation attains thickness of up to ~ 40 m, and unconformably overlies a range of Mesozoic–Precambrian rocks. The Lameta Beds overlie mid-Jurassic to early Cretaceous Jabalpur Formation, with a paraconformity in the east Jabalpur region (Chanda and Bhattacharya, 1966). This passes into an erosional unconformity towards the southwest. The Lameta Beds were originally sub-divided into five mappable units (Matley, 1921). Chanda and Bhattacharya (1966) suggested a modification of Matley's classification into a threefold division through merger of the upper three units into a single 'Upper Sandy Limestone' unit. Following the observations given in Tandon et al. (1995), a fourfold classification (Table 1) is used in this analysis; the lower three units of Matley (1921) are retained, while the Upper Limestone and Sandy zone of Matley (1921) are replaced by the Upper Calcified Sandstone.

Diverse freshwater and terrestrial faunas/floras include dinosaur skeletal remains and eggshells (Sahni et al., 1994), molluscs (Brookfield and Sahni,

Table 1
Geological setting and stratigraphy of the Jabalpur area

Late Cretaceous (Maastrichtian)		Deccan flows
		Intertrappean sediments
		Deccan flows
	Lameta Beds	Upper calcified sandstone
		Mottled nodular beds
		Lower limestone
		Green sandstone
Mid-Jurassic to Early Cretaceous		Jabalpur Group (Channel sandstones; overbank thin white to brown sandstones; fireclays)
Precambrian		Mahakoshal group (meta-sedimentary sequence, complexly deformed)
		Granite basement

1987), ostracods and charophytes (Bhatia et al., 1990), and pollen (Dogra et al., 1994).

It has been shown that the Lameta Beds, particularly in the Jabalpur sub-region, constitute a well-characterised Maastrichtian regolith (Tandon and Andrews, 2001; Tandon et al., 1995, 1998; Ghosh, 1997).

3.2. Nagpur (Dongargaon Basin)

The stratigraphy of the Lameta Formation of Chandrapur and Nagpur districts is summarised in Fig. 2. These beds attain a thickness of ~ 20 m and rest over the Precambrian basement unconformably, or overlie the Kamthi Formation of Gondwana Supergroup (Mohabey, 1996). The Lameta Formation, in turn, is covered by the Deccan lava flows which, in places, are separated by thin inter-trappean beds. The Lameta Formation mainly comprises clays, marls, limestone and cross-bedded sandstones and pebble conglomerates. The lithological characters of the Lameta facies deposited in various areas are quite variable. Mohabey (1996) identified the following lithofacies with fossil assemblages—(a) overbank red and green silty clays, (b) channel sandstone, (c) lacustrine cream and yellow laminated clays intercalated with limestone and marl beds (Fig. 3), and (d) paludal grey marls. Details of these facies are available in Mohabey and Udhoji (1990) and Mohabey (1996), and have been previously summarised from these sources in Tandon (2000).

3.3. Anjar

The inter-trappean beds near Anjar have received particular attention because of the presence of dinosaurian fossils and high iridium concentration of ~ 1200 pg/g (Ghevariya, 1988; Bhandari et al., 1995). The Anjar inter-trappean beds are ~ 5 m thick, and consist of limestone/sandy limestone, basalt clast-bearing mudstone, fossiliferous siltstone, and cherty limestone (Fig. 4). The basalt flows which overlie and underlie these inter-trappean beds at Anjar have been dated by Venkatesan et al. (1996), using the $^{40}Ar/^{39}Ar$ method, to 65.3 ± 0.6 and 65.1 ± 1.5 Ma, respectively. Recently, Bajpai and Prasad (2000) showed that the lacustrine inter-trappean beds overlying the iridium-enriched layers show abundant ornithoid eggshell fragments belonging to theropod dinosaurs. According to them, "lack of evidence of reworking, and the absence of any exclusively Paleocene taxa above the iridium levels together indicate that the extinction of dinosaurs in the Indian subcontinent occurred after the deposition of Ir layers at Anjar, and that these Ir anomalies may significantly predate the K/T boundary".

4. Influence of Deccan volcanism on lithological records

As noted earlier, the emplacement of lavas in a region will result in a constructional topography, which should affect the then existent surface and near surface sedimentary environments. Such changes should manifest themselves both in the mineralogy and palaeocurrent patterns (drainage adjustment) of coeval sedimentary sequences. With this in view, the clay mineralogical and palaeocurrent changes across the Jabalpur Group/Lameta Formation unconformity are examined.

4.1. Clay mineralogy across the Jabalpur Formation/Lameta Formation unconformity

The Jabalpur Group of the Gondwana Supergroup consists of fluvial channel sandstone and floodplain siltstone facies marked mainly by light grey, whitish grey, and brown colour. The Jabalpur sandstones are commonly assigned to the Early Cretaceous. In sharp contrast with these strata, the unconformably overlying fluvial channel sandstones/pebbly sandstones of the Lameta Beds show a marked green colour in many sections, and are usually assigned to the Maastrichtian (Sahni et al., 1994; Tandon et al., 1995). The clasts in the channel lag deposits include jasper, black chert, smoky quartz, derived from the pre-Deccan (i.e. Proterozoic) basement, and locally derived Jabalpur sandstone/claystone, and calcrete.

The 4–6-m-thick green sandstone (Matley, 1921) consists mainly of trough cross-bedded sandstone of varying colour—green to white (Fig. 5). At Chui hill, alternate laminae of foresets show dark green, light green, and white colour. Grain size appears to control subtle variations in the green colour; the darkest green laminae consist of relatively coarser-grained sediments. The fine-grained laminae are light green or even white.

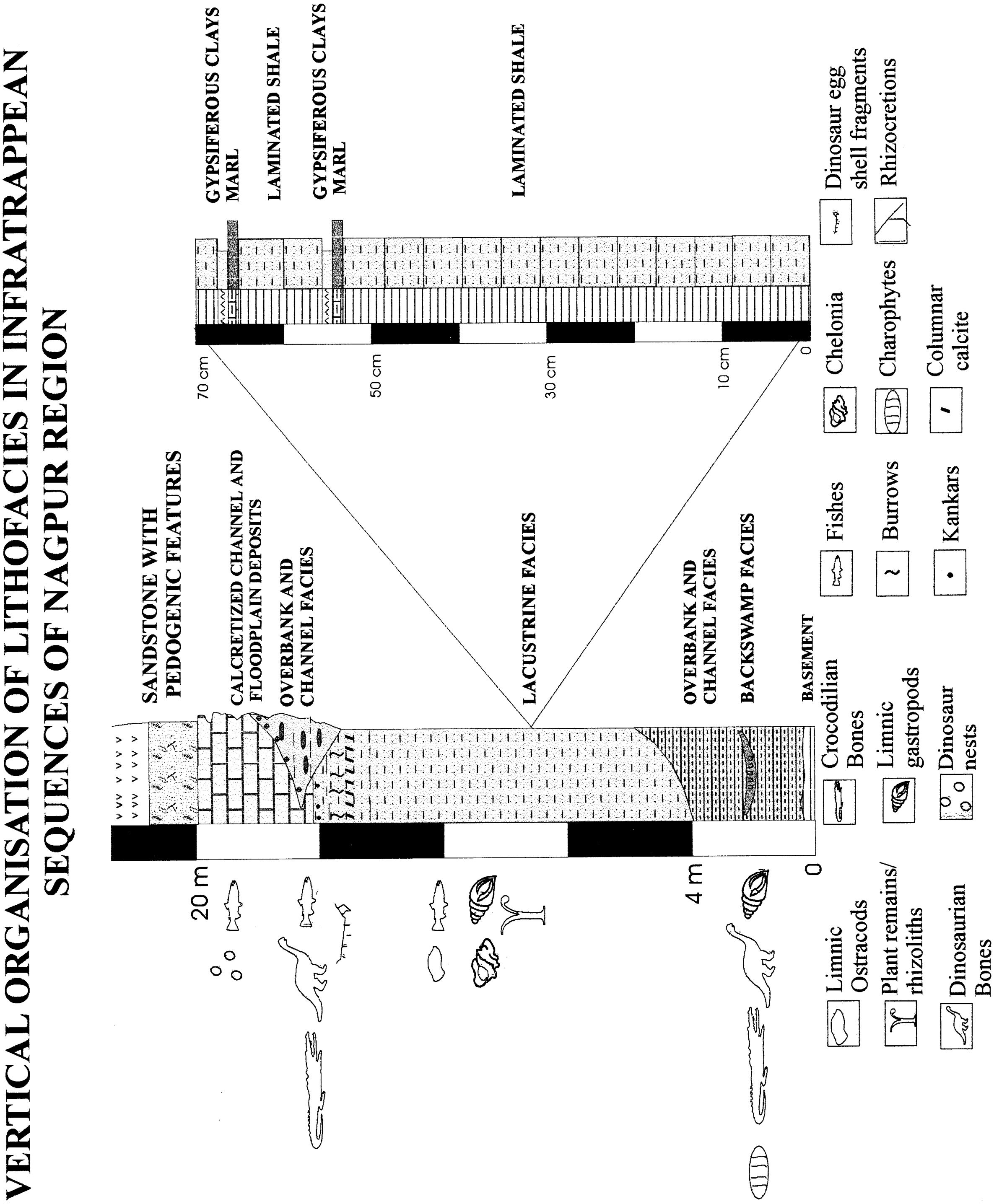

VERTICAL ORGANISATION OF LITHOFACIES IN INFRATRAPPEAN SEQUENCES OF NAGPUR REGION
SANDSTONE WITH PEDOGENIC FEATURES
CALCRETIZED CHANNEL AND FLOODPLAIN DEPOSITS
OVERBANK AND CHANNEL FACIES
LACUSTRINE FACIES
OVERBANK AND CHANNEL FACIES
BACKSWAMP FACIES
BASEMENT
20 m
4 m
0
GYPSIFEROUS CLAYS MARL
LAMINATED SHALE
GYPSIFEROUS CLAYS MARL
LAMINATED SHALE
70 cm
50 cm
30 cm
10 cm
0
Limnic Ostracods
Plant remains/ rhizoliths
Dinosaurian Bones
Crocodilian Bones
Limnic gastropods
Dinosaur nests
Fishes
Burrows
Kankars
Chelonia
Charophytes
Columnar calcite
Dinosaur egg shell fragments
Rhizocretions

Fig. 3. Field photograph to illustrate the interbedded cream and yellow laminated clays, marl, limestone, and gypsiferous clay facies association representing the lacustrine interval. Locality—Dongargaon (scale in cm).

The Jabalpur Formation clays are white in colour and consist predominantly of kaolin minerals (Patil and Lamba, 1989). Petrographic studies of the Lameta Formation green sandstones overlying the disconformity surface reveal quartz, biotite, muscovite, rare felspar, green matrix and siliceous/calcareous/limonitic cements. Importantly, and in contrast with the underlying Jabalpur strata, the green-coloured matrix occurs in the embayments and re-entrants of the quartz grains. The green matrix also occurs as ‘coatings’ on quartz grains. It consists of an inhomogeneous mass made up of minute detritus of multi-mineralogic composition. XRD data (Table 2) of the matrix of the green sandstones resulted in recognition of montmorillonite (nontronite?), celadonite, and kaolinite.

Later infiltration of the green minerals from the secondary products of the overlying basalts is negated, as there is no field evidence for migration of weathered green clays from the overlying basalts. As the clay mineralogical change is marked across the Gondwana Supergroup/Lameta Formation unconformity, and as the Gondwana sandstones are devoid of volcanic detritus, the shift is interpreted as resulting from additional sources due to weathering of the earliest Deccan lavas.

4.2. Drainage adjustments at Jabalpur

Cross-bedded sandstones are well developed both in the Jabalpur Group and Lameta Beds. There are

Fig. 2. Vertical organisation of infra-trappean lithofacies of the Dongargaon area, Nagpur region (main litholog after Mohabey, 1996; Mohabey et al., 1993). Log to the right is a generalised representative of the detail within the lacustrine facies made up of laminated shale, marl, and gypsiferous clays. Note the overall change from aquatic facies to sub-aerial dominated lithofacies towards the basal flow.

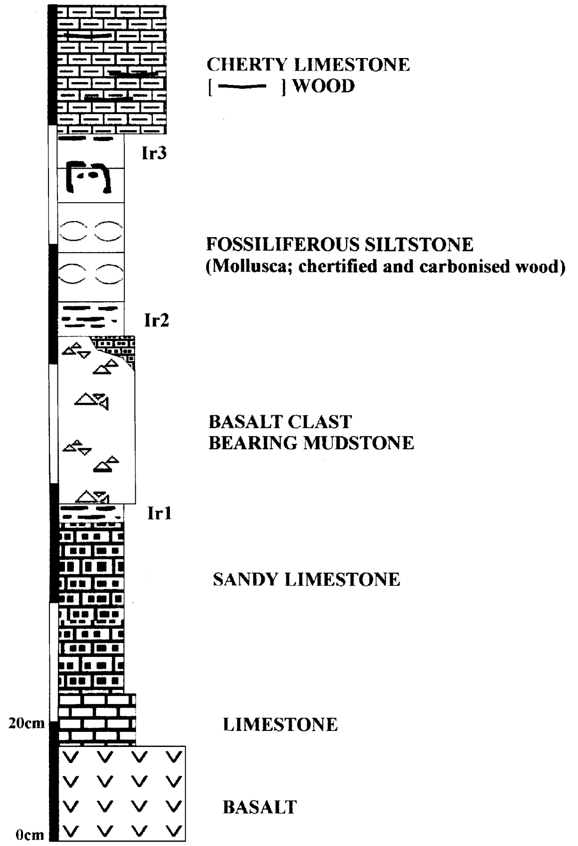


Fig. 4. Litholog is showing vertical facies association of a part of the Ir-bearing inter-trappean sequence at Anjar. Note the three Ir-enriched layers (after Tandon, 2000).

three important stratigraphic levels of fluvial channel deposits—(1) sub-unconformity channel deposits belonging to the pre-Deccan volcanic landscapes of Early Cretaceous, (2) channel deposits of the green sandstone of the Lameta Formation overlying the unconformity surface and belonging to landscapes coeval with the basal Deccan volcanics (Maastrichtian), and (3) channel deposits of the Upper Calcified Sandstone of the Lameta Formation well separated from the basal Lameta unconformity and belonging to a Maastrichtian landscape that was about to be buried by the first lavas that extended across this region.

Palaeocurrent data (Fig. 6) indicate a southerly to southwesterly palaeoflow direction for the channels of the Jabalpur Formation and the basal green sandstone of the Lameta Formation (Chanda and Bhattacharya, 1966; Bose, 1992). Uniformity in palaeoflow directions across the unconformity is maintained, and indicates that the constructional topography of the first lava flows to the northeast of Jabalpur area did not cause any changes in the palaeodrainage directions. However, basaltic degradational products from these first lavas were supplying the drainage catchment.

Subsequently, a palaeoflow change to the northeast is recognised in the uppermost sandstone units of the Lameta Formation (Fig. 6). This is attributed to adjustment of the local drainage pattern in the Jabalpur area to modifications in the palaeolandscape caused by the emplacement of the flows in the region. This adjustment took place just before burial of this sedimentary terrain by the Deccan lava flows. Incidentally, the basal and upper channel sandstones of the Lameta Beds are separated by a well-developed regolith consisting of a palustrine limestone–calcrete association (Tandon and Andrews, 2001; Tandon et al., 1995) and multiple calcrete profiles of the Mottled Nodular Beds (Tandon et al., 1998). This would imply a time separation on time scales of 10^5–10^6 years in respect of the basal and uppermost channel sandstones of the Lameta Formation.

4.3. Lithological records at Dongargaon

The Dongargaon Basin of the Nagpur area shows a contrasting facies association (Fig. 2). The lacustrine facies are vertically replaced by overbank-dominated facies, calcretised channel and floodplain deposits, and pedogenically modified sandstone clearly revealing a ‘shallowing up’ trend from shallow lake deposits to a palaeosol before the terrain was buried by the basal lava flow. In contrast with the Jabalpur area, this change from lacustrine to overbank to regolith may imply a changing base level related to the pre-volcanic surface uplift of the area in the order of metres only (cf. Menzies, 2000), and some possible influences of mock aridity (Harris and Van Couvering, 1995).

5. Influence of Deccan volcanism on biotas

Prasad and Khajuria (1995) carried out a detailed comparative analysis of the biotas of the infra- and inter-trappean beds from the Deccan province to assess the nature of changes that may have taken place on the

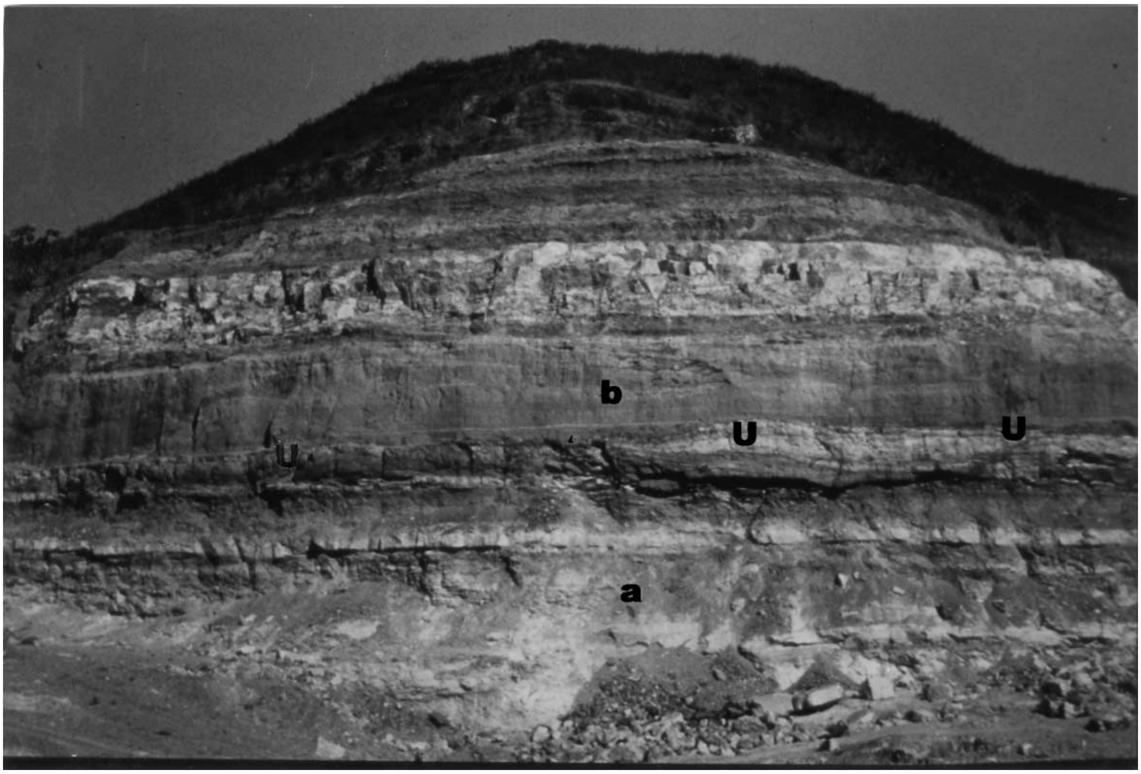
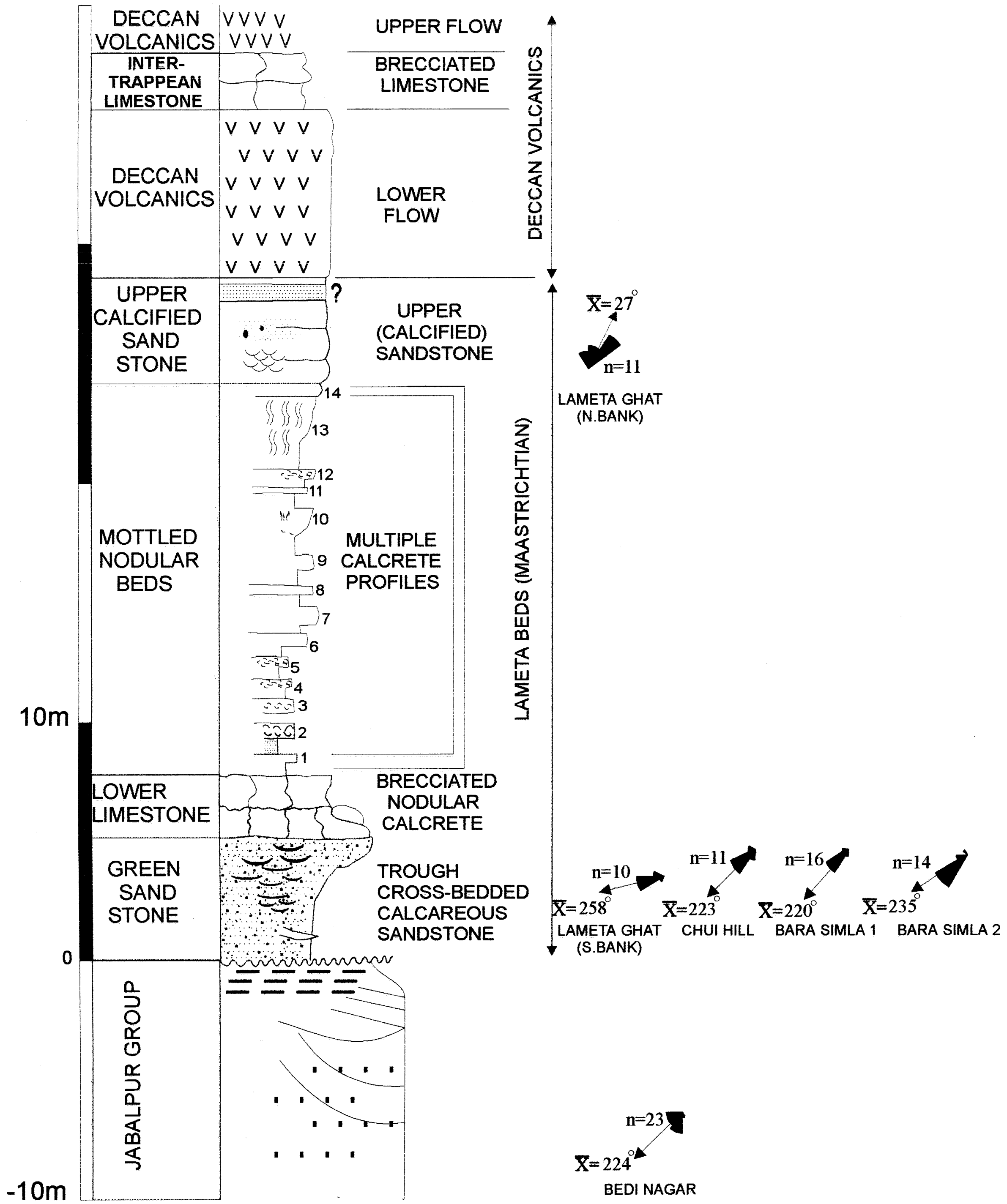


Fig. 5. Field photograph of the Jabalpur Group and Lameta Beds at the Chui hill quarry (photograph taken in 1989 before abandonment of the quarry and degradation of the fresh outcrop): upper part of the Jabalpur sequence consisting of brown mudstones and interbedded thin sandstones (a), channeled Green Sandstone of the infra-trappean Lameta sequenced (b). Note that the green clays appear in the section for the first time above the unconformity surface (U).

faunas/floras. Their analysis led them to believe that an overwhelming majority of taxa, especially the fresh-water lacustrine taxa, survived the initial effects of the Deccan volcanism without undergoing any drastic change. Episodic volcanism possibly allows the biosphere to recover during periods of intervening quies-

Table 2
Data on *d* spacings (Å) of the green clays separate from the sandstones of Green Sandstone unit

Sample number	Mineral phase	*d* spacing (Å)	
		Normal	Glycolated
CH CGE	(1) Montmorillonite	12.58, 4.98	16.35, 16.79, 5.57
	(2) Celadonite	9.97	–
	(3) Kaolinite	7.15, 3.57	7.14, 3.57
	(4) Quartz	4.03, 3.34, 2.45, 2.38	4.25, 3.32, 2.45, 2.38
CH CHE	(1) Montmorillonite	15.12, 4.97, 2.58	16.58
	(2) Celadonite	9.97, 4.35, 3.56	9.77, 4.35, 3.56
	(3) Kaolinite	7.12, 4.50, 4.35, 3.56, 2.49	7.09, 4.49, 3.56
	(4) Quartz	4.24, 3.34, 2.45, 2.38	4.24, 3.33, 2.45
CHD GS	(1) Montmorillonite	15.49, 2.58	
	(2) Celadonite	10.06, 3.58	
	(3) Kaolinite	7.15, 4.51, 3.58	
	(4) Quartz	4.25, 3.34, 2.46, 2.28	


DECCAN VOLCANICS
INTER-TRAPPEAN LIMESTONE
DECCAN VOLCANICS
UPPER CALCIFIED SAND STONE
MOTTLED NODULAR BEDS
LOWER LIMESTONE
GREEN SAND STONE
JABALPUR GROUP
10m
0
-10m
UPPER FLOW
BRECCIATED LIMESTONE
LOWER FLOW
UPPER (CALCIFIED) SANDSTONE
MULTIPLE CALCRETE PROFILES
BRECCIATED NODULAR CALCRETE
TROUGH CROSS-BEDDED CALCAREOUS SANDSTONE
DECCAN VOLCANICS
LAMETA BEDS (MAASTRICHTIAN)
X̄=27° n=11 LAMETA GHAT (N.BANK)
n=10 X̄=258° LAMETA GHAT (S.BANK)
n=11 X̄=223° CHUI HILL
n=16 X̄=220° BARA SIMLA 1
n=14 X̄=235° BARA SIMLA 2
n=23 X̄=224° BEDI NAGAR

cence (Cox, 1988); also, Cox indicated that stress induced by volcanism depends on the size of the volcanic province and the rate at which eruptions took place. In conclusion, Prasad and Khajuria (1995) stated that in the Deccan region, "no single phenomenon could have affected the selective extinction of groups of animals and plants. Such extinctions resulted from environmental stress that accumulated over a long period of time as a consequence of an extended period of volcanism, marine regression, and related climatic changes as visualised by Hallam (1987)." Detailed analysis on the aspect of the short-term effects of volcanism on biotas is mostly lacking, and little is known from this province about the rates of environmental stress built up through the duration of volcanism of ~5 Myr (cf. Cripps et al., 2000).

6. Influence of Deccan volcanism on climates

Reconstruction of palaeolatitudes for the Deccan province show that Central India moved from 35° to 15°S, between 80 and 60 Ma (Smith et al., 1981). In general, aridity/semi-aridity has been inferred by several workers from the lithological and palaeosol records of the infra-trappean sequences of Jabalpur (Brookfield and Sahni, 1987; Tandon et al., 1995). Semi-arid climates are also inferred from the inter-trappean lacustrine strata at Anjar (Khadkikar et al., 1999; Shrivastava et al., 2000). Khadkikar et al. (1999) used the concept of 'mock aridity' (Harris and Van Couvering, 1995) to explain semi-aridity of the Anjar inter-trappean beds. As calcic vertisols are generally absent in the infra- and inter-trappean beds, strongly seasonal conditions probably did not exist.

Estimates of the oxygen isotope composition of the soil–water in equilibrium with the infra-trappean palaeosol carbonates suggest average meteoric water composition of −8‰ (Ghosh et al., 1995). Tandon et al. (1995) also inferred that the regional rainfall values of $\delta^{18}O$ were in the range of −6‰ to −10‰. Ghosh et al. (1995) explained the lighter element isotopic composition in terms of cumulative effects of highly seasonal (monsoon-like) climatic regime, and a more pronounced continental effect due to a bigger size of Cretaceous India.

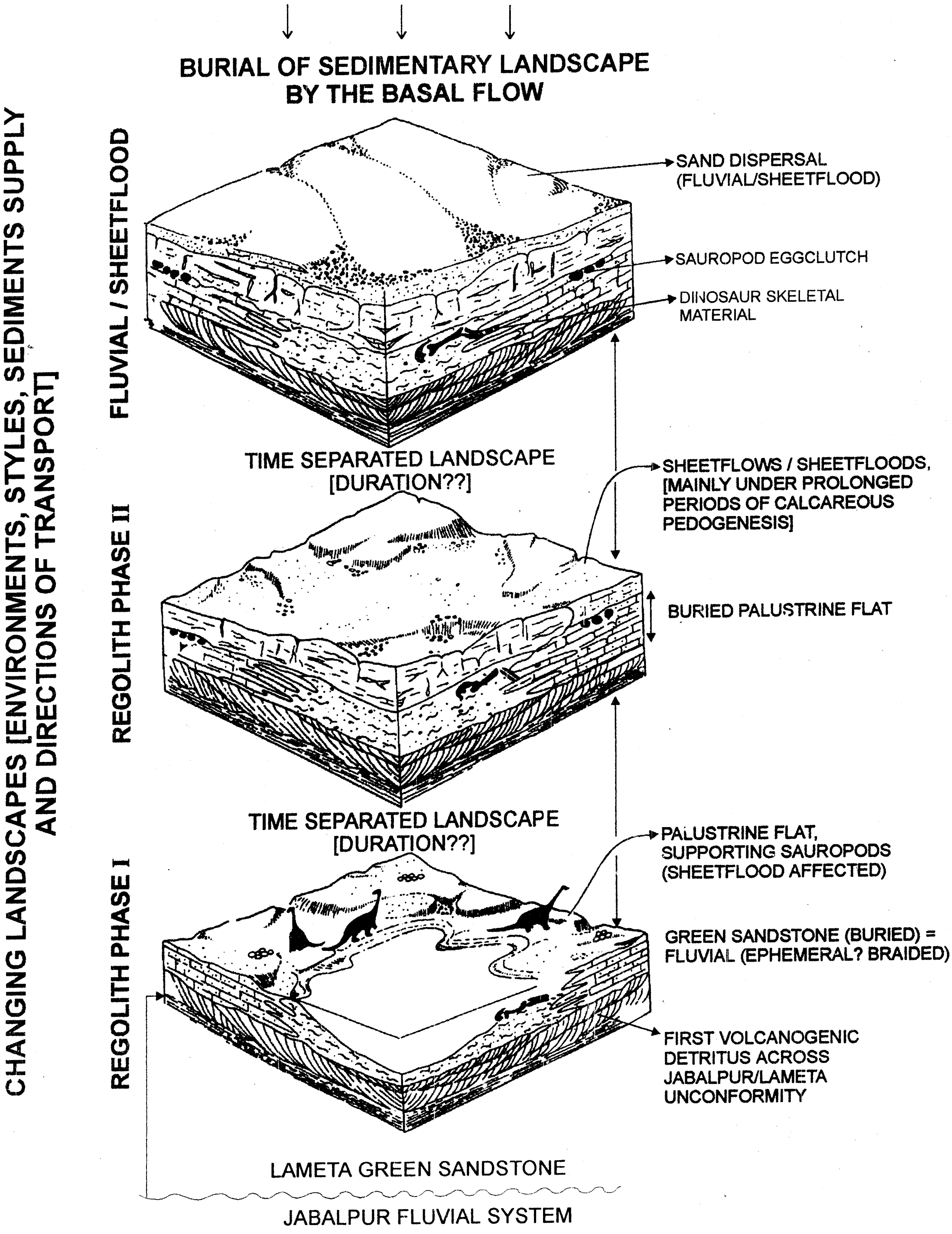
Against this background, the role of Deccan volcanism in the evolution of climate is assessed. Ongoing volcanism should effect long-term climate change because of extensive CO_2 and sulphate aerosol emissions. It is therefore important to know the concentration of CO_2 in the Maastrichtian atmosphere prior to the commencement of Deccan volcanism, and then to track changes through the duration of volcanism— ~5 Myr. However, such data are not currently available for the Indian region.

Carbonate palaeosols are commonly present in the infra-trappean sequences and their analyses shows that the Maastrichtian atmosphere coeval with the basal Deccan lava flows is unlikely to have contained >1300 ppm/V of CO_2 (Andrews et al., 1995). For comparison of this value, it is useful to recall the palaeo-pCO_2 of Aptian–Albian as determined from the Shimonoseki Formation of Japan to be in the range of 2400–4500 ppm/V (Lee, 2000). Barring these few data from the Asian region, little information is available on the CO_2 concentration of Cretaceous palaeoatmospheres. Hence, data on the influence of Deccan volcanism on CO_2 change and climate evolution in the Asian region, or more particularly the Deccan province, is negligible.

7. Discussion

Sedimentary deposits serve as recorders of past events; sedimentary deposits associated with continental flood basalt volcanism are, in principle, useful in tracking volcanism-induced changes in the surficial environments. Continental flood basalt volcanic episodes span short segments of geologic time, for example ~5 Myr in the case of the Deccan volcanism. Such accelerated and high rates of emission of lavas are believed to lead to rapid changes in the Earth's near

Fig. 6. Generalised log highlighting the three levels of occurrence of cross-bedded sandstones in the Gondwana–Lameta sequences of the Jabalpur area. Rose diagrams from various locations show major south and southwest transport directions both in the sub-unconformity Gondwana fluvial channel sandstones and in the basal sandstones of the Lameta Beds. Note that the sediment transport changes to the northeast in the upper sandstones of the Lameta Beds (data from the Upper sandstone are limited to two locations). Upper and lower sandstones of the Lameta Beds separated by a well-developed regolith implying major changes in the landscape.


BURIAL OF SEDIMENTARY LANDSCAPE BY THE BASAL FLOW
CHANGING LANDSCAPES [ENVIRONMENTS, STYLES, SEDIMENTS SUPPLY AND DIRECTIONS OF TRANSPORT]
FLUVIAL / SHEETFLOOD
SAND DISPERSAL (FLUVIAL/SHEETFLOOD)
SAUROPOD EGGCLUTCH
DINOSAUR SKELETAL MATERIAL
TIME SEPARATED LANDSCAPE [DURATION??]
REGOLITH PHASE II
SHEETFLOWS / SHEETFLOODS, [MAINLY UNDER PROLONGED PERIODS OF CALCAREOUS PEDOGENESIS]
BURIED PALUSTRINE FLAT
TIME SEPARATED LANDSCAPE [DURATION??]
REGOLITH PHASE I
PALUSTRINE FLAT, SUPPORTING SAUROPODS (SHEETFLOOD AFFECTED)
GREEN SANDSTONE (BURIED) = FLUVIAL (EPHEMERAL? BRAIDED)
FIRST VOLCANOGENIC DETRITUS ACROSS JABALPUR/LAMETA UNCONFORMITY
LAMETA GREEN SANDSTONE
JABALPUR FLUVIAL SYSTEM

surface and atmospheric environments. These changes, which are short lived, cause severe environmental stress and may eventually result in mass extinction (Mclean, 1985; Officer et al., 1987; Courtillot et al., 1990). Therefore, the rates and directions of change in the near-surface environments are required to be understood, particularly where short-term catastrophic perturbations, superimposed on long-term trends, have caused subsequent global changes.

7.1. Vertical facies and environmental trends—response to lava emplacement induced surface uplift, climate shifts, or what?

In Central India, most of the infra-trappean sequences are thin, and generally do not exceed approximately 40-m thickness. In the Jabalpur area of the Narmada region, ephemeral-braided stream deposits are replaced vertically by subaerially exposed palustrine carbonate deposits, multiple calcrete profiles, and eventually, by sheetflood (locally channelised) deposits marking a landscape that had adjusted to new constructional topography and surface uplift caused by the lavas (Fig. 7).

Central to any attempt to read the vertical record as an adjustment to volcanism and/or climatic change would be the completeness of time in this stratigraphic record. Lameta records in Jabalpur area represent a set of four significant events—fluvial systems-palustrine flats—carbonate palaeosols-multiple calcrete profiles in a succession of sheetflood events (locally channelled system) (Fig. 7). It is clear that significant time should have lapsed between the basal and upper sandstone events. One may speculate that the shift from the basal fluvial system to the carbonate-dominated regolith may be an indicator of progressive aridity, and the change to the upper sandy sheetflood deposits from the carbonate regolith possibly indicates the establishment of a sand dispersal system in relatively wetter conditions in a landscape that had adjusted itself to volcanic influence. Clear evidence of change of base levels is lacking in this region, but is better available in the Nagpur area where lacustrine facies are well developed.

These variable styles of facies development, and vertical trends in facies and environments may be related to the level of completeness of these records, in addition to the factors of surface uplift and climate change. The mode of preservation of sedimentary packets in terrains affected by continental flood basalt volcanism is indeed significant in evaluating volcanism-induced changes in vertical motifs in coeval sedimentary sequences. Vertical environmental shifts in the Dongargaon Basin appear to be base-level-related in response to surface uplift, and possibly represent a relatively shorter duration than the fluvial deposits-regolith-dominated record of the Jabalpur area.

8. Conclusions

(1) How is the effect of volcanism manifested in coeval sedimentary records? Volcanism causes certain direct changes in the terrain, both in terms of addition of new geological material, constructional topography, and surface uplift. The landscape then responds to these changes. In the eastern part of the Deccan province, these responses are reflected by the first input of basaltic degradational products in the fluvial system that deposited the basal unit of the Lameta Formation, i.e. the green sandstone. Locally, in the Jabalpur area, there was a substantial time lapse ($10^5 - 10^6$ years) before significant slope-driven changes in drainage direction took place. The change from the SW palaeoslopes of the pre-volcanic landscape to NE palaeoslopes prior to burial of the terrain by a volcanic pile was separated by events of drainage disruption, formation of subaerial-dominated palustrine flats, and formation of plains affected by sheetfloods. Stratigraphic synthesis of these events is rendered difficult because of the non-resolution of the durations of these events (cf. Tandon et al., 1998). Time resolution on $10^5 - 10^6$-year time scales is mostly unattainable in such continental sequences; moreover, the presence of carbonate palaeosols and stacks of calcrete profiles is a clear pointer of considerable periods of time characterised by non-sedimentation.

Fig. 7. Vertical changes in facies motifs suggest changes in the landscapes, mostly caused by contemporaneous volcanism. Change from a fluvial to palustrine to subaerial plains affected by sheetfloods is interpreted. Abundant carbonate palaeosols/calcretes suggest increased aridity, and separate the lower and upper fluvial deposits of the Lameta Beds.

Although evidence is available in coeval sedimentary deposits of the indirect effects of Deccan volcanism, detailed cause (volcanism)–effect (surficial environments) relationships at the event level remain elusive.

(2) In some areas, changing base levels due to volcanism-induced constructional topography and surface uplift resulted in a shift from lacustrine- to subaerial-dominated environments. Here again, because of the difficulties of time-resolution of these stratigraphic records, rates of surface uplift cannot be determined.

(3) A significant query is about the nature of changes that takes place in the CO_2 concentration of the atmospheres that are coeval with continental flood basalt volcanism. The lack of data from multiple stratigraphic levels of the Deccan-associated sedimentary strata precludes serious assessment of short-term effects, cumulative effects of clusters of short-term events, and the evolution of long-term trends (direction and rate) over the entire span of the Deccan volcanism.

Important gaps in our knowledge continue to exist, and issues and questions that require to be addressed are as follows:

(a) rates of environmental stress build up through the duration of the volcanism, particularly with respect to atmospheric CO_2 changes and the resultant responses of the vegetational ecosystem;
(b) understanding the upward changes in lithofacies from the lacustrine/palustrine to subaerial dominated in terms of causal factors such as uplift-/climate-induced base level changes and/or mock aridity;
(c) detailed documentation of the lacustrine lithofacies, and other related facies in the areas south of Nagpur, also detailed documentation of the lithofacies of the marine inter-trappean beds of Rajahmundry, and delimitation of the inland extent of marine transgression from the southeast.

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