Palynoflora from Deccan volcano-sedimentary sequence (Cretaceous-Palaeogene transition) of central India: implications for spatio-temporal correlation

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The sedimentary beds associated with Deccan Continental Flood Basalt (DCFB) sequences exposed in the volcanic subprovinces of Jabalpur-Mandla-Chhindwara (JMC) regions of Madhya Pradesh and Nand-Dongargaon (N-D) basin and the adjoining areas to the west in Yeotmal-Nanded in Maharashtra were studied for their palynofloral analysis. The sediments were characterized palynologically and changes in the palynoflora are observed at different stratigraphic levels in a number of sections including several new intertrappean localities recorded in recent years. For the purpose of effective correlation of different subprovinces, palynofloras of some of the previously studied intertrappeans are also reviewed. Our studies suggest that before the start of the Deccan volcanic activity, the palynoflora found in the Lameta sediments, was dominated by gymnosperms-angiosperm association. The plant canopy consisted mainly of gymnosperms (Conifers and Podocarpaceae) whereas, the understory members were mostly of palms and herbs (Poaceae and Asteraceae). The eruption of Deccan volcanic flows severely affected the existing floral association and proved fatal for the well established plant community. The immediately overlying sediments associated with the earliest volcanic flows are dominated by pteridophytes and angiosperm taxa (*Azolla cretacea, Aquilapollenites bengalensis, Ariadnaesporites* sp., *Gabonisporis vigourouxii* and *Triporoletes reticulatus).* Higher up in the stratigraphic sequence, similar forms continued with simultaneous appearance of new taxa including *Scabrastephanocolpites* spp. At still higher stratigraphic levels, abundance of fungi especially the mycorrhizal fungi, concurrent with sharp decline in pollen/spore recovery was observed. In the culminating phase (i.e. Palaeocene) of Deccan volcanic history a new palynofloral assemblage of typical Palaeocene taxa (*Dandotiaspora dilata, D. pseudoauriculata, D. plicata, Spinizonocolpites echinatus, Matanomadhiasulcites* sp., and *Lakiapollis ovatus*) was encountered.

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1. Introduction

The Deccan Traps are one of the largest Continental Flood Basalt (CFB) provinces in the world, occupying an area of about 500,000 km^2 in peninsular India (Jay and Widdowson 2008). The duration of activity of this Large Igneous Province (LIP) was debated for a long time, with estimates ranging from < 1 my (Duncan and Pyle 1988; Hofmann *et al.* 2000) to 7–8 my (Pande 2002; Sheth *et al.* 2001). However, recent data indicate that the volcanism was at its peak at 65 Ma (Chenet *et al.* 2007) and that the earliest eruptions occurred in the northwestern (Nasik and Narmada) region (Subbarao *et al.* 1994; Hooper 1999, Widdowson *et al.* 2000). Later activity occurred in the southern flank (Beane *et al.* 1986; Devey and Lightfoot 1986; Mitchell and Widdowson 1991), and the last phase of eruption occurred in the southern Deccan Volcanic Province (DVP) near Belgaum (Jay and Widdowson 2008). The Deccan volcanism is of considerable interest to biologists as well as to geologists as it is considered to be one of the causes of mass extinction at the Cretaceous-Palaeogene Boundary (KPB).

Keywords. Deccan volcanism; Early Paleocene; intertrappean beds; Lameta Formation; Late Cretaceous; palynoflora

The nature of impact of CFBs on ecosystems and the biological response to volcanic activity (Jolley *et al.* 2008) are still a matter of study, but CFB provinces have long been considered to be linked to most of the major extinction events in earth's history. CFBs are believed to cause environmental deterioration as they release large quantities of volcanogenic gases such as SO_2, NO_2, and CO_2 into the atmosphere (Self *et al.* 2005). The volcanic eruptions not only pollute the atmosphere but also cause a large influx of macronutrients into the atmosphere (Jolley 1997; Ellis *et al.* 2002; Jolley *et al.* 2008). These changes ultimately affect the biota, both in terrestrial and aquatic biomes. The terrestrial plants, unlike terrestrial animals, cannot modify their environment by their behaviour. Therefore the floral response to the environmental and climatic changes is well recorded in sediments deposited in periods of quiescence between the volcanic eruptions.

The Deccan Continental Flood Basalts (DCFB) are represented in various subvolcanic provinces having different or overlapping history of volcanic eruptions. The stratigraphic correlation of the different subvolcanic provinces has remained challenging and problematic, and attempts have been made to correlate on the basis of chemical stratigraphy (Jay and Widdowson 2008). The problem of correlation has been compounded by separation of the volcanic provinces owing to post-eruptive tectonic disturbances and vast stretches of pre- and post-trappean groups of rocks separating the provinces. A number of sedimentary beds occurring at different stratigraphic levels in different subprovinces offer an opportunity for faunal and floral analysis and study of depositional environments. Such studies are crucial not only for recording the effect of Deccan volcanism on contemporary biota and sediments but also for stratigraphic correlation of geographically separated DCFB subprovinces and resolving issues related to the Cretaceous-Palaeogene Boundary. The present work evaluates the record of microflora in a series of sedimentary beds in different volcanic subprovinces, and the floral changes as observed at different stratigraphic levels as response of flora to the environmental stresses created by Deccan volcanism. An attempt has been made to establish a time stratigraphic correlation based on palynofloral analysis of sediments associated with the Deccan volcanic eruptions.

2. Geology of the area

The sediments associated with the Deccan volcanic province are represented by infratrappean (Lameta Formation) and intertrappean beds. The Lameta Formation covers an area of over 5000 km^2, forming detached outcrops in states of Maharashtra, Madhya Pradesh, and Gujarat. The sediments of this formation were deposited in five inland basins: (I) Balasinor-Jhabua basin, (II) Sagar basin, (III) Jabalpur basin, (IV) Amarkantak-Ambikapur basin, and (V) Nand-Dongargaon basin (Mohabey 1996).

The intertrappean sediments present at different stratigraphic levels within the Deccan volcanic sequence, were deposited during periods of quiescence in the volcanic activity. They are exposed in central India (in the Nand-Dongargaon basin and the adjoining area of Yeotmal-Nanded to the west, and the Chhindwara-Mandla-Jabalpur sector both north and south of the Narmada River Valley), western India (in the northwesternmost volcanic province in Kutch, including the iridium-bearing Anjar section; Saurashtra in Gujarat, and Bombay in Maharashtra), and to the south in parts of Karnataka and Andhra Pradesh, including Rajahmundry. Some isolated localities also occur in Lalitpur in Uttar Pradesh (figure1).

In the Nand-Dongargaon (N-D) basin, the Lameta sediments are overlain by the Deccan Traps. The Deccan volcanic sequence of the N-D basin is classified as the Sahyadri Group (GSI 2000), comprising a ~500 m thick sequence of a total of 29 basaltic flows named as the Ajanta Formation, Chikli Formation, Buldana Formation, and Kharanja Formation in ascending order, with intertraps having thickness ranging from less than 1 m to over 5 m. In the Ajanta Formation, the palynomorph-bearing intertrappeans are exposed in the Daiwal River section, Anandvan (between flows F1 and F2) and Sindhi (between flows F4-F5). The intertrap sediments between the flows F3 and F4 at Kharwad, though rich in mollusks, have not yielded any palynomorph. The Jhuli and Podgawan intertrappeans occur in between flow F10 and F11 and F12 and F13, respectively.

In the Jabalpur-Mandla-Chhindwara (JMC) Sector, the Lameta sediments are overlain by the Deccan volcanic sequence of Amarkantak Group, comprising Mandla Formation, Dhuma Formation, Pipardhi Formation and Linga Formation in the ascending order (GSI 2000). The intertrappean beds are well developed at different stratigraphic levels between 570 m to 860 m RL. The palynomorph-bearing intertrappean beds of the JMC sector include the well known locality at Mohgaon-Kalan of Chhindwara district; the Ranipur and Padwar sections of the Mandla Formation; the Singpur and Jhilmili intertrappeans of the Dhuma Formation and the Butera and Lohara intertrappean beds in between the Pipardhi and Linga formations.

3. Microfloral record

The DCFB are associated with micro- and megafloral-rich Lameta Formation and intertrappean sediments. Besides the floral remains, rich faunal remains ranging from invertebrates to vertebrates including titanosauromorph dinosaurs also occur in these deposits. Palaeontological studies carried out

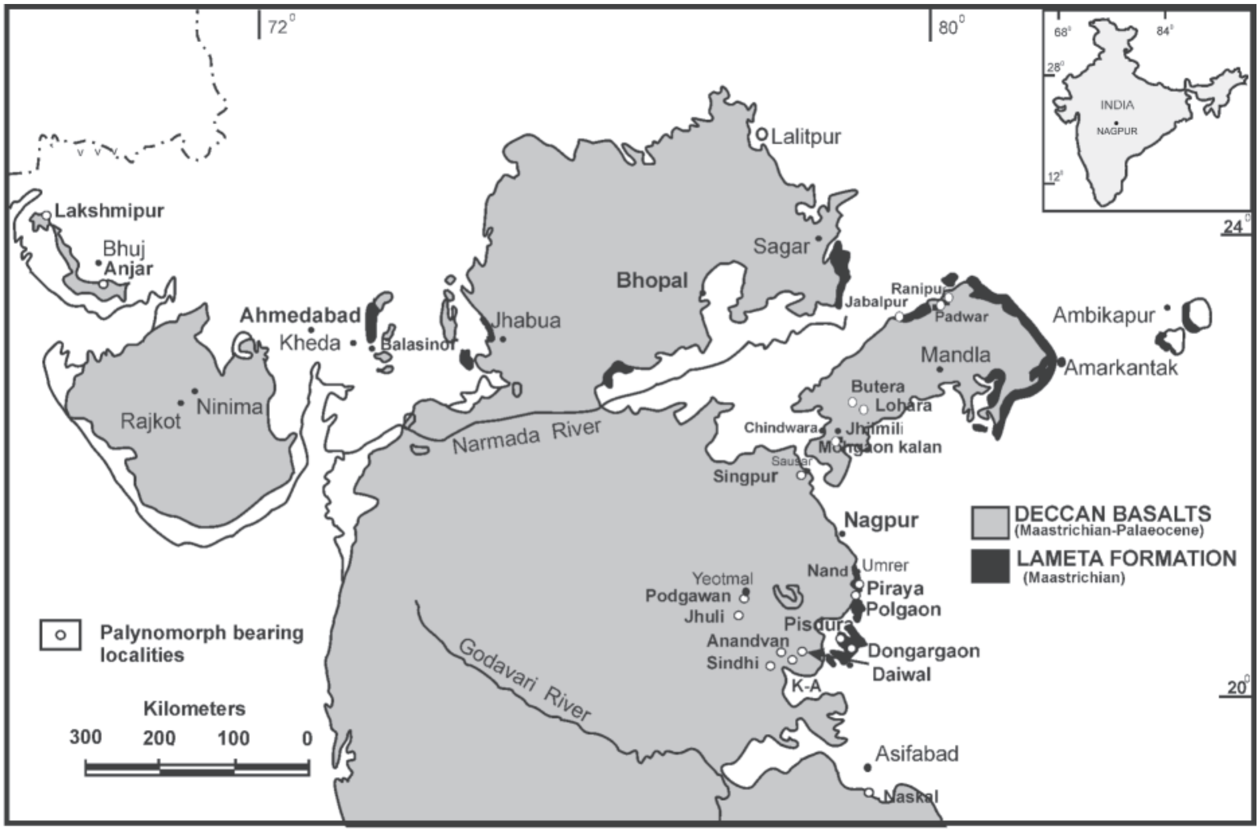

Figure 1. Map showing the location of palynomorph-bearing intertrappean deposits in the Deccan volcanic province

so far in the Lameta and intertrappean sediments have been summarized in detail by Khosla and Sahni (2003). Overall, the data shows that, of the five Lameta basins, only three (namely Balasinor-Jhabua basin in the western India, and the Jabalpur and Nand-Dongargaon basins in central India; figure 1) have been studied in detail for lithofacies and biofacies analysis. In comparison to a wide range of faunal records, the floral record (both mega and micro) from these sediments is relatively poor. To date, there has been only one report of a Boraginaceae seed from the Lameta sediments of the Kheda area of the Balasinor-Jhabua basin (Mathur and Mathur 1985). The Lameta sediments of central India (N-D basin and Jabalpur) have yielded relatively rich microfloral remains; however, the megaflora record is so far known only from the N-D basin.

The Lameta sediments of the N-D basin have yielded quite diverse mega- and microflora. The oldest record of megaflora from this basin is fossil palm wood and impressions of the monocotyledon fruit *Viracarpon* (Biradar and Bonde 1979; Bonde and Biradar 1981). Over the last two decades, a rich megafloral record represented by fossil woods of dicot (Sapindaceae, Euphorbiaceae Kar *et al.* 2004), leaves (*Bracheophyllum*, as well as of palm and dicot; Mohabey and Udhoji 1996), fruits of Capparidaceae (Dutta and Ambwani 2007), and conifer seeds (*Araucaria*; Mohabey and Udhoji 1996) have been reported from this basin. In addition to megaflora, a diverse palynofloral assemblage from the sediments as well as associated coprolites has also been documented from this basin.

The palynofloral assemblage is composed of algal remains (*Oedogonium, Lecaniella, Botryococcus*), fungal remains (spores of *Alternaria, Meliola, Helminthosporum, Aspergillus, Frasnacritetrus*, mycorrhizal fungi; Mohabey and Samant 2003; *Collestrochum, Erysiphe*, and *Uncinula*; Sharma *et al.* 2004), pteridophytic spores (*Azolla*, Mohabey and Samant 2003; *Gabonisporis vigourouxii*; Ghosh *et al.* 2003), gymnosperm pollen (A*raucariacites* sp*., Cycadopites* sp*., Podocarpidites* sp*., Classopollis* sp., *Calliasporites*, *Trilobosporites*; Mohabey and Udhoji 1996; Samant and Mohabey 2005 (figure 2) and angiosperm pollen *Palmaepollenites* sp., *Longapertites* sp., *Graminidites* sp., *Retimonosulcites* sp., S*apotaceoidaepollenites* sp*.,* and other tri- and tetracolporate pollen grains). Pollen grains of *Cretacaeiporites* sp. and C*ompositoipollenites* sp., belonging to the families Caryophyllaceae and Asteraceae, respectively, are also present in the Lameta sediments (table 1).

Apart from this palynoassemblage, other non-pollen palynomorphs such as phytoliths of grasses (Prasad *et al.* 2005), trichomes, scales of plants, centric (*Aulacoseira*) and pinnate diatoms (Mohabey 2001; Ambwani *et al*. 2003) and insect remains have been found in coprolites and Lameta sediments. Cut and polished samples of coprolites indicate the presence of permineralized ovules, seeds, flowers of angiosperm, leaves of *Araucaria* and pteridophytic remains (Mohabey and Samant 2003).

The Asteraceae and Caryophyllaceae pollen grains in the Lameta sediments of the N-D basin are the oldest known records of these families in the Indian subcontinent. In the Dongargaon lake sequence of the basin, varves containing the diatom *Aulacoseira* are present at four stratigraphic levels (Mohabey 2001). So far, this is the oldest known record of the non marine diatom *Aulacoseira* anywhere in the world.

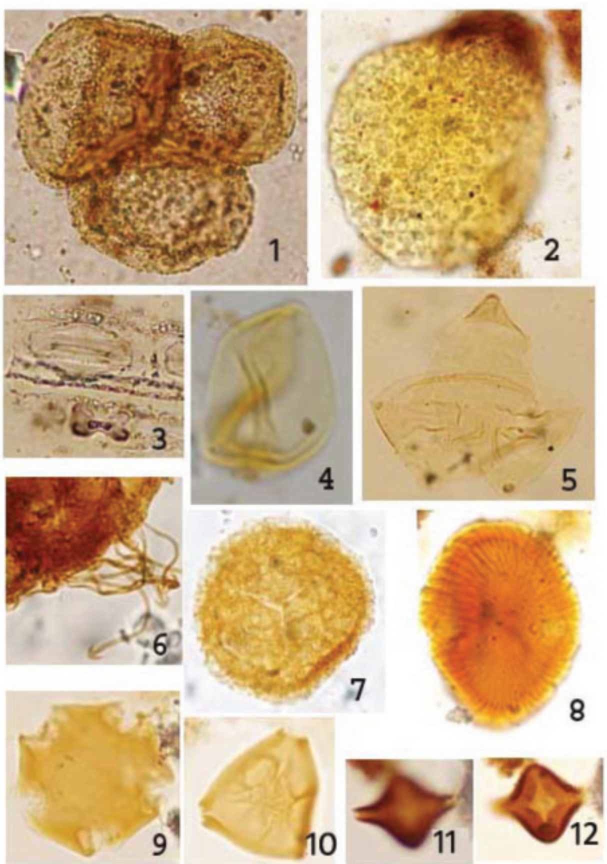

Figure 2. (1) *Classopollis* sp. Slide no. Pol (25),10; (2) *Oedogonium cretaceum* Zippi Slide no. Pis2,1; (3) Phytolith of Poaceae Slide no. Pis(P),2; (4) *Araucariacites* sp. Slide no. Pol. 3,3; (5) *Deccanodinium* sp. Slide no. Surla-1; (6) *Azolla cretacea* Stanley Slide no. Si-1,8; (7) *Gabonisporis vigourouxii* Boltenhagen Slide no. Si-1,8; (8)**,** *Aquilapollenites bengalensis* Bakshi and Deb Slide no. Pch-6; (9) *Scabrastephanocolpites singpurensis* Samant et al. Slide no. Si-17,4; (10) Normapolles group pollen Slide no. Si-17,4; (11-12) *Farabeipollis* sp. Slide no. IJ-5. (All magnifications 1000X or otherwise stated.)

Towards the north, the Lameta sediments in Jabalpur basin yielded the palynoassemblage containing *Aquilapollenites indicus* from the lower green sandstone/conglomeratic beds (table 1). The upper sandstone with carbonaceous clays and the upper limestone yielded a few palynomorphs; however, palynomorphs are rare in the lower limestone and mottled nodular marls (Dogra *et al.* 1988, 1994; Dogra and Singh 1996). The overall mega- and microflora from the Lameta sediments of Jabalpur and N-D basins show that both gymnosperms and angiosperms were prominent floristic members during the Lameta time.

A distinct floral turnover is observed in the palynoflora of the overlying intertrappean sediments, both in quantity and quality. In intertrappean deposits of N-D basin, a change in flora is observed in the beds occurring between flow F1 and F2 (Daiwal, Khandala-Ashta, Anandvan; Samant and Mohabey 2003; Samant *et al.* 2005). All these beds are characterized by appearance of new palynoassemblage (viz. *Azolla cretacea, Aquilapollenites bengalensis, Ariadnaesporites* sp., *Gabonisporis vigourouxii* and *Triporoletes reticulatus,* etc) dominated by pteridophyte spores and angiosperm pollen grains (table 1; figure 2). Apart from these palynomorphs, the dinoflagellate bloom is observed in these intertrappean beds. These beds also show a sharp decrease in diatoms from the Lameta sediments to successive intertrappean sediments, probably due to the appearance of heterotrophic peridinoid dinoflagellates (*Deccanodinium*), which feed on diatoms. The successive intertrappean beds of higher stratigraphic level (Sindhi) are characterized by the continuation of most of the earlier palynoassemblage as well as the appearance of new forms such as *Scabrastephanocolpites* spp, and diversification of the Normapolles group (Samant and Mohabey 2005). Towards the west of this basin and at still higher stratigraphic levels (Jhuli and Podgawan), a sharp decrease in the pollen spore recovery, increase in the fungal spores and mycorrhizal fungi and presence of highly fungal infected plant material is observed (figure 3). These changes could be related to the intense volcanic activity in the nearby area.

Similar floral associations are also observed in the intertrappean sediments of the JMC sector, such as Padwar (Prakash *et al.* 1990; Kar *et al.* 1998), Ranipur (Mathur and Sharma 1990), Mohagaon Kalan well section (Kumaran *et al.* 1997; Kar and Srinivasan 1998), and Singpur (Samant *et al.* 2008). The Singpur Intertrappean bed has yielded the megaflora such as buccate fruit and fruit of Euphorbiaceae (Mistry and Kapgate 1992; Bhowal and Sheikh 2004)

In Mohagaon-Kalan locality, two intertrappean deposits rich in micro- and mega flora are separated by a volcanic flow. The lower intertrappean beds exposed in a dug well has yielded the Maastrichtian palynomorphs (Kumaran *et al.* 1997; Kar and Srinivasan 1998) along with dinosaur egg

Table 1 Palynomorphs recovered from non-marine infra and intertrappean sediments

Lakshmipur Intertrappean	Anjar Intertrappean 29R	Lameta sediments N-D basin	Daiwal, K-A & Anandvan	Sindhi Intertrappean	Lameta sediments
Samant & Bajpai, 2005	Dogra *et al.* 2004	**30N -29R**	**Intertrappean 29R**		**Jabalpur, 29R**
		Samant & Mohabey, 2005	Samant & Mohabey, 2005	Samant & Mohabey, 2005	Dogra & Singh, 1996
		and present study	and present study	and present study	
	Dinosaur remains	Dinosaur remains	Appearance of Dinoflagellates		Dinosaur remains
	Sponge spicules	Diatoms dominant 30N	Epiphyllous fungi present		
Sponge spicules few diatoms	Diatoms	Mycorrhizal fungi	Diatoms		Dinoflagellates present
Pteridophytes	**Pteridophytes**	**Pteridophytes**	**Pteridophytes**	**Pteridophytes**	**Pteridophytes**
Cyathidites sp.	*Gabonisporis bacricumulus*	*Azolla*	*Gabonisporis vigourouxii*	*Gabonisporis vigourouxii*	*Ariadnaesporites*
Cyathidites sp.	*Gabonisporis sp.*		*Ariadnaesporites* sp.	*Gabonisporis bacricumulus*	*Todisporites*
Cicatricosisporites sp.			*Azolla cretacea*	*Azolla cretacea*	*Cyathidites*
Concavissimisporites sp			*Triporoletes reticulatus*	*Cyathidites australis*	*Baculatisporites*
Contignisporites sp.			*Lycopodiumsporites* sp.	*Lycopodiumsporites* sp.	*Dictyophyllidites*
Leptolepidites sp			Lygodiumsporites sp.	*Triplanosporites* sp.	*Cicatricosisporites*
Lygodiumsporites sp.			*Osmundacidites* sp.		*Leptolepidites verrucatus*
Murospora sp.			*Triplanosporites* sp.		*Contignisporites*
Triplanosporites sp.			*Todisporites* sp.		*Lametatriletes*
			Pediastrum		*Lycopodiumsporites*
					umstewensis
					Polypodiisporites
					Arecellites
					Coptospora
Gymnosperms		**Gymnosperms**	**Gymnosperms**	**Gymnosperms**	**Gymnosperms**
Araucariacites australis		*#Araucariacites* sp.	*Araucariacites* sp.	*Araucariacites* sp.	***Araucariacites limbatus***
Callialasporites sp.		*Callialasporites* sp.	*Cycadopites* sp.	*Equisetosporites* sp.	*Podocarpidites elipticus*
Cycadopites sp.		*Cycadopites* sp.	*Equisetosporites* sp.		***Baculatisporites***
		Classopollis sp.	*Podocarpidites* sp.		***Alisporites***
		Podocarpidites sp.			*Cedripites*
					Callialasporites trilobatus
Angiosperms	**Angiosperms**	**Angiosperms**	**Angiosperms**	**Angiosperms**	*Callialasporites segmentatus*
Aquilapollenites	*Aquilapollenites*		*Aquilapollenites*	*Aquilapollenites*	*Ginkgopites* .
bengalensis	*bengalensis*		*bengalensis*	*bengalensis*	*Laricoidites*
Proxapertites	*Aquilapollenites*	*#Palmaepollenites* sp.	*Proxapertites*	*Scollardia conferta*	*Cycadopites couperi*
opreculatus	*indicus*	*Longapertites* sp.	*operculatus*	*Scabrastephanocolpites* spp.	*Ginkgocycadophytus*
Proxapertites	*Proxapertites*	**Graminidites* sp.	*Palmidites* sp.	*Normapolles group pollen*	*Ginkgoretectina vastus*
microreticulatus	*granulatus*	#Tri and tetracolporate pollen	*Neocouperipollis* sp.		*Psilospora*

Table 1 *(Continued)*

Racemonocolpites sp.	*Proxapertite* sp.	*Retimonosulcites* sp.	*Racemonocolpites maximus*	**Note: megaflora present**	*Schizosporis*
Retitricolpites vulgaris	*Tricolpites* sp.	*Compositoipollenites* sp.	*Racemonocolpites* sp.		*Equisetosporites*
Tricolpites reticulatus	*Proteacidites reticulatus*	*Cretacaeiporites* sp	*Echitricolpites* sp.		*Narbadapollis indicus*
Tricolpites sp.	*Proteacidite* sp.	*Periporopollenites* sp.	*Echimonocolpites* sp.		
Longapertites sp.	*Triorites* sp.	*Sapotaceoidaepollenites* sp.	*Tricolpites* sp.		**Angiosperms**
Liliacidites trichotomosulcites	*Palmidites* sp.		***Normapolles group pollen***		*Aquilapollenites indicus*
	Racemonocolpites sp.	**Note: represented by phytoliths**			*A. andamanensis*
Note: megaflora absent		**# represented by megaflora also**	**Note: megaflora absent**		*Proxapertites crassimurus*
	Note: megaflora present	**Note: megaflora present**			*P. assamicus*
					P. granulatus
					Palmaepollenites eocenicus
					Palmidites maximus
					P. plicatus
					Proteacidites amolosexinous
					Liliacidites microreticulatus
					L. giganticus
					Lakiapollis
					Eucommidiites troedssonii
					Scollardia
					Polyadopollenits mesozoicus
					Note: megaflora absent
Ranipur intertrappean	**Padwar Intertrappean**	**Mohgaon-Kalan**	**Singpur**	**Naskal**	**Lalitpur**
29R	**29R**	**(well) Intertrappean 30N**	**Intertrappean**	**Intertrappean**	**Intertrappean**
Mathur & Sharma, 1990	Prakash *et al*. 1990	Kumaran *et al.* 1997	Samant & Mohabey, 2008	Singh *et al*. 2006	Singh & Ratan Kar, 2002
	Kar *et al.* 1998	Kar & Srinivasan, 1998			
Dinosaur remains		Dinosaur remains			
		Diatoms present			
Pteridophytes	**Pteridophytes**	**Pteridophytes**	**Pteridophytes**	**Pteridophytes**	**Pteridophytes**
Gabonisporis vigourouxii	*Gabonisporis vigourouxii*	*Gabonisporis vigourouxii*	*Gabonisporis vigourouxii*	*Gabonisporis vigourouxii*	*Cyathidites australis*
Gabonisporis sp.	*Azolla cretacea*	*Azolla cretacea*	*Gabonisporis bacricumulus*	*Azolla cretacea*	*Cyathidites minor*
Azolla cretacea	*Ariadnaesporites* sp.	*Ariadnaesporites* sp.	*Azolla cretacea*	*Ariadnaesporites intermedius*	

Table 1 *(Continued)*

Triporoletes reticulatus	*Triporoletes reticulatus*	*Triporoletes reticulatus*	*Ariadnaesporites* sp.	*Triporoletes reticulatus*	
Lycopodiumsporites sp.	*Cyathidites minor*	*Contignisporites* sp.		*Cyathidites* sp.	*Todisporites major*
Cicatricosisporites sp.	*Todisporites major*	*Cicatricosisporites*		*Cyathidites minor*	*Todisporites kutchensis*
Foveotriletes sp.	*Todisporites* sp.	*dorogensis*		*Todisporites major*	*Foveosporites* sp.
Todisporites major	*Osmundacidites*	*Cicatricosisporites* sp.		*Polypodiisporites* sp.	*Klukisporites*
Toroisporis major	*wellmanii*	*Alsophyllidites* sp.		*Maculatospora* sp.	*Biretisoprites bellus*
	Osmundacidites sp.	*Foveosporites* sp.		*Minerisporites triradiatus*	*Biretisoprites convexus*
	Alsophyllidites sp.	*Cyathidites* sp.			*Cingulatisporites* sp.
	Cicatricosisporites sp.	*Lycopodiumsporites* sp.			*Dandotiasopra dilata*
	Acrostichumsporites	*Todisporites major*			*Dandotiasopra plicata*
	meghalayensis	*Cyathidites minor*			
	Lygodiumsporites sp.	*Osmundacidites* sp.			
Gymnosperms	**Gymnosperms**	**Gymnosperms**	**Gymnosperms**	**Gymnosperms**	
Equisetosporites sp.	*Araucariacites* sp.	*Ephedripites* sp.	***Equisetosporites ovatus***	Cycadopites sp.	
	Ephedripites sp.		*Equisetosporites* sp.		
	Callialasporites trilobatus				
	Podocarpidites sp.				
Angiosperms	**Angiosperms**	**Angiosperms**	**Angiosperms**	**Angiosperms**	**Angiosperms**
Aquilapollenites	*Aquilapollenites*	*Aquilapollenites*	*Aquilapollenites*	*Mulleripollis bolpurensis*	*Matanomadhiasulcites* sp.
bengalensis	*bengalensis*	*bengalensis*	*bengalensis*	*Mulleripollis* sp.	*Lithoparaphysis paparensis*
Pulcheripollenites	*Proxapertites*	*Proxapertites*	*Spinizonocolpites*	*Lithoparaphysis* sp.	*Spinizonocolpites*
cauveriana	*cursus*	*cursus*	*echinatus*	*Spinizonocolpites*	*echinatus*
Echitricolporites	*Proxapertites*	*Proxapertites*	*Spinizonocolpites* sp.	*echinatus*	*Spinizonocolpites* sp.
maristellae	*opreculatus*	*opreculatus*	*Pulcheripollenites cauveriana*	*Proxapertites cursus*	*Lakiapollis ovatus*
Foveotricolporites sp.	*Spinizonocolpites*	*Spinizonocolpites*	*Racemonocolpites maximus*		
Rutihesperipites trochuensis	*echinatus*	*echinatus*	*Scabrastepanocolpites* spp.	*Liliacidites* sp.	
Crassitriaperturites gennatus.	*Spinizonocolpites*	*Spinizonocolpites*	*Tetracolporites* sp.		
Triangulipollis turonicus	*baculatus*	*baculatus*	*Normapolles group pollen*		
Stellatopollis araripensis	*Diporoconia* sp.	*Matanomadhiasulcites maximus*			
Echitetracolporites sp.	*Palmaepollenites* sp.	*Neocouperipollis kutchensis.*			
Triporotetradites sp.	*Neocouperipollis kutchensis*	*Bacutriporites orluensis*			
Kindopollis sp.	*Tricolpites* sp.	*Tercissus grandis*			
	Marsilea spores	*Tricolpites* sp.			
		Proteacidites sp.			
Note: megaflora absent	**Note: megaflora absent**	**Note: megaflora absent**	**Note: megaflora present**	**Note: megaflora present**	**Note: megaflora absent**

shells (Srinivasan 1996) and diatom *Aulacoseira* (Ambwani *et al.* 2003). Recently carried out palaeomagnetostratigraphic study of the volcanic flows and the associated intertrappean beds indicate their deposition during the 30N Chron. The upper intertrappean beds are rich in diverse megafloral remains discussed in detail by Kapgate (2005) and a few palynomorphs (Chitaley 1951).

In the intertrappean sediments of still higher stratigraphic levels in Chhindwara area (Butera and Lohara) a sharp decrease in pollen spore recovery, increase in concentration of fungal spores and mycorrhizal fungi and increase in biodegraded organic matter is observed (figure 3). This floristic change is similar to the one observed in the N-D basin.

Along the western flank of Deccan volcanic province in Gujarat, the palynomorphs are known only from the Lakshmipur and Anjar intertrappean beds. The Lakshmipur intertrappean beds have yielded Maastrichtian forms such as *Contignisporites* sp., *Retitricolpites vulgaris, Proxapertites* spp., and *Aquilapollenites bengalensis* (Samant and Bajpai 2005). The pollen data suggests that the intertrappean deposits of Lakshmipur might be older than that of the intertrappean deposits of central India. Jana *et al.* (1997) reported marshy fern *Isoetites* from Dayapar and Kora Intertrappean localities of Kutch. The iridium-bearing Anjar intertrappeans also contain the typical Maastrichtian palynomorphs like *Gabonisporis* spp., *Aquilapollenites indicus, A. bengalensis*, and *Proteacidites* spp. (Dogra *et al.* 2004), along with numerous diatoms and sponge spicules (Mohabey and Samant 2005) and fossil woods of dicot families such as Flacourtiaceae, Icacinaceae, and Euphorbiaceae (Guleria and Srivastava 2001). Dinosaur remains have been recorded from this locality both below and above the iridium levels by Bajpai and Prasad (2000) and this led them to suggest that the iridium layers are pre KPB and that dinosaurs became extinct significantly before the KPB. The claimed presence of K/T boundary in the Anjar section was later also discarded by Hansen *et al*. (2001). Hansen *et al.* (2005) further suggested that dinosaurs disappeared from the Indian subcontinent about 350 ky before KPB.

On the basis of the presence of dinosaur remains, Maastrichtian palynomorphs, megaflora, diatoms and sponge spicules and highly biodegraded and fungal infected organic matter, a stratigraphic correlation is proposed for the intertrappean beds exposed at different stratigraphic levels in the Deccan volcanic province of central and western India (figure 3).

The Naskal sequence is the sole palynomorph-bearing intertrappean locality in the southeastern Deccan volcanic province, and contains typical Maastrichtian palynomorphs such as *Mulleripollis bolpurensis, Ariadnaesporites intermedius, Gabonisporis vigourouxii, Triporoletes reticulatus, Minerisporites triradiatus and Azolla cretacea* (Sahni *et al.* 1996; Singh *et al.* 2006). The pinnate diatoms are also reported from this intertrappean bed (Singh *et al.* 2007). In northern India, the Lalitpur intertrappean in Uttar Pradesh has yielded the Palaeocene palynomorphs such as *Dandotiaspora dilata, D. pseudoauriculata, D. plicata, Spinizonocolpites echinatus, Matanomadhiasulcites* sp., and *Lakiapollis ovatus* (Singh and Kar 2002). The Mumbai Intertrappean deposits (Cripps *et al.* 2005) which were deposited in late stage (Danian) of Deccan volcanic activity, did not yield a significant palynoassemblage. However, palynofacies analysis of the Mumbai sediments suggest their deposition in increasingly humid climate. Based on the presence of significant amount of plant derived organic matter and other organisms sensitive to environment perturbation in the sediments, Cripps *et al*. (2005) suggested that Deccan volcanism did not influence ecosystem collapse to cause global mass extinction at KPB.

4. Discussion

The Deccan volcanic sediments, both infratrappean (Lameta Formation) and intertrappeans, are time-transgressive. The Lameta sediments were deposited during the 30 N Chron in the western region (Kheda), between the 30 N and 29 R Chron in the Nand-Dongargaon basin, and during the 29 R Chron in the Jabalpur basin (Hansen *et al.* 2005). The successive intertrappean beds in central and western India were deposited during the 30N- 29R- 29N Chron (i.e. Late Cretaceous and Early Palaeocene).

Lithologically, the Lameta sediments are mostly arenaceous, with well-developed calcrete profiles and overbank, lacustrine, paludal, and channel facies (Tandon *et al.* 1995, 1998; Tandon 2002; Tandon and Andrews 2001; Mohabey *et al.* 1993; Mohabey and Udhoji 1996). In contrast, the intertrappean sediments are mostly argillaceous, forming cherts, limestone and well-developed laterite profiles at higher stratigraphic levels. This change in lithology from the Lameta to intertrappean is related to Deccan volcanism, which affected both the depositional environments and climate.

The overall microfloral analysis of the Lameta and intertrappean sediments in the N-D basin shows that the onset of volcanic activity in western India and the associated release of volcanic gases did not have a considerable effect on the flora, as no major change is observed in the pollen/spore assemblage recovered from the Lameta sediments deposited in the 30N (Dongargaon Lake) and 29R Chron (Pisdura, Polgaon, and Piraya). However, a sharp increase in concentration of diatoms (*Aulacoseira*) is observed in the varved clay sequence of Dongargaon lake, which was deposited in the 30 N Chron (Hansen *et al.* 2005). This could probably be related to an increased micronutrient

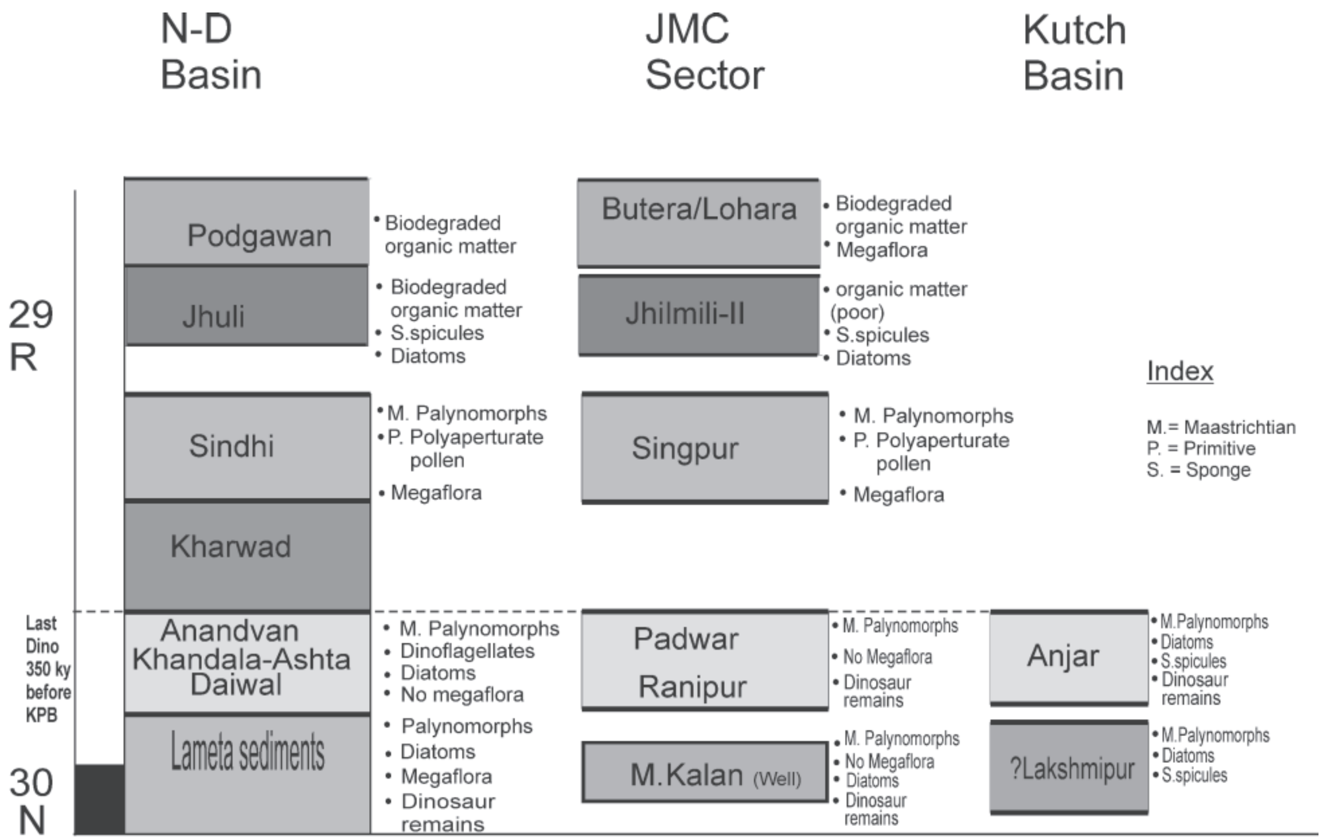

Figure 3. Proposed stratigraphioc correlation of intertrappean beds of Deccan volcanic province of central and western India.

availability likely caused by volcanic gases. Similarly, very high concentration of ostracods in some parts of the lake in the N-D basin could be related to such volcanically-induced productivity. In comparison to the indirect effect of volcanogenic ejecta, the direct effect of volcanic eruptions in the basin was most devastating for flora in central India. The onset of volcanic activity in the basin changed the depositional environmental from alkaline to acidic, affecting the water chemistry and the associated aquatic biota.

The volcanic flows completely destroyed the contemporaneous arboreal flora comprising gymnosperms and herbaceous angiosperms, and did not allow the well established pre-volcanic Lameta flora to continue in the volcanic terrain. The volcanic eruptions also resulted in formation of a new soil from the weathered mafic lava flows (Bestland *et al.* 1996), raised the level of atmospheric CO_2 and SO_2, and made depositional conditions increasingly acidic. Within the DVS, a new floral association that was capable of exploiting the extruded volcanic material and adapting to the hostile environment, made its appearance. This floral assemblage was dominated by pteridophytes and angiosperms (namely *Gabonisporis* spp. *Aquilapollenites bengalensis*, *Triporoletes reticulatus, Azolla cretacea,* and *Normapolles* group). A bloom of peridinoid (*Deccanodinium*) dinoflagellates in the intertrappean lake systems occurring in between flow F1 and F2 is also observed in the basin.

The record of similar types of palynoassemblage within the DVS of the N-D basin and JMC sectors of central India, as well as in the intertrappean beds of western India, could similarly be related to the prevailing volcanically-induced local microclimates and the ability of these plants to exploit the extruded volcanic material. A sharp decrease in pollen spore recovery and increase in the fungal spores and mycorrhizal fungi at the higher stratigraphic levels in the N-D basin and JMC sector could be related to peak volcanic activity on the subcontinent.

Comparison of the palynoassemblage of terrestrial intertrappean deposits with the marine intertrappean localities of the Krishna-Godavari and Cauvery basins (Prasad and Punder 2002) shows that the Late Cretaceous (Maastrichtian) sediments of these localities are also characterized by marker Maastrichtian forms such as *Gabonisporis* spp., *Aquilapollenites bengalensis, Azolla cretacea,* and *Ariadnaesporites*. However, overall floral diversity in these marine sediments is greater in comparison to those of non-marine terrestrial sediments.

4.1 *Age of the sedimentary sequences-associated with the Deccan volcanics*

The Lameta sediments were originally assigned a Turonian age by Huene and Matley (1933) on the basis on dinosaur remains. Later workers (Chatterjee 1978; Berman and Jain 1982) suggested the Santonian to Maastrichtian age for these sediments. On the basis of fauna such as dinosaur and fish remains, a Maastrichtian age is now generally agreed upon (Sahni and Tripathi 1990; Khosla and Sahni 1995; Jain and Sahni 1983; Prasad and Sahni 1999; Prasad and Cappetta 1993; Mohabey 1996). Based on ostracods also (Khosla and Sahni 2000), a Maastrichtian age has been assigned to the Lameta sediments of the Jabalpur area.

The intertrappean sediments of Nagpur were considered of Tertiary age by Lydekker (1890). However, later studies on the vertebrate remains (dinosaur, eggs, teeth, bones, fish, and mammals) by Sahni and coworkers suggested a Maastrichtian age for sediments associated with the Deccan volcanism. The record of palynomorphs such as *Aquilapollenites bengalensis, Azolla cretacea, Gabonisporis vigourouxii,* and *Triporoletes reticulatus* from the Padwar, Ranipur, and Mohagaon-Kalan (well) localities in the JMC sector and the Daiwal, Khandala-Ashta, and Anandvan localities in the N-D basin, the Anjar intertrappean in the Kutch basin, and the Naskal intertrappean in the southeastern part of the Deccan volcanic province indicate a Late Cretaceous (Early Maastrichtian) age for these sediments. The palynomorph assemblages of the Singpur intertrappean in the JMC sector and Sindhi in the N-D basin indicate a Late Maastrichtian age (Samant *et al.* 2008). Most recently, Keller *et al.* (2009) reported a major discovery of planktic foraminifers of early Palaeocene (P1) age from an intertrappean locality near Jhilmili, District Chhindwara (Madhya Pradesh).

The Lakshmipur intertrappean in Kutch represents the oldest palynoassemblage (Samant and Bajpai 2005), and the Lalitpur intertrappean of Uttar Pradesh, with distinct Palaeocene forms, represents the youngest palynomorph-bearing intertrappean (Singh and Kar 2002). Although Mumbai Intertrappean deposits did not yield an age marker palynoassemblage, ^{39}Ar-^{40}Ar dates of associated basalts suggest their deposition between 65-63 Ma (Cripps *et al.* 2005).

4.2 *Palaeoenvironment of the Deccan volcanics-associated sediments*

The Lameta sediments overlie the Vindhyans, Mahakoshal, Godhra, and Gondwana sediments of Precambrian to Early Cretaceous age. Lithologically, the Lameta deposits are characterized by thick calcrite profiles. The presence of well-developed gypsum veins in the Dongargaon lake sediments, as well as the oxygen isotope study of the dinosaur egg shells of the Lameta basin, suggest evaporative conditions at the time of deposition (Hansen *et al.* 2005; Sarkar *et al.* 1991). The high concentration of biodegraded organic matter in the lacustrine sediments could also be related to excessive desiccation and evaporation of lakes during low stands. The occurrence of finely laminated varve clay sequence in lake sediments reveals distinct seasonality at the time of deposition (Mohabey 1996).

Records of arboreal taxa such as conifers (*Cycades, Araucaria*) indicate mesothermal plant canopy, whereas herbaceous angiosperm families such as Poaceae, Caryophyllaceae and Asteraceae suggest open dry climatic conditions during Lameta times. The fossil woods of Lecythidaceae and Sapindaceae, and seed of Capperidaceae suggest a warm tropical climate at the time of deposition.

In the N-D basin, the presence of numerous algal remains, charophytes, *Oedogonium, Lecaniella,* and *Botrycoccus,* floating ferns like *Azolla*, fishes such as *Clupids, Phareodus, Pycnodus, Lepidotes*, *Dasyatis*, and *Lepisosteus* (Mohabey *et al.* 1993; Mohabey and Udhoji 1996) and ostrocod assemblage, all collectively suggests a fresh water environment. The presence of Charophytes, *Oedogonium,* and *Botryococcus* clearly indicate the prevalence of alkaline shallow water conditions (Nichols 1973; Fritsch 1961) at some places.

In intertrappean beds, the presence of gastropods (*Physa, Paludina,* and *Lymnaea*), pelecypods (*Unio)*, ostracods, fish (*Clupids, Igdabatis)* and floral remains like Charophytes, floating ferns such as *Azolla,* and *Salvinia* (*Ariadnaesporites)* suggest lacustrine conditions. The pollen grains of a typical estuarine palm *Nypa* (*Spinizonocolpites* spp.) in intertrappeans of the JMC sector (Singpur, Padwar, Mohagaon-Kalan) and Lalitpur in Uttar Pradesh, and a back water fern *Acrosticum* in Mohgaon-Kalan and Lalitpur, collectively indicate the brackish water conditions. The abundance of the *Ephedra* pollen in Singpur intertrappean beds indicates drier conditions or arid climate probably at higher reaches of the source area. The fossil woods of Flacouttiaceae, Icacinaceae and Euphorbiaceae known from the Anjar intertrappean (Guleria and Srivastava 2001) suggest a tropical climate with abundant rainfall. The abundance of fungal remains belonging to an epiphyllous family Microthyriaceae (*Phragmothyrites*) in the intertrappean beds also indicates heavy rain fall at the time of deposition (Cookson 1947; Dilcher 1965; Selkirk 1975).

Summing up, the analysis of flora, fauna and sediments of DCFB associated Lameta and intertrappean beds indicates the prevalence of open freshwater environment and dry tropical climate with seasonality during the deposition of Lameta sediments, and closed freshwater environment and increasingly humid tropical climate during the deposition of intertrappean sediments. In some locations, the intertrappean flora indicates brackish water conditions and dry climate.

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