doi: 10.3969/j.issn.1673-9736.2016.04.06
Article ID: 1673-9736(2016)04-0255-07

Episodes of subaerial Large Igneous Provinces (LIPs) linked to late Turonian/late Maastrichtian deep incursion of sea on the Indian continental block

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Abstract: Late Cretaceous sea inundation of major continents, surprisingly did not affect Indian block except by two major subaerial events of Large Igneous Provinces (LIPs). Marion hotspot induced LIP of Mahajanga Flood Basalt (ca. 92Ma) in Madagascar triggered high intensity earthquake along Narmada Lineament and permitted a short lived marine transgression during late Turonian with spectacular estuarine deposits of limited thickness, preserved as archive of "Greenhouse Climatic Record". Réunion hotspot induced LIP of Deccan Flood Basalt, stretching from western to eastern India around Rajahmundry area attracted worldwide attention for the unique fauna and flora preserved in the intertrappean beds straddling Cretaceous-Palaeogene boundary. This massive subaerial LIP (ca. 66Ma) permitted fairly deep penetration of sea along collision facing Subathu-Dogadda Lineament during late Maastrichtian-Danian, but due to thick vegetation cover, tectonic disturbance and scarce outcrops the evidence is less straightforward than along Narmada rift.

Key words: LIPs; marine incursions; Indian Block; late Turonian-Narmada Basin Lineament; Late Maastrician-Subathu Dogadda Lineament

1 Introduction

Magmatic events played a crucial role in shaping oceanic and continental crusts since the early evolution of planet Earth. Large Igneous Provinces (LIPs) signify substantial magmatic events encompassing short intervals (< 3 Ma), and are thought to have been caused by powerful thermal anomalies in the mantle known as "Superplumes" (Larson, 1991; Coffin and Eldholm, 2005). The enormous amount of crust produced by oceanic LIPs during mid-Cretaceous matching extremely long Normal- Polarity Super-Chron, nearly three times greater than in any other period of Cretaceous, possibly produced a variety of features such as Oceanic Anoxic Events and Metal Anomalies etc. Massive submarine LIPs like that of Ontong Java and Kerguelen probably induced environmental and biotic changes somewhat differently than subaerial LIPs, such as Marion hotspot triggering Mahajanga Flood Basalt in Madagascar (ca. 92 Ma) and Réunion hotspot causing massive Deccan Flood Basalt initially covering over 500 000 km^2 area of Indian continent (ca. 66 Ma). The possible role of these subaerial LIPs during rapid evolution of juvenile Indian Ocean, causing deep incursions of sea (> 800 km) on Indian block along prominent lineaments are examined in this paper.

Appreciable volcanism in East Africa, Antarctica and Madagascar coupled with rifting of combined

Received 30 September 2016, accepted 24 October 2016

continent Madagascar-Seychelles-India-Australia-New Zealand-Antarctica from twin continents of Africa-South America produced Proto-Indian Ocean during Early Jurassic (ca. 185 Ma). Prominent Early Cretaceous (ca. 145 Ma) rifting and subsequent Rajmahal volcanism produced Eastern Indian Ocean with well defined aulacogens and triple junctions at passive marginal basins of Cauvery, Palar, Krishna-Godavari and Mahanadi. It is noteworthy that during this time the South Fault of Narmada-Son lineament was activated and the Indian block with solid crustal support tilted eastward causing major rivers except Narmada-Tapti to flow eastward into the Bay of Bengal (Jafar, 1996). Enough evidence is lacking to support the hypothesis of mantle plumes causing doming and controlling continental drainage pattern in India (Cox, 1989). During this time Madagascar reached current position relative to Africa and India-Seychelles-Madagascar separated from Antarctica-Australia-New Zealand and none of the lineaments on Indian block received any deep incursion of the sea. As proto-Indian ocean continued to grow rapidly, rifting separated Australia-New Zealand from Antarctica (ca. 105 Ma). One of the most important plate tectonic event was the rifting causing separation of India-Seychelles from Madagascar, probably induced by Large Igneous Province (LIP at ca. 92 Ma) episode of Mahajanga Flood Basalt, which has recently yielded refined age of Turonian (Cucciniello *et al.*, 2013) and may have triggered the entry of short lived deep incursion of sea along Narmada lineament. Shallow epicontinental seas generally inundated most continents of the world during Late Cretaceous as the estimated sea level rose up to 200 m higher than today, but surprisingly, none of the lineaments on the eastern and western sector of India received any deep incursion of sea, with unique and notable exception of Narmada Valley.

2 Deep sea incursion along Narmada Basin Lineament

2.1 General

Narmada-Son lineament, which was formed during late Pre-Cambrian, is a prominent geotectonic feature dividing peninsular Indian block into northern and southern regions. Early Cretaceous, rifting carving the eastern margin of India, reactivated the deep seated fault system along the lineament creating a prominent graben, which was again activated in response to Marion hotspot induced LIP magmatic episode of Mahajanga Flood Basalt (92 Ma) during Turonian (Fig. 1), generating high magnitude earthquake and permitting a short lived incursion of sea extending deep into the heart of peninsular India (>800 km). A short lived marine incursion lasting for about a million year or so is envisaged for the cumulative thickness of outcrops and considering a conservative rate of sedimentation of about 3mm/year for the estuarine complex prevailing during Turonian (duration ca. 4Ma). Although Narmada Valley sedimentaries are largely concealed under Deccan Flood Basalts, the outcropping successions have been studied for over 130 years. More recent and refined studies envisage an estuarine complex model of sedimentation, but some controversies still persist concerning the lithostratigraphic, chronostratigraphic aspects, including palaeoenvironmental interpretations, which need to be sorted out, based on concrete and critical piece of evidence. A simplistic lithostratigraphic scheme in ascending order is followed here for the sake of discussion: Precambrian Crystalline Basement/ Jabalpur Formation-(unconformable contact)-Nimar Sandstone Formation-Nodular Limestone Formation-Coralline Limestone Formation-(unconformable contact)-Lameta Formation-(unconformable contact)-Deccan Flood Basalt.

Modern macrotidal estuaries serve as efficient sediment traps with tide influenced landward transport of large quantity of material, which is in contrast to delta distributaries where the sediment transport is essentially seaward. Dalrymple *et al.* (1992) define estuary as "a seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes."

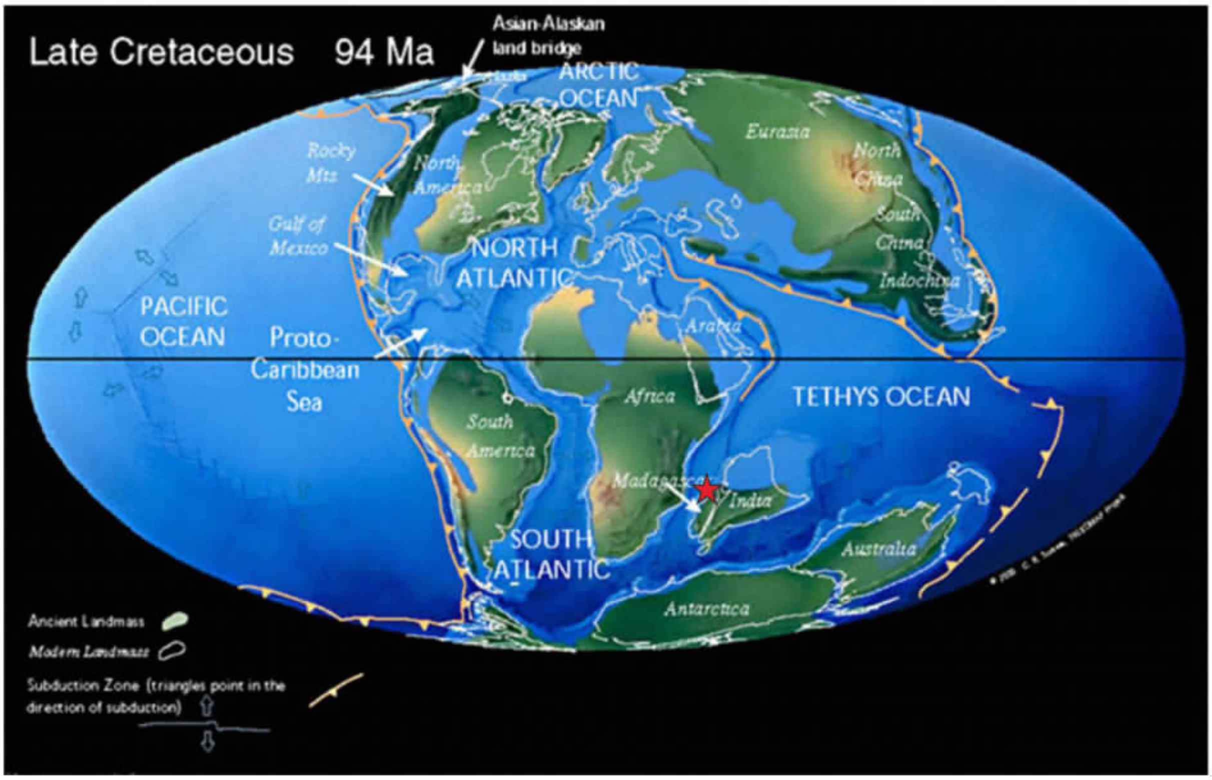

Fig. 1 Late Turonian (ca. 92 Ma) palaeogeographic map showing subaerial (LIP) of Mahajanga Flood Basalt of Madagascar positioned opposite Narmada -Tapti Lineament (red asterisk) causing deep incursion of sea (>800 km) (Modified after Ch. Scotese)

2.2 Nimar Sandstone Formation

For the sake of lithostratigraphic nomenclature, this formation name must be confined to nearly 40 m of exposed sections and should not be used for subsurface sandstones or other sandstones exposed beyond the limits of Narmada basin which can lead to faulty interpretations of sedimentation events (Racey *et al.*, 2016, Jha *et al.*, 2016). Lack of critical assessement of this well exposed and documented unit has resulted in erroneous age assignment and palaeoenvironmental interpretation. It may be recalled that landward extreme of river dominated part of estuarine complex has a small landward component of purely fluvial part, which is hard to detect in the field but can be readily identified by coarse-grained sandstone, conglomerates, extensive westward directed unimodal cross stratification, channel shape, wood and plant fragments, coal fragments and layers, root horizons and lack of marine trace fossils. The basal part of Nimar Sandstone Formation, could, therefore, be interpreted as fully marine as fluvial-tidal mixed facies. The upper part is characterized by frequent occurrence of marine skeletal elements, increased bathymetry and free connection with open ocean currents as evidenced by the recovery of diverse and dwarfed assemblage of calcareous nannofossils, possibly induced by subdued salinity (Jafar, 1982). Presence of tidal bundles, tidal rhythmites and seismites suggest LIP induced activation of faults resulting in soft sediment deformation structures during Turonian (Jha *et al.*, 2016). By a rule of thumb, if a level is well dated like upper Nimar Formation as late Turonian (CC 12 Zone) by calcareous nannofossils, the undatable or poorly datable underlying and overlying sequences must be also dated as late Turonian, unless we have concrete evidence to the contrary. Possible reworking of palynomorphs from the underlying Jabalpur Formation (non-marine Early Cretaceous) and failure to recognise Jabalpur Formation Sandstone containing lower Cretaceous Mega-Plant fossils could have possibly resulted in erroneous age interpretation of Nimar Sandstone Formation as Hauterivian-Albian by Racey *et al.* (2016).

2.3 Nodular Limestone Formation

Nodular limestones interbedded with marls attain about 10-15 m thickness and rest on Nimar Sandstone Formation with a sharp contact and are conformably overlain by Coralline Limestone Formation (ca. 10 m). Increased bathymetry and increased tidal currents permitted the entry of open ocean currents and the fossils including calcareous Nannofossils (Jafar unpub. data) were dwarfed, scarce and overgrown, but diverse, perhaps owing to subdued salinity. Hardgrounds are frequent. Reassessment of critical species of Molluscs, small benthic and planktonic foraminifera, calcispheres, Ammonites, Inoceramus, Echinoids, Ostracods, Bryozoa, Gastropoda and Bivalves suggest an age not younger or older than Turonian (Smith, 2010; Jaitly & Ajane, 2013).

2.4 Coralline Limestone Formation

High energy regressive facies contains scarce algal and coral fragments but abounds in Bryozoan remains. Benthic foraminifera, Ammonites, Echinoids and Bryozoa match those known from Madagascar and suggest Turonian age. In certain sections it is overlain by ca. 5m thick Green Sandstone rich in marine molluscan shells and yielded isolated Archosaur teeth, but were assigned rather vague Pre-Maastrichtian age (Prasad *et al.*, 2016). Oldest Cretaceous sauropod dinosaurs are known from Lower Nimar Sandstone Formation, which is of Turonian and not of Cenomanian age (Khosla *et al.*, 2003). More rigorous search is likely to yield more dinosaur and other vertebrate remains in Narmada basin.

2.5 Lameta Formation

Lameta Formation consists of a variety of sandstones including calcareous sandstones and limestones with chert concretions and are interpreted as non-marine subaerial and pedogenically derived lithounits with a variety of fossils including dinosaurian remains of late Maastrichtian age, despite several spurious earlier counter claims of marine origin (Tandon *et al.*, 1995).

2.6 Deccan Trap Formation

Réunion hotspot induced massive Deccan Flood Basalts (LIP) were erupted in three phases and cover a large area of sedimentaries including Cretaceous rocks in Narmada Valley. Exceptionally well preserved and rich fauna and flora straddling Cretaceous - Palaeogene boundary, are preserved in Deccan Intertrappean beds (Khosla and Verma, 2014).

2 Deep sea incursion along Krishna-Godavari Lineament?

Cretaceous-Palaeogene (K-Pg) boundary marine sediments are developed all along eastern margin of India, notably with coastal intertrappean beds of Krishna-Godavari lineament at Rajahmundry, during second phase of Deccan basalt eruption (Keller, 2014). Deccan intertrappean sediments have yielded diversified fossil fauna and flora, including titanosaurid dinosaurs (Khosla & Verma, 2014) from localities lying deep along Krishna-Godavari lineament, but so far no marine sediments of K-Pg interval are found in outcrops or bore well, thereby rejecting any deep incursion of sea during this time. However, a deep sea incursion was postulated over 150 years ago by the presence of certain mangrove/coastal elements like *Nypa*, *Cocos* and *Acrostichum* etc. More recently, a thin horizon (ca. 60 cm) yielding diminutive sized planktonic foraminifera of Danian age at Jhilmili led to a rather strange speculation that a marine seaway traversed through either Krishna-Godavari or Narmada Son lineament (Keller *et al.*, 2009; Keller, 2014). One could imagine a large ephemeral Athalassic saline lake which had all geomorphic features of a miniature sea and in contrast with brackish waters, was not connected to sea. Some kind of seeding mechanism including contamination by birds and storm was induced and coastal/mangrove elements including ostracods and planktonic foraminifera could be transported and adapt to flourish for a short spell. Similar occurrence of marine elements in fairly deep interiors are reported from

Songliao Basin of China, Amazon basin of Brazil etc. (Jafar, 2016).

3 Deep sea incursion along Subathu-Dogadda Lineament

Réunion hotspot induced (LIP) of Deccan Flood Basalt (ca. 66 Ma) triggering deep sea incursion along Subathu-Dogadda lineament (Fig. 2) is less straightforward when compared to Narmada basin lineament.

Strikingly, the LIP basalts are absent in both the lineaments but their episodes triggered deep marine incursions. Northern margin of Indian block represents collision face and much disturbed Lesser Himalayan sedimentary package bears signature of foreland basin evolution despite scarce outcrops and thick vegetation cover. Late Maastrichtian-Danian marine sediments are rarely exposed, like in Kakra Section containing marker dinoflagellates (Thakur *et al.*, 2013) and large areas remain unexplored. But global suite of calcareous nannofossil assemblage (dwarfed) was detected as tectonically sandwiched slices in Pre-Cambrian Krols or as reworked in several early Eocene sections of Subathu Formation in Simla Hills (Jafar and Singh, 1992). It must be emphasized that sudden appearance of reworked global suite of late Maastrichtian-Danian calcareous nannofossils detected in several sections of Subathu Formation (late Ypresian ca. 50 Ma), on an independent evidence signifies an unroofing event caused by actual collision and subduction of Indian block underneath Eurasian continent (Jafar, 2016).

3.1 Discussion and conclusion

Compared to submarine LIPs, the subaerial LIPs directly inject CO_2 in the atmosphere inducing rise in

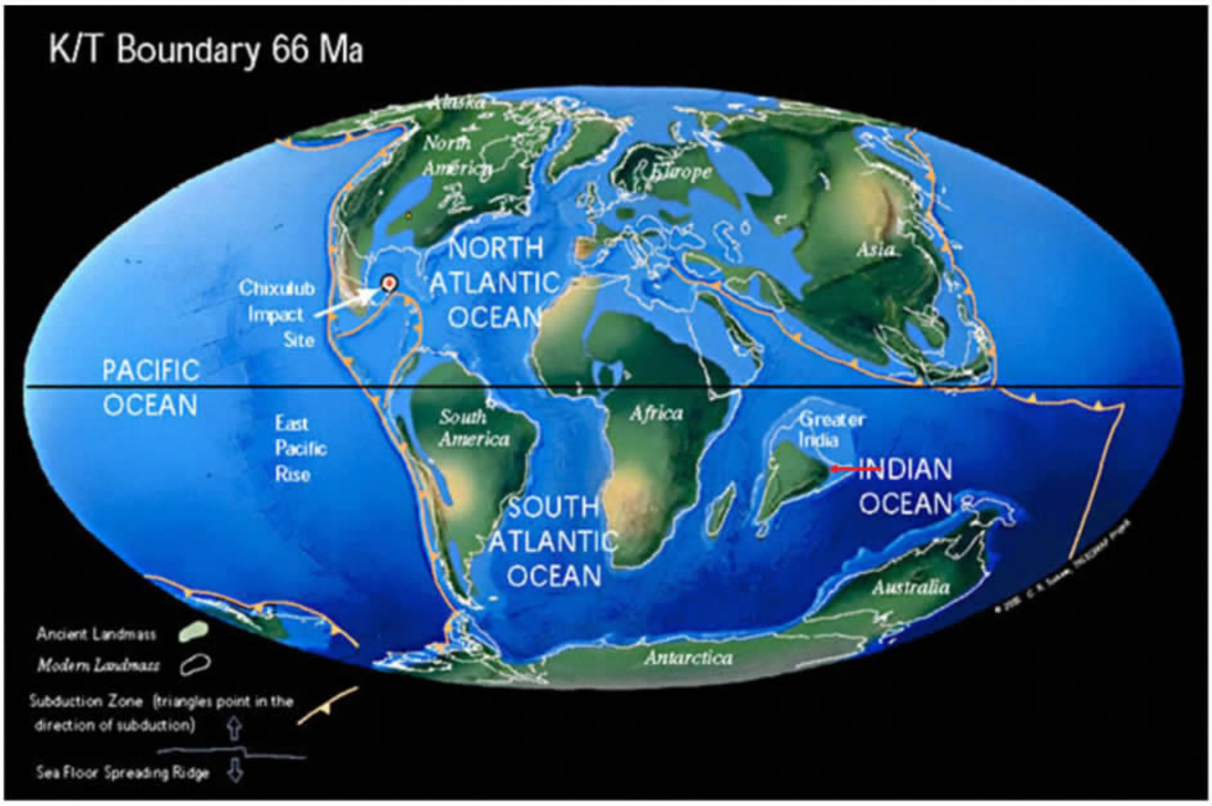

Fig. 2 Late Maastrichtian (ca. 66 Ma) palaeogeographic map displaying subaerial (LIP) of Deccan Flood Basalt triggering easterly entry of deep incursion of sea (>1000 km) along Subathu-Dogadda Lineament (red arrow) (Modified after Ch. Scotese)

global temperatures. Eustatic cycles were not globally synchronous, as for example when US Western Interior experienced major sea fall during mid-Turonian, the Narmada basin witnessed most spectacular short lived marine transgression. Narmada Valley sedimentaries were laid down essentially in an estuarine complex, with streams draining into it from northern and southern highlands, and serve as an archive for "Greenhouse Climatic Conditions" when average sea level rose up to 200 m and surface temperature were recorded 10℃ higher than today.

Mahajanga Flood Basalt induced subaerial LIP activity (Turonian 92 Ma) strongly suggests the possible reason for the deep entry of sea via Narmada Valley lineament. Critical re-appraisal of fossil fauna, flora, microfossils and palynofossils suggests late Turonian age for the entire estuarine succession: Nimar Sst. Formation-Nodular Lst. Formation-Coralline Lst. Formation. Deccan Flood Basalt LIP activity (late Maastrichtian ca. 66 Ma) permitted the deep penetration of sea along collision facing Subathu-Dogadda lineament. Basalt is absent in both the lineaments and the late Maastrichtian outcrop sections are scarce in Subathu Dogadda lineament warranting more rigorous search.

Acknowledgements

Thanks are due to Prof. Sun Ge for kindly inviting me to contribute this paper for the special volume of the Journal *Global Geology*. Several scientists over the years are thanked for stimulating discussions concerning sea incursions on Indian block.

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