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A History of the Mumbai Offshore through its changing Paleogeography

Abstract

The Mumbai Offshore Basin, repository of most of the country's oil and gas reserves, has seen a history of more than half a century of exploration and four decades of exploitation. It has generated an immense wealth of data and this study is an attempt to integrate all available data and encapsulate our understanding about the sedimentation history of the basin. The depositional history originated in the post Deccan Trap extrusion period and continued till recent times with three 2nd Order Sequence Boundaries defining the leitmotif of sedimentation. The events within the established 2nd and 3rd Order Sequence Boundaries were mapped and the study has endeavoured to demonstrate the link between tectonics, climate and sedimentation through a series of paleo-geographic reconstructions. The project entailed analysis of sedimentary, diagenetic and biostratigraphic data of more than 600 wells integrated with 90000 Sq Km of 3D seismic data. The maps were constructed through integration of isochronopach / isopach, lithofacies data with relevant geological information like bathymetry, porosity, diagenesis as well as magnitude and character of available provenance at any given instant. The linkages of major phases of Himalayan Orogeny (HOM cycles), the movement of Indian plate through Late Cretaceous to end of Mid Miocene, changes in climatic cycles and ultimately the cumulative effect of all of these on pattern of sedimentation, diagenesis and porosity creation / destruction have all been cohesively recreated in the maps.

The Sequence Stratigraphic Framework of Mumbai Offshore: The established Sequence Stratigraphic Framework *(PS Cube, Dave et l,unpublished report)* of the Mumbai Offshore has categorised the entire sedimentary column into **two 1st O** sequences, namely an older Rift and a later Passive Margin Sequence. The Rift sequence has been assigned a Palaeocene age, while the Passive margin one dates from Early Eocene to Recent.

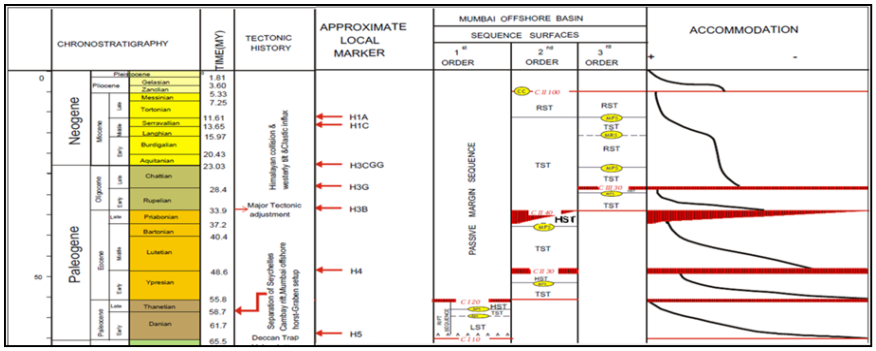

Fig 1a: Sequence stratigraphic summary of Mumbai Offshore (*PS Cube, Dave et al, 2005-06 unpublished report)*

Within the 1st O Passive margin Sequence, **three 2nd O** sequences beginning Early Eocene were identified. The lowermost 2nd O Sequence belongs to the Early Eocene chronospan with the lower boundary defined by the unconformity between the 1st O Rift and Passive margin sequences, CI 20. The upper boundary (CII 30) is the unconformity between Early/ Middle Eocene with a span of ~2Ma. The overlying 2nd O sequence covers the Middle-Late Eocene Chronospan bounded by the 2nd O SB of CII 40 (Base Early Oligocene) and CII 30. The third and uppermost 2nd O Passive Margin Sequence is recorded between CII 40 and CII 100 (Base Pliocene). Furthermore, two 3rd O Sequences, namely between CII 40 and CIII 30 (Early /Late Oligocene unconformity) and CIII 30 and CII 100 have also been identified.

The history of sedimentation in the Mumbai Offshore is recorded from the Late Palaeocene onwards during which time the Indian plate moved very rapidly towards Eurasia. The Mid-Palaeocene-Early Eocene times heralded a post-rift period of a slowly subsiding passive margin along the western margin of India, creating the basin floor. Commencement of sedimentation at Late Palaeocene time was therefore a response to the accommodation creation and nature of provenance. To depict the topography of the Basement as available provenance, a "Provenance Morphology" map has been attempted for the first time for the Mumbai Offshore **(Fig 1b)**. A probable topography of the exposed terrain has been deduced based on (i) the sediment thickness juxtaposed against the existing paleohighs of that of Mumbai High, Panna-Bassein, Heera and the Srivardhan horst, (ii) the time taken for the Basement to be submerged which was validated through paleotectonic sections and (iii) erosion. Based on these criteria, the topography indicates an extensive trap country, with granite and metamorphic inliers attaining higher elevations. It is estimated that that the highest area would be in the northern Mumbai High at around 900m. The massif of Mumbai High and its periphery would have an average height of around 400m with the eastern boundary defined by a sharp cliff, or the incipient Mumbai High fault.

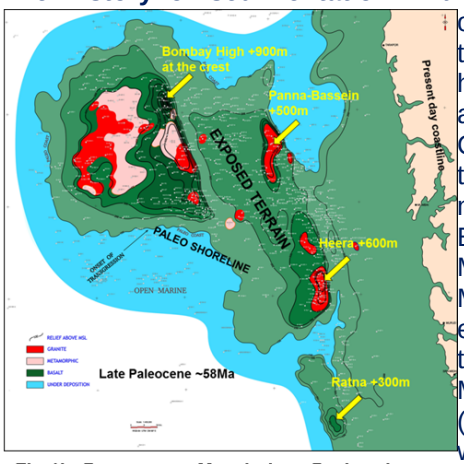

Fig 1b: Provenance Morphology During the Late Paleocene Transgression

Paleogeography of the Late Palaeocene-Early Eocene Sequence, (Panna Formation): In the Mumbai Offshore area, the PS Cube defines a 1st Order Rift sequence belonging to the Palaeocene and a 2nd Order Passive Margin sequence of Early Eocene age. In the area of study, the 1st Order Sequence Boundary CI 20 is not discernible, but a Transgressive sequence belonging to Thanetian age (FS-0) is eminently mappable. The sequence is dated, based on PMI and Dinoflagellate data at Thanetian (57Ma) within Latest Palaeocene in wells of the Central Graben. Therefore, it is being treated as the first transgression of Late Paleocene age recorded in the Mumbai Offshore.

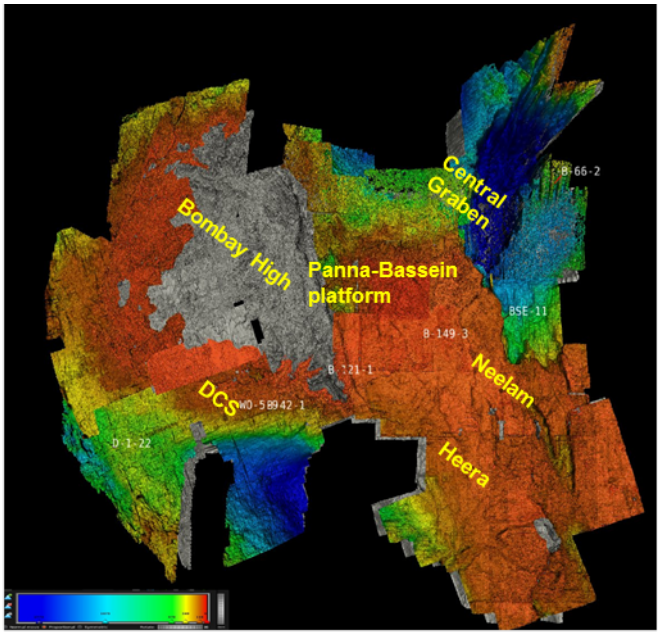

Fig 2: Isochronopach of Panna Formation

From Thanetian to end of Early Eocene, the basin witnessed multiple transgressions, each overriding the lower and inundating larger areas of the existing provenance. Prior work detailing the various transgressive phases identified three distinct stages of transgression, namely flooding surfaces FS-0, FS-2 and TC or "Transgressive Coal". These surfaces were mapped on seismic data, and the wedge out limits for the units established. The paleogeography for these individual sequences was worked out on detailed Isochronopach map and electrolog correlations that were carried out **(Fig 2).**

The time thickness map for the sequence brings into relief the fact that vast stretches of the Basement was exposed through most of Paleocene-Early Eocene time. The initial depocentres lay in the Central Graben, South Mumbai Low and the Vijaydurg Graben.

Additionally, the onset of transgression at Late Paleocene happened when the Indian Plate passed through warm humid tropical conditions leading to monsoonal climate and higher rate of erosion.

At the close of Late Paleocene, the Central graben, North of Mukta low, Ratnagiri area and the D33 low came under the influence of the first Marine Transgression culminating in a maximum flooding surface mapped as FS0. A very large basaltic provenance, punctuated by a few Archean inliers gave rise to the extensive deposits of trapwash in the basal sections of this sequence, which may be considered as the Initial rift fill sediments and are in general immature in nature. The Central graben area was a site of active accommodation, whereas the South Mumbai Low appears to be more of a sink area. The initial sediments of Central Graben do not carry any source potential and only at the later stage when restricted conditions of coal-shale domination takes over, the source pods start to develop. In contrast to this area, the Deep Continental shelf and South West Mumbai High area came under the influence of Open Marine conditions as the rock record shows carbonates in wells drilled through an equivalent sequence (Devgarh Formation) **(Fig 3a)**.

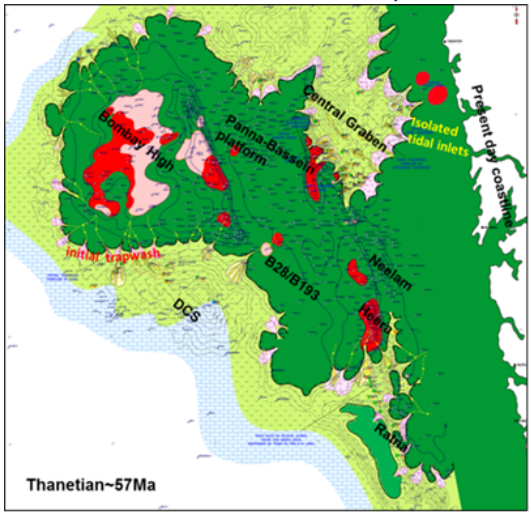

Fig 3a:Paleography map at the close of late Paleocene, Sub Unit FS0-Bsmt

The **Early Eocene Transgression (Within 55.8-48.6Ma)** is recorded in two distinct events known as FS-2 (Flooding Surface 2) and TC (Transgressive Coal). They represent an in-between phase within the first 2nd O Passive margin sequence. During these times, the transgression inundated areas further inland. The Provenance area diminished, but open marine conditions, helped to set up barrier-bar complexes. At places where the drainage system emanated from Archaean inliers, the response is seen in the profusion of sands where the disgorgement and reworking took place. The sand dominated areas are seen to back step from their erstwhile locales due to the rise in base levels, and their places taken over by finer clastics or carbonates depending on whether the prevailing conditions were that of restricted, nearshore or Open marine. The Central Graben accumulated considerable thicknesses of a predominantly shale–coal sequence which holds the maximum source rock potential. The thickness trends indicate that the basin was moving towards a “Filled stage” with very little thickness variation over the area**(Fig 3b)**. **By the end of Early Eocene time** the final phase of the transgression covered the entire basin except Heera and Mumbai high. The Devgarh Carbonates encroached far inland which brought to a close, the Early Eocene Transgressive phase**(Fig 3c)**.

Paleogeography of the Middle-Late Eocene Sequence (Bassein Formation): The end of Early Eocene period is marked by an unconformity CII-30. The overlying Middle-Late Eocene Chronospan is bounded at the top by the 2nd O sequence boundaries of CII 40 (48.8 Ma – 34Ma) during which time there was deceleration of the northward movement of the Indian plate and development of an extensive carbonate platform. It covered almost all the tectonic blocks of Mumbai offshore block, except the Mumbai high. The end of the sequence, at CII 40, represents a major hiatus in western offshore basin spanning ~ 3 million years (only Late Eocene) to ~ 6 million years (part of mid Eocene and entire Late Eocene). The event can be related to the major drop in sea level after HOM I (Development of Murree Foredeep, ending 41.3Ma). The carbonate sequence or the Bassein Fm

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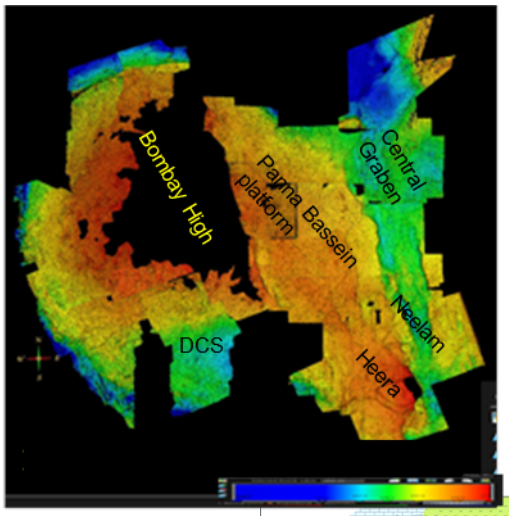

Fig 4a: Isochronopach Bassein Formation

began with a Transgressive Systems Tract and culminated in a 2nd O maximum flooding surface coinciding with end of Lower Bassein Formation. The overlying monotonous carbonates was deposited under Highstand Systems Tract and ends at SB CII 40 **(Fig 4a)**.

The Middle-Late Eocene and Planktonic zones: The oldest Middle Eocene carbonates have been assigned Lutetian age while the youngest Late Eocene carbonates belong to Priabonian. The carbonates have been categorised into P-zones (Planktonic foraminifera Zones) and the Bassein Formation has been divided into Middle and Late Eocene based P-zones. P-10 to part P-15 are assigned Middle Eocene age while part P-15 to P-17 are Late Eocene.

The Paleogeography during the Middle Eocene began with the precipitation of TST carbonates classified as Lower Bassein. The formation has a very large aerial extent and wedges out against the positive areas of the Mumbai High and Heera uplift. The end of TST is marked by a regional flooding surface. The Middle Eocene time gave rise to very stable platform conditions, with monotonous carbonate growths over most of Mumbai Offshore. Mapping of faunal assemblage has helped to establish areas of bathymetry change indicating conditions of very shallow restricted marine (10-20m) over the Panna –Bassein platform (Coskinolina-Epistomaria-Fascolites facies), Transitional conditions of 20+m (Nummulites-Fasciolites facies) in the DCS area and Open marine conditions of 30-40-50m (Nummulites dominated facies) beyond. A deeper Uvigerina facies (bathymetry of 60m) is recorded in well B-94-1 indicating the paleo shelf break**(Fig 4b)**.

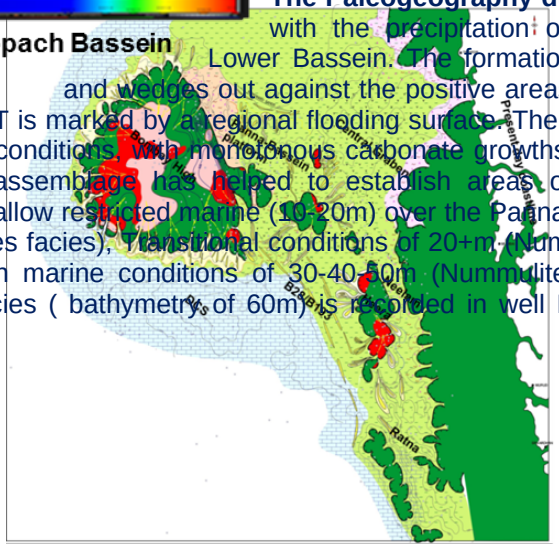

Fig 3b:Paleogeography during time TC(trangressive coal), Sub Unit TC

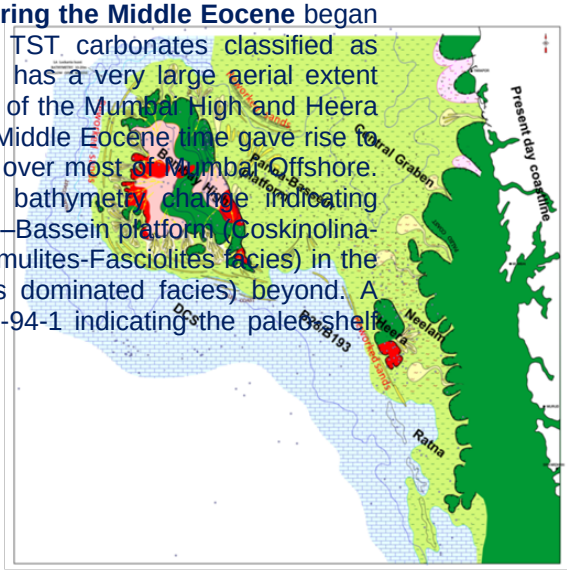

Fig 3c:Paleogeography at the end of Early Eocene, sub Unit H4

Paleogeography during the Late Eocene time forms part of the Sequence Boundary CII 40 which represents a major hiatus over the Mumbai offshore spanning ~ 1.5 million years to ~ 5 million years. The CII-40 Unconformity which extends from Bartonian (~37Ma) to end Priabonian (33.7Ma) has been mapped for the first time in the paleogeography map of Late Eocene. The map shows the areas where Late Eocene is absent (red) and points towards a longer period of erosion or non-deposition, while a continuous Middle-Late Eocene sequence indicates a shorter period of exposure.

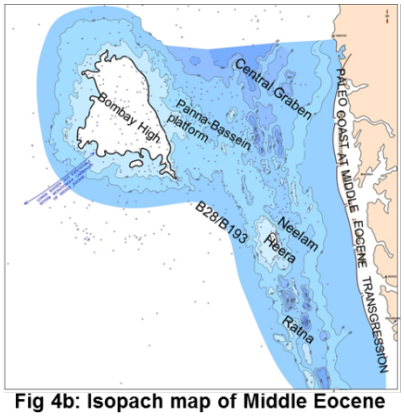

Fig 4b: Isopach map of Middle Eocene (TST), Lower Bassein

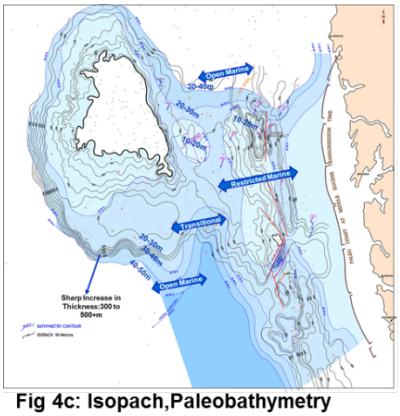

Fig 4c: Isopach,Paleobathymetry Bassein Lst at Middle Eoc. (TST+ HST)

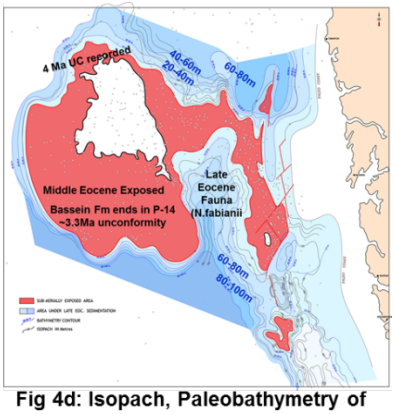

Fig 4d: Isopach, Paleobathymetry of Bassein Lst at Late Eocene

Paleogeography of Early Oligocene Sequence (33.9-28.4Ma), (Mukta and Heera Formation):

After the protracted period of the Bassein unconformity or SB CII 40, an Early Oligocene Transgression covered the entire Mumbai Offshore Basin except the Mumbai High massif. The transgression marked the commencement of the third and final 2nd Order Passive Margin Sequence. The sequence straddles the entire Oligo-Miocene period and is bounded by the Mio/Pliocene boundary (CII 100) at the top. The Early Oligocene chronospan forms a 3rd order sequence between CII 40 and the Early/ Late Oligocene unconformity (CIII 30). The extent of hiatus across Early/ Late Oligocene is inferred to be ~2.5-3Ma **(Fig 4c)**.

Global Climate Early Oligocene time: The Early Oligocene time saw the Earth entering the Ice Age Climate from a Green house climate for the first time. This first major climatic-glacial threshold was crossed 38 m.y. ago near the Eocene-Oligocene boundary, when substantial Antarctic sea ice began to form. The increase in Glaciation led to major Sea Level fall in Mumbai Offshore and thereafter oscillating and unstable shelf conditions existed in the Basin, through Oligocene times. The Oligocene transgression inundated all areas other than Mumbai High, and attained thicknesses ranging from 100-300m. The erstwhile stable Panna- Bassein-Heera platform came under shallow Marine oscillating conditions with a bathymetry of 10-20m. Computation of the shale percentage shows that the argillaceous content varied between 40-60% with higher shale content in the lows. The increase in clastics within the limestone was in response to the Prograding delta of the Tapti Daman area to the northeast. The thin limestone and shale alternations of the Mukta and Heera formations differ from each other in their nature of carbonates as well as cyclicity of the alternations**(Fig 5a)**. The Mukta formation has better reservoir characteristics and holds hydrocarbons in nearly all the structural entrapments. The intervening shale layers within Mukta do not occur at regular intervals. Whereas, the Heera Fm shows poor reservoir properties and the layering of shale and limestone is at shorter intervals, indicating very rapid oscillations. The higher porosities in Mukta as compared to Heera, is probably due periods of short diastems during Mukta time, which gave rise to diagenetic changes leading to creation of porosity, though no vadose zone exposure happened.

Paleogeography Of The Late Oligocene Sequence (28.4-23.03 Ma, Chattian): The Indian plate was at an intermediate stage of collision during this time. The rising mountains invigorated monsoon activity leading to higher precipitation aided higher erosion which is the defining element in the widespread Chattian regression in the Tapti Daman area. The climate event during this time was that of "Antarctic Melting" at around 27-28 Ma. With rise in Base levels, transgression overtook the Mumbai Offshore Basin simultaneously with a great deal of denudation triggered by the rising Himalayas. The westward dispersed muds spread over much of the basin,fine clastics were deposited over the area barring Mumbai High and Ratna which were subjected to marine Transgression for the

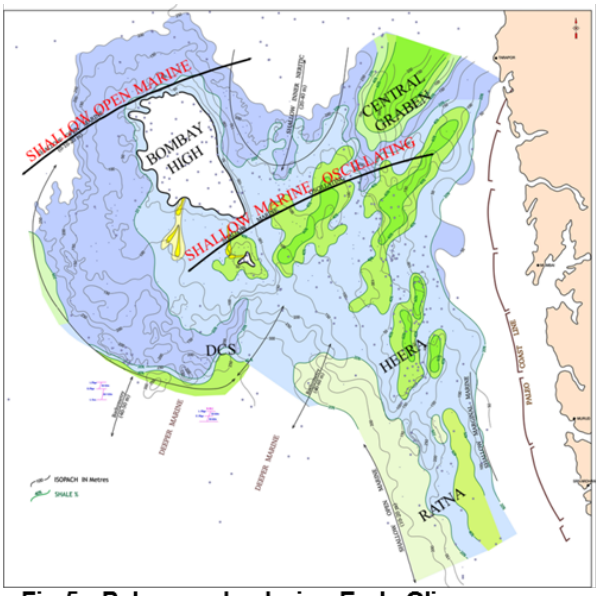

Fig 5a:Paleography during Early Oligocene

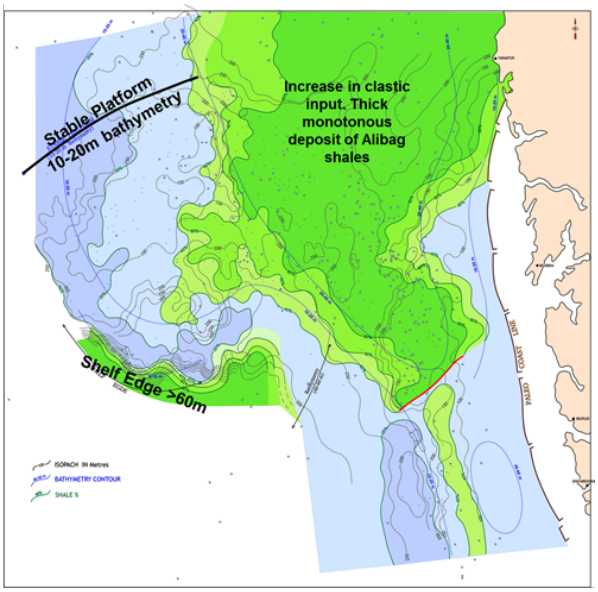

Fig 5b:Paleography during Late Oligocene

first time. Rest of the basin received an immense amount of argillaceous material which eventually killed the carbonate factory on the platform and later acted as the seal for the migrating hydrocarbons**(Fig 5b)**.

Paleogeography Of The Early Miocene Sequence (23.03-15.97ma, Aquitanian-Burdigalian) Bombay Formation: The Early Miocene Sequence in Mumbai Offshore is a 3rd Order RST within the 2nd Order Oligo-Mio Transgressive Systems Tract. The major tectonic event at this time was the HOM II or the Himalayan Orogenic Movement II, which was the development of the Siwalik Foredeep (~End Burdigalian, 16.4Ma). Over the Indian sub-continent, increased monsoon intensity in the Miocene, enhanced erosion aided by the tropical climate and the earlier established drainage brought in sediments along the west coast. Over the Indian sub-continent, increased monsoon intensity in the Miocene, enhanced erosion aided by the tropical climate and the earlier established drainage brought in sediments along the west coast. The resultant response of all this was an increased clastic incursion over much of the Basin,and the Mumbai High changing over to a highly unstable Carbonate Platform triggered by the HOM influx **(Fig 6a)**. The LIII reservoir of Bombay Formation which is the most prolific reservoir in the entire west coast of India, was laid down under these conditions where porosity generation was due to the short duration Hiatuses which occurred between the pulses of oscillation.

Paleogeography Of The Middle Miocene Sequence (15.97-11.6 Ma, Langhian-Serravalian) Bandra Formation: The Middle Miocene Sequence in Mumbai Offshore is the youngest 3rd Order TST within the 2nd Order Oligo-Mio Transgressive Systems Tract hat ends with Maximum Flooding Surface at the end of Serravallian or Middle Miocene.This mfs is the Drowning unconformity which represents the burial of carbonates by Prograding siliciclastics and shutting down of the carbonate factory. Locally, the Mumbai Offshore saw an immense increase in terrigenous clastic supply which allowed for the continued westward and southward dispersal of muds. As the paleogeography map depicts, carbonate growth was restricted to only over the Mumbai High and in the deep continental shelf. The end of Serravallian marks an important change in the sedimentation history of the Basin. Post Serravallian, the sedimentation changed from a carbonate regime to clastics. The clastics were predominantly a monotonous clay sequence across the shelf which switched off carbonate growth **(Fig 6b)**.

Post Mid Miocene: 11.6 Ma To Recent/ Chinchini Formation The final phase of sedimentation from 11.6Ma to recent times played a pivotal role in final shaping of the structures in Mumbai Offshore. The major tectonic events of HOM III (~3.6-2.58) and HOM IV (2.5 to Recent) induced very high rates of sedimentation. The thickness of the Chinchini Formation increases exponentially westwards and the scale of increase is from 300m near the Eastern Homocline to more than 1800m in the DCS area. This immense accumulation of sediments along the western flank of the basin re-activated some of the faults and aided in the hydrocarbon entrapment process.

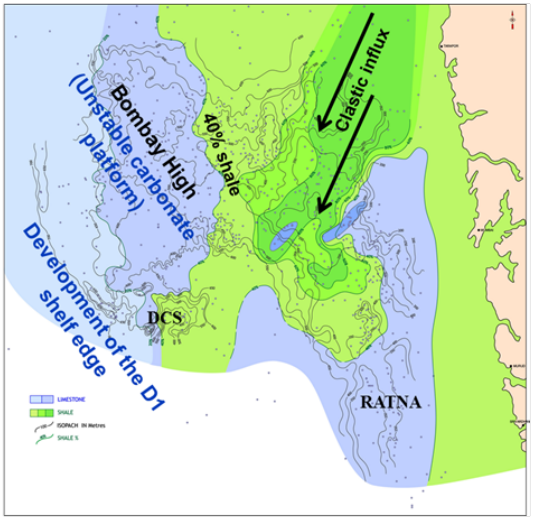

Fig 6a:Paleogeography during Early Miocene

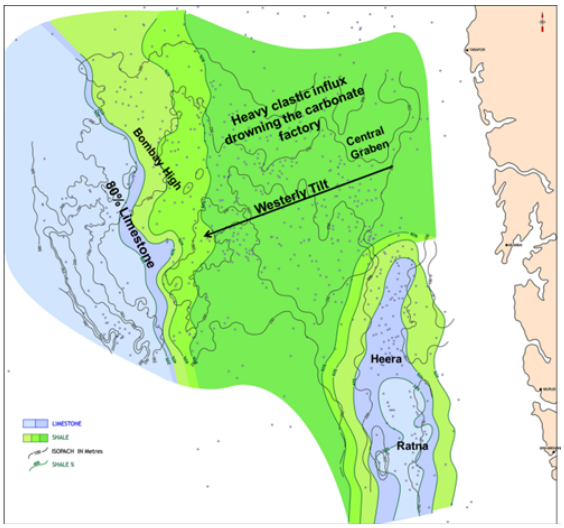

Fig 6b:Paleography during Middle Miocene

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