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Overview of Plate Tectonic Reconstruction, a Key Element of Modern-Day Petroleum Exploration

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Abstract: ***Plate tectonic reconstruction and visualization is an effective means of deciphering Earth's history through geologic time. It provides an optimum perspective of the fundamental requirements of petroleum exploration, which is an enabler in frontier and heartland basins. The movement of the Earth's surface impacts the locations of oil and natural gas deposits, making the study of Plate Tectonics essential for Petroleum Geologists. Currently, interactive modeling tools are available that allow the workout of the important elements of petroleum systems, including paleogeography and gross depositional environments, paleoclimate and palaeodrainage modeling, and source rock predictions. Plate tectonics study is indispensable to exploration at the basin scale. In India, unraveling the prospectivity of the deep-sea basins relies on the proper understanding of plate history. In this short paper, I attempt to address the plate modeling activities related to petroleum exploration and discuss examples from the sedimentary basins of India.***

Keywords: Plate tectonics, Petroleum Exploration, Modeling, Reconstruction, Visualisation

1. Introduction

Plate tectonics is the unifying Earth Sciences theory developed in the mid to late 20th century. It describes the large-scale motions(rates up to 20 cm/year) of lithospheric plates formed of the crust and the rigid upper mantle (up to 200 km thick) on the Earth's surface and within its interior (Figure 1). The lithospheric plates of the Earth exhibit relative motion to each other, and this movement is facilitated along their boundaries. The Figure 1 cross-section illustrates tectonic motion and the underlying processes, where rigid lithospheric plates move above the ductile convecting yet solid mantle asthenosphere. Plate boundaries can be either divergent (mid-oceanic spreading ridges), convergent (island arcs and subduction zones), or strike-slip (transforms). Convergent boundaries are characterized by the approach of plates toward one another, where one plate may subduct beneath another, creating trenches that indicate the bending and descending plate. Subduction zones can give rise to chains of island arc stratovolcanoes situated above the descending plate. Transform boundaries are formed when plates slide laterally past each other; in these oceanic transform fault zones, the process of seafloor spreading is transferred between segments of mid-ocean ridges. Divergent plate boundaries arise when plates separate at seafloor spreading ridges and continental rift zones.

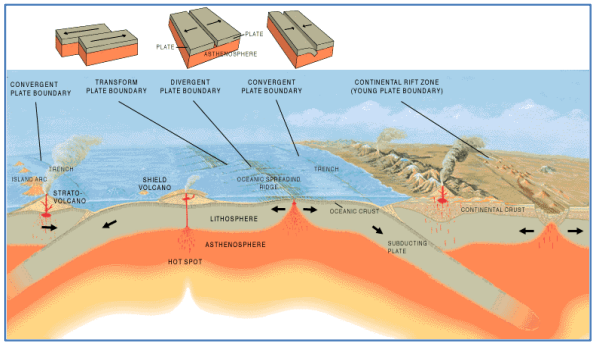

Figure 1: The artist's cross-section illustrates the main types of plate boundaries. An original illustration from This Dynamic Planet by Jose F. Vigil[1].

Significant efforts have been undertaken to understand the Earth's interior, beginning with attempts to chart the movements of tectonic plates through time and space. These indicate that hot plumes from the mantle rise from time to time, activate the plate tectonic cycles as well as arch up the earth's crust in several places, and stretch/sag it in some others[2]. Hot spots arise when plumes of heated mantle material interact with lithospheric plates, potentially leading to the formation of shield volcanoes and the eruption of flood basalts across the plates. The changes in geography due to plate tectonic processes will affect the size of restricted basins and the potential regions of upwelling along continental margins. At present, approximately 14 major plates and 38 minor plates are bound by three general types of plate boundaries: divergent, convergent, and strike-slip[3] (Figure 2). Plate motions and interactions ultimately control the distribution of oceans and continents, mountain ranges, and sedimentary basins along with their associated oil and gas accumulations, as well as earthquakes, volcanoes, and a host of other geological processes and features that impact hydrocarbon system prediction and discovery. Plate tectonic configurations and processes greatly influence global ocean circulation patterns, climate change, and paleogeography[4]. Models of tectonic plates are just approximations of the Earth. Elastic strain around locked faults and minor anelastic deformation within plates are often overlooked. This article treats plate models as practical, not absolute truths.

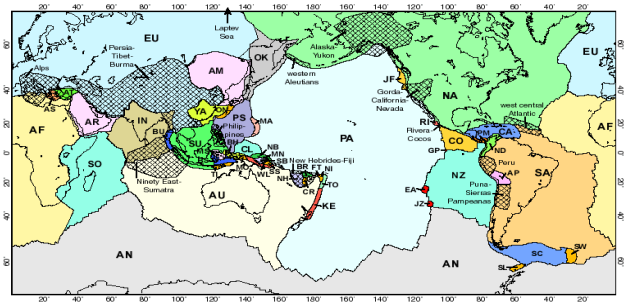

Figure 2: The present-day plate configuration shows 52 plates (14 major and 38 minor plates), each shown with a different colour[3].

2. Plate Tectonics and Petroleum Exploration

Plate reconstructions provide a regional framework for hydrocarbon prospects, basins, and regional evaluations, occupying an essential role in the exploration workflow. A plate-tectonic reconstruction involves determining the positions and orientations of tectonic plates at a specific moment in Earth's history. The principles of plate tectonics offer valuable insights to explorers in assessing hydrocarbon plays. Informed by the dynamics of global plate tectonics, exploration firms are implementing successful play strategies from one side of the South Atlantic to identify and validate analogous plays on the opposite side.

An examination of the identified oil and gas-bearing basins in India indicates that the mechanisms of plate tectonics have created a highly favourable environment for oil and gas exploration in areas such as Upper Assam, Cachar, Eastern Tripura, and Mizoram. The Cambay Basin, which originated as a rift in the Late Palaeocene and aborted in the Eocene, contains oil generated from Synrift shales that are abundant in organic material. While some oil is found in Synrift reservoirs, the bulk is reservoired in post-rift carbonate sediments in the Mumbai offshore petroleum province, or late Synrift or post-rift sands as observed in the Ankleshwar and Gandhar fields, as well as in late syn-rift or post-rift clastics associated with coal and shale in North Cambay.

The offshore shallow water, oil, and gas fields of the Krishna-Godavari Basin, such as D-6, occur within Miocene or younger sand formations. However, oil generation has occurred in organic shales located at the triple junction of the aborted Godavari rift and the pull-apart rift basin, a process that took place when Antarctica separated from India during the Late Lower Cretaceous period. The fields in the Cauvery Basin are all linked to the northeast-southwest trending basins, which are associated with subsidence resulting from convection cells in the infra-continental crust and upper mantle. In the oceanic region, these phenomena are reflected by the Mesozoic magnetic field reversal anomalies found in the southwestern part of the Bay of Bengal. The Mesozoic rift, Mannar Basin is also sourced by Synrift source beds.

India is endowed with an area of 2.1 km^2 upto 200m isobath with deep ocean waters, and there are several deep-water basins. The hydrocarbon prospectivity is related to the understanding of the rift formation as well as the drift of the rift through time to its present locale. The formation of the Bay of Bengal and its sedimentary basins is a story of two tectonic regimes: classic passive margin basins on the western side vs. complex fore-arc/back-arc basins on the eastern side[5]. The sedimentary basins in the eastern portion of the Bay of Bengal are typical fore-arc/back-arc types. These basins are situated to the east of the Andaman and Nicobar Islands, which are part of an island arc system that developed at the junction of the Indian Plate and the Burma microplate[5].

In the Kerala-Konkan Basin, where there is no west-flowing river of substantive bedload capacity, the likely source of the reservoir and source rocks must be traced to the plate tectonic evolution of the western coast, a part of the Indian plate. Following the breakup of Gondwanaland in the Jurassic, the western coast of the Indian landmass was conjoined with Madagascar and later disengaged from Madagascar. This association may serve as the origin for the reservoir and source rocks within the basin. During the Mesozoic era, the Mannar Basin and the Kerala-Konkan Basin were interconnected in a restricted environment with Sri Lanka blocking the deepwater circulation, which is particularly noteworthy given the discovery of oil and gas in Mannar[6] (Figure 3). Consequently, the potential for hydrocarbon resources in the Kerala-Konkan region, especially in the Cori-Comorin Depression, is significantly enhanced and worthy of hot pursuit.

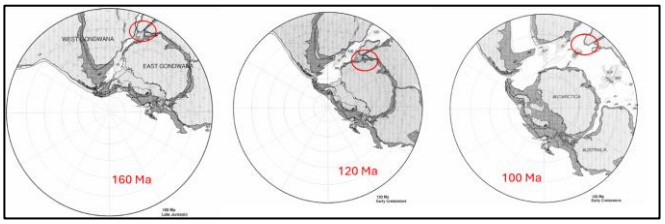

Figure 3: Palaeogeographic reconstruction through the Mesozoics[7].

The paleogeographic stages in the separation of Africa and South America concerning the Gulf of Guinea explain the prevalence of source rocks in the area's basins in West Africa[8] (Figure 4).

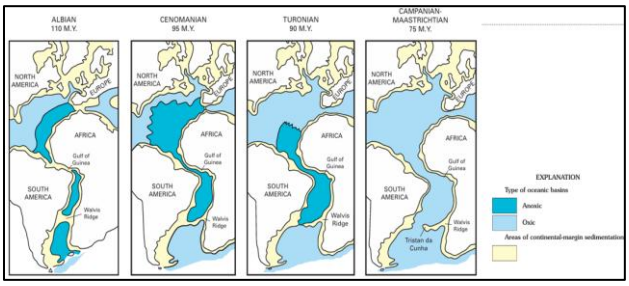

Figure 4: Paleogeographic stages in the separation of Africa and South America during the Cretaceous[9].

3. Plate Tectonic Modeling Tools

New plate tectonic reconstruction and visualization and modeling tools have been developed for upstream exploration to be more effectively explored in frontier and also heartland basins[10]. These tools have been developed through complex computer algorithms that reconstruct the continents in the past from the present-day properties of the lithospheric plates. These tools enable explorers to synthesize and illustrate the regional framework and important elements of petroleum systems, including palaeogeographic and gross depositional environment mapping, paleoclimate and palaeodrainage modeling, provenance studies, and source rock prediction (Figure 5). The easily accessible tools are EarthByte Group, 2009[11], Paleomap project, 2006[12], Plates project, 2009[13]. Visualizations are available in these works at different ages, which could enable the existence of conjugate rifts at that geologic time how the plates dispersed, and at what latitude they were at that time. GPlates is a desktop application designed for the interactive visualization of plate tectonics. The EarthByte Group spearheads the development of GPlates, an open-source software for plate reconstruction. GPlates allows users to interactively manipulate plate tectonic

reconstructions and visualize geological data across different time periods.

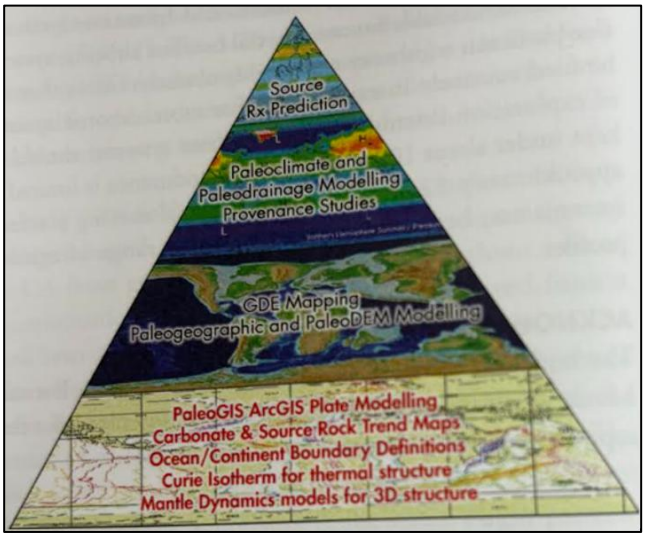

Figure 5: The pyramid of possible derivative products of plate tectonic modeling.

Major oil companies have developed their own proprietary plate tectonic modeling tools to help derisk the early stages of the exploration process in frontier basins. These tools give the user a straightforward way to visualize, analyse, create, modify, and otherwise interact with plate tectonic models, including adding their own data to the reconstructed maps[10] (Figure 6). Open-source software for plate tectonic reconstruction, such as GPlates, has significantly transformed work methodologies by providing non-experts with the necessary tools to create and incorporate reconstructions using their own datasets and knowledge[15].

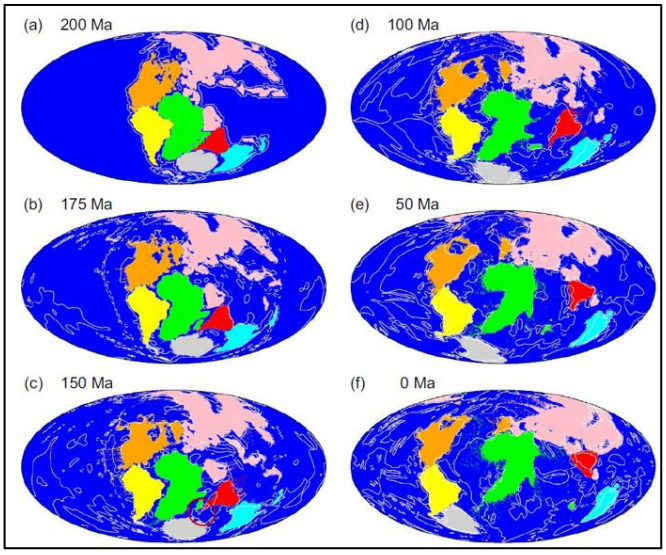

Figure 6: Time sequence of the positions of drifting continents for a particular Model with a viscosity ratio between Pangea and the ambient mantle of 103 °C. The Indian subcontinent is indicated in red. This map was produced using the Generic Mapping Tools56[14].

An illustration of the analysis of the plate model that is not always visible on a map is the azimuth and rate as a function of geologic time, as shown in Figure 7. The Azimuth and rate are plotted as a function of geologic time velocities, and the graph tracks the location of the point from a position at 120 Ma, when India was a part of Gondwana, until today. It is seen that the highest velocities occur between 68 and 60 Ma and begin to slow dramatically by 43 Ma. The true continent-continent collision of India with the Eurasian plate began. The slowdown that starts at about 62 Ma occurs when the outer edges of India begin to interact with the volcanic arcs in the northern Tethys.

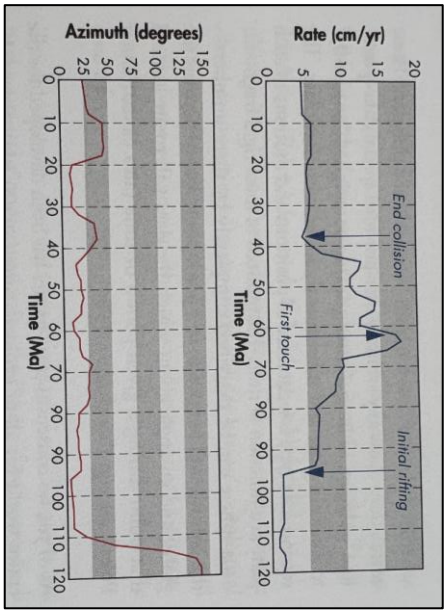

Figure 7: Azimuth and Rate plotted as a function of time for a point in Central India from a position at 120 Ma.

The role of plate tectonics in petroleum exploration is crucial for understanding basin evolution[16]. The brief examples illustrate that in contemporary petroleum exploration, connecting the narrative of plate movements offers a unique perspective. The principles and models of plate tectonics, along with their capacity to generate well-founded hypotheses for new exploration opportunities, serve as significant tools for investigating previously unexploited basins. Additionally, they prompt a reassessment of basins that have already been explored but were considered either devoid of hydrocarbons or too risky for development. The comparison between two gross depositional environments (GDE) maps for the base of the Triassic (250 Ma) includes all known depositional environments of that age. Figure 8 demonstrates the need to view GDE maps on a reconstructed base, the GDE makes more sense on a reconstructed map since that map represents the time of deposition.

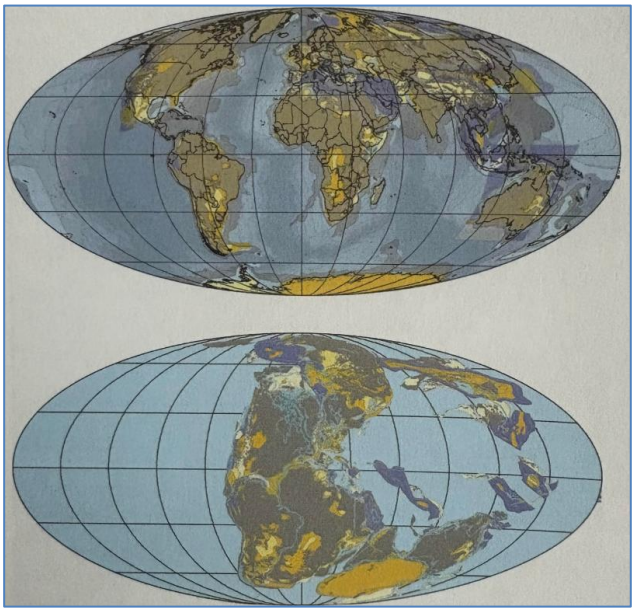

Figure 8: Top figure GDE map in the present-day position, and the bottom figure shows the same data in an Early Triassic configuration[8].

Plate tectonics thus serve as the essential framework for understanding the movement and alteration of the Earth's surface across geological time scales[17].

4. Concluding Remarks

Plate tectonics provides a robust framework for investigating continental margins and other frontier areas, which extend offshore to greater water depths and may potentially harbour greater oil and gas reserves than terrestrial regions. The relative movements of crustal plates allow for the classification of continental margins into divergent, convergent, and transform types. Furthermore, examining their origins within the context of structural characteristics, thermal history, overall stratigraphy, including source, reservoir, and trap potential, and the critical temporal and spatial relationships of these elements is essential for understanding the accumulation of oil and gas. The consideration of plate tectonics and the strategic planning of future work in particular regions is a domain where geologists must exclusively make decisions. It is essential for all explorers to become proficient in this methodology and to implement it effectively to find new oil and gas fields.

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Author Profile

Pratap Vikraman Nairreceived the B.Sc. Hons. and M.Sc. degrees in Applied Geology from the Indian School of |Mines in 1981 and 1983, respectively, with full honours. He was also conferred a Doctorate in Petroleum Geology. He worked at the National Oil Company, ONGC Ltd, from 1983 to 2007 in various positions as a petroleum geologist in most of the sedimentary basins of India before joining Royal Dutch Shell in 2007. In Shell, he worked on assignments in the Netherlands, Nigeria, India, and Malaysia before superannuating in 2021. As a Principal Technical Expert, he was part of several frontier basin campaigns across the globe. He continues to work as a Consultant Petroleum Geologist for Gujarat National Resources Ltd, Adani Welspun Ltd, and Oil India Ltd. Besides his interest in Petroleum Geology, he has specialized in Geomechanics, Geohazards, and Pore Pressure Prediction.