INTERNATIONAL JOURNAL OF LATEST TECHNOLOGY IN ENGINEERING, MANAGEMENT & APPLIED SCIENCE (IJLTEMAS)

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue III, March 2025

Reinventing the Science of Petroleum Source Rocks: A Contrarian Perspective

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DOI : https://doi.org/10.51583/IJLTEMAS.2025.140300052

Received: 28 March 2025; Accepted: 05 April 2025; Published: 18 April 2025

Abstract: Conventional models of petroleum source rock development have focused on the balance of productivity and preservation, and how various factors, such as upwelling and restriction, impact those processes. Yet, the critical question of why source rocks occur at particular moments in geological time has not been satisfactorily addressed. New alternative mechanisms of source rock formation are being postulated, which could have implications. These hypotheses involve the short-lived (<1 Ma) changes in the Earth's atmosphere-hydrosphere system driven by catastrophic events of global reach, which result from the emplacement of Large Igneous Province(LIPs). These new conceptual models offer an improved framework for source rock prediction and understanding source rock properties. The duplex model of both the legacy and the proposed model for petroleum source rock must drive the petroleum exploration strategy.

The new conceptual model has the capability to reveal previously overlooked petroliferous basins, particularly those currently assigned low priority, such as the Bay of Bengal and Kerala Basins. This short paper has addressed this topic in some detail.

Keywords: Large Igneous Province, productivity, preservation, source rock, oceanic anoxic event, temporal association

I. Introduction

The science of petroleum source rocks is fundamental to the fossil fuel energy industry. A century ago, the hypothesis that petroleum fluids are generated from organic-rich sedimentary rocks, under favourable geological conditions of elevated temperature and pressure, was an active area of research and debate[1]. By the late 1930s, due to the pioneering work of Alfred Treibs on porphyrins in crude oils and their relationship to chlorophyll[2], the sedimentary organic matter origin of petroleum was firmly established. Now, after almost a century, with advances in technology, novel paradigms to reinvent long-considered areas of study are being attempted.

Our understanding of the major controls on source rock formation has traditionally focused on the relative importance of productivity and preservation and the roles played by processes such as anoxia and upwelling (e.g.,[3]). Over the last sixty years, these paradigms have largely framed the study of petroleum source rocks. Recent advances in the quality of isotope analytical technology have led to dramatic improvements in absolute age dating precision and accuracy, as well as the discovery of new isotope systems for quantification of the geochemistry process in sediments. The application of these technologies has led to the observation of an apparent linkage between the temporal distribution of Large Igneous Provinces (LIPs) in geological records and that of petroleum source rocks[4]. This could imply that dramatic climate change caused by carbon dioxide-rich gaseous emissions from LIPs initiates the process of petroleum source rock formation.

Large Igneous Provinces (LIPS)

Large igneous provinces (LIPs) are extensive geological formations composed mainly of iron- and magnesium-rich (mafic) rocks, which arise from processes other than typical seafloor spreading[5] (Figure 1). Earth's history is marked by brief events, or significant surges within extended periods, characterized by the generation and emplacement of substantial volumes of predominantly mafic magmas through mechanisms distinct from typical seafloor spreading and subduction processes. These Large Igneous Provinces (LIPs) are most prominently recorded in the Mesozoic and Cenozoic eras, manifesting as continental flood basalts, volcanic rifted margins, oceanic plateaus, and flood basalts within ocean basins. Additionally, silicic rocks may be linked to these formations.

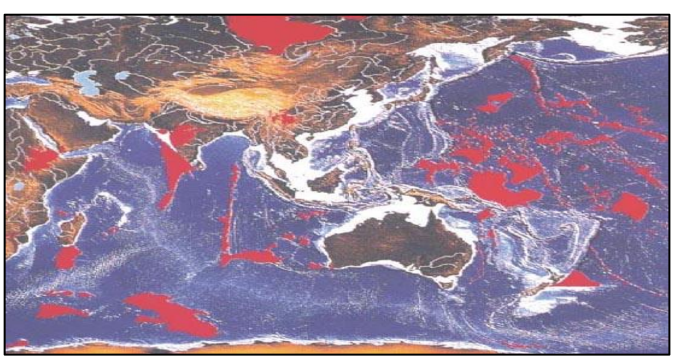

Figure 1 Large Igneous Provinces of the Circum-Pacific region (in red) emplaced since 250 Ma[6].

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue III, March 2025

II. Source Rock Formation

It was assumed that the processes that control source rock formation are uniformitarian, wherein one can study present-day controls and extrapolate the very same processes back into geological time. This implies that source rocks should be able to form at any age, in depositional settings where the appropriate boundary conditions are met. However, source rocks are not scattered randomly through time. Schlanger and Jenkyns[7] coined the term Oceanic Anoxic Event (OAE) to describe those moments in Earth's history, which appear to have been associated with widespread marine source rock deposition. Improved methods of dating and better global biostratigraphic correlations have enabled the recognition that many of the world's great source rocks occur at discrete time periods, frequently with development on multiple continents. This association appears to be not just limited to marine source rocks: some lacustrine sources also appear to show synchronicity with the ages of the major marine sources. Accurate correlation of marine and lacustrine sources is in the incipient stage due to challenges in the biostratigraphic correlation between these environments. These observations raise an important inquiry: if the majority of significant source rocks are globally distributed and confined to particular, limited time frames, what factors initiate their formation?

Initiation of Oceanic Anoxic Events

Many OAEs exhibit a characteristic light isotopic carbon spike at the base typically quite thin, followed by a thicker unit of heavy isotopic carbon above, which is associated with elevated total organic carbon contents[8]. Oxygen isotopes where not overprinted by diagenetic events, demonstrate significant warming trends associated with the overall excursions. This indicates that all of the OAEs are associated with episodes of global warming[8]. Global warming is also implicated in extinctions and changes in biodiversity through time[9]. Many source intervals are correlative with these extinction episodes,

Since 1990, attention has been drawn to the apparent concomitance of OAEs and some of the mass extinctions, and major igneous eruption events termed the Large Igneous Provinces (LIPs;[10]). These are massive eruptions of predominantly basaltic magma, which typically erupt at the Earth's surface over a short period of geological time (i.e., -2-5 my), and are believed to be the product of mantle plume heads[11].

The evolved magma releases large volumes of volatiles into the atmosphere, i.e., carbon dioxide (CO_2) and sulphur dioxide (SO_2). The CO_2 released has the potential to act as a greenhouse gas, giving rise to global warming implied by the oxygen isotope data from the OAEs. The elevated CO_2 would also help drive global productivity. Given that the carbon isotopic composition of mantle-derived CO_2 is ca. 6-7 $^{o}/_{oo}$,[8] emission of volcanogenic CO_2 does not fully account for the observed isotopic profiles of the OAEs, which include the initial carbon isotopic negative excursion. One explanation, which was originally proposed for the QAE at the Palaeocene-Eocene boundary, referred to as the PETM: Palaeocene Eocene Thermal Maximum is that the initial negative excursion is a product of the release of vast volumes of isotopically light methane from gas hydrates (δ13C typically < -60 $^{o}/_{oo}$) destabilized due to global warming[12]. Estimates for the Central Atlantic Magmatic Province LIP (200 Ma) suggest that ca. 8,500 Gtonnes carbon as CO2 was released directly as a result of volcanism, with an additional 5,000 Gtonnes carbon as methane from gas hydrates[13]. Such a rapid rise in greenhouse gas concentrations in the atmosphere will lead to a rapid rise in global temperature, and atmospheric humidity. These effects will drive increases in productivity via both increased availability of CO_2 and increased nutrient supply from more rapid continental weathering. This increased productivity will lead to the expansion of oxygen minimum zones, boosting preservation, which will also be enhanced due to the thermal warming of the oceans. Thus, both productivity and preservation are optimized as a result of the integrated effects of the LIPs.

The upstream oil and gas sector is significantly influenced by various elements of the petroleum system, including source rock, charge/maturation/uplift and erosion, trap structure, and reservoir. The connection between source rock and large igneous provinces (LIPs) primarily pertains to the nutrients released into the atmosphere and hydrosphere during the peak eruption phases of LIPs. This influx of nutrients fosters biotic hyper-productivity, which in turn leads to oceanic anoxia that aids in the preservation of source rock.

Temporal Association of Geological Events

A compilation of available data for the temporal occurrences of both LIPs and OAEs from the Devonian to Recent, together with the intensity of extinctions and approximate stratigraphic positions of some major source rock examples (Figure 2). One of the most notable instances in the record is at the Paleozoic-Mesozoic boundary, which marks the widespread global anoxic conditions, the breakup of the supercontinent Pangea, and one of the largest LIPs: the Siberian Traps[15]. The bottom panel of Figure 3 is a compilation of sedimentary mercury (Hg) anomalies, normalized to total organic carbon (TOC) by Grasby[16]. The red bars indicate mercury spikes at the major extinction boundaries, whereas the grey bars document mercury spikes associated with minor extinctions and/or oceanic anoxic events. The association of TOC from mercury anomalies at the mass extinctions is evident.

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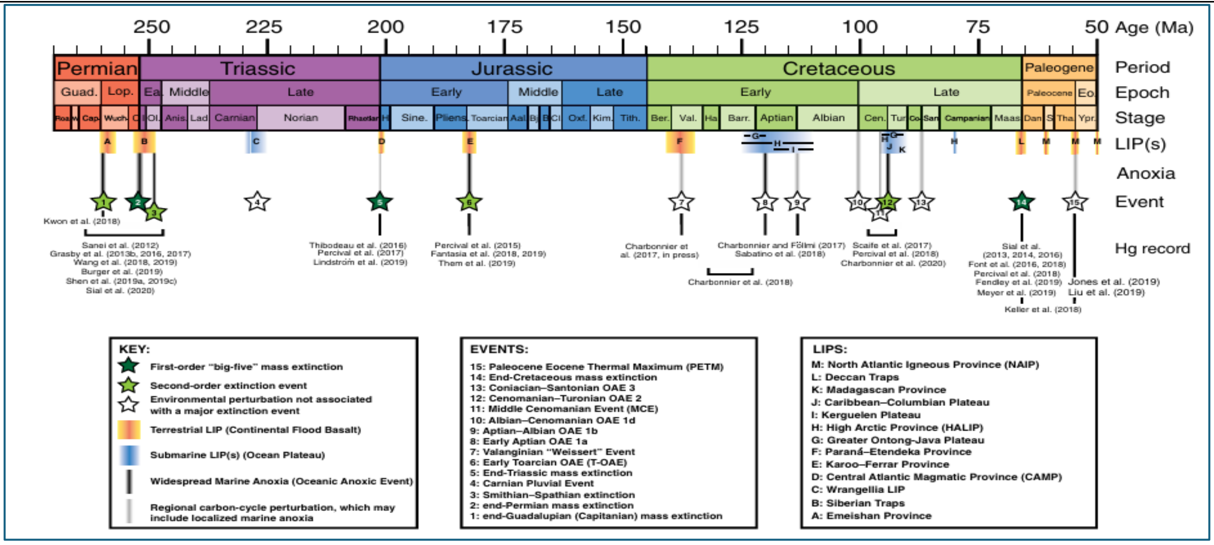

Figure 2 Comparison of the timing of LIPs, OAEs, source rocks, and extinction from the Devonian to Recent. An illustration depicting the temporal relationship among extinction events, significant environmental disruptions, carbon cycle disturbances, and large igneous province (LIP) formations from the Late Permian to the Paleogene period.[14]

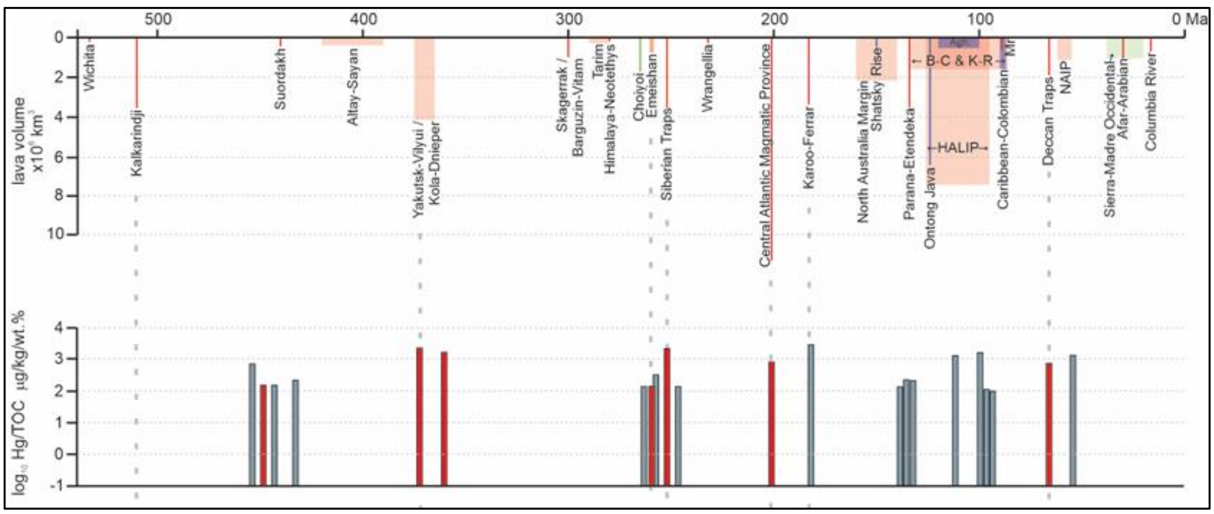

Figure 3: Summary of the temporal relationship between LIPs, mercury anomalies (TOC), and mass extinction. The red bars highlight the mass extinctions[14]

Sedimentological Controls on Source Rock Sections

The traditional consensus of source rock sedimentation, particularly for shales, is that fine-grained clastic and biological detritus slowly drop out of suspension and are deposited under quiet depositional conditions. Academic researchers reveal a more dynamic picture. Schieber[17] has shown examples from the Devonian of the Appalachian basin that shales contain abundant evidence of high-energy environments. Erosion surfaces are commonplace, and frequent lag deposits off heavier components like pyrite are often observed. The concept of mass transport and subsequent repositioning of source rock sediment has been postulated to extend petroleum systems away from better-constrained areas penetrated by drilling[18].

Integration of Source Rock Processes

Research has shown that even during periods of an Oceanic Anoxic Event (OAE), the quality of source rock exhibits spatial variability, with the highest quality linked to optimal environmental conditions. Factors such as upwelling and restriction, which are geographically dependent, play a significant role in both productivity and preservation. It is likely that the severity of the climatic crisis induced by Large Igneous Provinces (LIPs), whether stemming from substantial CO_2 emissions or methane release from hydrates, will influence the spatial distribution of source rock deposition. More pronounced effects from LIPs are expected to result in the formation of higher-quality source rocks over a larger area. Conversely, geographical changes due to plate tectonics will affect the extent of restricted basins and potential upwelling zones along continental margins. As a result, the overall global distribution of areas conducive to source rock development will fluctuate over time. The interplay between the intensity of climatic impacts from the LIP and the availability of optimal locations for source development will determine the global relevance of the resulting source formations. Additionally, climate change instigated by the LIP will affect sedimentological processes related to

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source rocks, as alterations in paleoclimate are likely to increase storm intensity, potentially leading to a higher frequency of turbidite events and associated mass flow deposits.

Implications for Geology and Petroleum Exploration

The concept presented in this document introduces a comprehensive and innovative framework for analyzing and forecasting the spatial and temporal distribution of petroleum source rocks. By integrating these ideas with elements of our established knowledge, a new cohesive model of source rock formation is developed, consisting of three primary components:

1. Catastrophic changes in climatic and atmospheric compositions are essential to initiate the formation of high-quality source rock.
2. Source rock sweet spots necessitate ideal environmental conditions and the availability of nutrients to enhance both productivity and preservation.
3. The depositional setting requires sufficient accommodation space to build adequate source rock thickness and preserve the source rock sequence.

By examining the occurrence of source rocks through this integrated framework, valuable insights can be obtained that will significantly influence future exploration efforts. The periodicity proposed by the Large Igneous Province (LIP) hypothesis allows for the estimation of potential stratigraphic ages of source rocks by correlating the timing of active sedimentation within a specific basin to documented global events. The combination of LIP effects with our current knowledge of source rock characteristics, geographical sweet spotting, and refined plate tectonic reconstructions for critical time periods will lead to enhanced models for predicting source rock locations. While this hypothesis may not encompass all instances of source rock formation, it effectively accounts for the major global source intervals. Ongoing research and development in Frontier Opportunities will persist in exploring how the aforementioned processes influence the spatial and temporal distribution of significant petroleum source rocks. The understanding gained from clarifying these essential processes will be utilized to bolster our predictive capabilities. By viewing the occurrence of source rocks via this integrated paradigm, practical learnings may be derived with profound impact for future conventional and unconventional exploration.

Indian Basins

In the Indian sedimentary basins affected by Deccan volcanism, by this concept, the Deccan Trap could have enhanced the source rock richness (Figure 2). This includes the petroleum province of the Cambay Rift and improves the potential of the Narmada Rift basin.

The Bay of Bengal serves as a significant sediment repository for the Bengal Fan and pre-collision sediments, distinguished by its three elongated arms that taper in thickness as they extend southward to 7° S. Two tectonic features, the volcanic ridges at 90° E and 85° E from the eruption of mantle source and run longitudinally segmenting the sediment apron into three distinct basins: the western basin, the central basin; and the eastern basin(Figure 3). When Curie isotherms are analyzed alongside oceanic transforms to assess heat flow patterns, the western basin emerges as a promising site for thermogenic hydrocarbons, while the central basin is primarily associated with biogenic hydrocarbons. Overall, the abyssal plains of the Bengal Ocean present a favourable outlook for the exploration of petroleum precursors. Based on the new paradigm, the emplacement of the two ridges could have promoted source rock productivity and preservation.

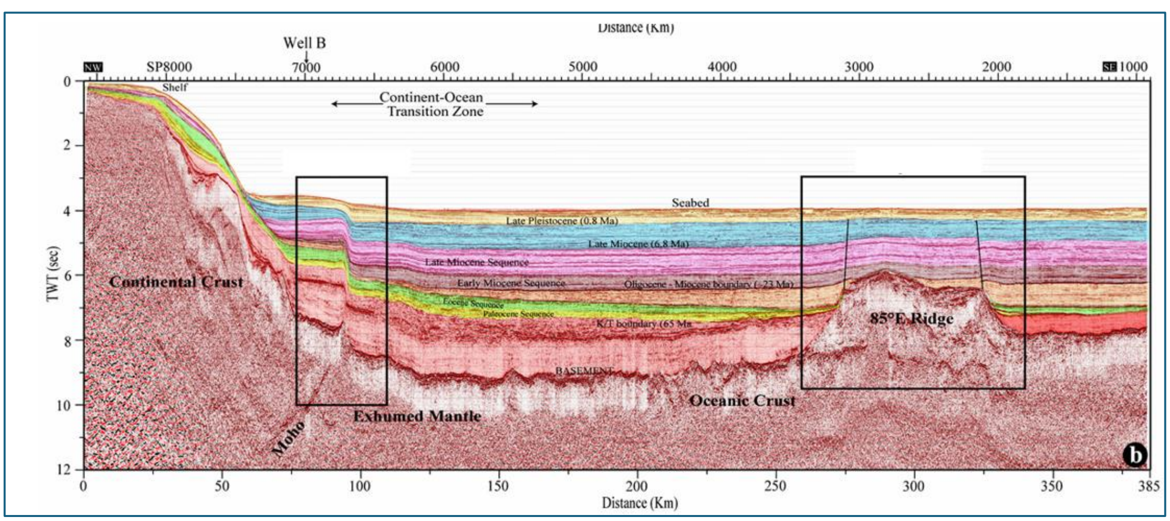

Figure 3 85 East Deep Basin on the East Coast, India[19]

The Kerala Basin also gets an impetus from the Madagascar LIP, which may have created OAE during the northward migration of the Indian plate (Figure 4). The plate tectonic reconstruction from the Late Jurassic to the Early Cretaceous indicates that the basin

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was located in the northeastern region of the Proto-Mozambique Ocean, with Antarctica serving as the primary source of sediment supply. The subsequent tectonic activities related to oceanic fracture zones and transforms have resulted in the formation of extensive sub-basalt geological structures that require prompt exploration focus.

The disintegration of the Australia-India-Madagascar continental block during the Cretaceous period was linked to volcanism associated with hot spots and the subsequent formation of the Indian Ocean. Following the Early Cretaceous phase that marked the opening of the Bay of Bengal, which is a segment of the Indian Ocean, the Late Cretaceous and Tertiary periods witnessed the expansion of the Arabian Sea. When viewed with the finding of oil and gas in the conjugate margin, Mannar Basin, this is important for petroleum exploration. Figure 5 depicts the continuing tectonic evolution to 65 Ma. The Seychelles plume scar could have influenced the Mumbai Offshore source rock inputs in 90 Ma and the Reunion Plume in 65 Ma.

Mesozoic rifting, aligned with the structural patterns of Proterozoic mobile belts, led to the creation of passive margin basins along the Indian coastline. During the Campanian period, as Madagascar separated from India, north-south-oriented normal faults extended into the Cambay Graben region. Late Maastrichtian doming over the incipient Deccan/Réunion hotspot imparted extensional stresses to the northwestern Indian coast and formed the fault block that became the Bombay High[20].

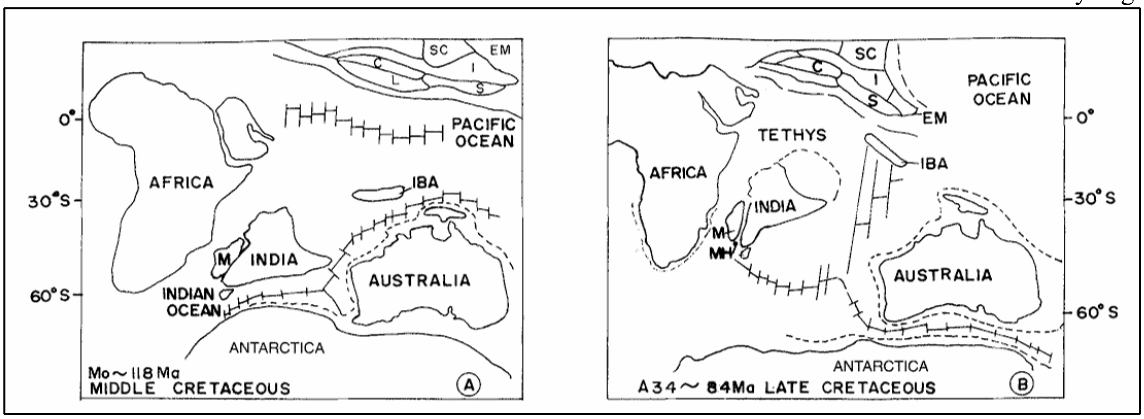

Figure 4 Break-up and dispersal of Gondwana during Cretaceous times(A-118Ma and B 84Ma), note Madagascar LIP and Kerala Basin welded together[21])

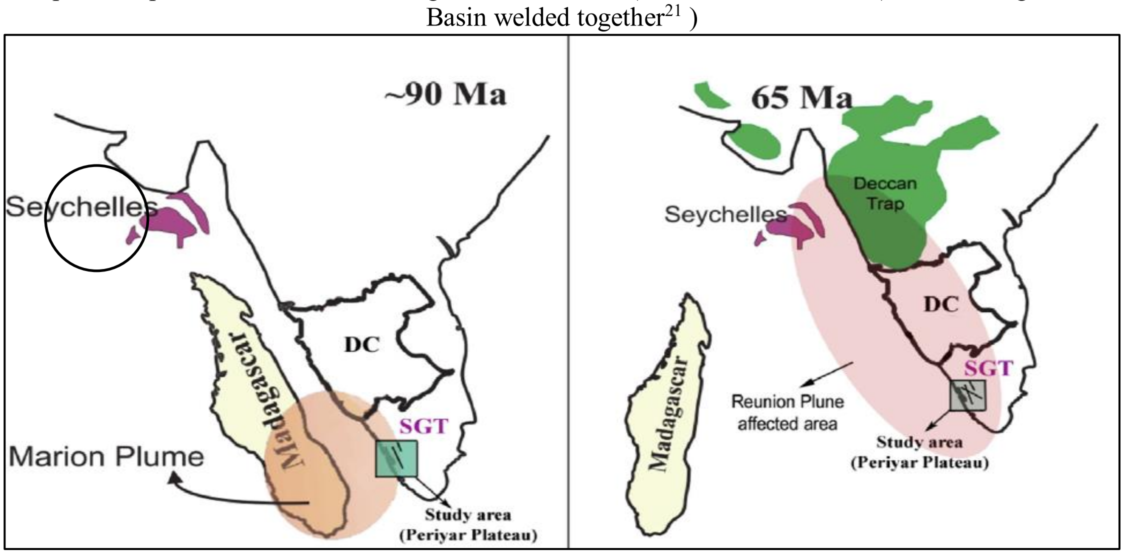

Figure 5 Cartoon depicting the different stages of evolution 90 Ma, 65 Ma[22]

Foreign Basins

The Ocean Drilling Program has identified numerous very high organic content OAE sequences on seamounts, where accommodation space is typically low, resulting in thin veneers of source rock. A nice example of the consequences of such a process is given by the Upper Jurassic sequence around the English Channel (Figure 6). Due to the basin inversion following the Alpine orogeny, it is possible to compare basin margin source control points with those positioned in less proximal positions. On the coast of Normandy, the proximal setting to the London-Brabant Massif has resulted in a relatively thin deposited Kimmeridge sequence with several arenaceous units, reducing the net source thickness further. Overall, this translates into marginal source potential.

An example of what can happen to a LIP is provided by the Sorochi example in the Upper Jurassic, which is known only from remnant, obducted crust in Japan[24]. The original size and extent of the LIP, which happens to occur at the same time as the Kimmeridge source rock interval, are highly speculative.

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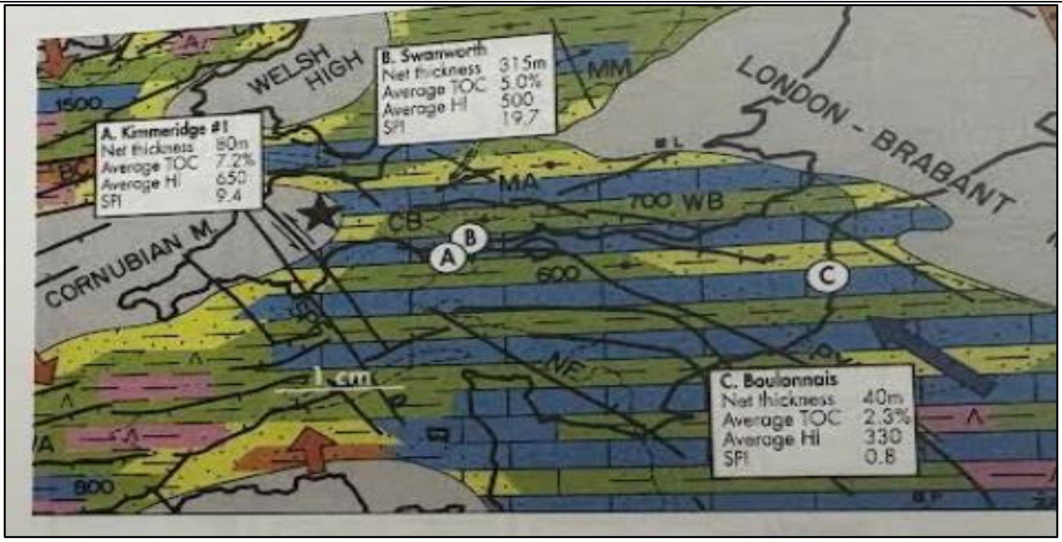

Figure 6 Source rock quality for three locations around the English Channel superimposed on Kimmeridge paleogeography[23]

The density of OAE events through the Cretaceous and Tertiary is partly a legacy of the Ocean Drilling Program site selection. The lack of frequent events between the Permian and the Triassic is due to the scarcity of marine sections in the available geological record for this period of time (Figure 2). Thus, the database of LIP and OAE occurrences currently recognised represents a minimum of what has probably formed through Earth's history.

III. Conclusions

Igneous geologists, through their highly precise radiometric dates on their samples, have opened a new vista for petroleum geologists to have a new model of the processes that control source rock formation. By applying new technology, exchanging data, and being open to new ideas, even long-studied topics can be reinvigorated and potentially reinvented. This is just the beginning, and when a lot more research work is done, the implications of this hypothesis, if it proves valid. The simple act of turning a subject matter around and looking at it from a different angle has proved to be very worthwhile.

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