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Gravity-Magnetic Data Analysis: Starting Point of Frontier Oil and Gas Exploration

Pratap V. Nair

Retired Exploration Petroleum Geologist, Devidarshan, Kawdiar, Thiruvananthapuram - 695003, Kerala, India
Email: *vpratapnair[at]gmail.com*

Abstract: ***Oil and gas exploration commences with the interpretation of the basin configuration. In frontier areas with poor or limited data, gravity and magnetic data can be effective in estimating depths to basement or other geological features. Estimating the depth of potential field data serves as a valuable technique for interpreting geological sources. This can be accomplished by employing a downward continuation technique that utilizes a normalized algorithm. Oil majors have developed rapid scanning tools that automatically estimate depths to density or magnetic contrasts in the subsurface from shallow volcanics to basement, to the Curie depth. In the absence of a regulated source, such surveys are typically considered environmentally acceptable. This short paper examines the knowledge and the utility of this tool in frontier area exploration. Exploration technologies at the forefront are essential for assessing regions that are either minimally explored or not thoroughly investigated, whether they pertain to geographical or geological boundaries. India's sedimentary basins encompass these types of vast areas.***

Keywords: Gravity-Magnetic, Depth Estimation, Curie depth, Frontier, Bay of Bengal

1. Introduction

Exploration targets for the near future remain very ambitious and are centered on sustaining and improving the success rate of finding oil and gas. The ability to evaluate the Frontier Basin faster and more accurately is the first step in frontier exploration. Gravity surveys provide a visual representation of the shape, depth, and spatial distribution of a Large igneous province (LIP) through the application of 3D inversion and modeling techniques[1]. Additionally, these surveys are instrumental in identifying significant regional fault zones. Oil explorers use state-of-the-art algorithms that use potential data, particularly magnetics, gravity, and gravity gradient, for rapid scanning and evaluation of large areas[2]. The estimation of the depths of the basement, volcanic formations, base of salt, and the Curie depth is crucial for constraining the structural and thermal models of a basin[3]. The Depth estimation tool is integrated into the 3D seismic interpretation software to accelerate the ability to find sweet spots in frontier basins and develop new insights in mature basins. Oil companies are doing their due diligence to have their own proprietary tools in the wake of stiff competition. Without a managed source, these surveys are generally regarded as environmentally benign.

Historically, the technology utilized gravity and magnetic anomalies, which do not always align with known surface structures or with each other[4]. The discrepancies between the outcomes of these two geophysical methods are understandable when one considers the different physical properties each method measures. Gravity anomalies typically arise from variations in density, which can occur at the interface between the sedimentary layer and the underlying basement or within the sedimentary layer itself. Consequently, without comprehensive subsurface data on rock densities, it is challenging to attribute gravity anomalies to a specific depth. As a result, the conditions suggested by gravity measurements may not directly correspond to the basement but could instead relate to an intermediate depth between the surface and the basement. On the other hand, magnetic anomalies stem from differences in magnetic susceptibilities. Since most sedimentary sequences are generally regarded as nonmagnetic, the anomalies depicted in magnetic maps are believed to indicate conditions in the basement.

When there is a strong correlation between the gravity and magnetic data, the findings can be interpreted as reflective of the basement conditions.

In each geological province, the physical characteristics are distinct. Consequently, the anomaly signature that is anticipated for each specific region will differ. Recognizing the pattern of an anomaly signature is crucial for all fields of interpretation science[5]. This discussion aims to provide geophysicists and geologists with a practical understanding of the signal patterns that should be identified to effectively combine gravity and magnetic data with seismic and geological information to develop exploration targets. The integration process in exploration has been recognized to mitigate risk, thereby lowering the overall exploration costs (Figure 1).

In 1970, Spector and Grant[6] released a significant paper demonstrating that the spectrum produced by a collection of sources sharing identical simple geometries is influenced by depth like that of each individual source. This indicates a statistical correlation between the group of sources and the overall signal. Consequently, this characteristic allows for spectral depth estimation to be conducted without concentrating on specific anomalies associated with a single source, thereby facilitating rapid scanning.

2. What "potential" anomalies could mean

The physical property of rocks that connect gravity anomalies to their composition is density, while total magnetization serves this purpose for magnetic anomalies. Consequently, each potential-field method offers a unique perspective on the subsurface. Density is a scalar quantity, whereas magnetization is a vector that encompasses a wide and often unpredictable range of remanent and induced magnetizations. Unlike density, magnetization can be influenced by minor variations in the presence and distribution of specific minerals, which may not correlate with the overall lithological characteristics. A geophysical anomaly refers to the discrepancy between the observed geophysical field value and the value that would be expected at the same location if the Earth's properties were uniform. Variations in the physical properties of rocks lead to the emergence of these geophysical anomalies.

Gravity and magnetic methods are particularly effective in detecting lateral variations in rock properties, making them well-suited for identifying steep discontinuities such as faults. In contrast, seismic methods excel at revealing vertical rock variations and low-angle discontinuities, such as layer boundaries. The gravity field is simple, unipolar, and predominantly vertical. In contrast, the geomagnetic field is intricate, featuring multiple poles and often exhibiting significant nonvertical characteristics. Additionally, it is subject to constant change, requiring regular updates from governmental agencies. Gravity lows, or negative anomalies, arise in areas where subsurface rocks possess lower density, resulting in a diminished gravitational pull. Conversely, regions with higher rock density produce gravity highs, or positive anomalies, due to an increased gravitational force. Magnetic anomalies present a greater level of complexity, as both the magnetic field and rock magnetization are intricate. With a nonvertical dipolar field, a single source of anomaly within the rock can misleadingly appear as two adjacent anomalies: one high and one low.

3. Screening Applications

Gravity and Magnetic data, because of their inexpensive synoptic spatial coverage, are useful tools for early screening of basins. Gravity data can quickly reveal key locations of depocentres and structural domains, including the identification of intrabasinal highs. Common applications of gravity data for screening purposes, which necessitate minimal analysis, include assessing salt thickness, identifying carbonate reef locations, and examining fold-thrust belt structures. Meanwhile, magnetic data can be utilized to evaluate volcanic features and, under favorable geological conditions, to determine the depth, orientation, and extent of basement structures.

4. Case for Action

Gravity and magnetic surveys serve a distinct function in identifying petroliferous basins and the structural patterns within these basins during the initial phases of exploration. This is particularly important for delineating buried basin boundaries, uncovering concealed depressions and uplifts, revealing carbonate reefs, and estimating the depths to the basement. Gravity and magnetic methods provide essential, low-cost de-risking for hydrocarbon exploration. High-resolution Gravity or High-resolution Magnetics can be acquired rapidly over large areas from marine vessels or aircraft at relatively low cost with low environmental impact[7]. Advancements in magnetometer technology and innovative software processing techniques demonstrate that marine magnetic data can significantly improve three-dimensional seismic geological analyses[8]. However, we are not exploiting the full potential of gravity and magnetic data and integrated interpretation workflows in many exploration areas due to a lack of powerful tools. This can be achieved by applying a downward continuation method that utilizes a normalized algorithm.

5. Application of Gravity and Magnetics at all scales

Gravity and magnetic data provide critical constraints during all phases of Play Based Exploration(PBE)[9].

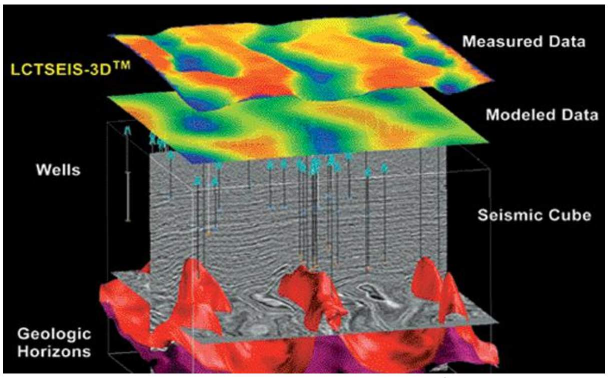

Figure 1: 3D Earth model[8]

The Play-Based Exploration workflow has been established to acknowledge the significance of basin development and offers a geological framework for the evaluation and assessment of potential prospects (Figure 2). The PBE workflow creates avenues for explorers to engage their geological curiosity in a manner that is geologically valid. It facilitates the development of play and prospect concepts that are not only innovative but also aligned with all available data, observations, and comprehension of geological principles across various scales. At the basin scale, the structural framework and charge analysis benefit from an early integration of regional gravity/magnetic data. The foundation of a good PBE should include plate models in the form of oceanic magnetic anomalies and oceanic fracture zones, depth of Moho, and basement interpreted from gravity and magnetic data, and used as constraints in basin models.

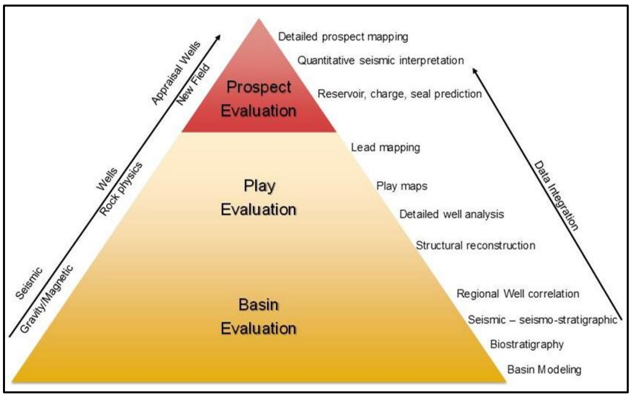

Figure 2: Play-based exploration pyramid[9]

At the play scale, play maps should include regional subsurface interpretation and model scenarios, validated with the help of gravity and magnetic data, especially in areas of

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complex structuration. large depths, salt, volcanics, or carbonates, where seismic imaging is challenged or where seismic data is sparse.

At the prospect scale, seismic data processing and pre-stack depth migration can be accelerated by using gravity data to update the velocity model, especially for thrust, salt, sub-salt, and other difficult-to-image areas. Prospect uncertainties can be reduced by geophysical-oriented basin modeling to further constrain the velocity model. Reservoir monitoring by time-lapse gravity using either micro-gravity or borehole gravity represents a low-cost complement/alternative to 4D seismic. When used in a borehole surveying mode, magnetic data can lower drilling costs and reduce borehole location uncertainty.

6. Depth Estimation

Potential field data, in particular gravity and magnetic data, can be used in hydrocarbon exploration for fast delineation of basin structures, to provide constraints for seismic and geologic interpretation, and for model building for seismic imaging[10]. However, estimating depth from potential field data is not a straightforward process. Tools are being developed by oil majors for rapid and simple depth estimation using potential data. The potential depth estimation algorithm estimates the depth to various targets of geologic interest is a challenging task in the interpretation of potential field data (Figure 3).

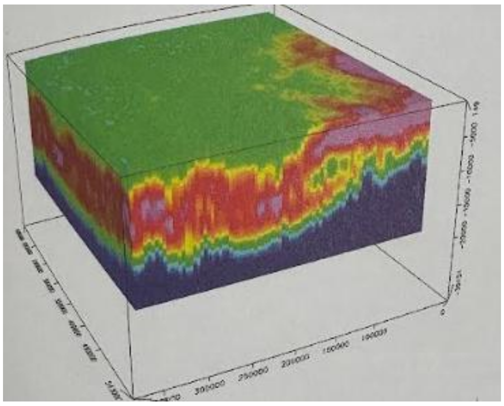

Figure 3: Depth Probability volume, red colour represents the high probability of a magnetic source like basement or volcanics

The technology to analyse magnetic or gravity data quickly produces estimates of depth to sources, for example, a map of depth to magnetic basement. The result is a depth volume trace (3D pseudo probability volume). The amplitudes of the traces represent the pseudo-probability that a source exists at that depth, typically magnetic basement or volcanics. The volume can be co-displayed with seismic and other data to provide an integrated interpretation indicating where the top basement or other magnetic sources can lie within the section. This volume can be presented in conjunction with seismic and other data, enabling a thorough interpretation that indicates the position of the upper basement within the geological profile (Figure 4).

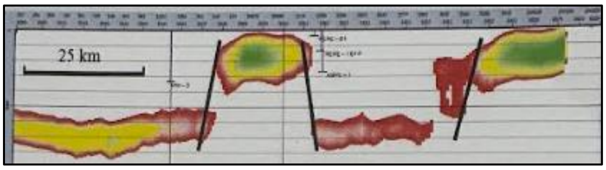

Figure 4: Traces of depth to basement displayed on a seismic traverse with interpreted fault

One explanation for this phenomenon is that geological gravity and magnetic fields are fundamentally time-independent for exploration-related issues, as outlined by Poisson's equation[11]. Consequently, time-phase data, which is crucial for determining the depth of sources in seismic imaging and controlled source electromagnetics, is not accessible. As a result, depth estimation from potential field data typically depends on examining the characteristics of the anomalies in the potential field or their spectral content[12].

The advantages of these techniques lie in their automation, speed, and ability to deliver an objective analysis of the specific anomaly wavelength in three dimensions. However, they do not automatically consider the amplitude of individual anomalies and necessitate an interpretation of the results obtained from the calculations. Traditional depth estimation methods can enhance these calculations, but they tend to be more time-consuming and may involve a greater degree of subjectivity.

Practitioners vouch that their motivation is the increasing need for a fast, cost-effective, and relatively simple method for potential field data interpretation over large areas of frontier exploration projects. Among the various techniques for depth estimation, spectral analysis has demonstrated its reliability across diverse geological conditions and has gained acceptance among numerous practitioners[13]. However, the conventional method of spectral depth estimation is labour-intensive, and similar to many other depth estimation techniques, the quality of the outcomes is significantly influenced by the experience of the interpreters. The significant improvement lies in the replacement of the interpretive element with a probabilistic approach.

The fundamental concept of spectral depth estimation is simple and straightforward. Typically, the spatial response of gravity and magnetic anomalies originating from shallow sources is characterized by a narrow and sharp profile, whereas anomalies from deeper sources exhibit a broader and smoother appearance. This distinction in the shape of anomalies is more clearly observed in the wavenumber components compared to the broader, smoother anomalies. In particular, the spectrum of a field generated by a buried point source has a very nice shape on a logarithmic scale (Figure 5), a line whose slope is proportional to the depth[6]. The magnetic anomaly from a small, compact source will also be a straight line, but with a different slope[14].

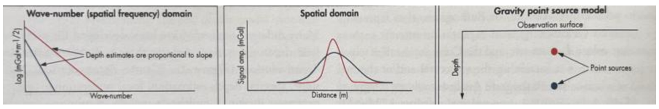

Figure 5: Spectral depth estimation[6]

In their important paper, Spector, and Grant in 1970[6] illustrated that the spectrum resulting from a group of sources with uniform simple geometries is affected by depth similarly to how each source would behave on its own. This establishes a statistical connection between the ensemble of sources and the total signal. Thus, this property allows for spectral depth estimation to be carried out without concentrating on specific anomalies tied to individual sources, which in turn promotes fast and efficient scanning. This approach for estimating the depth of magnetic sources involves analyzing the statistical characteristics of magnetic anomaly patterns. This technique establishes a connection between the spectrum of magnetic anomalies and the depth of the magnetic source by converting spatial data into the frequency domain.

The analysis is based on the premise that the anomalies in the potential field are produced by sources with simple, straightforward geometrical shapes. Additionally, we presume that the distribution of these sources remains uniform without any lateral variation within the windowed area. These assumptions are similar to the simplifications applied in the processing of common mid-point seismic data and have demonstrated considerable effectiveness in practical depth estimation. Two 500 km surveys conducted in the Priyenisey region of Siberia demonstrate the ability to identify various sources (Figure 6). In these instances, accurate geological calibration is crucial and essential[15]. The analysis relied on the available regional seismic data, well information, and geological outcrops to differentiate between the top basement, allochthonous basement, intra-basin intrusives, and shallow flood basalts.

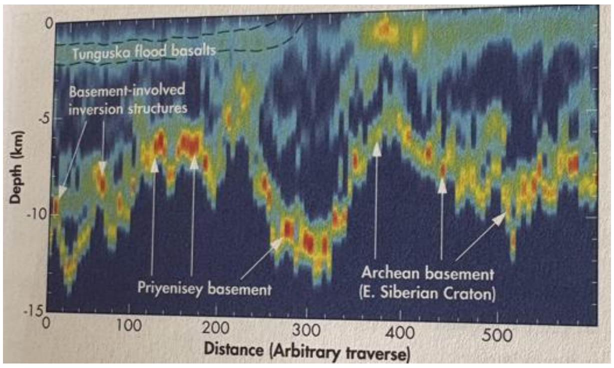

Figure 6: Multiple geological features in Siberia detected by the analysis[15]

Comparison with well data, seismic refraction depths, seismic information, and additional geological and geophysical parameters suggests that the technology operates effectively within the anticipated accuracy when appropriately calibrated with geological control.

7. Curie Depth Estimation

The Curie Temperature (Tc) is the temperature above which magnetic minerals lose their ability to support magnetization under the effect of increasing temperature[16]. The predominant magnetic mineral found in the crust and upper mantle is magnetite, which has a Curie temperature (Tc) of 580°C. Other significant magnetic phases that contribute to the Curie isotherm include hematite (675°C), maghemite (600°C), pyrrhotite (320°C), and Ti-magnetite (150°C). However, the magnetic susceptibility of these other phases is significantly lower than that of magnetite.

Curie depths are determined by analyzing peaks in the low wavenumber (longest wavelength) sections of radial power spectra, or by applying a curve-fitting technique to characterize these peaks[17](Bain Geo: Curie Depth™). One key use of Curie depth mapping is to provide a first-order estimate of the thickness of the magnetic crust, which can then be used to significantly improve depth to magnetic basement results[11]. Geothermal gradients in the crust mainly vary within the broad range of 10-100°C/km, so the depth of the Tc could range from 5.6-61 km for surface temperatures of 0-30°C.

A substantial magnetic crust aligns with stable continental areas, whereas a thinner magnetic crust may correspond to tectonically active regions, which are frequently linked to elevated heat flow[18]. It is important to note that significant earthquakes occur within the geothermal gradient zone, where thermal stress is concentrated. Therefore, it is plausible that the seismic activity in a particular area may be associated with estimates of Curie depth. A significant correlation exists between high-magnitude earthquakes and steep gradients in Curie depth[19]. This relationship is especially evident in tectonically active areas such as the Himalayas and the Arakan–Yoma fold belt[18]. Consequently, the Curie isotherm map reflects the tectonic history of these regions (Figure 7).

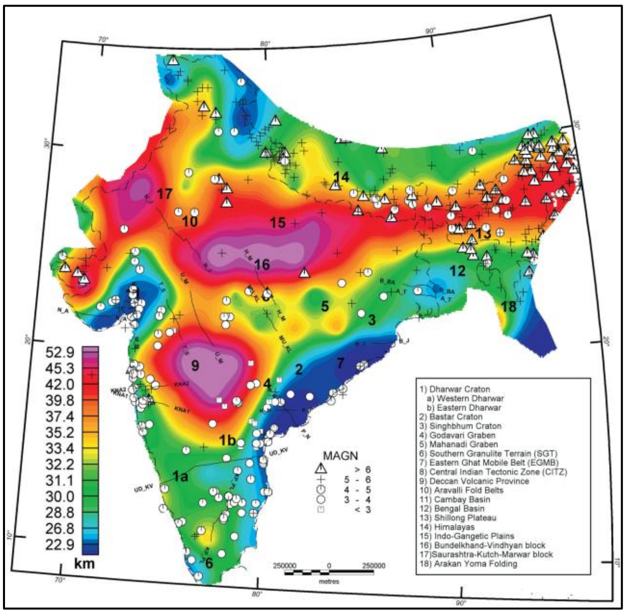

Figure 7: Image plot of the depth to the bottom of the magnetic crust. Overlaying this map is a simplified tectonic representation of India, redrawn from CGMW, 2000[19].

An innovative way to produce an interpretation of the Curie depth using aeromagnetic survey data was carried out in the Arabian platform and adjacent areas and calibrated with available well temperature and heat flow data[20]. The traverse starts in Africa with a deep Curie isotherm which becomes shallower under the Red Sea rift, deepens again under the thick and cool Arabian Shield, and then rises slowly towards Oman and the Arabian Sea (Figure 8). The Curie isotherm shallows to the east, suggesting a higher temperature in the easternmost block.

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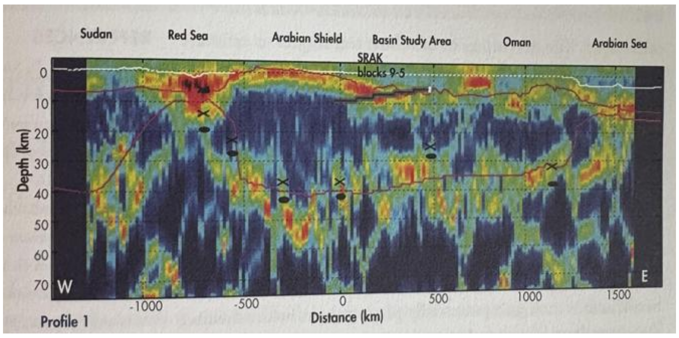

Figure 8: Curie isotherm for the Arabian Plate areas, white line for land/sea floor, magenta for top basement and base of crust (moho)[21]

Estimating the depth to the Curie isotherm using airborne and satellite magnetic data allows us to establish a crucial boundary condition for thermal and basin modeling[22]. In the context of the pseudo probability volume, the challenge lies in determining the depth to the most profound magnetic contrast, specifically the transition from a highly magnetic crust to a non-magnetic one. This is an extremely challenging problem.

8. Case of the Bay of Bengal

The Bay of Bengal is an interesting and challenging area that has the potential to be the next Gulf of Mexico when it comes to oil and gas. Subrahmanyam(2004)[23] delineated the Basement and Curie isotherm of the Bay of Bengal from the spectral analysis of magnetic data. The prominent geological features, the ocean-continent boundary, the 85° East ridge, and the 90° East ridge have been distinguished distinctly (Figure 9). The depth to the basement varies between 8-10 km in the southern profiles of the study to between 10-12 km in the north. The curie isotherm depth varies between 15-17 km in the south to between 20-22 km in the northern profile.

9. Final Remarks

In summary, there have been substantial advancements in gravity-magnetic technologies in recent years, with a range of methods providing enhanced resolution, precision, and cost efficiency. These improvements have facilitated the discovery of hydrocarbon resources, minimized exploration risks, and bolstered economic feasibility. The primary catalyst for initiating exploration in frontier basins is the technology that enables rapid scanning, analysis of magnetic or gravity data, leading to automatic estimations of the depth to potential sources for a potential field data of sufficient quality and resolution. This process yields a depth volume, with amplitude traces indicating the likelihood of a source being present at a specific depth, often associated with magnetic basement or volcanic formations. This volume can be displayed alongside seismic and other data, facilitating a comprehensive interpretation that suggests the location of the top basement within the geological section. The advantages of this technique include its automation and speed. This accelerates the ability to find sweet spots in frontier basins and develop new insights in mature basins.

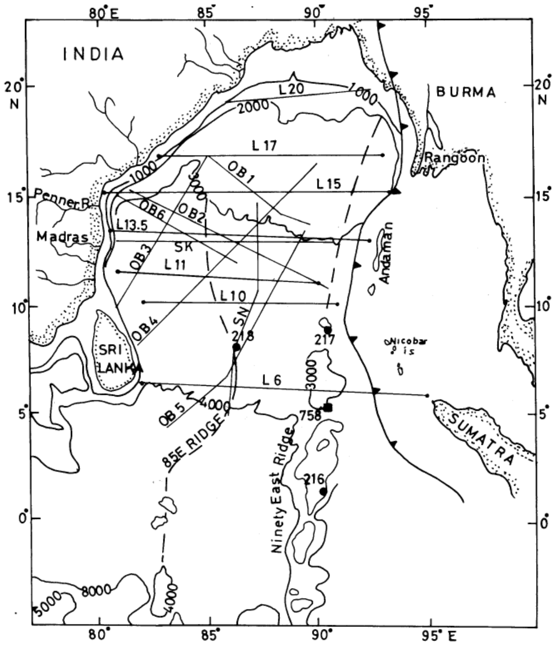

Figure 9: Magnetic profile layout[23]

Such frontier exploration technologies are crucial for evaluating lightly explored or under-explored regions, be they geographical frontiers or geological frontiers. India's sedimentary basins contain these categories. It is concluded that gravity- magnetic surveys represent the most efficient and cost-effective approach for revealing hidden and deeply buried structures. This method is particularly useful for identifying and mapping sedimentary basins that contain oil and gas, as well as for pinpointing significant trap structures within productive basins during the initial phases of exploration.

India is endowed with 26 sedimentary basins, with a large part of them offshore. So far, 8 basins are hydrocarbon productive. Therefore, the rest of the basins are frontiers to be worked upon, and the thoughts expressed through this paper would be the optimum way to explore them.

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Author Profile

Pratap Vikraman Nair received 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.