Overview of Basement Exploration Techniques

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Abstract

Exploration and production from basement play has unique challenges because of unconventional nature of reservoir. These are more difficult and expensive to explore while their evaluation is more complex than conventional reservoirs. Regarded as non-productive for many years in the industry, finding hydrocarbon in them has been left to chance during exploratory drilling for conventional reservoirs. Exploration and development of these plays was dominated by post-drill methods like- Analysis and integration of well data, especially core, borehole image logs, dipole sonic and dynamic data (mud losses, production logs, well tests etc.) which provide information of the fractures with sufficient accuracy at well location. Many seismic techniques have been developed recently for providing fracture information between wells or exploring fractured basement before drilling a well. Recognition and prediction of fracture pattern is the key to the basement exploration and specific to the task seismic imaging or processing and interpretation efforts is required.

Various seismic techniques available for characterization of faults and fractures are based on seismic attributes and azimuthal anisotropy. The structural interpretation with the help of coherence and curvature seismic attributes and other techniques enhances subtle variation in seismic data due to fractures system. Azimuthal anisotropy in amplitude, velocity, attenuation and frequency of seismic data along with integration with other data are used to predict fractures. Application of these techniques for identifying fractures in Basement is challenging due to quality of seismic data which might had been acquired over these deep seated basement with parameter suited to primary objective at shallower depth. Availability of highest quality data with full azimuth; continued improvements in various seismic processing & interpretation techniques and development of new technique has contributed in better characterization of fractures in Basement plays. All these factors and distribution of basement production in various petroliferous regions throughout the world is drawing attention of explorationists in these play.

This article provides an overview of the various techniques available for detection and mapping of faults and fracture. A brief account of Basement plays in Indian petroliferous Basin is also given.

Introduction

Natural and induced fractures play and important role in porosity and permeability in fractured reservoirs. Sandstones, carbonates, cherts, shale and basement rock are the most common naturally fractured reservoirs. Many definitions of basement rocks exist and it usually refers to the thick foundation of ancient and oldest metamorphic and igneous rock that forms the crust of continents. According to AAPG Bulletin 44 (Landes et. Al. 1960), basement rocks are considered any metamorphic or igneous rocks regardless of age which are unconformably overlain by a sedimentary sequence. Some geoscientists also consider sandstones and carbonates with little or no porosity as basement rock even if they conformably underlie oil-bearing or oil-generating formations.

Favourable conditions for basement to act as a reservoirs lie on an uplift or high of basement. These have continuously uplifted for long periods of geologic time and may have been subjected to weathering and erosion. Structural highs in the basement are created by fault tectonics or by the submergence of surrounding. Intrusive igneous bodies within sedimentary sequences may also cause formation of structural highs. Most basement rocks are hard and brittle with very low matrix porosity and permeability. Reservoir quality depends on the development of secondary porosity of tectonic origin like joints/faults/fractures and dissolution porosity. Younger sediments juxtaposition with them or overlying unconformably acts as hydrocarbon sources. Migration of hydrocarbon from these provides an opportunity for entrapment of oil in the basement. The usual cap rock for basement reservoirs is relatively low permeability sedimentary rocks or a tight zone in the basement rock.

Fractures, joint, faults and microcracks

Fracture is general term that includes natural and induced features (Fig.1). The two principal naturally occurring fracture types are joints and faults. Joints are natural fractures that show no shearing offsets. They are extensional opening fractures. Faults are shear features or extension fractures on which shearing displacement has

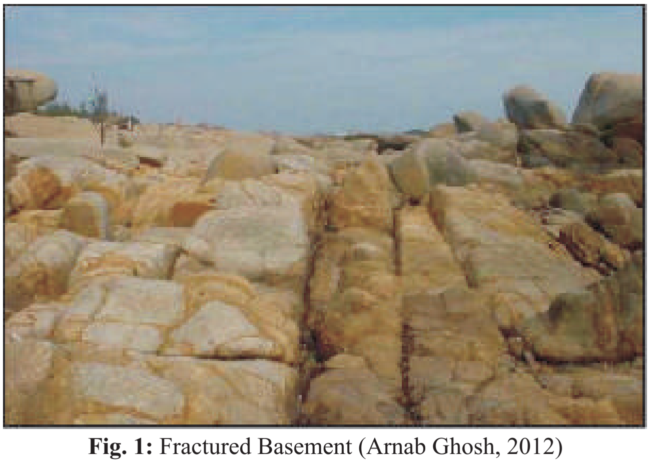

Fig. 1: Fractured Basement (Arnab Ghosh, 2012)

occurred. Microcracks are the most compliant element of rock mass and are less stress sensitive. It is generally believed that both microcracks and large scale sub-seismic fractures contribute to observed seismic anisotropy. Several geological features and tectonic stress are the main controlling factors of fracture patterns. They exist across a vast range of scales, from nearly ubiquitous millimetres- scale microcracks to kilometre-long features. Fracture in the intermediate scale or mesoscopic range appears as clusters, corridors or swarms. The intermediate – scale fractures which are often sub-seismic, are called formation- scale fractures. (Enru Liu and Alex Martinez, 2013).

Why Basement Exploration?

Historically, basement had been regarded as nonproductive and therefore it had not drawn the attention of the explorationists. In-fact their mapping was limited to eliminate out the area of non-interest for further exploratory efforts. Companies stopped drilling as soon as basement rock is intersected. Most of the oil fields producing from the basement were discovered by accident.

A good understanding of intensity, orientation and spatial distribution of the fractures in basement is essential for reservoir exploration/development. The knowledge of fracture characteristics allows design of well trajectory/path to intersect larger number of permeable zones due to fractures for increasing production (Fig.2). Their knowledge also enables to optimize placement of injectors well for better control of the reservoir pressure.

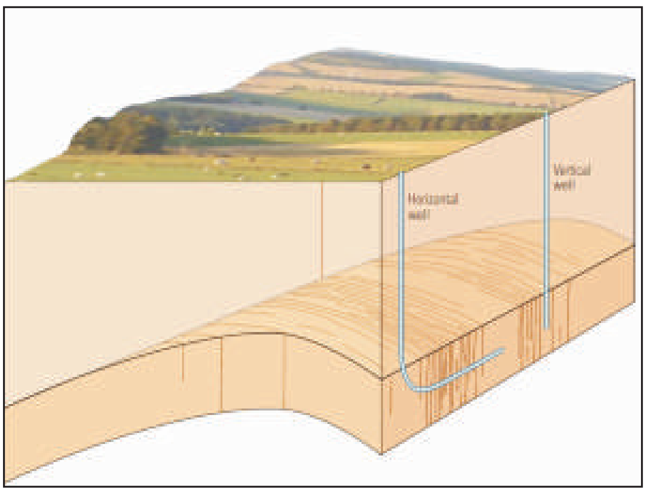

Fig. 2: Well Trajectory (Oilfield Review, 2012)

Challenges in Basement Exploration

Absence of traceable reflection horizons below the basement is the serious handicapped in mapping of heterogeneity within the basement. Even mapping of basement top with seismic data is not so easy due to its uneven surface in many cases. Being at deeper depths causes poor amplitude of the event and absorption of high frequency results in poor resolution. Multiples of shallower reflectors and mode converted energy may deteriorate the reflection from the basement. It is very difficult to get reflection within the basement from various layers/flows. In general high contrast at interface is good for reflections but it also causes high degree of scattering, mode conversion and ray bending which poses problem for imaging of deeper interface.

Faults and fractures of sufficiently large scale can directly be interpreted from seismic image. But fractures in the basement which provide porosity and permeability to the zone are below the seismic wavelengths and hence avoiding their detection. Various Seismic attributes techniques helps in enhancement of subtle changes due to fractures clusters or swarms. Zones of sub seismic fractures system can be inferred from azimuthal anisotropy in velocity and amplitude. However applicability of these techniques to fractured basement requires full azimuth data with good S/N ratio.

Geophysical Methods for Fractured Reservoir Exploration

Various methods for characterization of natural faults and fractures in the subsurface may be broadly categorized into following three groups.

1. Methods based on Direct Measurement data

Information about fracture systems can be obtained from outcrops and aerial or satellite imaging. However, this information is very indirect as rock outcrops may be located hundreds of kilometres away from an area of interest. Therefore, wells are the only source of direct measurements of defining the subsurface fracturing. Three main types of well data give information about fracturing: Core sample analysis, logging and test/production data. Core observations and image log interpretation provide fracture characterization on a centimetre scale. Analysis and integration of well data, especially core, borehole image logs, dipole sonic and dynamic data (mud losses, production logs, well tests etc) provide characterization of the fractures with sufficient accuracy (Fig.3).

2. Non-Seismic methods

Gravity and Magnetic methods provide the depth of basement but it is difficult to characterize the fractures in the basement except in very special favourable circumstances. Gravity and Magnetic data play a reconnaissance tools for mapping of Basement highs (Fig.4).

3. Techniques based on seismic data

Seismic methods can image faults and fractures of sufficiently large scale with the structural interpretation obtained from conventional seismic data volumes. Use of coherence and curvature seismic attributes, use of ant tracking technology etc. increases the detectability of large scale fractures and faulting.

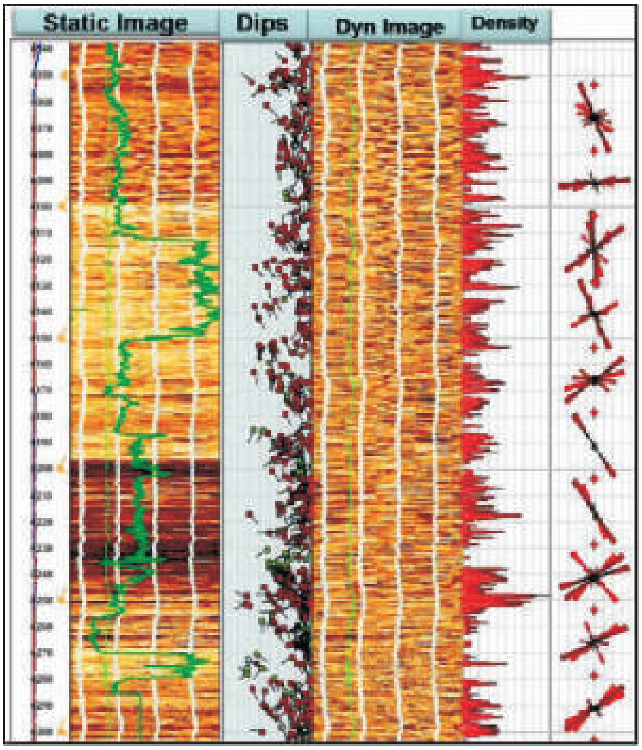

Fig. 3: Direct measurement: FMI image showing fracture intensity to be the highest in conductive part (dark brown) & fractures oriented in NW-SE and ENE-WSW directions (Uma Goyal, 2013).

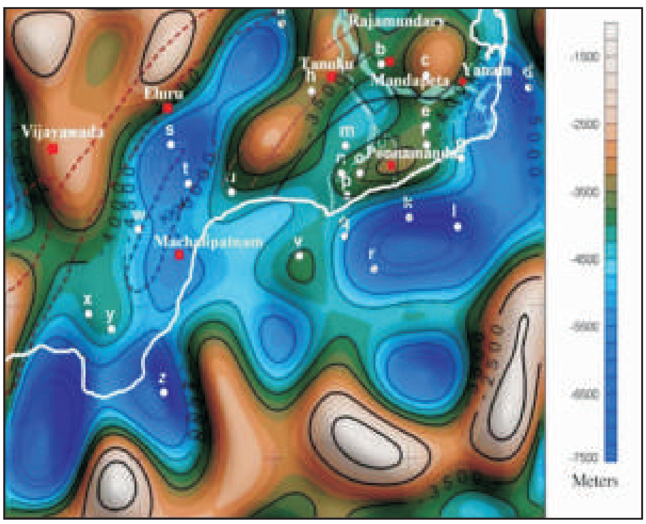

Fig.4: Basement map of Krishna-Godavari basin derived from the inversion of residual anomalies (gravity data) showing Horst and Graben. (B Singh 2009)

Seismic azimuthal anisotropy derives fracture density & orientation from compressional wave data and shear wave splitting from S-wave or converted wave data. Swarms of small and intermediate scale fractures may be characterized with these methods. Techniques are based on Amplitude (AVAZ) or velocity variation with azimuth (azimuthal anisotropy). Passive seismic data has also been used to image seismic anisotropy and to estimate fracture characteristics. Tools have been developed to image seismically active hydraulic fractures and natural fractures as complex surfaces and networks from Passive seismic data. Various techniques of active seismic data which have made considerable advancement in recent past are briefly discussed below:

a. Acquisition and Processing Techniques

In the last few decades, significant progress has been made in seismic acquisition technology. Use of recording instruments with almost unlimited channels capacity, digital sensors and Cableless technology has made possible to acquire wide azimuth and full azimuth 3D seismic data with high fold and dense sampling in both marine and land settings with any topographic conditions. Ocean Bottom Cable/Node technology has made possible to acquire multi-component data in marine condition. Seismic fracture characterization is benefitting from advances in Amplitude preserving processing and advanced imaging techniques such as reverse time migration, beam migration and full waveform inversion.

The data from Cuu Long Basin, offshore Vietnam which was re-processed with beam migration has achieved significant improvements in signal-to noise ratio and steep dip imaging inside the basement (Fig. 5). It is successful and important case study of imaging the granite basement with its fractures using seismic methods. The fractures that were barely visible in Kirchhoff migration were clearly imaged with Controlled Beam Migration (CBM). The top of the basement is also better focused with CBM. In this area, the fractured granite basement forms an excellent reservoir rock, and is the main target of exploration and development activities (Don Pham, ASEG 2007). Two of the main challenges were the poor signal to-noise ratio inside the basement and the imaging of the steeply dipping fractures. CBM has an advantage of enhancing signal-to-noise ratios and imaging steeply dipping events. It handles multi arrivals, resulting in a cleaner image than Kirchhoff migration, and preserves the steep dips.

b. Enhancement of structural interpretation with Seismic attributes:

Various Seismic attributes have been developed which enhances subtle features such as faults and fracture systems. The seismic attributes of variance, coherence, curvature are all useful indicators of faults and fractures. These attributes derived from seismic dataset following along a horizon or surface is displayed graphically. Variance measures the difference between seismic traces while coherence measures the similarity and therefore these have a reciprocal relationship. Variance emphasizes the unpredictability of seismic horizons-their edges and interruptions while coherence emphasizes their predictability: their connectedness and continuity. High variance and low coherence may indicate faults or fractures zones, clusters or swarms. The curvature attribute at points on a horizon can be measure of structural strain. Areas in which curvature is high may have been subjected to high strain to transform them into areas of flexure, folding, faulting or high fracture intensity. Coherence and curvature provide complementary structural

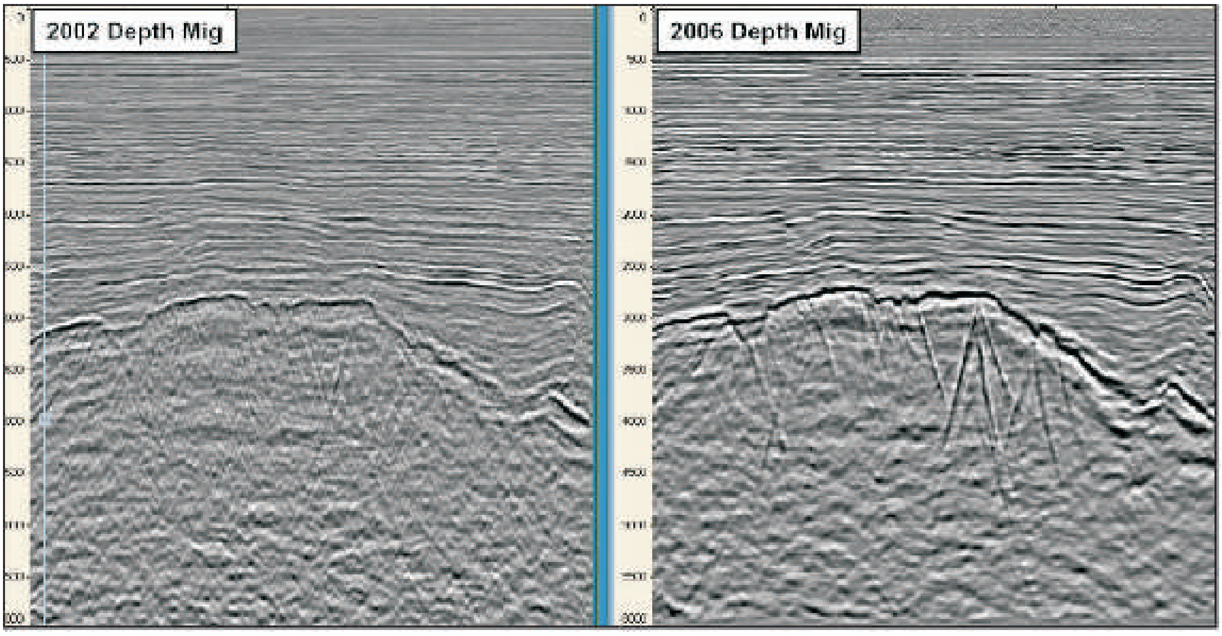

Fig.5: Improvement in imaging of fractures with Beam Migration over Kirchhoff Migration (DonPham, 2007)

information. Integration of more than one attributes and advancement in visualization techniques has made possible detection of fault and fractures.

c. Ant-tracking technology

Discontinuity evaluation software can help automate fault interpretation and attempt to map features that are on a scale approaching a seismic wavelength. Ant Tracking is such a technique which takes analogy of the behaviour of ants. Ant tracking methodologies produce a new seismic cube called Ant Track cube for extraction of fault networks. The principle of the Ant Track method is automatically re-picking the variance attributes which have the same character. The process is divided into four main stages: seismic conditioning, edge detection, edge enhancement and interactive interpretation. The advantage of using the Ant Track cube is that faults and fractures appear more explicitly (Fig.6). The ant track cube can be analysed qualitatively or quantitatively. Noise or patterns caused by lithology or by the specific orientation of fractures can be filtered out.

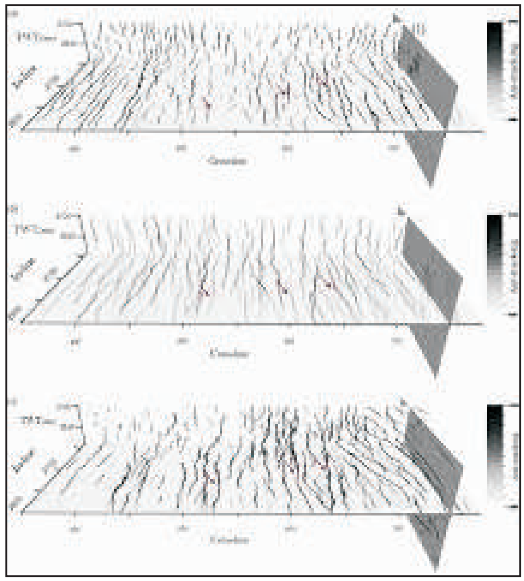

Fig.6: Muti-attribute ant -Tracking

Spectral decomposition:

Spectral decomposition is a powerful tool for illuminating subtle features such as shear faults that control the geometry of the fracture system but that are below the resolution of the full frequency surface seismic data. Spectral decomposition, or time-to-frequency analysis, is a method for separating seismic signals into their frequency components (Fig.7). The spectral content of recorded seismic data depends on cumulative effects of the seismic properties and interfaces of rock strata encountered by the propagating signals. By isolating certain frequencies, interpreters may be able to extract subtle features. Higher frequency components contain information about shorter wavelength structural features hidden within a dominantly long wavelength signal of the full frequency seismic data. Spectral decomposition is applied for image enhancement- improving resolution, balancing frequency content or supressing noise. These technique also used for reservoir characterization- evaluating sequence stratigraphy and depositional features, stratigraphic thickness and determining fracture properties and fluid content.

e. Azimuthal anisotropy:

The availability of wide/full azimuth 3D data volume has provided analysis of anisotropy with azimuth which can be exploited for predicting vertical fractures system. Aligned natural fractures in a formation cause elastic anisotropy-the

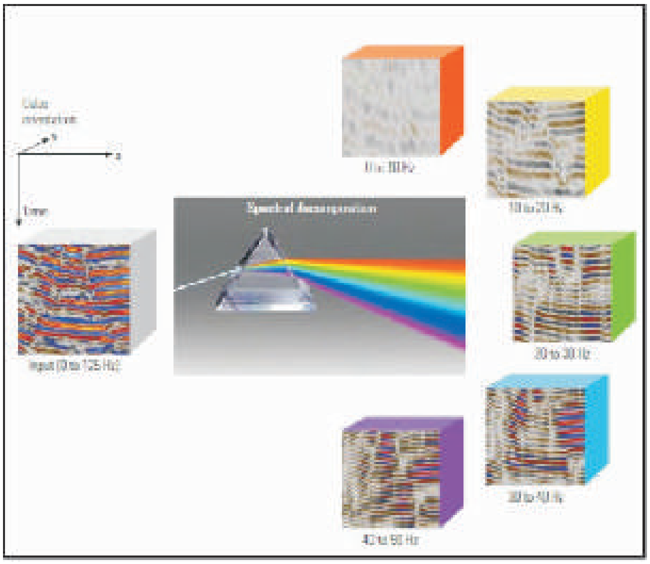

Fig.7: Spectral decomposition (Victor Aarre, 2012)

variation of elastic wave properties with direction. Seismic properties that vary with azimuth include velocity, reflection amplitude and S-wave birefringence or splitting. Azimuthal variation of these properties are deduced from analysis of 3D seismic data that have been acquired in multiple azimuths.

P-wave data: In the case of velocity anisotropy caused by oriented natural fractures alone, P-wave and S-wave velocities are at their maximum in the direction parallel to the fractures and at their minimum in the direction perpendicular to the fracture trend. P-waves are somewhat less sensitive to fracture, but respond also to fracture contents. Multi-component data: Azimuthal anisotropy is based on the shear wave splitting into two upon encountering fractures (Fig.8). An arbitrarily polarized vertically propagating shear wave will split into the fast shear wave polarized parallel to the stiff direction of the rock, and the slow shear wave, polarized perpendicular to the fast shear wave. The time difference between two provides the fractures density. It is also

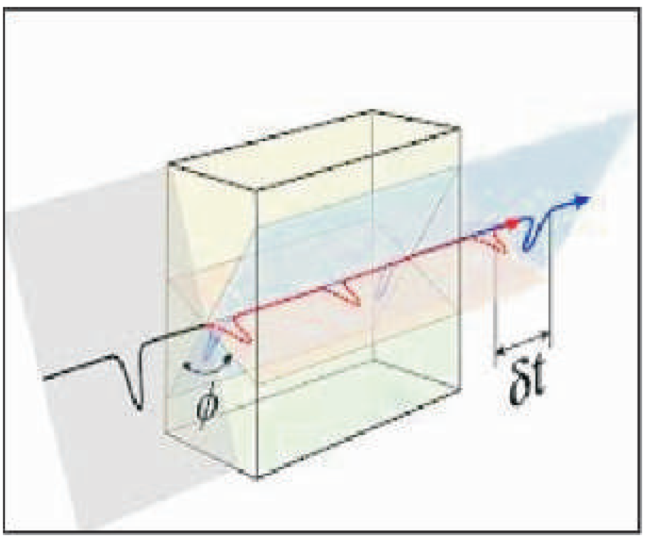

Fig.8: S-Wave Splitting

important to note that as shear waves are not sensitive to fluids, seismic anisotropy inferred from shear wave data can be correlated to crack density distribution. S-waves can map fracture density and orientation and are insensitive to fracture contents. AVAZ : The analysis of amplitude vs. angle and azimuth (AVAZ) can be used to derive relative contrasts in anisotropic parameters along a layer interface. It is important to note that AVAZ method often provides high-resolution estimates of anisotropy than travel-time method (between the seismic bandwidth of the wavelet). In addition AVAZ analysis can also be performed on shear wave data if data quality is sufficient.

f. Duplex Wave Migration (DWM) amplitude cube analysis:

Duplex wave migration is a completely different of pre-stack depth migration developed recently. DWM separates duplex wave energy from single bounce energy and uses wavefields to image vertical boundaries. Duplex wave energy has undergone two reflections prior to returning to the surface, from sub-horizontal surface (base boundary) and the targeted sub-vertical surface (Fig. 9). Duplex wave energy is much less than primary. Standard imaging methods treat duplex energy as noise and these wavefields are suppressed in conventional PSDM. Kinematics of duplex and primary reflected wavefields are very different thereby enabling DWM to separate them effectively. DWM has low vertical resolution but high horizontal resolution. DWM amplitude cube provide the detailed information about the vertical boundaries within the reservoir. Interpretation of DWM cube has been used successfully for prediction of permeable facture zones.

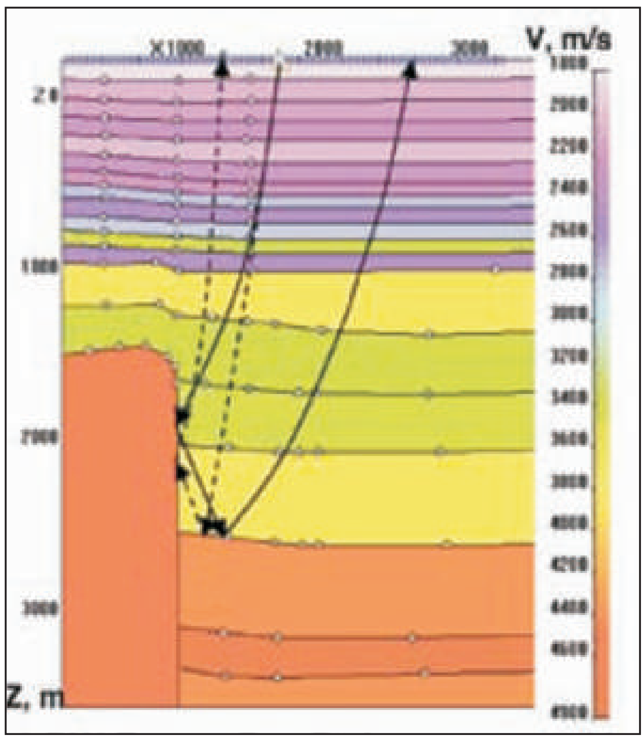

Fig.9: Duplex Wave Energy Ray paths (Inga Khromova, FB 2011)

Basement Plays in India

The area of the hydrocarbon production from fractured basement formations which are distributed in various petroliferous regions throughout the world is shown in figure 10. In India also, almost each petroliferous basin is either producing or hydrocarbon presence has been established from basement play (Fig. 11). There is established hydrocarbon potential in Basement play in India. Borholla and Changpang area in NE India are well known basement producers. Archean basement and Deccan trap in Mumbai High and Heera fields in the western offshore has proven hydrocarbon bearing and wells are producing from these basement. In Cambay Basin, occurrence of hydrocarbon in Deccan traps has been established in Padra fields and other areas along eastern margin faults. Hydrocarbon occurrences in basement in Pondicherry offshore, Mattur-Pundi, Vadatheru, Madnam and Portonovo highs have rejuvenated exploration thrust on basement exploration. Hydrocarbon was discovered in weathered Razole Trap sequence in KG Basin.

Fig.10: Fractured Basement Reservoir around the world. (Arnab Ghosh,2012)

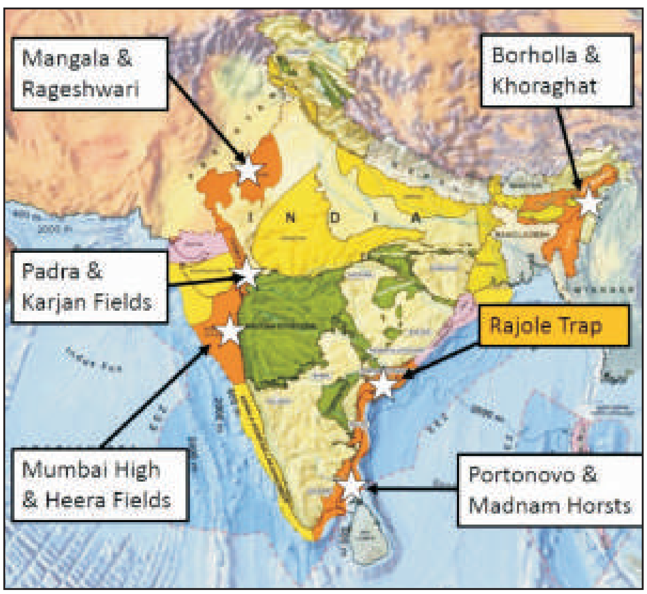

Fig. 11: Indian Basement Plays

1. Borholla-Changpang are in NE India

Producing field from basement, Borholla- Changpang is situated on a basement high. Basement domal feature dissected by NNE-SSW trending normal faults, flanking a number of antiformal highs, which in turn are further affected by E-W trending fault set giving rise to a complex fracture pattern. Anticlines and faulted anticlinal structures which are sub-parallel to, and associated with the northeast trending Naga thrust, are primary traps. Fractured basement is charged with hydrocarbon by the juxtaposing Kopili source rocks.

3D seismic survey of Borholla and Changpang contained no reflection event corresponding to Basement top probably because of absorption and dissipation of seismic energy. It is very difficult to assess the orientation, dip and aperture of the fractures in absence of reliable data. Coherency attribute on top of interpreted basement shows the complex fault system. The seismic methods in these areas may be supplemented with passive geophysical methods to map the basement and to map the potentially prospective zone.

2. Cambay Basin

Many prospects on the eastern margin faults in Cambay Basin have shown commercial presence of hydrocarbon in Deccan trap which is the technical basement in this basin. A number of wells have been drilled in Padra fields to probe the trap and have flowed oil from trap section. 3D seismic data interpretation of Padra area has redefined the architecture of the field into series of narrow basement ridges separated by lows. Fault and fractures orientation as well as the degree of fracture cementation are not well understood in this field as most of the FMI logs indicate closed fractures. Recent finding of hydrocarbon in a well which was deviated based on multi-component data will further increase use of multi-component data in characterization of fractures and possibly the fluid dynamics of the trap reservoirs.

3. Mumbai High

Mumbai field located in the western offshore of India established the hydrocarbon accumulations both in limestone reservoir and in the Basement rocks. The field is giant paleo-high of the Precambrian granitic rocks overlain by Deccan Traps at some parts and clastics and carbonates over the greater part of the area. Basement is unique and unconventional in the context of reservoir nature and hence complex to characterize and isolate the areas of interest. It is known hydrocarbon accumulations are seen in the fault zones and its associated interconnected network of fractures by which basically the porosity and permeability are generated. Well data analysis suggests that wells drilled away from fault zones are devoid of hydrocarbons whereas some wells drilled over the structures or close to faults struck hydrocarbons.

The entire 3D seismic volume of Mumbai High and Heera fields were used to generate different kinds of attribute maps like dip curvature attributes, heterogeneity, rugosity, reflection energy strength for deciphering and outlining fractured areas in basement. FMI logs recorded in wells drilled to basement has been analysed to decipher the principal stress direction. FMI log shows fracture orientation concentrated in NW-SE and ENE-WSW directions corresponding to the major orogenic trends which have affected the craton. It can be considered that major fractures have genetic linkage to the Dharwar trend while the Aravalli and Satpura trends have generated fractures offsetting the earlier ones thus creating the much needed fracture mesh for hydrocarbon accumulations.

The available data in Mumbai High areas is OBC of 1997 vintage with limited azimuth and S/N ratio. Multi-component data with OBN technology in small area of North Mumbai High is acquired recently in pilot basis. The image obtained by C-wave data has limited resolution at shallow but improvement in continuity is seen in the deeper reflections corresponding to basement. Multi-component data with full azimuth may be helpful in further exploring the basement in the area.

4. Cauvery Basin

The reservoir hosted in heterogeneous, precambrian, weathered granite has been reported in a well drilled in 1980 in offshore area of Cauvery basin. The most significant tectonic features in basin are a series of NE-SW trending horsts separated by intervening grabens. Juxtaposition of the rock against basement high as well as high angle faults offset by cross faults has created reservoirs condition in basement. Recent success from basement in the wells drilled on the north eastern flank of Madanam Horst and north western flank of Portonovo horsts have re-affirmed the role of proximity to kitchen and faulted areas in hydrocarbon accumulations in Basement. The attributes generated from structure cube volume indicate fracture intensity increasing with depth from basement top hinting to the presence of accumulation locales deeper within basement. Production of hydrocarbon from basement reservoir in Cauvery Basin is in Mattur, Pandanallur and Madanam fields. Learnings and challenges faced in pursuit of hydrocarbon exploration in basement reservoirs has opened up a large area for further exploration. Studies based on 3D Seismic data, well log data viz FMI, ECS, DSI and generation of Ant Track attributes helped in identifying the fracture orientation and density. Challenges are being faced regarding placing and completion of exploratory and development wells.

5. Rajasthan Basin

Many wells in Mangala and Raageshwari fields in Rajasthan have encountered oil and/or gas column hosted by the underlying fractured basement. Exploration wells drilled in Mangala field encountered oil in Fatehgarh Sands and followed by 30 m oil column hosted by the underlying fractured basement. Production tests confirmed the basement rock as a viable exploration target in the heavily faulted areas of the basin.

The Raageshwari Deep Gas Field is located over a Basement high in the northern part of the southern Barmer Basin with a significant lean gas condensate accumulation mainly in the lowpermeability fractured Basaltic and Felsic Basement. It was discovered in 2003 and put under

production in 2010 for meeting the internal fuel requirements through 10 development wells.Integration of image log, core and 3D seismic data indicates a dominantly shear fracture system parallel to the maximum horizontal stress direction. The fault pattern from the average negative amplitude attribute over variance Ant Tracked Volume on basalt top and felsic top indicates the fault/fracture orientation in the critically stressed direction and natural fracture network is anticipated over the major part of the field. (GeoTech 2015)

6. KG Basin

Hydrocarbon was discovered in Narsapur-Razole, Elamanchilli and Mummidivaram areas in weathered Razole Trap sequence. However, no significant discovery has been reported from fractured granitic basement in KG Basin. Prospective areas for basement exploration in this basin are the NE-SW trending Tanuku Horst and Poduru-Yanam-Draksharama-Endamuru high and Kaza-Kaikalur high. In gudivada graben the horst is directly juxtaposed to the proven source rock Gajalpadu shale while in Bantumilli graben the Kaza-Kaikalur horst is either overlain by or juxtaposed to the Raghavapuram shale.

Discussion

Various exploration techniques for basement plays have been presented broadly categorizing into methods based on direct measurement, non-seismic methods and techniques based on seismic data. The seismic techniques are based on structural interpretation enhancement with various seismic attributes and seismic azimuthal anisotropy.

Enhancement of the image and fractures in basement on re-processing of data of Vietnam offshore is remarkable with beam migration which has an advantage of enhancing signal-to-noise ratios and imaging steeply dipping events as well as it handles multi-arrivals. Recently developed technique of duplex wave migration has low vertical resolution but high horizontal resolution. Interpretation of DWM cube has been reported to be used successfully for prediction of permeable fracture zones.

Analysis of seismic data with Seismic attributes plays a crucial role in helping interpreters to identify subtle features.

Various techniques scrutinize the seismic signal in pre-stack or post stack data for subtle variations in frequency and amplitude response with azimuth and dip. Advanced seismic imaging and processing techniques and workflows have been developed to assist geoscientists in this challenging interpretation task. Integration of different attributes may further enhance the detectability of fractures. Most fractures are too small to be sensed individually by seismic waves, sets and networks of fractures can have a collective impact on seismic response. Techniques based on azimuthal variation of amplitude, frequency and travel time of P-wave as well as S-wave requires full azimuth seismic data with good S/N ratio. The seismic data must be sampled at as many azimuths as possible with sufficient offset to obtain accurate azimuthal anisotropy. Also vital is integration of seismic results with large scale geologic trends, log data, outcrop studies and real time drilling results.

Basements plays are having good hydrocarbon potentials in India. All the sedimentary basins of category one has shown hydrocarbon potential in basement with varying degree.

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