7th International Conference & Exposition on Petroleum Geophysics

"HYDERABAD 2008"

P 309

Hydrocarbon Exploration Modeling in Cambay Rift Basin: An Alternative

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Summary

Five decades of hydrocarbon exploration in Cambay rift basin – the largest onland petroliferous basin of India- resulted in many a discovery. Exploration models, hither-to, targeted structural 'highs' with ('north-sourced') reservoir facies deposited over 'palao-highs' due to 'winnowing'. However, the designation of the so-called 'highs' and 'lows' themselves and the absence of 'clean', 'winnowed' reservoir 'facies' over paleo-highs, are some of the grey areas of the present models. In the light of recent developments in half-graben rift basin studies, a revisit of seismic data from the west-central part of the basin suggests , an alternative model. This model comprises 1) 'Short' depositional systems typical of half-graben rift basins (in contrast to conventional 'long' depositional systems) and 2) attendant, structure (mainly fault)-controlled **fan-deltas** *as principal exploration targets within these structural 'lows'. In addition, the north-ward tilt of depositional sequences and the systematic alignment of oil and gas fields are also suggestive of hydrocarbon entrapment (exploration) corridors calling for a modular approach - for individual fan-deltas at half-graben level to the migration / exploration corridors at inter-basinal level.*

Introduction

Cambay Basin, the largest onland petroliferous basin of western India, is inferred as an aborted intracratonic, broadly NW-SE oriented 'rift graben system' (Fig.1) Recent works by Negi et al (2006) and Wandrey (2004) attempt to reflect the prevalent concepts and understanding of the basin.

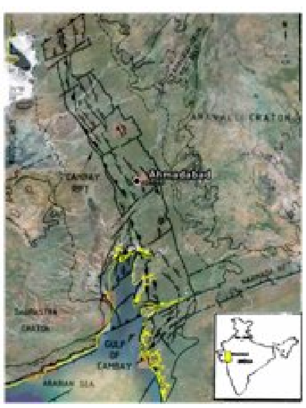

Figure 1: Location Map of Cambay Basin

The generalized startigraphy of Cambay basin is shown fig.2. The basin which is a portion of western Indian plate passive margin, was formed during Late Cretaceous by failed rifting. Intense volcanism during Late Cretaceous resulted in expulsion of Deccan Trap basalts which form the basin floor. Trap derivatives were followed by deposition of continental non-marine sediments of Paleocene to lower Eopcene age (Olpad Formation).The faices comprise sandstone, siltstone, trap-wash (coarser clastics with poor reservoir properties) and claystone deposited in alluviasl fan-, alluvial fan delta-, overbank- and lacustirine environments and generated substantial hydrocarbons. (Negi et al, 2006). The lower to middle Eocene, dark 'marine' shale sequence (Cambay Shale Formation) comprises the 'syn-rift sequence' which is considered primary soure rock for the southern Cambay basin. This Formation is further divided into an Older and an younger unit ; the former containing episodic arenaceous intercalations The overlying middle Eocene 'Kalol Formation is the major producer in the basin especially with sandy facies intercalated with silts and 'regressive' coals and have been assigned shallow marine (deltaic) to alluvial environment, which prevailed till late Miocene when large volumes of terrestrial sediments inundated the basin.

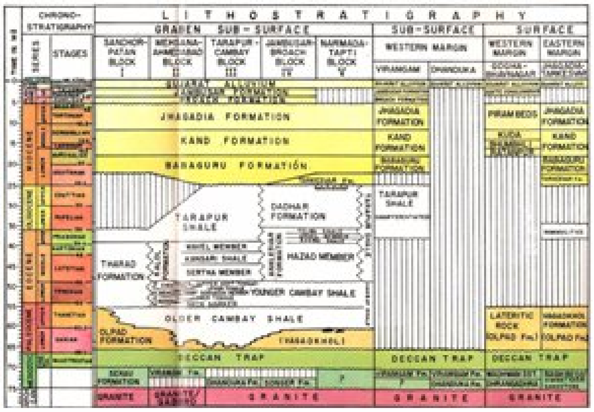

Figure 2: Generalised Stratigraphy of Cambay Basin (After Pandey et al, 1993)

Exploration Modeling - Conventional and Alternative:

Hydrocarbon source rock potential has been established mainly in Cambay Shale and also in Olpad Formations. The basin has no dearth of reservoir facies –principally the Kalol formation and episodic coarser clastic facies of Older Cambay Shale and also in Miocene sequence. These reservoir facies are construed to be deposited over 'paleo-highs' (due to 'winnowing') and formed structural 'horst' blocks or anticlines. Stratigraphic traps and pinch-outs against these structural highs are also secondary exploration targets. Hydrocarbon exploration efforts, hither-to, hovered around these anticlinal models envisaging horst-graben set-up. The whole gamut of exploration (depositional-, structural-, reservoir -, source-rock- and entrapment-) models were thus focused on these horst features. While these anticlinal models did give success in the forma of hydrocarbon pools and larger fields for the past almost half-a-century of exploration, severl grey areas remain unanswered, especially pertaining to presence and or extension of reservoir-facies and –properties, such as the presence of reservoir facies over 'paleo-highs' that too due to winnowing. It is generally expected that winnowing would form a 'rim' of sand around a 'paleo-high' and not just over it. Also the reservoir quality of such winnowed sand should be excellent. Thirdly, such a model demands usually a very high energy depositional set up, unlike a predominantly coaly/silty/shaly one, spanning over large vertical/ temporal and areal extension as is typical of most of encountered reservoir facies. In addition, new exploration trends embarking upon such concepts as basin-centre gas accumulations (BCGA) etc. also necessitate a detailed review of basin modeling with regard to the exact definition of basin-centre or 'low' often defined by transfer faults laterally connecting all high and low trends.

In the light of the recent developments in half-graben rift-basin studies, a relook into available seismic (mainly 2D and 3D) and well data of west-central part of the Cambay basin was attempted. The model is a combination of two elements - involving the '**short**' siliciclastic depositional systems (in contrast to the conventional 'long' one ranging from alluvial fans through fluvial- and transitional (deltaic) systems to marine and deep-water settings) with their attendant sequences and their strati-structural significance in hydrocarbon exploration. ***The 'short' systems (Fichter et al,1991) are depositional environments with abbreviated depositional sequences proximal to silici-clastic source lands, typical of tectonically active regimes, e.g. rift-basins.*** The basic depositional element in such an 'abbreviated' sequence model is a ***fan delta – an alluvial fan that progrades directly into a standing body of water (lake or sea) from adjacent highland*** – which is ***deposited over the steep depositional slopes with substantial relief, caused by (normal fault-controlled) hanging-wall subsidence and drowning***. These fan deltas are generally ***thickest near the fault scarps, thin rapidly basinward and deposit little subaerial sediment.*** (C.J.Dart *et al*, 1994). Ravnas & Steele (1998) exhaustively discussed geometry of marine half-graben rift basins, (Fig.3) highlighting the relative distribution of 'highs' and 'lows' and uniqueness of sequences in each of these half graben. Gawthorpe et al, (2003), while numerically modeling half-graben rift-basins, identified three locales for fan-delta development, resulting in fault-tip, hanging-wall dip-slope and foot-wall sourced (fan) deltas. Thus, the hither-to amalgamated 'high-' and 'low-' or 'basinal' trends often laterally expressed by transfer-faults in conventional modeling, may actually represent independent half graben entities without any simple geometric as well as depositional continuity. Differential compaction of coarser clastics within these fan deltas (vis-à-vis adjacent finer clastics) may invariably results in subtle structural features.

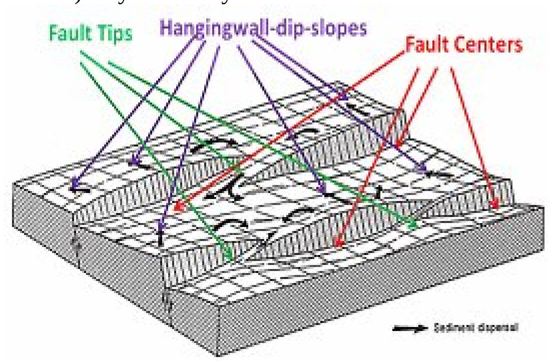

Fig.3 : Structural geometry of Half-graben rift Basin (After Ravnas & Steele (1998) showing locales of fan- delta development defined by Gawthorpe et al (2003).

Some of the 2D and 3D seismic data of west central Cambay basin were revisited, for an alternative exploration modeling of Cambay basin, with this concept. Approximate location of these 2D and 3D sections is shown in Fig.4

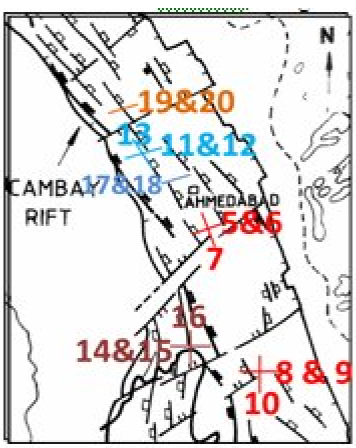

Fig.4 : Approximate location of seismic sections referred with corresponding Figure numbers (Not to Scale)

The first example (Fig5) is based on data pertinent to a major producing field of Cambay basin, the Nawagam field (with over four decades of production history). Early to Middle Eocene Kalol sands are the main producers in this field with a strati-structural entrapment style (Thomas et al, 1999). In this WNW-ESE oriented 'anticlinal' structure, two main (Lower Eocene) reservoir sands – Kalol-IX and X are the main hydrocarbon producers. The slope of this structure is 'steeper' on the eastern side and an adjacent structure on its east has 'gentler' slope. (*ibid*.) Each sand unit is construed as a parasequence consisting of siltstone to fine sandstone layers with 'subjective' lateral continuity. Lithologically, these sands are 'interlayered' with shale, sideritic claystone, silts and carbonaceous shales. Each parasequence is punctuated by 'marine' shale and coal.

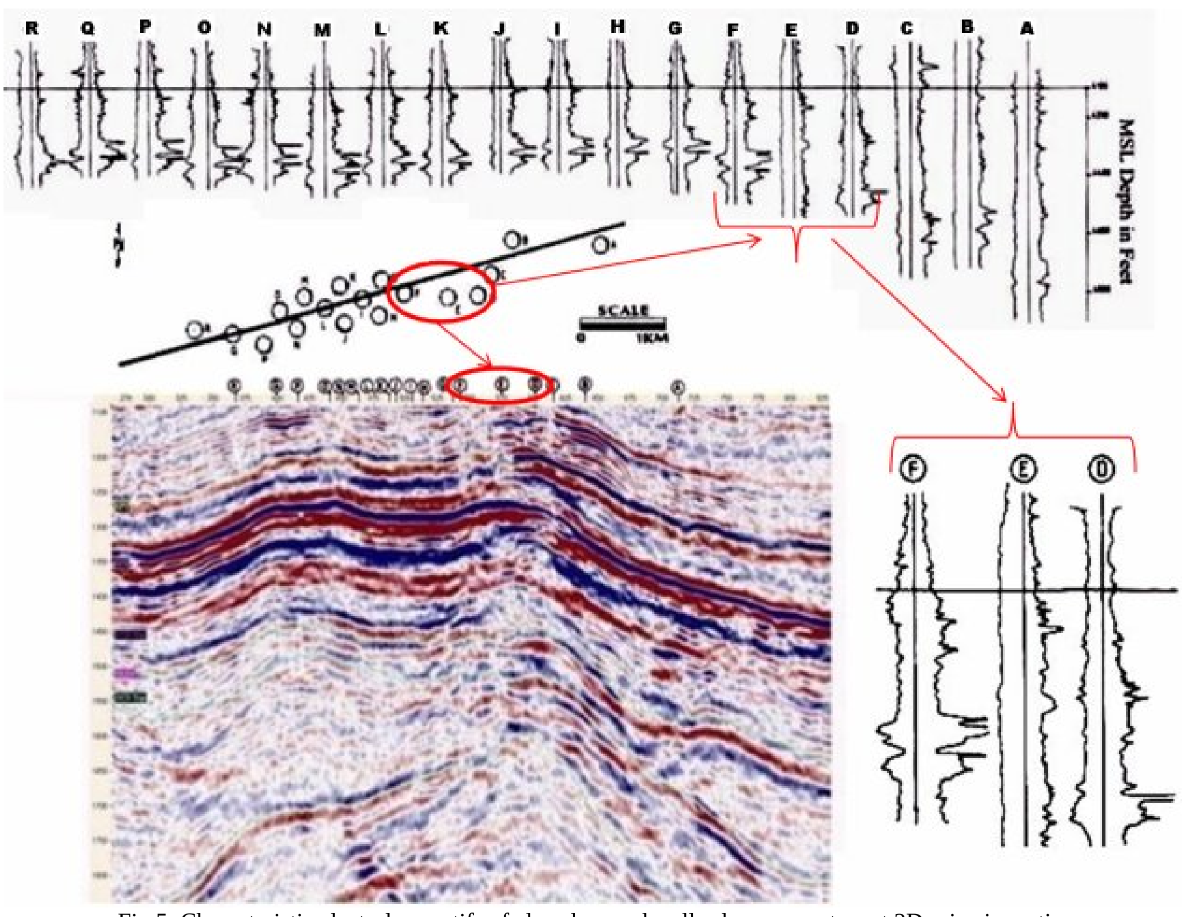

Fig.5: Characteristic electrolog motifs of closed spaced wells along an east-west 2D seismic section

It has been concluded that paleolows apparently comprise the sand maximasand are thus better sand-prone areas.

Fig.5 depicts an east-west 2D seismic section cutting across the field. Wells spaced at about 200 to 300m apart, along the

2D seismic line are shown with respective log motifs of Kalol pays. It is interesting to note that three closely positioned wells D, E and F show independent reservoir facies distribution. While the reservoir facies as well as the coals are clearly defined in wells D & F, albeit, dissimilar in their log characteristics, they are conspicuously 'absent' in well E, which is located on the so called 'crest' of the 'structural high' as seen in the seismic section also. Wells F to R depict a uniformity in these facies which is absent in Well E while wells D to A show a time-equivalent, but varied facies. Flattening of the said seismic section (Fig.6) close to the reservoir level, however, reflects two independent lows defined by two major, basin-defining faults on either side of a 'structural high', with a clear-cut demarcation of seismic facies both above and below the flattened horizon These facies anomalies at the fault scarps suggest the presence of two independent ***fan deltas***, typical of structure- (fault-) controlled ***short system*** of siliciclastic depositional set-up.

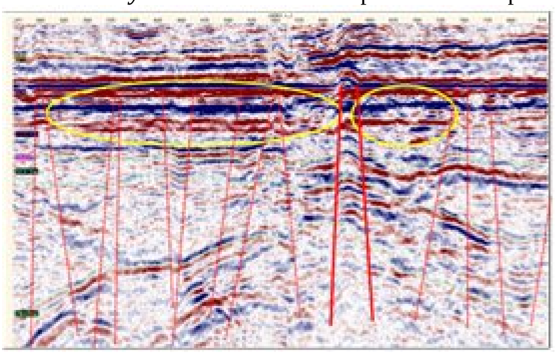

Fig 6: 2D seismic section same as in Fig.5, flattened at a horizon close to Kalol reservoir reflecting two independent, fault-controlled lows with attendant seismic facies attributes

Other faults, albeit minor, have an impact on basin geometry and attendant sedimentation at various stratigraphic levels and define independent 'blocks' with attendant seismic facies development and or variation.

.Most of these 'minor' faults which are construed to be 'unmappable' in 'conventional interpretation', however, have directly impact for basin-building as well as sedimentation-especially of reservoir facies. The steep slope of the eastern flank suggests a steeper fault scarp close to a transverse anticline and the gentler slope of a field east of the present area (Thomas et al 1999) probably represents the hanging-wall dip slope of the half-graben set up. The facies association/ amalgamation – silts and fine sands along with 'marine' shales and siderite and coal / carbonaceous matter all suggest a 'short-system' facies ***('fan-delta')*** typical of sudden deepening of the basin along the fault scarp rather than a fluvial or deltaic ('long' depositional') set up. The coaly facies represent an overall transgressive (lacustrine) depositional set up rather than an 'open' regressive 'transitional' depositional set up as is conventionally inferred. Limited lateral correlatability of facies also supports a 'short'depositional system.

A north-south 2D seismic section crossing the line in question (Fig7), reflects a 'transverse anticline' typical of half graben rift basins with an interestingly northward dipping sedimentation pattern for all the depositional / stratigraphic levels. It also implies that basin dipping towards north may thus necessitate an alternative for hither-to construed northward source for the clastic facies.

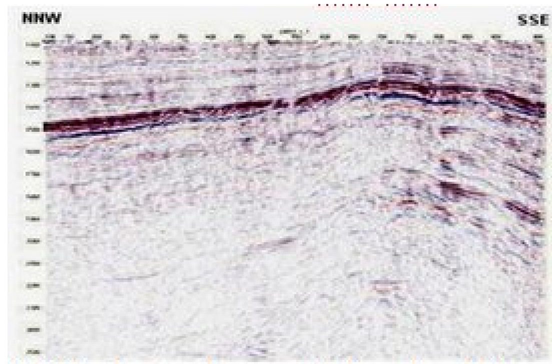

Fig 7: 2D seismic section perpendicular to that of Figs. 5 &6, showing a transverse anticline and northward dipping depositional sequences.

Upper Eocene reservoir sands of Kathana field also show a more or less similar strati-structural geometry. A cluster of wells along an E-W 2D seismic section (Fig.8) with development of reservoir pay sands are located over a 'paleo-high' in a half-graben rift basin set up. Flattening of this 2D line at a horizon immediately above the reservoir level (Fig.9), reveals a strati-structural anomaly, within a fault scarp commensurate with reservoir development – a probable ***fan delta***.

A perpendicular 2D seismic line (Fig.10) to that in figs 8 & 9 as in the previous examples also reflects a transverse anticline and the northward dipping and thickening of sequences contradicting the north-source for these sediments. A 2D section perpendicular to this line (Fig.13) reflects the so-called deep basinal part – commensurate with the north-dipping sediments within a half-graben set-up.

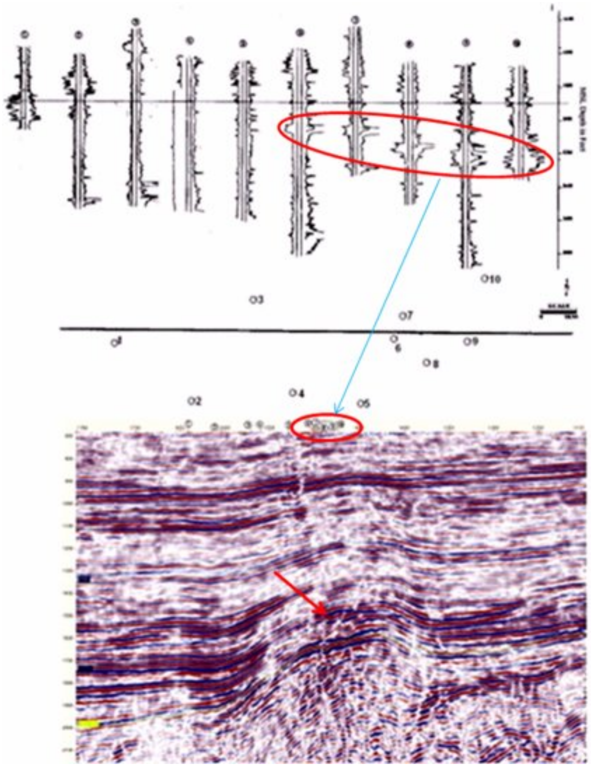

Fig.8 : Electrolog correlation of wells along an E-W 2D seismic section, with U.Eocene reservoir facies development over a 'Paleo-high' within a half-graben rift basin set-up.

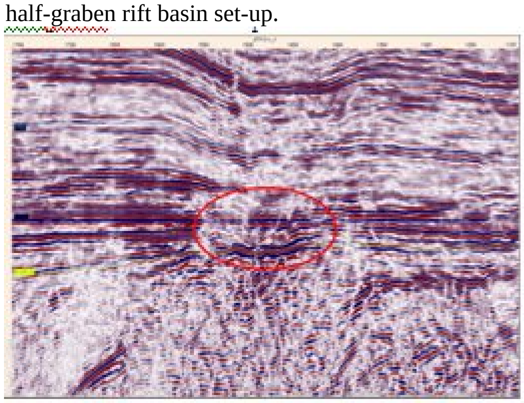

Fig.9: E-W 2D seismic section as in Fig.8, flattened at a horizon immediately above U.Eocene Pay showing a probable fan-delta development on the flank of paleohigh.

The same section has been inferred as that of deep basin centre set up. (Fig.17 of Negi et al,2006). An E-W 3D seimic section (Fig.14) from Akholjuni area shows two 'paleohighs' with basal Miocene oil reservoir pays especially within a typical half-graben set-up. As shown in the flattened section (Fig.15), laterally and vertically restricted fine sandstone reservoir reveals a fault-controlled channel-fill like feature on the flank of the paleo-high.

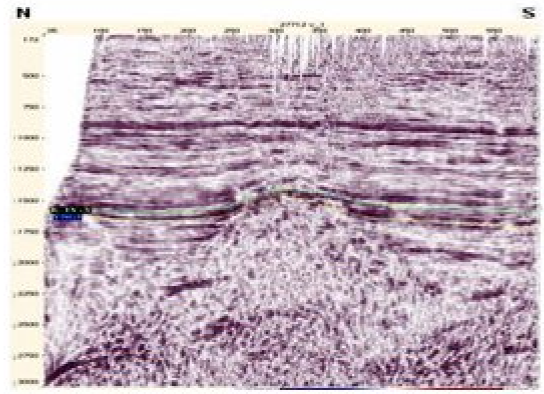

Fig.10: 2D seismic section perpendicular to that of Figs. 8 & 9 showing a transverse anticline and northward thickening and dipping of basin.

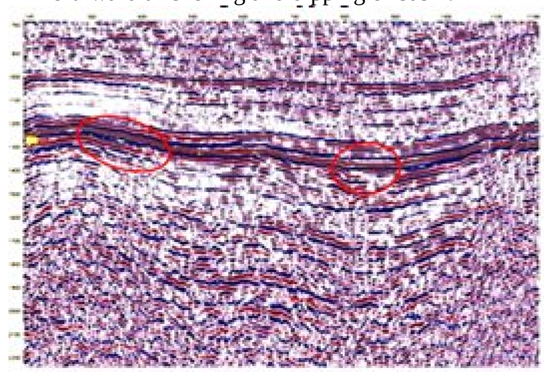

Fig.11: 2D seismic section showing two strati-structural anomalies (red ovals)

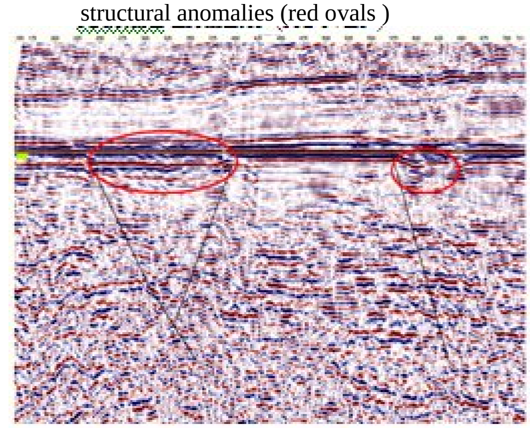

Fig.12: 2D seismic section as in Fig.10, flattened at a horizon close to Kalol pay sands showing two fault controlled strati-structural anomalies.

A perpendicular cross-line in Fig.16 reflects a northward dipping (and thickening) of sedimentary sequences, as seen in other north-south lines. A conspicuous amplitude variation is evident northward commensurate with facies variation within Kalol level, from non-coaly facies in the south to probably coaly facies development in the north.

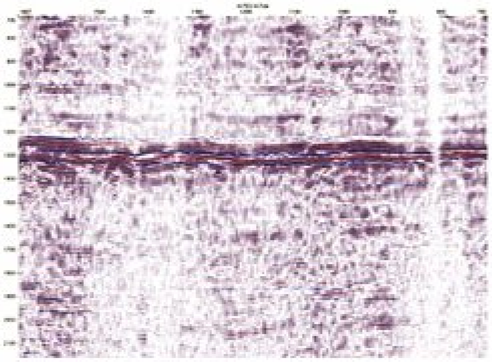

Fig.13: 2D seismic section perpendicular to that of Figs. 11 & 12 showing a transverse anticline and northward thickening and dipping of basin.

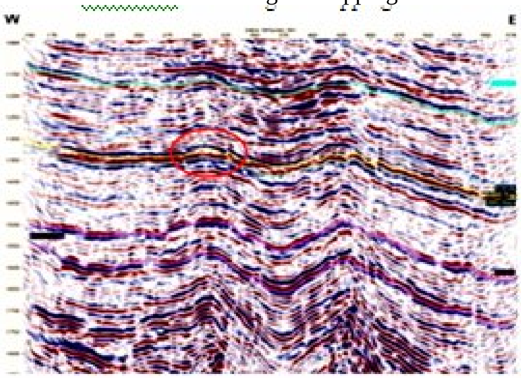

Fig.14: An E-W 3D seismic section in Akholjuni field showing two paleo highs and a Miocene strati-structural anomaly

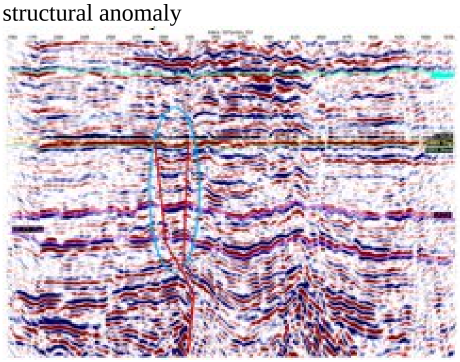

Fig.15: Same seismic section as in Fig.14 flattened at a horizon close to Miocene pay showing a fault-controlled low.

A structural 'high' at Kalol level in Sanand field in 2D seismic section (Fig.17), on flattening, reflects a fault-controlled depositional feature, a 'Fan Delta' (Fig.18) with conspicuous variation in thickness of facies within a fault-defined 'low'. Similarly, the enigmatic early Eocene, South Kadi pays (within Older Cambay Shale) of South Kadi field, also suggest a similar, fault-controlled facies distribution/

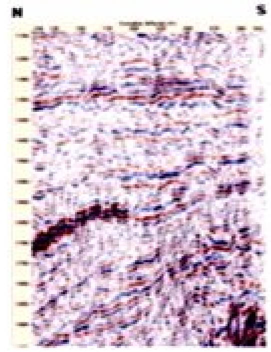

Fig.16: Cross line to that of Fig.15 showing north trending sequences

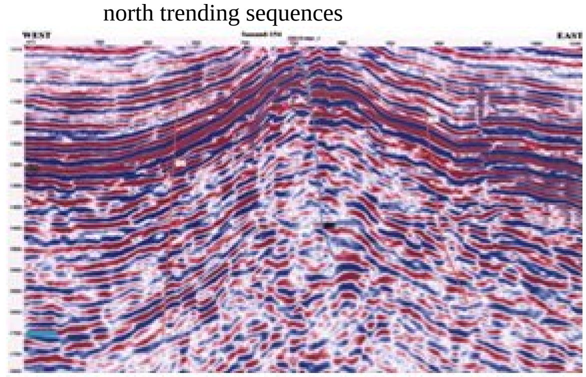

Fig.17: E-W 2D seismic section showing a stratistructural anomaly at Kalol level

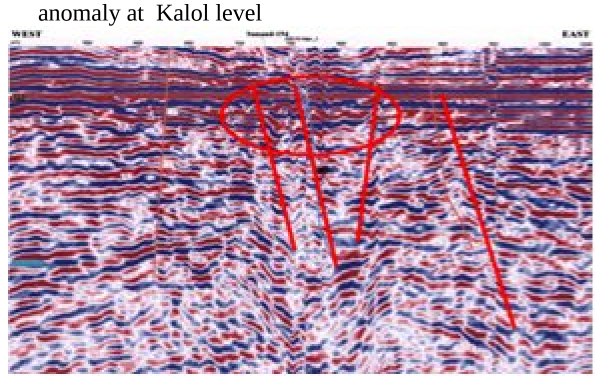

Fig.18:Same 2D line as in Fig.17, showing fault controlled Sequences (Fan Deltas) with varying thickness

variation as depicted in a 3D seismic line (Figs. 19 & 20). It is interesting that each faulted block comprises unique seismic facies which tries to explain the short-distance variation of reservoir pays.

Envoi

Exploration efforts in Cambay basin nearly for a half century, focussed on 'anticlinal' models, which envisaged deposition of reservoir facies over paleo-highs due to winnowing. These models try to identify the Palaeogene reservoir facies in

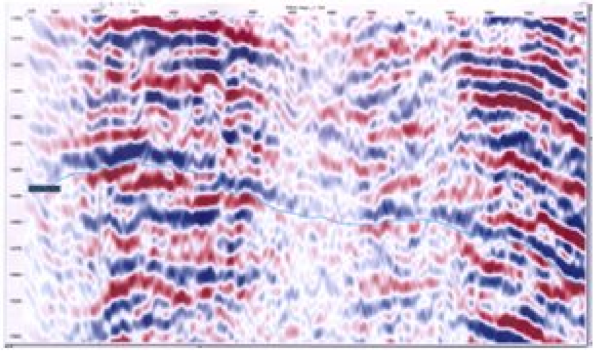

Fig.19: A 3D seismic section from South Kadi field showing subtle highs at payzone (South Kadi) level

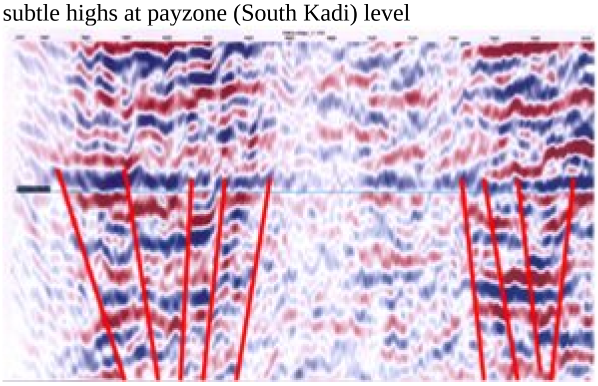

Fig.20: Same section as in Fig 19, flattened at South Kadi pay level showing fault-controlled, varied seismic facies

terms of long-depositional systems - alluvial fan-, fluvial-, transitional- and marine- systems while the facies associations are predominantly silty, shaly and carbonaceous (coaly), restricting the sampling to ‘horsts’. These models envisaged a generalized startigraphic and/or sequence stratigraphic determinations with uniform attributes for the whole basin. The models also construed a ‘northward ‘source’ for the so-called syn-rift and post-rift sequences. However, the reservoir distribution and/or prediction remained enigmatic or even a serendipity, despite a large number of wells as well as advanced interpretation techniques/ technologies contributed to exploration and development models. The (dip-oriented) low- and high-trends which are often inferred as bounded by the so-called transfer-faults need to offer a lot of explanation, in terms of the noticeable impact of such large, younger (transfer) faults on older sequences. These explanations are all the more essential while attempting to embark upon such new concepts as the basin centre gas accumulations, since the very designation of ‘basin-centre’ is subjective especially in a structure controlled half-graben rift basin set-up. In this context, simple revisiting of mainly old 2D and limited 3D seismic data, as demonstrated above, attempt to offer an alternative interpretation model the significance of fault- controlled sedimentation especially in short depositional regimes typical of half-graben rift basins with their attendant depositional units, the ***fan deltas***. An ideal fan delta within a half-graben rift basin set-up (Fig.21) comprises all the requisite elements of total petroleum system(TPS), as amply demonstrated by each of the afore-said examples.

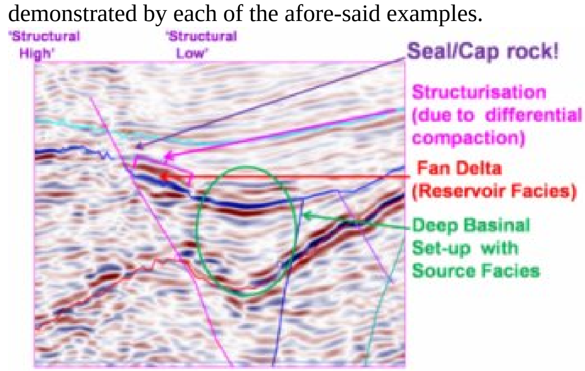

Fig.21: A 3D seismic section form Cauvery Basin depicting an idealised petroleum system within a ‘low’ in a Half-graben set up.

Precise mapping of the fan deltas can enable – ***discovery*** of new pools, their meaningful ***delineation*** and ***development.*** A glance at the distribution of hydrocarbon fields / pools suggests ‘non-coincidental’ trends. The pools / fileds on the eastern part of the basin comprise oil bearing Eocene pays. Gas bearing Oligocene pays are found in the central part of the basin, while oil bearing (prolific) Miocene reservoirs characterize the western part of the basin. It is not just confined to the Cambay basin alone. These trend extend further southward, through Cambay offshore to Mumbai offshore basin (the western Miocene Mumbai-high oil trend, the central B-55 (Oligocene) gas trend and the western Bassein trend) as well, suggesting discrete corridors of hydrocarbon entrapment or independent pertroleum systems/ sub-systems (Ramakrishna & Pati, 2003). These may well be corridors for exploration – a small prospect within the western (Mumbai-high & Akholjuni) corridor could result in a prolific producer while gas prone prospects can be expected in the central corridor. In addition, the distribution of reservoir facies also form episodic; the lower Eocene South Kadi pays appear to be coeval to the ‘lower Pays’ of the Nawagam area, making their distributions interesting in the intervening Sanand-Jhalora areas. Similarly middle Eocene Kalol pays, upper Eocene Kathana pays, Oligocene Cambay pays and basal Miocene Akholjuni pays The ubiquitously north dipping sequences as seen in the N-S seismic sections also suggest a northward tilt of the basin for most part of the post-Cretaceous deposition period. This tilt also makes the hither-to inferred northward source for coarser clastic facies. With best of the sand facies confined to the southern most (Gandhar) part of the basin, a southern or south-eastern source contributed through the Narmada rift towards this north-tilted basin may be a more plausible alternative. With well established Palaeogene and Neogene marine (carbonate) basins – the Rajasthan basin in the north, and the Mumbai Offshore basin in the south, the Cambay basin might have acted as a large transitional lacustrine basin into which structure rift related controlled fan deltas were formed at fault scarps, hyphenating the ubiquitous Kalol coals- typical of a coastal (marine) transgressive 'lake'. A modular approach at sub-basin or half-graben level may help in identifying reservoir- or TPS-specific fan deltas. At inter-basinal level, between Mumbai offshore and cambay basin, this approach may unravel the true hydrocarbon potential within the entrapment (and/or exploration) corridors.

Acknowledgements

The Authors gratefully acknowledge their sincere gratitude to ONGC Authorities for enabling them to carry out the contained work in bringing out this paper in its present shape.

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