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Understanding of Reservoir Heterogeneity and its Impact on Flow Behaviour to Facilitate Improve Recovery in a Mature Carbonate Reservoir: An Example from Western Offshore Basin, India

Abstract

Structural style and facies architecture are the two fundamental elements that defined the reservoir heterogeneity of Mumbai High field in western offshore Basin, India, affecting drainage capability. Heterogeneity of MMC-I reservoir is linked to varied depositional environments, distribution of clays, and changes brought in due to post depositional tectonic activities and diagenesis.

To describe these heterogeneities, integrated interpretation was adopted employing data, information, clues and the results of the different disciplines fulfilling compliances of geology.

The above approach has culminated in deciphering areas of un-swept hydrocarbons, facilitating work out strategies for economic realization of these sweet sectors through infill drilling, water flood optimization, and strategic re-completions.

Key words: Structural style, facies architecture, heterogeneity, and un-swept hydrocarbons.

Introduction

Middle Miocene Carbonate (MMC-I) reservoir of Mumbai high located in western offshore basin, India (Figure-1), covers a producing area of 105.00 sq. km. It is on regular production since June 1985. The productivity of the reservoir, remained by and large, good till 1989-90, but thereafter, production started declining due to falling reservoir pressure (Figure-2&3), and increase in water cut on initiation of water injection.

To facilitate improve recovery, an integrated approach was adopted, wherein interpretation results of geological and geolophysical studies were merged to reservoir and other engineering data for a comprehensive description of the reservoir establishing causes of heterogeneity and its impact on flow behaviour.

The aim of this paper is to illustrate reservoir heterogeneity arising out of; structural style and depositional facies architecture, which has led to better understanding of the reservoir to facilitate improve recovery.

Geological Setting

Mumbai high field is a large doubly plunging anticline (Paleohigh), bounded towards east by NNW-SSE trending basement controlled fault (Mitra et al., 1983); and towards west, it grades into monoclinal deeper continental shelf.

The stratigraphic framework of Bombay offshore basin has been worked out by numerous workers (Basu, 1982; Nair et al., 1992; Zutshi et al., 1993). The depositional floor of basin is made up of Granite gneiss (inliers) of Precambrian and Deccan Traps of Upper Cretaceous with thin section of basal clastics. Tertiary sedimentary sequences of Early Oligocene to Recent overlying the basal clastics were deposited in response to various transgressive and regressive

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events registered during geologic past. The major Carbonate reservoirs of Mumbai high were deposited during upper part of Early Miocene (Bombay Formation) and Middle Miocene (Bandra Formation). In between these two major carbonate reservoirs, a thin sheet like sand/silt body is deposited, which is designated as Mahim Formation. Thick clastic sediments of Chinchini Formation of Post Middle Miocene to Recent age, overlying Bandra Formation unconformably provide the main seal (Satyanarayana et al., 1998)

Structure

The basement-involved tectonics is the principle carriage where the structural grain inherited during Precambrian, is responsible in shaping the dominant structure style. The older NNW-SSE trending tectonic elements parallel to Dharwarian trend is one of the dominant feature, which has influenced the depositional pattern (Mitra et al., 1983). Many workers believe that Post Middle Miocene (Serravallian) tectonics in the area is dominated by strike-slip deformation giving two principal structural trends, one in NE-SW and the other in NNE-SSW direction. The interpretation of recently acquired 3-D seismic data has brought out structural elements confirming to these trends.

Faults have been mapped using vertical seismic sections (Figure-4), and seismic attributes (Figure-5). They display two trends, one oriented in NNW-SSE are older, and another set of faults oriented in NE-SW and NNE-SSW direction are younger. The interaction of these sets of faults has resulted in compartmentalization of MMC-I reservoir (Figure-6).

Faults F10-F10 and F11-F11, trending NNE-SSW have given rise to development of open fractures in its vicinity (Figure-5), imparting better permeability.

Facies Architecture and Analysis

A significant amount of challenge is placed in identifying the genetically related litho facies and finding semblance to diagenesis to understand the reservoir heterogeneity. Well log signatures and core data at different locations were used in defining vertical and horizontal heterogeneity, as well as trends in porosity and permeability distribution at parasequence scale (Table-1).

MMC-I reservoir was deposited in a cyclic pattern due to sea level fluctuations within highstand systems tract (HST). The well log signatures display three depositional packs, which on finer scale can be divided into six fairly correlatable units A, B, C, D, E and F, from top to bottom, across the field. Thin shale bands of 0.5 to 2m separate each unit (Figure-7).

The lower pack consists of unit F and E, composed of mudstone and wackestone facies, and is capped by carbonaceous shale. This represents low energy shallow lagoonal environment. The middle pack comprising unit D is represented by packstone/wackestone facies, deposited in high-energy environment. The upper pack comprising units C, B and A depicts deposition in low to moderately high energy environment, in response to low amplitude-high frequency sea level fluctuations, resulting into intercalation of wackestone/packstone followed by mudstone and shale in ascending order.

Reservoir Evaluation

Reservoir has been evaluated using well logs, core data and seismic attributes, and the conclusions validated with reservoir and production data. The influence of facies architecture and structural style on reservoir properties is described below:

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Interval (m)	Litho-facies	Lithology	Depositional environment	Reservoir Properties			
				Phie (%)	KHz (mD)	Kv (mD)	Swi (% of Pore volume)
971.35-971.50	Unit-C	Mudstone	Low Energy	11.5	4.6	1.4	
972.33-972.48	Unit-C	Wackestone	Moderate-High Energy	22.0	4.6	1.3	
973.63-973.75	Unit-C	Mudstone	Low Energy	13.7	8.6	2.4	
974.68-974.83	Unit-C	Mudstone	Low Energy	22.6	9.2	2.5	
974.93-975.09	Unit-C	Mudstone	Low Energy	8.6	1.3	0.2	
975.58-975.73	Unit-C	Wackestone	Moderate Energy	24.0	8.9	4.0	50.0 (UOR-52.5%)
976.30-976.48	Unit-C	Packstone/ Wackestone	High-Moderate Energy	29.3	54.4	1.5	
976.58-976.68	Unit-C	Packstone	High Energy	27.7	11.7	6.1	
977.13-977.28	Unit-C	Packstone	High Energy	23.4	21.0	4.4	
977.83-977.98	Unit-C	Packstone	High Energy	30.0	61.0	28.5	36.3 (UOR-53.0%)
979.63-979.75	Flooding surface	Calc. shale	Low Energy	29.8	15.1	2.7	
981.17-981.32	Unit-D	Mudstone	Low Energy	17.1	1.4	0.2	
982.87-982.97	Unit-D	Mudstone	Low Energy	16.7	2.8	1.2	
983.06-983.10	Unit-D	Wackestone	Moderate Energy	26.0	2.0	1.1	50.0 (UOR-51.0%)
985.77-985.89	Unit-D	Packstone	High Energy	37.8	328.0	7.5	
987.27-987.45	Flooding surface	Carb. Calc. shale	Low Energy	27.8	70.9	9.7	
991.50-991.66	Unit-E	Wackestone	Moderate Energy	25.5	14.7	0.3	
991.66-991.76	Unit-E	Packstone	High Energy	28.4	-	8.2	37.7 (UOR-57.0%)
992.15-992.30	Unit-E	Wackestone	Moderate Energy	21.0	2.7	1.2	
995.50-995.60	Unit-F	Wackestone	Moderate Energy	25.3	5.9	1.8	
Phie-Porosity, Kh& Kv- Horizontal and vertical permeability, Swi- Irreducible water saturation, UOR- Ultimate oil recovery							

Table-1: Core derived reservoir data and analysis of well Z1 located updip displaying the impact of facies architecture on reservoir properties.

Facies Influence

Facies and core description (Table-1) demonstrates the cyclic nature of deposition, due to sea level fluctuations resulting into deposition of varying lithology within a unit. This change in lithology has influenced reservoir properties and eventually the capacity of fluid flow. Variations in horizontal and vertical permeability (Figure-8) even within the rock mass deposited under similar energy regime are common due to sparatization caused by diagenesis, destroying porosity (Figure- 9).

Core description also affirms that wherever the rock type is clean like packstone, displaying high porosity, good Kh and moderate to poor Kv, the productivity of the reservoir is better, but soon they become conduit for water, when injection is initiated. The whole of updip area is characterized by this kind of reservoir properties/behaviour.

X-ray diffractrometry on core samples and NGS log interpretation shows that MMC-I reservoir contains mainly Montmorilonite clays (Figure-10) and are dispersed in matrix. These clays have a tendency to swell on coming in contact with drilling mud and/or injection water, adversely affecting the permeability and productivity (Thomas, 2001). It has further been observed that performance of the reservoir deteriorate when clay volume is more than 12% of total rock volume, and becomes extremely poor beyond 14%.

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Faults Influence

Reservoir is segmented into number of fault blocks as a result of interaction of NNW-SSE and NE-SW trending faults (Figure-6). Some of the faults are of sealing nature, while others are non-sealing type. Faults have played a very significant role on:

- Reservoir compartmentalization
- Vertical and lateral distribution of hydrocarbons within fault compartments
- Communication across faults, and
- Movement of fluids during production and injection

The composite map of He/Hg (effective to gross thickness ratio), Vclay distribution (Figure-11 & 12) and seismic attributes depicts a good coherence between structural configuration, reservoir facies and hydrocarbon distribution. Sealing and non- sealing nature of the faults and presence of fractures have influenced the hydrocarbon distribution and fluid flow. It has also been observed that water cut is not governed by one particular flow unit; rather the whole reservoir is affected due to network of faults and associated fractures offering preferential paths to injection water (Figure-13).

Future Strategies for Revitalization of Reservoir

To improve recovery and contain unwanted water production, focus is placed on areas 1) likely to retain un-swept oil, 2) flooded with injection water, and 3) having few completions. It has been worked out by superimposition of reserves and recoveries, on property maps. This approach has helped in placing the strategy for infill drilling at appropriate locales, optimization of water flooding and strategic completions (Figure-14).

Conclusions

- Heterogeneity of MMC-I is linked to cyclic depositional pattern due to sea level fluctuations, structural style, and type of clay and its distribution in space
- Better porosity development and related permeability is controlled by post depositional phenomenon due to diagenesis creating solution channels/vugs, and tectonic activities causing fractures. Destruction of porosity is also noted at places due to sparatization
- The present day structure is a result of extensional deformation. The structural elements have segmented the MMC-I reservoir into numerous compartments. Faults have played a role in hydrocarbon distribution and entrapment, yielding different oil-water-contact (OWC), non-uniform pressure depletion, and variations in water cut
- The temporal and spatial distribution of reservoir properties vis-à-vis Initial volume of hydrocarbons in each fault block together with cumulative production has led to identification of potential sectors of un-swept / bypassed hydrocarbons
- A detailed understanding of the structural style, depositional facies architecture and distribution pattern of clays have led to better understanding of the reservoir to facilitate improve recovery

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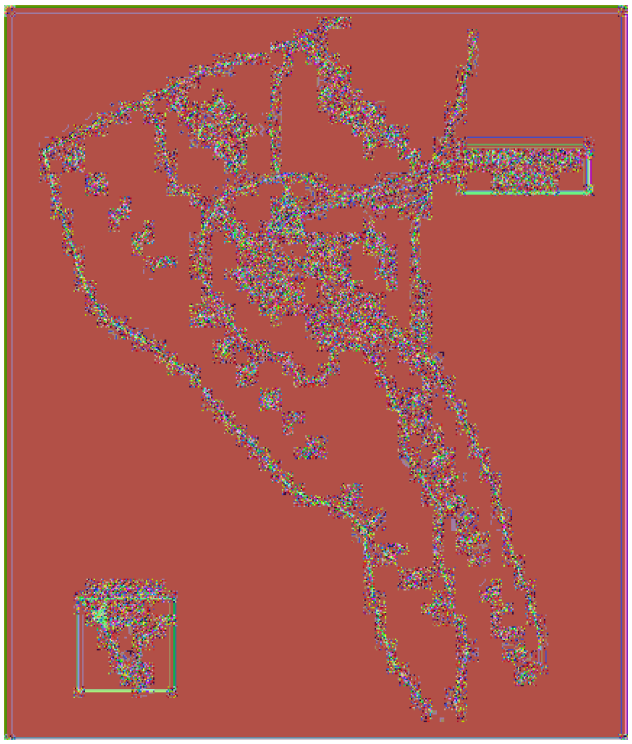

Figure 1: Location map of Mumbai high field.

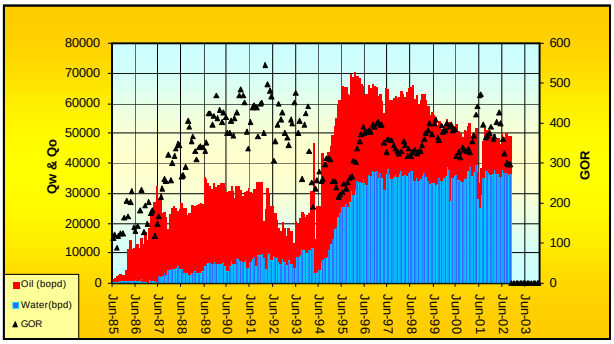

Figure-2: Production performance of MMC-I reservoir.

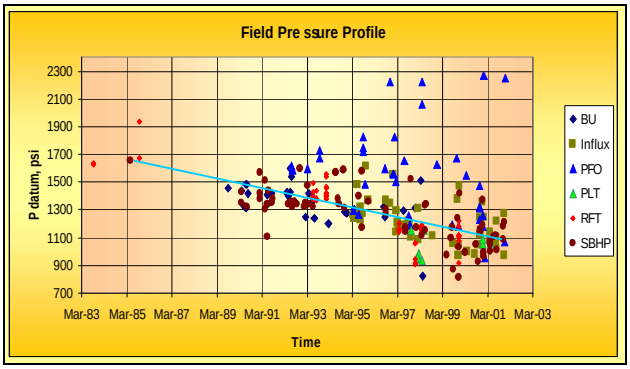

Figure-3: Pressure profile of MMC-I reservoir.

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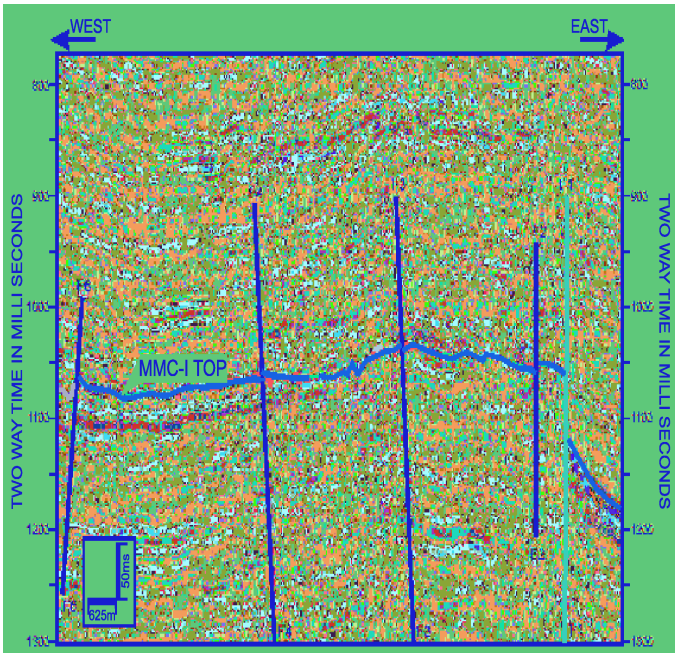

Figure 4: 3D inline seismic section passing through central part (near well Z1) showing major faults.

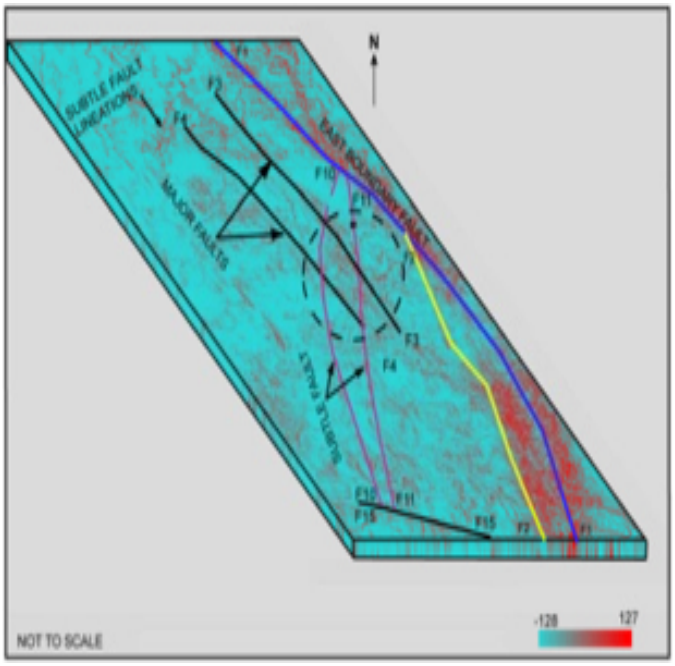

Figure5: 3-D seismic derived coherency (variance) at the top of MMC-I showing some major and subtle faults. Structural discontinuities are seen within the circle in the central part towards updip, which are interpreted as minor fractures (red colour). The presence of fractures is supported by core data and production behaviour of the wells located within this area.

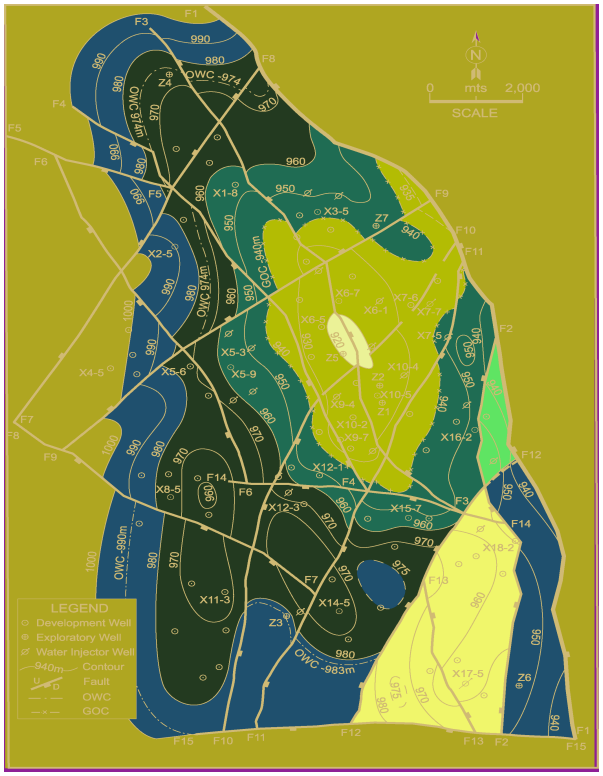

Figure 6: Depth map at the top of MMC-I reservoir.

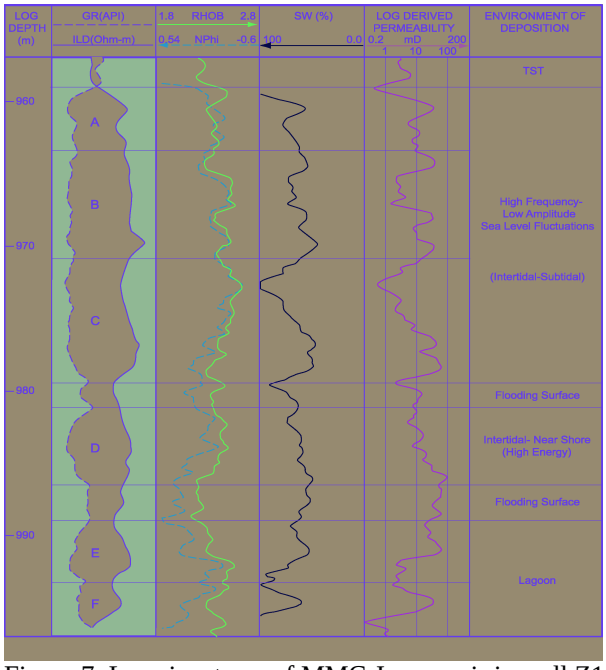

Figure 7: Log signatures of MMC-I reservoir in well Z1 located updip depicts how varied depositional environments have influenced the facies architecture and reservoir properties. The variations in permeability have greater effect on fluid dynamics throughout the reservoir. Note- see this figure along with Table-1

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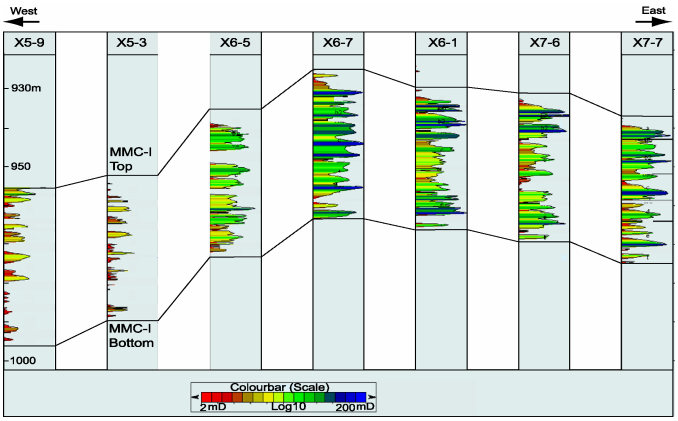

Figure 8: Log derived permeability distribution within MMC-I reservoir along dip showing vertical heterogeneity. Note- low permeability towards downdip, good permeability in updip, and very high permeability (blue colour) corresponds to solution channels/vugs and fractures.

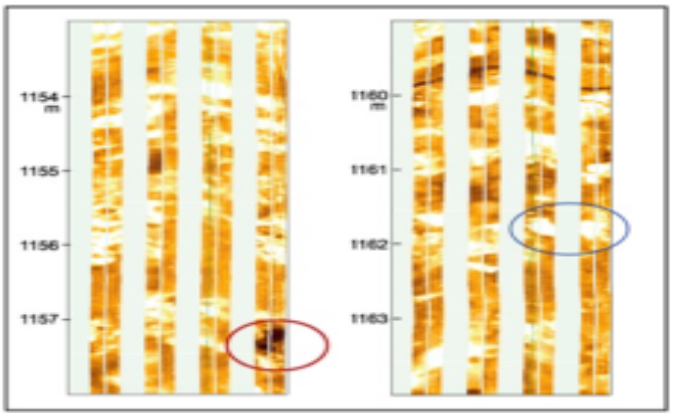

Figure 9: FMI log of X7 series well showing preservation and destruction of vuggy porosity. Red circle depicts preservation of vugs, whereas blue circle depicts destruction of vugs due to sparatization.

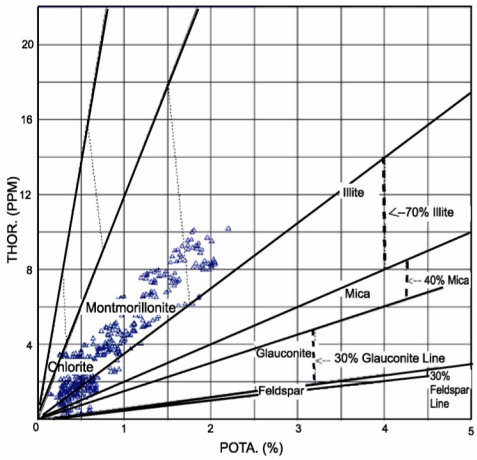

Figure 10: Clay mineral identification through NGS cross lot (Thorium Vs Potassium) of well X16-2. Montmorillonite is the main clay mineral.

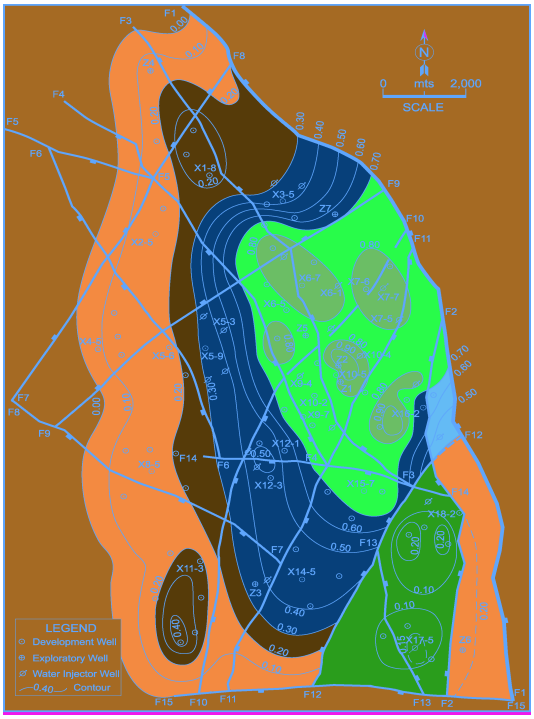

Figure 11: Effective/Gross thickness (He/Hg) ratio map depicting reservoir heterogeneity. Reservoir is less heterogeneous towards updip, and becomes extremely poor when He/Hg ratio falls below 30%.

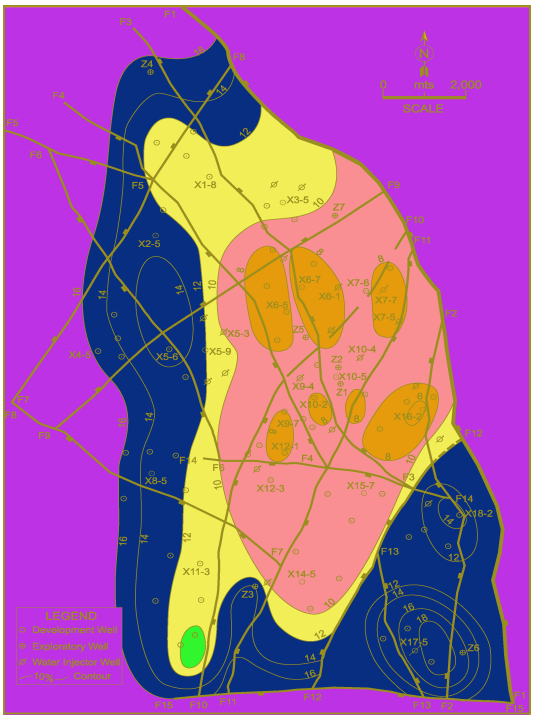

Figure 12: Average Vclay distribution within MMC-I reservoir influencing the reservoir quality. Deliverability of the reservoir is good upto 10% Vclay. Reservoir becomes extremely poor when clay volume increases beyond 14%.

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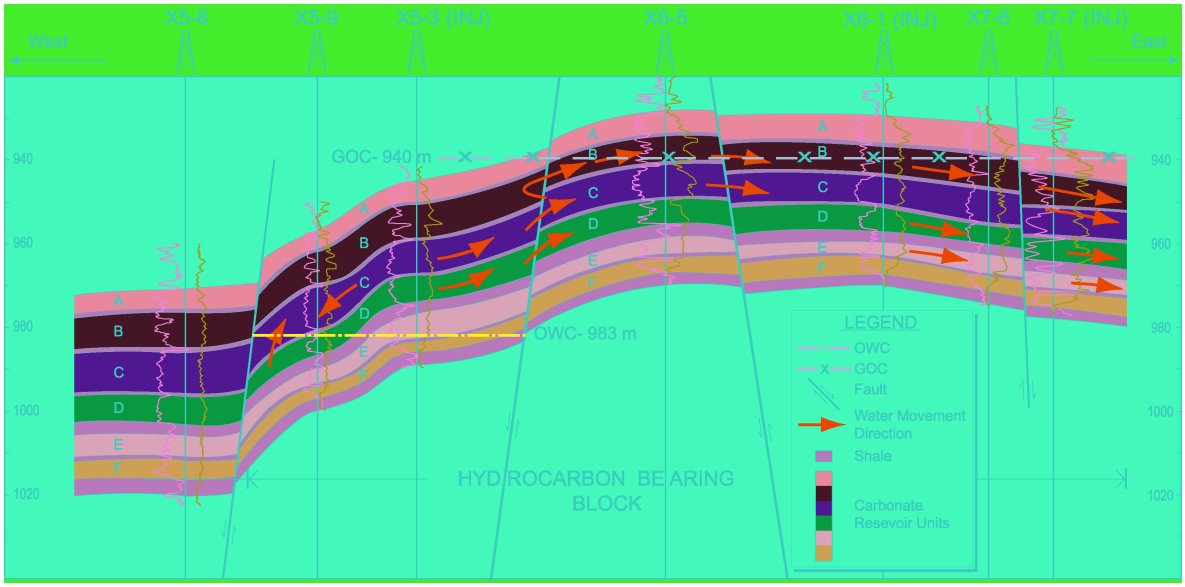

Figure 13: Geological cross section along dip showing deterioration in reservoir properties from east to west. Also, depicting role of structural elements in entrapment of hydrocarbons and water movement in MMC-I reservoir

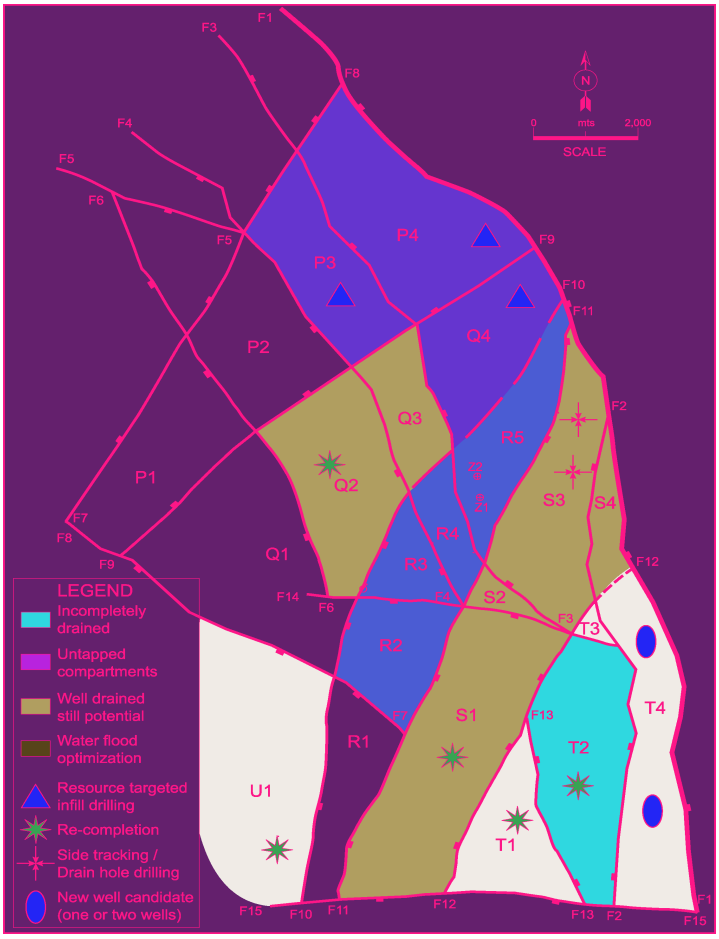

Figure 14: Multi-faceted portfolio of improved recovery opportunities resulting from integrated reservoir characterization of MMC-I reservoir.

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