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Lithobiostratigraphic Correlation and Paleoenvironment of Hazad Pays in Eastern Part of Jambusar – Broach Block, Cambay Basin

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Summary

In Jambusar-Broach block there are numbers of hydrocarbon bearing pays in Hazad member of Ankleshvar Formation that form NE-SW and E-W prograding delta lobes. Due to persistent sediment supply and changing coast line during deposition of Hazad Member under a normal regressive set up, the overall geometry of sand lobes has wide lateral spread. Towards the NE part of Gandhar field and close to eastern rising flank, younger Hazad pays are inconspicuous due to poor development resulting in ambiguity in their correlation and nomenclature. A biostratigraphic approach based on biochronohorizons as bounding surface within Ankleshwar Formation has been adopted for correlation and depositional model of GS units have been proposed in the area covering NE Gandhar, Jambusar, Gajera, Amod, North Sarbhan, Matar, Dabka and Kural. A dichronous and persistent hiatus spanning 2 MY(51/49 MY) equating C II 30 has been mapped between the YCS and Hazad Member across basin as evident by absence of GS-1, 2 and 3 units. Similarly, the top of Hazad Member is dated 44MY (Middle Eocene) marking the onset of transgression (44-42 MY) represented by Kanwa shale. To establish correlatibility with in Hazad Member, eleven flooding surfaces recognized in well G#CI and tide across to propose micro level genetic correlation of GS units. The depositional model of GS-4 and 5 units indicate a N-S trending narrow prograding delta lobe which further spreads out towards east and west depositing GS-6 to 9 units, prominent being along the wells G#CI, EFF & EB. There is to a certain extent restriction in delta development during GS-9 and 10 due to paucity of sediments supply. A prominent tidal flat has developed in the area during deposition GS-12 unit, as evident from increasing argillaceous facies, occurrence of coal and restricted development of sandstone in G#CI & EB as being deposited as tidal channel. The study is helpful in standardizing the biohorizons and flooding surfaces, and establishes litho-bio correlation in the area for delta modeling.

Keywords: Cambay Basin, Data Interpretation

Introduction

The Broach depression in southern Cambay Basin lies between Dadhar River in the north and Narmada River in the south. The depression initially developed at the end of the Mesozoic simultaneous to the formation of Cambay graben. Rapid sedimentation during the Paleogene, topped with deltaic sequence acted as basin fill and renewed active subsidence with slight eastward shift in the depocenter during the Neogene. The rising flanks of this depression developed into suitable locale for potential hydrocarbon accumulations. Due to development of multiple reservoirs within the Paleogene section, the area remained prospective for active hydrocarbon exploration. After the recent discoveries in Matar and nearby areas towards the north, a number of prospects were explored for their hydrocarbon prospectivity. Gandhar field represents a combination trap on the northwestern rising flank of Broach depression, wherein updip wedging of deltaic sand units of Hazad Member have entrapped large accumulation of hydrocarbons. The Hazad member has 12 main sand units (GS1-12) and these are further subdivided into 19 sands mainly on the basis of electrofacies correlation and their production testing data suggest that these sands have different hydrodynamic continuities. Out of the 12 main sand units, the GS-7 and 10 have not been found hydrocarbon bearing. From the electrofacies correlation, it appears that most of these sand bodies are fairly continuous and spread over a large area. However, the fluid distribution and integrated seismic analysis suggest that majority of Hazad sands are of discontinuous nature, thus, it becomes significant to establish the exact geometry of these pay sands for successful exploration and development.

Objective

The objectives of the study is dating and demarcation of litho-biofacies to establish depositional environment and correlatibility of pay zones of Hazad sands in the area

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covering North Gandhar, Jambusar, Dabka, Matar, Amod, Kural, Gajera and N. Sarbhan fields.

Material and Method

The laboratory data from twenty two wells have been considered to establish biostratigraphy and paleodepositional environments of Hazad sediments and integrated with electologs and basic principles of sequence stratigraphy for correlation and in combination with process sedimentology to understand the depositional setup and distribution patterns of the pay sand units.

General Geology and Stratigraphy

The Paleogene succession of the area under investigation has been classified into Olpad, Cambay, Anklesvar, Dadhar and Tarkeshvar formations in ascending order. The subsurface stratigraphic classification proposed by Pandey et al., (1993) is followed.

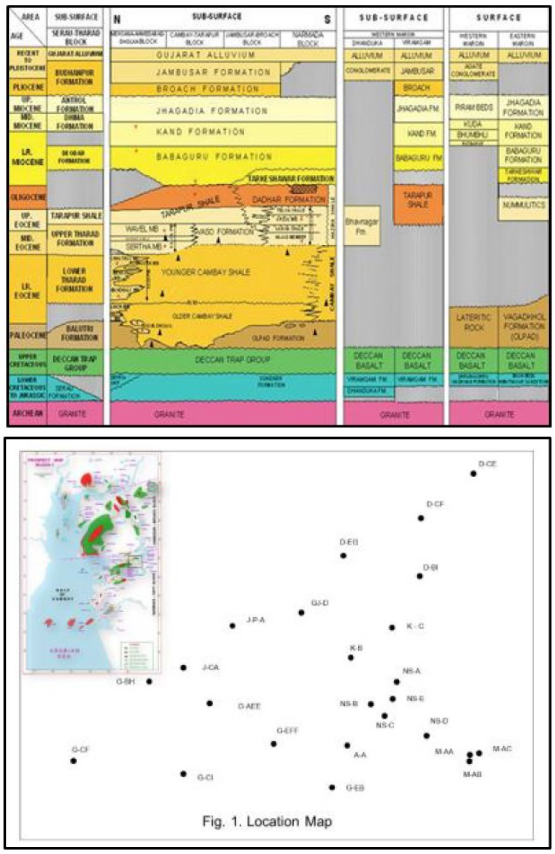

Fig.1: Generalized Stratigraphy (after Pandey et al., 1993) and location map

Biostratigraphy and Sequence Stratigraphy

On the basis of integration of laboratory data, electrolog facies, flooding surfaces within chronostratigraphic framework the correlation of pay sands have been standardized (Table-2). The biochronostratigraphic studies based on foraminifera and dinoflagellates cysts events; the top of Early Eocene has been established on the basis of last occurrence datum (LAD) of *Nummulites burdigalensis, Glaphyrocysta ordinate(51MY) and Hystrichosphaeridium tubiferum(49MY).* These events suggest a hiatus of 2MY at the top of Early Eocene. The LAD of dinoflagellate cyst species *Muratodinium fimbriatum* marks 44 MY, at the top of Hazad Member and LAD of *Apectodinium homomorphum* marks 42 MY at the top of Kanwa Shale Member, while the top of Ardol Member is marked by the LAD of Lentenia *serrata* marks 37MY while the Telwa Member top is marked by LAD of *Homotryblium tenuispinosum* which marks 36MY. Based on these events the Hazad Member is dated 49-44MY, Kanwa 44-42MY, Ardol 42-37MY and Telwa 37-36MY in age.

The hiatus at the top of Early Eocene spans 2 MY. Parakh et al., (2007) named this unconformity as C II 30, a second order sequence boundary. The integration of this sequence boundary with the electrolog facies suggest that this unconformity lies at the bottom of GS-4 in well G#BH, CF, CI, AEE & EFF, A#A, J#CA and J-P-A. In well G#EB this unconformity marks the bottom of GS-5, while in wells of North Sarbhan, Matar, Gajera, Kural and Dabka fields to the NE and E (up dip) the unconformity has been marked at the bottom of GS-6. In the wells of Dabka and Gajera the integrated studies suggest another hiatus at the top of Hazad Member spanning approximately 2 MY (from 46-44MY) representing the absence of GS9-12 in the area. The upper contact of the Hazad Member is marked by a transgressive Kanwa Shale Member, is considered as MFS without any break in sedimentation in main Gandhar Field.

To understand the correlatibility of these sands eleven flooding surfaces have been identified in well G#CI and are tied across the study area with biochronohorizon, to attempt construction of micro level genetic sequences. The C II 30 extends in the north eastern rising flank of Broach depression and that forms the base for Hazad sedimentation though in the study area only GS 4-12 are developed. These Flooding Surfaces (FS) are named as per international convention i.e. FS 10, 20, 30……..110. Total 11 FS's have been recognized. In the area FS-30 marks the top of Cambay Shale in well G#CI, BH, AEE, EFF, A#A,

J#CA, and J-P-A, FS-40 in G#EB and GJ#D. In North Sarbhan, Matar, Kural and Dabka fields FS-50 marks the top of Cambay Shale (Table -3).

The depositional patterns of these sequences suggest that the Hazad Member may have been deposited in low stand normal regressive set up (Fig.17) in which the younger sediments keep onlapping the unconformable surface and above this surface the Hazad sediments are deposited as Low Stand Normal Regressive aggradation followed by a transgression represented by Kanwa Shale.

Lithofacies, Texture and Depositional Model of Hazad Sands

The Hazad member is classified in to 12 major Gandhar sand units (GS) namely GS-1 to GS-12 in ascending order. There is inconsistency in development and distribution of these sand units in the area NE of the Gandhar field, in Jambusar, Gajera, Dabka, North Sarbhan, Kural, and Matar fields towards the eastern margin (Table-1). The overall distribution of the sediments suggests development of a constructive, lobate delta with occasional influence of tidal currents in the proximity to the coast. The depositional model of these sands to the south of the study area (Pandey et al., 1989,) is in geometric conformity to the present area. Due to very high sediment supply and relatively limited accommodation there is wide variation in the sand characteristics and geometry of the GS units. In the study area, the development of GS units and its equivalent starts from GS-4 as the oldest unit. The underlying GS-1, 2 & 3 units are mostly argillaceous and indistinguishable from the underlying Younger Cambay shale (YCS). The integration of lab data and electrologs resulted in process response depositional model of the GS units and understanding their extension due south. The demarcation of each GS units has been rationalized based on the flooding surfaces and micro genetic sequences and with WCR, log characteristics, principle of deposition of deltaic sedimentation. For the construction of depositional models of the sand units, their correlation based on lithological, biostratigraphic, electologs facies and bounding surfaces represented by flooding surfaces have been considered. The electrolog facies identification has helped in recognition of depositional sedimentary facies and subsequently these facies have been analysed and related with process sedimentology for inferring the depositional setup and constructing the depositional model. The distribution of each GS units is tabulated in Table-2. The petro facies description and depositional environment is discussed below:

Table- 1. EFFECTIVE SAND THICKNESS

WELLS	GS-4	GS-5	GS-6	GS-7	GS-7+8	GS-8	GS-9	GS-10	GS-11	GS-12
G-BH	2	1(silty)	6	2		2	9	4	3	
G-AEE	5	5	4		5		3	3	6	
G-EFF	5	2	5		14		9	4	4	4(coal)
G-CI	5	5	7		22		5	6	5	8
A-A			6	4		2	5	4	9	2
J-CA	3	4	5			2	4	2	3	
J-P-A	4	4	5							
G-EB			8		17		5	8	8	3
K-C			5	2		5	2(silty)	4	2(silty)	2(silty)
GJ-D			5			3				
K-B			3	3		2	2	4	2(silty)	
D-BI			3			3				
D-EG			4			3				
NS-A				silty		2	4	2(silty)		
NS-B			7	2(silty)		5	2	silty		
NS-C			4	1(silty)		1(silty)	2	silty		
NS-D			2(silty)	2		9	3	1(silty)	2	2(silty)
NS-E			2	silty		5	3	silty		
M-AA				4		3	4		2	
M-AB				5		2	4		5	
M-AC				3		2	2		1	
D-CE			3			8				
D-CF			4			2				

Table-1: Effective sand thickness

TABLE - 2: CORRELATION OF GANDHAR SAND UNITS (all depth are log depths)

WELLS	GS-4	GS-5	GS-6	GS-7	GS-7+8	GS-8	GS-9	GS-10	GS-11	GS-12
G-BH	2636-53	2624-30	2608-18	-	2593-2606	-	2575-91	2542-47	2528-35	-
G-AEE	2631-40	2619-26	2599-2608	-	2575-2594	-	2567-73	2557-63	2540-48	-
G-EFF	2628-35	2619-21	2611-19	-	2592-2610	-	2575-90	2565-72	2555-60	2542-52
G-CI	2964-61	2943-28	2907-26	-	2875-2904	-	2866-75	2848-63	2836-47	2823-33
A-A	-	-	2414-23	-	2404-13	-	2387-2400	2374-84	2346-72	2341-44
J-CA	2543-59	2531-40	2505-16	-	-	2492-95	2472-87	2454-58	2443-48	-
J-P-A	2318-27	2304-10	2292-2302	-	-	-	-	-	-	-
G-EB	-	2572-77	2559-71	-	2538-58	-	2527-35	2506-18	2492-2503	2485-90
K-C	-	-	1783-90	-	1762-80	-	1745-50	1732-43	1727-30	1719-24
GJ-D	-	-	2131-38	-	-	2119-29	-	-	-	-
K-B	-	-	2082-89	-	2066-75	-	2057-62	2044-53	2036-40	-
D-BI	-	-	1552-55	-	-	1542-49	-	-	-	-
D-EG	-	-	1646-51	-	-	1638-45	-	-	-	-
NS-A	-	-	1985-89	1981-84	-	1972-77	1969-65	1951-54	-	-
NS-B	-	-	2022-30	2018-21	-	2002-15	1994-2000	1987-90	-	-
NS-C	-	-	2042-49	2035-38	-	2026-31	2018-23	2014-17	-	-
NS-D	-	-	1997-2000	1992-95	-	1975-89	1966-73	1961-65	1956-61	1952-55
NS-E	-	-	2001-05	1995-99	-	1985-93	1970-76	1962-65	-	-
M-AA	-	-	1778-85	-	1759-74	-	1750-58	-	1723-25	-
M-AB	-	-	1793-97	-	1773-85	-	1764-71	-	1753-58	-
M-AC	-	-	1770-79	-	1757-68	-	1749-55	-	1743-45	-
D-CE	-	-	1070-75	-	-	1058-68	-	-	-	-
D-CF	-	-	1429-34	-	-	1425-27	-	-	-	-

Table-2: Correlation of Gandhar sand units

Table - 3: CORRELATION OF FLOODING SURFACES (all depths are log depths)

FS	30	40	50	60	65	70	80	90	100	110
G#BH	2624	2607.5	2605	2595	2588.5	2574.5	2562	2549	2541	2525
G#AEE	2640.5	2626	2619	2611		2596	2574	2566.5	2551	2537
G#EFF	2640	2621.5	2618	2611		2591	2571	2562	2552.5	2540
A#A	2424	2406.5	2403	2394	2380.5	2373	2364	2354	2342	2337
NS#D	-	-	2005	1997	1991	1973.5	1965.5	1958	1955.5	1950
M#AC	-	-	1786.5	1784.5	-	1772	1767	1763	1759	1752
J#CA	2559	2536.5	2531	2504.5	2492	2471.5	2460	2453	2442	2425
J-P#A	-	-	2327.5	2314	2304.5	2298.5	2291.5	2282	2270	2255
NS#B	-	-	2031	2021	2017.5	2005	1990	1985	1982	1977.5
NS#E	-	-	2006.5	1996.5	1993	1977	1965	1962	1957	1950
GJ#D	-	-	2154	2141.5	2130.5	2126	2119	2110	2098	2081
K#C	-	-	1793.5	1771	-	1755	1743	1736	1725	1711
G#CI	2965	2946.5	2942	2905	-	2877.5	2864	2848	2835	2823
K#B	-	-	2101	2092	-	2071	2056.5	2046	2040	2028
D#BI	-	-	-	1551	-	1541	-	-	1541	1528
G#EB	-	2577	2571	2559	-	2536.5	2526.5	2505	2490	2476
NS#C	-	-	2650	2639.5	-	2025	2017	2012	2005	1998
NS#A	-	-	1991	1984	-	1965	1959	1954	1950	1941
D#EG	-	-	1652	1646	-	1638	-	-	1638	1630
D#CE	-	-	1075	1069	-	1055.5	-	-	1055.5	1046.5
M#AB	-	-	1787	1777.5	-	1767	1763	1760	1752	1750
M#AA	-	-	1776.5	1765.5	-	1754.5	1750	1745.5	1741.5	1740
NS#D	-	-	2005	1997	-	1973.5	1965.5	1958	1955.5	1991
D#CF	-	-	1433.5	1429	-	1425.5				

Table-3: Correlation of flooding surfaces

Gandhar Sand Unit (GS): 1, 2 and 3

The Gandhar sand (GS) 1, 2 and 3 units have limited distribution away from the main Gandhar field and in the

study area the Younger Cambay Shale (YCS) is directly overlain by GS-4 or younger units. In the southern proximity to the study area in well G#EFF, the GS1, 2 & 3 equivalent units are silty sandstone and shale and are very poorly developed. To the south of G#CF & CI there is gradual development of GS1, 2 & 3 units with pinch out line passing in between. The overall distribution of the three units suggest a EEN-SSW trending prograding delta lobe (Pandey et al, 1989) developed in south where there is distinct shift of sediment lobe towards south from GS1 - GS2, the latter having relatively poor development. The main delta building commenced during GS-3 unit, when the northern lobe of the delta covered the southern part of the area close to G#CI & CF and also further progradation westward (Fig.2).

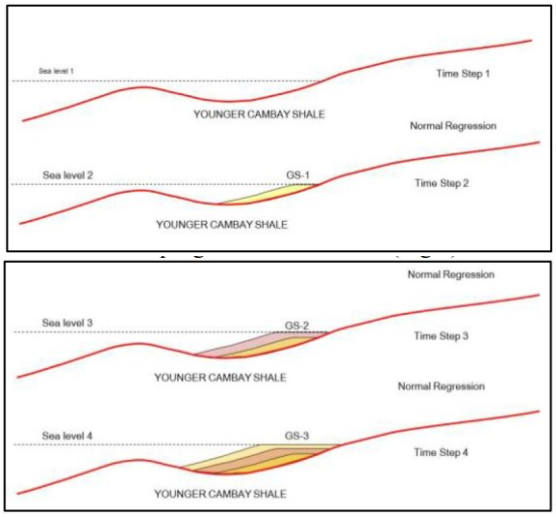

Fig. 2: Conceptual sequence stratigraphic (SS) forward modeling of time step 1-4

Gandhar Sand Unit (GS): 4

The GS-4 unit is widespread and developed mostly in the deeper part of the Gandhar field. The unit is developed within a narrow north-south oriented corridor in the study area in wells G#CF, BH, CI, AEE, & EFF, J#CA and J# P-A (Table-2). The thickness ranges from 7-15m. Its development in eastern part in Gajera, Kural, Dabka, Matar and N. Sarbhan fields is poor and absent may be due to gradual topographic relief and falling away from the depositional axis. In well G#CF, the GS-4 (2889.5-2898m) comprises thin sandstone with grey-dark grey, fissile shale. The sandstone is light grey to dirty white, medium - fine grained, subangular to subrounded, moderate the well sorted, dominated with argillaceous matrix. In G#CI it is well developed showing a typical CU followed up by FU logpattern separated by grey shale, the sand stone at the bottom is medium to fine grain, moderately sorted having argillaceous matrix. The upper lobe has got similar characteristic grading into conspicuous shale. Development in J#CA and G#BH is very poor probably forms the flank of prograding deltaic lobe.

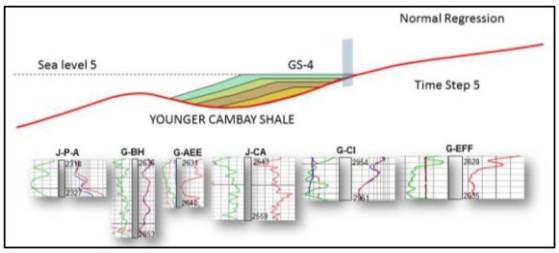

Fig.3: Conceptual SS forward modeling time step 5.

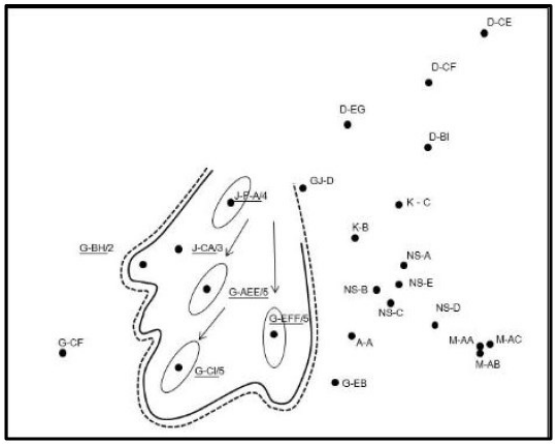

Fig. 4. Depositional Model of GS-4 unit

In well G#EFF, the GS-4 (2628-2635m) comprises dirty white, medium to fine grained, subrounded, moderately sorted sandstone having calcareous cement interbeded with shale. In G#AEE, GS-4 (2631-2640m) comprises moderately sorted, medium to fine grained sandstone interbedded with grey to dark grey, fissile shale and with interlaminations of siltstone. In both the wells, G#AEE and J#P-A, the GS-4 unit shows coarsening up (CU) mouth bar/ channel lobe facies with minor shale laminae. In well G#EFF, is better developed medium-coarse grain well sorted sandstone, argillaceous towards the top, poor and sand: shale ratio is very low. There is poor development of this unit in A#A suggest that the well does not fall in the path of the prograding delta lobe. This unit is not developed in Dabka, N. Sarbhan, Matar, Kural and Gajera area (Fig.3&4).

Gandhar Sand Unit (GS): 5

The GS-5 unit is divisible into three subunits namely 5A, 5B and 5C, separated by the shale. GS-5 unit has been cored in well J#P-A(CC#1:2305.5-2313.7m) comprises medium to fine grained sandstone with discontinuous laminae of carbonaceous matter in top 3m whereas the bottom portion is poorly fissile shale, thereby exhibiting a typical CU lithofacies. This unit is well developed in J#P-A, J#CA, G#AEE, CI, EFF & EB from north towards south. In well G#EFF(2619-2621m) it comprises moderately sorted, feebly calcareous and fine grained sandstone. In well G#EB(2572-2577m) comprises of silty sandstone that is medium to fine grained and sideritic towards top. In G#BH, this unit (2624-2630m) comprises sandstone interbeded with shale and towards bottom is silty. In G#AEE, the GS-5 (2619-2626m) comprises argillaceous sandstone interbeded with shale towards bottom and top it is medium grained.

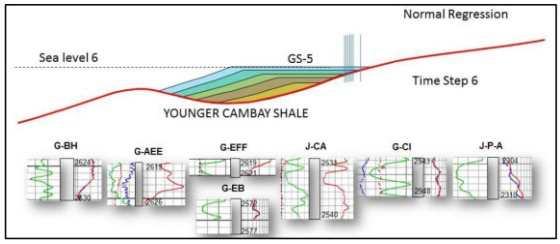

Fig.5: Conceptual SS forward modeling time step 6.

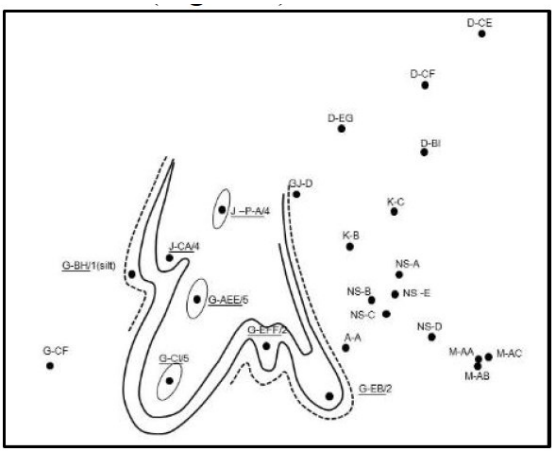

Fig. 6. Depositional Model of GS-5 unit

There is overall CU or multiple stacking of the facies. The sandstone is fine to medium grained moderately sorted having minor shale in between at times the prograding lobe is cut by distributary channel (G#AEE). The unit is depositedas distributary channel mouth bar sands at times cut by channel (G#AEE) indicate an overall prograding lower delta plain towards south in G#CF,CI,EB. The area covering Gajera, Kural, N. Sarbhan, Amod and Matar does not have development of GS-5 sand (Fig.5&6).

Gandhar Sand Unit (GS): 6

The GS-6 unit is divisible into GS-6B and 6A sub units in main Gandhar field. The unit is light to medium grey, medium to fine, at times coarse grained, moderately sorted sandstone. The microfacies is mainly quartzwacke and quartz arenite. The sandstone show minor specks and scales of carbonaceous matter and bioturbation. It is developed over the entire study area, suggesting advent of main delta building activity. Barring very silty nature of the facies in NS#C and marginal development in A#A, the unit having both CU lithofacies, aggradation and at places followed up by FU depicting a channel. In G#CF, GS-6 (2864-2875m) comprises of sandstone intercalated with shale. Towards NE, in G#BH, GS-6(2608-2618m) sandstone comprises of dirty white, fine grained, rounded to sub rounded, well sorted, dominated with transparent quartz grains inter beded with grey to dark grey, moderately fissile shale. In G#AEE, GS-6 (2599-2608m) is divided into GS-6A in the bottom interval and separated by shale in the top interval as GS-6B, is fine grained, subrounded to subangular, moderately sorted and dominated with transparent quartz grains which are gradationally changing to medium to fine grained in the top part. In G#EFF, this unit (2611-2619m) has been cored (CC#4: 2607-2613.30m) comprised of argillaceous sandstone towards bottom and sandstone towards top having thin shale intercalations. In well G#EB, GS-6 (2559-2571m) comprises of medium to fine grained, moderately sorted sandstone interbeded with shale. In well A#A, GS-6 (2414-2423m) comprises of dirty white, medium to fine grained sandstone. In Dabka field the GS-6 equivalent facies is Dabka Lower Pay. In D#CF, this unit (1429-1434m) has been cored as CC#1(1429.65-1438.65m) comprised of fine to medium grained calcareous sandstone at the bottom followed by sandstone with higher clay matrix and occasional siderite grading up further in to burrowed siltstone and finally shale, indicating a typical FU. In D#EG, both lower pay (1646-1651m) and upper pay (1638-1645m=GS-8) are developed and has been cored (CC#1:1640.50-1649.5m), is non-calcareous siltstone with argillaceous matrix towards bottom and grades upward into medium to fine grained, sandstone with carbonaceous matter and calcareous cement. In between there is fissile shale having lenticular sandstone and followed up by sandstone at the top, suggesting CU. In K#C, GS-6 (1783-1790m) comprises of sandstone is dirty

white, fine to coarse grained, subrounded to subangular, moderate to poorly sorted, rarely calcareous. In well NS#D, GS-6 (1997-2000m) comprises of medium to fine grained sandstone is moderately sorted, having argillaceous matrix. In M#AA, GS-6 (1778-1785m), M#AB, GS-6 (1793-1797m) and M#AC, GS-6 (1770-1779m) comprises of sandstone of dirty white, yellowish, fine to coarse grained, sub rounded to sub angular, moderate to poorly sorted, interbeded by grey to dark grey, poorly fissile, non-calcareous shale with disseminated pyrite.

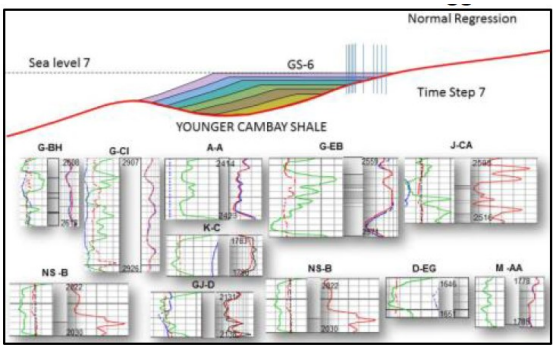

Fig.7: Conceptual SS forward modeling of time step 7

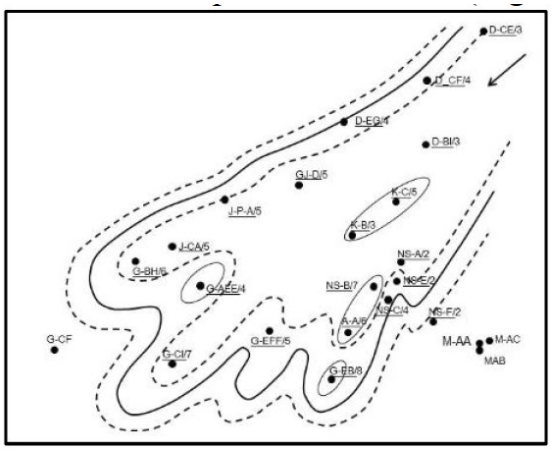

Fig. 8. Depositional Model of GS-6 unit

The distribution of GS-6 suggests widespread development of the prograding delta lobe with slight swing in input direction towards NE. In NS#C, the facies is more argillaceous. In A#A basal part shows CU followed up by shale and silty shale probably suggest a crevasse splay. Overall along the main axis there is better development of sandstone gradually deteriorates towards flanks in the east in A#A, NS#C. The log characters in the central part show CU as mouth bar and stacked pattern due to aggradation. There is a significant development of sandstone in east in Matar field interpreted as separate delta lobe. The increase in argillaceous matrix, presence of siderite, rare carbonaceous laminae and burrows suggest that area had been subjected to tidal action at periodic interval (Fig.7&8).

Gandhar Sand Unit (GS): 7

The development of GS-7 unit is mainly confined in the central part of the study area and is best developed in wells G#CI, EB, EFF, A#A and K#C and B. The unit is poorly developed in G#BH, CA, AEE, NS A, B, C and E . There is probably a separate lobe in Matar field having moderate development in M#AA, AB &AC and NS#D. In the Gandhar field the GS-7 and 8 units have often been taken as one unit (GS-7+8) in view of poor development of parting shale. In well G#EFF, CC#4 ((2607-2613.30m) comprises of light grey to dirty white, medium to fine grained with coarse grains sandstone in the interval (2608.65-2607). In well G#EB in CC#2 (2544-2552m) the bottom portion is made up of medium to coarse grained sandstone is moderate to poorly sorted, having calcareous cement and followed up by relatively fine grained sandstone having the wavy and cross laminations with thick laminations of dark grey, moderately fissile shale. The stacking pattern reflects an incomplete channel fill sequence. In A#A, GS-6 (2414-2423m) and 7+8 (2404-2413m) has been taken together and comprises coarse to medium grained, subrounded to subangular, moderately sorted sandstone dominated with transparent to translucent quartz grains bounded with argillaceous matrix. The GS-7+8 in G#BH (2593-2606m) and G#AEE(2575-2594m) comprises of thin bands of sandstone with dominant shale. In NS#D, GS-7 (1992-1995m) comprises of sandstone of dirty white, medium to fine grained, subrounded to subangular, moderate to well sorted, dominated with transparent quartz grains bounded with feebly calcareous cement. In well M#AA, AB & AC, GS-7 appears to be well developed. In K#C the GS-7 (1762-1780m) and K#B (2018-2021m) comprises of sandstone which is medium to fine grain towards bottom and gradually changing to fine grained towards top.

Gandhar Sand Unit (GS): 8

The GS-8 unit is divisible in to GS-8A and 8B subunits separated by shale. GS-8 sand is best developed in wells G#CI, EFF, EB and A#A, NS#D and M#AA, AB & AC. There is very poor development in J#CA, G#AEE, D#EF, and GJ#D. The distribution follows the pattern of GS-7, however a separate lobe initiated towards J#CA having gradual deterioration of facies towards G#BH. Numbers

of cores of the unit have been taken in M#AA, AB, AC, G#EB and NS#B. In well M#AA, the CC#6(1772-1778.5m) in the basal part comprises alternation of fine to medium grained sandstone showing bioturbation and shale which is often sideritic and carbonaceous. The CC#5 (1759-1763.5m) is argillaceous sandstone and silty shale. In well M#AB the CC-1(1765-1774m) is medium to fine grained sandstone (quartzwacke) having argillaceous matrix. In well M#AC the CC#2(1758-1761.5m) is calcareous sandstone is occasionally bioturbated and comprises fine, transparent to translucent, subangular to subrounded, moderately sorted quartz bound by argillaceous matrix. In well NS#B, CC#2 (2010-2018.9) has been cut in GS-8 (2002-2015m) comprises medium to fine grained bioturbated sandstone interbeded with shale. In D#EG, the core CC#1(1640.50-1649.5m) covers both Dabka upper pay (1638-1645m=GS-8) and Dabka lower pay (1646-1651m=GS-6) comprises grey to brownish grey, non-calcareous, silty sandstone having argillaceous matrix and shale having carbonaceous matter with top 5cm having lenticular bodies of coarse grained feebly calcareous sandstone. In wells G#3I, EFF, EB & A#A, the GS-7+8 are sandstone exhibits multiple stacking.

It appears that the overall spread of the prograding delta lobe has been reduced from GS-6.The bay mapped close to NS#B in GS-6 has become prominent, while GS-7 unit is poorly developed in NS#A, B, C & E and makes prominent lobe in Matar area. The characteristic CU of lithofacies, log signature and moderate sorting in wells G#EI, EFF,EB and A#A suggest both aggradation and progradation of the delta mouth bar sands in the close proximity. The relative dominance of argillaceous sandstone facies and FU in wells K#B & C suggest presence of distributary channels in lower delta plain in the area.

The lithofacies association, distribution of facies and overall log pattern indicate a more or less similar depositional pattern as considered in GS-7. The bay developed in N.Sarbhan area remained prominent and there is better development of reservoir facies in Matar area with likely progradation to further southwest. The distributary channel persists in K#B &C. The overall trend remains NE-SW with progradation of a few lobes due south (Fig. 9&10).

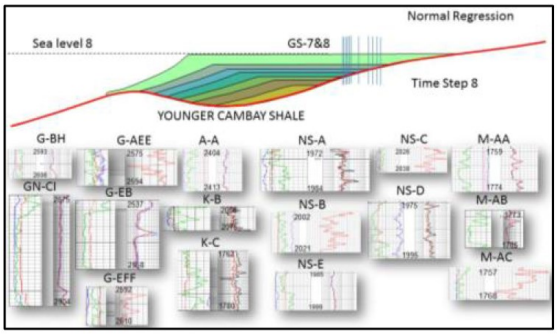

Fig.9: Conceptual SS forward modeling of time step 8.

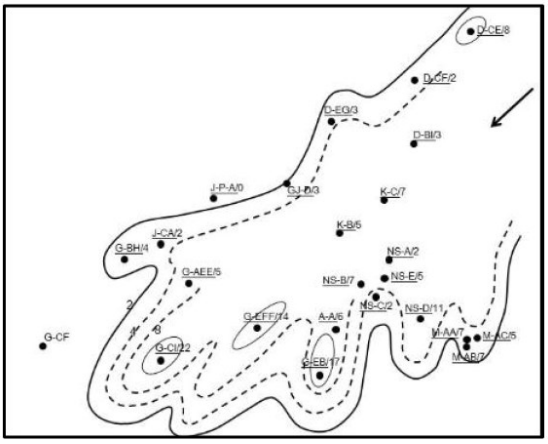

Fig. 10. Depositional Model of GS-7&8 unit

Gandhar Sand Unit (GS): 9

The GS-9 unit is divisible into three subunits, GS-9A, 9B and 9C separated by shale and is best developed in wells G#BH, CA, CI, EFF, EB, A#A and in Matar field. The facies developed in wells G#AEE; K#B & C, NS # B and C is moderate and is mostly argillaceous sandstone/siltstone and shale. It is absent in wells J#P-A, GJ#D, and in the wells of Dabka area. In general the GS-9 unit comprises medium to fine grained, moderately sorted and weakly calcareous sandstone exhibiting both FU and CU sections. In Matar area it is characterized by typical FU sequence with an exception in M#AA showing both CU and FU sections indicating distributary channels prograding due south. In N. Sarbhan the unit is developed as two distinct CU lobes separated by shale. In Kural there is deterioration of reservoir facies in K#B & C wherein, the lower lobe is relatively better developed. The unit is well developed in A#A, G#EFF and G#BH wherein, two to three distinct lobes exhibiting CU followed by FU. In G#AEE it is poorly developed.

The GS-9 unit has been cored in NS#B (CC#1:1993-2002m); NS#D (CC#1:1968-1969.7m); M#AA(CC#4:1748-1755.6m); M#AB (CC#1:1765-1774m); M#AC (CC#1:1745-1754m), G#AEE (CC#2: 2565-2574m); G#EFF (CC#3: 2582-2589m) and G#BH (CC#2 : 2577-2582m). In NS#B, the CC#1(1993-2002m) is sandstone (quartzarenite) having medium to fine grained, subrounded to sub angular, moderate to poorly sorted, quartz having argillaceous laminations. In NS#D, the CC#1(1968-1969.7m) is siltstone having silt size quartz grains floating in argillaceous matrix with rare occurrence of fine sand size quartz grains towards bottom. In M#AA, the CC#4, (1748-1755.6m) is fine to coarse grained sandstone with clay matrix comprising of carbonaceous matter and fine grained siderite. The sandstone is overlain by shale which shows initiation of bioturbation. The bioturbation is more intense in the upper part. In M#AB, the CC#1(1765-1774m) is quartzwacke microfacies having medium to fine grained quartz floating in argillaceous matrix having point contact. In M#AC, the CC#1(1745-1754m) is quartzwacke comprising fine to coarse, bimodal, moderately sorted quartz. In G#AEE, the CC#2 (2565-2574m) the sandstone is quartzwacke having medium to fine grained, subrounded to subangular, moderate to poorly sorted quartz floating in argillaceous matrix and also has carbonaceous laminations and medium to fine grained quartzarenite. In G#EFF, the CC#3 (2582-2589m) shows quartzarenite microfacies having medium to coarse grained, sub rounded to sub angular, moderately sorted quartz grains with point to line contact. In G#BH, the CC#2 (2577-2582m) comprises medium to coarse grained sandstone.

On the basis of lithofacies distribution pattern CU followed by FU, quartzwacke microfacies, moderate sorting and presence of burrows suggest the deposition of GS-9 unit in a series of prograding channel and mouth bars often punctuated by thin shale in between. The development of GS-9 as prograding lobes are evident in Gandhar and N. Sarbhan area and poor development in Kural and Matar fields dominated by thin sandstone and shale deposited in lower delta plain. The prominent lobes culminating at G#CH, CI, EFF, A#A and Matar suggest a general progradation of a constructive delta lobe to SSW and south of the area. The bay envisaged during GS-6, 7 and 8 no longer exists in GS-9. The prominent distributary channel feeding the delta passes through K#B & C (Fig. 11&12).

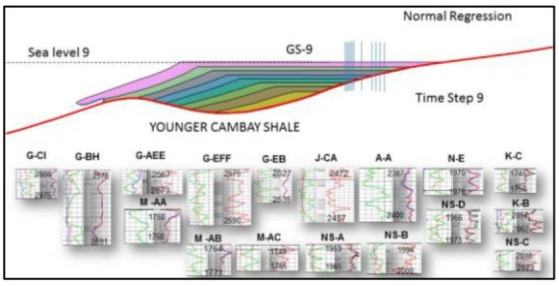

Fig.11: Conceptual SS forward modeling of time step 9.

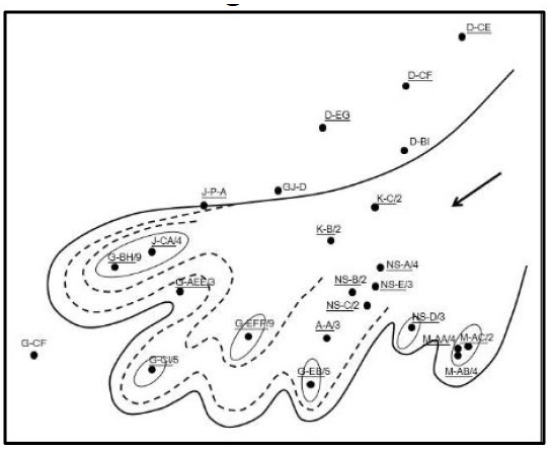

Fig.12. Depositional Model of GS-9 unit

Gandhar Sand Unit (GS): 10

The GS-10 has been divided into GS-10A 10B, 10C subunits separated by shale in main Gandhar field, however in the study area such classification has not been attempted. It is developed in the central part of the area in wells G#CI, EFF, EB, A#A, K#B &C and in N. Sarbhan. This unit is not developed in Dabka, J#P-A and Matar. In K#B, it is very well developed with prominent FU pattern. In well K#C (1726-1730m), there are three separate lobes, the upper one being separated by thick shale, comprise of argillaceous dirty white, medium to fine grained sandstone having moderate to poorly sorted and argillaceous matrix. In Gajera, Dabka, Matar and Jambusar area the reservoir facies within GS-10, is not developed with an exception in J#CA where the facies is mainly siltstone. In N. Sarbhan area, this unit is developed uniformly in all the wells with typical FU pattern thereby indicating positioning of prominent channels in the area. In NS #D, the GS-10 unit exhibits prograding lobe. In the E-W trending profile the GS-10 unit in wells G# CA, BH, AEE, EFF and A#A is well developed. The southernmost profile trending E-W the G#EB &CI has thick and very well developed GS-10 unit exhibiting typical CU pattern. The GS -10 unit has been cored in well G#EFF (CC#2, 2558-2567m), shows

sandstone (quartz arenite) having medium to very coarse grained, moderately sorted sandstone with siltstone and thin shale towards top with carbonaceous matrix showing FU sequence. In G#BH, the GS-10 (2542-2547m) comprises dirty white, fine grained, moderate to well sorted and feebly calcareous sandstone. There is thin shale in between the sandstone.

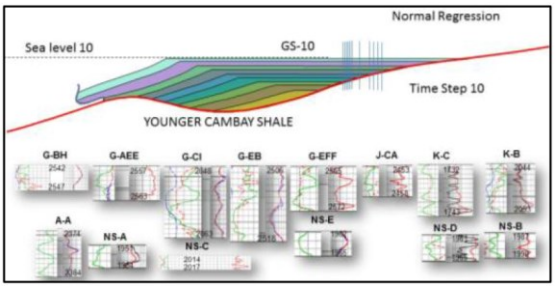

Fig.13: Conceptual SS forward modeling of time step 10.

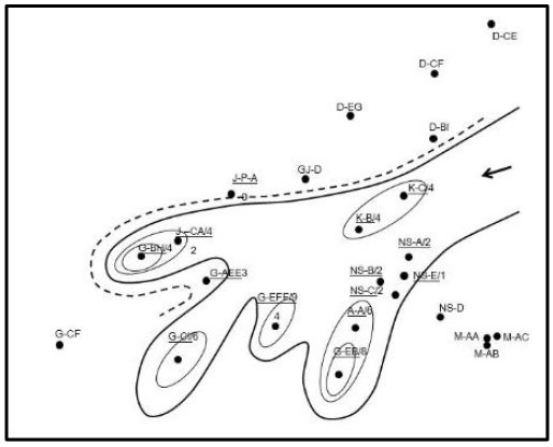

Fig. 14. Depositional Model of GS-10 unit

The overall lithofacies distribution and association of GS-10 reflected on the log pattern suggest a prograding distributary channel from E - SSW direction, in conformity to the GS-9 unit. However its distribution and extent is limited and is mostly absent towards the northern part in Dabka, Gajera and J#P-A and is also absent in Matar in the southeastern part, suggesting that the prominent prograding lobe as envisaged in GS-7,8 & 9, no longer exists. The GS-10 in the central part of the area in N.Sarbhan and Kural exhibit mostly FU pattern having fine to medium grained sandstone and shale and deposited as distributary channels in mostly lower delta plain which continues with better development in GN#566. The wells further towards SW and SSW in NS#D, A#A, G#EB, EFF, AEE & CI shows good development and represent the prograding lobe of the delta forming mouth bar (Fig.13&14).

Gandhar Sand Unit (GS): 11

The GS-11 unit has been informally subdivided into 11A and 11B subunits with intervening shale in main Gandhar field. However, in study area such subdivision has not been attempted. This unit is best developed in G#BH, CA, CI, EB and A#A. In well G#EFF it is fine grained sandstone towards bottom and gradationally increases in grain size from fine to medium grained in the middle part with ferruginous matrix and towards top medium to coarse grained, moderately sorted sandstone with lesser matrix and the entire interval is showing CU sequence. The cored interval CC#1(2552.50-2557m) in G#EFF is grey fissile silty shale with streaks of carbonaceous matter, grading to fine to medium to occasionally coarse grained moderately sorted bimodal sandstone with bioturbations. In G#BH, the CC#1(2542-2545.7m), has alternation of shale at the bottom followed up by medium to fine grained sandstone towards top and the overall facies is very fine sandstone to siltstone. The sandstone (quartzarenite) is coarse to fine grained, moderately sorted, sub angular to sub rounded, quartz grains with line contact and quartz wacke with medium to fine grained, subrounded to sub angular moderately sorted, quartz grains floating in argillaceous matrix and siltstone with microlaminations of carbonaceous matter. The similar facies has been recorded in well G#AEE, the CC-1(2537-2544m). In well G#EB, this unit comprises medium to fine grained sandstone which is silty in the middle part. In Matar field the GS-11 unit is better developed in M#AB having CU sandstone facies. There is gradual thinning of the sandstone facies in M#AA & AC. In M#AB, the GS-11(1753-1758m) comprises of dirty white, fine to medium grained sandstone with gradual increase of grain size towards top showing CU sequence. In A#A, GS-11(2346-2372m) comprises three distinct lobes of sandstone separated by shale. The CC-1 (2349-2358m) shows medium to coarse grained, poorly sorted sandstone towards bottom, followed up by argillaceous sandstone and finally to silty shale and again grades upward in to next cycle of fining up facies. In well K#C, GS11 (1727-1730m)+12 (1719-1724) comprise of medium to fine grained, argillaceous sandstone, with argillaceous matrix and feebly calcareous cement, whereas the GS12 is mostly silty shale. The distribution of GS11 unit suggest a more or less SWS distribution pattern of the prograding delta front lobe having best development in wells J#CA, BH,CI, EB and A#A. There is complete absence of GS-11 in N. Sarbhan area, whereas, there is reappearance of this unit in Matar field. In G#EFF, there is first time occurrence of coal towards the upper part,

thereby suggesting a lower delta plain in this part. The overall distribution indicates a segmented coastline to SW and also south of the study area and gradual shrinking from the northern part in Gajera and Dabka field. The proximal end of the prograding lobe in Kural field does not have good development and probably belong to lower delta plain (Fig.15&16).

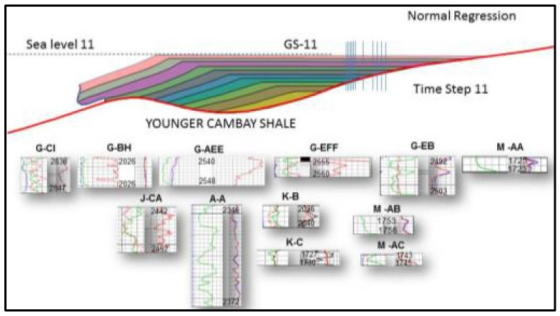

Fig.15: Conceptual SS forward modeling of time step 11.

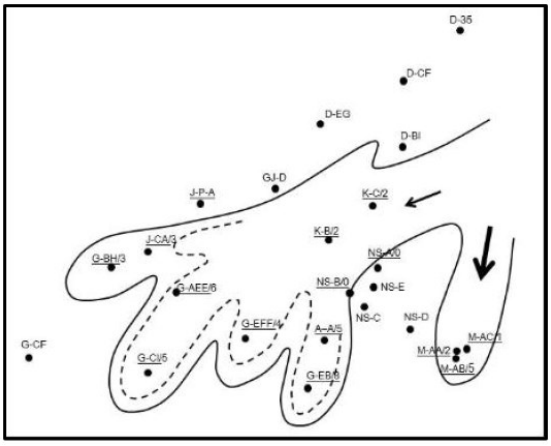

Fig.16. Depositional Model of GS-11 unit

Gandhar Sand Unit (GS): 12

The GS-12 unit is characterized by dominance of argillaceous facies comprising argillaceous silt stone, shale, and thick coal (G#566). This unit is poorly developed except in A#A and G#EB, where there are two isolated sand lobe separated by shale and indicate FU facies. Baring in a narrow corridor of A#A and G#EB, CI, K#C mad NS#D the GS-12 is mainly argillaceous siltstone/ silty shale having carbonaceous laminae and coal (G#EFF), suggesting a prevailing tidal flat environment having prominent mud flat. Occurrence of sandstone in G#EB showing FU lithofacies and general deterioration of the sandstone in A#A suggests the presence of a tidal channel. The overall distribution of the GS-12 unit and lithofacies suggests cessation of the delta building activity. The GS-12 marks the end of delta building activity in the area and represent the lowermost event of the subsequent basin wide transgression of Kanwa shale (Fig.17)

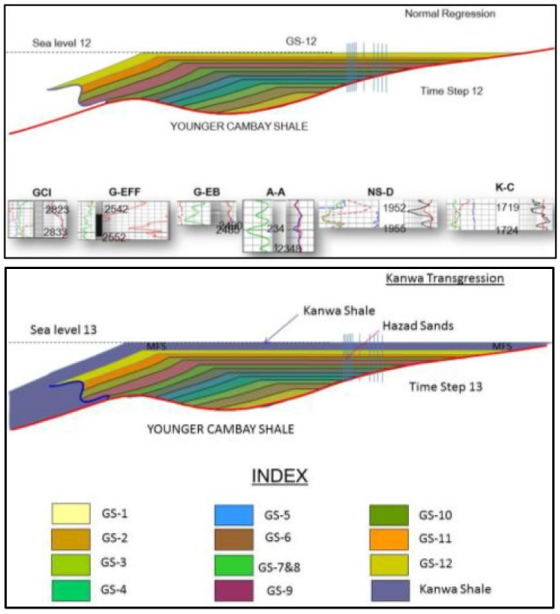

Fig.17: Conceptual sequence stratigraphic forward modeling of time step 12.

Conclusions

(1) On the basis of biostratigraphic studies, the top of Younger Cambay Shale Formation has been dated 51/49MY Early Eocene), Kanwa Shale from 44-42 MY, Ardol Member from 42-37 MY (Middle to Late Eocene) and the overlying Telwa Member from 37-36 MY (Late Eocene).

(2) The top of YCS is marked by a hiatus spanning 2MY and has unconformable relationship with Hazad member. The hiatus is time transgressive as evident from absence of GS-1, 2, 3, 4 and 5, units in various studied fields. Total 10 FS have been marked as datum for establishing micro genetic correlation amongst the Hazad units.

(3) The commencement of normal regression in the area started with deposition of GS-4 unit within initial narrow N-S trending delta lobe with sand maxima in G#CI & EB. With further progression during GS-6, there is a shift of sand maxima towards SSW.

(4) The maximum delta building in the area took place during GS-9 and thereafter there is a restriction in

input through the study area, having no deposition of GS-9 and younger units in Dabka field.

(5) The GS-12 unit forms a wide spread tidal flat with sand maxima in G-CI & EB as being part of possible tidal channel in south prior to major transgression in the area represented by Kanwa Shale.

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