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High Resolution Bio-Sequence Stratigraphy and Carbonate Microfacies: A tool to explore the sedimentary history of a basin - applied on the Paleocene-Eocene Petroleum System of the Salt Range, Pakistan

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The Late Paleocene-Early Eocene mixed carbonate siliciclastic system of the Potwar Basin is known amongst the world's oldest exploration targets. This system having multiple source and reservoir quality facies is producing since the last 100 years from its structural components while its stratigraphic potential is hardly tested. Sequence stratigraphy is a key to understand and target the stratigraphic potential. The present work is a first endeavour towards this goal by starting with identifying indications for sedimentary cyclicity based on high resolution biostratigraphy and carbonate microfacies. This combination proved to be an efficient tool for establishing the chronostratigraphy, predicting the source rock, and reservoir facies potential as well as the distribution of these parameters within the basin. Understanding the depositional history of a basin is a prerequisite for predicting potential areas for reservoir facies pinch outs. It also helps to envisage autocyclicity.

This Paleocene-Eocene mega sequence comprising of seven rock units (Hangu, Lockhart, Patala, Nammal, Sakesar, Chorgali and Jatta) is exposed along the Salt Range monocline that forms a southern border of Potwar Basin (Figure-1). These rock units were measured and densely sampled from a large number of outcrop sections (Afzal, 1997; Afzal et al., 2000 and Jurgan et al., 1988). About 400 samples were analysed to investigate foraminiferal fauna (planktonic, smaller and larger benthics), carbonate microfacies and their reservoir quality. Planktonic and larger foraminifera, together with an additional nannofossil-control provided a precise chronostratigraphic correlation of different litho- and microfacies units across the whole basin. Four quantitative parameters (plankton/benthic ratio, keeled/non-keeled planktonic foraminiferal ratio, total population/gram of sample and diversity) in combination with whole rock lithofacies, variety of microfacies and biofacies were logged. Published literature was also integrated for additional control. These logs revealed depositional breaks/hiatuses, age controlled minor as well as major flooding surfaces and maximum shallowing events which correlated throughout the basin to develop chronostratigraphic layers (including reservoir quality facies). The water depth estimation helped to integrate these layers into a depositional model. The well-known Nammal Gorge section of the Salt Range offers a very good opportunity to understand cyclicity in sedimentation (Figures-1 and 2) due to its excellent exposure and appropriate location within the intra shelf basin. In this section 16 cycles based on biofacies and 12 cycles based on litho- and microfacies are identified. The coherent litho-, microand biofacies cycles are interpreted as potential third order sequences. Some of the biofacies cycles identified in the Nammal Gorge section correlate well with microfacies cycles in other sections, and qualify therefore likewise as potential third order sequences. These cycles are named from T0 to T120.

The regional Cretaceous unconformity is marked by erosion and subsequent deposition of laterite beds which were followed by a major transgressive phase during the Late Paleocene (P4 zone of planktonic foraminifera, NP6 zone of nannofossil and SB3-SB4 zones of larger foraminifera) that resulted into deposition of marginal marine to non-marine Hangu Sandstone and Lockhart Limestone beds. The transgressive nature of the sandstone is interpreted based on the presence of limestone beds, mollusk rich lag beds and marine fossils. Four cycles (T10-T40) are identified within this transgressive phase. The top of cycles T20 and T30 is marked by a green algal limestone facies within Lockhart Limestone. The top of cycle T40 is interpreted to exist within the basal part of the Patala Formation by showing a break in biofacies associated with an entry of fresh water fauna. The rocks of this transgressive phase were deposited upon a westward dipping gentle ramp. The transgressive phase still continued, while the carbonate system was temporarily overwhelmed by the clastics of the Patala Formation. This formation is a proven source rock, consisting of shale, carbonaceous shale, coal and sandstone. These clastics were deposited during Late Paleocene (P5/NP9/SB5). Within this time one sequence (T50) and two biofacies cycles are identified. During this period the eastern Salt Range received siliciclatics from the east forming a barrier bar sand deposit (Warwick and Wardlaw, 2007). This barrier bar divided the basin into an outer and an inner shelf area. The inner shelf served as a favourable site for coal deposition whereas its coeval carbonaceous shale facies got preserved in the outer shelf area. A remarkable lithological as well as faunal break was observed at the top of T50 cycle where more than 70% shallow water fauna was replaced by open marine fauna within a dark gray to black shale horizon. This layer indicated a rapid sea level rise causing a water depth of greater magnitude than suggested within the global eustatic sea level curve (Haq et al., 1987), also see comments by Gibson (2007). Our data show a restricted occurrence of this litho- and biofacies, which indicate a down-warping of the central part of the Potwar Basin. This down-warping occurred during Late Paleocene (P5, upper NP9 and upper SB5) and may possibly attributed to the Late Paleocene India-Asia collision (Beck et al, 1995). Obtained data revealed a remarkable facies change from shallow water carbonate deposits of the Nammal Formation (Rotalids, *Alveolina* and *Nmmulities* rich facies) located on the stable platform in the east, changing to the west into planktonic foraminiferal black shale, deposited in the down-warped central part of the basin. The qualitative estimation of deepening at different stages is shown in Figure-1.

The sea level rise and down-warping continued during Early Eocene (P7, NP11 and SB8). At Nammal Gorge section, the black shale gradually changed to gray marl and light bluish gray open marine limestone (mudstone) of the Nammal Formation. Within this interval, three biofacies cycles

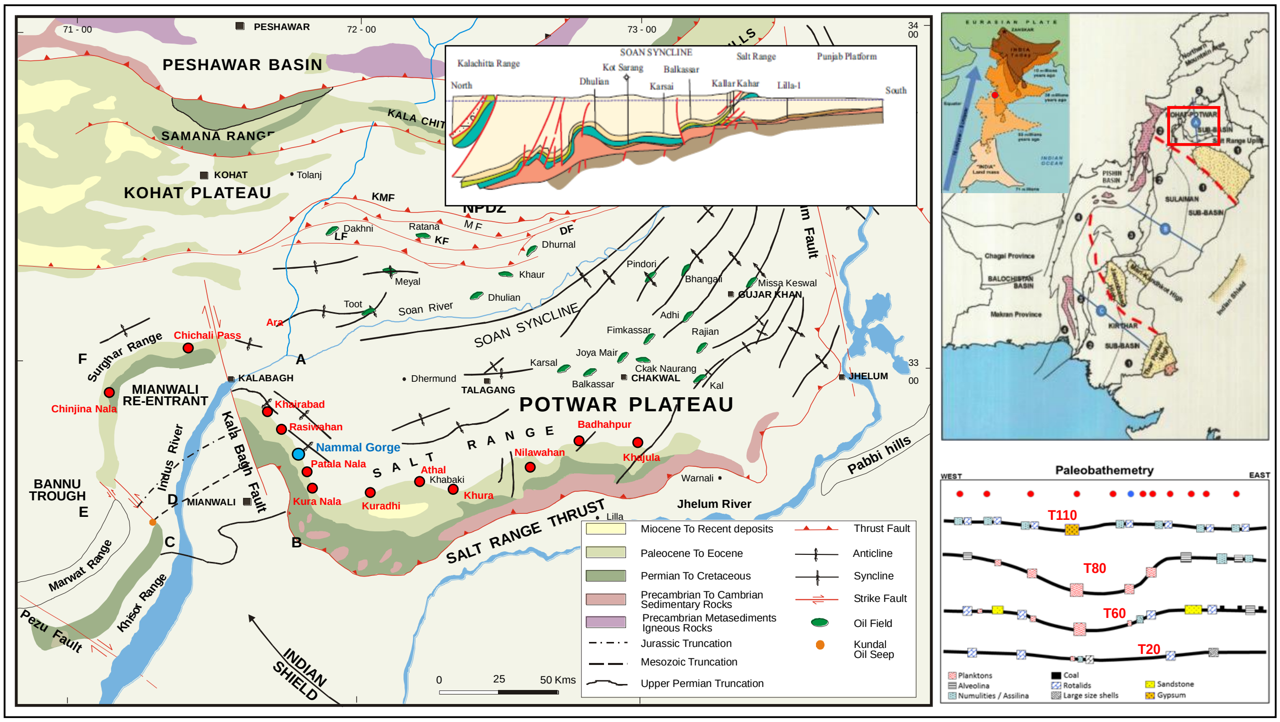

Figure-1: *Location map of the studied sections in the Salt Rage monocline that forms the southern margin of the hydrocarbon bearing Potwar Depression. The Nammal Gorge section is shown in blue colour. Paleogeography of the basin during the Paleocene-Eocene time is given on right base while present day structural cross section is given on top middle (Modified after Mughal et al., 2001 and Afzal, 1997).*

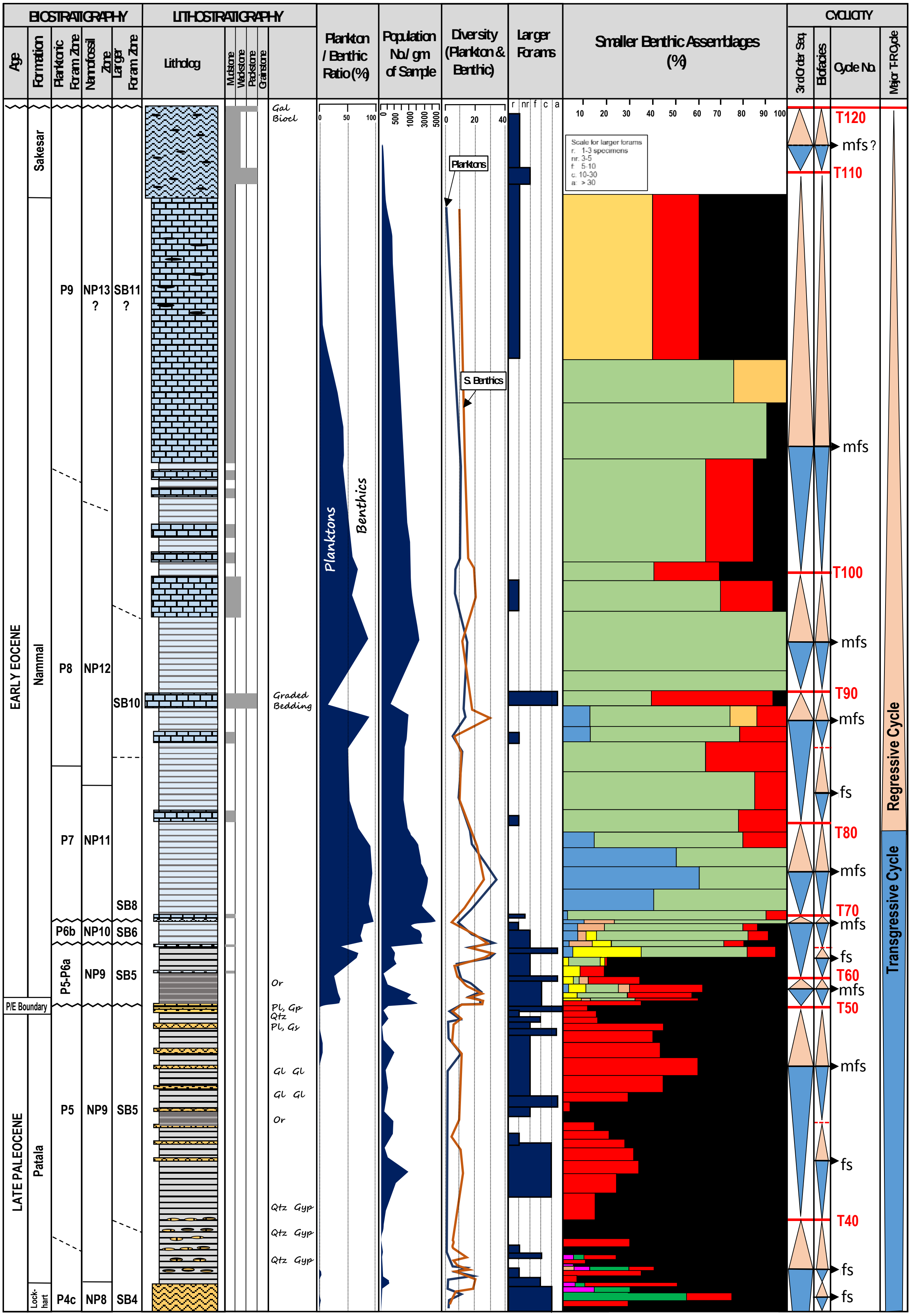
BIOSTRATIGRAPHY
LITHOSTRATIGRAPHY
Age
Formation
Planktonic Foram Zone
Nannofossil Zone
Larger Foram Zone
Lithology
Mudstone
Wackestone
Packstone
Grainstone
Plankton / Benthic Ratio (%)
Population No./ gm of Sample
Diversity (Plankton & Benthic)
Larger Forams
Smaller Benthic Assemblages (%)
CYCLICITY
3rd Order Seq.
Biofacies
Cycle No.
Major T-R Cycle
EARLY EOCENE
LATE PALEOCENE
P/E Boundary
Sakesar
Nammal
Patala
Lockhart
P9
P8
P7
P6b
P5-P6a
P5
P4c
NP13 ?
NP12
NP11
NP10
NP9
NP8
SB11 ?
SB10
SB8
SB6
SB5
SB4
Gal Biocl
Graded Bedding
Or
Pl, Gp
Qtz
Pl, Gs
Gl Gl
Qtz Gyp
Planktons
Benthics
Planktons
S. Benthics
r nr f c a
Scale for larger forams
r: 1-3 specimens
nr: 3-5
f: 5-10
c: 10-30
a: > 30
T120
mfs ?
T110
mfs
T100
T90
fs
T80
T70
T60
T50
T40
Regressive Cycle
Transgressive Cycle

Figure-2: *Summary diagram of biosequence stratigraphy of the Nammal Gorge section, Salt Range. Biofacies colour refers to different water depth assemblages: (1) Mauve: - brackish water, (2) Black: - marginal marine, (3) Orange: - inner shelf, restricted marine lagoonal, (4) Red: - inner shelf normal marine, (5) Green: - outer shelf to upper slope (midway type fauna), (6) Yellow: - upper slope to basinal, (7) Blue: - upper slope to basinal (velasco type fauna). Text abbreviations refers to:* ***Or*** *- organic,* ***Gyp*** *- gypsum,* ***Gl*** *- Glauconitic,* ***Qtz*** *- quartz,* ***Gal****- green Algae,* ***Biocl****- bioclast,* ***Pl****- pelecypod,* ***Gp****- gastropod,* ***fs*** *- flooding surfaces,* ***mfs*** *- maximum flooding surface. Sequence boundaries are numbered in red. Other abbreviations refer to graded bedding and fossil content, including pelecypods, gastropods, green algae, miliolids etc. Major cycles are based on shallowing upward lithofacies trends and minor cycles are based on biofacies assemblages*

are identified and two sequences (T60 and T70) are interpreted. In cycle T70, a sandstone bed within the basal part of Nammal Formation entirely comprised of globigerina shells is present, immediately underlain by a limestone bed containing larger foraminifera. This combination suggests a major break in sedimentation and a landward shift of a carbonate buildup, which lateron prograded seawards. Maximum water depth was encountered within cycle T80 by appearance of a deep water agglutinated foraminiferal biofacies. About a 20m thick interval of upper Patala to basal Nammal formations (cycles T50-T80) at the Nammal Gorge section represents the basin ward equivalence of almost the total thickness of the Nammal-Sakesar carbonates of the eastern Salt Range having at least 3 to 4 cycles. Whereas its time equivalent facies in the central part of the basin (Khairabad section) is represented by a plankton rich dark gray to black shale (similar to Patala shale facies).

The top of cycle T80 marks the end of a transgressive phase. A new T90 cycle starts with another deepening event but ends at a coquinal limestone bed (larger foraminiferal wack-packstone) showing graded bedding. Presence of similar larger foraminiferal limestone beds is observed towards east at Kaura Nala section. These carbonates are interpreted as a keep up phase and their downslope shedding and transportation into the deeper part of the basin is encountered in many sections up to Khairabad in the west. At the Nammal Gorge section this event shows a graded bedding and its occurrence is coeval in all the sections within P8, NP12 and SB10 zones. This event marks the end of a transgressive, and the start of a regressive phase. During this time a carbonate buildup east of Kaura area divided the eastern and western Salt Range into two depressions, a major one towards west with considerable accommodation and connection with the open sea, while a second depression developed towards the, east possessing lagoonal environments. This lagoonal depression was filled by deposits of the Chorgali Formation during SB9-SB10 time. Its microfacies association suggested deposition within at least two cycles (T80-T90). The formation is mainly thin bedded limestone and gray to brick red shale while at a few locations it is dolomite indicating supratidal environments due to local paleohighs (Mujtaba, 2001). The features like intra-formational breccia within the formation and intra-formational conglomerate at its top (at Khajula section) suggests subareal exposures and/or fresh water dissolution and subsequently complete filling of the accommodation and local uplift.

In the western depression at Nammal Gorge section, the open marine carbonate facies continued to deposit forming two more cycles (T100 and T110) with noticeable chert nodules and chert patches. Its prograding toesets are interpreted in Rasiwahan section where the basal part of Nammal formation shows an alternative thin limestone and chert layers. At this location a nearly 140m thick carbonate package starts from open marine Nammal facies, changing gradually into a shallowing upward trend receiving larger foraminifera and attaining nodularity (a character of

Sakesar limestone). It ends into a thin limestone and dolomite (a character of Chorgali Formation). Within Sakesar type carbonates two cycles are interpreted (Boustani, 2001). We interpreted that first cycle starting at the base with open marine mudstone facies (Nammal Formation) and ending with a Miliolidal packstone facies, whereas the second cycle also starts from the open marine mudstone but ends with highly brecciated Alveolinal-Miliolidal pack-grainstone. The microfacies within the last cycle (T120) at the Nammal Gorge showed inner lagoonal facies and its extreme coeval facies are dolomites at the Rasiwahan section. At the end of this cycle the basin was almost filled and restricted marine conditions prevailed further in the west where evaporates (Jatta Gypsum) started to deposit with interbedded limestone at the base of it.

The basin-wide chronostratigraphic correlation shows an early filling of the eastern Salt Range depression and thereon westward progradational with a major facies change pattern from the carbonate dominated facies in the eastern Salt Range towards a shale/marl and evaporitic dominated fcies in the western Salt Range. Within this fcies chance the progradational topsets and stringers (pinch-outs) bear potentials for stratigraphic trappings towards both downdip and updip direction (depending upon structural conditions). Whereas the flooding surfaces within various cycles containing deposits such as coal, carbonaceous shale of Patala, Nammal formations and limestone of Lockhart and Jatta formations qualify for source rocks facies (also see Wandrey and Shah, 2004). This paper represents a brief summary of the new concept and provides strong evidences to depart from an earlier “layer-cake-model” and therefore may serve as an analog for the adjacent oil/gas bearing Potwar Basin. This concept will help to trigger a new round of exploration in this basin starting with a well based sequence stratigraphic model and comprehensive gross depositional environment maps to highlight potential areas for stratigraphic traps and unconventional shale gas resources.

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