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Sequence Stratigraphy of the Neogene and Quaternary Siliciclastics in the Offshore Indus Basin of Pakistan

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ABSTRACT

The siliciclastic dominated sequences interpreted within the Neogene (Miocene-Pliocene) and Quaternary (Pleistocene-Recent) in the Offshore Indus Basin of Pakistan indicated conventional interpretation of unconformity bound depositional sequences. These sequences were preserved as a result of combined effect of the relative sea level fluctuation and tectonism. The post Paleogene siliciclastic sequences in the post-rift Tertiary mega-sequence reveal prominent incisions in most of the Neogene and Quaternary sequences. The Paleogene carbonate dominated mega-unit is separated from the overlying Neogene siliciclastic dominated mega-unit by an unconformity produced as a result of high amplitude lowstand of sea level, associated with Early Miocene tectonism in this region. Another high amplitude lowstand of sea level produced an erosional unconformity between the Neogene and Quaternary mega-units. The basal sequence of the Neogene mega-unit comprising Early-Middle Miocene Gaj Formation has been the target for hydrocarbon exploration in past due to existence of reservoir quality rocks. This sequence has been divided into its systems tracts/units and time thickness maps have been produced for each unit. The rest of sequences above the Early-Middle Miocene in the Neogene and Quaternary mega-units are not important for hydrocarbon exploration in the basin. However high quality incision produced in these sequences, make them important for interpretation of younger sequences with erosional unconformities. This also gives good knowledge of interpretation about the incised valleys, channels and levees in the siliciclastic sequences of the Neogene and Quaternary mega-units in the Offshore Indus Basin of Pakistan.

Key words: Siliciclastic Sequence Stratigraphy, Incisions, Offshore Indus Basin.

INTRODUCTION

A seismic stratigraphic interpretation was carried out in the Neogene and Quaternary siliciclastics of the Offshore Indus Basin using about 7000 km mixed migrated and stack 2D seismic data recorded by the Oil and Gas Development Corporation of Pakistan (OGDC) in 1986 and OGDC/NORAD in 1982 (Figure 1). Well data available for 5-shelf area and 5-basin area wells was found very useful for well seismic data integration to identify the siliciclastic sequences in the Neogene and Quaternary mega-units of this basin.

SEQUENCE STRATIGRAPHIC INTERPRETATION

The standard seismic stratigraphic reflection criteria used in this work include amplitude, continuity, frequency, the internal seismic reflection patterns, spacing within the seismic facies, shape of clinoforms and the seismic reflection termination patterns to identify major seismic sequences in the Mesozoic, Tertiary and younger strata (Figure 2 and 3). These are the pre-rift megasequence (Mesozoic), consist of Lower Goru, Upper Goru and Parh Formations (Figure 3) as penetrated in the shelf area well Dabbo Creek-1. The syn-rift megasequence (Late Cretaceous), comprises of Mughalkot and Pab Formations, as penetrated in almost all the shelf area wells. The Mesozoic is named as T1 (Not interpreted in detail). The Tertiary pos-rift megasequence (Interpreted in detail) is divided into three mega-units i.e. Paleogene, Neogene and Quaternary. The Paleogene is predominantly carbonate and comprises of sequences T2, T3, T4 and T5 (Figure 2 and 3), including Paleocene Ranikot, Eocene Laki-Ghazij, Kirthar and Oligocene Nari formations penetrated in all the shelf area wells. The Neogene and Quaternary consisting of sequences T6 to T11 are predominantly siliciclastic and thickens SW in the deeper part of basin.

Scope of this paper is to discuss the siliciclastic sequence stratigraphy of the Neogene and Quaternary mega-units. The interpreted sequences were further divided into their seismic units/system tracts, based on their internal seismic configurations and integration with well data. The Early-Middle Miocene sequence is important for hydrocarbon exploration due to existence of reservoir quality siliciclastics and source rocks within its intraformational shale intervals. The basal sequence in the Neogene mega-unit and its seismic units 6.1, 6.2 and 6.3 have been correlated with the Offshore Indus Basin wells to help in understanding the position of the formations in the wells and their extent in the basin (Figure 4). The time thickness maps were produced for reservoir quality siliciclastics of Early and Middle Miocene units/system tracts in the basin.

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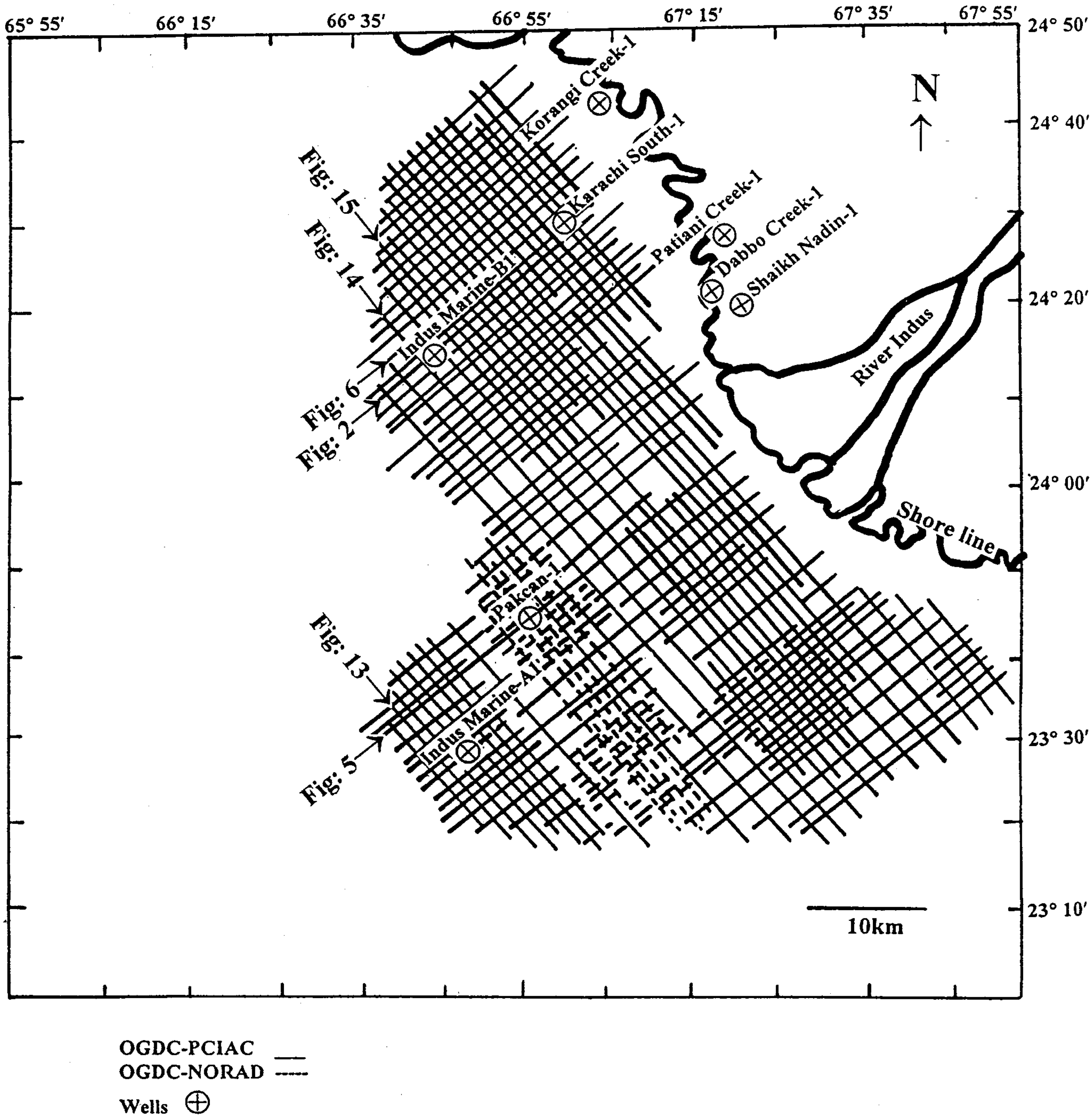

Figure 1- Map showing the study area with position of seismic grid lines and some of the important figures used in this study.

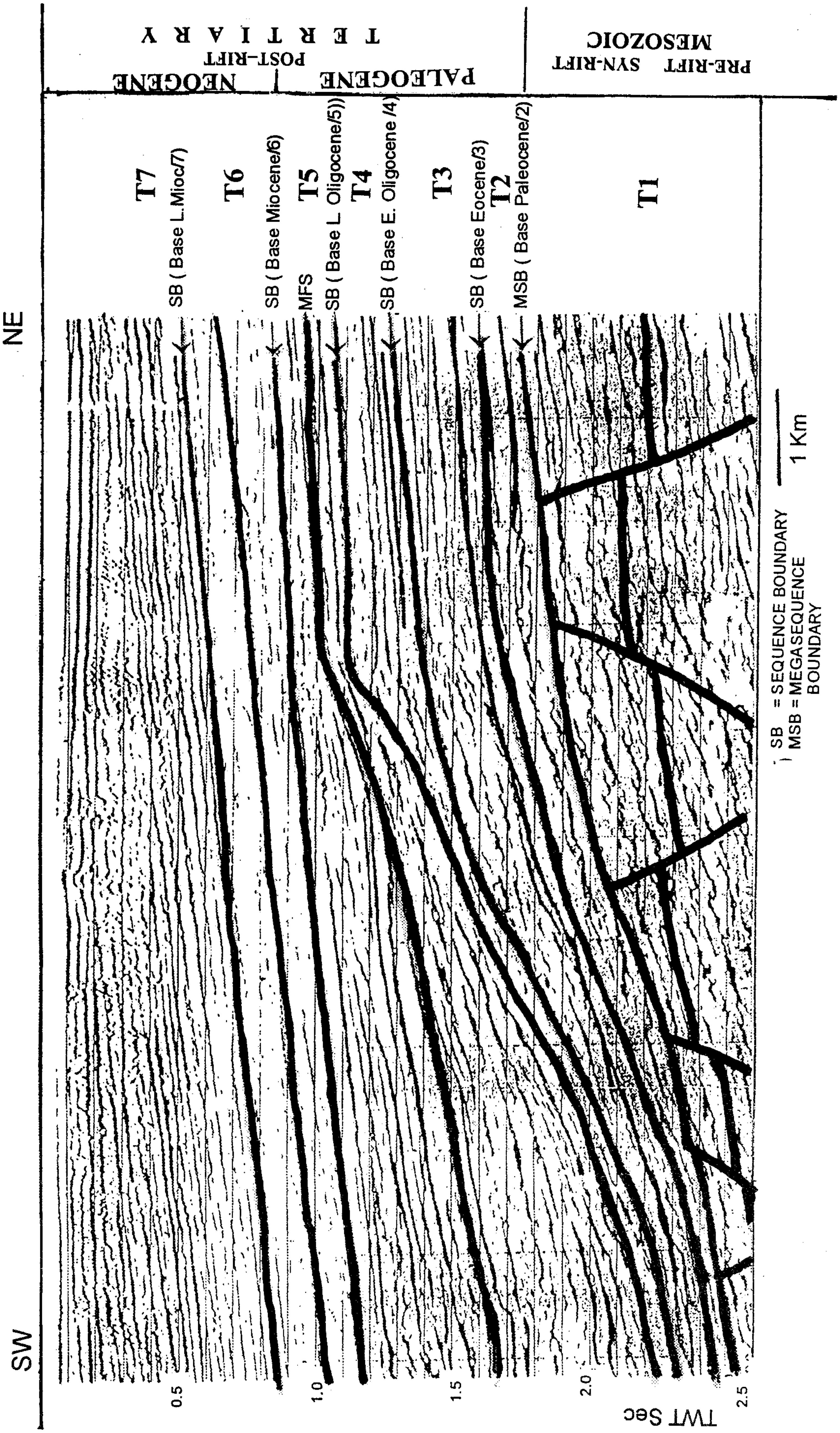

Figure 2- Seismic profile showing interpreted Pre-Rift and Syn-Rift (Mesozoic) and Post-Rift Tertiary megasequences.

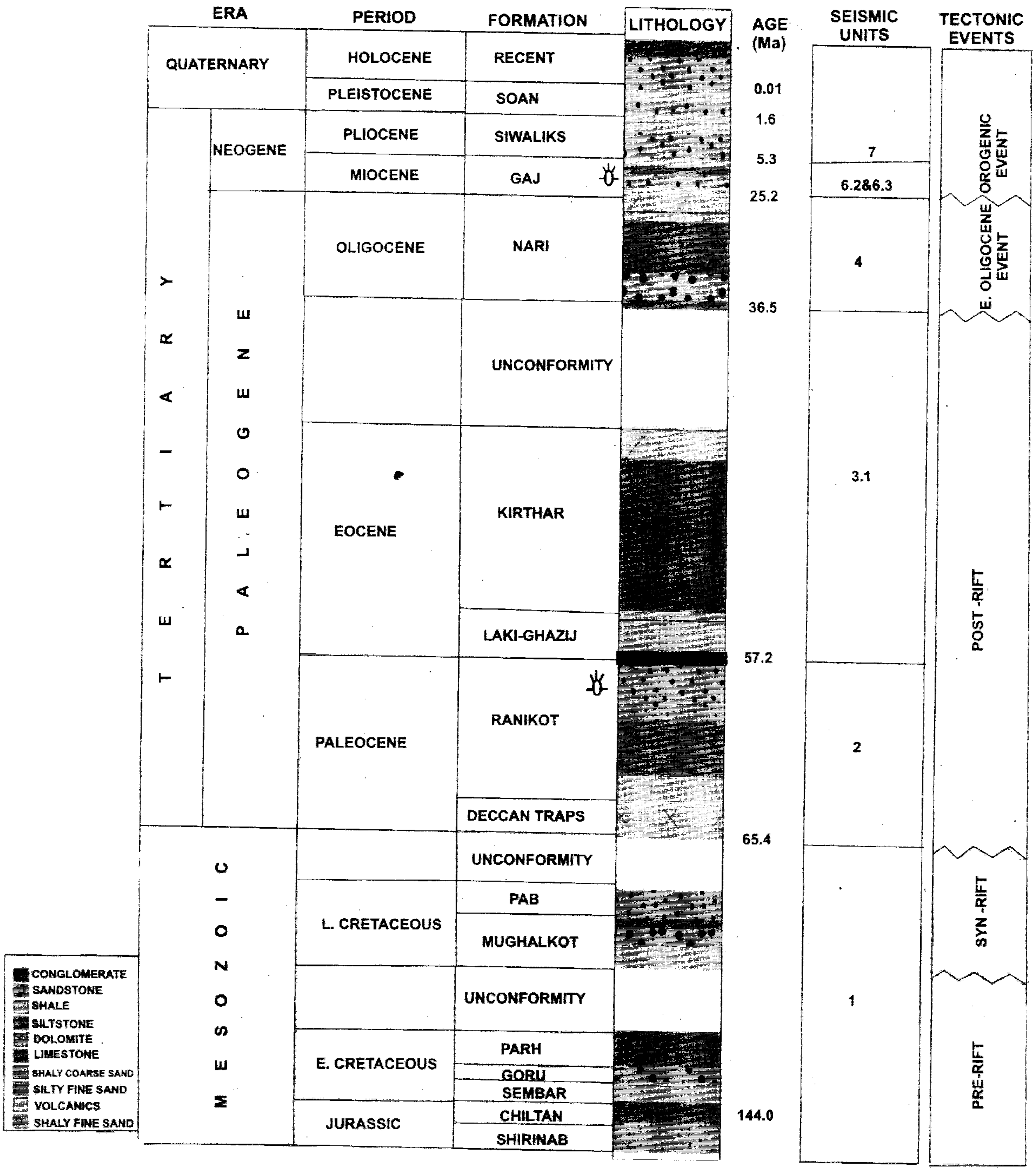

Figure 3- Comparative position of sequences and respective units/systems tracts against the stratigraphy of the Offshore Indus Basin.

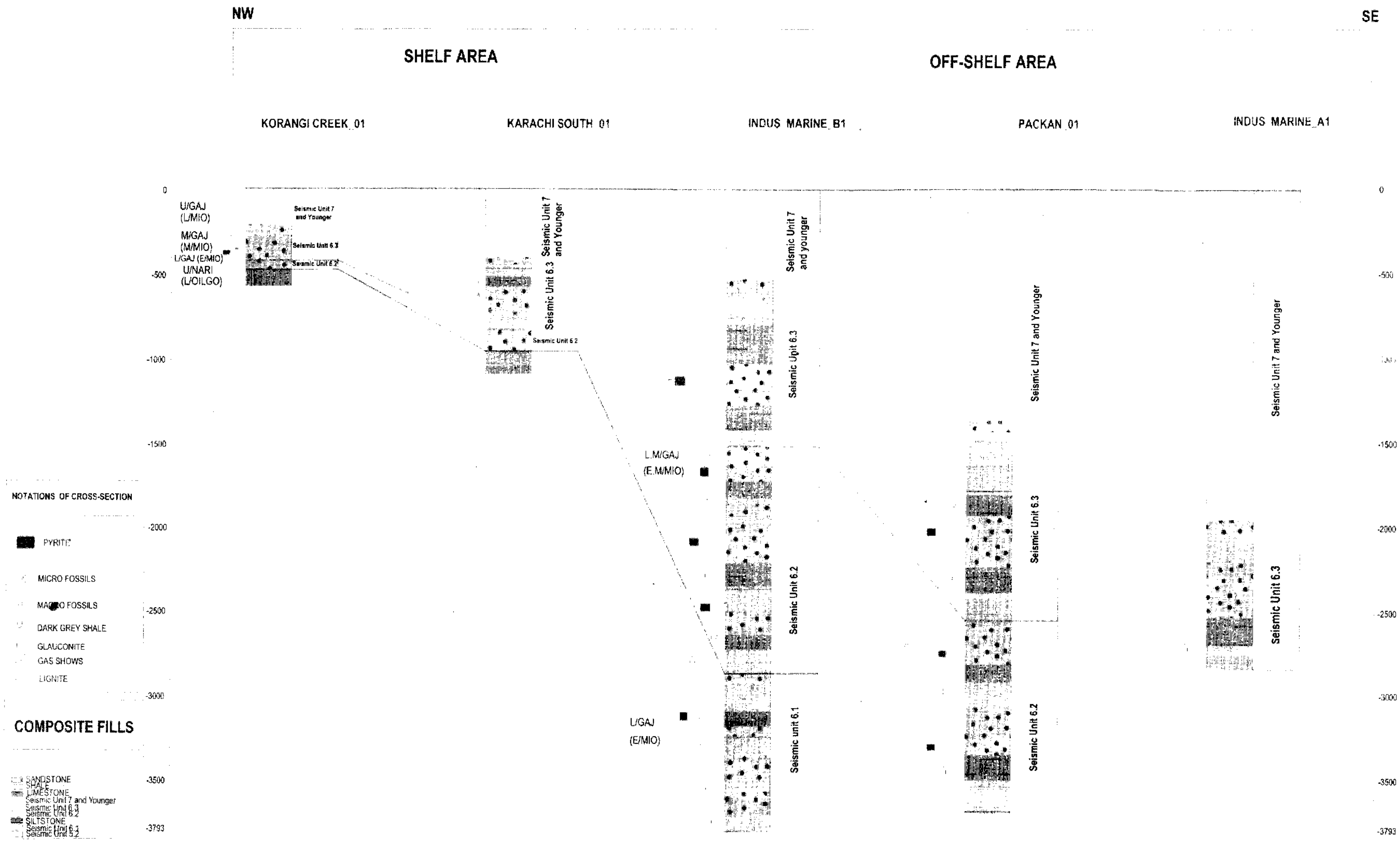

Figure 4- Correlation of seismic units with the shelf and off-shelf area wells (Neogene mega-unit).

Sequence T6 (Aquitaniun-Burdigalian/Miocene)

Observations

This sequence is preserved in the shelf, slope and basin areas (Figure 5). The lower boundary of sequence T6 is interpreted as a medium to high amplitude reflection in the inner shelf area and high amplitude in the outer shelf and slope areas. This variation in amplitude represents variation in lithology in the shelf and slope areas. This boundary has apparent truncation below and onlap above in the slope area, separating Early-Middle Miocene siliciclastic sequence T6 from the underlying Oligocene carbonate sequence T5 (Figure 2 and 3). This produces a megasequence boundary between the Paleogene and Neogene mega-units. The upper boundary of sequence T6 is a variable medium to low amplitude reflection with apparent truncation below and downlap above. Internally T6 contains medium to low amplitude reflections, continuous in the shelf area and have sigmoidal clinoforms in the slope area (Figure 5).

The sigmoidal clinoforms with medium to low amplitude internal seismic facies may represent medium to fine grain sediments. The distal sigmoidal facies are truncated by sediments of submarine canyons. In the deeper part of basin fanning against the down thrown blocks of the normal faults are observed at this sequence. The upper boundary separates Early-Middle Miocene sequence T6 from the overlying Middle Miocene sequence T7.

Interpretation

Sequence T6 is composed of aggradational concordant reflections in the inner shelf area. It represents that the topset accommodation was equal to the rate of sediments deposition. The concordant reflections have also been recognized as signs of uniform sediment deposition. This sequence is thinner in the inner shelf area (Figure 4 and 5).

The outer shelf and slope areas have thicker sediments. The slope area is composed of sigmoidal clinoforms with medium to low amplitude reflections represent preservation of medium to fine grain sediments. These clinoforms show basinward progradation (Figure 5). When the relative available topset accommodation becomes less than the amount of sediment deposition in the shelf the strata begins to prograde basinward (Vail et al., 1977 and Emery and Myer 1996). The onlap fills associated with the relative fall of sea level in the basal part of this sequence represents inclined seismic facies along the slope associated with the incised valley fill. This widespread distribution of valley incision and fill is critical in understanding the variation of type-1 sequence boundary expression in the shelf and slope areas, with regional distribution of shallow marine and coastal sediments and reservoir distribution within a sequence (Van Wagoner et al., 1990). In the shelf edge the incised valleys commonly contain the best quality reservoir sediments within this sequence.

The basin area at sequence T6 is composed of fans with onlapping stratal pattern. The relative sea level fall caused the turbid flow of the sediments along the inclined slope and their deposition in the deep basin area. The shape of lowstand fans has been distorted by the faults reactivation which becomes higher in magnitude in the distal basin area (Figure 6). The basin area represents significant fanning against the reactivated normal faults. These depositional episodes are bounded by the flooding surfaces during the relative sea level rise or by shifting the delta lobes (Galloway 1989). Recognition of these bounded surfaces is difficult in the distal basin area due to distortion of stratal patterns. However, in the slope area where reactivation is relatively low the bounding surface is easily traceable. The rapid fall of sea level at this sequence coupled with a large amount of sediment supply, which was delivered in the basin and resulted in a sequence boundary, which is strongly marked with onlap truncations prominent along the slope (Figure 5).

This sequence comprises of lowstand, transgressive and highstand systems tracts and is considered as a type-1 sequence. A type-1 sequence is formed when the rate of eustatic fall exceeds the rate of subsidence at the depositional shoreline break producing a relative fall in sea level (Jervey 1988).

Unit 6.1 (Aquitanian-Burdigalian)

This unit is interpreted as a lowstand systems tract in the basin area. It is equivalent to about 930m thick coarsening upward parasequences in the well Indus Marine-B1 (Figure 7). It has onlap seismic facies along the underlying boundary with sequence T5. Onlap moving toward the shelf area indicates a relative rise in sea level (Vail et al., 1977; Allen and Allen, 1990 and Emery and Myers, 1996). The seismic facies produce fan against the down thrown walls of the normal faults in NW to SW areas of this basin. It is composed of reservoir quality sandstone in the Early-Middle Miocene as penetrated in the basin area well Indus Marine-B1. The lowstand systems tracts are the dominant systems tract preserved in siliciclastic sequences and in the shelf area its major component is the incised valley (Van Wagoner et al., 1990).

The Lowstand systems tract at sequence T6 is mainly composed of siliciclastic sediments. It contains thick deposition of siliciclastics triggered in the basin as an effect of force regression (Posamentier, 1993). The internal seismic facies of unit 6.1 indicate prominent onlap against the lower boundary with sequence T5, producing a sequence boundary between T6 and T5. Most of the sea level falls that produce sequence boundaries are related to tectonic pulse (Mondejar and Mendiola, 1993). The siliciclastic sediments of T6 overlying the carbonate reef at the highstand systems tract of sequence T5 and buried the Oligocene carbonate reef to death (Figure 5). The highly developed lowstand fans at this system tract represent a high amplitude low sea level fall with deposition of thick siliciclastic sediments in the deep basin. The high amplitude lowstand of sea level is associated with the effect of climate, tectonism and eustacy. The River Indus heading to the Himalayan Mountains is considered as sediment supply source at this level (Kolla and Coumes, 1987, Wood et al., 1993). The time thickness map of this unit indicates that sediments are thickest in a SSW direction in the basinal area (Figure 8). The stratal characteristics of siliciclastic sequences are given in table-1.

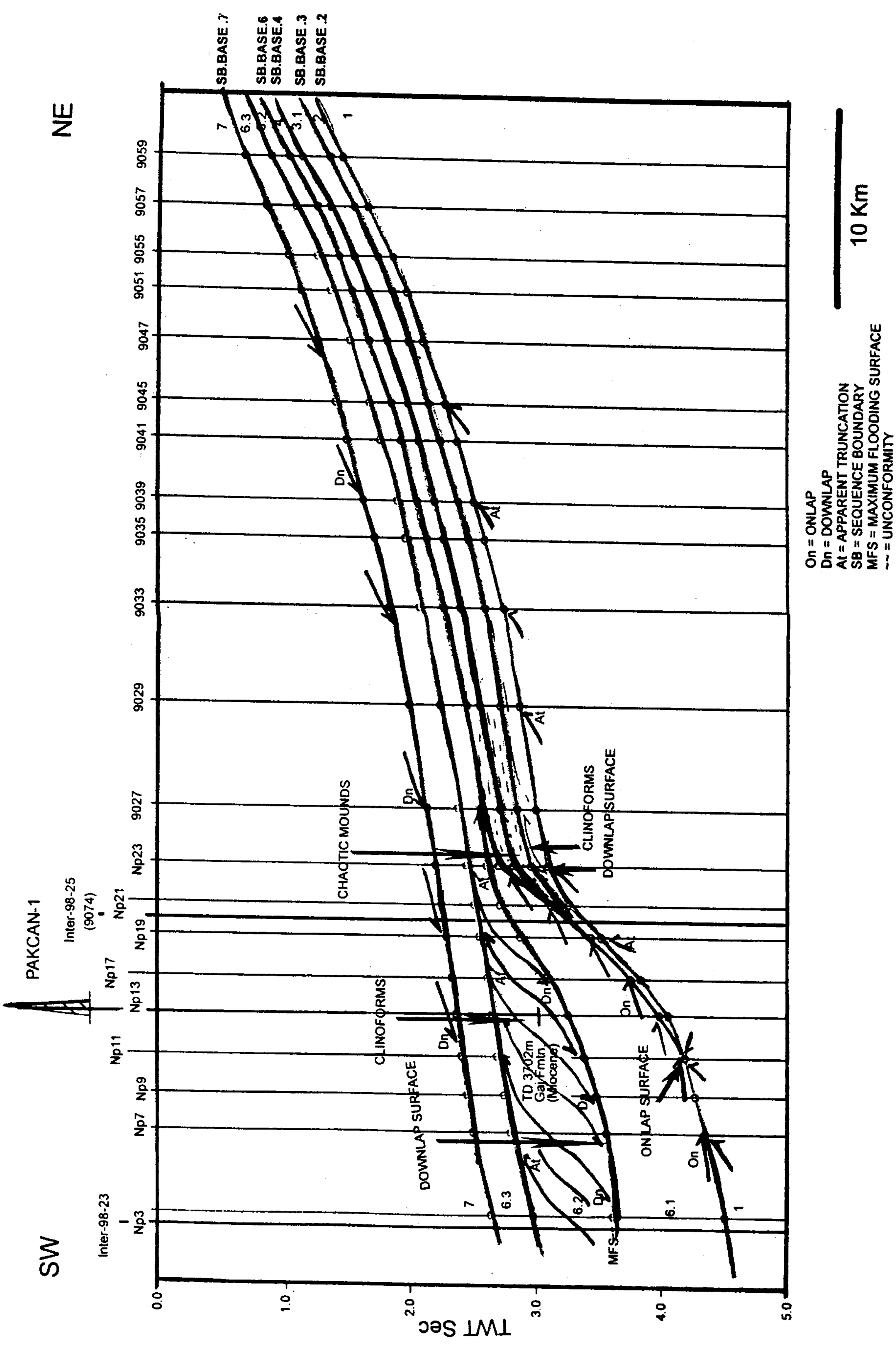

Figure 5- Profile showing the position of units 6.1, 6.2 & 6.3.

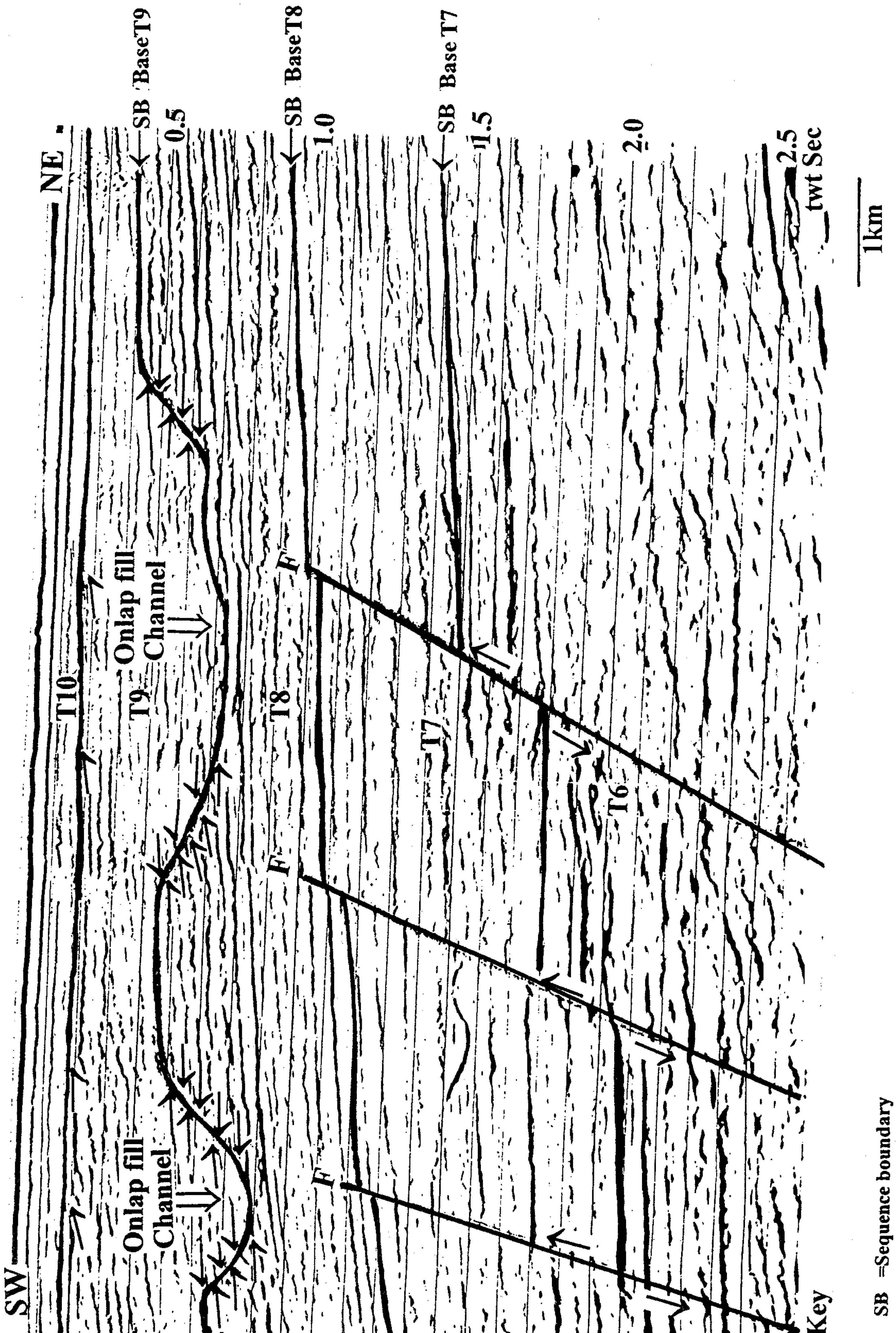

Figure 6- Seismic profile showing the position of sequences T6-T9 (E.M. Miocene-Pliocene) with prominent incisions.

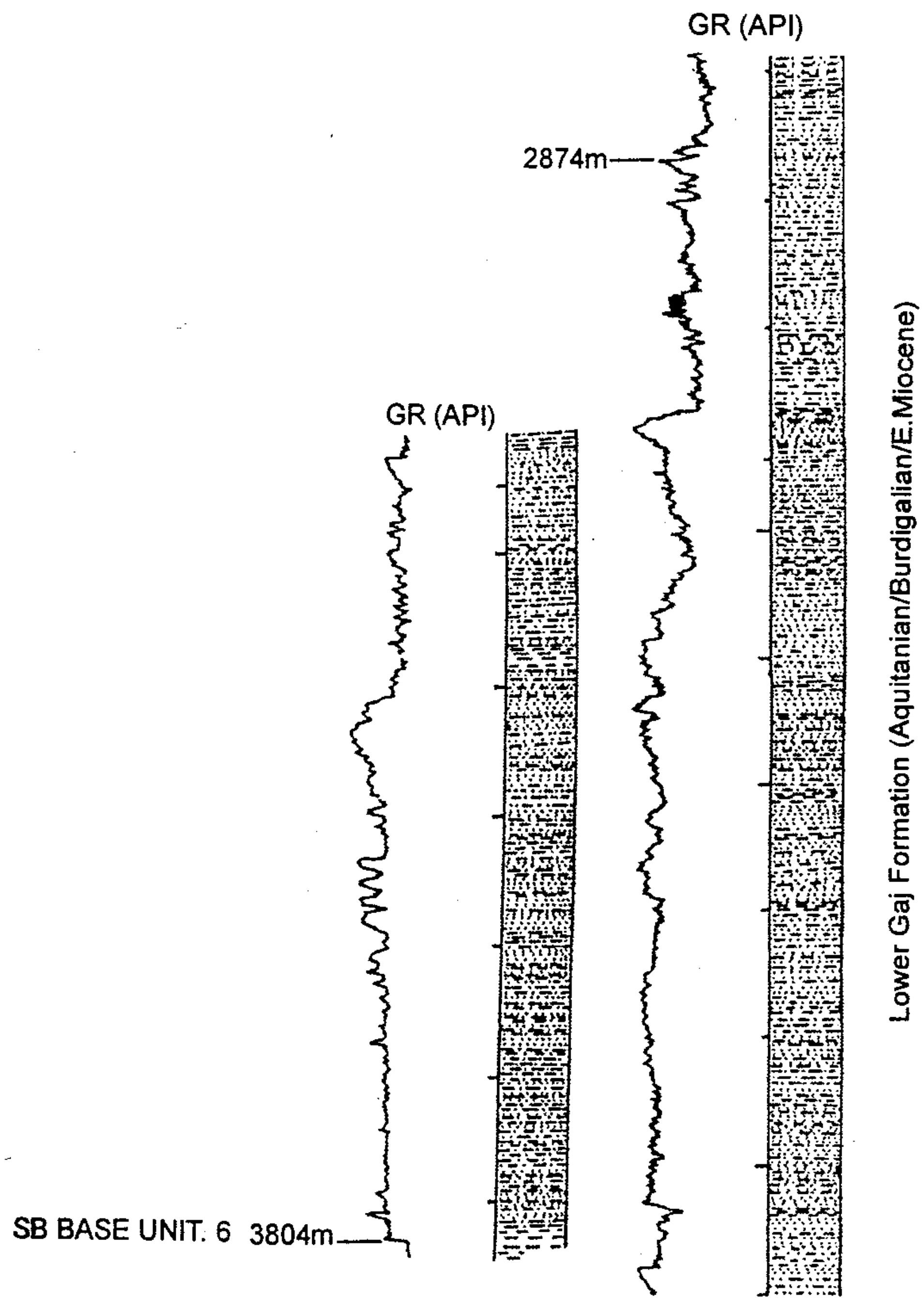

Figure 7- Well log response to unit 6.1 (Indus Marine-B1).

Unit 6.2 (Middle Burdigalian-Early Langian)

This unit is interpreted as a highstand systems tract. It is composed of concordant seismic facies in the shelf area, which indicates that the relative rise in sea level was equal to the rate of sediment deposition in the shelf. Along the slope this systems tract is composed of sigmoidal clinoforms (Figure 5). These clinoforms downlap the underlying boundary of unit 6.1 with unit 6.2. The basinward movement of clinoforms beyond the shelf edge represents progradation of sediment in southwest. This unit thins eastward toward the shelf and thickens in the west beyond the shelf edge in the deeper part of basin (Figure 4 and 5).

The shape of clinoforms is disrupted in the area of well developed normal faults. Unit 6.2 is equivalent to about 1363m thick siliciclastic sediments in the basin area well Indus Marine-B1 (Figure 9). The time thickness map of unit 6.2 indicates that thickest sediments are preserved in an area between the wells Indus Marine-B1 and Karachi South-1 (Figure 10).

Unit 6.3 (Langian)

This unit is interpreted as a transgressive systems tract. It comprises of concordant seismic facies in the shelf area and is disrupted in the basinal area where normal faults are well developed. It has apparent truncation below with the underlying unit 6.2 along the slope and downlap terminations above on its upper boundary with the overlying sequence T7 (Figure 5). This systems tract is equivalent to about 926m thick siliciclastic sediments of Gaj Formation in the well Indus Marine-B1 (Figure 11). The log curve indicates small scale finning and coarsening upward parasequences in the lower section and blocky shape in the upper part in the basin area well Indus Marine-B1 (Figure 11). The time thickness map of unit 6.3 indicates that the sediments are thickest in a SW direction of the well Indus Marine-B1 (Figure 12). It thins eastward toward the shelf and penetrated 387m siliciclastic in the well Karachi South-1 (Figure 4 and 12).

Sequence T6 in the Early Neogene is found important with existence of reservoir quality sandstone and hydrocarbon source rock within its systems tracts. Most of the basin area wells in the Offshore Indus Basin proved existence of hydrocarbon by test and shows. Enormous normal and rollover structural features and their compartments remains undrilled at this level. Similar normal and rollover structural features with existence of same reservoir and source rocks have been found hydrocarbon bearing in various extensional basins like Sirte, Niger, Chad, Gulf of Mexico and Offshore Louisiana (Moretti, 1998, Alexander and Handschy, 1998). The Offshore Indus Basin has type-II kerogene producing source rocks in the intra formational shales of the Early-Middle Miocene Gaj Formation, as interpreted by Baloch and Quirk while using the data of the wells for evaluation of tectonic subsidence and hydrocarbon generation of the Offshore Indus Basin of Pakistan.

Sequence T7 (Langian/Miocene)

Observations

The lower boundary of T7 is interpreted as a variable medium to low amplitude reflection with apparent truncation below and onlap above in the shelf area. It represents an erosional boundary with the underlying sequence T6 (Figure 13 and 14). The upper boundary of sequence T7 is a medium to high amplitude reflection. The lower boundary of T7 represents incisions with numerous channels and have no significant levees. Internally, medium to low amplitude and closely spaced seismic facies are observed within this sequence.

Interpretation

This sequence is equivalent to about 926m thick interval in the well Indus Marine-B1. Its lower about 200m thick interval represents a finning upward trend of parasequences indicating transgression. The top of this finning upward trend contains abundant planktonic foraminifera. This may represent a flooding surface. It is overlain by a thick interval of above 700m of coarsening upward parasequences trend on the GR log curve in the same well. It may represent

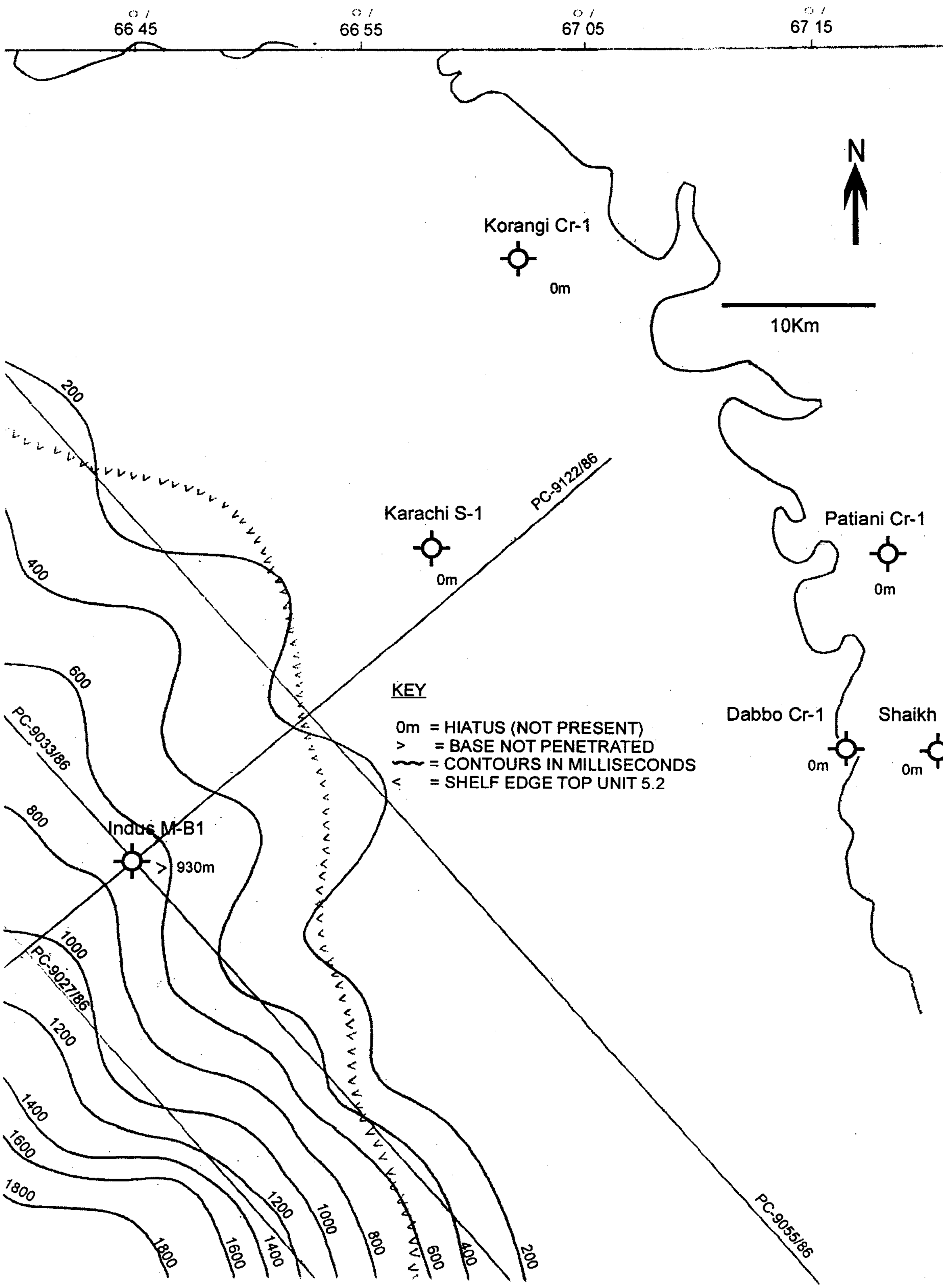

Figure 8- Isotime thickness map of unit 6.1.

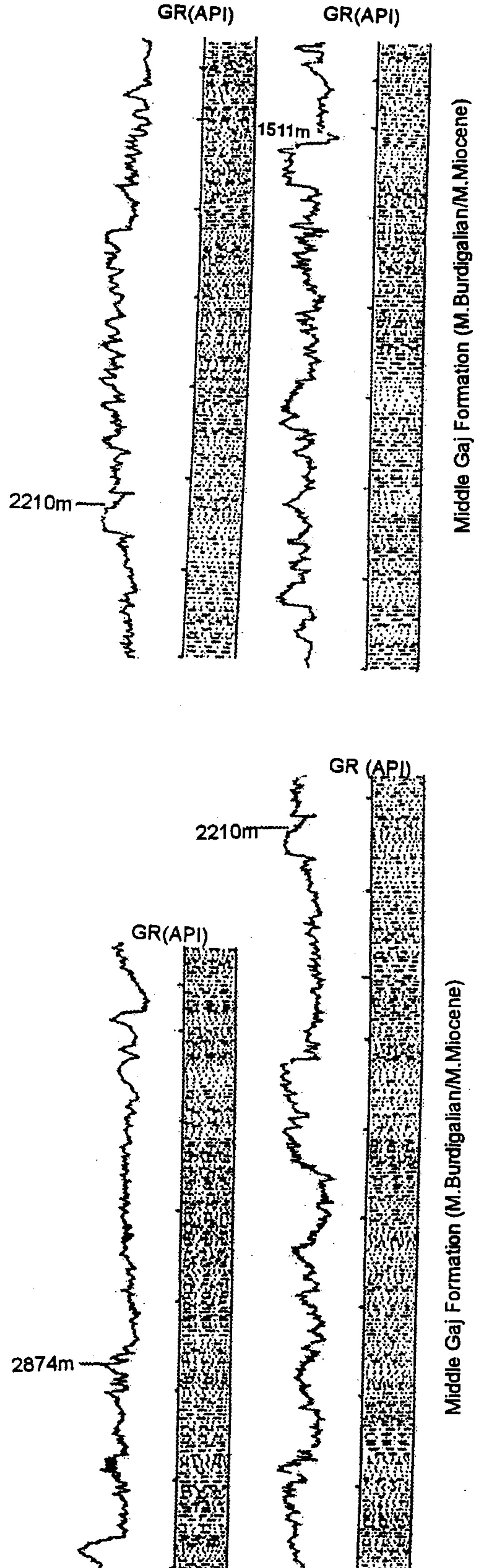

Figure 9- Well log response to unit 6.2 (Indus Marine-B1).

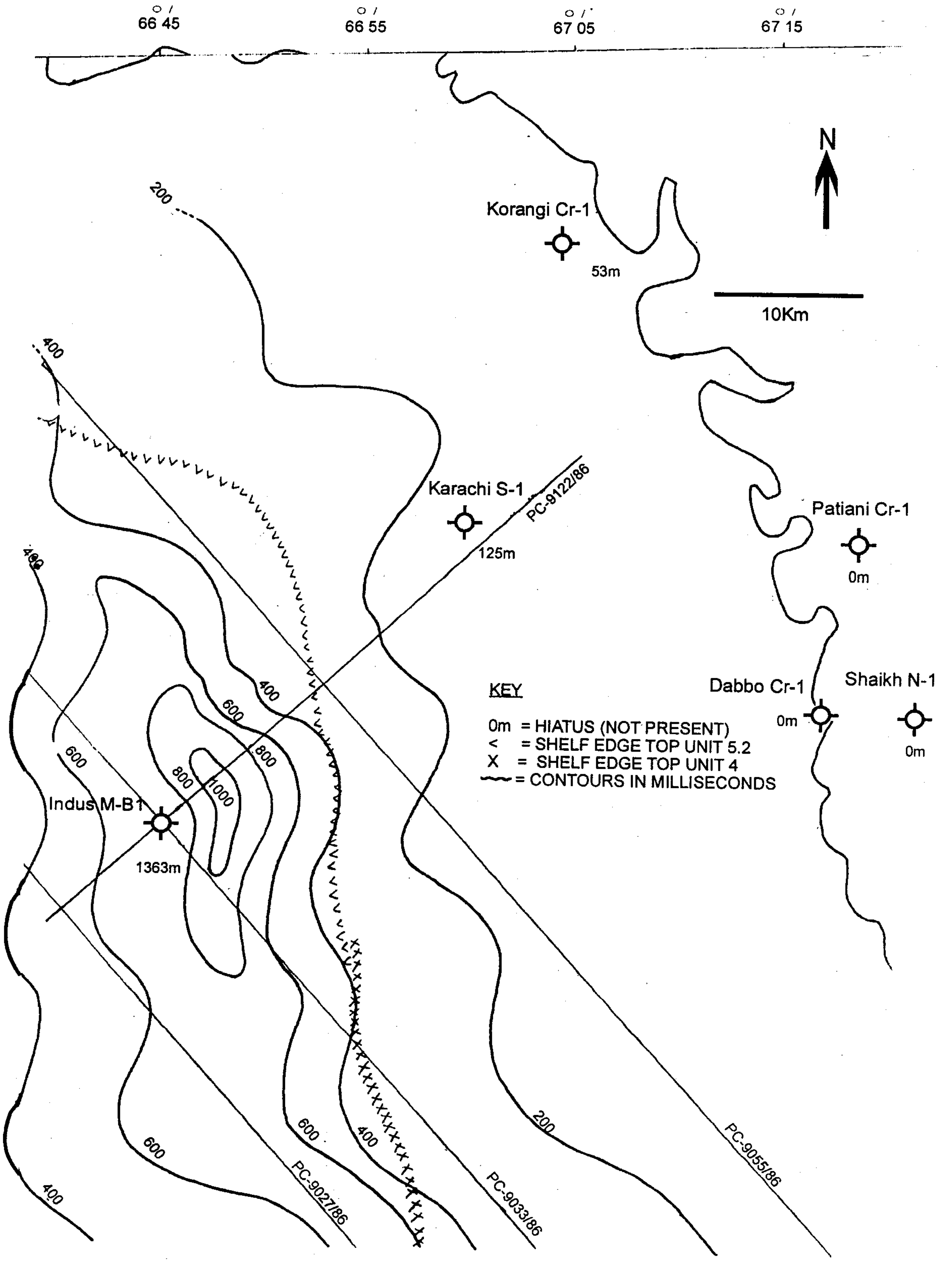

Figure 10- Isotime thickness map of unit 6.2.

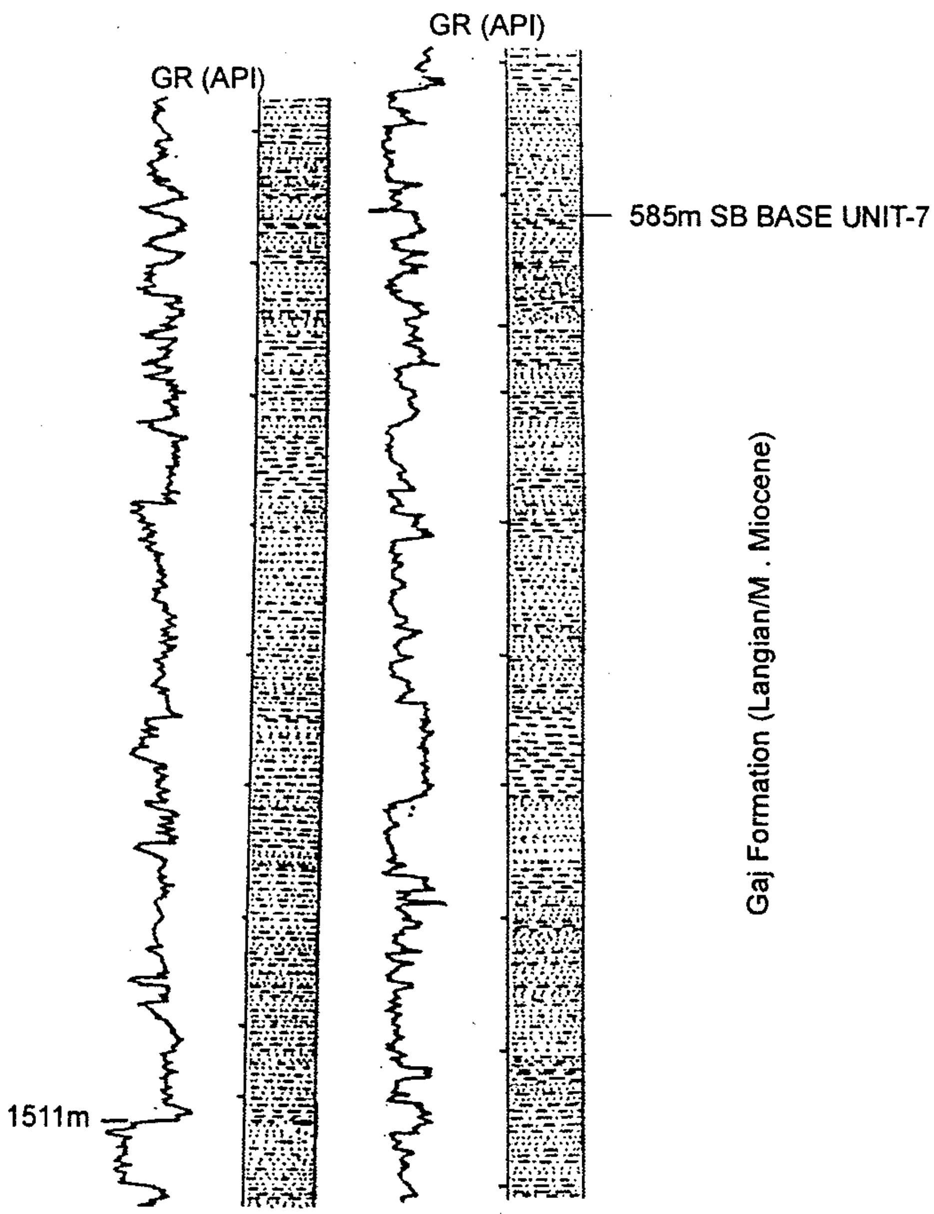

Figure 11- Well log response to unit 6.3 (Indus Marine-B1).

highstand of sea level at this sequence. The upper part of the coarsening upward parasequences contains larger forminifera (Shaw, 1965, Martin, 1973, Robertson Research, 1978, Nuricon Petroservices, 1990).

Sequence T7 represents significant incisions in the underlying sequence T6 down to twt 0.4-0.5 seconds with a width of 6-7km and filled with parallel to sub-parallel seismic facies (Figure 13 and 14).

Sequence T8 (Tortonian-Messenian/Miocene)

Observations

The lower boundary of T8 is interpreted as a medium to high amplitude reflection with concordant seismic reflection facies below and above in the shelf area, separating sequence T8 from T7. The upper boundary of T8 has medium amplitude with apparent truncation below and onlap above (Figure 13 and 14). This boundary is produced between the sequences T8 and T9. The internal seismic facies of sequence T8 are composed of medium to high amplitude with medium to close space seismic facies. It is composed of alternating sandstone, shale and claystone with interbeds of marl and trace pyrite and forams in the wells Pakcan-1 and Sadaf-1.

Interpretation

Sequence T8 is equivalent to about 171m thick finning and coarsening upward trends of parasequences on GR log curve in the well Indus Marine-B1. The lower about 90m thick interval represents a finning upward trend of parasequences. The top of this finning upward parasequences contains abundant planktonic foraminifera. This may represent a flooding surface. It is overlain by a thick interval of above 81m of coarsening upward parasequences trend on the GR log curve in the same well. The lower part of this interval contains minor amount of microforams with decreasing upward trend in their number and presence of larger foraminifera and shell fragments (Shaw, 1965, Martin, 1973, Robertson Research, 1978, Nuricon Petroservices, 1990). This has concordant stratal pattern on seismic profiles in the shelf area and occasionally disrupted in the basin area due to faulting. This sequence bears significant incision with parallel to sub parallel valley filled seismic facies.

Sequence T9 (Lower Siwaliks/Pliocene)

Observations

The lower boundary of sequence T9 is interpreted as a medium amplitude reflection with erosional truncation below and onlap above, separating sequence T9 from the underlying sequence T8 (Figure 6, 13 and 14). The upper boundary of this sequence has apparent truncation below and downlap above, separating sequence T9 from the overlying sequence. The internal seismic facies of this sequence have medium to high amplitude with medium spacing. Incisions were observed down to twt 0.5-0.6 seconds with a width of 5-6km, filled with chaotic seismic facies. In the southern part of basin the incision have significant channel levee relief.

Interpretation

This sequence is equivalent to 107m thick coarsening upward trend of parasequences on GR log curve in the well Indus Marine-B1. It posses concordant stratal pattern on seismic profile in the shelf area and occasionally disrupted in the basin area due to upward extension of normal faults.

Sequence T10 (Upper Siwaliks Pleistocene)

Observations

The lower boundary of sequence T10 is interpreted as a medium to low amplitude reflection with erosional truncation below and onlap above. This boundary separates sequence T10 from the underlying sequence T9. The upper boundary of sequence T10 is interpreted as a medium to high amplitude reflection with erosional truncation below and onlap above. This boundary separates T10 from the

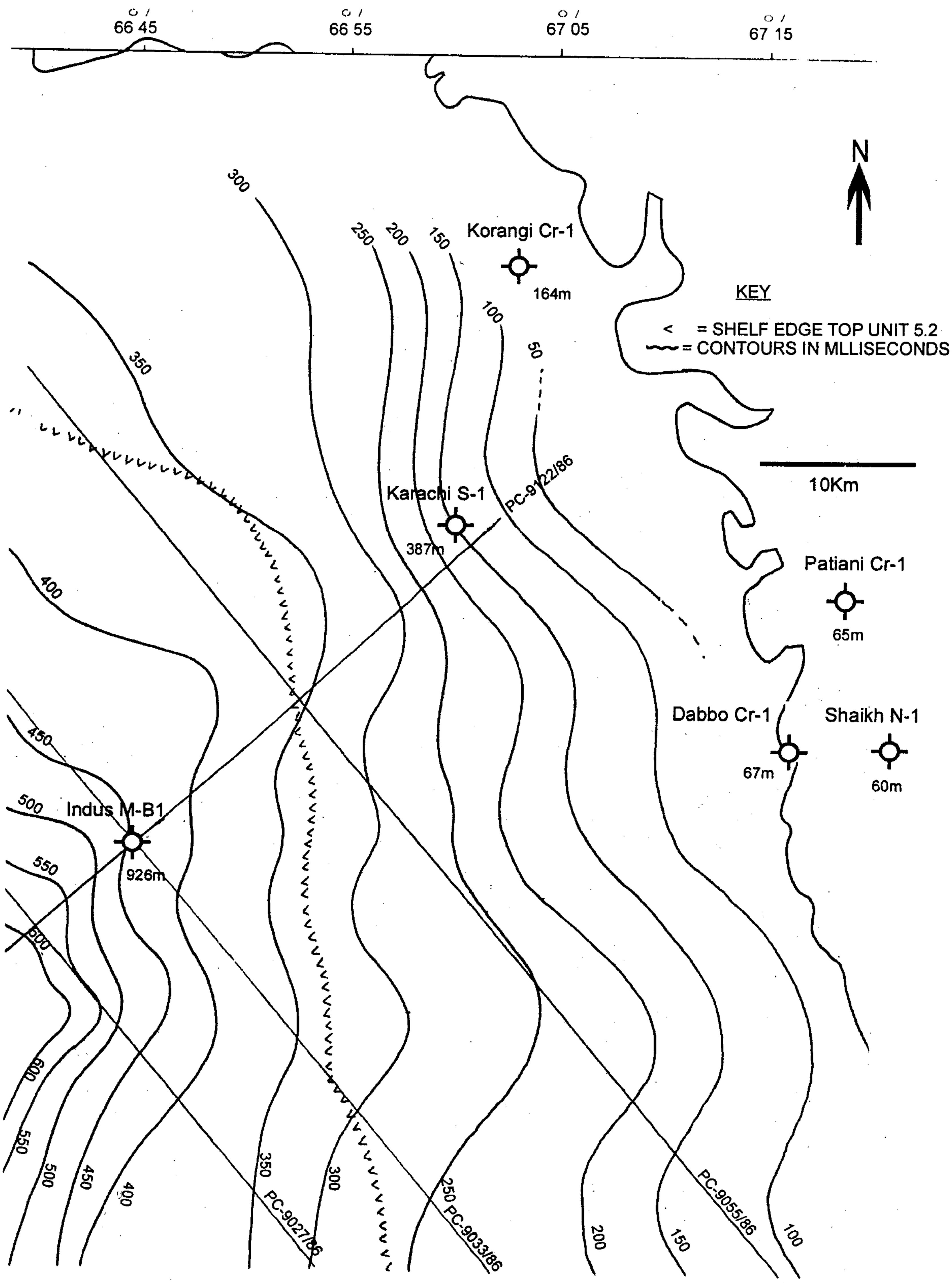

Figure 12- Isotime thickness map of unit 6.3.

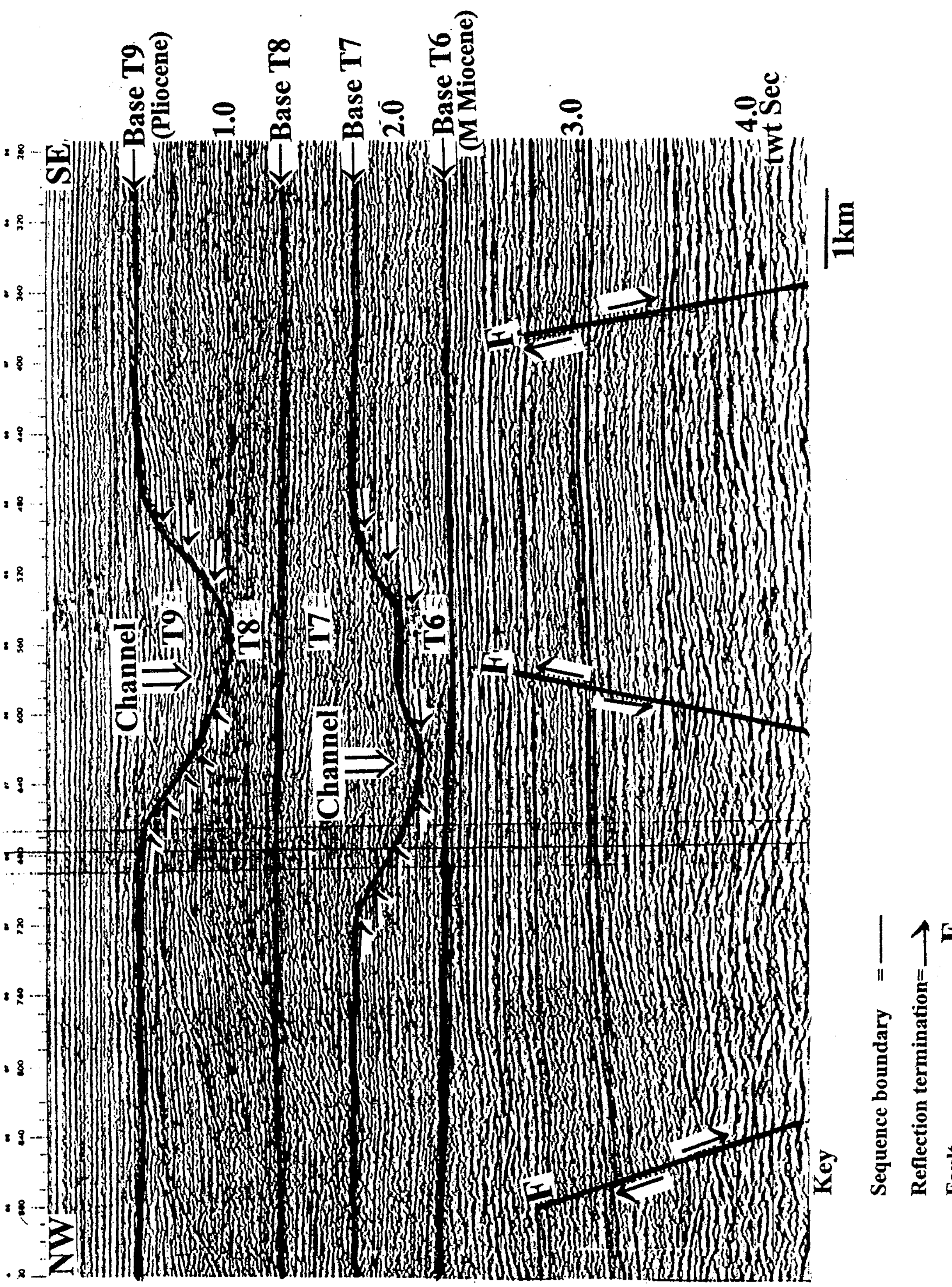

Figure 13- Seismic profile showing incisions in Miocene and Pliocene siliciclastic sequences.

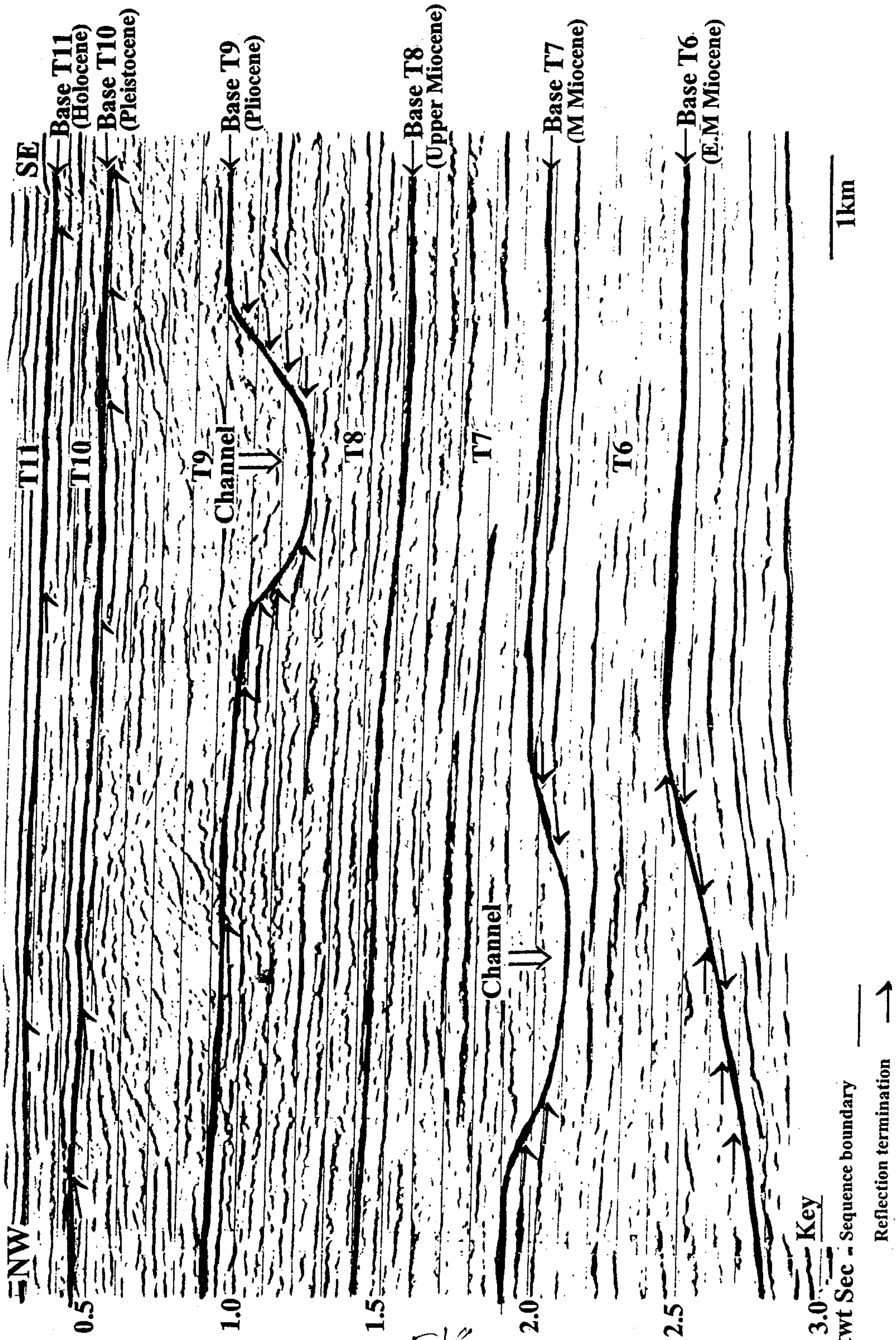

Figure 14- Seismic profile showing the position of Neogene and younger sequences with significant incisions.

overlying sequence T11 (Figure 15). Internal facies of sequence T10 indicates medium to high amplitude with medium to close spacing reflections. The incisions are filled with chaotic seismic facies and have high channel levee relief (Figure 15).

Interpretation

This sequence is equivalent to about 500m thick finning/coarsening upward trend of parasequences on GR log curve in the well Sadaf-1. It has concordant stratal pattern on seismic profiles in the shelf area (Figure 14) and occasionally disrupted in the basin area (Figure 15). It represents incision with well-developed valley and levee relief with exceeding width of 100m down to vertical incision of twt 0.5-0.7seconds. These channels may be produced as an effect of lowstand of sea level and later on filled during the highstand of sea level. An other reason for such incision has been associated with the turbidity currents. The low scale turbidity current may play an important part of filling in these channels. The transparent facies filled in the incised valleys may represent pelagic sediments (Kolla and Coumes, 1987).

Sequence T11 (Holocene Recent)

Observations

The lower boundary of sequence T11 is interpreted as a medium to high amplitude reflection with erosional truncation below and onlap above. It represents an erosional boundary between the sequences T10 and T11. The upper boundary of sequence T11 is interpreted as a medium to low amplitude reflection. Internally T11 is composed of medium to high amplitude with medium spaced seismic facies. This sequence represents significant incisions into the underlying sequence T10 down to twt 0.6-0.8 seconds with a width of 7-8km (Figure 15). These incised valleys are filled with wavy seismic facies.

Interpretation

This sequence is equivalent to about 214m thick finning and coarsening upward trend of parasequences on GR log curve in the well Sadaf-1. It has concordant stratal pattern on the seismic profiles in the northern part of the basin in the shelf area (Figure 14). This sequence is significantly incised down to twt 0.6-0.8 seconds (Figure 15). These younger incisions represent high valley and levees relief with wavy facies fill. The incisions may result as an effect of lowstand of sea level or turbidity current effect and the valley was filled later during the highstand of sea level.

The younger strata incised into the underlying sequence T11 down to twt 0.6-0.8 seconds with a width of 10-11km and were filled later with sub-parallel seismic facies during the highstand of sea level. In the recent valleys relatively high channel levee relief was observed (Figure 15).

The relative sea level curve produced for the sequences interpreted within the Paleogene and Neogene mega-units of the post-rift Tertiary megasequence, indicates the important sea level history for preservation of the interpreted sequences and their seismic units (Figure 16). The constructed profile against the dip oriented seismic lines reveals an ideal depositional model for the sequences and their units/system tracts preserved within the Tartiary megasequence of the Offshore Indus Basin (Figure 17). This model represents a ramp with predominantly preserved carbonate sequences and their units shelfward in the east in the Paleogene mega-unit and siliciclastic dominated sequences and their system tracts in the Neogene mega-unit are thickest beyond the shelf edge westward in the deeper part of basin (Figure 17).

SUMMARY

- The concept of sequence stratigraphy has primarily been evolved from interpretation of seismic reflections, while carrying out the seismic stratigraphic interpretation and its integration with the well data for this basin.
- The sequence stratigraphic signature is controlled by sediment accumulation rate relative to the distribution and rates of accommodation creation. The accommodation in turn is controlled by slope and rate of migration of the base level associated with tectonism in this basin.
- This interpretation enabled identification of pre-rift and syn-rift megasequences in the Mesozoic and a post-rift mega sequence in the Tertiary.
- The pre-rift includes the basement Chiltan Formation (Bathonian-Callovian/Jurassic), Sembar Formation (Neocomian-Aptian/Cretaceous), Lower Goru Formation (Albian/Cretaceous), Upper Goru Formation (Cenomanian-Turonian/Cretaceous) and Parh Formations (Early Maastrichtian/Cretaceous).

Table 1. Stratal characteristics of the Neogene and Quaternary siliciclastic sequences in the Offshore Indus Basin.

Sequence (units)	Sediment Type (Well)	Shelf Area	Basinal Area
T11	Siliciclastic (Sadaf-1)	Concordant	Thickest
T10	Siliciclastic (Sadaf-1)	Concordant	Thickest.
T9	Siliciclastic (Indus Marine-B1)	Concordant	Thickest and partially disrupted
T8	Siliciclastic (Indus Marine-B1)	Concordant	Thickest and partially disrupted
T7	Siliciclastic (Indus Marine-B1)	Concordant	Thickest and disrupted
T6(unit-6.3)	Siliciclastic (Indus Marine-B1)	Concordant	Thickest and disrupted.
T6(unit-6.2)	Siliciclastic (Indus Marine-B1)	Concordant	Thickest and downlaps the underlying boundary with unit 6.1.
T6(unit-6.1)	Siliciclastic (Indus Marine-B1)	Absent	Thickens towards basin centre and onlaps the underlying boundary with sequence T5.

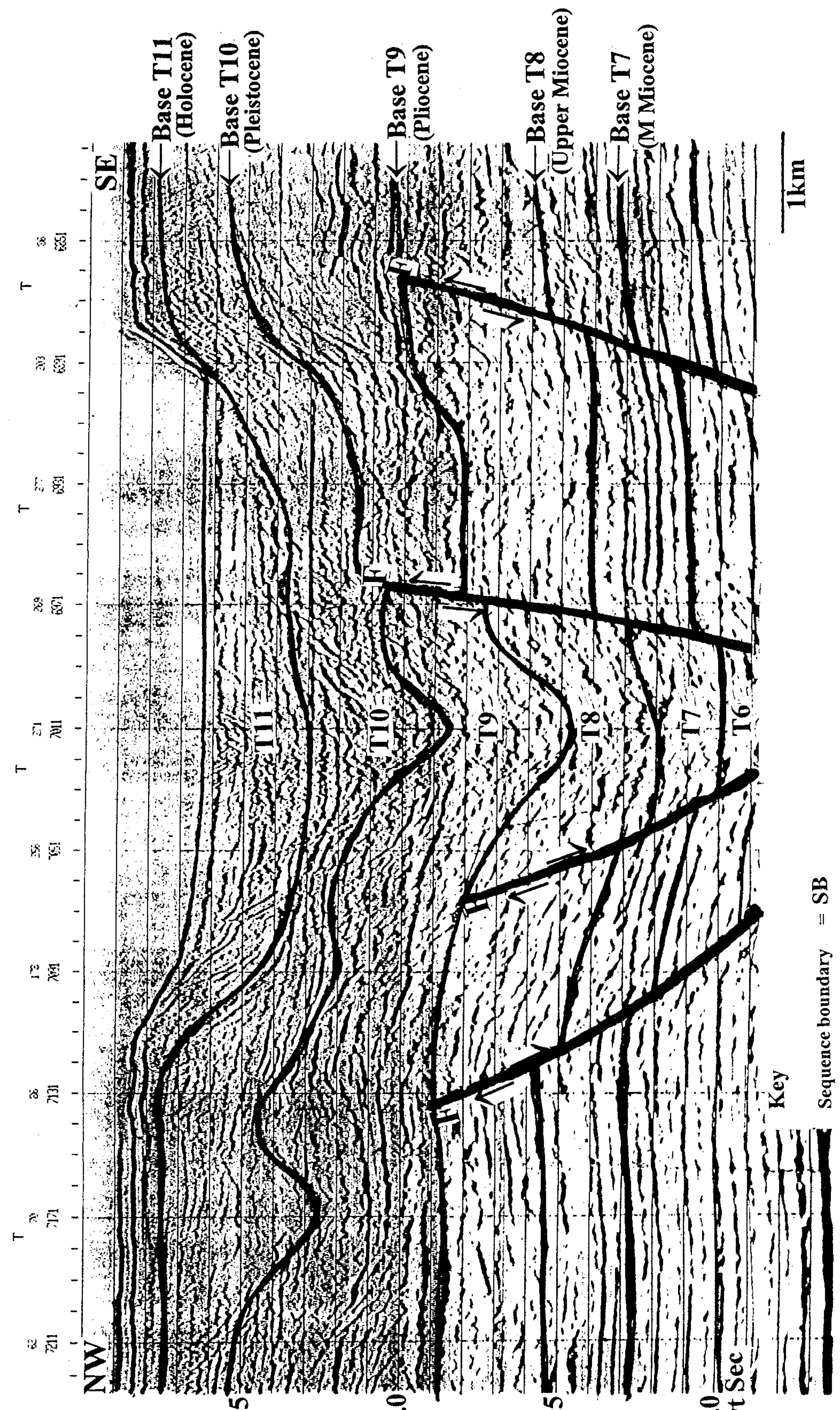

Figure 15- Seismic profile showing incisions as a combined effect of subsidence and upward extension of normal faults.

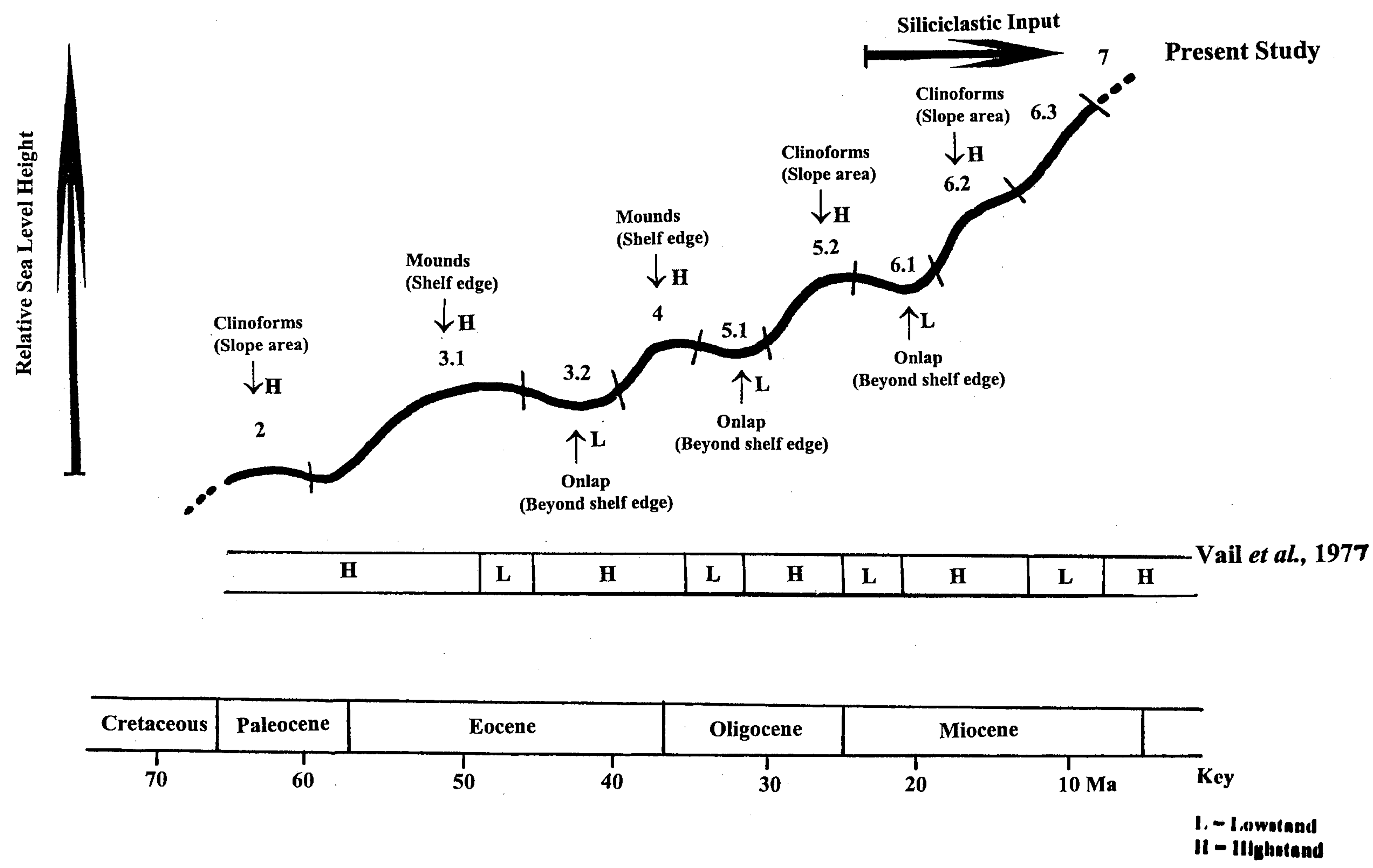

Figure 16- Relative sea level curve for the sequences interpreted within the Tertiary Post-Rift mega-sequence.

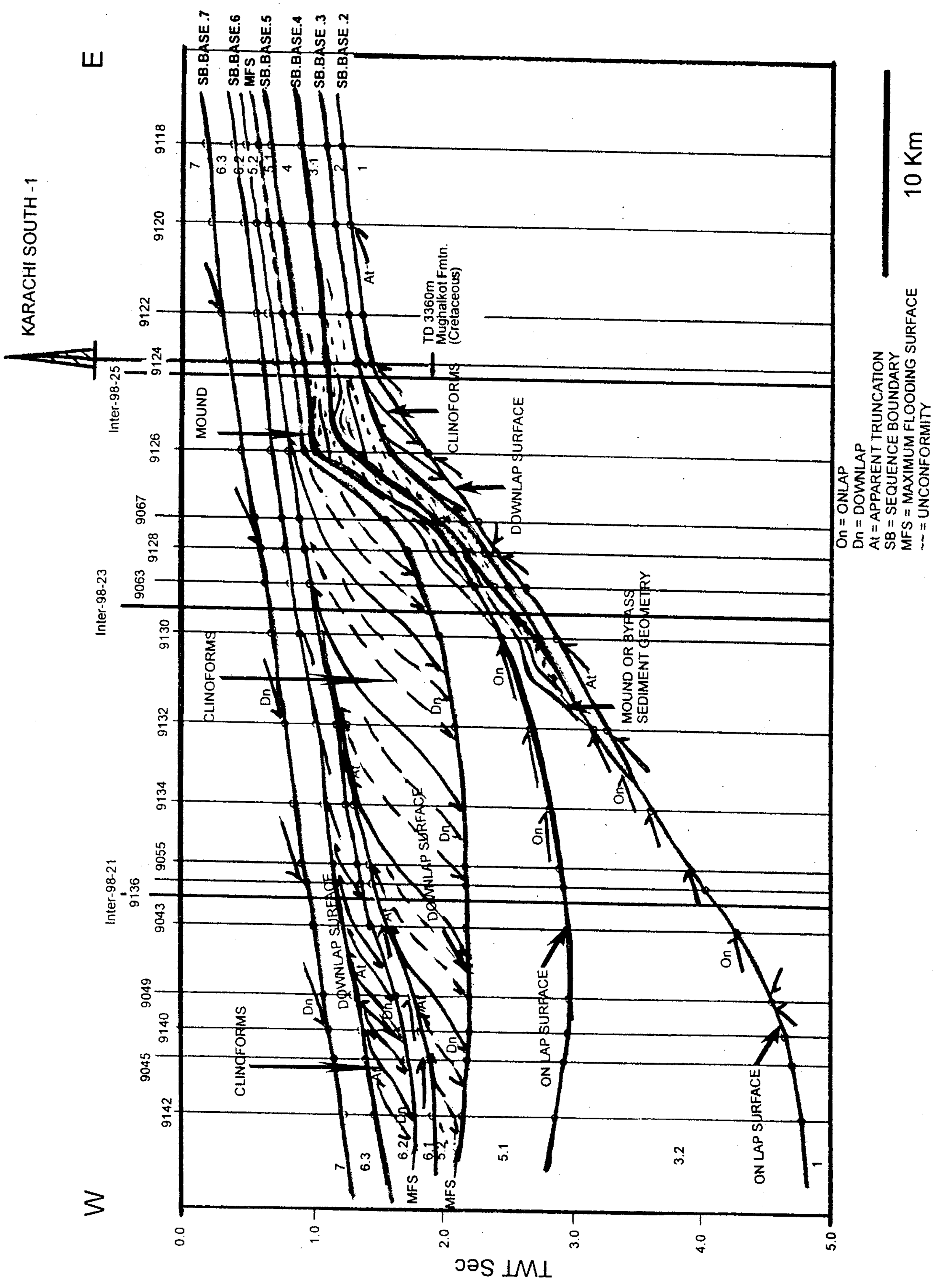

Figure 17- Constructed profile representing a depositional model for the Offshore Indus Basin of Pakistan.

- The syn-rift consists of Mughalkot and Pab Formations (Maastrichtian/Cretaceous).
- The post-rift includes Ranikot Formation (Danian-Thanitian/Paleocene), Laki/Ghazij and Kirthar Formations (Ypresian-Thanitian/Eocene), Nari Formation (Rupalian-Chatian/Oligocene), in the Paleogene mega-unit and Gaj Formation (Aquitanian-Messinian/Miocene), Siwaliks and Soan Formations (Miocene-Pliocene) in the Neogene mega-unit and younger (Pleistocene-Recent) sediments in the Quaternary mega-unit of the Offshore Indus Basin of Pakistan.
- The siliciclastic dominated Neogene and Quaternary mega-units are discussed in detailed in this paper. This comprises the important reservoir quality Early-Middle Miocene sandstone in the basal sequence of the Neogene mega-unit.
- Sequence T6 in the Early Neogene is found important with existence of reservoir quality sandstone and hydrocarbon source rock within its units/system tracts. The twt thickness maps produced for the units 6.1, 6.2 and 6.3 indicates that the objective thick and coarser sediments of Early-Middle Miocene remains undrilled.
- The relative sea level curve for the sequences of Paleogene and Neogene mega-units indicates the important sea level history of the interpreted sequences and their units.
- The constructed profile against the dip oriented seismic lines represents an ideal depositional model for the sequences and their units/systems tracts preserved within the Tartiary megasequence.

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