

Seismic stratigraphy of the offshore Indus Basin

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Abstract: In 1997 Lasmo Oil Pakistan Ltd (Lasmo) gained a significant position in the offshore Indus Basin with the award of the Indus A and B Blocks. The main hydrocarbon play comprises Miocene shelf-delta sands interbedded with intraformational shale seals and sourced by gas-prone offshore equivalents. Approximately 12 000 km of seismic data have been interpreted in the detailed evaluation of these blocks. However, only four wells have tested the preferred play type and no core or rock data were available to provide further insights into facies or age dating. Log data from two key wells in the offshore Indus area record the initial infilling of the basin by shale-dominated basinal or outer shelf sediments, followed by stacked thin-bedded sandstone-shale sequences of a shelf-delta nature. A zone of progradational sequences marks the transition between the two, but no other workable stratigraphic divisions were apparent. Regional seismic correlation established the diachronous nature of the prograding shelf package and this was matched by distinct bands of seismic progrades. A series of simple palaeogeographies of the prograding shelf margin were developed showing initial sediment input from the north and rapid progradation towards the south and west. The Oligo-Miocene basin fill of the offshore Indus Basin appears to be a 'one-step' fill process of a significant depocentre created between the Karachi Platform and the Murray Ridge. Canyons are a very distinct feature on seismic profiles and two main phases of development are apparent. The earlier phase is interpreted to be of Early Miocene age. Downcutting at this time rarely exceeded 400 m. The second phase of canyon development occurred during Plio-Pleistocene time, and these younger canyons often dominate the shallow section, with multiple phases of downcutting sometimes exceeding 1000 m. Where drilled, canyons of both ages have been found to be shale prone. These drilled canyons are interpreted to be on the palaeo-slope where erosion and sediment-by-pass occurred during the active phase, and were subsequently filled by fine-grained deposits after abandonment. The two phases of canyoning are considered to relate to phases of tectonic activity in the collision zone between the western margin of the Indo-Pakistan plate and the Eurasian plate.

Lasmo Oil Pakistan Ltd ('Lasmo') signed exploration agreements with DGPC of Pakistan on 21 September 1997 for two substantial offshore blocks, Indus A and B, totalling 14 704 km². The initial exploration term was for 3 years, but at each anniversary, the blocks could be relinquished entirely, or renewed upon committing to a pre-agreed minimum work programme. The first renewal required 1500 km seismic acquisition per block and the second required one exploratory well to be drilled in each block. On the basis of the prospectivity perceived after Year 1, Lasmo elected to renew the A Block but relinquished the B Block. Offshore Indus F Block was a new block successfully applied for, and awarded on 1 December 1998. It covered 67% of the original B Block and carried a first year commitment of

850 km of seismic acquisition. The outlines of the Indus A and F blocks are shown in figures as reference to the main study area.

A seismic acquisition campaign collected 3659 km of 2D data across the A and F blocks in November and December 1998, infilling and extending existing coverage across both blocks. During 1999, Lasmo interpreted and incorporated all the new data but did not elect to renew either licence on their anniversary dates.

The Indus A and F blocks lie in the nearshore zone, south and east of Karachi and offshore from the present-day Indus delta. The regional water depth map (Fig. 1) shows that the blocks are located within the broad (60–80 km wide) shelf. Water depths increase gradually to 200 m and thereafter, slopes increase to 1000 m or more.

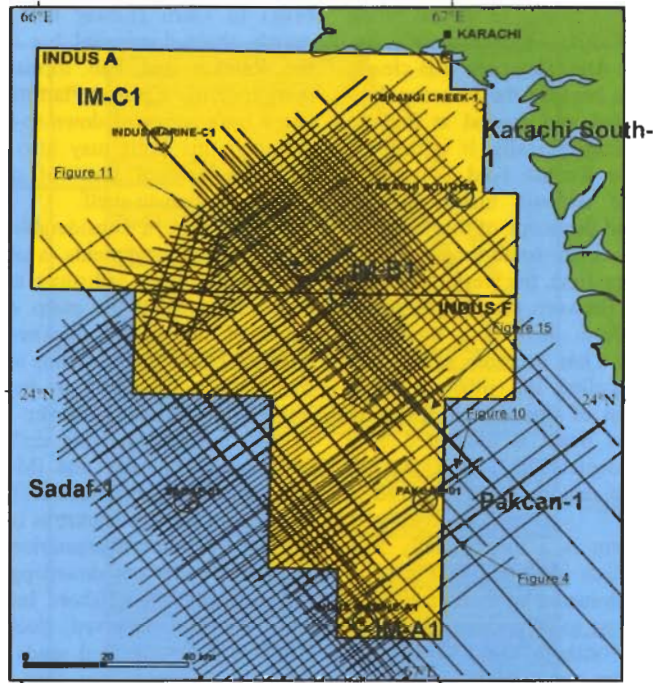


Fig. 2. Digital seismic and well database. Locations of seismic figures are indicated.

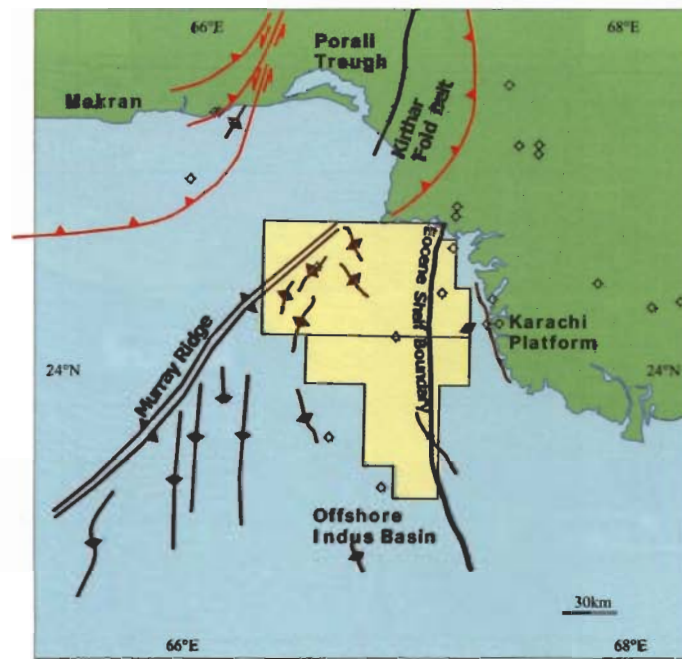


Fig. 3. Miocene tectonic elements. Main Murray Ridge Anticlinorium and other anticline axes are labelled. Eastern limits of Makran and Kirthar Fold Belt provinces are indicated by thrust fault with triangles symbol. Lasmø Indus A and F blocks are highlighted.

Indus A and F blocks lie mostly to the SE of the NE-trending Murray Ridge, which is poorly imaged by sparse seismic data. However, it is clearly a major structural high because the Miocene (and younger) beds are tilted and eroded at the sea floor on its flanks. Geographically, it is the offshore extension of the Kirthar Fold Belt but a detailed study of the tectonic history of the Murray Ridge is beyond the scope of this study.

Figure 3 shows the north-south-trending shelf boundary at mid-Eocene time, the western limit of the Karachi Platform. Between the Murray Ridge and the Karachi Platform there is a significant depocentre containing 6 km or more of Tertiary sediments and here called the offshore Indus Basin. The relationship of the Karachi Platform and the offshore Indus Basin is illustrated by a regional seismic line depicted in Fig. 4, and the stratigraphy of the two regions is summarized in Fig. 5.

The Karachi Platform is a monoclinal SW-dipping unit. The portion identified in Fig. 4 as 'Paleogene shelf' is dominated by shelf carbonates ranging from mid-Eocene to Oligocene age, which are equivalents of the onshore Laki, Kirthar and Nari formations. Deeper penetrations from some of the nearshore drilling have encountered older formations, ranging down through Ranikot (Paleo-

cene) to Goru (Lower Cretaceous) formations, mostly shale dominated but with some sands in the Ranikot and Pab formations. The western margin of the Karachi Platform is abruptly terminated by a series of down-to-basin normal faults, although this limit may also coincide in places with the western limit of progradation of the Tertiary carbonate shelf.

To the west, a considerable thickness of post-Lower Eocene sediments is observed, much of it seismically rather indistinct and appearing to be passively infilling the steep eastern margin. Because of their great thickness, these strata are untested by drilling and they are therefore inferred by seismic correlation to be of Oligocene and Early Miocene age. However, the uppermost parts of this basinal fill were drilled by the deepest sections of Pakcan-1 and IM-B1, both of which encountered shaley sections. The apparently 'passive' fill of the depocentre is capped by a prograding seismic unit characterized by seismic-scale sigmoidal reflectors downlapping into the basin. Subsequently, the offshore Indus Basin and Karachi Platform received thick deposits (1000–2000 m) of interbedded sands and shales of Mid- to Late Miocene age that are interpreted as shallow-water shelf or deltaic deposits. Overlying this is a widespread muddy shelf unit of Pliocene

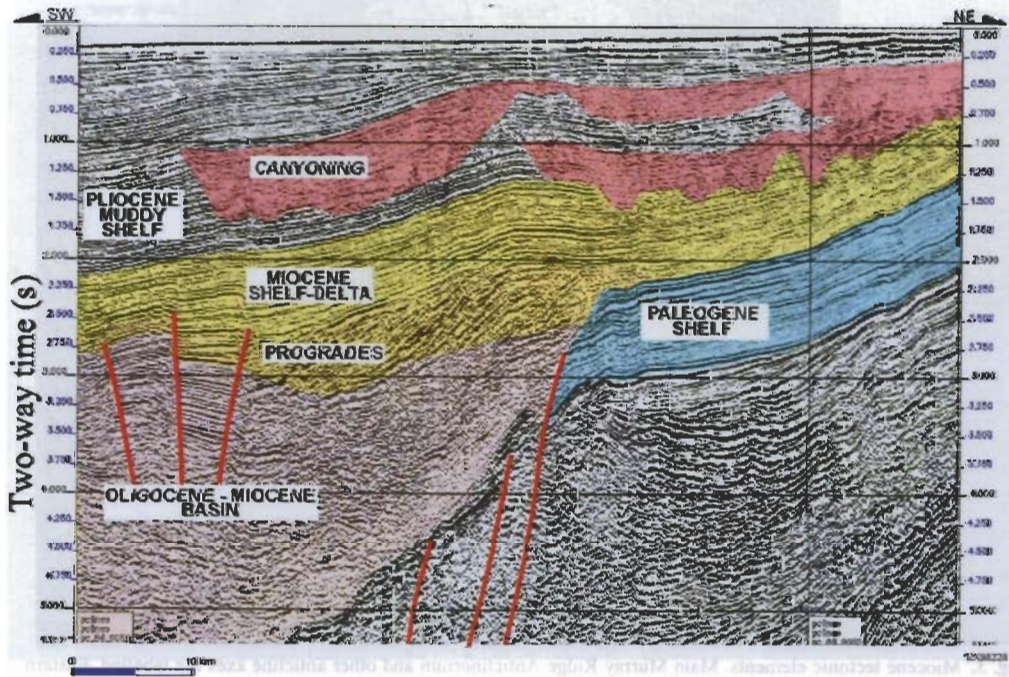


Fig. 4. Regional seismic line.

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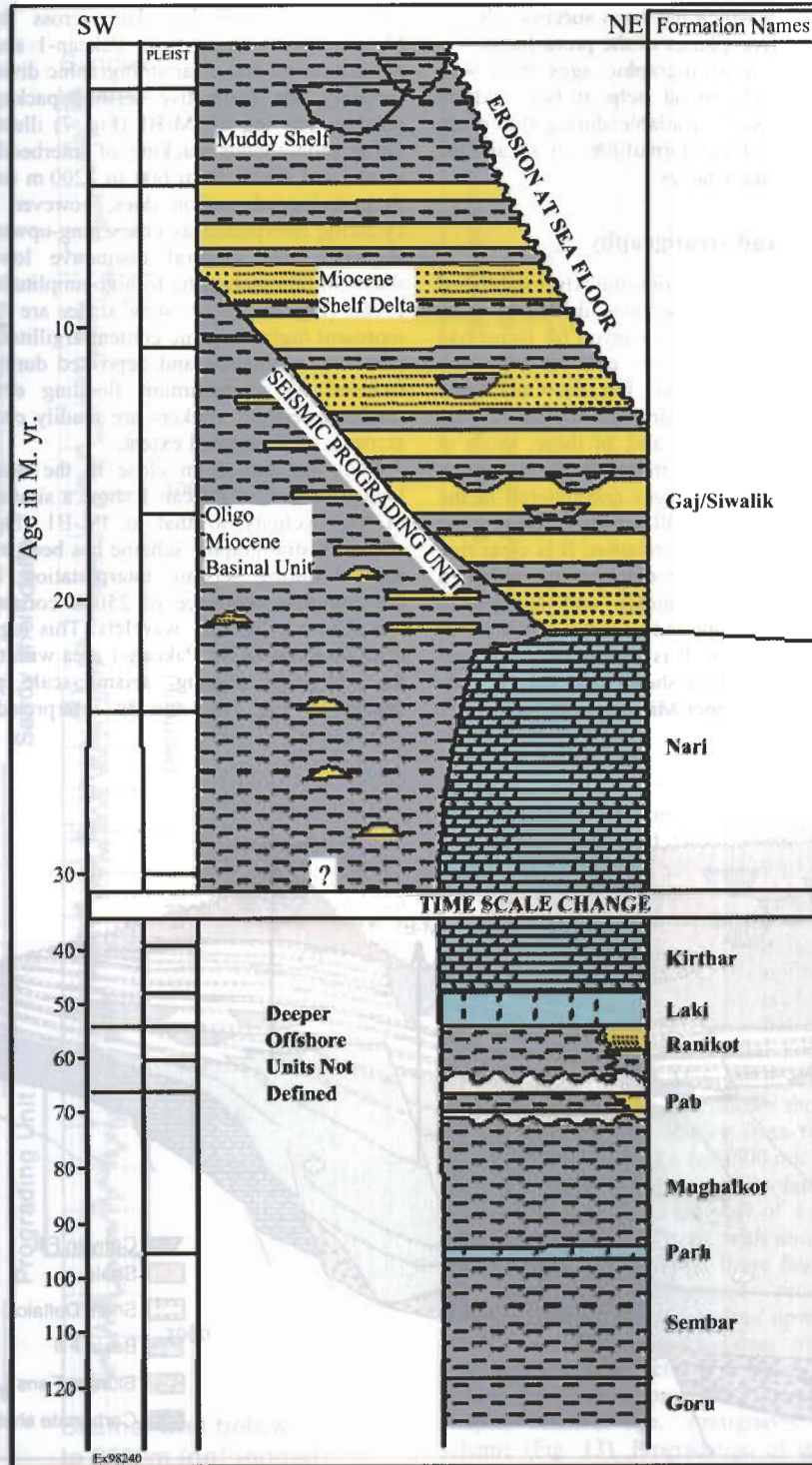
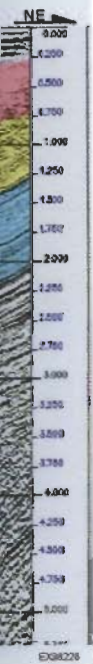


Fig. 5. Offshore Indus stratigraphic column.

formations, sands in the western... terminal faults, in places... of the... of post-... much of it... ing to be... margin. Be-... strata are... inferred... ocene and... most parts... the deepest... of which... ntly 'pas-... a prograd-... mic-scale... the basin... and Kar-... s (1000-... s of Mid-... rpreted as... Overlying... f Pliocene



and younger age, which has been successively cut by extensive canyon phases of the proto-Indus.

Unfortunately, biostratigraphic ages from well reports are of only broad help at best and no samples or core were available during this study to confirm ages of the formations, or to aid the interpretation of their facies.

Seismic data and stratigraphy

Regional seismic correlations quickly established the relationships of the sections drilled to date, and it was recognized where canyon fill facies had been penetrated, helping to put reported age determinations into context (Fig. 6). Only three wells have penetrated the targeted Miocene clastic rock reservoir-seal system and, of these, sands at Sadaf-1 are thinner and more distal in nature. Several of the shale packages encountered in the existing wells are canyon fill deposits, and at some levels, this impedes log correlation. It is clear that the sandy shelf facies are diachronous, although the overlying Pliocene muddy unit appears to represent a fairly abrupt and possibly synchronous event across the region. It is also worth emphasizing that this correlation shows that IM-1A only just penetrated the Upper Miocene sediments.

Examining well log data across the sandy Miocene shelf strata from Pakcan-1 and IM-B1 did not reveal any clear stratigraphic divisions and certainly few distinctive seismic packages were notable. The log of IM-B1 (Fig. 7) illustrates the rather monotonous stacking of interbedded sandstones and shales from 600 to 2200 m depth. The deepest logged section does, however, reveal a cyclicity, interpreted as coarsening-upwards parasequence sets. Several distinctive low-velocity shales in this section tie to high-amplitude seismic events (Fig. 8). These 'slow' shales are thought to represent higher organic content argillites, perhaps relatively condensed and deposited during a time spanned by a maximum flooding event. The resulting seismic markers are readily correlatable across a semi-regional extent.

Well log data from close to the base of the logged section in Pakcan-1 show a similar pattern of log cyclicity to that at IM-B1 (Fig. 9). A sequence stratigraphic scheme has been tentatively applied during seismic interpretation. However, the complete sequence of 250 m corresponds to less than two seismic wavelets. This log package does correlate in the Pakcan-1 area with the top of the obliquely dipping, seismic-scale progrades shown in Fig. 10, and is interpreted as the

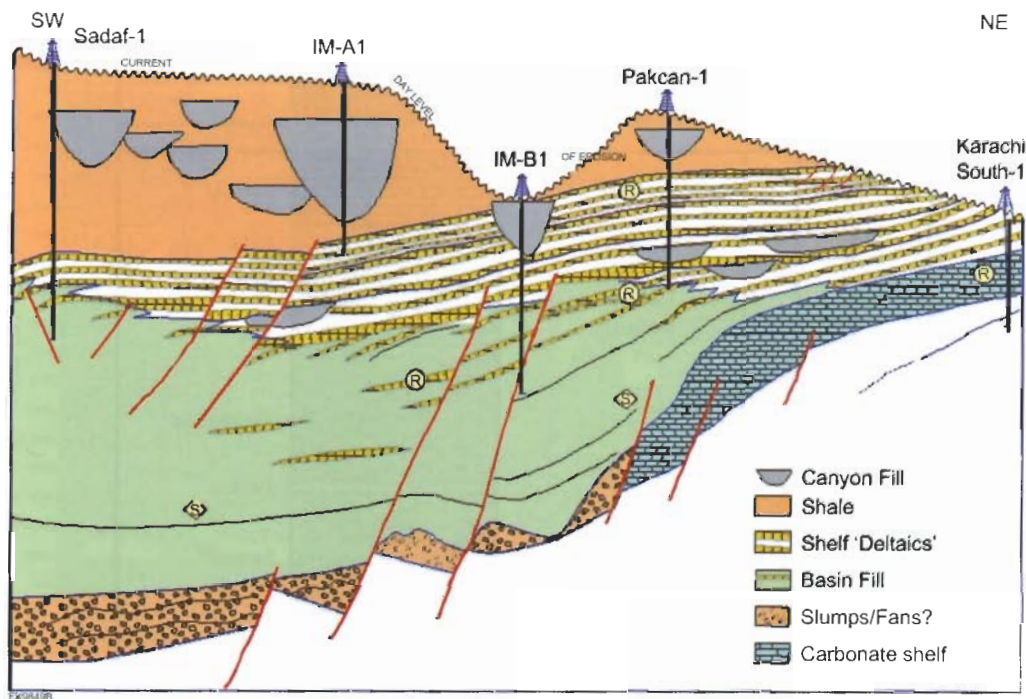


Fig. 6. Schematic correlation of Oligo-Miocene lithostratigraphy. Vertical section c. 6 km, section length c. 100 km. R in circle indicates possible hydrocarbon reservoirs. S in diamonds indicates possible hydrocarbon source.

Fig. 7. Gar
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the sandy and IM-B1 divisions and stages were ascertained. This illustrates the increased sand depth. The logs, however, reveal a gradual increase in sand towards paraclastic velocity units. It is thought that this may be a time-related event. The correlation is not as clear as the

base of the unit (Fig. 9). A tentative correlation is shown. However, this corresponds to the top of the progrades and is not as clear as the



at a distance of 100 km.

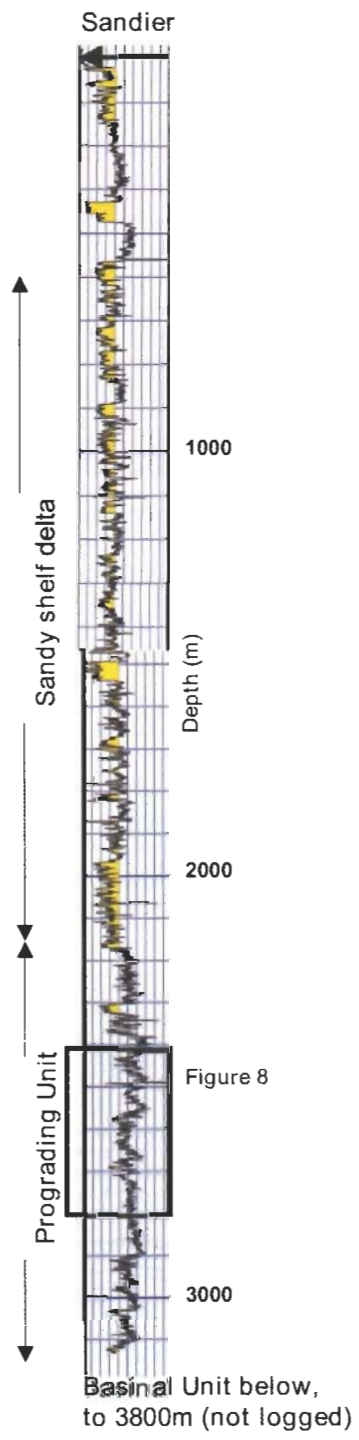


Fig. 7. Gamma well log from IM-B1, indicating the main sandier v. shale sections.

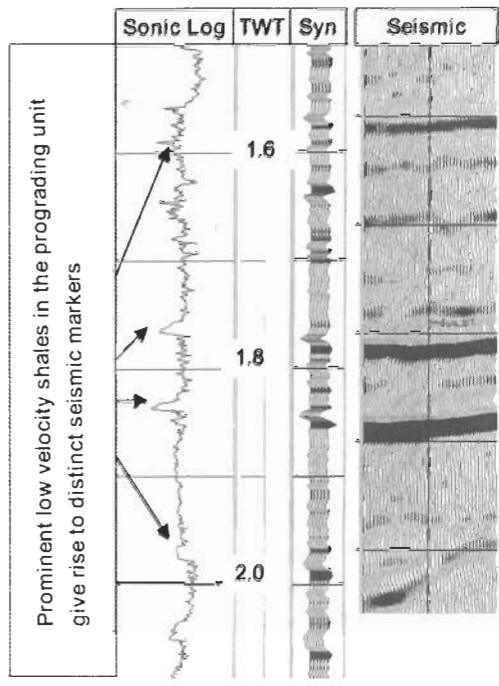


Fig. 8. Part of well-to-seismic tie for IM-B1. 'Syn', synthetic seismogram.

transition between dominantly basinal facies below and stacked shelf facies above: the result of overall basin fill and subsequent progradation of the shelf.

The seismic line shown in Fig. 11, a dip line along strike to IM-B1, highlights the compelling correlations that the higher-amplitude seismic events allow across faults. However, further east, their character fades, perhaps reflecting the proximal limit of these maximum flooding surfaces as distinctive litho-facies. Mapping at an intra-Lower Miocene marker (Fig. 12) shows the monoclinical dip down to the SW, ranging from two-way time of 1 s (c. 1500 m) to 3 s (c. 4500 m). The normal, down-to-the-basin faults, seen as fairly planar in seismic cross-sections, are part of a 60 km long, gently curved, fault system, with antithetic faults. Sedimentary growth across these faults is mostly contained within shale-prone 'pre-shelf' sediments, and their throws decline upwards to zero into the sandy elastic rocks above.

Refining regional seismic correlations and delimiting the seismic prograding units leads to a simple, relative age, stratigraphy and facies scheme (Fig. 13). Progradation of the shelf was mapped (Fig. 14), which appears to originate in the north, and at first has a strong southerly component. Later, a more southwestward progra-

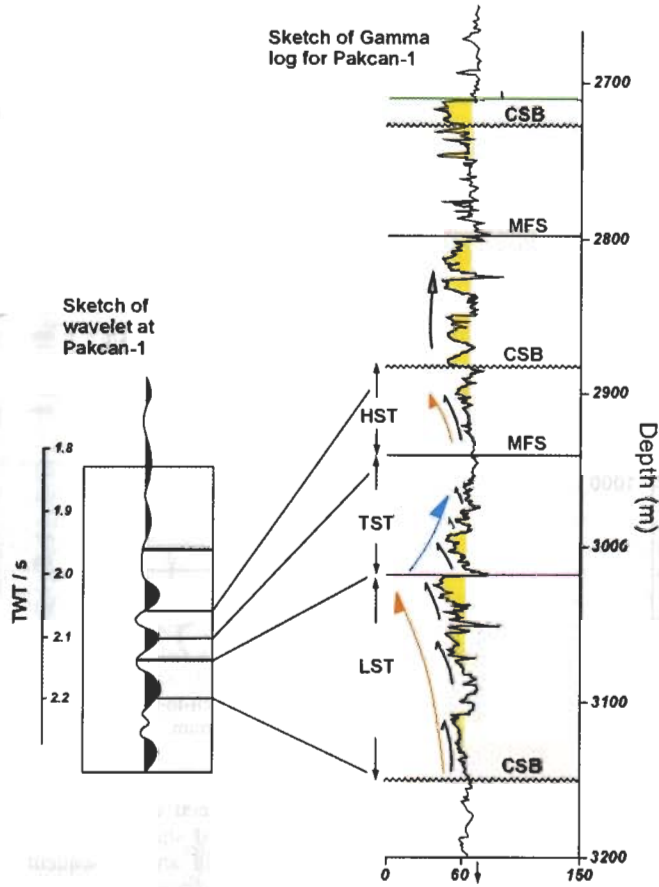


Fig. 9. Part of well log from Pakcan-1 across 'Prograding Unit'. CSB, candidate sequence boundary; HST, highstand systems tract; TST, transgressive systems tract; LST, lowstand systems tract; MFS, maximum flooding surface; TWT, two-way travel time.

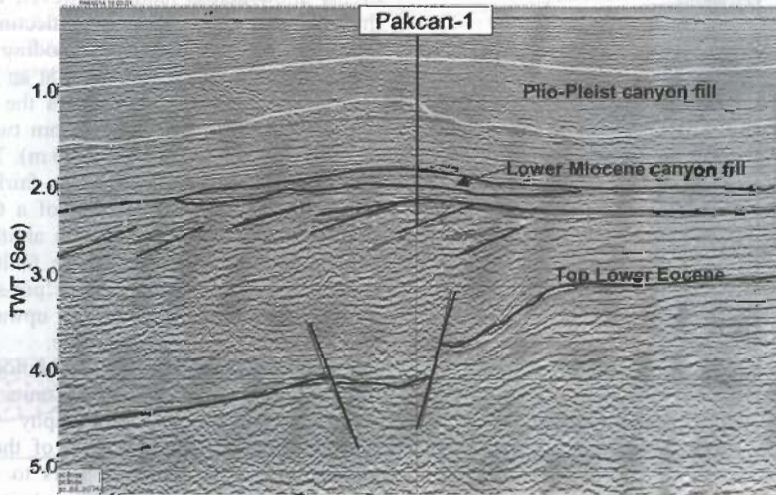


Fig. 10. Seismic scale progrades illustrated in seismic data through Pakcan-1.

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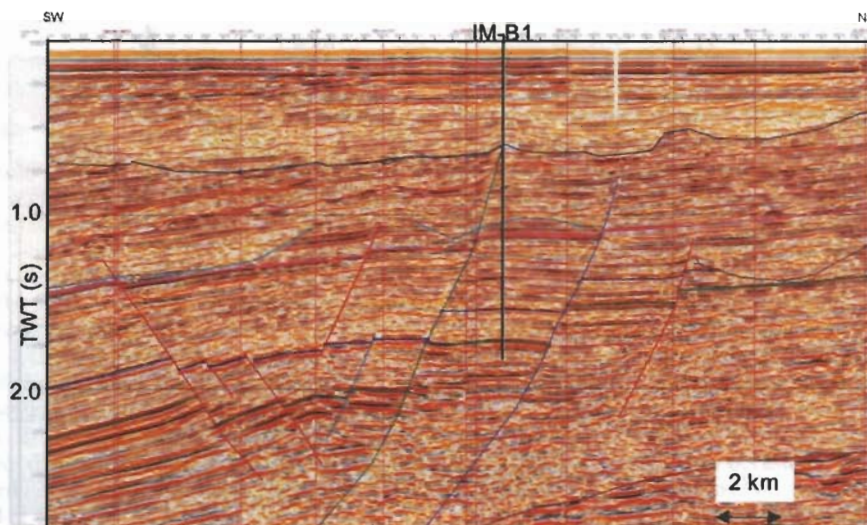


Fig. 11. Seismic dip line, along strike to IM-B1, showing down-to-basin normal faults (SW dipping) and antithetics (NE dipping).

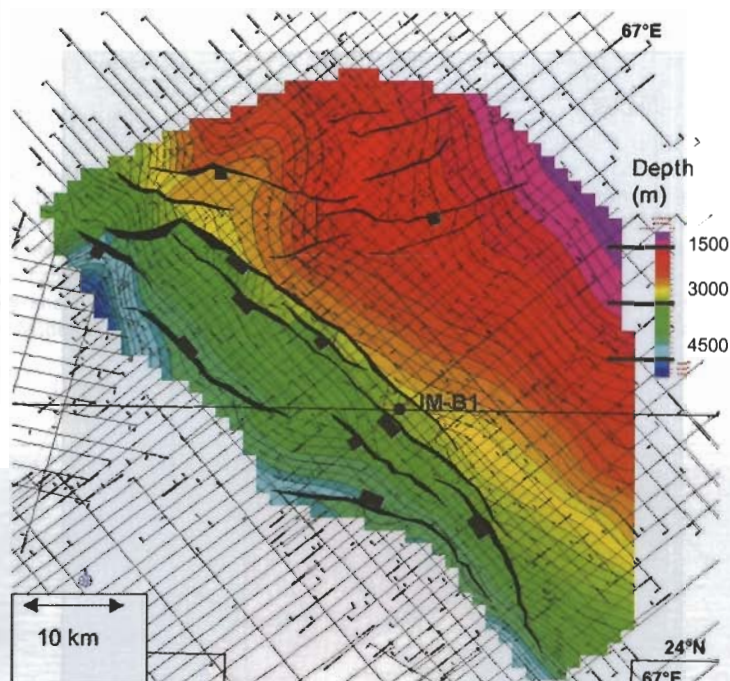


Fig. 12. Intra-Lower Miocene Marker two-way travel time map, in centre of project area with IM-B1 well shown for reference.

direction resulted as increasing sediment contributions arrived from the Karachi Platform. Sadaf-1 well appears to be close to the western limit that the coarser Miocene clastic deposits

reached, before their termination and blanketing by muddy shelf deposits of Pliocene times.

This work therefore implies that the Oligo-Miocene sedimentary fill of the offshore Indus

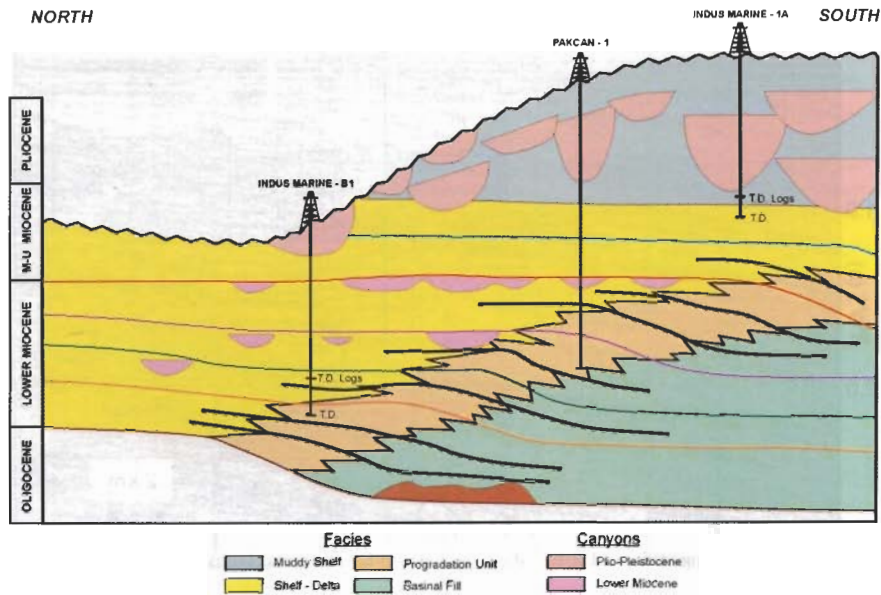


Fig. 13. Miocene stratigraphy and facies scheme.

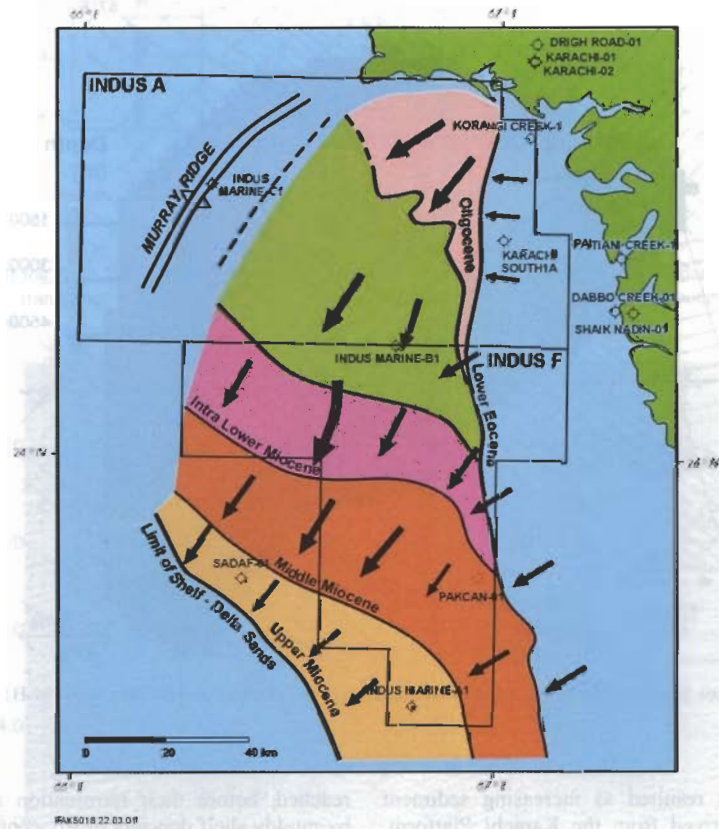


Fig. 14. Map of progradation of Oligo-Miocene shelf. Outlines of Indus A and F blocks are shown. Arrows suggest direction of sedimentation through time.

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Fig. 15.

Basin was a 'one-step fill', from basinal to shelfal, with sedimentation originating from the north.

Canyons

Canyon cut and fill facies dominate the shallow section across much of the study area and have been the subject of numerous references in the region. This study area covers the 'degradation zone' as defined by McHargue & Webb (1986), where the upper erosional canyon complexes are filled by pro-delta deposits. Seismic illustrations in Figs 4, 10 and 11 show the form and dimensions of the canyons, and their relative positions in the sequence have been indicated schematically in Figs. 6 and 13. The canyon cuts and fills observed divide into two main age categories, identified in Fig. 15, whose distributions are mapped at four time intervals in Fig. 16a-d.

An older group, of Early Miocene age, is generally limited to a maximum downcutting of 400 m. These commence as relatively isolated and individually mappable units cutting 70–80 km back into the shelf (Fig. 16a) and extending out to the shelf-slope break of the time. At a time believed to correspond to the end of Early Miocene time, canyons became widespread across much of the shelf of the study area (Fig. 16b) and many have laterally coalesced, or eroded into previous canyon fills. Thereafter, canyon activity wanes, although three examples have been preserved of canyons that appear to have been active during Mid- or Late Miocene time (Fig. 16c).

The younger canyon phase cuts through the Pliocene muddy shelf, and in many cases, down into the coarser Middle and Upper Miocene clastic

rocks below. It is widespread (but excluded from A Block, Fig. 16d), multiphase (at least eight levels can be demonstrated), and downcutting frequently exceeds 1000 m. Preserved individual canyon fills are rare, such was the intensity of repeated cut and fill events, although Kolla & Coumes (1987) separated three canyon complexes cutting the shelf west of the current Indus canyon. They indicated an easterly migration of canyon fill events, although Kolla & Coumes recognized 'jumps' in canyon location, and dated them to Late Miocene to Late Pliocene time.

Exploratory drilling to date has penetrated Plio-Pleistocene canyon fill facies on three occasions but an Early Miocene canyon fill facies has been encountered only once. The lithologies logged were shale dominated with occasional silty levels. This suggests that the position in which these canyons were drilled lay in the slope zone of erosion and sediment by-pass at their time of formation. The subsequent fill would have occurred after abandonment, by passive basinal or outer shelf fine-grained sediments.

It is thought that the magnitude and intensity of canyon events should reflect the scale and proximity of onshore tectonics, as well as sedimentation rates and relative sea level, and therefore could match the timing of uplift and inversion events. Early Miocene time, in the onshore Kirthar Fold Belt province, is considered a time of active inversion and uplift (Smewing *et al.* 2002), perhaps correlating with the older canyons phase. However, Plio-Pleistocene time is the main phase of uplift in western Pakistan, coinciding with the timing of the considerable offshore canyon development. This event is related to final docking

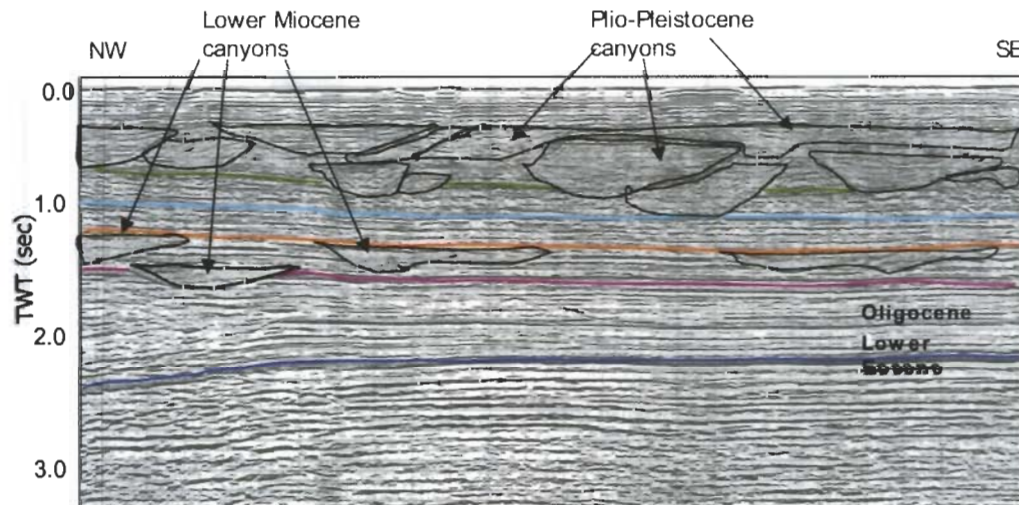


Fig. 15. Seismic strike line illustrating canyon cut and fill facies.

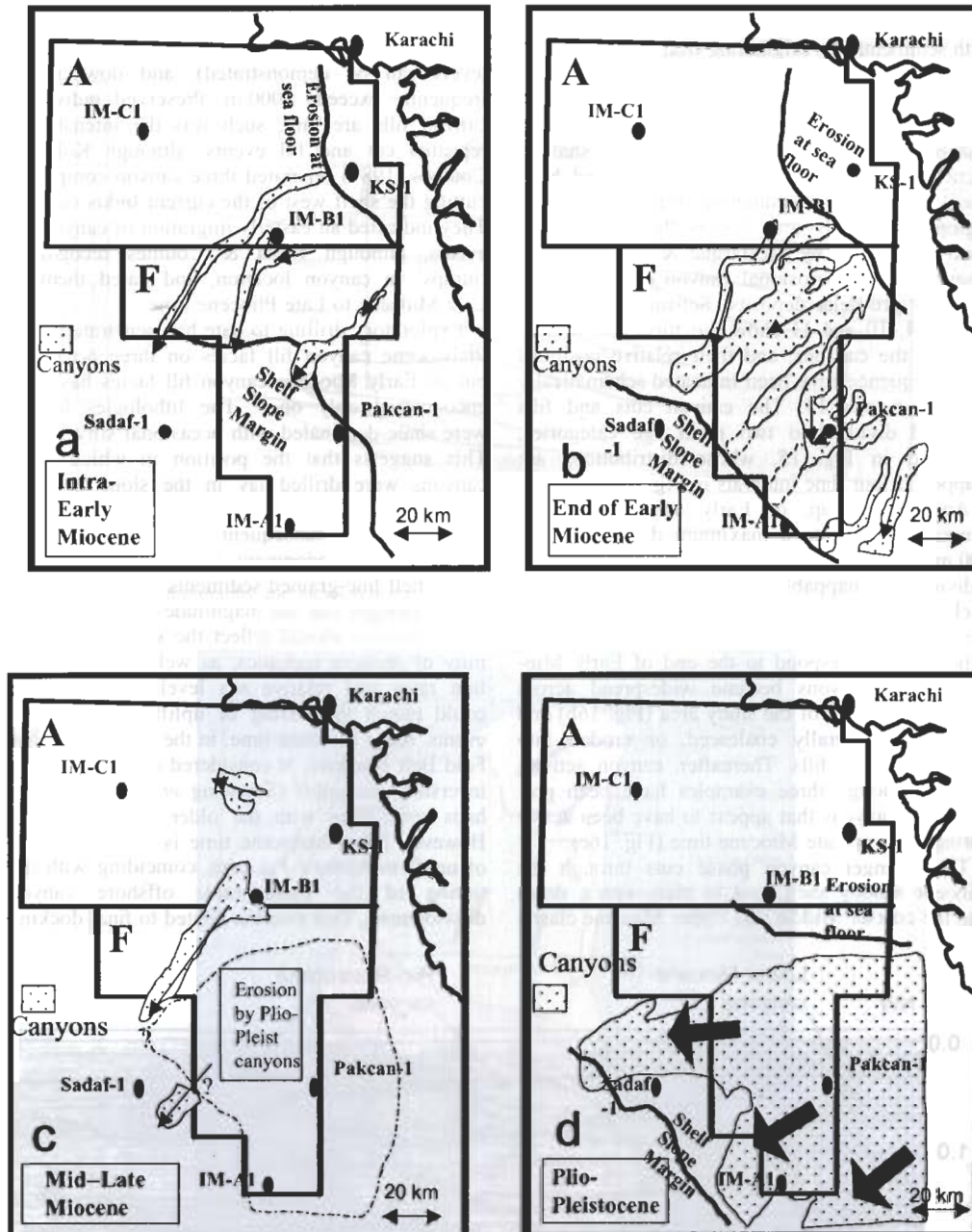


Fig. 16. Distribution of canyon incisions at four time intervals: (a) Intra-Early Miocene time; (b) end of Early Miocene time; (c) Mid-Late Miocene time; (d) Plio-Pleistocene time.

of the Kirthar margin with the Afghan plate (Smewing *et al.* 2002). Reliable age dating of canyon-fill sediments and onshore tectonic events is required to expand further the theme of correlating phases of canyon development with tectonic events.

Conclusions

The sedimentological history of the Oligo-Miocene offshore Indus Basin appears to record a broadly 'one-step' basin fill. The basinal section is essentially undrilled, up to 6 km thick, but inter-

preted to facies and age. Coarse basin deposits of Oligocene

The coarse sands are up to 20 m fill and sequence prograde of monoclinic facies (subsidence over any

The formed the eastern not extensive to the M is apparent section varying adjacent. According to the basin age and the post-dating basin in time, section. By Mid was also westerly contribu

Canyon feature is

puted to be mostly a passive fine-grained fill facies and mostly of Oligocene to Early Miocene age. Coarser clastic deposits may have reached the basin depocentre via Early Miocene, and possibly Oligocene, canyon systems.

The overlying shelf section comprises stacked sands and shales of Mid- and Late Miocene age, up to 2000 m thick. The transition between basin fill and shelf facies is marked by cyclic parasequence sets in well logs and oblique basinward progrades in seismic data. The overall dominance of monotonous stacking of apparently similar log facies (transition zone excepted) suggests that subsidence and sediment input rates are dominant over any eustatic imprint.

The offshore Indus Basin appears to have formed during Oligocene time, as large faults at the eastern margin with the Karachi Platform do not extend beyond Oligocene reflectors. A substantial fault zone with the northwestern boundary to the Murray Ridge also appears likely, as there is apparently only a much thinned Oligocene section on the current high, whereas a thickness varying from 2 to 4 km can be correlated into the adjacent part of the basin from nearshore well ties. According to these correlations, the majority of the basin fill is of Oligocene and Early Miocene age and does not confirm within this study area the possible presence of Indus Fan sediments dating back to mid-Eocene time (Clift 2002). The basin initially filled from the north in Oligocene time, sediments rapidly prograding southwards. By Mid- and Late Miocene time, progradation was along a wider front and adopted a south-westerly direction with an increasing sediment contribution from the Karachi Platform.

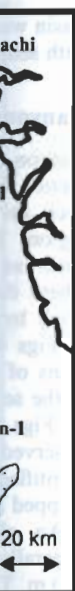
Canyon cut and fill facies form a distinctive feature in the seismic data and separate into Early

Miocene and Plio-Pleistocene phases, with maximum downcutting of 400 m and 1000+ m, respectively. The former could be coeval with inversion and uplift in the Kirthar Fold Belt and the latter related to the final collision of the western Pakistan margin with the Afghan plate.

We wish to acknowledge the contributions to the project by our coworkers, principally N. Ahmed, S. Alam, S. Beswetherick and A. Qadri. We also thank DGPC of Pakistan for its support throughout our studies. J. Craig, A. Sharp and P. Clift are thanked for critically reviewing this paper.

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