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The Stratigraphic and Sedimentological Evolution of the Mahim, Daman and Mahuva Formation Reservoirs of the Tapti Fields: Tidally-Influenced Deposition in an Oligo-Miocene Tropical Estuarine Embayment on the Continental Shelf of Western India

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Introduction

The Tapti Fields are located offshore west coast of India 160km from Mumbai with Oligo-Miocene sand as reservoir (Fig. 1 A). Although many wells have been drilled on these fields, only limited core is available through the main reservoir interval. Additionally, seismic imaging of the reservoir bodies is often limited and poor. Previous studies of the Oligo-Miocene reservoir section, encompassing the Mahuva, Daman and Mahim Formations, invoked a tropical deltaic to shallow marine depositional setting (Deb et al., 1997). Zutshi et al. (1986) extended the description of depositional systems further in suggesting that the delta systems were both wave- and tide-influenced. As the depositional slope across the whole gulf is very low, relatively small fluctuations in sea level resulted in large shifts in the shoreline, extending as far as the palaeo-shelf break ~400km to the south-west (Fig. 1 B; Pandey, 1986). Following regional uplift and tilting at the end of Mahuva Formation deposition, a series of sea level rise/fall resulted in deposition of the Daman Formation coastal plain facies. These tropical coastal plain deposits were successively flooded during the early Miocene in response to progressive relative sea level rise. The cores from all the wells are used to build the depositional model of the fields which is strengthened with seismic mapping and well logs. This study develops a detailed integrated stratigraphical and sedimentological model for predicting reservoir distribution in the equatorial Oligo-Miocene reservoirs of these fields.

Depositional model

A combination of vertical sequence trends and spatial changes in facies belt character within stratigraphically constrained reservoir layers has facilitated the construction of a conceptual depositional model for the reservoir interval. Fourteen distinct facies associations are recognized that collectively indicate deposition within and adjacent to a gulf. Two constrasting but inter-related depositional systems characterise the palaeo-gulf: (i) an inner gulf region of tidally-influenced distributary channels and associated estuarine complexes, flanked by a flat, low-lying tropical coastal plain with coastal saltmarsh, mangrove swamps, fluvial channels and inter-channel floodplains, and (ii) an outer gulf region of tidal ridge fields (Off, 1963) lying in shallow open water upon a substrate of offshore mud forming a open marine embayment. The geometries of the sand bodies are derived from seismic and our overall understanding comes from the outcrop analogues and satellite images.

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As well data only provides very limited X-Y spatial information, seismic is essential to constrain the spatial distribution of facies in the depositional interpretation. Seismic imaging of sand bodies in the Tapti Fields is sub-optimal, largely because of the stacking of reservoir and wide variation in sand porosity and clay content (Rana et al., 2006). Rock physics studies of the reservoir section indicate that a combination of acoustic and elastic attributes could be used as a lithology discriminator so that inversion of the seismic volume to rock property attributes should reveal more spatial information on sand geometries. Accordingly, a simultaneous inversion was undertaken on the Tapti angle-limited stacks for acoustic impedance, (AI), Poissons' ratio (PR) and Lambda-Rho (LR) to attempt to differentiate lithology, in particular clean porous channel sand from background shale and argillaceous tidal bars (Parks et al., 2006). Representative seismic amplitude maps are reproduced to provide a geometrical framework for the sedimentological studies. The seismic data reflectors were transferred to the GEOFRAME software for interpretation and reservoir modelling was carried out using PETREL.

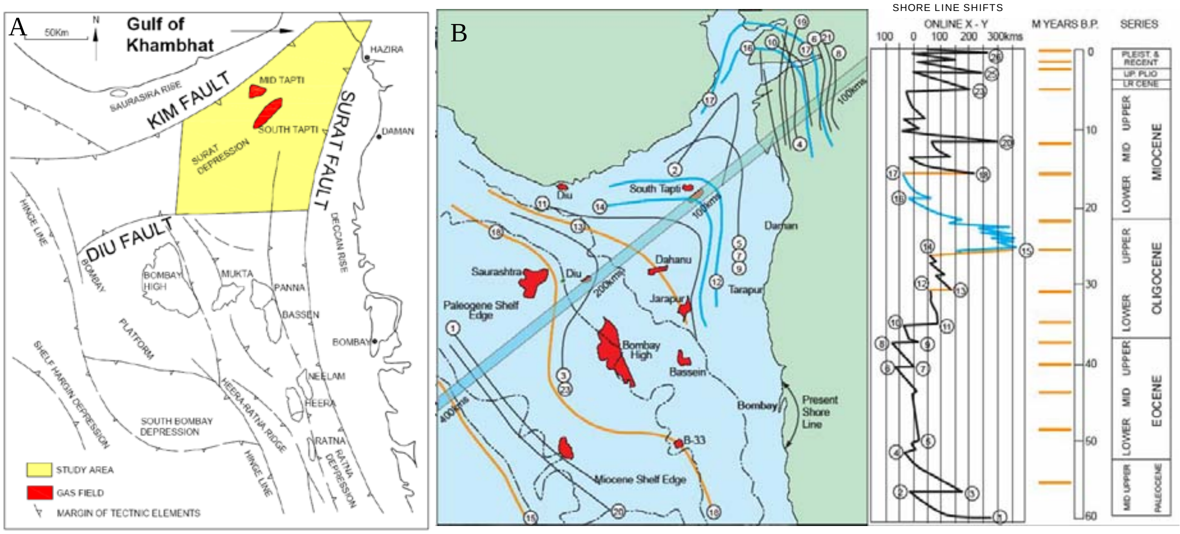

Fig. 1 (A): Map of Bombay Offshore Basin with various tectonic elements (after Deb et al., 1997). The Oligo-Miocene hydrocarbon fields are marked by red colour. Diu Fault, Kim Fault and Surat Fault define the boundaries of the Surat Depression. (B) Lateral shoreline shifts along western India through the Tertiary. Shorelines during different times (marked by numbers) are presented in left. Magnitudes of lateral shoreline shifts through time are marked in right (after Pandey, 1986). Major gas fields are also marked.

Estuaries and related deposits – the inner gulf

This depositional system developed at the head of the gulf which is highly dynamic in nature (Fig. 2A). It reflects interaction between fluvial and marine forces forming a tidally-dominated shallow-marine system. The facies association developed in these zones are fluvial channel, fluvial point bar, tidally influenced fluvial channel, saltmarsh, subtidal-intertidal mudflat, subtidal-intertidal mixedflat, subtidal sandflat, tidal channel, tidal bar, lag deposits and shoreface. Fluvial channels are characterised by m-scale, sharp-based, stacked/amalgamated fining-upward sand with medium-scale cross-stratification. The fluvial point bars are characterised by granule-grade conglomerate containing common pebble-sized components with crude low-angle cross-stratification in it. Fluvial channels traversing the coastal plain became increasingly tidally-influenced and become tidally influenced fluvial channel until they widened into major estuarine complexes at the mouth with tidal bars and associated tidal channels. Saltmarsh covered much of the lower coastal plain, with muddy channel fills probably reflecting the development and filling of tidal creeks. Poorly drained rooted palaeosols rich in sphaerosiderite predominate, often perforated by *Thalassinoides* burrow networks. Thinly bedded heterolithic sand sheets and rippled mud represent subtidal-intertidal mixedflat deposits. These commonly display paired mud drapes indicative of subtidal deposition. Bioturbation levels tend to be relatively weak, with shallow spreiten burrows and *Planolites* most common, although sand-filled burrows of *Thalassinoides* and infaunal bivalves locally testify to firmground development. High levels of bioturbation, principally by infaunal bivalves, typify these deposits. The subtidal-intertidal mudflat preserved mm-scale lamination, but may also show pale pinstripes of well sorted very fine to fine sand. Subordinate cm- to lower dm-scale sand-mud heteroliths exhibiting lenticular and flaser bedding. Sometimes these shows prominent burrow fills of fine to coarse sand and associated bivalve shells and occasional gastropods in it. Subtidal sandflat deposits show dm-scale sharp-based sandstones with uniform or subtle fining upward profiles. The sandstones are biogenically admixed coarse sand with mud intraclasts of pebble grade. Lower parts of these deposits shows display medium-scale cross-stratification or planar stratification, whilst upper parts are either bioturbated or show diffuse ripple cross lamination. Estuary mouths comprised of tidal bars and tidal channels represented by upward-coarsening and -fining of sand respectively. The ‘cleanest’ sands were therefore deposited on bar crests and in the deeper reaches of the channels. Evidence of tidal current control upon deposition is widespread, medium-scale cross-sets (attributed to migrating megaripples) exhibiting size- and particle-sorted foresets, often with well developed paired mud drapes, and current-rippled heteroliths sometimes showing bi-directional foresets. Trace fossil evidence indicates that infaunal bivalves were the dominant agent of bioturbation in the channel/bar complexes, although burrows such as *Ophiomorpha*, Palaeophycus and Planolites indicate that crustaceans and annelids were also present. The shoreface deposits are characterised by silty and argillaceous sandstones (>80% sand) which exhibit a subtle 'cleaning-upward' profile above offshore mud. These are dominated by scattered coarse sand grains plus mud intraclasts to pebble grade with occasional bivalve shells. The shoreface deposits occur in a tidally influenced shoreline which becomes more wave-influenced along strike down the gulf.

Tidal influence in the rivers is initially manifest in the form of occasional mud drapes in the upper parts of the channel-fills, together with occasional bivalve burrows. Closer to the river mouths, major tidal exchange is reflected in an increase in the scale and diversity of traction-dominated sedimentary structures, more abundant mud drapes (locally paired, and often rich in carbonaceous debris), as well as the presence of *Ophiomorpha* burrows. Palynological samples also show a locally significant dinocyst component, this group being absent in ‘clean’, non-bioturbated channel-fills generated upstream of any tidal influence. Microforaminifer test linings are also locally prominent, as are freshwater algae and a range of pollen and spore types. The diverse nature of this assemblage, with prominent marine- and terrestrially-derived components, is typical of an estuarine system.

Embayment and related deposits– the outer gulf

Analysis of retrogradational cycles indicates that away from the head of the gulf a distinctive facies belt developed in what was a clearly a deeper water setting subject to normal marine salinities. The facies association that characterise are tidal ridge, offshore mud and sand sheet. Sand ridges are nucleated upon grey-brown and grey-green claystones which, in common with mudflat deposits, preserve a distinct swelling component and are chlorite-rich. Sand ridge deposits largely comprise upward-'cleaning'/coarsening cycles shows medium-scale cross-stratification generated by the migration of subaqueous dunes. Dune-scale foresets often exhibit size-sorted laminae, sometimes with alternations rich or poor in larger foraminifers (cf. *Nummulites*). Distinct clay drapes, reflecting the suspension fall-out of 'fines' during slackwater periods, are also present, and may compartmentalise the sand deposits vertically and laterally. Bioturbation levels tend to be low, although the tops of sand may exhibit *Thalassinoides* burrow networks. This bioturbation style reflects the abandonment of a sand-ridge, water depth increases resulting in progressively weaker tidal currents until the ridge structure became moribund. Tidal sand sheet are meter-scale shallowing-upward sand bodies and thin sheet sand interbedded with offshore mud suggest the development of tidal sand-ridge fields in the middle to outer part of the gulf. The sand sheets are results of tidal reworking of the sand from the sand ridges. The deposition of discrete sand-ridges and its sedimentary structure indicates a deposition under marine transgression in an embayment. The interaction between the dominant tidal current regime and large volumes of inshore sand during marine transgression give rise to the elongated sand ridges (Fig. 2B).

Sequence stratigraphic framework and system tracts

Core studies integrated with logs, biostratigraphy and seismic data over the Tapti Fields suggest that broad facies development over the reservoir interval is characterised by a vertical cyclicity. Discrete cycles are characterised by a basal unconformity surface, locally with fluvial-distributary channel complexes incised into underlying estuarine/offshore mud deposits. The bases of these cycles are interpreted as sequence boundaries.

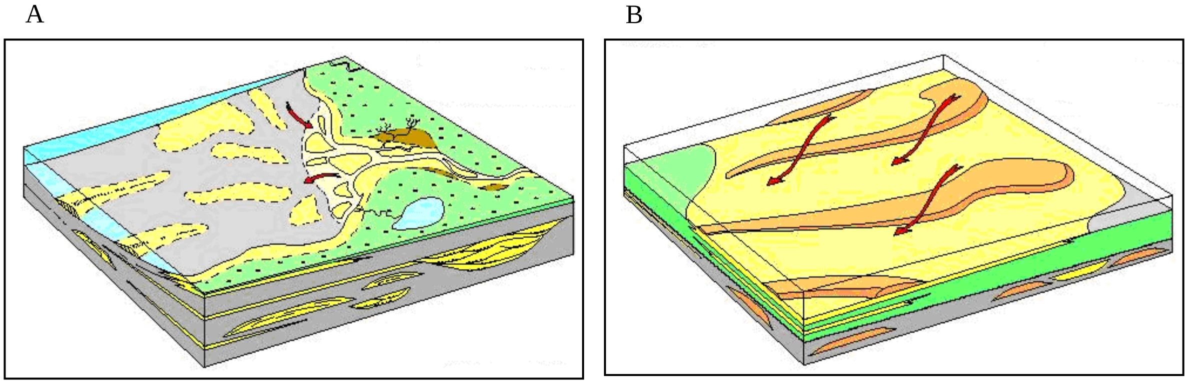

Fig. 2: Block diagrams for the depositional environment of the inner gulf (A) and outer gulf (B) of the Tapti Fields.

Lowstand systems tracts

These deposits appear confined to incised valley fills developed at various levels in the Daman Formation (including the base). In core they are largely represented by stacked m-scale fluvial channel deposits separated from overlying tidally-influenced distributary channel deposits by a transgressive surface. The magnitude of incision indicates periods of significant relative sea level fall during which down-cutting fluvial systems carved out the large scale valley features. As a consequence, subtidal mud and heteroliths were subaerially exposed across extensive interfluves. At some time between initial exposure, and subsequent marine inundation, these muddy interfluves became sites of palaeosol development. Thus deposits of the subtidal realm were over-printed by pedogenic mottling, nodular siderite cementation and root development.

Transgressive systems tracts

Deposits of the transgressive systems tract show evidence of early topographic confinement within incised valleys. However, this was followed by an areally extensive phase of deposition achieved as continued sea level rise inundated interfluves and established the floor of a broad, tidally swept gulf. There are two different expressions of ‘early’ marine transgression in the valley-fills (i) the development of a transgressive surface clearly separating lowstand fluvial channel sands from overlying tidally-influenced distributary channel deposits and (ii) apparently conformable upward passage from fluvial channel to tidally-influenced distributary channel deposits. Since in the latter case distinct lowstand deposits cannot be recognised with confidence, the valley floor at this time must largely have been a major bypass surface. All evidence from core and seismic data supported with present day analogues suggests that during ‘early’ marine transgression palaeo-valleys were largely occupied by sandy bed-load river systems. These were strongly tidally-influenced in their lower reaches and ‘estuarine’ at their mouths (Khadkrikar and Rajshekhar, 2005; Saha et al., 2006). Continued marine transgression completed the infilling of palaeovalleys and brought about the subsequent flooding of interfluves. With increased distance for the shoreline, subtidal ‘estuarine’ mud graded to ‘offshore’ mud, and the sand was organised into tidal sand ridge fields.

Maximum flooding surfaces and highstand systems tracts

Limited core coverage through mud-prone facies means that defining the sedimentological and palaeontological expression of maximum flooding within a depositional sequence is difficult. In a more distal location, foramanifer-rich offshore mud, with or without associated tidal sand ridge deposits, may well be an expression of maximum-flooding. Indeed, it is likely that distal elements of sand ridge fields became either moribund at this time (temporarily inactive) or were permanently abandoned. In the most proximal locations maximum flooding may be confined to distributary channels, a feature that might persist 10s of kms upstream of river mouths. Deposits of the highstand systems tract are not well defined, given the fact that base-level falls have repeatedly generated major incision surfaces, it is probable that, from a preservational point of view, stratigraphic architecture is biased much more towards the lowstand and transgressive systems tracts (Saha et al., 2006).

Rather than the previous ‘deltaic’ interpretation we view deposition as having taken place in and adjacent to a shallow, tidally-swept embayment. Ichnological (trace fossil), palynological and micropaleontological data indicate that the outer reaches of this palaeo-gulf were subject to ‘normal’ marine salinities, whereas the inner parts were dominated by brackish water and had a distinctly ‘estuarine’ character. Evidence suggests that the reservoir interval is broadly ‘transgressive’ in nature, which accords well with a general background of eustatic sea level rise. However, superimposed upon this trend are several episodes of rapid (scale of 1000s of years) relative sea level falls. These falls are believed to reflect uplift episodes in the Himalya region brought about by compressive stresses associated with Indian Ocean seafloor spreading, and ‘locking-up’ of the northward-migrating Indian Plate with the Eurasia. Interaction between eustasy and tectonics therefore shaped the palaeo-gulf and, combined with tropical climatic factors, governed the range of depositional processes that operated.

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