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Research paper

The morphology and evolution of tidal sand bodies in the macrotidal Gulf of Khambhat, western India

Sourav Saha [a, b, *], Stuart D. Burley [b, c, 1], Santanu Banerjee [a], Anupam Ghosh [d], Pratul K. Saraswati [a]

[a] Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India
[b] BG Exploration and Production India Ltd, BG House, Hiranandani Business Park, Mumbai, India
[c] Basin Dynamics Research Group, School of Earth Sciences, University of Keele, Staffordshire, UK
[d] Department of Geological Sciences, Jadavpur University, Kolkata 700032, India

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ABSTRACT

Tidal sand bars and tidal sand ridges are extensively developed in the macrotidal Gulf of Khambhat, offshore western India. The inner and outer regions of the gulf are characterised by the development distinct tidal sand bodies with discrete geometries and dimensions. The outer gulf ridges are long, narrow, curvilinear and several metres high (~20 m). They are asymmetric in cross-section and migratory in nature, forming 'ribbon' like sand bodies separated by tidal channels. Active dunes on these ridges indicate the presence of sand and their orientation parallel to palaeo-shorelines supports a tidal origin. In contrast to the outer gulf tidal sand ridges, sand bars associated with macrotidal estuaries flanking the Gulf of Khambhat typically have an elongate to diamond shape and are only hundreds of metres in width and a few kilometres length. These tidal sand bars occur in the estuary mouths and within the tidally influenced fluvial reaches of the rivers flowing into the gulf. The height of these sand bars is in the range ~1–3 m. Due to high tidal ranges and bi-directional flow the sand bars do not develop significant height and are formed between the mutually evasive ebb and flow channels. Their bi-directional foresets and the presence of abundant mud drapes associated with the dunes within in-channel sand bars indicate a tidal origin.

The Gulf of Khambhat acquired the present configuration in the last few thousand years since the Pleistocene sea-level lowstand (last glacial maximum, ~18 ka) when the entire continental shelf was subaerially exposed and rivers down-cut into the coastal plain. With increasing sea-level rise, the exposed shelf was drowned, flooding parts of the Modern western Indian peninsula, and large tidal sand ridges formed in the outer gulf. After the fall of sea-level at 2 ka the gulf acquired the Modern configuration with multiple estuaries on both coastlines, rivers supplied the embayment with sandy sediment, and tidal sand bars formed in the Modern estuaries.

Quantitative data gathered from the Modern Gulf of Khambhat indicates that for the P50 case, a vertical drill hole will encounter tidal sand bodies (ridges and bars combined) of approximate dimensions 1700 m long, 470 m wide and 1.5 m high, with a spacing of 400 m. In subsurface hydrocarbon reservoirs, where data is sparse and only limited amount of core is available, this quantitative dataset can be useful to constrain subsurface geocellular models. Also, the overall geometry, distribution and aspect ratio of the tidal sand ridges and tidal sand bars can be used to identify ancient counterparts through seismic geomorphology or in core.

1. Introduction

Sand ridges and sand bars of tidal origin exhibiting varying shapes and sizes are found on many continental shelves and coastal regions across the world. They are deposited in a wide range of

* Corresponding author. Present address: Shell International Exploration and Production, Inc., 150 N Dairy Ashford, Houston, TX 77079, USA. Tel.: +1 2817949373.
E-mail address: sourav_presi@yahoo.co.in (S. Saha).
[1] Present address: Murphy Oil Corporation, Petronas Twin Towers, Kuala Lumpur, Malaysia.

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depositional settings that includes estuaries, coastal embayments and continental shelves (Caston, 1972; Swift, 1975; Huthnance, 1982; Belderson et al., 1982; Dalrymple et al., 1990; Yoshida et al., 2004; Reynaud and Dalrymple, 2012). Their size and location depends upon several parameters, principally accommodation space, sediment type and availability, tidal currents and elongation of tidal ellipses (Johnson and Belderson, 1969; Caston, 1972; Kenyon et al., 1981; Swift and Field, 1981; Belderson et al., 1982; Stride et al., 1982; Huthnance, 1982; Amos and King, 1984; Dalrymple et al., 1990; Harris et al., 1992; Snedden and Dalrymple, 1999; Dyer and Huntley, 1999). Such tidal deposits are known to form oil and gas reservoirs in the subsurface. As modern tidal ridges and tidal bars are relatively poorly documented in the literature, except in a few specific cases such as the Bay of Fundy (Dalrymple et al., 1990, 1991) and the Fly River Delta (Dalrymple et al., 2012a), there are relatively few analogues for subsurface tidal reservoirs (but see Wood, 2004; Davies et al., 2007).

The Gulf of Khambhat provides an excellent dataset to document modern tidal bar forms, their internal architecture, geometries, and dimensions in one of highest macrotidal environments in the world. For this study the Gulf of Khambhat is divided into two broad regimes, the inner gulf and outer gulf (Fig. 1A). The inner gulf includes several estuaries, on both the eastern and western flanks of the gulf, whereas the outer gulf is located away from the direct influence of rivers on a broad, funnel shaped, tidally dominated, wide shelf (Fig. 1A). Off (1963) first reported the presence of ridges offshore western India but did not undertake detailed analysis of their geometries and origin. No work has been undertaken to date on the modern bars in the estuaries.

In the literature, tidal bars are variously termed elongated tidal bars, tidal ridges and shelf ridges (Huthnance, 1982; Amos and King, 1984; Dalrymple et al., 1991; Harris et al., 1992; Dalrymple and Rhodes, 1995; Snedden and Dalrymple, 1999; Reynaud et al., 1999; Dalrymple and Choi, 2007; Dalrymple et al., 2012b). Here, tidal ridges and tidal bars are referred to as two distinct 'bar forms'. Tidal bars are defined as generally single bedforms with a height of less than 3 m, a width of less than 1500 m, and typically less than 5 km long. Tidal ridges, on the other hand, are much larger composite bar forms that stack up to become much thicker (Huthnance, 1982; Davis and Balson, 1992; Harris et al., 1992; Snedden and Dalrymple, 1999; Reynaud et al., 1999). These ridges attain heights of ~20 m, are commonly more than 2000 m wide, and more than 20 km long (Davis and Balson, 1992; Snedden and Dalrymple, 1999; Reynaud et al., 1999).

An integrated description of these tidal bar forms based on remote sensing imagery, bathymetric data, shallow seismic together with field study of the ridges developed in the outer gulf and the tidal bars formed within the inner gulf is presented herein. A discussion on the possible origin of these tidal bar forms within a macrotidal environment is also presented based on a regional understanding of the Quaternary evolution of the Gulf of Khambhat. Dimensional data of tidal bars and ridges were acquired to understand their distribution and spatial relationships to provide quantitative data for characterisation of tidal systems. These tidal bar forms are then placed in the Modern to Quaternary stratigraphic framework of the western Gujarat based on published work that integrates studies of the fluvial deposits and river terraces (Maurya et al., 1997; Juyal et al., 2006; Khadkikar and Rajshekhar, 2005) to propose a geological evolution of the Gulf of Khambhat.

2. Geological framework of the Gulf of Khambhat

2.1. Location and features of the study area

The Gulf of Khambhat is a large estuarine embayment that opens southwards into the Arabian Sea (Fig. 1A). The gulf is broadly an inverted funnel-shape, more than 200 km long and up to 70 km wide at its southern end, narrowing to 20 km towards its northern, proximal part. The gulf originated during the Late Cretaceous, as

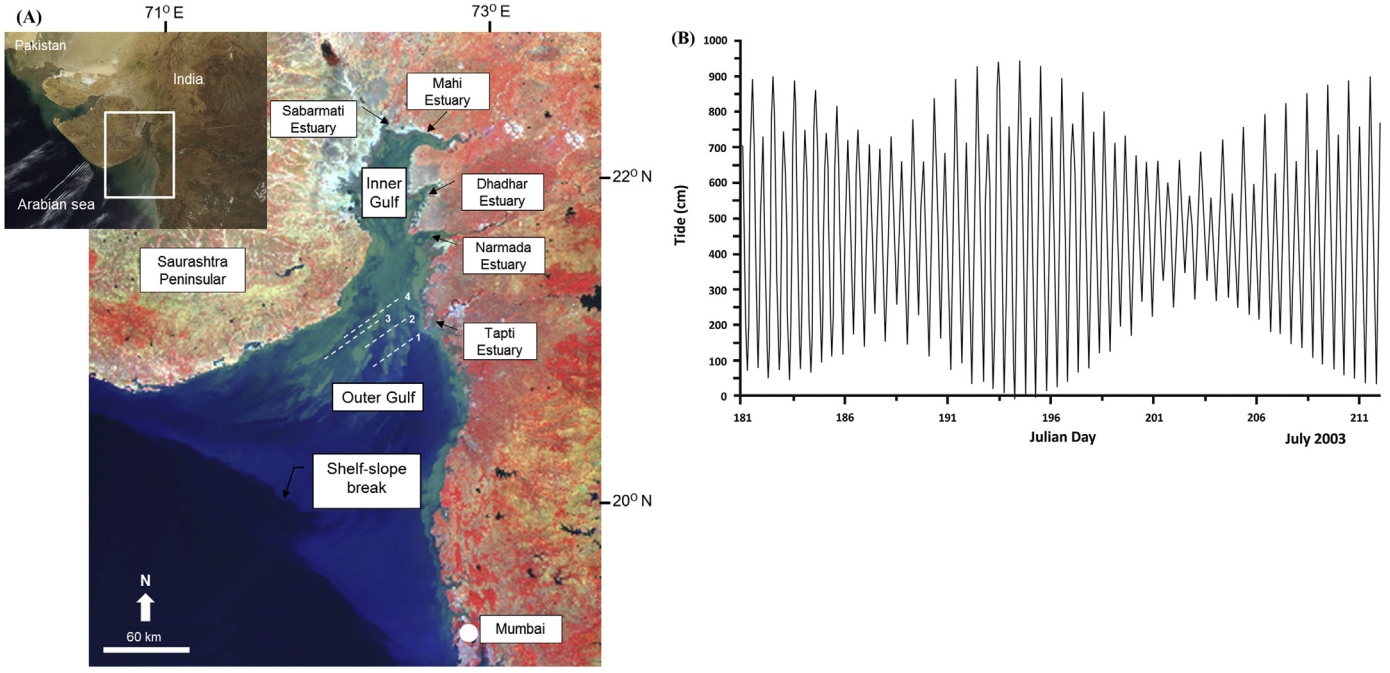

Fig. 1. (A) Satellite imagery of the Gulf of Khambhat showing the location of the study area. Inset: Study area in the context of western India and the Arabian Sea (NASA Images Archive). Main image: Post-monsoon FCC image for IRS P4 (OCM) data taken on 20th November, 2004. The presence of the shelf-slope break, about 400 km south from the northern tip of the Gulf of Khambhat is marked by a change in colour. Dotted white lines mark the location of seismic lines in Figs. 4 and 5. (B) Variation of tidal range in the Gulf of Khambhat (from Kumar and Kumar, 2010). See text for details. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).