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Highstand vs. lowstand turbidite system growth in the Makran active margin: Imprints of high-frequency external controls on sediment delivery mechanisms to deep water systems

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A B S T R A C T

Late Quaternary turbidite system growth along the Makran convergent margin is investigated through a set of deep-sea cores from upper slope and piggy-back basins to deep basin plain settings. High-resolution stratigraphy in these various depositional environments permits reconstruction of the evolution of sand-to-mud ratio, sedimentation rates, frequencies, and thickness of turbidite deposits during the last 25 ka BP. This study demonstrates how tectonics, climate and eustasy can interplay at high resolution (<20 ka) and control the input of terrigeneous sediment along the tectonically active Makran convergent margin, in a source-to-sink perspective.

The Makran turbidite system growth has been continuous throughout sea-level lowstand, transgressive, and highstand conditions. However, the frequency, rates, and nature of sediment supply varied in response to climate, sea-level, and tectonically induced changes in source-to-sink sediment dispersal modes. These changes include conditions of sediment production and availability in the drainage basin, capacity of transport from fluvial systems, and rates of sediment storage on the shelf and upperslope areas. Climate in the hinterland appears as a first-order control on the properties of turbidity currents that feed the turbidite system, controlling the average sand-to-mud ratio in the deep water deposits. The onset of sea-level highstand after ~8 ka BP resulted in a notable change in turbidite system growth, characterized by the occurrence of large volume, thick turbidity currents (>300 m thick along the continental slope) originated from successive, multiple slide or slump-induced surges. Their related deposits have low recurrence intervals, close to those calculated from the large magnitude earthquake and tsunami record in the Makran area.

Comparison with the Nile and Indus turbidite systems growth during the Late Quaternary provides an evaluation of the relative importance of shared forcing parameters (i.e. monsoon-induced phases of arid/humid conditions and post-glacial sea-level rise), in significantly different basin settings. The Indus fan appears mainly controlled by eustasy during the last 25 ka. Inversely, similarities are found between the Nile and Makran turbidite systems, where sea-level changes are modulated by the climate impact on fluvial dynamics in the hinterland. However, the Makran turbidite system growth is continuous through times, because both the uplift in the coastal area and the fluvial dynamics of short, mountainous river systems allow high sediment transfer rates to the marine basin, even though arid conditions and associated low water fluxes. Earthquake-induced highstand turbidite deposits form a thick sedimentary succession in the Oman abyssal plain, and are significant in the geologic record. This study finally illustrates how the complex interplay between external (allogenic) forcings can complicate the interpretation of high-resolution sedimentary successions in turbidite-filled basins.

1. Introduction

The nature and timing of sediment distribution in basins is mainly related to the dynamic processes and feedback mechanisms between

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the external (allogenic) and internal (autogenic) forcings that govern sediment dispersal in erosional/depositional systems (Stow et al., 1985; Richards et al., 1998; Castelltort and Van Den Driessche, 2003; Allen, 2008; Sømme et al., 2009). As they represent the final position for source-to-sink sediment flux across continental margins, turbidite systems potentially record the interaction between climate, tectonic, and sea-level parameters, which strongly influence the timing, rates, and location of sediment supplied to basins. Impact of external forcings on sediment dispersal to the deep marine basins at short (<100 ka) time scales have been investigated for a long time, because they are important parameters governing the stratigraphic succession and resulting sedimentary architecture in deep water systems (Perlmutter and Mattews, 1989; Posamentier and Kolla, 2003). Although there has been some continued focus on sea-level in conceptual stratigraphic model that predict the delivery and formation of deep water deposits at 5th to 6th orders, corresponding to time scales <100 ka (Bouma et al., 1989; Posamentier and Vail, 1989; Posamentier et al., 1991; Brami et al., 2000; Catuneanu et al., 2009), an increasing number of studies show that climatically-driven variations in fluvial water and sediment discharge have a strong influence on turbidite system growth. This includes both glacially/ice-sheet-controlled (Skene and Piper, 2003; Zaragosi et al., 2006; Tripsanas et al., 2007; Toucanne et al., 2008); and monsoon-controlled (Ducassou et al., 2009) Pleistocene turbidite systems along passive margins. However, less data is available concerning high-frequency forcings on tectonically active systems such as fold-and-thrust belts depositional systems in convergent margins. Active margins are often associated with short river systems and fluvio-deltaic source, from which sediment supply is thought to be very sensitive to climate changes (Milliman and Syvitski, 1992; Weltje and De Boer, 1993; Mutti et al., 2003; Sømme et al., 2009). The importance of tectonics over global sea-level changes at long time scales have been observed in many tectonically active basins, uplift causing slope creation and forced-sea-level lowstands that promote changes in rates of sediment flux and depositional architecture (e.g. Mutti et al., 2003; Underwood et al., 2003). Earthquake-induced turbidite deposition along present-day active margins such as the Cascadia subduction zone, among others, show that tectonics can also influence the timing of sediment transfer to deep basins over short time scales (Goldfinger et al., 2007). However, the relative importance of short-term tectonic control on sedimentation in comparison to climate and eustasy remains poorly understood.

Our study investigates the growth pattern of the Makran turbidite system during the Late Quaternary from an extensive piston core data set that constrains high-resolution stratigraphy in various depositional environments (upper slope, piggy-back basins, canyon mouths and deep basin plain settings). Preliminary work done by Prins et al. (2000b), Prins and Postma (2000) and Stow et al. (2002) from a few cores in western piggy-back basins and abyssal plain suggested that turbidite deposition was frequent through the last sea-level lowstand (at ~20 ka), continued during the post-glacial rising sea-level and became infrequent after the onset of sea-level highstand (Prins et al., 2000b; Stow et al., 2002). However, detailed morpho-bathymetric analysis from a nearly complete subsurface mapping of the basin showed that the Makran turbidite system architecture and related sedimentary processes are highly variable along-strike (i.e. from east to west), depending of the upstream distribution of fluvial inputs and along-strike variation in tectonic regime (Bourget et al., in press). Thus, evolution of sediment input and turbidite system growth in the complex Makran setting cannot be only considered in isolated depositional environments, and must be analyzed at the system scale, both longitudinally and laterally. The Late Quaternary sedimentary infill of the Makran turbidite system is especially well-suited for investigating high-frequency interplay between climate, tectonics and eustasy as the margin is characterized by i) high convergence rates (~3 cm ka^{-1}; Ellouz-Zimmermann et al., 2007b) and significant uplift rates in the hinterland (Snead, 1967; Page et al., 1979; Vita-Finzi, 1987; Sanlaville et al., 1991; Hosseini-Barzi and Talbot, 2003); ii) strong terrigeneous sediment input from coastal streams and mountainous rivers (von Rad et al., 1999a; Luckge et al., 2001) and iii) high-frequency (<20 ka) monsoon-driven climate changes (i.e. arid/humid phases) in response to orbital and sub-orbital cycles during the last 25 ka (Sirocko et al., 1996; Schulz et al., 1998; Clemens et al., 2003).

Reconstructing the evolution of sand-to-mud ratio, sedimentation rates, frequencies, and thickness of turbidite deposits allowed a better understanding of how external forcings interplay at high resolution (<20 ka) and controlled the input of terrigeneous sediment along the tectonically active Makran convergent margin.

2. Regional setting

2.1. Tectonic setting and physiography

The Makran accretionary prism results from the northward subduction of the Arabian plate beneath the Iranian and Afghan continental blocks since the Late Cretaceous times (Kukowski et al., 2001; Grando and McClay, 2007; Ellouz-Zimmermann et al., 2007a; Fig. 1). The plate convergence rate has been estimated between 2.5 and 4 cm yr^{-1} (DeMets et al., 1994; Ellouz-Zimmermann et al., 2007b; Grando and McClay, 2007). The Makran subduction zone is an area of significant seismic activity (Quittmeyer, 1979; Ambraseys and Melville, 1982; Byrne et al., 1992; Ambraseys and Bilham, 2003), periodically affected by devastating earthquakes such as the 1945 Makran earthquake (M_w 8.1–8.3), which is the largest known in this region (Page et al., 1979; Ambraseys and Bilham, 2003; Bilham et al., 2007; Heidarzadeh et al., 2009). Low- to moderate-magnitude earthquakes (mainly related to thrust activity) occur more frequently (<50 y return time) in the Makran area (not restricted to the coast; Quittmeyer, 1979; Ambraseys and Bilham, 2003). The pattern of seismicity is distributed over a 700 km long and 200 km wide segment of plate boundary (Byrne et al., 1992; Ambraseys and Bilham, 2003). The Makran accretionary prism is more than 350 km wide (Platt et al., 1985). Over 60 % of the prism is presently sub-aerial, separated from the submarine part (~100–150 km) by a nearly undeformed continental shelf (Ellouz-Zimmermann et al., 2007a). This continental shelf is relatively narrow (from 10 to 40 km wide), with a shelf break at ~20 to 50 m water depth (Fig. 1). It only enlarges in the Sonmiani Bay area (Fig. 1), where it is about 100 km wide, with a shelf break at ca. −120 m (Fig. 1). The offshore (frontal) prism consists of a sequence of thrust slices units forming accretionary ridges (Fig. 1) with steep flanks and variable length, associated with intraslope "piggy-back" basins (White and Louden, 1983; Fruehn et al., 1997; Kukowski et al., 2001; Ellouz-Zimmermann et al., 2007b; Grando and McClay, 2007). The abyssal plain forms a smooth trench with low gradients, and is confined southward by the Murray Ridge (Fig. 1). To the west, it deepens and widens gently towards the Oman abyssal plain located at 3200 m water depth, where it becomes unconfined (Fig. 1). Sediments are brought to the basin by a dense network of streams and rivers distributed irregularly along-strike (i.e. from west to east). Numerous small ephemeral coastal streams are observed in the western Makran (Fig. 1), whereas larger, high-gradients rivers (such as the Hingol, the Pohr, or the Hab Rivers), which are more perennial, feed the eastern Makran (Fig. 1).

2.2. Past and present-day climate

The Arabian Sea corresponds to the present-day northern limit summer position of the Intertropical Convergence Zone (ITCZ; Gasse, 2000; Fleitmann et al., 2007). The present-day Makran climate is arid to semi-arid, but is dominated by the seasonal reversal of the