Offshore Frontal Part of the Makran Accretionary Prism: The Chamak Survey (Pakistan)

Ellouz-Zimmermann N. · Lallemant S.J. · Castilla R. · Mouchot N. · Leturmy P. · Battani A. · Buret C. · Cherel L. · Desaubliaux G. · Deville E. · Ferrand J. · Lügcke A. · Mahieux G. · Mascle G. · Mühr P. · Pierson-Wickmann A.-C. · Robion P. · Schmitz J. · Danish M. · Hasany S. · Shahzad A. · Tabreez A.

Abstract. The Makran accretionary prism developed in the north-western part of the Indian Ocean as a consequence of the subduction of the Arabian Sea since Late Cretaceous times. It extends from southern Iran to the Baluchistan region of Pakistan where it joins the Chaman-Ornach-Nal left-lateral strike-slip fault systems to the north and the Owen Fracture Zone-Murray Ridge transtensional (right-lateral) system to the south in a complex triple junction near the city of Karachi. In September to October of 2004, we surveyed most of the accretionary complex off Pakistan with R/V Marion Dufresne. We achieved a nearly continuous bathymetric mapping of the prism and the subduction trench from 62°30′E to the triple junction near 65°30′E together with nearly 1000 km of seismic reflection (13 lines) and we took 18 piston cores in different geological settings. One of the main results is that the frontal part of the Makran accretionary prism is less two-dimensional than previously expected. We interpret the along-strike tectonic variation as a consequence of lateral variations in sediment deposition as well as a consequence of the underthrusting of a series of basement highs and finally of the vicinity to the triple junction.

1 Introduction

The Arabian Sea, possibly one of the oldest parts of the Indian Ocean, is now underthrusting beneath the Afghan block, currently at the southern edge of the Eurasian plate. This subduction occurs between two major collision systems of the Zagros (Iran) and the Himalaya (Pakistan-Tibet). The subduction of this Arabian Sea lithosphere, composed of Arabian and Indian oceanic and transitional crusts (Miles et al., 1998), started at the end of the Cretaceous and resulted in the development of the oblique Chagaï volcanic arc along the Pakistan and Afghanistan borders. The subduction system stops at a triple junction between the three Arabian-Eurasian-Indian plates located near Karachi city (Pakistan). This junction corresponds to the intersection between the Makran subduction zone (Arabia/Eurasia motion), the Chaman-Ornach-Nal left-lateral transform fault system (India/Eurasia motion), and finally the Murray transtensional Ridge as a part of the Owen Fracture Zone right-lateral system (India/Arabia motion). The Makran accretionary prism results from the northward motion of the oceanic crust (White and Klitgord, 1976; White, 1983; Minshull et al., 1992), with an average speed of 3 cm/year at present. Large historic earthquakes, such as the magnitude 8.2 recorded in November 1945 (Pacheco and Sykes, 1992; Byrne et al., 1992), are clearly related to the shallow dipping inter-plate mega-thrust. The coseismic motion might be related to the episodic uplift of small mud volcanoes rising up above the sea-level, confirming an overpressure regime imposed at depth.

Our specific interest on the Makran prism was driven by the following facts:

1. Over 60% of the accretionary prism is presently emerged, allowing a detailed structural study onshore as described in a companion paper (Ellouz et al., this issue).
2. The frontal part, located offshore, is where the most recent processes can be analysed, and seems to be more or less linear as far as it joins the transform fault systems.
3. The sedimentation rates vary presently along strike and have been varying through geologic times.
4. Numerous fluid and gas seepages are described both onshore and offshore, outlining high fluid pressures at depth and suggesting fluid circulation linked to both the high sedimentation rates and the overpressure due to horizontal deformation.

2 Geodynamic Setting

2.1 Present-Day Plate Kinematic Setting

The present-day geodynamic setting of the Makran area corresponds to a northward subduction of the Arabian Sea beneath the Iranian and Afghan continental blocks resulting in large interplate thrusting earthquakes (Byrne and Sykes, 1992). Although they exhibit widespread seismicity, the overriding blocks can be considered as the southern edge of the large Eurasian plate. The western part of the downgoing Arabian Sea lithosphere belongs to the Arabian plate whereas the eastern part is part of the Indian plate. The present-day plate boundary between the Arabian and Indian plates is running along the mostly strike-slip Owen Fracture Zone (Quittmeyer and Kafka, 1984; Gordon and DeMets; 1989, Fournier et al., 2001). The plate boundary shows a nearly east-west bend along the Murray Ridge associated with extensional earthquakes before intersecting the subduction boundary west of Karachi city (Fig. 1a). This point corresponds to a triple junction with a connection to the north with the boundary between Eurasian and Indian plates that is mostly left-lateral strike-slip along two prominent faults: the Ornach-Nal fault system to the south-east and the Chaman fault to the north-west (Quittmeyer and Kafka, 1984). According to traditional plate motion modelling, such as NUVEL-1a (DeMets et al., 1994), the Arabian plate is moving at about 30 mm/yr toward the north (Figs. 1a & b). Although these traditional global models are in quite good agreement with the motions obtained from space geodesy (DeMets et al., 1994), the more recent instantaneous global models based on space geodesy (Sella et al., 2002) show a significant difference in relation to NUVEL 1a in the velocities of the African and Arabian plates. This nearly 30% difference has been confirmed when switching to ITRF2000 reference frame for both the African plate (Calais et al., 2003) and the Arabian plate (Vigny et al., 2006). These authors conclude that the two plates have slowed down during the last 3 Ma. In this paper, we favour the Vigny et al. (2006) model because it provides a better agreement with the observed deformation in the Murray Ridge area. We are not following Kukowski et al. (2000) who propose a new Ormara microplate between India and Eurasia, neither are we using the Reilinger et al. (2006) model who introduce a Lut block moving independently from Eurasia. Figure 1a summarises the linear velocities along the three plate boundaries according to the three main models quoted above.

2.2 Plate Kinematics Since Late Cretaceous Times

The present configuration of the subduction zone results from a long lasting geodynamic evolution involving several major plate reorganisations since the breakup of this part of the Gondwana at 157 Ma (Cochran, 1988). The evolution of the plate motions in the studied area has been recorded in the Indian Ocean floor and can be divided in two main stages with respect to the Indian continent motion. In a first sequence ranging from Late Cretaceous (Albian) to the Middle Eocene, the Indian plate is moving northwards at relatively fast velocities (Norton and Sclater, 1979), both in terms of absolute motion and the motion relative to Eurasia (10 to 15 cm/yr from west to east) (Patriat

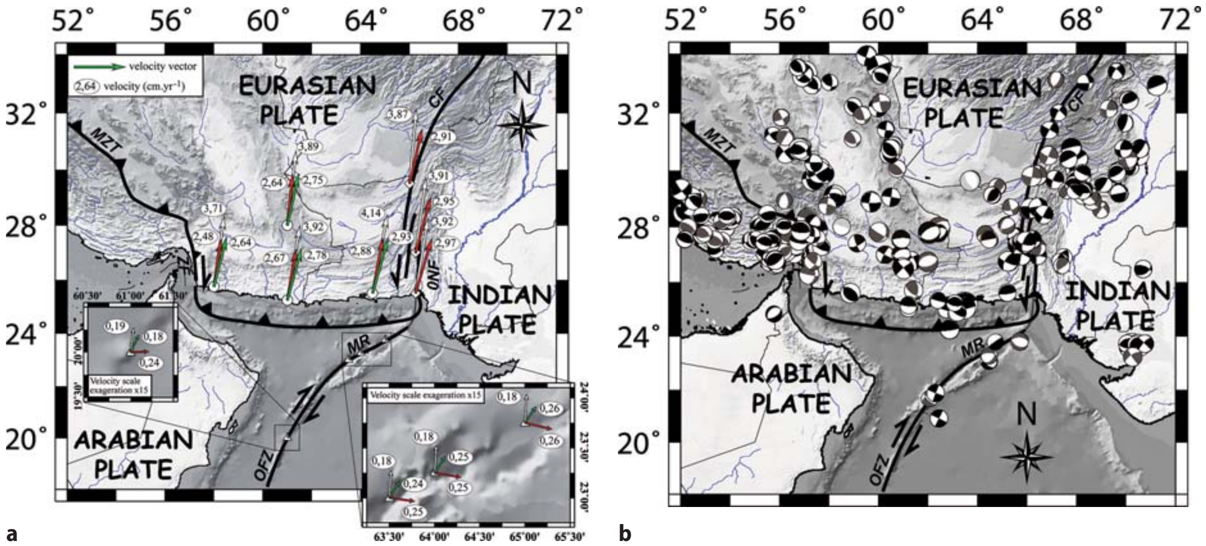


Fig. 1. Present-day plate tectonics setting **a** Relative velocities of the Arabian plate with respect to the neighbouring Eurasian and Arabian plates. The arrows are the linear velocities computed from three recent models: the white arrows according to the "classical" Nuvel-1A model (DeMets et al., 1994) whereas red arrows correspond to the space geodesy model REVEL1 (Sella et al., 2002) and green arrows to a recent GPS based model from Vigny et al. (2006). White circles are Eurasian plate motion relative to fixed Arabia and white diamonds are Indian plate motion relative to fixed Eurasia; **b** Map of the major earthquakes focal mechanisms over the studied area. Hypocentres are represented in 4 depth intervals: 0-30 kms; 30-60 kms; 60-100 kms and >100 km. The earthquakes focal mechanisms are respectively represented by black shaded; dark grey shaded; light grey shaded and very light grey shaded compressive quadrants. Data are compiled from Quittmeyer, R. and Kafka, A., 1984; Laane and Chen, (1983); Jacob et al., (1979); Byrne and Sykes, (1992) and from the Harvard CMT database

and Achache, 1984). After a significant increase in velocity between chron 28 (approx. 61 Ma) and chron 22 (49 Ma), the motion changed suddenly between chron 20 (43 Ma) and chron 18 (39 Ma) to a slower and more northeastward one. This major change in the Indian Ocean spreading pattern is usually related to the onset of the collision between Indian and Eurasian continents (Patriat and Achache, 1984). More precisely, Patriat and Achache (1984) suggested that the change occurred in two stages: from chron 22 to chron 20, the relative motion slowed down along the same direction corresponding to the final closure of the Neotethys. From chron 20 to chron 18, a complete reorganisation of the mid-ocean ridge system accommodated the incipient collision with a major change in the spreading direction. The Indian-African plate boundary had a slightly more complex history. The spreading prior to the chron 28 (83 to 59 Ma) resulted in the Mascarene and Laxmi basins (Bhattacharya et al., 1994; Chaubey et al., 1998; Bernard and Munschy, 2000). The velocity increase of the Indian plate at chron 28 coincides with the jump of the spreading centre to a new location between the Seychelles-Mascarene Plateau and the Laxmi Ridge producing the Arabian Basin to the north and the Eastern Somali Basin to the south. The spreading centres in a complex pattern of propagating rifts, the spreading rate decreasing from 7 cm/yr at chron 22 to less than 2 cm/yr at chron 20 (Chaubey et al., 2002). After 43 Ma, the spreading centre had the present-day configuration of the Carlsberg ridge with a 2 cm/yr rate. The last major change occurred at about 17.6 Ma (chron 5d) as the Sheba ridge started to produce oceanic crust in the Gulf of Aden when the Arabian plate started to drift northeastwards with respect to the African plate (Leroy et al., 2004). As stated above, the present-day plate boundary between India and Arabia is located along the Owen Fracture Zone (Matthews, 1966; Sykes, 1968; Quittmeyer and Kafka, 1984; Fournier et al., 2001) north of a complex triple junction (Fournier et al., 2001) and the whole seafloor underthrusting the Makran margin belongs to the Arabian plate. This plate boundary has probably been active since the onset of spreading in the Gulf of Aden in the Early Miocene (17.6 Ma according to Leroy et al., 2004). An open question remains regarding the India/Africa plate boundary before that time. The simplest interpretation would be to use the same prominent sea-floor topography of the Chain Ridge and Owen Fracture Zone as the main transform system. Several data sets however suggest that the pre-Oligocene transform system was multiple with a large strike-slip fault zone located westward, closer to the southern coast of Oman (Mountain and Prell, 1989 and 1990; Barton et al., 1990; Minshull et al., 1992). For example, the depth to basement in the Oman basin, sediment correlations from seismic profiles on the Owen Ridge, unidentified magnetic lineations and the contrast in crustal thicknesses, all suggest that the Oman margin was a transform margin in the Late Cretaceous time to Early Tertiary times. As shown by Mountain and Prell (1989) and summarised in Minshull et al. (1992), choosing one hypothesis or the other results in dramatic differences in the age of the subducting Arabian Sea basin.

2.3 Sedimentary Inputs Through Time

Another important factor determining the tectonic regime of an active margin is the amount of sediments entering into the trench system (von Huene and Scholl, 1991; Le Pichon et al., 1992). In the present-day situation, most of the Himalaya-derived oceanic sediments are trapped in the Indus fan and have very little involvement in the Makran accretionary processes due to the presence of the Murray Ridge bathymetric high. According to Qayyum et al. (1997), the deposition of thick Himalaya-derived detrital sequences in the modern Indus fan did not start until the Early Miocene (Fig. 2). These authors propose relating the thick Eocene-Oligocene turbidites from the onshore Makran accretionary prism to the oceanic fan of a fluviatile system known in Pakistan and Afghanistan as the Katawaz formation. Despite an apparent continuity of the accretionary processes in the Makran prism, the geological history is clearly divided into two stages. During the early times of the collision zone, the Makran prism grew by accreting the sedimentary products of the Himalayan collision zone through the shortening of a Palaeo-Indus deep sea fan more or less parallel to the paleo-trench. On the other hand, since the Miocene, the accretionary complex is mostly recycling sediments coming from the erosion of the older prism and conveyed to the modern trench through a series of river and canyon systems.

3 Regional Investigation and New Data

3.1 Pre-Existing Data

Prior to our CHAMAK survey, some scattered swath bathymetric data were acquired with hydrosweep multibeam system during cruises SO90, 122, 123, 124 and 130 of the German R/V Sonne (Kukowski et al., 2001). During the same SO123 ('MAMUT') cruise in 1997, wide-angle seismic data were acquired (Kopp et al., 2000) completing the older seismic reflection data set from the Cambridge group (White, 1976; White and Louden, 1983; Minshull et al., 1992). Thanks to a previous visit to DGCP, some of us had an overview of the scattered seismic information on the Coastal Range,

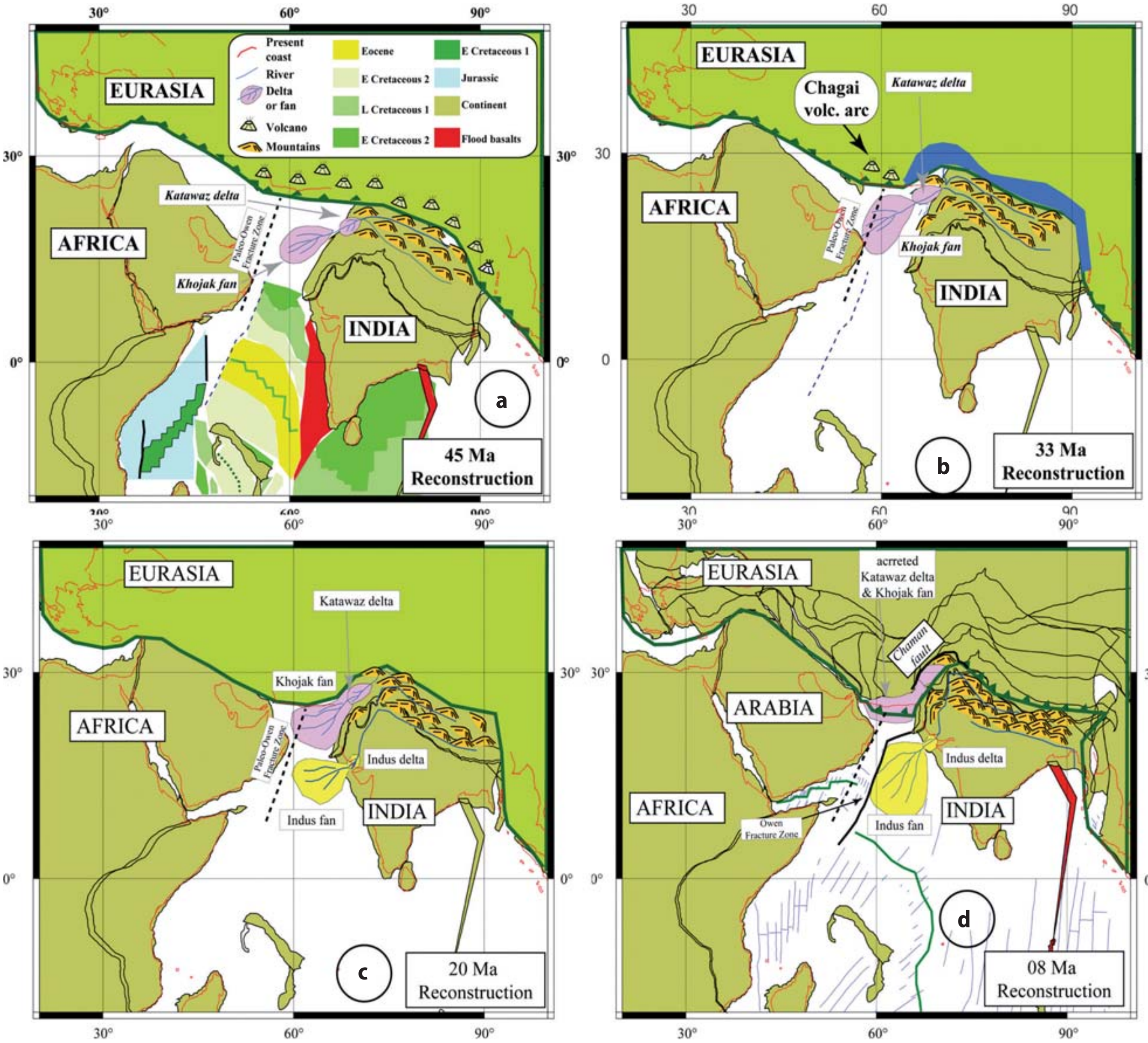


Fig. 2. Plate kinematics in a fixed Eurasia reference frame and sedimentary inputs in the Arabian Sea since Eocene times. Reconstructions have been made using the ODSN interactive facilities which are based on databases from Hay et al. (1999) (http://www.odsn.de/odsn/services/paleomap/paleomap.html) and the Sedimentary bodies is slightly modified from Qayyum et al., (1994). **a** Middle Eocene (45 Ma), onset of the Himalayan collision whose drainage results in the Khojak delta and the Katawaz fan. **b** Eocene-Oligocene (33Ma). The previous delta & fan system is now mature. **c** Lower Miocene (20 Ma). Due to the onset of deformation in the western edge of the Indian continent, a new drainage system appears and results in the modern Indus delta and deep-sea fan system. **d** Upper Miocene (8 Ma). The system of the Owen Fracture and now active Murray Ridge is isolating the Indus fan from the Makran Trench, The old Khojak-Katawaz system is undergoing shortening in the Makran accretionary complex

and of some recent deeper offshore seismic lines. Over the shelf, a couple of already published seismic profiles (Harms et al., 1984) have been re-interpreted. This study benefited from the interpretation of reprocessed CEPM (1977) Indus NW-SE seismic lines (see Ellouz et al., this issue),

On the other hand, the calibration of the seismic reflectors is difficult because only few exploration wells were drilled in the Pakistani Makran continental shelf off the coastal Range. Most of these wells are very old and reached only the Pliocene or the Miocene strata at the oldest, with rather poor constraints on the stratigraphic levels. Unfortunately, we had no access to the Pasni and Gwadar recent wells drilled by Ocean Energy company, both located on the shelf edge.

3.2 New Data from CHAMAK Cruise

CHAMAK Survey was a part of an integrated project which started in 2000 as a collaboration with the Geological Survey of Pakistan (GSP) and National Oceanographic Institute of Pakistan (NOI). The first step was a field reconnaissance in the Makran accretionary prism carried out with the logistical support of the Geological Survey of Pakistan, in February-March 2001. The main results of this field work are presented in a companion paper (Ellouz et al., this issue). CHAMAK cruise was initially planned to start in October 2001. For political and safety reasons, the cruise has been delayed and finally was achieved in September and October 2004. We benefited from the participation and administrative support from the Pakistani navy. The offshore survey was conducted onboard R/V. "Marion Dufresne" operated by IPEV (Institut Polaire Paul Emile Victor) and was devoted to the mapping of the external part of the Makran prism offshore Pakistan. During the cruise, we covered a 65,000 sq. km area with the multibeam echosounder Sea-Falcon. We combined these data with the existing hydrosweep resulting in a nearly continuous complete mapping of the continental slope between 62°30' – 65°30'E & 23°–25°N (Fig. 3).

During the second part of the cruise, around 1000 km of multichannel seismic lines have also been acquired along 13 profiles. The seismic sources were produced by an array of 4 TI sleeve guns (total volume of about 110 cu in) and recorded by two short streamers (respectively a 100 m long 6-channel streamer and a 180 m-long 18-channel one) allowing us to investigate the sediments down to 2.5 s (two way time) with a relatively high spatial resolution on the seabed.

In order to constrain the present-day sedimentary pattern, 27 long cores (half of them with the Calypso giant core) were acquired along the different units of the prism, as well as in the abyssal plain and in the northern flank of the Murray Ridge. When possible these cores were also sampled for fluids, water and gas, sometimes in-situ with the "Goldorak" piston core from A. Lügcke (BGR).

Following the CHAMAK data acquisition cruise, along the Pakistani active margin, several studies were undertaken as parts of an integral project in the aim of understanding the construction of the Makran accretionary prism. Among all the activities, the processing and interpretation of multichannel seismic-reflection lines, the 3.5 kHz profiles and the morphotectonic analysis of the multibeam bathymetry data, as well as the sedimentology, organic matter and gas analysis from the cores, represent the main lines of investigation.

The purpose of this paper is to present a preliminary interpretation of some of the seismic lines and the results from the analysis of the multibeam bathymetric data, illustrating the various structural styles along the recent prism, as well as the main mechanisms involved.

4 Morphology of the Recent Prism

The swath bathymetry data acquired during CHAMAK survey allow us to obtain a good definition and image of the sea-floor morphology and the 3D geometry of the submerged part of the prism, which was poorly documented east of Pasni. In the frontal part of the Makran tectonic wedge, thrust faulting is responsible for the formation of accretionary ridges developed with more or less steep flanks and variable length (White and Louden, 1983; Flueh et al., 1997; Fruehn et al., 1997; Kukowski et al., 2000). At a regional scale, the front of the prism looks rather two-dimensional with an along-strike steepening of the average bathymetric slope toward the east. Focusing on the frontal part of the prism, it appeared that not only the bathymetry profile is shallowing to the east but also the size, the length, and the distance between each thrust is diminishing dramatically.

South of the deformation front, the sediments are deposited in a flat and smooth trench, which is disturbed by some prominent SW-NE trending bathymetric highs more or less buried, like the Little Murray Ridge close to 63°45'E; 24°10'N. The bathymetry shallows drastically on the flank of the northern Murray Ridge where "fossil" meandering channels are identified, marking the southward migration of the distal course of the submarine part of the Indus River (Fig. 3). Southward, the depths increase rapidly in several elongated basins, down to about 4500 m in the Dalrymple trough, representing the southernmost part of the transtensional boundary between the Arabian and Indian plates (Quittmeyer and Kafka, 1984; Edwards, 2000; Fournier et al., 2001).

East of 63°45'N, the accretionary ridges seem to be more sinuous and more prominent than in the area investigated during the 1997 MAMUT survey (Kukowski, 2000) located west of 63°45'N. Consequently, the distance between each ridge is not constant along N-S dip profiles and locally great variations can be observed. Sinuosity is particularly spectacular for the frontal accretionary ridge and results in an indented shape of the prism deformation front (Fig. 3). Moreover the slope of the seaward flank of the frontal ridge is dependant on the distance between two ridges (Fig. 4a), for example becoming steeper where wavelength decreases (Fig. 4b).

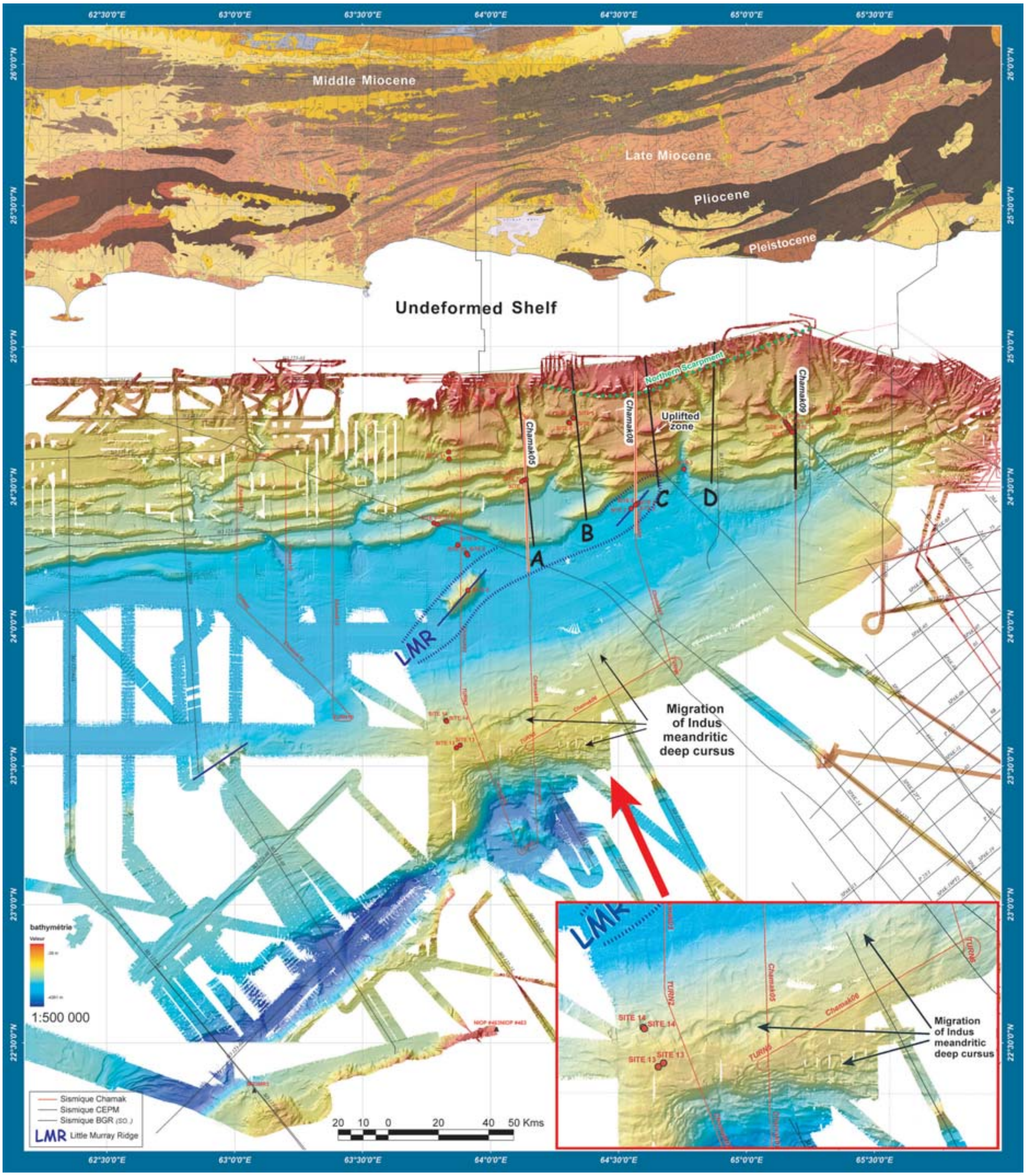
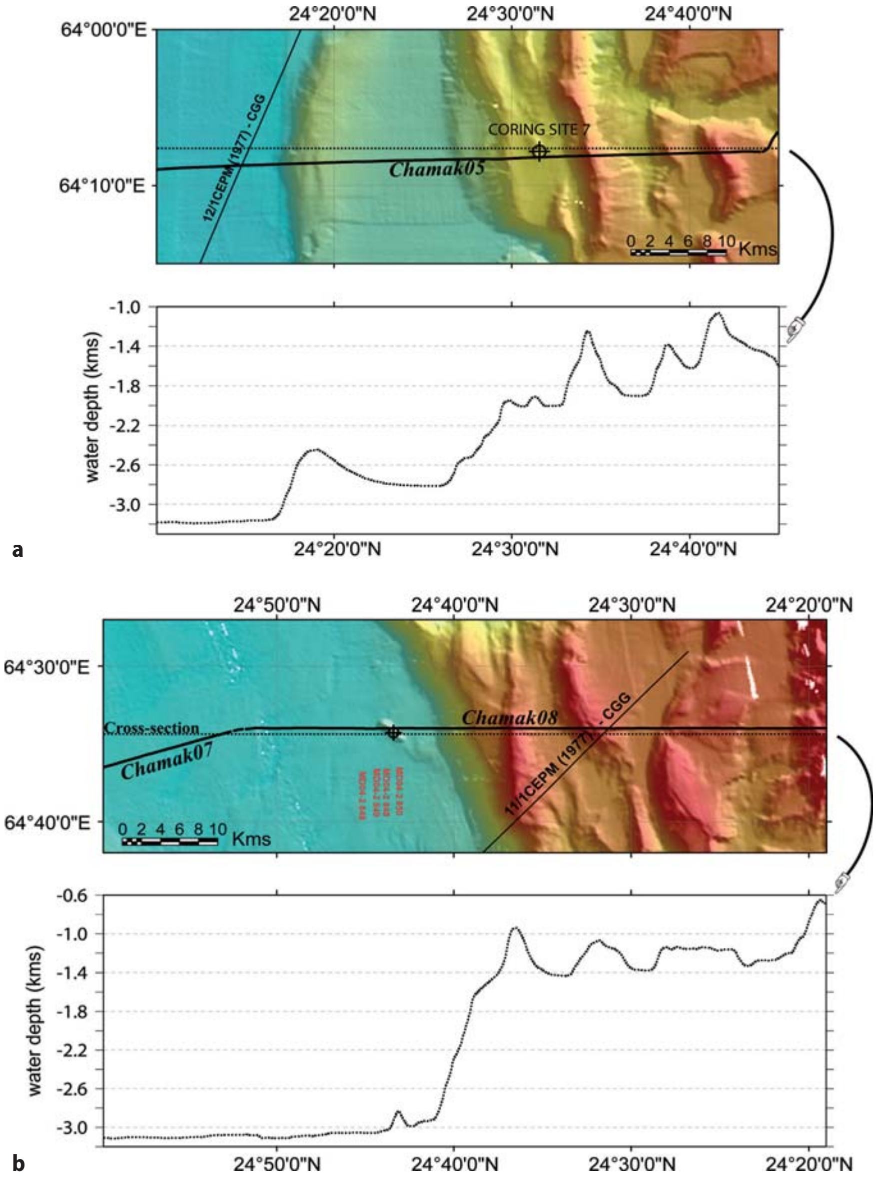


Fig. 3. Composite bathymetry map of the Makran prism using mostly Sea-Falcon multibeam data acquired during Chamak survey combined with the existing hydrosweep data (Kukowski et al., cruise report). The 13 seismic reflection profiles acquired during the cruise are located as well as the cores

The entire offshore wedge is cut by a dense dendritic canyon network (Fig. 3) which is sometimes directly connected to the north with streams or small rivers as Hab, Nal-Hingol or Dasht rivers, from east to west. One of the most striking morphological characteristics of the Makran accretionary wedge is the amount of sediment removal by erosion. Many circular and linear slump scars can be distinguished along the entire prism. The first ones are frequently clustered and generally cut a large portion of the ridges while the linear ones affect only the top of them. Major erosion and sediment transfer processes are expressed in

Figs. 4. Close-up of the bathymetry at two different sites located at the deformation front of the Makran accretionary wedge. **a** Close-up of the seismic CH05 profile (reference profile); **b** Close-up of the seismic CH05 profile (subducted basement high)



the bathymetry as these large sinuous canyons often are associated with circular slump scars. They consist in small canyons and gullies in the upper slope which rapidly coalesce into large canyons downslope. They flow through the prism down to the trench where they incise into the abyssal plain sea floor. These canyons usually cut perpendicular to the ridges but sometimes, when relief is too high, turn and run parallel to the ridges for several kilometres. The associated debris flows have no obvious morphological expression at the sea floor, either because of the substantial hemipelagic sedimentation (Prins et al., 2000) or because of a complete remobilisation of the sediment packets transferred to a wider area.

5 Deformation Style of the External Central (and Eastern) Makran

Multi-channel seismic reflection lines acquired during the Chamak cruise, image the frontal part of the Makran accretionary prism, from the upper slope-break to the abyssal plain. Seismic data show how shortening of ocean floor sediments from the continental slope, is achieved through imbricate thrust faults, forming an E-W oriented ridge network, to the front up to the easternmost salient close to the Bela depression. The tectonic style is governed dominantly by a forward propagation of the deformation, expressed by off-scrapping of the sediment deposited in the foreland basin with a variable thickness. At a large scale a classical large submarine fold and thrust belt develops progressively to the south through time. The connection with the emerged part of the prism is expressed as a wide shelf, where surface deformation is not expressed by compressive structures.

5.1 Nature of the Incoming Sequences

On the north-south trending seismic lines (Fig. 5, locations in Fig. 3), one can see a shallow-dipping regional unconformity, marked by the onlap terminations of the overlying sequence. In a companion paper (Fig. 11 and 12 of Ellouz et al., this issue), this unconformity has been interpreted as the result of intense shortening and erosion of the Makran prism during the Late Miocene times. This tectonic pulse was marked by the increase of reworkings (including Middle Miocene) species found in the Upper Miocene and Pliocene deposits. Schlüter et al. (2002) proposed assigning an Upper Miocene age to this surface interpreted as a major unconformity known at a regional scale and controlled by drilling in Iran. The northward tilting of this surface results both from the flexure of the downgoing elastic lithosphere entering the subduction zone and from the Murray Ridge system deformation, explaining the common tilt observed at the top of the basement highs reflector and at the regional unconformity. Between the unconformity and the basement, the sedimentary units (variable in thickness, locally more than two stwt) have been recorded. They are composed of sub-parallel and continuous reflectors at the base, hosting the basal décollement, and channel-levees system at the top. Above the unconformity, a sedimentary sequence is composed of packages of high amplitude and highly continuous reflectors (hemipelagic sediments?, where the décollement develops at the front) and medium to high amplitude and poor continuity reflectors (distal turbiditic facies?). This sequence shows little flexure and can be recognized to the north as deformed by the imbricate thrusts described above. A lateral facies variation of the supposed distal turbidite sequences is inferred from the presence of channel-like geometries deformed inside the folds on the imbricate thrusts sheets.

5.2 Mechanisms of Deformation

As in other parts of the prism, the imbricate system accounts for the significant structural relief (~ 2 sec. TWT visible in this section) created as a consequence of the off-scraped sediments from the oceanic crust.

The continuity and parallelism at the sea floor change along strike. The western part of the prism (west of 65°5’W) shows mostly continuous E-W directed structures. Nevertheless, despite the apparent two-dimensional aspect at a large scale, the seismic data show a slightly different configuration at smaller scale. Lateral changes concern the wavelength and the amplitude of the anticlinal ridges (Fig. 6a), as well as the vergence which can even vary within a short distance along strike. Such a rapid change can be seen in the frontal thrust between lines CH10 and CH11 (Figs. 5 and 6b).

East of longitude 63°5’W, sea floor ridges show cuspate geometries reflecting an important variation in the tectonic style. The wavelength of these structures varies not only along strike but also along dip (N-S). From a “high standing” plateau (CH08) to a more classical wedge geometry (CH09), lateral variation on the overall geometry of the prism reflecting different internal structure, outline the great impact of the deep structures on the development of the prism.

These lateral variations in morphology are induced by the highly variable deformation mechanisms active in the Makran accretionary prism. The frontal thrust can be interpreted either as a deep blind thrust (seismic line CH09 in Fig. 5) or as an emerging fault (seismic line CH11 in Fig. 5), even as a triangle zone as interpreted in the profile CH 10 (Fig. 5). Folding associated with this frontal thrust shows an up-section decrease of the vertical throw, which indicates the progressive upward propagation of the fault plane (similar to a fault propagation fold system). At the same time folding associated to limbs tilting are shown by piggy-back basins (Fig. 6b). As a consequence of flat and ramp thrust system, the back limb generally rotates, as recorded locally in some of the piggy-back basins sedimentation. However, it is sometimes difficult to tell whether back limb have rotated progressively or not, due to the lack of syntectonic deposits in some of the piggy-back basins.

The upper part of the margin is constituted by a large platform running along the coastline, in which episodic and minor deformation is expressed, either as regional uplift due to deformation propagation at depth, or as out-of-sequence faulting or to normal faulting mainly driven by gravity gliding like in the western Makran off Iran (Grando and Mc Clay, 2006). Mud volcanoes and gas seepages are quite common in the shelf (Schlüter et al., 2002, Delisle et al. 2001, Ellouz et al. this issue), as a typical consequence of overpressure at depth.

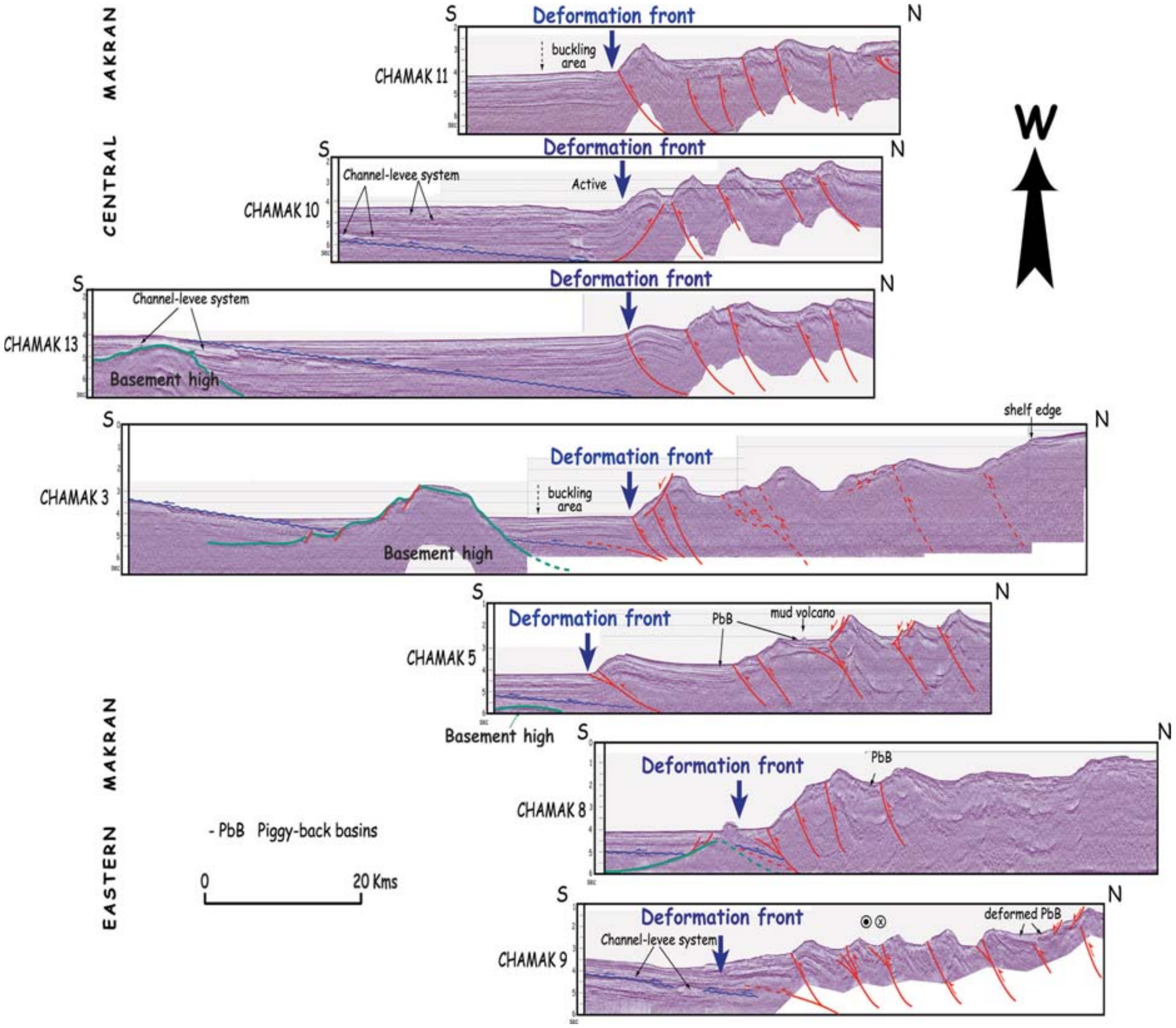


Fig. 5. Display of the seven N-S trending seismic reflection profiles obtained during the CHAMAK cruise. See location on the bathymetric map in Fig. 3

5.3 Piggy-Back Filling

On seismic line CH10 (Fig. 6a), at the foot of the deformation front, an active channel can be recognized (on both seismic and bathymetry data) showing an onlap dominated infill over an erosive surface. The deformation front shows a high degree of lateral variation. In this section an asymmetric fold is observed that can be modelled as a structure of dominant landward (northward) vergence. This unusual tectonic style is well documented for Cascadia (Gutscher et al., 2000; Smit et al., 2003). The imbricate system observed north of the front allows for the formation of several piggy-back basins. To the south, these basins are small and of limited depth. On the other hand, to the north, two wide basins are present showing a history of multiple deformation pulses with several onlap surfaces indicating their progressive tilting.

Piggy-back basins have developed north of most of the ridges showing a sedimentation recording multiple stages of deformation. An analysis of the reflector geometry in the piggy-back basins of seismic line CH11, allows an identification of a polyphase evolution (Fig. 6b). First, the oldest filling sequences usually terminate southwards as onlaps against pre-growth reflectors with a significant fanning of the growth-strata. Contrasting with these deep layers, the overlying sequences are dominated by pinch-out against growth strata. They are in general associated with sub-parallel

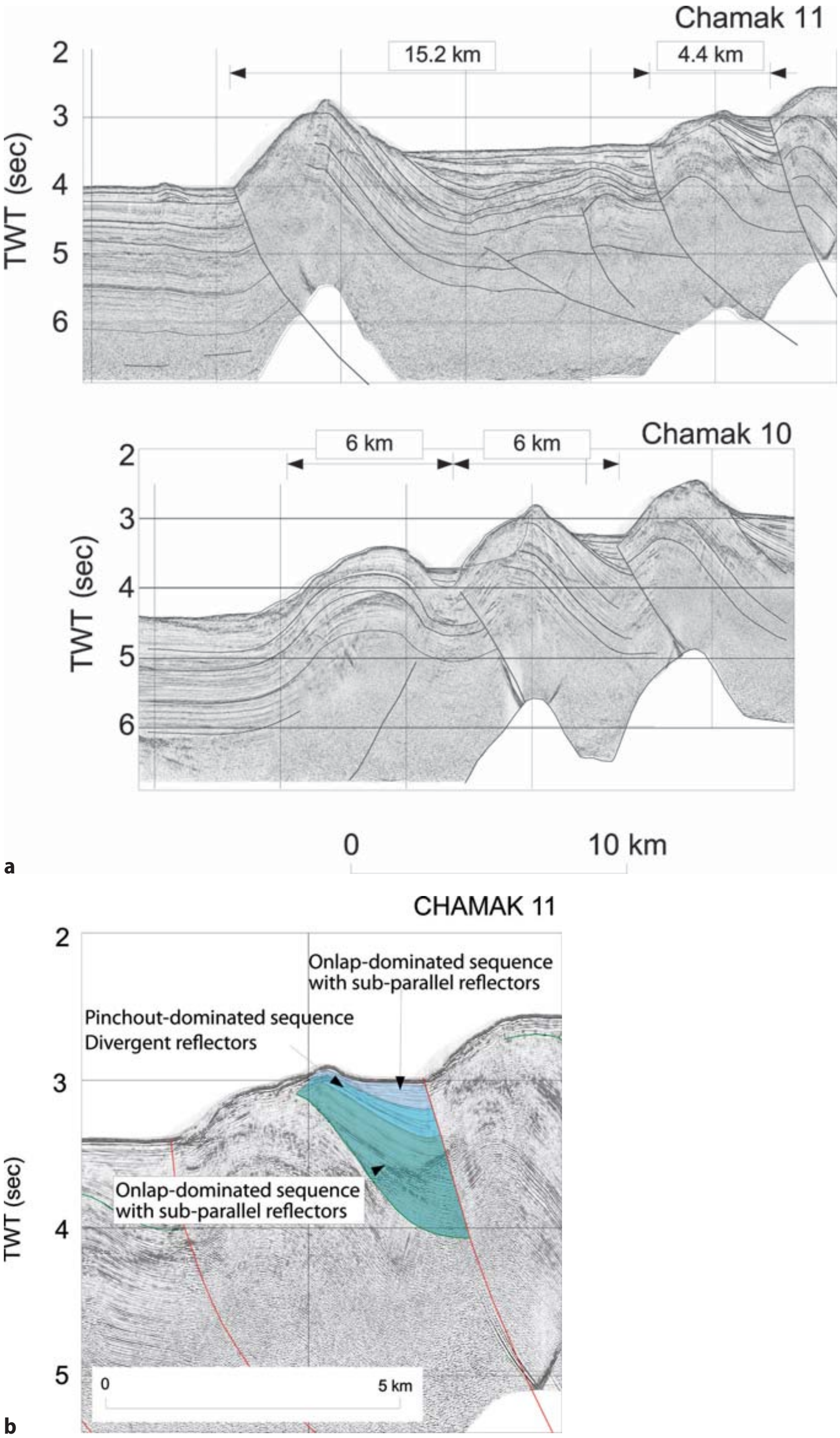


Fig. 6. Detailed seismic interpretation illustrating different mechanisms in the piggyback basins at the rear of the frontal imbricate thrusts; **a** Comparison between profiles CH10 and CH11 concerning the spacing between the main thrust imbricates along the frontal part of the prism; **b** Detail of a piggyback basin on seismic profile CH11 illustrating the geometric relationships between sedimentary reflectors. The nature of reflector terminations allow to identify at least 3 different episodes reflecting changes on the sedimentary/tectonic dynamics

reflectors. This can be interpreted as a period during which sedimentation has been more active than the tectonics, indicating periods of either enhanced tectonic pulses or a slowing of sedimentation rates. The uppermost layer is more similar to the lower piggyback infill with onlaps and fanning corresponding either to a faster deformation rate either to a slower sedimentation rate or any combination.

6 Parameters Affecting the Along–Strike Morphologic and Tectonic Variations

The wavelength between two tectonic sheets is not constant along dip and along strike. The frontal thrusts implies overlap of series from 1.5 s TWT thick in the east of the prism, to 3 s TWT to the west. The bathymetric profiles are changing from east to west locally and can show dramatic variations. Two major parameters seem to guide the deformation style variation: underthrusting of basement ridges and the sedimentation processes. The facies distribution could also be another parameter involved.

6.1 Basement Heterogeneities and Morphological Signature of an Oblique Ridge Subduction

The nature and morphology of the basement through time is still poorly known. Nevertheless, some ridges of various amplitude have been mapped. The most prominent one joins the Owen Fracture Zone to the triple junction, the so-called SW-NE Murray Ridge. Some smaller ridges, with the same orientation are entering the frontal deformation zone and nearly parallel to it (i.e. the "Little Murray Ridge", White, 1983).

Along-strike variations of the tectonic style are illustrated on the two N-S profiles CHAMAK 5 (Fig. 7) and CHAMAK 8 (Fig. 8), which are located in the central part of the Pakistani Makran, where the deformation front's shape reflects a non-cylindrical deformation along strike. On profile 5 (Figs. 3 & 7), the deformation front is characterized by the development of a single thrust more than 20 km off the previous frontal sheet, rooted on more shallow detachment level than the level implied in the inner thrusts.

South of the Makran accretionary prism front, an alignment of sea-mounts following a rough NE-SW direction enters progressively into the subduction zone. An abnormally elevated zone along the Makran prism leads straight to one of these seamounts, suggesting that the ridge has been partly subducted and has resulted in a significant uplift of the prism (Fig. 9, profile C).

The geometry of the front is very different on CHAMAK 8 (Fig. 8), where the frontal part is formed by the stacking of several thrust sheets, resulting in a drastic sharpening of the surface geometry profile. The nature of the seamount at the front is complex. It is clearly related to an old basement high corresponding originally to a horst structure which has probably been reactivated very recently by the seaward migration of the compressional front. This strong heterogeneity in the subducted plate may be related to the blocking of the deformation which will not propagate southward until a critical stability profile will be reached.

A morphological analysis of the prism surface has been performed in order to characterize the morphological effects of the subducted ridge along several morphological sections perpendicular (N-S, dip) or parallel (E-W, along-strike) to the prism. Dip sections allow us to compare the bathymetric level of the piggy-back basins. The two western profiles A and B (Fig. 9) are located out of the so-called "uplifted zone" and there flat areas corresponding to piggy-back basins level are approximately at the same depth. In Fig. 9, one section crosses the uplifted zone (profile C) while the other is out of this zone. All flat areas corresponding to piggy-back basins are shifted and an offset of 400–500 m can be measured.

This offset is also observed along the northern escarpment but rapidly disappears north of it. The area of the prism uplifted due to subduction of the LMR is 40–50 km long (N-S direction) and is 20–30 km wide (E-W direction).

6.2 Sedimentation Rates and Location of the Depocentres

We have observed above that the wavelength between two tectonic units is neither constant along dip nor along strike. Along the frontal part, the thickness of the sedimentary sequence above the regional unconformity involved in the thrusting, varies from 1.5 s TWT to the east to 3 s to the west. It is clear that at present the distribution of eroded products is not two-dimensional over the offshore domain. In the eastern side, presenting a more condensed deformation along dip, the dominant process is the progradation of the shelf to the south. Then, most part of the sedimentary input is trapped in the Upper Margin with a few sediments deposited in the piggy-back basins. Due to a strong water flow, probably the lightest part of the sediment could be transferred to the abyssal plain very dynamically through a ‚canyon network' in a probably steady-state process. Some catastrophic events could sometimes allow the transfer of heavier material to the abyssal plain, expressed as turbidite systems, which can be deposited far from the canyon mouth.

To the west, sedimentation is more regular and evenly distributed between the shelf, the piggy-back basins and the abyssal plain. The sedimentary sequence filling the foreland basin is thickening from the CH 09 to CH 11 toward the Iranian border and gets much thicker offshore Iran (Grando and McClay, 2006).

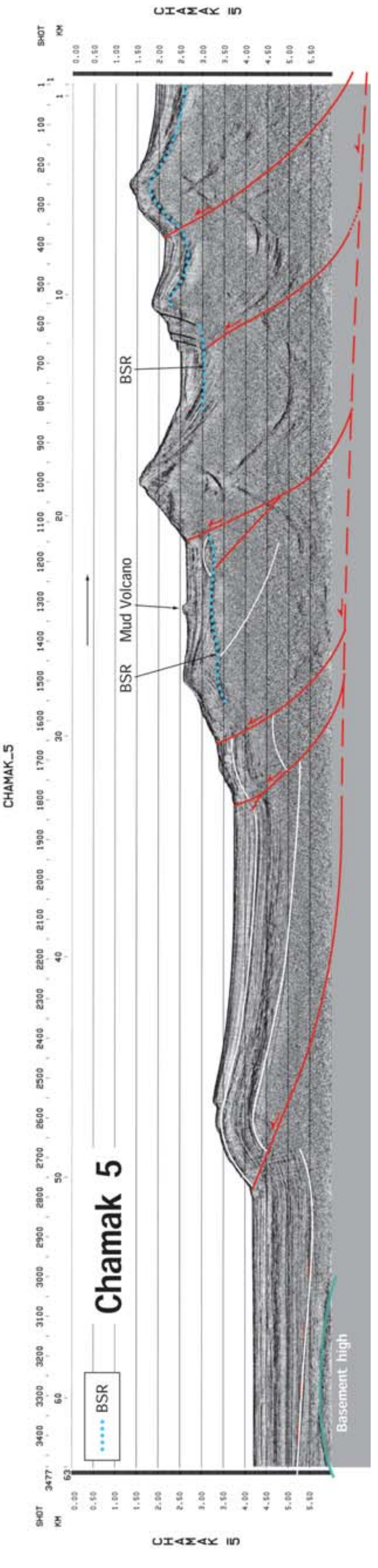


Fig. 7. Interpretation of the seismic profile Chamak number 5 (CH05)

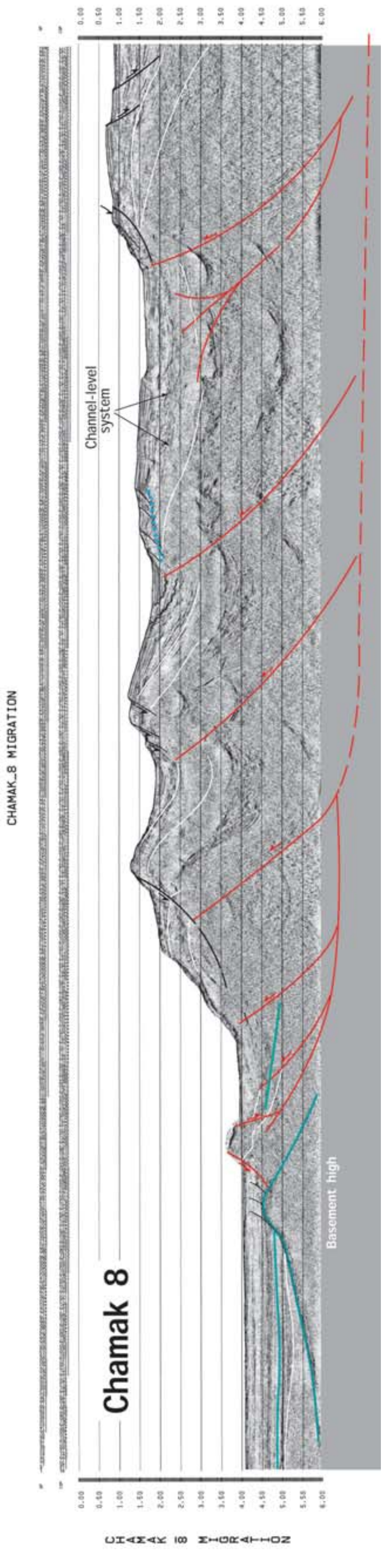


Fig. 8. Interpretation of the seismic profile Chamak number 8 (CH08)

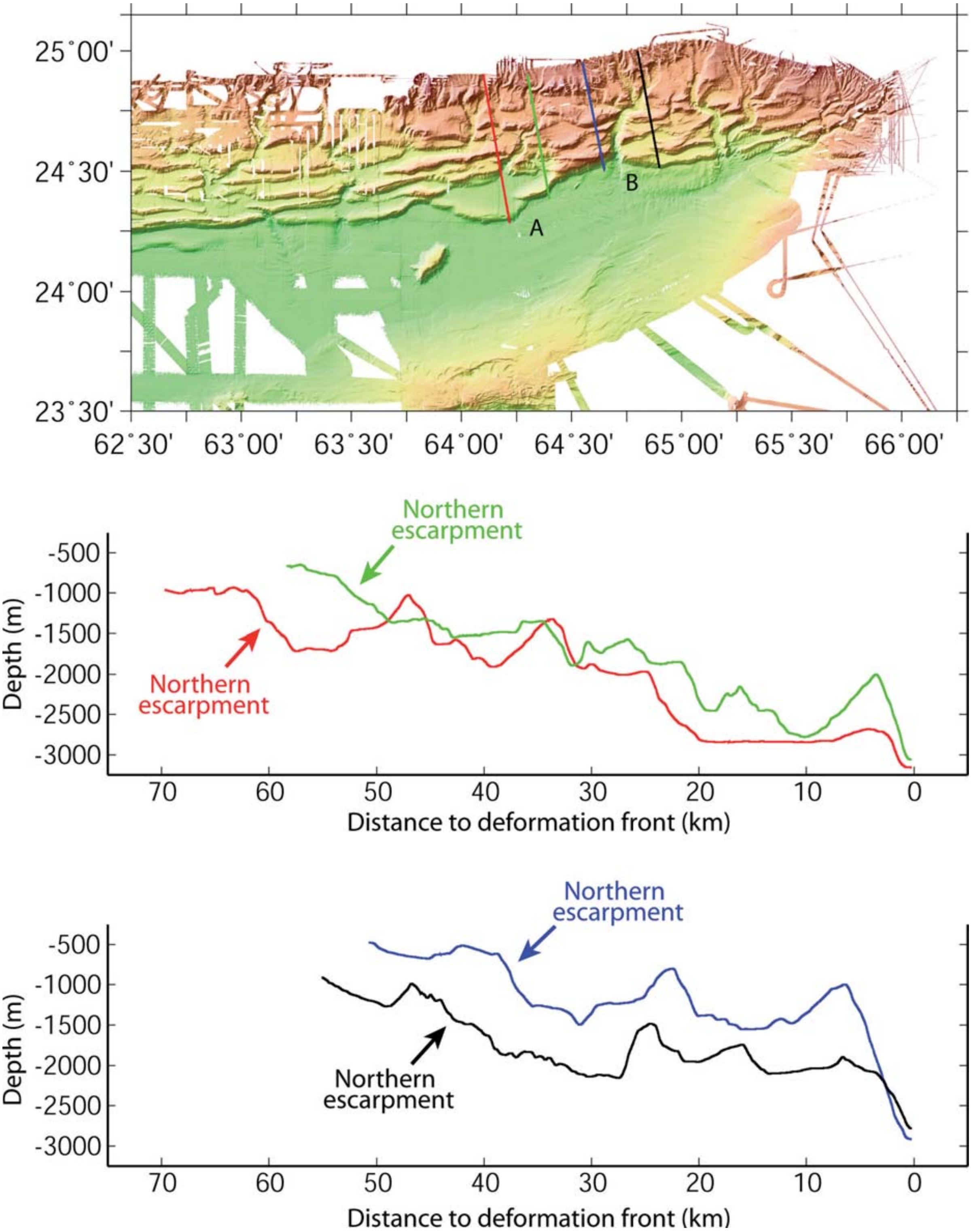


Fig. 9. Bathymetry variation profiles related to the subduction of an oblique ridge

6.3 Change in the Deformation Front in the Vicinity of the Triple Junction

The precise location of the triple junction between Arabian, Indian and Eurasian plates is not well identified. It joins (1) the southernmost part of the India/Eurasia transform system, which is represented by N-S trending series of left-lateral strike-slip crustal faults, which developed progressively toward the Southwest, since Oligocene times. The Chaman, Ghazaband and Ornachnal faults have been connected at each stage to the paleo-subduction front. In the present-day situation it is probable that the triple junction lies below the offshore extension of the Bela Depression.

The Plio-quaternary sediment thickness increases significantly toward the east. In fact, all the erosion products from the prism and Inner Baluchi Ranges (along Chaman and Ornachnal system and Mor Range) are drained up to the Bela depression, and then deposited over the eastern termination of the subduction front. In this situation, due to extremely high sedimentation rates in the extreme Eastern offshore part, the deformation is less well expressed at surface except if shallower décollement levels have been locally used, or alternatively as mud volcanoes or normal compensation faults. The triple junction is not visible at the sea floor because of deep accommodation of this active convergence (early collision?), it cannot emerge and is migrating through time to the south-east. Further complexity arises from intra-plate deformation within the Indian Plate, expressed as a series of E-W trending “en échelon” fold and fault systems, joining the Kirthar Ranges and the offshore Karachi.

Conclusions

Our survey confirms the previous first-order interpretation of a sea-floor morphology tectonically controlled by the offscraping of the Makran into large thrust packets involving the Makran units deposited in the trench. We also confirm that the anticlinal ridges are suffering a much stronger erosion than most of the other accretionary prisms, probably caused by a rapid uplift related to the shortening of thick units. Despite an apparent linearity of the accretionary system at a broad scale, the preliminary results of our survey indicate a significant local non-linearity of the deformation front. The variation in tectonic style along strike is linked to two interacting factors: 1) architecture of the subducting plate where oblique ridges, the Little Murray Ridge and some seamounts parallel to the Murray Ridge (s.s.) have been identified, and 2) variation along strike of the sedimentation rates, due to a change in the location of the sediment supply source - i.e. Indus (draining Himalayan erosion products), or sediment directly derived from erosion of the prism itself since Late Miocene times. The new dating and determination of paleoenvironments from a previous study conducted onshore Makran (Ellouz et al. this issue) identified a dramatic change of the main sedimentary supply at the end of Miocene times.

The structural interpretation first outlines the strong variation in architecture of the frontal part of the prism along strike, linked with the geometry of the subducted plate, depth to the décollement and sedimentary rates variation. The connection between the onshore part and the highly deformed offshore part of the prism is expressed by a large shelf platform, showing little internal deformation but bounded to the south by a major fault (northern escarpment).

Acknowledgements

N.E and S.L., as co-chief scientists, wish to acknowledge the excellent work done by Captain J.P. Hedrich and the R/V “Marion Dufresne“ officers and crew members. We’d also like to warmly thank Y. Balut and the Institut Polaire Paul Emile Victor (IPEV) technical team for their skillful dedication to the data acquisition. This cruise has been made possible through of an offshore programme developed with the NIO, National Institute of Oceanography of Pakistan. We’d like to thank Mr Hasany, Mr M. Danish-Shaika and Mr A. Tabreez from NIO as well as Mr A. Shahzad from Pakistani Navy who joined the Chamak survey and helped the cruise to happen. The seismic reflection survey from CHAMAK leg 2 was accomplished by the Dutch team from the Royal Netherlands Institute for Sea Research (NIOZ), thanks to H. De Haas, B. Koster, L. Lourens, G. Reichart, J. Schilling, M. Smit and W. Van der Linden. We gratefully acknowledge our colleagues C. Kissel, L. Beaufort, D. Blamart, P. Böning, C. Cleroux, A. Gourlan, G. Menot-Combes, L. Pichevin and A.van Toer who were of incredible help in the hard work of onboard core processing. We are also indebted to our German colleagues from the Federal Institute for Geosciences and Natural Resources (BGR) in Hannover: K. Hinz, C. Reichert, U. von Rad and C. Gaedicke who offered us access to some of the seismics done during the R/V Sonne surveys in 1999. N. Kukowski formerly from Geomar (Kiel, Germany) and now at GeoForschungsZentrum (Potsdam, Germany) was of great help by providing Hydrosweep data from the Sonne cruises.

References

Barton PJ, Owen TRE, White RS (1990) The deep structure of the east Oman continental margin: preliminary results and interpretation. Tectonophysics 173(1–4):319–331.

Bernard A, Munschy M (2000) Le bassin des Mascareignes et le bassin de Laxmi (océan Indien occidental) se sont-ils formés à l'axe d'un même centre d'expansion ?: Were the Mascarene and Laxmi Basins (western Indian Ocean) formed at the same spreading centre? Comptes Rendus de l'Académie des Sciences - Series IIA - Earth and Planetary Science 330(11):777–783.

Bhattacharya GC, Chaubey AK, Murty GPS, Srinivas K, Sarma KVLNS, Subrahmanyam V, Krishna, KS (1994) Evidence for seafloor spreading in the Laxmi Basin, northeastern Arabian Sea. Earth and Planetary Science Letters 125(1–4):211–220.

Byrne DE, Sykes LR, Davis DM (1992) Great thrust earthquakes and aseismic slip along the plate boundary of the Makran subduction zone. 97(B1):449–478.

Calais E, DeMets C, Nocquet J-M (2003) Evidence for a post-3.16-Ma change in Nubia-Eurasia-North America plate motions? Earth and Planetary Science Letters 216(1–2):81–92.

Chaubey AK, Dyment J, Bhattacharya GC, Royer JY, Srinivas K, Yatheesh V (2002) Paleogene magnetic isochrons and palaeo-propagators in the Arabian and Eastern Somali basins, NW Indian Ocean. In: Clift PD, Gaedicke C, Craig J (eds). The tectonic & climatic evolution of the Arabian Sea region. Geological Society of London, pp 71–85.

Chaubey AK, Bhattacharya GC, Murty GPS, Srinivas K, Ramprasad T, Gopala Rao T (1998) Early Tertiary seafloor spreading magnetic anomalies and paleo-propagators in the northern Arabian Sea. Earth and Planetary Science Letters 154:41–52.

Cochran JR (1988) Somali basin, chain ridge, and origin of the northern Somali basin gravity and geoid low. Journal of Geophysical Research 93(10):11985–12008.

Delisle G., von Rad U., Andruleit H., von Daniels C.H., Tabrez A.R. & Inam A., 2001. Active mud volcanoes on - and offshore eastern Makran, Pakistan. Int J. Earth Sciences (Geol Rundsch), v. 91, pp 93–100.

DeMets C, Gordon RG, Argus DF, Stein S (1994) Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. Geophysical Research Letters 21(20):2191–2194.

Edwards RA, Minshull TA, White RS (2000) Extension across the Indian-Arabian plate boundary: the Murray Ridge. Geophysical Journal International 142(2):461–477.

Ellouz N., Deville E., Müller C., Lallemant S., Subhani A. and Tabreez A. (2007) Tectonic evolution versus sedimentary budget along the Makran accretionary prism (Pakistan), this issue.

Flueh ER, Kukowski N, Reichert C, cruise participants (1997) F.S. SONNE Cruise Report SO 123, MAMUT, Kiel. GEOMAR Rep 62.

Fournier M, Patriat P, Leroy S (2001) Reapraisal of the Arabia-India-Somalia triple junction kinematics. Earth and planetary science letters 189:103–114.

Fruehn J, White RS, Minshull TA (1997). Internal deformation and compaction of the Makran accretionary wedge. Terra Nova 9: 101–104.

Gordon RG, DeMets C (1989) Present-day motion along the Owen fracture zone and Dalrymple trough in the Arabian Sea. Journal of Geophysical Research 94:5560–5570.

Grando G., McClay K. (2006), Morphotectonics domains and structural styles in the Makran accretionary prism, offshore Iran. Sedimentary Geology (in press).

Gutscher MA., Klaeschen D., Flueh E., Malavielle J. (2001), Non-Coulomb wedges, wrong-way thrusting, and natural hazards in Cascadia. Geology, 29, 5: 379–382.

Harms JC, Cappel HN, Francis DC (1984) The Makran coast of Pakistan: it's stratigraphy and hydrocarbon potential. In: Haq BU, Milliman JD (eds). Marine geology and oceanography of Arabian Sea and coastal Pakistan, pp 3–26.

Hay, W.W., DeConto, R., Wold, C.N., Wilson, K.M., Voigt, S., Schulz, M., Wold-Rossby, A., Dullo, W.-C., Ronov, A.B., Balukhovsky, A.N. and E. Soeding (1999): ALTERNATIVE GLOBAL CRETACEOUS PALEOGEOGRAPHY, in Barrera, E. and Johnson, C. (eds.), The Evolution of Cretaceous Ocean/Climate Systems, Geological Society of America Special Paper 332, pp. 1–47.

Jacob KH, Quittmeyer RL (1979) The Makran region of Pakistan and Iran: Trench-arc system with active plate subduction. In: Farah A, DeJong,KA (eds). Geodynamics of Pakistan, Quetta. Geological Survey of Pakistan, pp 305–317.

Kopp C., Fruehn J., Flueh E.R., Reichert C., Kukowski N., Bialas J., Klaeschen D. (2000),.Structure of the Makran subduction zone from wide-angle and reflection seismic data. Tectonophysics 329,1,:171–191.

Kukowski N, Schillhorn E, Flueh ER, Huhn K (2000) Newly identified strike-slip plate boundary in the northeastern Arabian Sea. Geology 28(4):355–358.

Laane JL, Chen W-P 1989 The Makran earthquake of 1983 April 18: A possible analogue to the Puget Sound earthquake of 1965? Geophysical Journal International 98(1):1–9.

Pichon X, Henry P, Lallemant SJ (1993) Accretion and erosion in subduction zones: the role of fluids. Annual Review of Earth and Planetary Sciences 21:307–332.

Leroy S, Gente P, Fournier M, D'Acremont E, Patriat P, Beslier M-O, Bellahsen N, Maia M, Blais A, Perrot J, Al-Kathiri A, Merkouriev S, Fleury J-M, Ruellan P-Y, Lepvrier C, Huchon P (2004) From rifting to spreading in the eastern Gulf of Aden: a geophysical survey of a young oceanic basin from margin to margin. Terra Nova 16(4):185–192.

Matthews DH (1966) The Owen fracture zone and the northern end of the Carlsberg Ridge. Philosophical Transactions of the Royal Society of London 259:172–186.

Minshull TA, White RS, Barton PJ, Collier JS (1992) Deformation at plate boundaries around the Gulf of Oman. Mar. Geol. 104: 265–277.

Mountain GS, Prell WL (1990) A multiphase plate tectonic history of the southeast continental margin of Oman. Geological society special publications 49:725–743.

Mountain GS, Prell WL (1989) Geophysical reconnaissance survey for ODP Leg 117 in the northwest Indian Ocean. In: Stewart NJ (ed). Proceedings of the Ocean Drilling Program, Initial Reports, 117. Ocean Drilling Program, College Station, TX, pp 51–64.

Norton IO, Sclater JG (1979) A model for the evolution of the Indian Ocean and the breakup of Gondwanaland. Journal of Geophysical Research 84(12):6803–6830.

Patriat P, Achache J (1984) India-Eurasia collision chronology and its implications for crustal shortening and driving mechanisms of plates. Nature 311:615–621.

Prins MA, Postma G, Weltje GJ (2000) Controls on terrigenous sediment supply to the Arabian Sea during the Late Quaternary: the Makran continental slope. Marine Geology 169(3–4):351–371.

Qayyum M, Lawrence RA, Niem AR (1997) Molasse-Delta-Flysch continuum of the Himalayan orogeny and closure of the Paleogene Katawaz remnant ocean, Pakistan. International Geology Review 39:861–875.

Quittmeyer RC, Kafka AL (1984) Constraints on plate motions in southern Pakistan and the northern Arabian Sea from the focal mechanisms of small earthquakes. Journal of Geophysical Research 89(4):2444–2458.

Schlüter H.U., Prexl A., Gaedicke Ch., Roeser H., Reichert Ch., Meyer H., von Daniels C. (2002) The Makran accretionary wedge: sediment thicknesses and ages and the origin of mud volcanoes. Marine Geology 185 (2002) 219–232.

Sella GF, Dixon TH, Mao A (2002) REVEL: a model for recent plate velocities from space geodesy. Journal of Geophysical Research 107(B4):2081.

Smit JHW, Brun JP, Sokoutis D (2003), Deformation of brittle-ductile thrust wedges in experiments and nature, Journal of Geophysical Research 108, B10, 2480, doi:10.1029/2002JB002190.

Sykes LR (1968) Seismological evidence for transform faults, seafloor spreading, and continental drift. In: Phinney RA (ed). The History of the Earth's Crust. Princeton University Press. Princeton, NJ, pp 120–150.

Vigny C, Huchon P, Ruegg J-C, Khanbari K, Asfaw LM (2006) Confirmation of Arabia plate slow motion by new GPS data in Yemen. 111:B02402.

Von Huene R, Scholl DW (1991) Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental crust, Reviews of Geophysics 29(3):279–316.

White RS, Klitgord KD, (1976) Sediment deformation and plate tectonics in the Gulf of Oman. Earth Plan. Sci. Lett. 32: 199–209.

White RS, (1982) Deformation of the Makran accretionary sediment prism in the Gulf of Oman (north-west Indian Ocean). In: Leggett, J.K. (Ed.), Trench and Fore-Arc Geology: Sedimentation and Tectonics on Modern and Ancient Active Plate Margins, pp. 357–372.

White RS, Louden KE, (1983) The Makran Continental Margin: Structure of a Thickly Sedimented Convergent Plate Boundary.Studies in Continental Margin Geology, Watkins and, J.S., Drake, C.L. (Eds.). Mem. Am. Ass. Petrol. Geol. 34: 499–518.

White RS, (1983) The Little Murray Ridge. Seismic Expression of Structural Styles, Bally, A. (Ed.), AAPG Stud. Geol. 15: 1.3.19–1.3.23.

Whitmarsh RB (1974) Some aspects of plate tectonics in the Arabian Sea, in Leg XXXIII. In: Whitmarsh RB, Weser OE, Ross DA et al. (eds). Initial Reports of the Deep Sea Drilling Project, 23, US Government Printing Office, Washington DC, pp 527–535.