Origin of the northern Indus Fan and Murray Ridge, Northern Arabian Sea: interpretation from seismic and magnetic imaging

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Abstract

The nature and origin of the sediments and crust of the Murray Ridge System and northern Indus Fan are discussed. The uppermost unit consists of Middle Miocene to recent channel–levee complexes typical of submarine fans. This unit is underlain by a second unit composed of hemipelagic to pelagic sediments deposited during the drift phase after the break-up of India–Seychelles–Africa. A predrift sequence of assumed Mesozoic age occurring only as observed above basement ridges is composed of highly consolidated rocks. Different types of the acoustic basement were detected, which reflection seismic pattern, magnetic anomalies and gravity field modeling indicate to be of continental character. The continental crust is extremely thinned in the northern Indus Fan, lacking a typical block-faulted structure. The Indian continent–ocean transition is marked on single MCS profiles by sequences of seaward-dipping reflectors (SDR). In the northwestern Arabian Sea, the Indian plate margin is characterized by several phases of volcanism and deformation revealed from interpretation of multichannel seismic profiles and magnetic anomalies. From this study, thinned continental crust spreads between the northern Murray Ridge System and India underneath the northern Indus Fan.

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1. Introduction

We summarize the area of the Dalrymple Trough and the subparallel running northern and southern Murray Ridges to the Murray Ridge System. This northeast–southwest striking Murray Ridge System forms the northernmost extension of the Owen Fracture Zone, and comprises part of the boundary between the Indian and Arabian plates. Only a few multichannel seismic (MCS) profiles cross the Murray Ridge System (Collier and White, 1990; Minshull et al., 1992; Edwards et al., 2000). Additional single-channel and MCS lines (Collier and White, 1990) were recorded by RRS Shackleton (1980) and RRS Charles Darwin (1986). They indicate active NW–SE extensional tectonics with graben formation. Exten-
sional normal faulting (Edwards et al., 2000; White, 1984) is accompanied by seismic activity, for which fault plane solutions indicate right lateral motion (Minshull et al., 1992). Gordon and DeMets (1989) suggest an extension of 2 mm year^{-1} and a dextral slip rate of 0.2 cm year^{-1} for this part of the boundary. Fault-bounded basins contain more than 8 km of Neogene sediments (DeMets et al., 1990; Gordon and DeMets, 1989). Transtensional strain has resulted in local volcanism, close to the Murray Ridge crest (e.g., Jinnah Seamount).

East and south of the Murray Ridge System spreads the Indus Fan which is bordered by the Owen Fracture Zone on its western edge and the Indian continental margin to the southeast. The Indus river is the 11th largest river in the world (Droz and Bellaiche 1991; Kolla and Coumes, 1987), and supplied 450×10^{6} t year^{-1} sediments to the sea prior to recent upstream damming. The river drains an area of approximately 1×10^{6} km^{2} (Searle and Owen, 1995). North of the Murray Ridge and the Indus Fan extends the Oman Abyssal Plain which is underlain by northward subducting oceanic crust of presumed Cretaceous age (Minshull et al., 1992).

The origin and evolution of the crust between the Murray Ridge and the Indian shelf is poorly known, as well as the oceanward boundary of the Indian continental crust. We here present reflection seismic profiles and potential field data, and discuss the crustal origin of this area (Figs. 1 and 2).

2. Plate tectonic history

The early evolution of the Indian Ocean is still a matter of debate. Powell et al. (1988) conclude from magnetic anomalies west of Australia that India has separated from Antarctica at M11 time (133 Ma). Roeser et al. (1996) conclude from the crustal age of the Somali Basin (M22–M0; Cochrane, 1988) that Madagascar separated from Antarctica at M0 time, later than Africa and India. After a phase of strike-slip movement between Madagascar and India, spreading in the eastern Mascarene Basin (Norton and Sclater, 1979) started during chron 34 (84 Ma) and ended at chron 28 (64 Ma). Talwani and Reif (1998) speculate that spreading in the Laxmi Basin (also called Eastern Basin) off the west coast of India lasted from chron 33 to 28. At that time, the two basins were separated by the 100 km wide Laxmi Ridge and the 200 km wide Seychelles Bank which are both underlain by continental crust (Talwani and Reif, 1998).

The Laxmi Ridge, the Seychelles Plateau and the Saya de Malha Bank remained part of the Indian Plate until chron 28 (63 Ma) when spreading jumped north-westward by about 200 km into crust of the Indian continental margin, thus, separating the Seychelles and the Saya de Malha Banks from India. The age of this jump (63 Ma) is documented by the well-developed magnetic anomaly pattern in the eastern Mascarene Basin (Schlich, 1979) and by the oldest anomalies generated at the Carlsberg Ridge. The change closely followed the onset of Deccan flood volcanism 67–65 Ma ago (Courtillot et al., 1986). Subsequent spreading along the Carlsberg Ridge generated the first clear anomaly pattern in the Indian Ocean. Between chron 24 (54 Ma) and 10 (30 Ma), spreading slowed down and the spreading axis changed direction from E–W to NNW–SSE (Gorodnitsky, 1995).

3. Methods

Center of this study is a network of 25 MCS lines with a total length of 2927 km that was acquired in 1997 during cruise SO-122 with a digital streamer (Fig. 1). Due to problems with crossing fishing boats the streamer length varied between 600 and 3000 m. Data were recorded in 2.5-byte SEG-D format. Sampling rates were 1 and 4 ms. After calculation of the shotpoint-receiver geometry, the field data were sorted into Common Mid Point (CMP) gathers with an interval of 25 m. Standard processing, including a poststack \( \omega-\tau \) time FK migration using a constant sound velocity \( V_{p}=1500 \text{ m/s} \) was applied. The intervals for stacking velocity analyses were variable, depending on the seafloor morphology and the quality of subseafloor reflections. Because of the reduced length of the streamer cable in combination with the great depths to the target horizons, there are no sound velocity information, preventing conclusive depths migrations. After transition into SEG-Y all lines were loaded into a Schlumberger GeoQuest™ software package for interactive interpretation.
Fig. 1. Location map of multichannel seismic profiles recorded during FS SONNE cruise SO122. Bathymetric contours of the northern Arabian Sea (in meters) were taken from GEBCO sheet. Profiles shown are highlighted.
During cruises SO-122 and SO-123, a gravimeter Bodenseewerk KSS31 and a Geometrics G-811G longitudinal gradiometer were used. The magnetic variations were reduced by use of the integrated gradient and in addition by use of records of the observatory Karachi. The magnetic anomaly map (Fig. 2a) was compiled from data of SONNE cruises SO-122 and SO-123, digitized records of the HMS Dalrymple cruises 1961 and 1963 (Barker, 1966a,b) and selected data from the GEODAS data set on CD-ROM distributed by the NGDC in Boulder, USA.

Fig. 2b is a gravity map that is based on satellite altimetry (Sandwell and Smith, 1997). It gives an excellent overview. However, for modelling, we prefer the shipboard observations which are more precise and have a much better resolution.

4. Multichannel seismic profiles

4.1. Indus Fan area

Near the present delta front, the Indus Fan is up to 9 km thick. Sediment thickness decreases with the distance from the continental slope and the mouth of the Indus delta. Reflection seismic studies (McHargue and Webb, 1986; Kolla and Coumes, 1987; Droz and Bellaiche, 1991; McHargue, 1991) have shown that the major fan deposits migrated southeastward since the onset of fan sedimentation after rapid unroofing of the Himalayas about the Early Miocene (Qayyum et al., 1997).

The Indus Fan and the Murray Ridge are covered by a grid of MCS profiles obtained during SONNE cruise SO-122 (Fig. 1). The well Indus Marine A1 encountered the base of Middle Miocene at 2725 m depth (Shuaib, 1982) and is located on the continental shelf close to line SO122-16. The stratigraphy from this well was extrapolated to our seismic data set (Clift et al., 2000).

The following four major seismic units could be distinguished due to their internal reflection pattern and structure.

4.1.1. Channel–levee sediments (sequence I2)

The area between the Indian continental margin, Owen Fracture Zone and Murray Ridge in the west and northwest and approximately 15°N is covered by terrigenous deposits supplied by the Indus River (Droz and Bellaiche, 1991; McHargue 1991). The Indus Fan megasequence I2 is composed of a heterogeneous unit of at least 21 channel–levee complexes (Clift et al., 2000). Along the Indian continental slope and adjacent to the recent Indus submarine canyon, megasequence I2 reaches up to 2.2 s (TWT) thick, decreasing to the southwest to 1.8 s (TWT). The individual channel–levee complexes are commonly separated by small bands of easily traceable, continuous, high-amplitude reflections (Figs. 3 and 4). These horizons at the top of each levee complex are closely linked to the sediment supply of the main channel system (Flood et al., 1991; Weimer, 1991) and, thus, give an age control over long distances. According to extrapolated results from wells, Indus Marine A1, B1 and C1 sequence I2 is of Middle Miocene to recent age.

4.1.2. Sediments of the drift phase (sequence I1)

Sequence I1 covers the acoustic basement of the entire Indus Fan area. The sequence consists of parallel to subparallel, continuous reflections. The seismic facies is uniform within this sequence and characterized by low to moderate amplitudes and high frequencies. The lower boundary appears to be concordant to the strong reflection of the basement top, but onlaps subseafood basement ridges (Fig. 4). Its thickness varies from 1.2 s (TWT) in basin areas to zero above basement ridges. The usually concordant upper boundary to the younger megasequence I2 is clearly traceable due to a significant change of the internal reflection pattern. The internal seismic facies

Fig. 2. (a) Map of magnetic anomalies as shadowed relief; insert map shows profiles used for compilation. Bathymetric contours (in meters) derived from satellite altimetry. (b) Free-air gravity map (Sandwell and Smith, 1997). Dark shading in the Murray Ridge area denotes our interpretation of the extension of Indian continental crust. Earthquake epicenters (black dots, 1973–2000) from the PDE catalog provided by the US National Earthquake Information Center. Thin black lines: location of reflection seismic profiles of cruise SO-122 (OCB= ocean continent boundary; SDR= seaward dipping reflectors).
and structure of sequence I1 are typical for deep sea terrigenous input (Posamentier et al., 1991) transported by turbidity currents and intercalated into pelagic sediments or deep sea carbonates. The sequence is deposited in a wide hemipelagic basin environment during the Paleogene after the breakup of India, the Seychelles and Africa in the Upper Cretaceous and prior to the rapid uplift and subsequent unroofing of the High Himalayas in the Early Miocene.

4.1.3. Predrift sediments (sequence I0)

At 21°30' N/65°E on profile SO122-23 (SE part) the basement forms a 90-km wide subseafloor ridge, which is overlain by sequence I0 of continuous, subparallel reflections with moderate amplitudes (Fig. 4). The ridge and sequence I0 is also cut by MCS profile SO122-24 suggesting a N–S trend, while magnetic data exhibit weak, SW–NE to W–E trending anomalies (see following section). Further investigation are necessary to clear the geometry of this feature. Sequence I0 is up to 0.8 s (TWT) thick and is only observed above the basement ridge. Our survey supports earlier published profiles (Droz and Bellaiche, 1991; Kolla and Coumes, 1990). Sequence I0 is supposed to consist of remnants of well stratified sediments, that are truncated on either side of the ridge by erosion. Whether the sediments were truncated in a marine environment or under subaerial conditions is unclear. The lack of a clear basement reflection at the base of the sequence I0 suggests similar acoustic properties for both sedimentary sequence I0 and the basement. In view of the fact that Paleocene hemipelagic sequence I1 onlaps the ridge and because the channel–levee deposits of the Neogene sequence I2 also cover the older stratified sediments of sequence I0, a pre-Tertiary (Mesozoic?) age for this sequence seems reasonable.
4.1.4. The acoustic basement

The top of the acoustic basement is defined as the first strong, high-amplitude reflection at the base of the layered sedimentary sequence I1. Based on the reflection character of the basement top, the internal reflection pattern and the structure, three basement types were distinguished beneath the Indus Fan to the southeast of the Murray Ridge System.

The most widespread acoustic basement type occurs east of the southeastern slope of the southern Murray Ridge (Fig. 3). Its top appears as a smooth undulating, low-frequency, high-amplitude reflection. Some hyperbolic diffractions hint at a rough surface. The depth of the basement reflection ranges between 6 and 7 s (TWT). The lack of pronounced internal reflections, the diffractions at the top reflection and its high-amplitude point to attenuated continental crust with volcanic components or to a modified crust of oceanic origin. Due to the missing magnetic signature, we tentatively interpret this type to be of continental origin. At 0.2–0.3 s (TWT) above the acoustic basement a strong, low-frequency reflection occurs locally trending subparallel to the basement top. This strong reflection might represent high-velocity igneous flows or deep sea carbonates above the acoustic basement. At the flanks of the Murray Ridge,
the basement rises and images a block-faulted structure.

On profiles SO122–24, on the SE part of SO122–23 and on the SW part of SO122–26, the second acoustic basement type is noted lying at depths of 5.5–7.0 s (TWT). The top is characterized by low frequencies and high amplitudes. Bands of continuous, low-frequency reflections are exhibited beneath the top reflection down to 8.0–9.0 s (TWT). Reflections with high lateral extent are traceable for approximately 10–12 km. Hyperbolic diffraction patterns of the top reflection are uncommon. The strong basement reflection indicates differences in the acoustic impedance between the basement and the overlying sedimentary sequences.

Below the southernmost part of the Indus Fan area, a third type of acoustic basement is characterized by a wedge of south to southeast-dipping reflectors (Fig. 5) that occur over a length of 40 km. The sequence of dipping reflectors is visible within this basement type.
from 7.0 to 9.0 s (TWT). Beneath 9.0 s (TWT), the seafloor multiple masks the internal reflection pattern. Single low-frequency, high-amplitude reflectors are traceable over 17 km. Individual reflectors dip from 7.0 to 7.6 s (TWT). Tentatively, this wedge is interpreted as a sequence of seaward-dipping reflectors (SDR) caused by basalt flows as noted in several passive margin settings (Hinz, 1981), where SDRs are interpreted to represent the ocean–continent transition. In this case, the wedge of seaward-dipping reflections may indicate the paleo-continental margin of the Indian Plate. Reexamination of published seismic data (Kolla and Coumes, 1990) identified this oceanward-dipping sequence on adjacent profiles.

4.2. Murray Ridge system

The Murray Ridge is composed of a number of different topographic structures. It extends about 750 km from the northern Owen Fracture Zone in the southwest to the triple junction offshore Karachi in the northeast. Due to large variations in morphology and geologic structure within the ridge, the term Murray Ridge System is used here for the northern and southern Murray Ridge and the Dalrymple Trough (Edwards et al., 2000) and its northeastern continuation.

The Murray Ridge System consists of three distinct parts: the southern ridge with its crest at water depths <1000 m, the northern ridge zone showing a subdued topography with water depths of 2000 m and the >4400 m deep Dalrymple Trough, which splits into several subbasins in its northeastern prolongation. According to the bathymetry, the southern and northern parts of the Murray Ridge and the Dalrymple Trough show lateral offsets along strike, which is consistent with earthquake focal mechanism (Gordon and DeMets, 1989; DeMets et al., 1990).

4.2.1. Sedimentary sequences and deformation pattern

Due to a lack of tie-lines, the correlation of sedimentary sequences within the Murray Ridge System is difficult. Only few wells, located at the outer shelf of Pakistan, could be used for age assessments. But seismic facies and sequence boundary pattern allows a rough correlation from the Indus Fan over the Murray Ridge System into the Dalrymple Trough.

The uppermost sequence I3 in the Dalrymple Trough (SO122-18 and -17; Figs. 6 and 7) is marked by a continuous, narrow-spaced, subparallel internal reflection pattern with moderate amplitudes and frequencies. Sequence I3 is assumed to consist of turbidities derived from the Indian continental slope and from the flanks of the southern Murray Ridge. The thickness of I3 increases from 0.4 s (TWT) along the flanks to 1.4 s (TWT) in the center of the basin where several unconformities mark phases of increased subsidence which have been compensated by high sedimentation rates.

The sediments below sequence I3 exhibit a complex truncation pattern in combination with rapid changes in internal shape. Reflectors are subparallel, of limited lateral extent and have moderate amplitudes. We correlate these sediments with the Middle Miocene to recent channel–levee sequence I2 of the Indus Fan due to the similar seismic character. Since sequence I2 is reduced in thickness and the cut and fill structures are less pronounced along the southern Murray Ridge and in the Dalrymple Trough compared to areas further south, tectonic uplift of the southern Murray Ridge after the early Middle Miocene is assumed. This age is supported by slump structures within higher stratigraphic levels along the southern slope and a time transgressive erosion or nondeposition at the top of the southern Murray Ridge (SO122-17, -18, -23; Fig. 8). On the northern Murray Ridge sequence I3 is missed pointing to a recent hiatus. Sequence I2 is cut by extensional faults (SO122-17; Fig. 7) which reach the seafloor.

Below sequence I2, a sequence up to 0.8 s (TWT) thick (Figs. 6 and 7) is characterized by parallel to subparallel closely spaced reflections with high lateral continuity. Due to its internal shape, we correlate this lower sequence with Paleogene to Mid-Miocene sequence I1 of the Indus Fan area. The lower parts of sequence I1 exhibits discontinuous reflectors with strong amplitudes and low frequencies. We interpret this seismic facies to reflect a volcano-sedimentary unit originating from early rifting processes along the Murray Ridge System during continental break-up. Since the sequence I1 onlaps the flanks of the basement highs of the Murray Ridge, the highs must have existed before the Paleogene.

Sequence I1 lies conformable on the SE-facing flanks of the southern Murray Ridge (Figs. 6 and 7).
Fig. 6. MCS profile SO122-18 showing down-faulted crust of the Dalrymple Trough overlain by sequences I1 and I2. The chaotic reflection pattern of sequence I1 point to a volcano-sedimentary origin. The sedimentary basin fill reaches 4.5 s (TWT) in the center of the Dalrymple Trough. An Upper Neogene age is assumed for the volcanic cone because it has dragged sequence I1 and lower parts of sequence I2. Streamer length 600 m, 24 channels. See Fig. 1 for location.
Fig. 7. MCS profile SO122-17 showing northward dipping lava flows below the top reflector of the acoustic basement along the northern Murray Ridge. Growth faults within sequences I1 and I2 indicate persistent extensional tectonic along the Murray Ridge System. Streamer length 600 m, 24 channels. See Fig. 1 for location.
The dip of the sequence is consistent with the angle of the basement, indicating tilting and uplift of the southern Murray Ridge after deposition of sequence I1. The sediments are truncated at the crest of the Murray Ridge where the whole sedimentary pile is now exposed (Fig. 7). Along the southeast flank of the Murray Ridge the acoustic basement forms a small high, which is overlain by less than 0.1 s (TWT) thick...
sediments. The sequence has a ‘downlap’ contact to this basement high at its northeast slope. Hence, the sequence is younger than the acoustic basement and was deposited after tilting. We guess that this ‘downlap’ contact is caused by faulting.

4.2.2. Acoustic basement

In the cross-section, the basement surface of the southwestern asymmetric ridge crest shows a rough, conical morphology, occasionally piercing the overlying sediments (Fig. 8, line drawing of profile SO122-23). At depths of 0.6–1.8 s (TWT) below the top reflection, coherent seismic horizons with low frequencies could be correlated. These are clearly offset along large normal faults (SO122-23; Fig. 8). The throws of the faults increase along strike from 0.8 km in the northeast to more than 3.0 km in the southwest. The block faulting structure occurs below the southern Murray Ridge crest sensu stricto, is down-faulted within the Dalrymple Trough and also exists below the northern flank of the trough. The entire structural fabric of the acoustic basement is interpreted to be composed of faulted and tilted blocks of continental origin overlain by the 1.0–2.0 s (TWT) thick sequence I1. This interpretation is consistent with results of wide angle and refraction seismic measurements (Flueh et al., 1997) indicating thinned continental crust with thicknesses of 14–20 km below the Dalrymple Trough and southern Murray Ridge and with a velocity layer of 6.5–7.3 km s\(^{-1}\) above the Moho (Flueh et al., 1997). There is also good correlation between the incident reflection seismic interpretation along the western Dalrymple Trough for the top of the basalts at depths of 8.4–8.6 s (TWT) and wide angle seismic modelling for the top of pyroclastic rocks at depth of 8.4 s (TWT) (Flueh et al., 1997).

The southern slope of the southern Murray Ridge is made up by two to three basement highs of volcanic origin presumably bounded by normal faults. Between these volcanic features there are narrow, steep sided and sometimes v-shaped sedimentary basins with infills of up to 2.0 s (TWT) (SO122-18 and -23; Figs. 6 and 8). The geologic and tectonic setting of this part of the Murray Ridge System resembles a complex rift system with propagating graben structures extending south from the more advanced Dalrymple Trough in the north.

The acoustic basement of the northern slope of the northern Murray Ridge is characterized by a sequence of northward-dipping reflectors below the basement top (Fig. 7, for location see bold line Fig. 2b). This divergent reflection pattern most probably is caused by basalt flows, recognizable throughout the studied area and interpreted as a sequence of SDRs which may indicate the continent–ocean transition along the Murray Ridge System. This interpretation is supported by wells offshore Karachi (i.e. Korangi Creek-1, Karachi South A-1, Paitani Creek-1) which are also located on the Indian Plate (Shuaib, 1982). There, 1329 m of Paleocene sandstones and shales with intercalated basalts were drilled. According to wide-angle profile SO123-07 (Fig. 1; Flueh et al. 1997) and reflection seismic results, the crust below the northern Murray Ridge thins from 17 km to about 6 km toward the Oman Abyssal Plain. Hence, we conclude that the northern slope of the Murray Ridge System represents a part of the paleo-Indian continental margin.

5. Potential field data

5.1. Magnetic anomalies

The major tectonic boundaries discussed above are partly visible in the free air gravity (Fig. 2b) and magnetic anomaly maps (Fig. 2a). The Murray Ridge and the Dalrymple Trough are clearly represented by gravity anomalies but are poorly defined in the magnetic map. Although the bathymetrically most distinct part of the Murray Ridge appears as a volcanic structure in the MCS sections it does not have a large-scale magnetic signature (Fig. 2a). However, its whole crest is overprinted by magnetic anomalies with wavelengths of 4–8 km and amplitudes over 100 nT, which are visible on all individual lines. This indicates that the uppermost parts of the Murray Ridge may be magnetically different from its lower, more voluminous part. Dredge samples from the Murray Ridge support this interpretation. They show two petrologically and magnetically different basalt types (Burgath et al., in press). The higher magnetized (sulfidic) basalts may form the crest of the southeastern Murray Ridge. The second type of weakly magnetized basalt has a clear petrologic affinity to island arc basalt. It may make up the bulk of the Murray Ridge, however,
there are clear indications for block faulting, which would be more consistent with continental crust.

The most pronounced magnetic feature of the studied area is a positive anomaly extending from 22.5°N/62°E to 25°N/65°E. It is not related to a well-defined gravimetric anomaly. To the north of the Murray Ridge System, the positive anomaly is accompanied by a wide and smooth negative anomaly indicating a single deep-lying body as a common source of both anomalies. On some lines, the minimum or the slope of the positive anomaly is associated with local gravimetric anomalies and small scaled bathymetric features piercing through the thick Oman Abyssal Plain sediments. This indicates a NE trending ridge structure parallel to but north of the Murray Ridge System (Fig. 2a). The continuation of the magnetic anomaly to the northeast suggests an extension of the inferred ridge below the Makran accretionary prism to 25°N/65.5°E. To the southeast of the broad SW–NE striking magnetic anomaly, an area of moderate amplitudes exists (Fig. 2a) bordered in the south by a line from 21°N/63°E to 23°N/66°E. It broadly coincides with the Murray Ridge System and we suggest that the anomalies are caused by the products of volcanic activity possibly related to the tectonic events that resulted in the development of the Dalrymple Trough/Murray Ridge System.

Further to the southeast, in the Indus Fan area, a magnetically smoother region occurs that is bounded to the south by an area with higher amplitudes. The latter area might be an indication for the transition to oceanic crust. The exact trend of the anomalies is not entirely clear due to gaps in the magnetic map, but two different directions seem to be present, a clear E–W trend at about 20°N and an ENE–WSW trend between 20°N/64°E and 21°N/66°E. Both directions can also be found in the gravity map. The E–W trend would be compatible with magnetic lineations (Miles and Roest, 1993; Malod et al., 1997) south of the Laxmi Ridge which is located at about 19°N. In analogy to the anomalies of the Laxmi Basin (Talwani and Reif, 1998), the linear magnetic anomalies may indicate sea-floor spreading older than anomaly 28.

5.2. Free-air gravity anomalies

In general, the gravity field in the Murray Ridge System area corresponds to the bathymetric features (Fig. 2b). The most distinct anomaly southwest of the Murray Ridge System is a broad gravity high of about 50 mGal followed farther to the southwest by a gravity low of less than −50 mGal. The transition (21°N/63.5°E to 22.5°N/65.5°E) between the two areas does not correspond to any magnetic boundary. The flank of the anomaly is crossed by the reflection seismic line SO122-23 (Fig. 8) showing that the area of the negative anomaly is associated with an elevated basement ridge.

For the gravimetric model of MCS line SO122-23 (Fig. 8), we used the projected crustal thickness from the southeastern end of refraction seismic line SO123-07 (Fig. 1) (Flueh et al., 1997) to constrain the deep crustal structure in the northwestern part of the profile. The model indicates a gentle increase in crustal thickness to the northwest that coincides with the elevated basement seen in the seismic profile. Due to the lack of two-dimensionality, this part of the line (0–50 km) was not modeled in detail. The area of extremely thin crust from 90 to 175 km on profile SO122-23 might be explained either by highly thinned continental crust or by thick oceanic crust. Recognizing the probable continental origin of the Murray Ridge and of the basement high in the southwest (Figs. 7 and 8), as well as the lack of a magnetic signature, we interpret this area as extremely thinned continental crust.

The basement high in the southeastern part of the profile also shows a crustal root with an estimated Moho depth of 20 km. We suggest that this area represents a piece of continental crust that experienced less extension. The southern boundary of this area and, therefore, the inferred transition to oceanic crust as suggested above from the analysis of magnetic data remains unclear in the gravity map (Fig. 2b). There is a transition to higher gravity values at about 20°S which is also the location of a clear linear magnetic anomaly but other magnetic anomalies would suggest a margin located up to 100 km farther north (Fig. 2a).

6. Conclusions

Interpretation of MCS profiles, sampling and magnetic surveys across the Murray Ridge System verify at least three phases of magmatism along the Murray Ridge System.
The first magmatic event is only proven in Upper Paleocene basalts drilled on the continental shelf off Karachi (Shuaib, 1982). We speculate that the sequence of SDRs dipping to the north along the northern Murray Ridge (Fig. 7) are of the same origin. No significant magnetization occurs either along the northern Murray Ridge or in the Oman Abyssal Plain to the north. We interpret the SDRs along the northern Murray Ridge as a hint to the Indian continental margin during the initial continental break-up. Recently the plate boundary of the Arabian and Indian Plates follows the Murray Ridge System. Since the oldest basin deposits in the Dalrymple Trough are of assumed Paleogene age, the basin evolution started at that time. Therefore, we speculate that the plate boundary has established already in the Paleogene.

The second magmatic phase with production of weakly magnetized material took place in (Early?) Paleocene during sedimentation of sequence I1. This material forms aprons along the flanks of the faulted ridges.

The bulk crust of the Murray Ridge System has no significant magnetization and may consist of weak magnetized material typical for active margins, or of continental material with some basaltic components. The ridge crest is significantly magnetized, indicating a third magmatic event, which is also visible in MCS profiles by a sequence of wedge-like, discontinuous, high-amplitude reflections (Fig. 6) between the block-faulted basement and the overlying sedimentary units. Modeling of the gravity field of the Murray Ridge System gives evidence for a total crustal thickness of up to 20 km. Therefore, we suppose that the Murray Ridge System consists of Indian continental crust with magmatic components of different ages. Magmatism started along the paleo-Indian margin during continental break-up in the Upper Cretaceous to Early Paleocene. The northward boundary of the paleo-Indian continent is marked by a sequence of SDRs on profile SO122-17 (Fig. 7) shows faulted and tilted blocks of continental crust and uplifted along the Murray Ridge in the northwest. To the southwest, the continental crust is extremely thinned. Malod et al. (1997) previously interpreted this area as oceanic in origin (Fig. 2b). The basement high at the southeastern end of line SO122-23 (Fig. 4) corresponds with a modeled Moho depth of 20 km (Fig. 8). Here, the Mesozoic(? ) sedimentary rocks cover the basement high and would, thus, have been deposited prior to the initial rifting of Late Cretaceous age. Subsequent to rifting and erosion crustal thinning and subsidence led to sedimentation of sequence I1, which onlaps the basement ridge. The southern margin of the Indian continental crust is marked by a sequence of SDRs on profile SO122-25. This implies that continental crust extends further to the SW than suggested by Malod et al. (1997). The inferred ocean–continent boundary (OCB) at the location of the SDRs marks also the transition to higher magnetic anomalies in the south. The possible extension of the OCB can be deduced from the magnetic and free-air gravity maps (Fig. 2). According to the transition to stronger magnetic anomalies and a minor gravity high between 20.2°N/64°E and 21°N/66°S we propose the OCB to be slightly north of that as defined by Malod et al. (1997). The dark shaded area in Fig. 2b shows our tentative interpretation of the extend of continental crust.

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western Tibet, the Trans-Himalaya and High Himalayan Ranges.


