BUNDESANSTALT FÜR GEOWISSENSCHAFTEN UND ROHSTOFFE

HANNOVER

Fachlicher Abschlussbericht

zum Projekt

Tektonische Entwicklung und Fluidtransport

im Makran-Akkretionskeil / Pakistan

FS SONNE Fahrt SO-122

Forschungsprojekt 03G 122 A

Final Report

of the Project

The Makran Accretionary Wedge off Pakistan:

Tectonic Evolution and Fluid Migration

FS SONNE Cruise SO-122

Research Grant 03G 122 A

- 1. Sachbearbeiter/ Authors: Dr. C. Gaedicke, Dr. H.U. Schlüter,
- Dr. H.A. Roeser, Dr. H. Meyer,

Dr. B. Schreckenberger,
Dipl.-Geol. A. Prexl (all BGR),

Dr. M. Tahir (NIO), Dr. A.M. Cheema (HDIP)

2. Auftraggeber/ Bundesministerium für Bildung und Forschung,

Funding Agency: Projektträger BEO FZ Jülich GmbH

3. Datum/Date: Mai 2000

4. Archiv-Nr./Archive-No.: 0119892

Content I

Figure captions

Fig. 2. Compiled structure map: 1. onshore geology according to PLATT et al. (1988), BANNERT et al. (1992); 2. shelf geology according to QUADRI & QUADRI (1997); geology west Makran area according to KUKOWSKI et al. (in press); VILLINGER (1997); Little Murray Ridge according to BARKER et al. (1966a); WHITE (1983). Additional information taken from EDWARDS et al. (in press).

Fig. 3. Plate tectonic situation and compiled magnetic anomalies of the Arabian Sea and Indian Oceans according to TALWANI & REIF (1998), CHAUBEY et al. (1998), MILES et al. (1998), MALOD et al. (1997), TODAL & ELDHOLM (1998); bathymetry from GEBCO sheet.

Fig. 4. Paleogeographic reconstruction for the time of magnetic anomaly 11, 32 my ago (middle Oligocene).

Fig. 5. Flow diagram for standard processing of the MCS data.

Fig. 6. New acquired system for the interactive interpretation of multichannel reflection seismic data.

Fig. 7. GeoQuest™ screendumps of a 'composite line' created from three seismic sections (122-19; 27; 18) used for tracing reflectors over crossing lines. A good match of all reflections is visible on both tie points. Due to 2D-migration effects the mistie increases with increasing depth and dip of the strata. The lower image shows a part of the survey basemap with position of composite line marked in red.

Fig. 8. GeoQuest™ screendump of line 122-14 shows an example of the 'fault sliding' tool. The option 'fault slide' allows the interpreter to define and move a block of seismic data along a defined fault trace. The shown growth fault exhibits a noticeable increase of offset with depth visible on the colored marked sequence boundaries. Lowermost is the presumed base Middle Miocene unconformity showing erosional truncation of underlying strata.

Fig. 9. GeoQuest™ screendumps of a 'composite line'. First a composite section was created from lines 122-12 and 122-14 (left part of upper picture). Due to the gap of approximately 15 Km there is a mistie of 300 ms. This have been removed by flattening the seabed reflector as shown on the right side. Noticeable is the remaining mismatch of the basement reflection caused by the high relief of the basement, which is independent from relief of the overlying sediments. The multiple reflection visible in the lower right corner is due to its steep dip not completely flattened. The lower image shows a part of the survey basemap with position of composite line marked in red.

Fig. 10. The configuration of the tow system of the magnetic gradiometer; the difference slave value - master value is called "gradient".

Fig. 11. Kp values for the time of the surveys SO-122 and SO-123.

basement. Asymmetric flanks exhibit tilting of Paleogene drift sediments and lower parts of Micocene channel-levee complexes at the eastern slope and a major fault bordering to the Dalrymple Trough.

Fig. 24. Part of seismic profile 122-22 across the eastern Murray Ridge slope. Interpretation with GeoQuest™ system shows the acoustic basement of continental(?) origin with volcano-magmatic cover. The drift sediments below base-Mid-Miocene (bMM) unconformity onlap the basement and were tilted together with lower parts of the channel-levee complexes during a period of uplift.

Fig. 25. Part of seismic profile 122-23. Seismic facies of channel-levee complexes are shown with different colors. The thickness and extend of distinct channel-levee complexes increases in time above the unconformity (bMM).

Fig. 26. Line drawing of profiles 122-16 and 122-26. The channel-levee complexes above unconformity bMM are correlated to the well IndusMarine A-1.

Fig. 27. Part of seismic profile 122-09. Interpretation with GeoQuest™ system shows tilted continental fault blocks below lava flows of assumed Paleogene age.

Fig. 28. Part of seismic profile 122-10. Interpretation with GeoQuest™ system. Northward dipping reflectors are interpreted as Paleocene basalt flows extrapolated by drilling results from Korangi Creek-1 about 90 km to the east of the profile. Basalt flows overlying tilted blocks of continental origin.

Fig. 29. Part of seismic profile 122-10. Interpretation with GeoQuest™ system shows positive flower structure along the symmetric eastern continuation of the southern Murray Ridge buried below thick sediment package off Karachi.

Fig. 30. Part of seismic profile 122-04 across the Murray Ridge. Interpretation with GeoQuest™ system shows volcano-magmatic(?) basement of Upper Cretaceous to Lower Paleocene rift episode along the asymmetric western Murray Ridge System pierced by younger volcanic intrusives (see also magnetic model Fig. 37).

Fig. 31. Part of seismic profile 122-10. Interpretation with GeoQuest™ system shows a graben structure of the acoustic basement below the thrusted Makran accretionary wedge.

Fig. 32. Part of seismic profile 122-11. Interpretation with GeoQuest™ system shows flower structure covered by dipping layers of volcanoclastics and basalt flows.

Fig. 33. Part of seismic profile 122-18. Interpretation with GeoQuest™ system shows downfaulted continental crust of the

Dalrymple Trough overlain by (Late Cretaceous?) Paleocene volcanic aprons and Late Paleogene to Neogene basin fill due to extensional tectonics of assumed Late Oligocene to subrecent age.

Fig. 34. Part of seismic profile 122-17. Interpretation with GeoQuest™ system shows northward dipping lava flows below the top reflector of the acoustic basement along northern Murray Ridge. Growth faults indicate persistent extensional tectonic along Murray Ridge System.

Fig. 35. Part of seismic profile 122-04a. Interpretation with GeoQuest™ system shows onlap of sequence M1 on the N' flank of Little Murray Ridge. Unconsolidated sequence M2 onlaps above Makran unconformity. Apron of little Murray Ridge is overlying faulted oceanic crust.

Fig. 36. Bathymetry of the Murray Ridge System based on HYDROSWEEP swath mapping during SONNE cruises 122 and 123; processing made by KUKOWSKI and WEINREBE, GEOMAR.

Fig. 37. Magnetic model for that part of line SO122-04 that crosses the southern Murray Ridge. Below the sediments (yellow) the model indicates highly magnetized extrusions (gray, 1 – 3 A/m), which produce the short-wavelength anomalies, a weakly magnetized upper part (red, 0.2 A/m) and a higher magnetized lower part (1 A/m) for the ridge.

Fig. 38. Part of seismic profile 122-12. Interpretation with GeoQuest™ system. The seismic sequence below unconformity M onlaps the acoustic basement. Channel-levee facies in the Late Oligocene to Early Miocene sediments above M1 is visible.

Fig. 39 Free-air gravity model for profile SO122-04/04A which shows a strong regional misfit. See Fig. 2 for the final model. Densities in kg/m^3.

Fig. 40 Free-air gravity model for profile SO122-04/04A after introduction of a lateraly varying mantle density. Moho depths within the outlined box are from Minshull et al. (1999). Densities in kg/m^3.

Fig. 41. Free-air gravity model for profile SO122-23. Densities in kg/m^3.

Fig. 42. Stress regime and main tectonic features in the vicinity of the triple junction. Red arrows indicates assumed stress field along plate boundaries, length of black arrows gives relative velocities of Arabian and Indian Plates with regard to a fixed Eurasian Plate. Main tectonic domains are shown in different colors.

Listing of tables

Summary

The **Sonne Cruise SO 122** was carried out by the Federal Institute for Geosciences and Natural Resources (BGR, Hannover) from 3 August - 9 September, 1997, in cooperation with GEOMAR (Kiel), the National Institute of Oceanography (NIO, Karachi) and the Hydrocarbon Development Institute of Pakistan (HDIP). During the joint project with R.V. SONNE the Makran accretionary wedge off Pakistan should have been investigated in detail with multi-channel reflection seismics, magnetics and gravimetry. Intense fishery offshore Pakistan forced a change of the area of investigation to the south with the following objectives:

- investigation of the crustal structure and occurrence of the bottom simulating reflector (BSR) in the Makran accretionary wedge;
- investigation of the structure of the Murray Ridge System in order to reconstruct the geodynamic evolution of the eastern Indian Plate margin;
- determination of the origin of the crust underlying the Indus Fan;
- reconnaissance of the sedimentary history of the Indus Fan in order to reveal the uplift and erosion history of the Himalayas.

Major results of the expedition are:

- The Little Murray Ridge is a Cretaceous(?), magmatic ridge. Its eastern parts become subducted in the vicinity of the Eurasian, Indian, Arabian Plates triple junction.
- Sequences of dipping basement reflectors along the northern Murray Ridge and around 20°30'N / 64°30'E (Indus Fan) are interpreted as basalts extruded during the initial continental break up and marking the ocean-continent transition.
- The Murray Ridge System is of continental origin and experienced a multi-phase volcanism lasting until Upper Miocene/Pliocene. The Murray Ridge

System borders the Indian and Arabian Plates and is active since the Paleogene. Recently the Murray Ridge System is in a trantensional, dextral strike-slip setting.

- The Indus Fan is underlain by thinned continental crust in the area of investigation. Relict sedimentary ridges of the Mesozoic(?) age are onlapped by hemipelagic drift sediments and deposits of the Indus Fan.

The northern Arabian Sea is distinguished by physiographic and structural reasons into four units: (1) the Makran accretionary wedge, (2) the Oman Abyssal Plain, (3) the Murray Ridge System, and (4) the Indus fan. The units meet at the triple junction of the Eurasia, Arabian and Indian Plates west off Karachi.

(1) The **Makran accretionary wedge** extends some 1000 km from Iran to Central Pakistan ranging from water depth more than 3000 m up to 1500 m above sea level. Horst-and-graben structures in the acoustic basement hint to the subduction of the Little Murray Ridge in the east, near the triple junction.

(2) The **Oman Abyssal Plain** extends between the Makran accretionary wedge to the north and the Murray Ridge System to the south. The SW-NE trending Little Murray Ridge divides the abyssal plain into two parts. The sediments reach a maximum thickness of 7 km above the oceanic crust in the north near the Makran accretionary wedge. Due to the lack of magnetic anomalies no age of the oceanic crust could be determined. A Cretaceous age is presumed from estimation of sedimentation rates and correlation with results of ODP Leg 117. The M-unconformity separates a lower hemipelagic sequence dipping with the oceanic crust to the north along the Makran subduction zone, from a flat lying, turbiditic sequence, derived from the Makran wedge. The M-unconformity crops out along the Little Murray Ridge. The age of M-unconformity is thought to be Oligocene or Lower Miocene possibly caused by the opening of the Gulf of Aden, closing of the gateways along the Indian suture, and the subduction of the Arabian Plate under Eurasia.

(3) The **Murray Ridge System** is interpreted as a transform margin of the Indian Plate since Upper Cretaceous. Stages of transpression and transtension caused negative and positive flower structures. The Murray Ridge System is divided into SW-NE trending basins and ridges. The rifted continental basement is covered by volcano-sedimentary sequences. Magnetic modeling based on rock samples and on structural interpretations of seismic profiles gives evidence for two magmatic events: during an older, Paleocene(?) magmatic sequence weakly magnetized material became extruded above the continental basement, while an younger, Neogene complex is characterized by strong magnetic material. Paleocene volcanism is correlated with a sequence of seaward (northward) dipping reflectors along the northern Murray Ridge, where Paleocene basalts of the rift phase were drilled off Karachi. The basalts together with the underlying continental basement of the Murray Ridge became subducted under the Eurasian Plate near the triple junction. It can be concluded that this part of the Makran subduction zone is governed by continent-continent collision (Indian with Eurasian Plates), while to the west the oceanic Arabian Plate collides with the continental Eurasian Plate. NW-SE trending transfer faults cross the Murray Ridge System and extend to the Makran accretionary wedge (Sonne-Fault). At intersections of this faults with ENE-WSW trending extensional zones of the Murray Ridge system a sub-recent volcanism may occur.

(4) Thinned continental crust underlies the northern **Indus Fan**. A ridge consisting of relict, Mesozoic sediments above the acoustic basement is draped by sediments of the rift and drift stage of the Indian Plate. For the first time a sequence of seaward dipping reflectors were recognized in seismic profiles. This sequence is interpreted to belong to basalt flows extruded during the continental breakup exhibiting the initial continent-ocean transition. During the northward drift of India a hemipelagic sequence became deposited which is overlain by post Middle Miocene channel-levee complexes of the Indus Fan.

Zusammenfassung

Die SONNE-Fahrt SO-122 fand unter Federführung der BGR vom 3.8.-6.9. 1997 statt. BGR, GEOMAR, das National Institute of Oceanography (NIO, Karachi) und das Hydrocarbon Development Institute of Pakistan (HDIP) wollten in einem gemeinsamen Projekt den Makran-Akkretionskeil reflexionsseismisch, gravimetrisch und magnetisch untersuchen. Intensive Fischerei in den Gebieten vor der pakistanischen Küste zwang zur Verlagerung des Arbeitsgebietes nach Süden unter folgender Zielsetzung:

- **Untersuchung der Krustenstruktur und der Verbreitung von Meeresboden simulierenden Reflektoren (BSR) an der Basis von Gashydraten im Makran-Akkretionskeil;**
- **Untersuchung der Strukturmerkmale des Murray-Rücken-Systems zur Rekonstruktion der geodynamischen Geschichte des östlichen indischen Plattenrandes;**
- **Bestimmung der Krustenstruktur unter dem Indus-Fächer;**
- **Bestimmung der Sedimentationsgeschichte im Indus-Fächer als Hinweis zur geologisch-tektonischen Geschichte des Himalayas.**

Die wichtigsten Ergebnisse sind:

- **Der Kleine Murray-Rücken ist ein magmatischer Rücken kretazischen(?) Alters. Er wird in Nähe des Tripelpunktes der Eurasischen, Arabischen und Indischen Platte subduziert.**
- **Nördlich des Murray Rückens und bei 20°30'N / 64°30'E (südlichstes Arbeitsgebiet Indus Fächer) existieren keilförmige, divergierende Basaltkomplexe im akustischen Basement (seaward dipping reflectors), die während der initialen Riftphase entstanden und die Grenze von ozeanischer und kontinentaler Kruste markieren.**
- **Das Murray-Rücken-System ist kontinentalen Ursprungs mit mehrphasigem Vulkanismus unterschiedlicher magnetischer Signatur, der bis ins Obermiozän(?)-Pliozän reicht. Es ist als Plattengrenze der arabischen und der indischen Platte seit dem Paläozän(?) aktiv. Heute dominiert eine dextrale, transtensionale Bewegung, die auf Phasen mit Transpression folgte.**
- **Der Indus Fächer wird im Arbeitsgebiet von ausgedünnter Kruste kontinentalen Ursprungs unterlagert. Reste, sedimentärer Rücken mesozoischen Alters werden**

von hemipelagischen Driftsedimenten und den Sedimenten des Indus-Fächers bedeckt.

Physiographisch und strukturell lässt sich das nordöstliche Arabische Meer von Norden nach Süden in vier Einheiten untergliedern: (1) Makran Akkretionskeil, (2) Oman Tiefsee-Ebene, (3) Murray Rücken System und (4) Indus Fächer. Die Einheiten treffen in dem westlich Karachi gelegenen Tripelpunkt von Eurasischer, Arabischer und Indischer Platte zusammen.

(1) Der Makran Akkretionskeil erstreckt sich über eine Länge von 1000 km vom Iran bis Zentralpakistan und reicht von mehr als 3000 m Wassertiefe bis in Höhen von 1500 m üNN. Im Osten, in der Nähe des Tripelpunktes, deuten Horst- und Grabenstrukturen im akustischen Basement auf die Subduktion des Kleinen Murray Rückens.

(2) Die Oman Tiefsee-Ebene liegt zwischen dem Makran Akkretionskeil und Murray Rücken System und bildet ein sich nach Nordosten verjüngendes Dreieck. Die Tiefsee-Ebene wird durch den SW-NE streichenden Kleinen Murray Rücken in einen nördlichen und einen südlichen Teil untergliedert. Die von ozeanischer Kruste unterlagerten Sedimente erreichen im Norden am Übergang zum Makran Akkretionskeil eine Gesamtmächtigkeit von 7 km. Das Alter der ozeanischen Kruste konnte mangels erkennbarer magnetischer Anomalien während der Krustenentstehung nicht bestimmt werden. Nach Abschätzung von Sedimentationsraten im Vergleich mit Ergebnissen des ODP Leg 117 besitzt die ozeanische Kruste der Oman-Tiefsee-Ebene vermutlich ein kretazisches Alter. Die regionale Winkeldiskordanz M trennt eine liegende hemipelagische Sequenz, die mit der ozeanischen Kruste zur Makran-Subduktionszone nach Norden einfällt, von einer horizontal lagernden, turbiditischen Sequenz, die weitgehend vom Akkretionskeil gespeist wird. Die M-Diskordanz beißt entlang des Kleinen Murray Rückens aus. Als Arbeitshypothese wird für die M-Diskordanz ein oligozänes bis untermiozänes Alter angenommen, bedingt durch paläo-ozenaographische Veränderungen bei der Öffnung des Golfs von Aden und bei der Schließung des Seewegs entlang der Suturzone von Indien, sowie durch das Abtauchen der arabischen Platte entlang der Makran-Subduktionszone.

(3) Das Murray Rücken System wird als ein transformer Rand der indischen Platte mit Transpressions- und Transtensionsphasen interpretiert, der seit der späten Oberkreide existiert. Die transpressionalen und transtensionalen Bewegungen sind mit positiven und negativen *'flower'* Strukturen assoziiert. Das Murray Rücken System ist in SW-NE streichende Rücken und Becken untergliedert. Das akustische Basement besteht aus Blöcken kontinentaler Herkunft, die von vulkanischen Einheiten überlagert sind. Aus der Modellierung magnetischer Anomalien aus geologischen Beprobungsergebnissen und aus Hinweisen der strukturgeologischen Interpretation wird geschlossen, dass die kontinentale Kruste des südlichen Murray Rückens von zwei unterschiedlichen vulkanisch-magmatischen Komplexen. überlagert wird: Einem wenig magnetischen, älteren, vermutlich paläozänen Komplex und einem stark magnetischen jüngeren, vermutlich neogenen Komplex. Der Vulkanismus des Paläozän wird zeitlich mit seewärts (nördlich) geneigten Basalten (*seaward dipping reflectors*) des nördlichen Murray Rückens korreliert, die im Schelf vor Karachi erbohrt sind, und die der frühen Riftphase zugeordnet werden können. Im Gebiet der Tripelzone *offshore* Karachi werden die Basalte mit darunter liegenden Kippschollen kontinentaler Herkunft vom Makran-Akkretionskeil überschoben. Daraus kann geschlossen werden, daß in diesem Teil des Arbeitsgebietes die Makran-Subduktion zwischen arabischer und eurasischer

Platte von einer Kontinent-Kontinent Kollision zwischen indischer und eurasischer Platte abgelöst wird. NW-SE streichende 'Transfer'-Störungen kreuzen das Murray Rücken-System und reichen teilweise bis zum Makran-Akkretionskeil im Norden (*Sonne-Fault*). Im Schnittpunkt mit der ENE-WSW streichenden Dehnungszone des Murray-Rücken-Systems existiert offensichtlich ein noch jüngerer Vulkanismus.

(4) Ausgedünnte kontinentale Kruste bildet das akustische Basement unter dem nördlichen Indus Fächer. Ein Rücken aus Relikten, mesozoischer(?) Sedimente über dem akustischen Basement wird von Sedimenten der Rift- und Drift-Phase der indischen Platte überlagert. Erstmalig konnten im südlichsten Teil des Arbeitsgebiets seewärts einfallende Basement-Reflektoren festgestellt werden, die als Reflexionen von Basalten interpretiert und die Lage des Kontinentalrandes der Indischen Platte zur Zeit des Beginns der Drift nach Norden markieren. Während der Drift-Phase kamen hemipelagische Sedimente zur Ablagerung, die von einer komplexen Sequenz von post-mittelmiozänen *Channel-Levee* Sedimenten des Indus Fächers überlagert werden.

1. Introduction and scientific objectives

About 80% of the world's population is settling at continental margins. In particular the active continental margins have highest risk potential due to their seismicity, volcanism and frequency of floods. On the other hand, the bulk amount of hydrocarbon resources is concentrated at continental margins both in ancient deposits and recently trapped in gas hydrates. Moreover, mostly on active convergent margins there is a great potential of proven or suggested ore mineral deposits related to subduction governed volcanism. Therefore the knowledge of geological processes in this geodynamic setting is crucial to minimize hazards, and to explore and guarantee natural resources for coming generations.

The Makran accretionary wedge is located in the southern part of western Pakistan and off the south coast of this area. It has formed by the subduction of oceanic crust of the Arabian Plate under the Eurasian Plate. Subduction lasts since 45 - 55 mill. years, at minimum. Two features make this accretionary wedge especially interesting: Firstly, the sediment thickness on the oceanic crust is extremely high, secondly the angle of subduction is extremely low. Bottom Simulating Reflectors (BSR) indicate the presence of gas hydrates at a large part of the complex.

The Indus fan is substantially smaller than the Bengal fan but nonetheless covers 1.1 x 10^6 km^2, stretching 1500 km into the Indian Ocean from the present delta front. At its thickest part the fan may be as much as 9 km thick. The present river drains an area of approximately 1 x 10^6 km^2 with peak discharge during the summer months due to the seasonal melting of Himalayan glaciers, together with the increased run-off generated by the summer monsoon. Therefore the sediments of the Indus fan exhibit the history of collision of the Indian and Eurasian Plates, the uplift and erosion of the Tibetan plateau and the Himalayas and changes in climate and activity of the monsoon.

The Murray Ridge forms the northernmost extension of the Owen Fracture Zone and comprises part of the boundary between the Indian and Arabian plates. Seismic reflection profiles show present day extensional tectonics along the Murray Ridge and Dalrymple Trough containing more than 8 km of Neogene sediments. Trans-