Geophysical Investigations of Submarine Prolongations of Alluvial Fans on the Western Side of the Gulf of Aqaba-Red Sea

Dissertation

zur Erlangung des
Doktorgrades der Naturwissenschaften

im Fachbereich 5
der Universität Bremen

vorgelegt von
Mohamed Salem
Bremen
2003

Tag des Kolloquiums: 12.11.2003

Gutachter:

1. Professor Dr. Volkhard Spieß
2. Dr. Jürgen Pätzold

Prüfer:

1. Prof. Dr. H. Villinger
2. Prof. Dr. T. von Dobeneck

To all staff members of Geological Department, Faculty of Science, Zagazig University (Benha Branch) and also to my parents, wife and kids

Table of contents

CHAPTER ONE

General introduction

1 General introduction

1.1 Submarine fans

Submarine fans have been intensively studied for more than three decades (e.g. Normark, 1970; Walker, 1978; Bouma et al., 1985; Reading and Richards, 1994; Richards et al, 1998, Bouma, 2000). Most investigations of submarine fans are motivated by their hydrocarbon potential as well as by their potential as recorders of long- and short-term climatic changes (Richards et al., 1998; Bouma, 2001). The term, submarine fan, typically relates to a modern sediment accumulation exposed at the present sea floor while the term, turbidite system, is more used for a subsurface occurrence or outcrop. Many earth scientists, however, use the terms, submarine fan and turbidite system, interchangeably (Bouma, 2000).

The general architecture and geometry of submarine fans are well known, and several depositional models have been developed for their characterization and classification. (Richards, et al; 1998; Bouma, 2000; Stow and Mayall, 2000). The key factors controlling the fan architecture of most published models are: tectonics, climate, nature of sediment input, and sea-level fluctuations (Richards et al., 1998; Bouma, 2000). The tectonics factor includes the location of the sediment source relative to the sea, the elevation of the mountains, the susceptibility of the rocks to erosion, the shelf width and gradient, and the basin morphology. Climate mainly controls the rate and type of weathering in the sediment-source area as well as the fluvial transport capability. The nature of the sediment input may be a point source, multiple source, or linear source. The sediment distribution might vary in terms of grain size, sorting, grain shape, and mineral composition. Sea-level fluctuations, either global or regional, are directly dependent on tectonics and/or climate, and may influence the timing of sediment transport from land or coastal areas to the deepwater basin.

The key-factors controlling the fan architecture are commonly interdependent. Sediment supply, for example, is controlled by a complex interplay of geographic and climatic factors, such as: (1) the relief or mountain heights, (2) the size and temporal storage capacity of the drainage area, (3) the regional climatic conditions, (4) the amount and seasonality of precipitation, and (5) the vegetation cover (Van der Zwan, 2002).

Stow et al. (1985) and Kolla and Macurda (1988) classified the factors controlling the development of submarine systems into two groups. The first group are primary controls including: the type of continental margin, the relief and tectonic setting of the hinterland, the continental shelf-slope relief, the nature of basinal areas and the basin size, the distance

from the source region, the width and the gradients of the shelf-slope, and the type and amount of sediment supplied. The second group, which are secondary controls, includes the climatic nature and vegetation of the source area, the timing of snowmelt waters, and high rainfalls during sea-level changes.

Bouma (2000) characterizes fan systems based on the key-factors controlling fan architecture, i.e., tectonics, climate, nature of sediment input, and sea-level fluctuations, into two end-members in terms of the sand/clay ratio, i.e., coarse-grained vs. fine-grained, and observes that the coarse-grained, sand-rich complexes are typical for regions in active margin setting, characterized by a short continental transport distance, a narrow shelf, and a canyon-sourced nonefficient basin transport system that results in a prograding type of fan. Fine-grained, mud-rich complexes are typical for passive margin settings with long fluvial transport systems, large delta structures, a wide shelf, and efficient basin transport resulting in a bypassing system.

Richards et al. (1998) classify submarine fans on the basis of (a) volume and grain size of available sediment, and (b) nature of the supply system (Fig. 1.1). Based on the grain size, they further classify the submarine fans into (i) mud-rich system, (ii) mixed sand-mud system, (iii) sand-rich system, and (vi) gravel-rich system. The nature of the supply system varies between (i) submarine fan point source, (ii) multiple source ramps and (iii) slope apron linear source. The classification of Richards et al. (1998) provides 12 different models of submarine fan systems but there is a continuum between these categories.

The studied fans in this thesis are submarine prolongations of alluvial fans, which develop off major wadis. Alluvial fans are masses of sediment deposited at some point along a stream where a sharp decrease in gradient occurs. An alluvial fan can be described as a depositional response to the expansion of a confined channel flow as it leaves a rockhead valley to emerge onto the fan surface (Leeder, 1999). Alluvium is first deposited by a large movement of water, such as would occur during a flood, which then becomes erosive through the action of smaller streams (Fig. 1.2). The alluvial fans at the western coast of the Gulf of Aqaba have submarine prolongations, which are usually larger than the subaerial fans themselves. The sizes of the submarine fans in the Gulf of Aqaba, however, are small compared to other major submarine fans.

Characteristic features of submarine fans include slope failure deposits and submarine canyons. Gravity failures (slides, slumps, and debris flows) are usually found in the proximal areas of the fans where slope gradients are relatively large. The possible causes for instability and slope failures in submarine fans are numerous but not well understood.

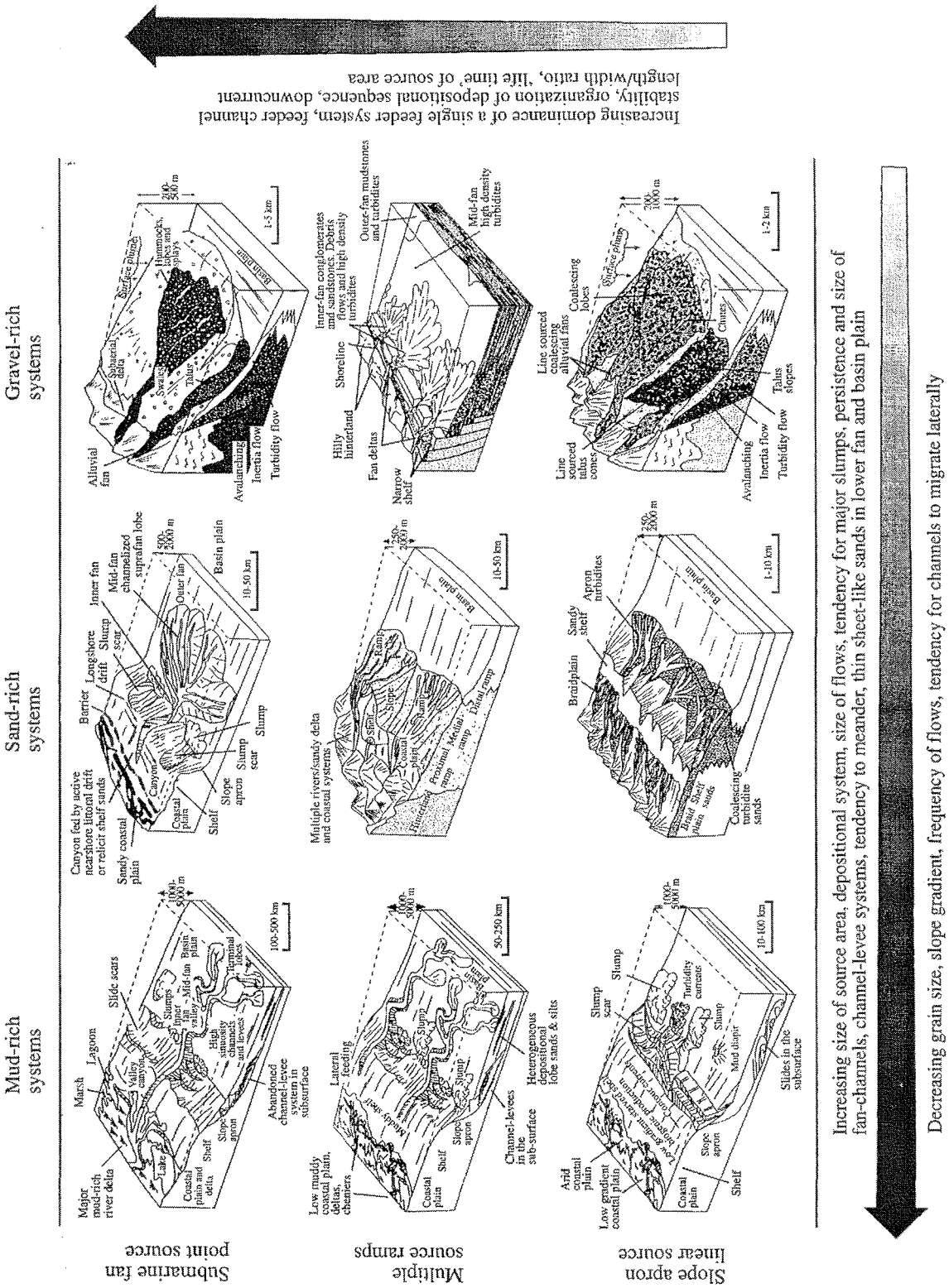


Fig. 1.1: *Schematic drawing of 9 of the 12 models of Richards et al. (1998). The models are classified on the basis of (a) volume and grain size of available sediment, and (b) nature of the supply system. The models for a mixed sand-mud system are not shown. The Figure is taken from Stow and Mayall (2000).*

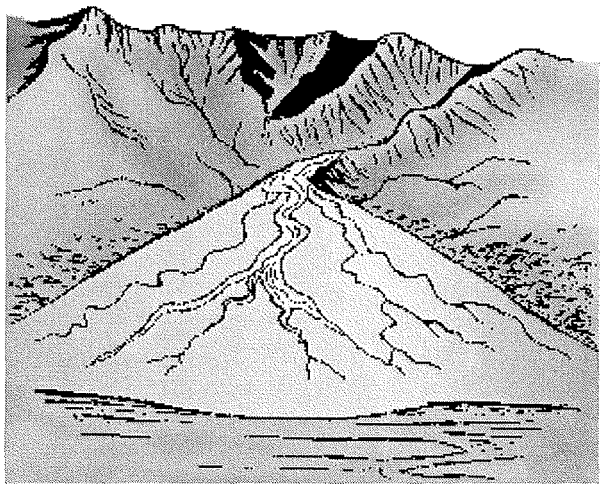


Fig. 1.2: *Schematic drawing of an alluvial fan (taken from Meriam Websters online Collegiate Dictionary).*

Mechanisms include erosion, sedimentation, earthquake activity, diapirism, sea level fluctuations, and wave action (Locat, 2001). In this thesis, we follow the terminology originally proposed by Varnes (1958), Dingle (1977) and Shanmugam et al. (1994). A *slide* is a mass or block that moves downslope on a planar slide plane or shear surface and shows no internal deformation, whereas a *slump* is a block that moves downslope on a concave-up glide plane or shear surface and undergoes rotation which causes internal deformation. In other words, slides represent translational movements and slumps represent rotational movements along shear surfaces. An increase in mass disaggregation and mixing with water, as a slump moves downslope, can result in the transformation of the slump into a *debris flow* in which sediment is transported as an incoherent, viscous mass via plastic flow. If the fluid content further increases, a plastic debris flow may evolve into a fluidal *turbidity current.* Debris flows and turbidity currents may, however, directly result from slope failures as well.

Submarine canyons usually play an important role in the evolution of submarine fans. The position and configuration of the canyons are controlled by multiple factors, including structural fabric, tectonism, sea-level variations, and sediment supply (Laursen and Normark, 2002). Submarine erosion by turbidity currents plays a key role in the formation of submarine canyons but other processes, including sediment creep, localized slides and slumps, and currents are important in moving sediment downslope and eroding canyon walls as well (Shepard, 1981). Several canyons are also carved into the submarine prolongations of the alluvial fans in the Gulf of Aqaba, and they seem to play a significant role in sediment transport within these fans.

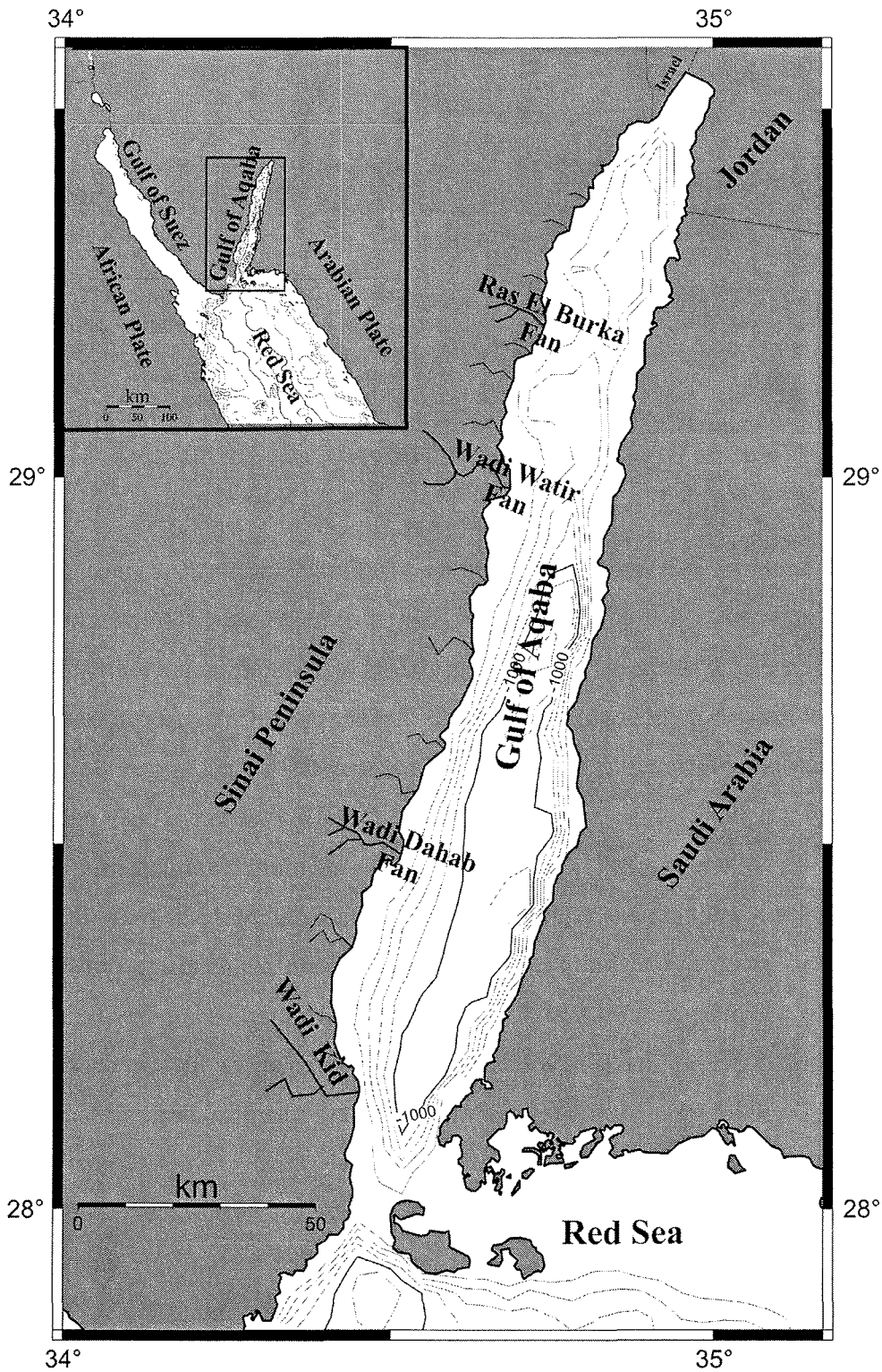


Fig. 1.3: *Overview map of the Gulf of Aqaba showing the location of the studied fans.*

1.2 Geological setting of the Gulf of Aqaba

The Red Sea, which runs almost 2000 km from the Mediterranean Sea to the Indian Ocean, lies in a fault depression in the Arabian-Nubian shield. At its northern end it bifurcates into the Gulf of Suez and the Gulf of Aqaba (Fig. 1.3). The Gulf of Aqaba is bordered to the

west by the Sinai Peninsula and to the east by the Arabian mainland. It is known as a region of intensive crustal movement.

Tectonically, the Gulf of Aqaba forms the southern part of the Dead Sea rift (Figs. 1.4, 1.5). The Dead Sea transform relates to the boundaries of the Arabian and African plates as well as to the Sinai Peninsula subplate. On a larger scale, divergence in the Red Sea is accommodated by plate convergence in Iraq-Iran (Zagros Mountains) as the Arabian plate moves north relative to the African plate (Fig. 1.5, Mechie and El-Isa, 1988).

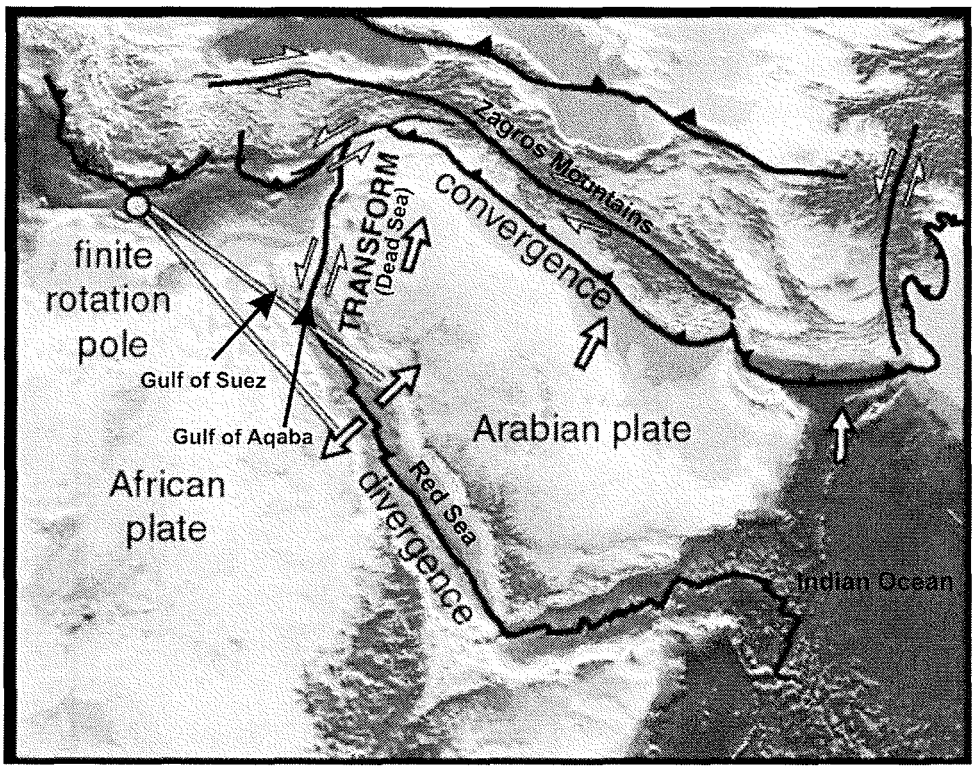


Fig 1.4: *Tectonic overview map of the Red Sea and the Dead Sea Transform (modified after http://earth.leeds.ac.uk/leb/tectonics/regional/regional.htm).*

Bayer et al. (1988) concluded that the kinematics of the Red Sea area changed from passive rifting with a WSW-ENE extension direction to sinistral shear along a NNE direction (Aqaba-Levant transform, Fig. 1.5) in the Late Miocene. The change was accompanied by the opening of the Red Sea as a result of the oblique drift of the Arabian Plate. This rearrangement led to a stagnation of extension and subsidence in the Gulf of Suez, and created a new plate-boundary, the Aqaba-Levant structure (Fig. 1.5). Bayer et al. (1988) further concluded that strike-slip movement along the Aqaba-Levant structures started at ~14 Ma.

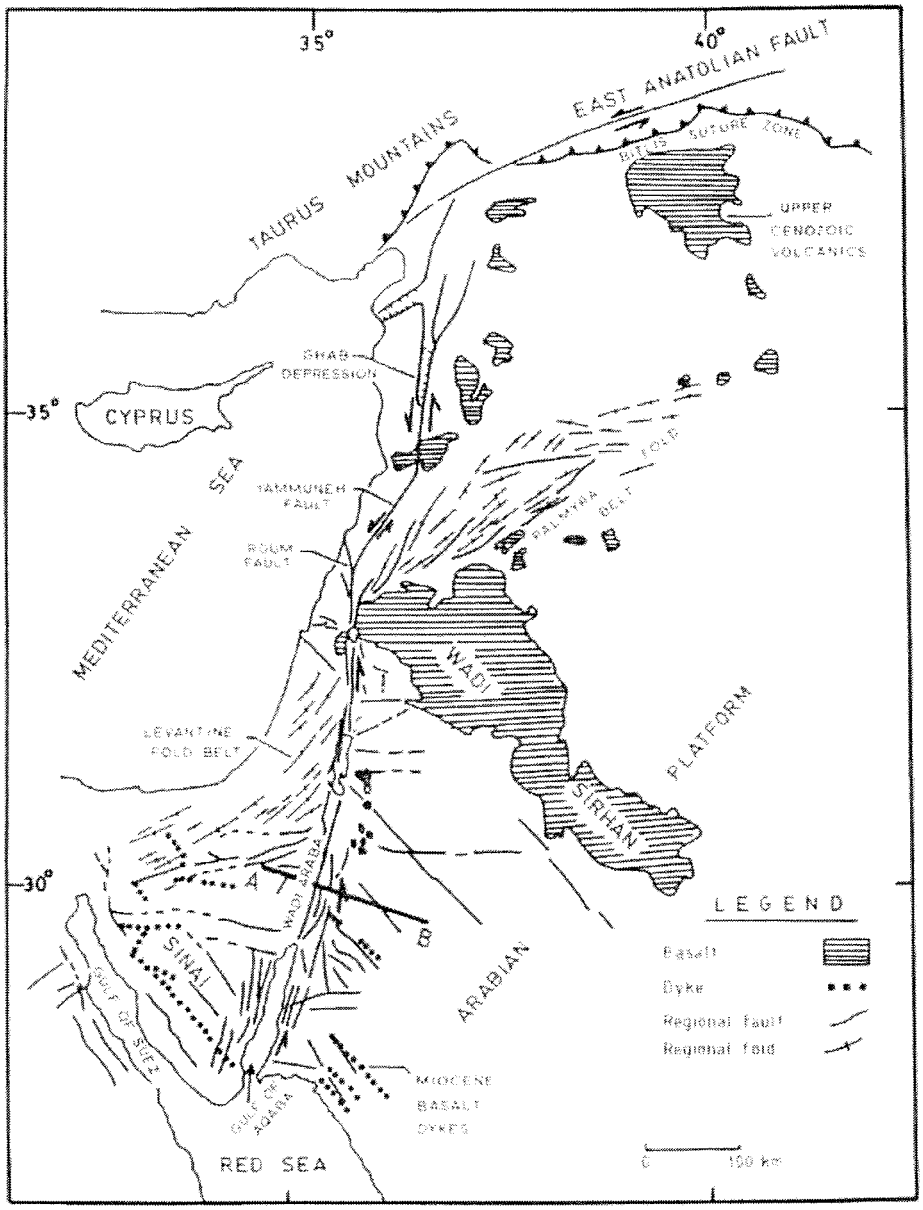


Fig. 1.5: *Regional tectonic map of the Jordan-Dead-Sea Transform (from Mechie and El-Isa, 1988).*

Quennell (1958) and Freund et al. (1970) suggested that the strike-slip movement occurred in two phases, i.e., one of 60 km, during post-Cretaceous times and another of 45 km, from the Pliocene onwards. Bartov et al. (1980), on the other hand, suggested a single-phase movement during which a slip of 105 km occurred, beginning in the Middle Miocene. The oldest movements along the Dead Sea rift, therefore, are younger than those in the Suez basin (Eyal et al., 1981).

The Gulf of Aqaba is unique for its great depth in proportion to its width. Its maximum depth is ~1850 m; the average depth is ~650 m (Morcos, 1970). The Gulf of Aqaba is 160

km long, and has a maximum width of 24 km. The tectonic development of the region around the Gulf of Aqaba deformed the surrounding coastal areas as well as the areas within the Gulf itself, and created faults with main directions in the N-S to NNE-SSW (Fig. 1.6, Ben-Avraham et al., 1979a, Ben-Avraham, 1985; Bayer et al., 1988). According to Garfunkel (1981) and Ben-Avraham et al. (1979b), the Gulf of Aqaba forms a succession of three deep and elongated NNE-SSW pull-apart basins which are separated by shallow sills. The Sinai Peninsula Mountains rise steeply on the western side of the Gulf, where they are bound by coastal faults.

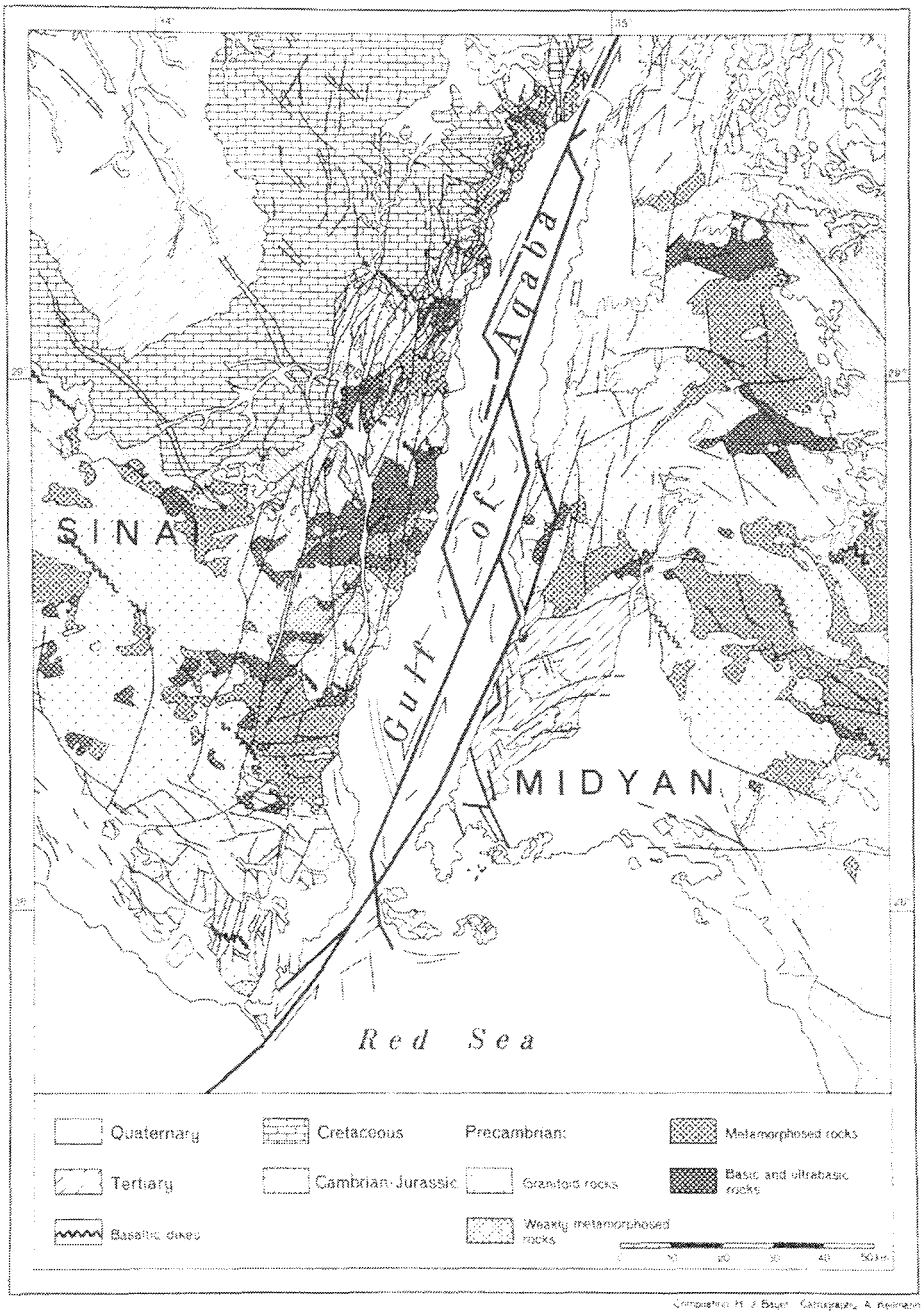


Fig. 1.6: *Geological map of the Northern Red Sea/Gulf of Aqaba (Bayer et al., 1988).*

The rocks of the Sinai Peninsula on the western side of the Gulf of Aqaba (Fig. 1.6) consist of Precambrian basement rocks, which are mainly metamorphic and magmatic rocks of Late Proterozoic age (Eyal et al., 1981). The basement rocks are covered in some places by up to 1.3 km thick sedimentary rocks (Ben-Avraham et al., 1979a). The sedimentary rocks consist of a lower sandy part of Early Paleozoic age, which is overlain by Cretaceous-Eocene sediments made up of marine carbonaceous rocks with some sandy portions. The Sinai Mountains are drained by many wadis of different sizes (Geological map of Sinai, 1994). The main wadis on the western side of the Gulf are Wadi Watir (Fig 1.7), Wadi Dahab, and Wadi Kid.

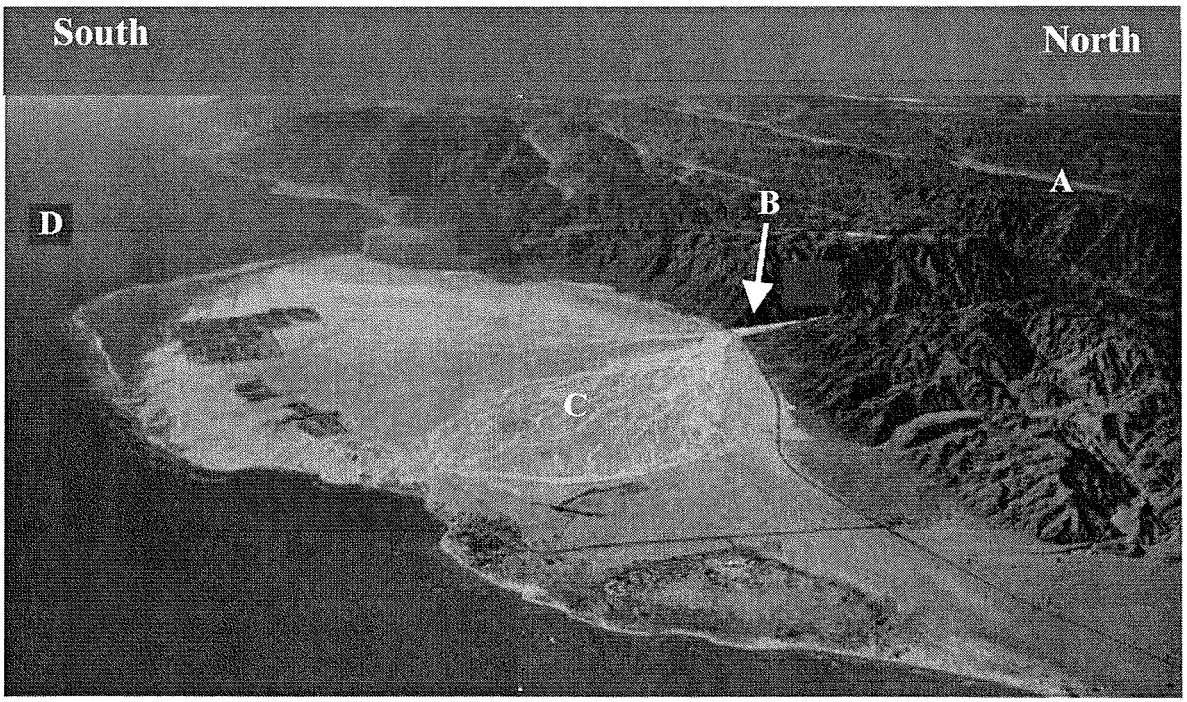


Fig. 1.7: *Aerial photograph of Wadi Watir alluvial fan at the mouth of Wadi Watir on the western side of the Gulf of Aqaba (National Geographics). A) Basement and sedimentary rocks of the Sinai Mountains, B) Wadi Watir, C) Wadi Watir alluvial fan, D) Gulf Of Aqaba.*

Ben-Avraham et al. (1979a; 1979b) reported that the western side of the Gulf is characterized by large alluvial fans that extend as submarine cones into which many canyons are dissected. The alluvial fans are built at the mouths of major wadis and have variable sizes. (Fig. 1.3). Large alluvial fans are formed at the mouths of the two largest wadi systems, Wadi Watir and Wadi Dahab (Fig. 1.7). A smaller alluvial fan, the Ras El Burka alluvial fan, is found at the mouth of the Wadi Almahash Al Asfal. The sediment

input into the fans results from sporadic rainfalls on the Sinai Peninsula. The rainfalls might develop flashfloods in the wadis, which transport large amounts of eroded sediments from the rocky desert of the Sinai Peninsula into the Gulf of Aqaba.

1.3 Aims of this study

The aim of this study is to present results of detailed investigations about the origin and development of the submarine prolongations of alluvial fans in the Gulf of Aqaba based on a dense grid of bathymetric, sediment echosounder, and high-resolution multichannel seismic reflection data collected during the R/V Meteor Cruise M44/3 in 1999.

The study focuses on the investigations of the three major submarine prolongations of alluvial fans constructed at the mouths of the wadis (Fig. 1.3, 1.8) which are characterized by ephemeral streamflow. These alluvial fans are Ras El Burka alluvial fan (at the mouth of Wadi Almahash Alasfal), Wadi Watir alluvial fan (at the mouth of Wadi Watir, Fig. 1.7) and Wadi Dahab alluvial fan (at the mouth of Wadi Dahab).

The primary aims of the investigations are:

- to plot and analyze detailed bathymetric maps of the submarine prolongations of the alluvial fans for the first time. These maps can be used to identify the significant morphological features which reflect the evolution of the fans.
- to study the acoustic and seismic facies in the investigated areas based on the Parasound and multi channel seismic data, respectively. The acoustic and seismic facies in the study areas can be correlated with results of lithofacies from other areas with a similar setting, in order to interpret the depositional processes. A study of the lateral and vertical distribution of these facies will also allow to investigate the various processes involved in the creation of these facies, i.e., climatic changes, sea-level fluctuation, and tectonics, and the geological processes responsible for the origin and evolution of the fans.
- to interpret the mode of initiation and evolution of the canyons dissecting the submarine prolongations of alluvial fans in the Gulf of Aqaba based on an integrated interpretation of the bathymetric maps and Parasound and seismic data. These data were used to develop a model for the canyon initiation and development as well as to assess the significance of the canyons for sediment transport in the submarine fans.

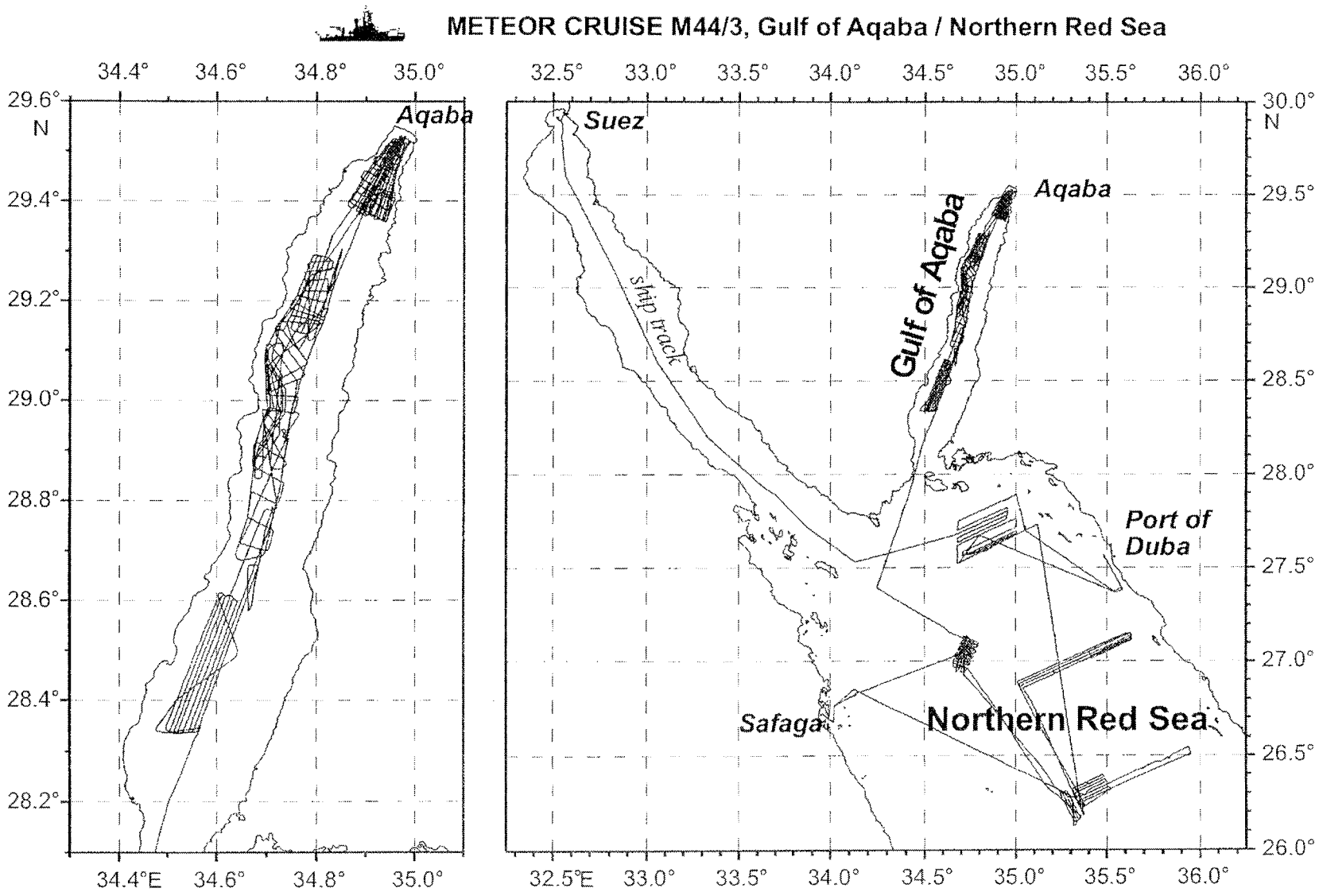


Fig. 1.8: *Cruise Track of Meteor-Cruise M44/3.*

1.4 Methods

The main methods used in this thesis are high-resolution reflection seismics, and mapping of the seafloor by means of the Hydrosweep bathymetric multibeam system and the narrow-beam Parasound sediment echosounder. The data used in the study were collected during R/V Meteor Cruise M44/3 in 1999 (Fig. 1.8, Pätzold et al., 2000). A total of 1680 km of multichannel seismic profiles were collected along 89 profiles in the northern Red Sea and the Gulf of Aqaba but only the data from the submarine prolongations of the alluvial fans have been analyzed for this work. The high-resolution multichannel reflection seismic data, combined with Hydrosweep and Parasound data, provide new insights into the architecture and development of the submarine prolongation of alluvial fans in the Gulf of Aqaba.

1.4.1 Hydrosweep and Parasound

During the R/V Meteor Cruise M44/3, the bathymetric data were collected using the Krupp Atlas Electronics Hydrosweep system. The Hydrosweep system is a bathymetric multibeam system which uses 59 beams with a swath width of 90°, giving a coverage of 2 times the water depth (Grant and Schreiber, 1990). The system was routinely used during the entire cruise. Typical accuracies of the system are 0.25% of water depth, reduced to 1% in areas of steep slopes. The data were processed with the mb-system software package which consists of more than 20 programs that manipulate, translate, process, list, or display swath-mapped sonar data (Caress and Chayes, 1996). The data were finally gridded with a grid-size of 70 m and displayed using the Generic Mapping Tools (GMT) software (Wessel and Smith, 1998).

The Parasound system works both as a low-frequency sediment echosounder and a high-frequency narrow beam sounder to determine the water depth. The system propagates a primary frequency of 18.0 kHz which is used for the determination of the water depth. The primary frequency is superimposed by a secondary frequency between 21.5 kHz and 23.5 kHz resulting in a differential frequency between 3.5 kHz and 5.5 kHz. Due to the parametric effect, the new component is traveling within the emission cone of the original high frequency waves which are limited to an angle of only 4° for the equipment used. Therefore, the footprint size is much smaller than for conventional systems, and both vertical and lateral resolutions are significantly improved. The source signal is a sinusoidal wavelet with a duration of 2 periods. Digitizing and recording of the seismograms were

done with the software package Paradigm which was developed at the University of Bremen (Spieß, 1993).

1.4.2 High-resolution multi-channel reflection seismics

Multi-channel seismic measurements were carried out with the instrumentation of the Department of Earth Sciences, Bremen University. The primary source was a 0.4 l GI-Gun (Generator-Injector Gun; SODERA Inc.) generating a source signal with frequencies of up to 350 Hz. The GI-Gun was shot every 10 s. Owing to an average ship speed of 4.9 kn, a shot distance of ~25 m was thus obtained. A SODERA Inc. S-15 water gun was also shot as secondary source on some profiles. The frequency of the watergun ranges from 200 – 1200 Hz. Both guns were operated with an air pressure of 150 bar.

The data were recorded using a 24-channel 300 m-long Syntron streamer. A tow-lead of 40 m and one stretch section of 50 m were used resulting in a total streamer length of 390 m. In order to optimize the frequency response of the streamer in shallow water and at large reflection angles, hydrophone groups of only 2 hydrophones at a distance of 0.32 m were used. The midpoint distance between individual channels was 12.5 m. The streamer was equipped with 4 cable-levelers (birds), which kept the streamer at a constant depth of 3 m. Recording was done by means of a BISON spectra seismograph. This recording unit was specially designed for the University of Bremen and allows a continuous operation mode to acquire very high-resolution seismic data (sampling with up to 20 kHz). The sampling frequency for the survey in the Gulf of Aqaba was set to 8 kHz. The Bison Spectra allows online data display (shot gather), online demultiplexing, and storing in SEG-Y format. Pre-amplifiers were set to 60 dB, analog filters to 16 Hz (low-cut) and 2000 Hz (high-cut). The data were stored on a DLT4000 cartridge tape. An outline of the seismic system is shown in Fig. 1.9.

The data were processed in a combination of in-house software of Bremen University and the public domain package SEISMIC UN*X (Stockwell, 1997). First steps were the set up of the geometry and a static correction of the data based on the streamer depth measured at the bird positions. Binning of the data was done with a distance of 10 m giving ~10-fold CMP-gathers. A velocity analysis was carried out to establish stacking velocities. The stacked sections were filtered with a bandpass (55/110 – 600/800 Hz) and, thereafter, time migrated. The time-migrated sections were used for interpretation of the data.

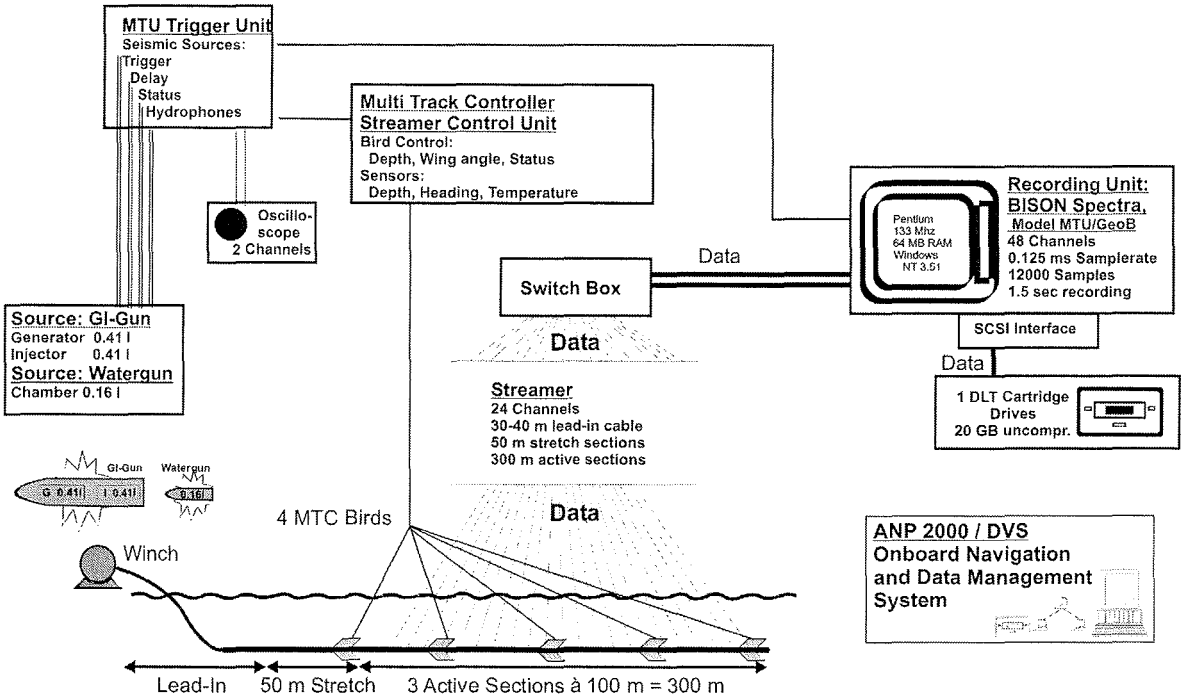


Fig. 1.9: *Outline of the Bremen high-resolution reflection seismic system as used during Meteor-Cruise M44/3.*

1.5 Outline of this study

This study was realized to understand the major processes during the formation and evolution of the submarine prolongations of alluvial fans in the Gulf of Aqaba. The thesis consists of three separate manuscripts (chapter 2-4) prepared for submission to peer-reviewed international scientific journals. The following gives a short overview of these manuscripts.

Chapter 2 deals with the interpretation of the bathymetric and sediment echosounder profiles which were collected of the submarine prolongations of Ras El Burka, Wadi Watir, and Wadi Dahab alluvial fans. The data allowed us to plot detailed bathymetric and slope maps of the major submarine prolongations of alluvial fans in the Gulf of Aqaba for the first time. Several different echo types were identified and mapped. A detailed analysis and interpretation of the bathymetric and echo facies map allow to investigate key processes for the formation of the fan.

Chapter 3 focuses on the evolution of the submarine prolongation of Wadi Watir alluvial fan deduced from high-resolution multi-channel seismic reflection data. A detailed analysis of the seismic facies helps to understand the growth pattern of Wadi Watir submarine fan. Special emphasis is put on the importance of faults and mass wasting events during the evolution of the fan. The new results, combined with previously

published geological and geophysical data, allow a structural analysis of the submarine prolongation of Wadi Watir alluvial fan.

Chapter 4 deals with the description and interpretation of the origin of the canyons which dissect the surface of the submarine prolongations of Wadi Watir and Wadi Dahab alluvial fans. The study is based on bathymetric, Parasound, and seismic data, and includes the description of the canyons and an analysis of the principal geological processes responsible for their formation and evolution.

Final conclusions are drawn in Chapter 5. Some suggestions for further investigations of the submarine prolongations of alluvial fans in the Gulf of Aqaba are also given in the chapter.

References

Bartov, Y., Steinitz, G., Eyal, M., Eyal, Y., 1980. Sinistral movement along the Gulf of Aqaba-ist age and relation to the opening of the Red Sea. Nature 285, 220-225.

Bayer, H.J., Hötzl, H., Jado, A.R., Roscher, B., Voggenreiter, W., 1988. Sedimentary and structural evolution of the northwest Arabian Red Sea margin. Tectonophysics, 153, 137-151.

Ben-Avraham, Z., 1985. Structural framework of the Gulf of Elat (Aqaba, Northern Red Sea). J. Geophysics Res. 90, 703-726.

Ben-Avraham, Z., Almagor, G., Garfunkel, Z., 1979a. Sediments and structure of the Gulf of Aqaba - Northern Red Sea. Sedimentary Geology 23, 239-267.

Ben-Avraham, Z., Garfunkel, Z., Almagor, G., Hall, J.K., 1979b. Continental breakup by a leaky transform: The Gulf of Elat (Aqaba). Science 206, 214-216.

Bouma, A.H., 2001. Fine-grained subamarine fans as possible recorders of long- and short-term climatic changes. Global and Planetary Change 28, 85-91.

Bouma, A.H., W. R. Normark, Barnes, N.E., 1985. Submarine fans and related turbidite systems, Springer Verlag, New York. 343pp.

Bouma, A.H., 2000. Fine-grained, mud-rich turbidite systems: model and comparison with coarse-grained, sand-rich systems. AAPG Memoir 72, 9-20.

Caress, D.W., Chayes, D.N., 1996. Improved processing of Hydrosweep DS multibeam data on the R/V Maurice Ewing, Marine Geophysical Researches 18, 631-650.

Dingle, R.V., 1977. The anatomy of a large submarine slump on a sheard continental margin (SE Africa). Journal of Geological Society of London, 134, 293-310.

Eyal, M., Eyal, Y., Bartov, Y., Steinitz, G., 1981. The tectonic development of the western margin of the Gulf of Elat (Aqaba) rift. Tectonophysics 80, 39-66.

Freund, R., Garfunkel, Z., Zak, I., Goldberg, M., Weissbrod, T., Derin, B., 1970. The shear along the Dead Sea Rift. Philos. Trans. R. Soc. London A-267, 107-130.

Garfunkel, Z., 1981. Internal structure of the Dead Sea leaky transform (rift) in relation to plate kinematics. In: Freund, R., Garfunkel, Z. (Eds), The Dead Sea Rift. Tectonophysics 80, 81-108.

Geological map of Sinai, Arab Republic of Egypt, 1994. Geological map of Sinai, A.R.E. (Sheets No. 1 and 2), scale 1: 250 000. Ministry of Industry and Mineral Resources. Geological Survey of Egypt.

Grant, J.A., Schreiber, R., 1990. Modern swath sounding and sub-bottom profiling technology for research applications: the Atlas Hydrosweep and Parasound systems. Marine Geophys. Research. 12, 9-19.

Kolla, V., Macurda, Jr., D.B., 1988. Sea-level changes and timing of turbidity current events in deep-sea fan systems. In: Wilgus, C.K., Hastings, B.S., Kendall, C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C., (Eds.), Sea-level Changes, an International Approach, Tulsa, Oklahoma, USA, SEPM Special Publication 42: 381-392.

Laursen, J., Normark W.R., 2002. Late Quaternary evolution of the San Antonio Submarine Canyon in the central Chile forearc (~33°S). Marine Geology 188: 365-390.

Leeder, M., 1999. Sedimentology and sedimentary basins; from turbulence to tectonics, Blackwell Science; Oxford, UK. 592pp.

Locat, J., 2001. Instabilities along ocean margins: a geomorphological and geotechnical perspective. Mar. Petrol. Geol 18, 503-512.

Mechie, J., El-Isa, Z.H., 1988. Upper lithospheric deformations in the Jordan-Dead Sea transform regime. Tectonophysics, 153, 153-159.

Morcos, S.A., 1970. Physical and chemical oceanography of the Red Sea. Oceanogr. Mar. Biol. Ann. Rev. 8, 73-202.

Normark, W.R., 1970. Growth patterns of deep sea fans. Bull. Am. Assoc. Petrol. Geol. 54, 2170-2195

Pätzold, J., M44/3 Shipboard Scientific Party, 2000. Report and preliminary results of Meteor Cruise M44/3, Aqaba (Jordan) – Safaga (Egypt) – Duba (Saudi Arabaia) – Suez (Egypt) –Haifa (Israel), March 12 – March 26 – April 2 – April 4, 1999. Berichte aus dem Fachbereich Geowissenschaften der Universität Bremen, 149, pp. 135.

Quennel, A.M., 1958. The structural and geomorphic evolution of the Dead Sea Rift. Q.J. Geol. Soc. London 114, 1-24.

Reading, H.G., Richards, M., 1994. Turbidite systems in deep water basin margins classified by grain size and feader system: AAPG Bulletin 78, 792-822.

Richards, M., Bowman, M., Reading, H., 1998. Submarine-fan systems I: characterization and stratigraphic prediction. Mar. Petrol. Geol 15, 689-717.

Schanmugam, G.I., Lechtonen, R., Straume, T., Syversten, S.E., Hodgkinson, R.J., Skibeli, M., 1994. Slump and debris flow dominated upper slope facies in the Cretaceous of the Norwegian and Northern North Seas (61°-67°): Implications for sand distribution. AAPG Bulletin, 78, 910-937.

Shepard, F.P., 1981. Submarine canyons; multiple causes and longtime persistence. AAPG Bull, 65, 1062-1077.

Spieß, V., 1993. Digitale Sedimentechographie - Neue Wege zu einer hochauflösenden Akustostratigraphie. Berichte, Fachbereich Geowissenschaften, Universität Bremen 35, 1-199.

Stockwell, J.W., 1997. Free software in education: A case study of CWP/SU: Seismic Un*x, Leading Edge, 16, 1045-1049.

Stow, D.A.V. and M. Mayall, 2000. Deep-water sedimentary systems: New models for the 21st century. Mar. Petrol. Geol. 17, 125-135.

Stow, D.A.V., Howell, D.G., Nelson, C.A., 1985. Sedimentary, tectonic, and sea-level controls. In: Bouma, A.H., Normark, W.R., Barnes, N.A., (Eds.), Submarine Fans and Related Turbidite Systems, Springer-Verlag, New York, pp. 15-22.

Van der Zwan, C.J., 2002. The impact of Milankovitch-scale climatic forcing on sediment supply. Sedimentary Geology 147, 271-294.

Varnes, D.J., 1958. Landslide types and processes. In: Landslide and engineering practice, Eckel, E.D., (Eds.). Highway research Board Special Report 29, 20-47.

Walker, R.G., 1978. Deep water sandstone facies and ancient submarine fans: models for exploration for stratigraphic traps. Am. Assoc. Petrol. Geol. 62, 932-966.

Wessel, P. and Smith, W.H.F., 1998, New, improved version of Generic Mapping Tools released. EOS trans. Amr. Geophys. Un. 79: 579.

CHAPTER TWO

Submarine prolongation of alluvial fans into the Gulf of Aqaba: results from Parasound and bathymetric studies

(To be submitted to International Journal of Earth Sciences)

M. Salem[1], S. Krastel[1], V. Spieß[1], C. Hübscher[2]

[1]*Department of Geosciences, University of Bremen, PO Box 33 04 40, D-28334 Bremen, Germany.*

[2]*Institute of Geophysics, Hamburg University, Bundesstr. 55, 20146 Hamburg.*

msalem@uni-bremen.de

Submarine prolongation of alluvial fans into the Gulf of Aqaba: results from Parasound and bathymetric studies

M. Salem[1], S. Krastel[1], V. Spieß[1], C. Hübscher[2]

[1]Department of Geosciences, University of Bremen, PO Box 33 04 40, D-28334 Bremen, Germany. Email: msalem@uni-bremen.de

[2]Institute of Geophysics, Hamburg University, Bundesstr. 55, 20146 Hamburg, Germany.

Abstract

The Gulf of Aqaba is part of the Syrian-African rift system extending some 6000 km from Turkey to Mozambique. The Gulf itself forms the northern extension of the Red Sea. Periodic flashfloods developing in onshore intermittent stream valleys (so called wadis) during the sporadic rainy season transport large amounts of sediments from the rocky desert of the Sinai Peninsula into the Gulf of Aqaba. These flashfloods build alluvial fans of different sizes. The submarine prolongation of Ras El Burka, Wadi Watir, and Wadi Dahab alluvial fans were studied during Meteor Cruise M44/3 using the Hydrosweep multibeam bathymetric system and the sediment echosounder system Parasound. The largest submarine fan (Wadi Dahab submarine fan) covers an area ~25 km long and ~8 km wide and can be traced down to a water-depth of 1000 m, while Ras El Burka submarine fan is much smaller and covers an area of ~15 km long and ~7 km wide due to a much smaller catchment area of the corresponding wadi. Four echo facies types (rugged, hyperbolic, bedded, and partially transparent/discontinuously bedded echo facies) were recorded in the investigated submarine fans, which differ in character and distribution according to the substrate morphology and the type of sediments. Low penetration of the Parasound system close to the coast is caused by abundant coarse sandy sediments while increasing penetration of the Parasound system with increasing distance to the coast is related to an increase of fine-grained sediments. The submarine fans in the Gulf of Aqaba can be classified as coarse-grained, sand-rich, point source turbidite systems, which are dissected by numerous V-shaped and few U-shaped canyons. Several slumps and slides were identified all over the fans.

2.1 Introduction

The Gulf of Aqaba (Fig. 2.1) is the southern, active segment of the Dead Sea rift, which accommodates about 105 km of left lateral slip between the Arabian plate and the Sinai subplate (Garfunkel et al., 1981). Geologically, the Gulf of Aqaba is part of the complex East African Rift System which runs through most of eastern Africa. The Gulf of Aqaba varies in width from 15 to 25 km and is ~180 km long. The Gulf lies in a pronounced cliff between hills rising abruptly to about 600 m above sea level.

Several studies of the Gulf of Aqaba were carried out, both onshore and offshore. The onshore geology and structure of the Gulf of Aqaba has been investigated among others by Garfunkel (1970), Freund and Garfunkel (1976), Bartov and Steinitz (1978), Abdel Khalek et al. (1993), and Badawy and Horvath (1999). Offshore, geological and geophysical studies of the Gulf of Aqaba were carried out by Hall and Ben-Avraham (1978), Ben-Avraham (1985), and Ben-Avraham and Tibor (1993).

Results of previous studies in the Gulf of Aqaba demonstrate that it is dominated by en-echelon faults which delimit three elongated basins striking NE at 20°-25°. The basins, as well as the Gulf itself, have been ascribed to a strike-slip faulting origin. The basin fill consists of syntectonic turbidites and pelagic deposits. The basin flanks are built by marginal blocks, which are much wider on the western side of the Gulf of Aqaba than on the eastern side. The marginal blocks on the west form topographic terraces in some locations. The undulating western coastline is the direct result of alluvial fans building out into the Gulf. The fans build submarine cones which are dissected by many canyons.

Submarine fans are constructional bodies formed by the gradual outbuilding of sediments into the deep sea. The sediment source may come from land wadis, river estuaries, or other supply systems through submarine canyons (Shepard, 1981; Uenzelmann-Neben et al., 1997). Canyons may reach form the shelf or slope where they are fed by mass flows, including slides/slumps, debris flows and turbidity currents, which erode their way downslope and gradually deposit their bedload as the gradient decreases oceanward. The key factors controlling the fan architecture of most published models are tectonics, climate, nature of sediment input, and sea level fluctuations (Stow et al., 1985; Richards et al.; 1998; Bouma, 2000).

In this paper, we discuss three of the larger submarine prolongations of alluvial fans into the Gulf of Aqaba: Ras El Burka submarine fan, Wadi Watir submarine fan, and Wadi Dahab submarine fan (Fig. 2.1), all located off the mouths of major wadis. The fans were fed through the wadis with coarse-grained terrestrial deposits mainly obtained from the

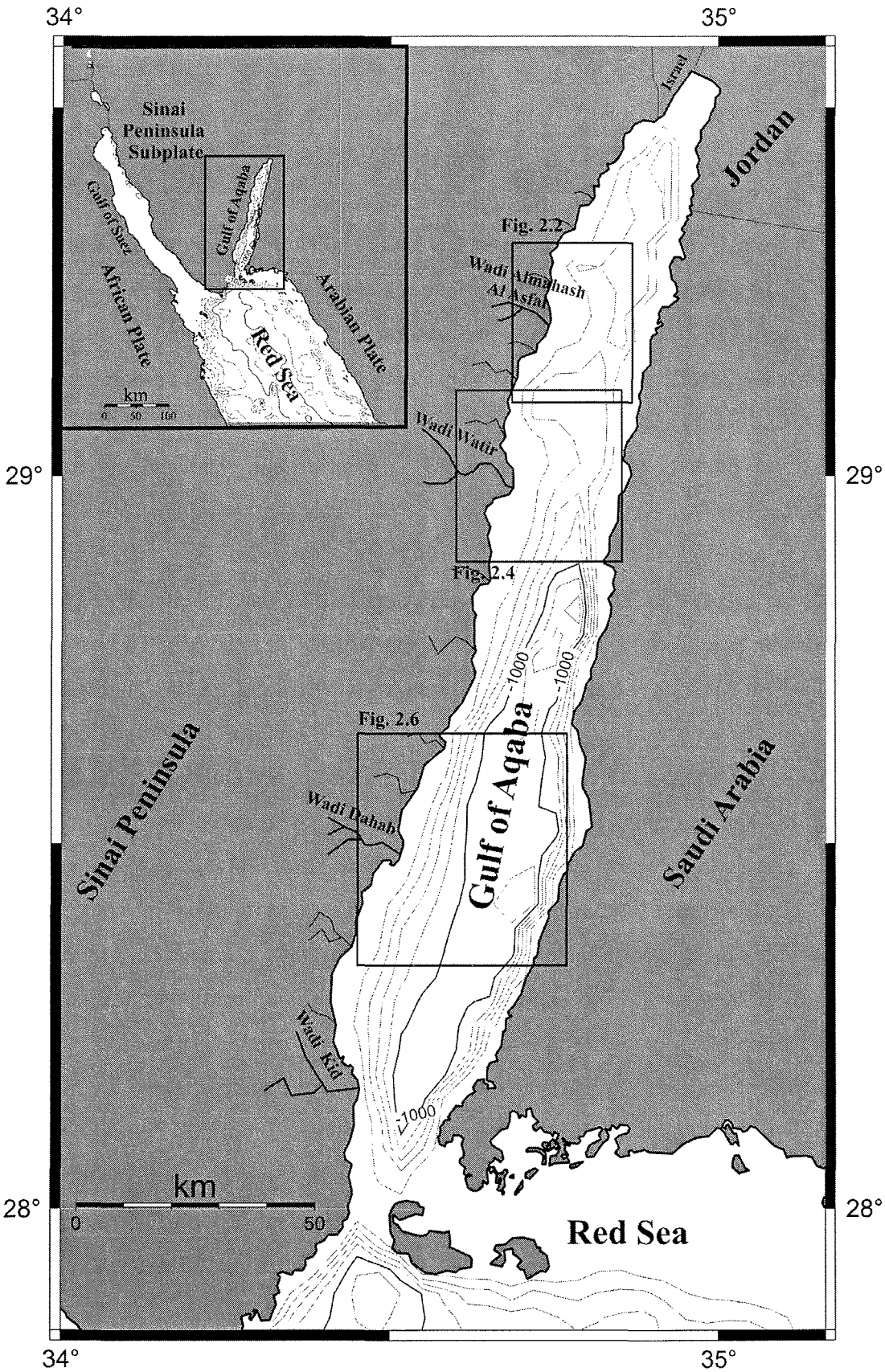


Fig. 2.1: *Overview map of the study area. Locations of detailed bathymetric maps are shown as boxes.*

erosion of sediment and basement rocks on the Sinai Peninsula during sporadic rainy seasons (Ben-Avraham et al., 1979). The submarine fans were studied using a Hydrosweep swath bathymetric system and the digital sediment echosounder system Parasound. Reconnaissance data for studying the morphology and the structure of the uppermost sediments of the fans in greater detail were collected during R/V Meteor Cruise M44/3 for the first time. Particularly we will try to answer the following questions:

(1) What are the dimensions of the submarine prolongation of alluvial fans in the Gulf of Aqaba? (2) Which sediment and facies types occur within the submarine fans and how are they distributed? (3) What is the influence of tectonics, climate and sea level fluctuations on the formation of the submarine fans in the Gulf Aqaba?

2.2 Geological setting, previous investigations

From a tectonic view, the Gulf of Aqaba is the southern active segment of the Dead Sea rift, which connects the sea-floor spreading axis of the Red Sea in the south with the Arabian-Turkish collision zone in the north. It is a fault-controlled depression (Mechie and El-Isa, 1988). According to Freund and Garfunkel (1976) and Abdel Khalek et al. (1993), structures in the Gulf of Aqaba can be grouped into: 1) Primary structures caused by deep crustal processes, e.g. strike-slip faults (Arabian strike slip fault) and basin margin faults which are related to the plate movement striking N-S at a direction of 30°. 2) Secondary structures, directly related to, and a direct consequence of, the primary structures, e.g. folds developing in the sedimentary cover over deeper fault basement blocks and subsidiary faults related to stresses developed by major basement-involved structures. 3) Passive or adjustment structures developed as a consequence of, or as an effect of, primary and secondary structures, e.g. local crestal faulting of competent beds over the crest of anticlinal folds, salt diapirism triggered by basin subsidence and other related factors, folding developed in association with strike-slip faulting, as well as detached listric normal faults developing in prograding sequences. Studies of the submarine geology and topography of the Gulf of Aqaba suggest that the deep and narrow shape of the Gulf is a direct reflection of the pattern of the long subparallel faults that bound the margins and its internal basins (Ben-Avraham et al., 1979; Ben-Avraham, 1985).

The area west of the Gulf of Aqaba, which is part of the Arabo-Nubian massif, consists of metamorphic and magmatic rocks of Late Proterozoic age. The detailed stratigraphy of the sediments covering this massif on land is well known Garfunkel et al., 1974; Ben-Abraham et al.; 1979; Abdel Khalek et al.; 1993; Ben-Abraham and Tibor, 1993). The ~1.3

km thick sections encountered are of pre-Aqaba origin and partially overlain by syntectonic sediments. The pre-tectonic sediments start with Lower Paleozoic continental clastics, and are unconformably overlain by the continental sandstones of the Early Cretaceous (Nubian Sandstone attains a thickness of up to 600 m). This cycle is succeeded by the first marine sediments (carbonate shelf facies, 300-700 m thick) of Late Cretaceous up to Middle Eocene age.

The Gulf of Aqaba can be divided into subaerial and submarine depositional environments (Friedman, 1985). The former include fans, dunes, sabkhas, berms, and beaches. These environments are dominated by detrital sediments of terrigenous origin. The submarine depositional sites include lagoons, reefs, marginal slopes, and basins. A special characteristic of submarine sedimentation in the Gulf is the deposition of clastic debris of terrigenous origin concurrently and side by side with carbonate sedimentation. On the western side of the Gulf of Aqaba, the Sinai Mountains, which are bound by coastal faults, rise steeply. Large alluvial fans were built in front of these fault scarps, resulting in an undulating coastline. The fans extend as submarine cones into the basin, being dissected by many canyons of over 150 m depth (Ben-Avraham et al., 1979).

A first bathymetric map for the Gulf of Aqaba was prepared by Hall and Ben-Abraham (1978) mainly on the basis of a geophysical survey which was conducted aboard R/V Ramona in 1976. The Gulf of Aqaba reaches a maximum depth of 1850 m. The interior of the gulf is constructed by three deep and elongated basins, striking N20-25°E, which are arranged en echelon. Shallow sills separate the basins. The margins of the Gulf are very steep. Its eastern side descends abruptly to the deep basins, but on the western side the descent may be broken by sloping terraces. The eastern margins attain slopes of 25-30° while the western slope has typical slope angles of 7-16°.

2.3 Data collection and data processing

The submarine alluvial fans on the western side of the Gulf of Aqaba were studied during R/V Meteor Cruise M44/3 in 1999 by means of the bathymetric multibeam system Hydrosweep and the digital Parasound/ParaDigMa sediment echosounder.

The Hydrosweep system is a multibeam echosounder operating at a frequency of 15.5 kHz (Grant and Schreiber, 1990). Depth values are generated for 59 beams with an angular coverage of 90° resulting in a swath width of twice the water depth. Typical accuracies of the system are 0.25% of water depth reduced to 1% in areas of steep slopes. The system was routinely used during the entire cruise. The locations of the profiles in the central areas

of the submarine fans were chosen in order to get complete bathymetric coverage. The data were processed with the Multibeam-system software (Caress and Chayes, 1996) and finally gridded with a grid-size of 70 m. The data are displayed using the Generic Mapping Tools (GMT) software (Wessel and Smith, 1998).

The Parasound echosounder is a narrow-beam system used for accurate determination of water depth, with a sediment echosounding system (subbottom profiler) for sedimentological and acoustostratigraphic surveys. With this system two sound waves of similar frequencies (here 18 kHz and 22 kHz) are emitted simultaneously, and a signal of the difference frequency (i.e. 4 kHz) is generated at sufficiently high primary amplitudes. Due to the parametric effect, the new component is traveling within the emission cone of the original high frequency waves which are limited to an angle of only 4° for the equipment used. Therefore, the footprint size is much smaller than for conventional systems, and both vertical and lateral resolutions are significantly improved (Rostek et al., 1991; Spiess, 1993). The Parasound sediment echosounder system was used continuously during the cruise and the data were collected in digital form with ParaDigMa data acquisition system (Spieß, 1993).

2.4 Results

2.4.1 Ras El Burka

Bathymetric data off the Wadi Almahash Al Asfal were collected in an area of 20 km by 7 km. This area covers the extent of the submarine prolongation of Ras El Burka alluvial fan except for a 2-6 km wide stripe near the coast (Fig. 2.2a), where no measurements could be carried out. The mapped area with water depths ranging from 100 to 950 m can be subdivided into a slope and a basin part.

The slope area extends from the coast to a water depth of ~900 m. It is characterized by a rough topography with large slope gradients (Fig. 2.2b), averaging to ~4° with maximum values >20°. Three morphological highs were identified close to the coast. The largest lies off the mouth of the Wadi Almahasch Al Asfal, while the other two are located ~5 km to the north and south, respectively. Seawards of these highs the slope gradient steepens to >15° for water depths between ~100 and 400 m. Such a step in the morphology is not visible in the northern part of the survey area but bathymetric coverage is incomplete close to the coast. Further downslope the slope gradient decreases again in an up to 3 km wide area off the Wadi itself while it is narrower to the south and north. Water depths in this area range from 400 to 700 m; slope angles are usually less then 4°. Locally, steeper slopes

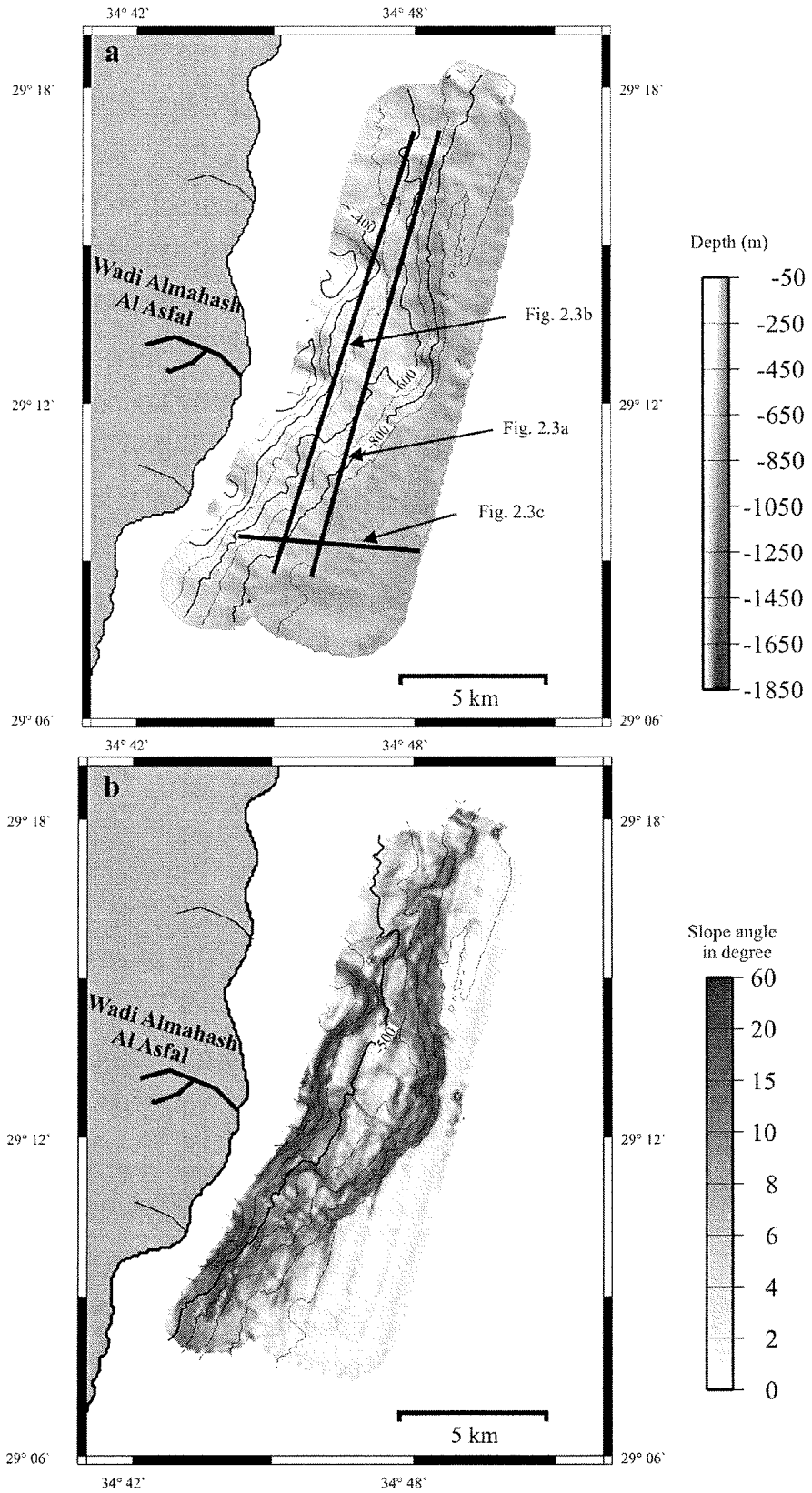


Fig. 2.2: *a) Bathymetric map of the submarine prolongation of Ras El Burka alluvial fan. Parasound and bathymetric profiles presented in this manuscript are shown as black lines. b) Slope angle map of the submarine prolongation of Ras El Burka alluvial fan.*

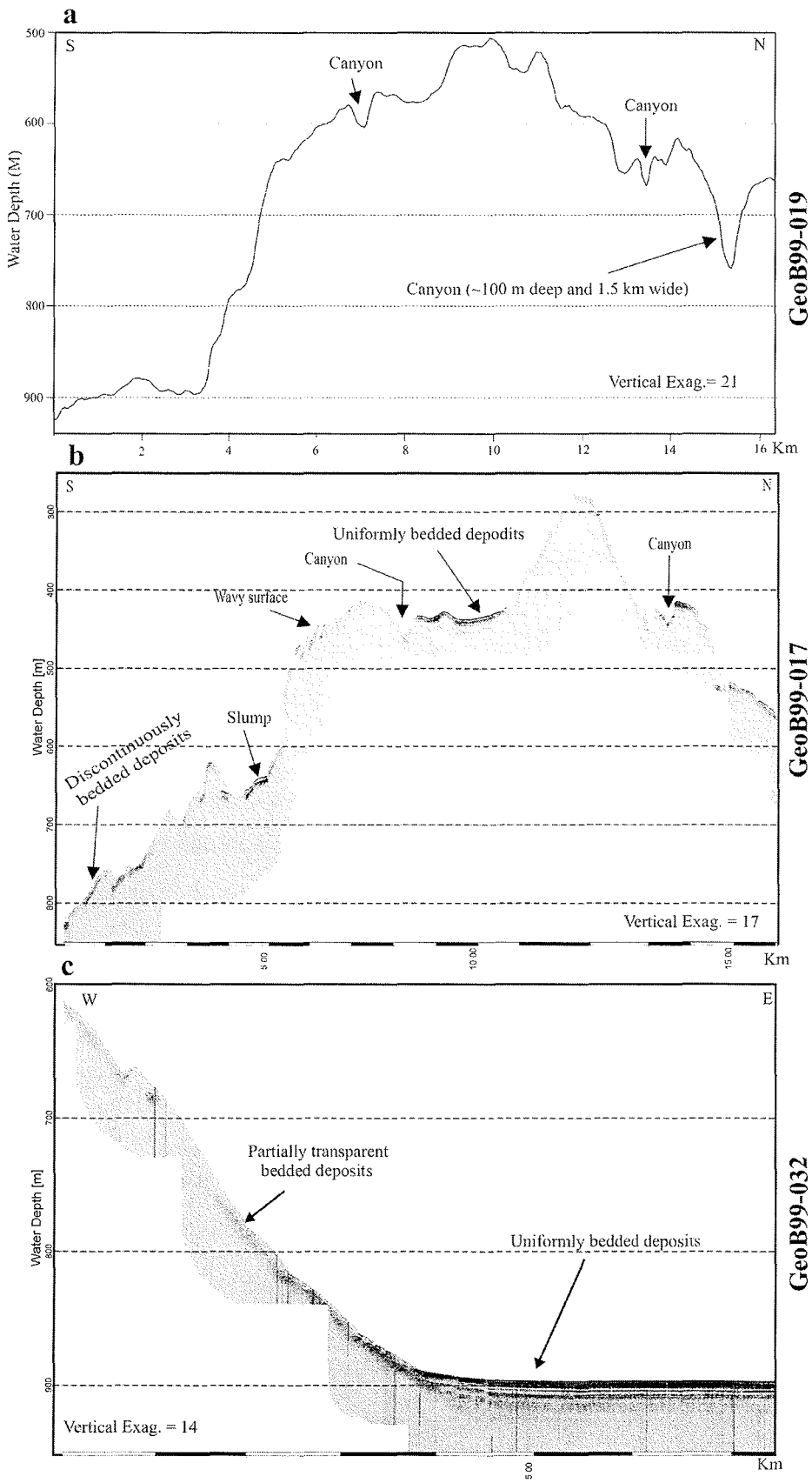


Fig. 2.3: *Bathymetric and Parasound profiles of the submarine prolongation of Ras El Burka fan. a) Bathymetric Profile GeoB99-019. b) Parasound Profile GeoB99-017. c) Parasound Profile GeoB99-032.*

are associated with few canyons in this area. A second sharp step in morphology is visible at a distance of ~6 km from the coast. Slope gradients steepen to >15° for water depths between 700 and 900 m. This step in morphology is steepest off the mouth of the Wadi. A distinct step is also visible in the northern part but it is missing in the southern part. Slope gradients in the southern part in water depths between 700 and 900 m are generally less than 10°. The slope area is dissected by a few short straight canyons extending from the coast to 900 m water depth. The canyons are up to 1.5 km wide and 100 m deep (Fig. 2.3a). The number of canyons is significantly lower than for the two other submarine fans described in this paper.

The basin area is characterized by a relatively flat sea floor with water depths of ~950 m. Note that the linear features showing steeper slopes are artifacts caused by the processing of the Hydrosweep data.

2.4.2 Wadi Watir

The bathymetry of the submarine prolongation of Wadi Watir alluvial fan was surveyed up to a distance of ~13 km off the coast except for a narrow (generally less than 1.5 km wide) area along the coast (Fig. 2.4a). The water depth typically ranges from 100 to 900 m. Water depths greater than 900 m were only found in the southeastern part of the survey area. There, very steep slope angles (>12°) occur, marking the border to one of the deep basins in the Gulf of Aqaba (Fig. 2.4b). A broad morphological high lies in front of the mouth of Wadi Watir; the mouth itself is located at the southern part of this high. This morphological high can be traced for about 5 km to the north while the water depth rapidly increases south of the mouth of Wadi Watir. The general slope angle off Wadi Watir has a relatively constant value of ~4° down to a water depth of ~700 m. Further downslope, the slope gradient gradually decreases, but slope angles are still 1° - 2° in the distal parts. No major steps in the morphology were identified except for the above-mentioned transition to the deep basin.

Though the fan is generally sloping with a relatively constant angle, large slope angles (>10°) are widespread in the fan area indicating steep canyon walls. The Wadi Watir submarine fan is intensively dissected by canyons (Fig. 2.5c), which are unevenly spaced and reveal different dimensions with a maximum width of 1.5 km and a maximum depth of 130 m.

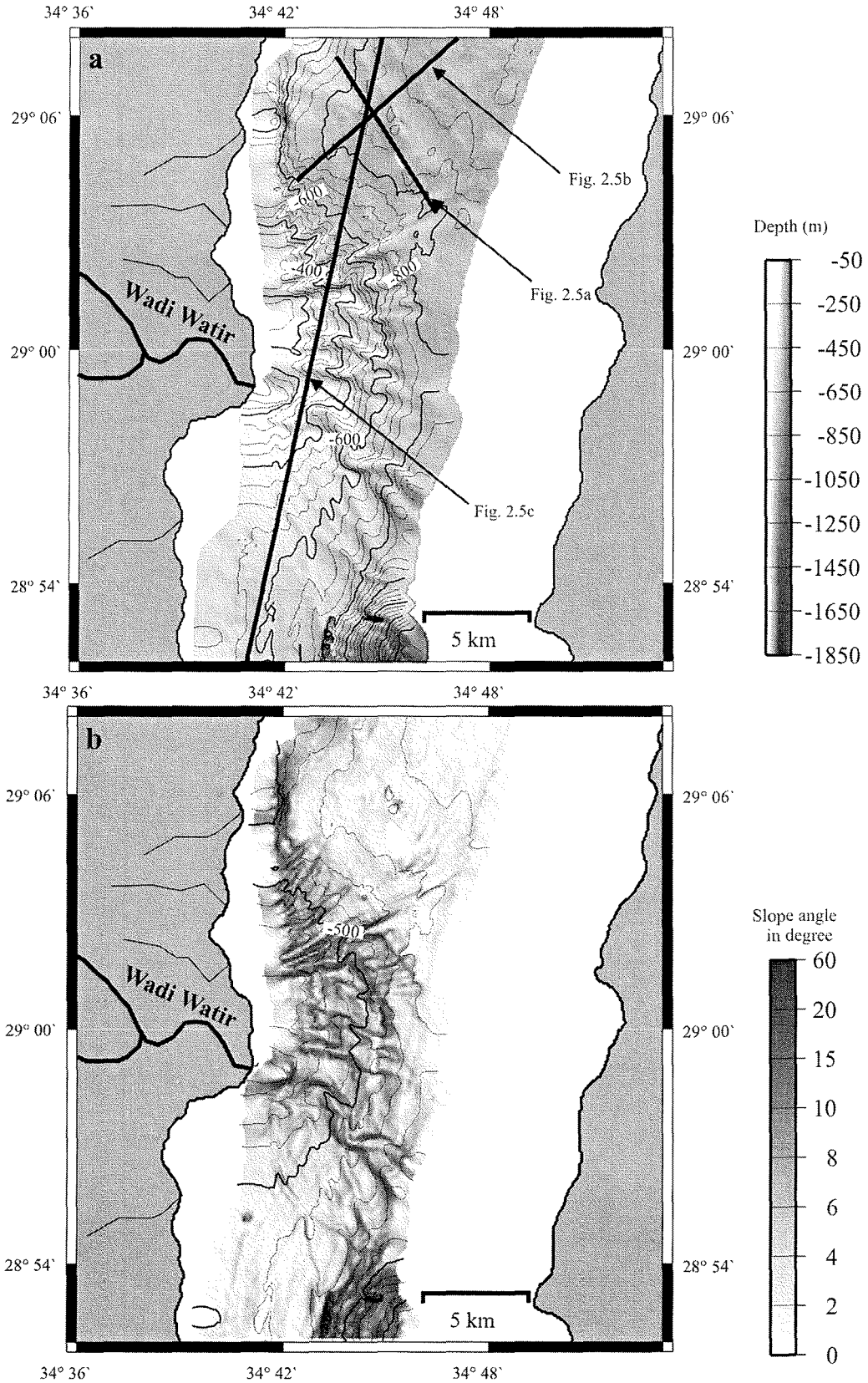


Fig. 2.4: *a) Bathymetric map of the submarine prolongation of Wadi Watir alluvial fan. Parasound profiles presented in this manuscript are shown as black. b) Slope angle map of the submarine prolongation of Wadi Watir alluvial fan.*

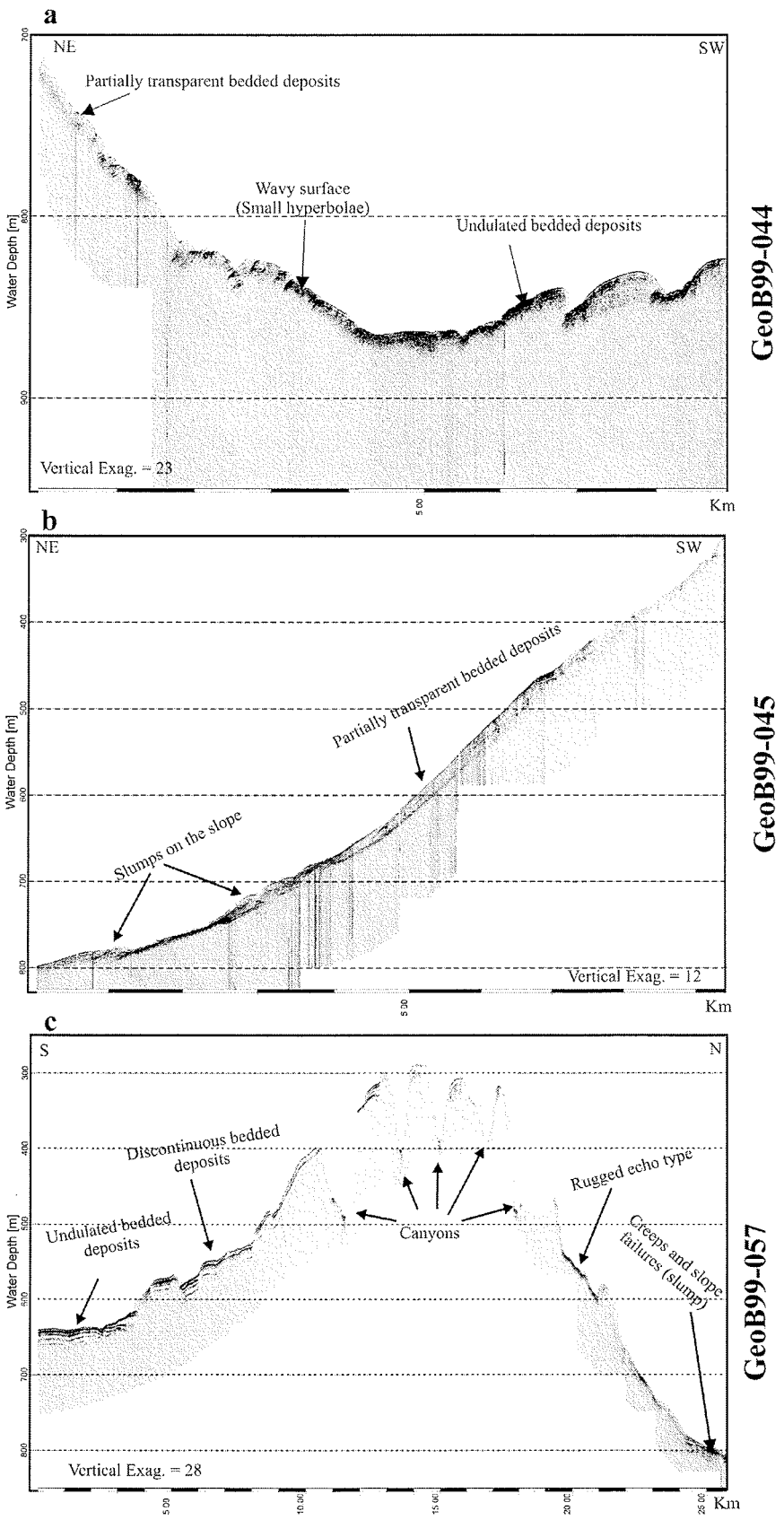


Fig. 2.5: *Parasound profiles of the submarine prolongation of Wadi Watir fan a) Parasound Profile GeoB99-044. b) Parasound Profile GeoB99-045. c) Parasound Profile GeoB99-057.*

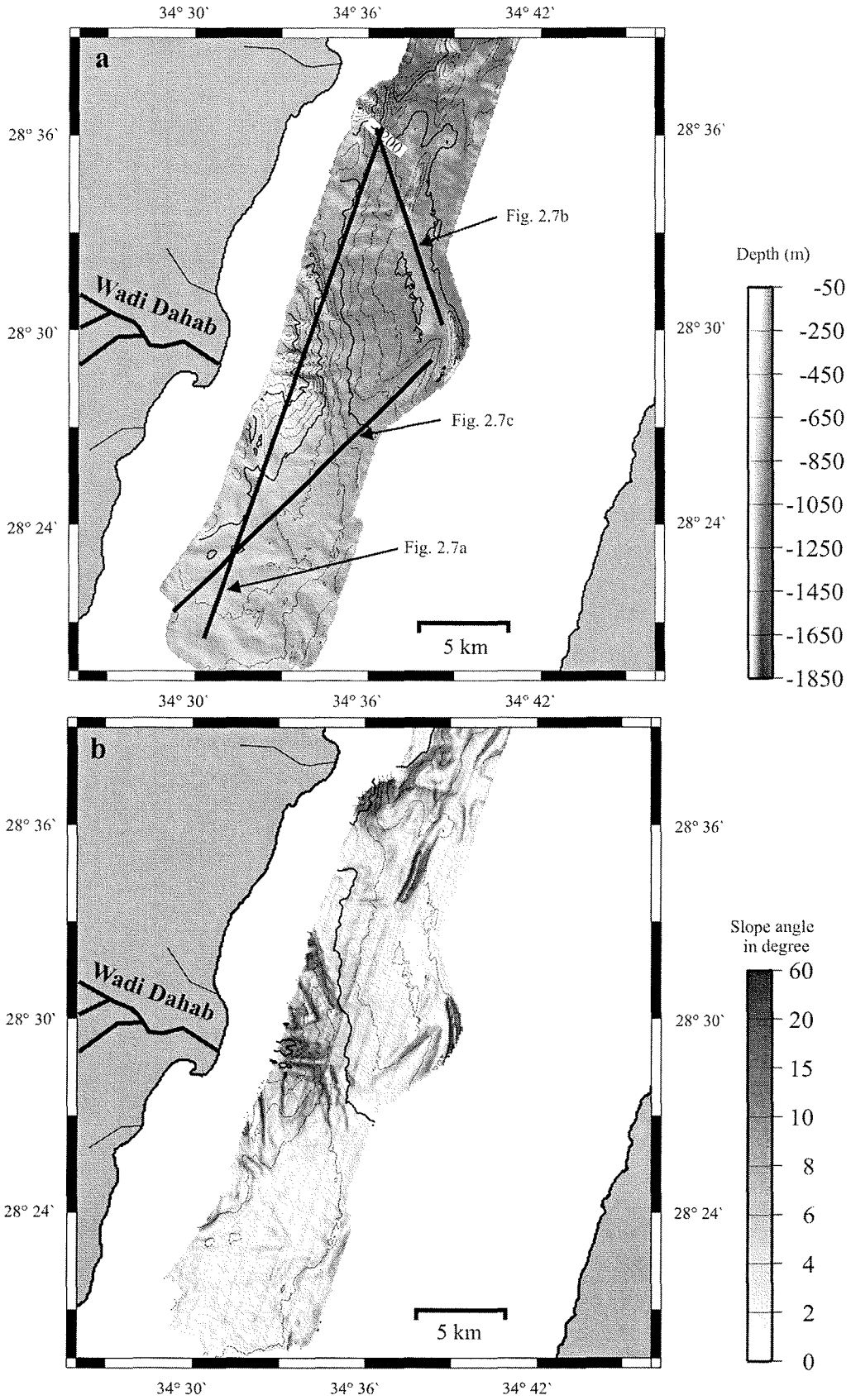


Fig. 2.6: *a) Bathymetric map of the submarine prolongation of Wadi Dahab alluvial fan. Parasound profiles presented in this manuscript are shown as black. b) Slope angle map of the submarine prolongation of Wadi Dahab alluvial fan.*

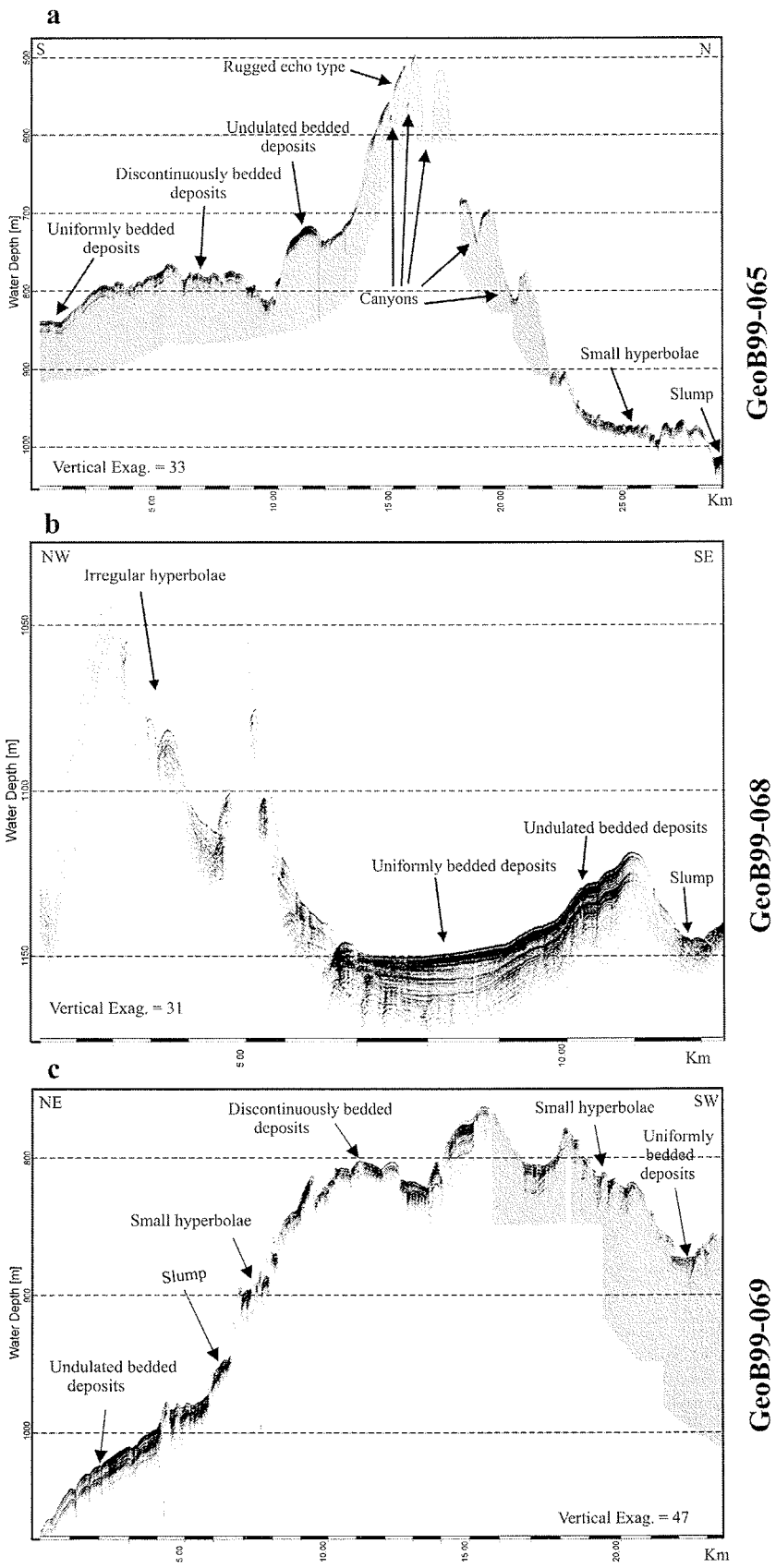


Fig. 2.7: *Parasound profiles of the submarine prolongation of Wadi Dahab fan a) Parasound Profile GeoB99-065. b) Parasound Profile GeoB99-068. c) Parasound Profile GeoB99-069.*

2.4.3 Wadi Dahab

Bathymetric data off the Wadi Dahab were collected in an ~40 km by 10 km wide area (Fig. 2.6a). This area covers the extent of the submarine prolongation of Wadi Dahab alluvial fan except for a 6 - 8.5 km wide stripe close to the coast. The water depth in the mapped area ranges from ~450 to ~1500 m. Most of the fan is characterized by slope angles between 1° and 4°. Local steeper slopes are associated with small morphological steps and canyons (Fig. 2.6b). The V-shaped canyons in the submarine prolongation Wadi Dahab alluvial fan are less deep than in Wadi Watir (Fig. 2.7a).

2.4.4 Sedimentary structure of the fans

Sedimentary structures of fans were studied by means of Parasound echograms, which define the echo character of the sea floor and sediments. The types and regional distribution of reflected echoes are an important basis for the interpretation of depositional and erosional processes. The main factors that control the echo characters are surface topography, subsurface geometry, and sedimentary texture of the sequence. Highly variable and complex surface topography of submarine alluvial fans generally causes relatively poor acoustic images as well as abrupt changes in the echo types and their regional distributions (Damuth, 1975, 1980; Embley, 1976).

Following the definition of Damuth (1980) and Loncke et al. (2002), seven distinctive echo types were recognized in the study areas, which were grouped into four major classes (Tab. 2.1): (1) Rugged echo character; (2) Hyperbolic echo character (regular and irregular types); (3) Bedded echo character (uniformly bedded, undulated bedded, and discontinuously bedded types); (4) Partially transparent/discontinuously bedded echo character.

(1) The rugged echo character as shown in the middle of the Profile GeoB99-057 (Fig. 2.5c) is characterized by prolonged bottom echoes with no apparent subbottom reflectors. This type is observed along the axes of submarine canyons and valleys, spreading downslope into the deep basin.

(2) The hyperbolic echo is divided into two subclasses. Regular overlapping hyperbolas are shown on Profile GeoB99-044 (Fig. 2.5a), while irregular hyperbolic echoes with varying vertex elevation are found on Profile GeoB99-068 (Fig. 2.7b). Both subclasses are generally recorded from areas with rough sea-floor morphology and show no subbottom penetration.

(3) The bedded echo character is divided into three subclasses:

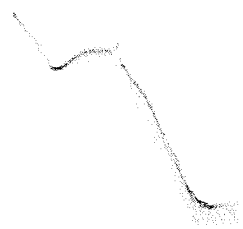
(3a) The uniformly bedded echo-type is shown on Profile GeoB99-032 (Fig. 2.3c). This type is characterized by layered sequences of smooth, distinct, continuous subbottom reflectors parallel to the sea floor which can extend over several kilometers. It is widely observed in the study area especially in the basins.

(3b) The undulated bedded echo type is visible at the NE part of Profile GeoB99-069 (Fig. 2.7c) which shows wavy bedded reflectors. This echo type is characterized by distinct, wavy, continuous reflections associated with intercanyon or moderate sloping areas.

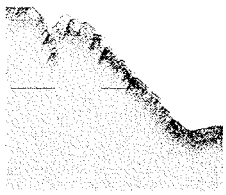
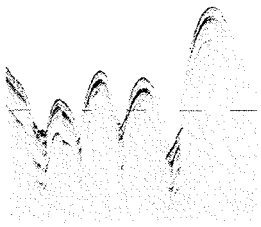
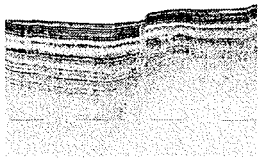
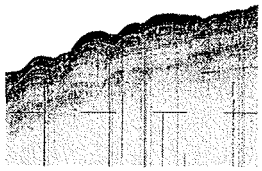
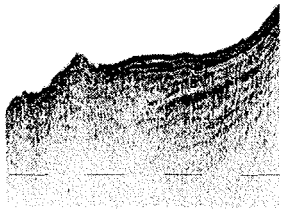
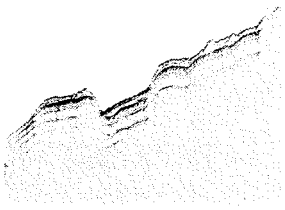
(3c) The discontinuously bedded echo-type is found at the southern part of Profile GeoB99-065 (Fig. 2.7a). This type of facies shows parallel subbottom reflectors, which alternate with zones of diffuse or discontinuous subbottom reflections, forming an irregular bedding. It is mainly found in areas of moderate slopes.

(4) Partially transparent/discontinuously bedded echo type: this definition was chosen because profiles parallel and perpendicular to the coast show different echo types. The transparent echo type is easily recognizable and is widely observed throughout the study area especially close to the coast in profiles perpendicular to the coastline of the Gulf of Aqaba (Fig. 2.3c). It is characterized by low reflection amplitudes and low penetration, while the previously mentioned discontinuous echo type is mainly found on slopes of the profiles parallel to the coast (Figs. 2.3b, 2.7a).

Tab. 2.1: *Description and interpretation of sediment echo-facies identified in the Gulf of Aqaba.*

Example	Echo-facies	Description	Interpretation
	**Rugged echo-facies**	It is characterized by indistinct, very prolonged bottom echoes with no apparent subbottom reflectors. It is associated frequently with hyperbolic facies and principally observed in the axes of submarine canyons and steep slopes.	Rugged echo character is recorded from particularly hard sea floor covered with heterogeneous and coarse-grained turbidite deposits and subjected to strong erosional processes (Damuth, 1975).

Tab. 2.1 (cont): *Description and interpretation of sediment echo-facies identified in the Gulf of Aqaba.*

Example	Echo-facies	Description	Interpretation
 	**Hyperbolic echo-facies** a) Regular overlapping hyperbolas b) Irregular hyperbolic echoes with varying vertex elevation	This echo facies is characterized by regular overlapping hyperbolas or irregular hyperbolic echoes with varying vertex elevation. Both subclasses are generally recorded from areas with rough sea-floor morphology and show no subbottom penetration.	Hyperbolic echo facies are recorded on steep slopes and commonly controlled by basement structures (Damuth, 1975, 1980). The hyperbolic signature may result from very coarse sediments, including large rafted blocks, probably deposited by mass wasting processes (Damuth, 1975; Jacobi, 1976).
   	**Bedded echo-facies** a) Uniformly bedded echo-facies b) Undulated bedded echo-facies c) Discontinuously bedded echo-facies	This type is characterized by layered sequences of smooth, distinct, continuous subbottom reflectors parallel to the sea floor. This echo type is characterized by distinct, wavy, continuous reflections. This example illustrates parallel subbottom reflectors, which alternate with zones of diffuse subbottom reflections. This example shows distinct disrupted subbottom reflectors	The uniformly bedded echo type is related to thin turbidites deposited in the basins and local depressions. The undulated bedded echo facies probably indicates deformed turbidites (e.g. Damuth, 1980). This type of the discontinuously bedded echo-facies indicates coarse-grained turbiditic materials (Gaullier and Bellaiche, 1998). This type of the discontinuously bedded echo-facies is caused by interruption of the reflectors by faults.
	**Partially transparent/ discontinuously bedded echo facies**	This definition was chosen because profiles parallel and perpendicular to the coast show different echo types. The transparent echo facies is characterized by low reflection amplitudes and low penetration, while the discontinuously bedded echo-facies is described above.	This echo facies indicates disturbed sediments including slope failure deposits (Embley, 1976; Guallier and Bellaiche, 1998). This facies mainly consists of coarse gravels.

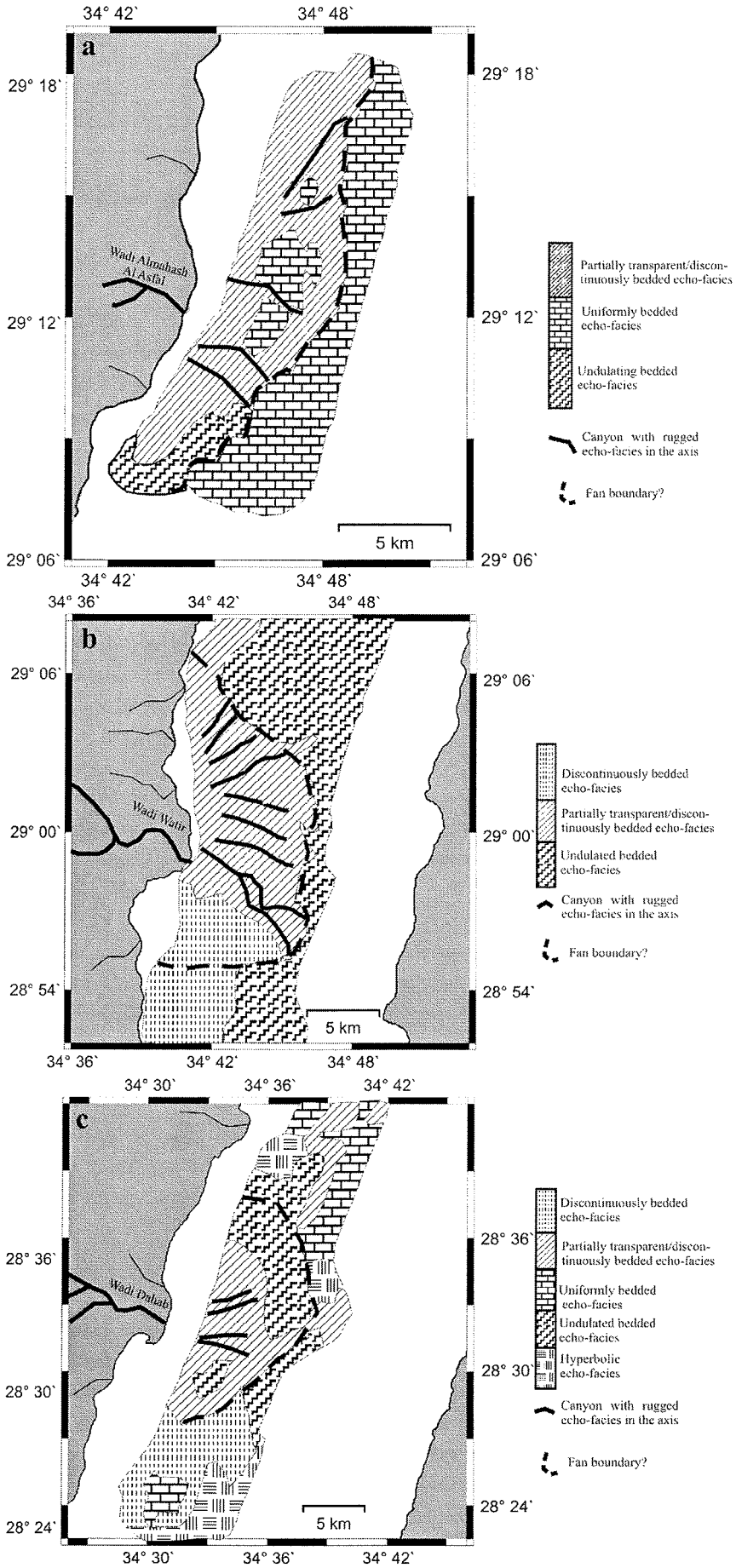


Fig. 2.8: *Echo facies maps. a) Echo facies map of the submarine prolongation of Ras El Burka fan. b) Echo facies map of the submarine prolongation of Wadi Watir fan. c) Echo facies map of the submarine prolongation of Wadi Dahab fan.*

2.4.5 Distribution of acoustic facies in the fans

The distribution of acoustic facies in the studied submarine fans in the Gulf of Aqaba is illustrated on Figure 2.8. The facies in the submarine prolongation fans changes sharply or transitional, likely depending on the distribution of the grain sizes in the sediments in addition to the morphology of the fan.

The partially transparent/discontinuously bedded echo facies shows the most widespread distribution. It is present off the mouths of the wadis, but it also extends over large distances close to and along the coast. Canyons in this facies are mainly found in direct vicinity of the wadis. The canyons are characterized by a rugged echo facies. Most canyons were identified in the Wadi Watir submarine fan, but several canyons were identified in the other fans as well (Fig. 2.8).

The discontinuously bedded echo facies is often found next to the partially transparent/discontinuously bedded echo facies. It is difficult to distinguish between these two facies and the boundaries are not sharp. The southern part of Parasound Profile GeoB99-065 (Fig. 2.7a), oriented parallel to the coast, is characterized by discontinuously bedded echo-facies; the signal penetration is ~20 m. Several small but no major canyons were identified within this facies.

The undulated bedded echo facies is also recorded in direct proximity to the above-described facies. It is commonly observed on the moderate slopes, e.g. at the northeastern part of Parasound Profile GeoB99-069 (Fig. 2.7c) and Parasound Profile GeoB99-044 (Fig. 2.5a).

Hyperbolic echo facies was only identified at the southwestern part of Wadi Dahab submarine fan. Many slope failures are found in this facies. An example of this facies is visible at the northwestern part of Parasound profile GeoB99-068 (Fig. 2.7b).

The uniformly bedded echo facies is found at greatest distance from the coast in all submarine fans. This facies characterizes the basins or areas with very small slope angles. Parasound Profile GeoB99-045 (Fig. 2.5b) running perpendicular to the coast of the Gulf of Aqaba shows the transition from gentle slope sediments (partially transparent echo facies) to the basin deposits with signal penetration of about ~15 m.

2.5 Discussion

2.5.1 Sediments in the fans

The analysis of the Parasound profiles allowed to distinguish a number of different echo facies in the study area. The variations in reflectivity and penetration express variations in

the sedimentary facies. In the following we try to relate the echo facies to specific sediment types. Nevertheless, due to the absence of cores in the study areas, the interpretation of the echo facies remains speculative. The interpretation of the echo facies is summarized in Table 2.1.

The rugged echo character is observed in the axes of submarine canyons and channels and is returned from hard bottoms with coarse-grained heterogeneous turbidites and subjected to strong erosional processes (e.g. Damuth, 1975). It is probably deposited by energetic gravity-flow processes.

The hyperbolic echo character is recorded from areas with rough bottom morphology. Irregular to regular hyperbolae echo type corresponds to steep slopes, which are generally controlled by basement structure (e.g. Damuth, 1975, 1980). The hyperbolic signature may result from very coarse sediments, including large rafted blocks, probably deposited by mass wasting processes (Damuth, 1975; Jacobi, 1976). Mass wasting events might be triggered by earthquakes which frequently occur in this area.

The partially transparent/discontinuously bedded echo facies is mainly found in areas of steep slopes in the central parts of the submarine fans. This echo facies indicates disturbed sediments including slope failure deposits (Guallier and Bellaiche, 1998). We assume that this facies mainly consists of coarse gravels and sands of unsorted grain sizes, which would explain the disrupted pattern of this facies.

The bedded echo character is widely observed in the basins or areas with a relatively flat sea floor. The uniformly bedded echo type is related to thin turbidites deposited in the basins and local depressions, whereas the discontinuously bedded echo type corresponds to more coarse grained turbiditic materials (sand and silt) or mass flows. The undulated bedded echo facies probably indicates deformed turbidites (e.g. Damuth, 1980). Though the bedded echo character generally expresses turbidites, it also might correspond to hemipelagic deposits.

The echo characters interpreted from our Parasound data generally suggest that the coarsest material, most likely sand or gravel, accumulate close to the Wadi mouth or in high-energy regions, whereas the finer sediments are deposited farther seaward or in the lower energy regions. A typical example is Profile GeoB99-032 (Fig. 2.3c) where two different echo facies were identified (partially transparent and uniformly bedded echo facies). It is interesting to notice that we also observe differences in reflection amplitude within the partially transparent echo facies. The reflection amplitude generally increases

with increasing distance to the coast probably indicating a gradual change to finer and better sorted deposits.

2.5.2 Size and volume of the fans

It is difficult to estimate the size of the fans. Generally, the fans in the Gulf of Aqaba were composed essentially of fine to coarse clastic sandy sediments, gravels and boulders with carbonate debris in some places. The partially transparent/discontinuously bedded as well as the hyperbolic echo facies clearly reflect these sediments. But these echo facies types are also found all over the submarine slope of the Gulf, far away from any wadi and submarine fan. The uniformly bedded echo facies probably consists of an interlayering of turbidity deposits and hemipelagic background sedimentation. Some of the turbidites might originate in the submarine fans, because the fans accumulate large amounts of sediments, which easily become unstable and might result in slope failures and turbidites. Hence, fan sediments might be transported over larger distances into the deep basins.

We decided to define the central fan area from a combination of the facies maps and the bathymetric data. The bathymetry shows morphologically elevated areas off the wadis, which are probably caused by the increased sediment supply. This is supported by the acoustic facies in these areas, which is typically characterized by more or less chaotic reflection patterns. The reflection patterns indicate a complex depositional history of accumulation, erosion, and mass wasting. These areas are also dissected by numerous canyons, which indicate downslope transport processes. However, it is not possible to assign precise boundaries of the extent of the submarine fan due to gradual changes in facies distribution.

Our definitions of the central fan areas are shown together with the echo facies in Figure 2.8. These boundaries result in the following sizes of the fans. The largest fan is Wadi Dahab submarine fan, which is about 10 km wide and 27 km long. It can be traced down to a water depth of 1000 m. Wadi Watir submarine fan covers an area of 25 x 7 km and extends down to 900 m water depth. The smallest submarine fan is Ras El Burka, which is 7 km wide and 15 km long.

An estimate of the volume of the fans is even more difficult. We constructed bathymetric profiles of the slope in- and outside the fan area (Fig. 2.9). The bathymetric profiles of the central fan are relatively similar but the cross sections of the slope north and south of the fan differ significantly from each other. The water depth about 5 km off the coast south of the fan is almost 200 m shallower than in the north. The cross sections of the

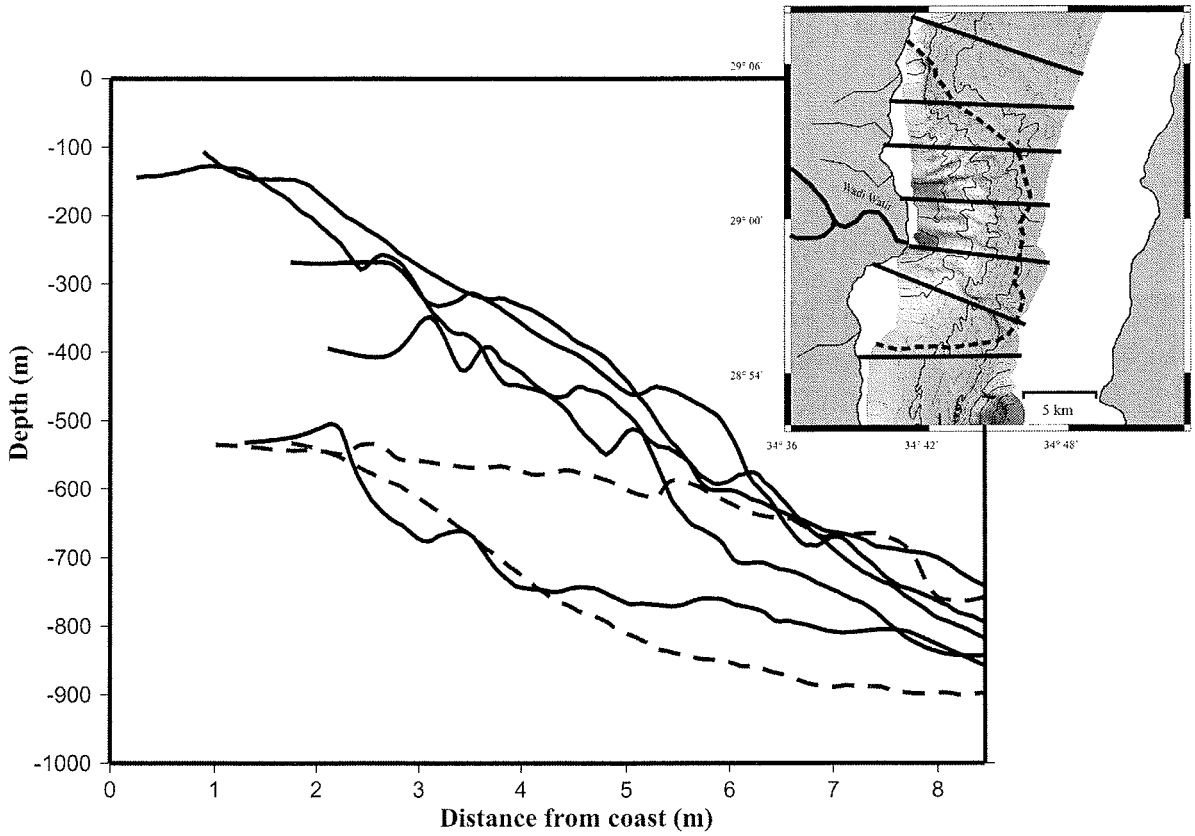


Fig. 2.9: *Bathymetric profiles of the slope. The location of the profiles is shown in the inset map. The dashed profiles are located outside the central fan area; the solid lines cross the fan. The profiles inside the fan indicate additional deposits of ~400 m thickness except for the profile which crosses the northernmost edge of the fan. The profiles were used to estimate the volume of the fan.*

central fan, however, clearly show additional sediment deposits of up to 400 m thickness. The difference in morphology of the profiles in- and outside the fan were used to calculate its volume, which is ~15 km^3 for the submarine prolongation of Wadi Watir alluvial fan. The error of this estimate is large because of missing bathymetric data close to the coast and the uncertainty of the morphology of the slope not affected by additional sediment input through a wadi. The volume estimate only includes the sediments of the central fan and neglects distal turbidites, which transport fan sediments far into the basins. The volume of the distal turbidites might exceed the volume of the central fan itself. A volume estimate for the other fans is even more difficult due to larger gaps of the bathymetry close to the coast. Rough estimates result in a similar volume for Wadi Dahab submarine fan (~15 km^3) and a much smaller volume (<5 km^3) for Ras El Burka submarine fan. The different sizes and volumes of the fans are a direct result of the different sizes of the

catchment areas of the corresponding wadis. The catchment area of Ras El Burka is in the range of hundreds of square-kilometers, while Wadi Watir and Wadi Dahab collect sediments of catchment areas of ten-thousands of square-kilometers.

2.5.3 Key processes for the formation of the fans

Three primary controls on submarine fan development and deep-sea sedimentation can be identified: 1) sediment-type and supply, 2) tectonic setting and activity, and 3) sea level variations (Richards et al., 1998; Bouma, 2000). These controls are by no means independent; for example, tectonic factors play an important role in determining sediment supply or local sea level changes (Stow et al., 1985). Major subcategories of the tectonic category include the location of the sediment source relative to the sea, the elevation of the mountains, the susceptibility of the rocks to erosion, the shelf width and gradient, and the basin morphology. Climate controls the rate and type of weathering in the sediment-source area, the precipitation, and the runoff and fluvial transport capability. Sediment type includes grain size, sorting, grain shape, and mineral composition, and hence also the degree of maturity. Sea level fluctuations, global or regional, are directly dependent on tectonics and/or climate. The fluctuations can be large or small, and a sea level change of any magnitude is likely to be recorded in the deposits, particularly in fine-grained submarine fans. Sea level fluctuations often dictate the timing of sediment transport from the land or coastal area to the deep-water basin. Most major submarine fans develop during periods of low sea level (Shanmungam and Moiola, 1982).

In the following we will discuss the importance of the above discussed processes for the Gulf of Aqaba: 1) Sediment-type and supply: the catchment areas of the wadis, which supply the fans with their sediments from the hinterland of Sinai Peninsula, probably play an important role. At the Gulf of Aqaba, infrequent rain falls on catchment areas of up to ten-thousands of square kilometers of rocky desert highlands were funneled in wadis and develop flashfloods which feed alluvial fans and their submarine prolongations along the entire western coast of the Gulf of Aqaba. Ras El Burka submarine fan is by far the smallest fan and has the smallest catchment area. In contrast the larger fans of Wadi Dahab and Wadi Watir are located off a large wadi system, hence having a larger catchment area. The sediment succession in the catchment area is pre tectonic starting with Lower Paleozoic continental clastics, conformably overlain by the continental sandstones of the Early Cretaceous. This cycle is succeeded by the first marine sediments of Late Cretaceous up to Middle Eocene age (Abdel Khalek et al., 1993). These sediments are easily erodable

resulting in large amounts of sediments transported through the wadis out to the narrow coastal margins and into the submarine fans. 2) Tectonic setting and activity: the continuous tectonics (faulting and folding) and earthquake activity of the Dead Sea Rift play an important role on both the sediment type and supply in the gulf by their influence on relief, resedimentation processes, and eustatic or local sea level changes. As a result we observe many slumps and slides, in addition to the shape and slope gradients that confine and control depositional patterns of the submarine fans. 3) Sea level variations: sea level fluctuations in the Gulf of Aqaba might have played a role in the formation of the submarine fans in the gulf during the Pleistocene glacial time. During glacial times the climate cooled and became more humid and increased precipitation caused massive influx of terrigenous sediment into the fans. The Gulf of Aqaba, however, has no continental shelves and coastal plains are very narrow, hence sea level changes are probably not as important during fan development as in larger fans (e.g. Amazon or Bengal submarine fans).

Several classification schemes and models for submarine/turbidite systems have been published, based on tectonic setting, basin characteristics, grain size, types of gravity flow, relative sea level fluctuations, and other factors. Richards et al. (1998) divided submarine fans/turbidite systems into twelve classes based on (1) the volume and grain size of available sediment, and (2) the nature of the supply system – point source, multiple source ramps, or slope apron linear source. Among the various general and specific models are two siliciclastic end members that are important guides for many turbidite studies (Bouma, 2000): i) fine-grained, mud-rich complexes are typical for passive margin settings, with long fluvial transport, fed by deltas, wide shelf, efficient basin transport, resulting in a bypassing system. ii) coarse-grained, sand-rich complexes are typical for regions in active margin setting, characterized by a short continental transport distance, narrow shelf, and a canyon-sourced, nonefficient basin transport system that results in a prograding type of fan. According to these classifications, the fans in the Gulf of Aqaba can be classified as sand-rich, point source turbidite system. Most of the sediments were supplied by a central wadi though some smaller wadis might transport sediments into the fans as well.

2.6 Conclusions

- The three studied prolongations of alluvial fans into the Gulf of Aqaba (Wadi Watir, Wadi Dahab, and Ras El Burka fan) differ in size and volume according to the

catchment area of the wadis which supply the fans with sediments from the hinterland of Sinai Peninsula.

- Acoustically, four groups of echo facies characters were distinguished (rugged, hyperbolic, bedded and partially transparent/discontinuously bedded echo facies). All echo facies are characteristic for fan sediments except the uniformly bedded echo facies which represent the basin deposits. The character and the distribution of the echo facies reflect the morphology and the type of the sediments.
- Clastic sediments (coarse gravels and sands) are the dominant sedimentary composition in the submarine fans in the Gulf of Aqaba. The grain size of the clastic deposits decreases towards the basins which are filled with turbidite deposits and pelagic sediments. The fans in the Gulf of Aqaba can be classified as sand-rich, point source turbidite system.
- The surface of the fans is dissected by numerous V-shape and few U-shape canyons. The canyons are up to 1.5 km wide and 130 m deep.
- The numerous slumps and slides identified on the Parasound profiles are probably initiated by a combination of earthquakes, growth faults, oversteepening of the slope and subsequent failure, and other submarine processes, i.e. the interaction of deposition and erosion.

Acknowledgements

Many thanks to Captain Bülow and his crew for the friendly cooperation and technical support during Meteor Cruise M44/3. We are grateful to our colleagues from Bremen University for fruitful discussions and the most valuable help. The study were carried as part of the PhD-thesis of M. Salem at the 'Marine Technology/Environmental Research'-Group at the Department of Earthsciences, Bremen University. The work was funded by the Deutsche Forschungsgemeinschaft grants no. PA 492/2 and PA 492/3. MS received a scholarship from the 'Office of Higher Education' in Egypt.

References

Abdel Khalek, M.L., Abdel Wahed, N., Sehim, A.A., 1993. Wrenching deformation and tectonic setting of the northwestern part of the Gulf of Aqaba. Geol. Soc. Egypt., Spec. Publ. 1, 409-444.

Badawy, A., Horvath, F., 1999. The Sinai subplate and tectonic evolution of the northern Red Sea region . J. Geodyn. 27, 433-450.

Bartov, Y., Steinitz, H., 1978. Horizontal displacement along faults, eastern Sinai (preliminary evaluation). Geol. Surv. Israel (in Hebrew), mapping division, Report MM/2/78, pp. 7.

Ben-Avraham, Z., 1985. Structure framework of the Gulf of Aqaba, northern Red Sea. J. Geophysics. Res. 90, 703-726.

Ben-Avraham, Z., Almagor, G., Garfunkel, Z., 1979. Sediments and structure of the Gulf of Aqaba - Northern Red Sea. Sed. Geol. 23, 239-267.

Ben-Avraham, Z., Tibor, G., 1993. The northern edge of the Gulf of Elat. Tectonophys. 220, 319-331.

Bouma, A.H., 2000. Fine-grained, mud-rich turbidite systems: model and comparison with coarse-grained, sand-rich systems. AAPG Memoir 72, 9-20.

Caress, D.W., Chayes, D.N., 1996. Improved processing of Hydrosweep DS multibeam data on the R/V Maurice Ewing, Mar. Geophys. Res. 18, 631-650.

Damuth, J.E., 1975. Echo character of the western equatorial Atlantic floor and its relationship to the dispersal and distribution of terrigenous sediments. Mar. Geol. 18, 17-45.

Damuth, J.E., 1980. Use of high-frequency (3.5-12 kHz) echograms in the study of near-bottom sedimentation processes in the deep sea: a review. Mar. Geol. 38, 51-75.

Damuth, J.E., Hayes, D.E., 1977. Echo character of the east Brazilian continental margin and its relationship to sedimentary processes. Mar. Geol. 24, 93-95.

Embley, R.W., 1976. New evidence for occurrence of debris flow deposits in the deep sea. Geol. 4, 371-374.

Freund, R., Garfunkel, Z., 1976. Guide book to excursion along the Dead Sea rift. Dep. Geol., The Hebrew University of Jerusalem, Israel, 43p.

Friedman, G.M., 1985. Gulf of Aqaba, geological and sedimentological framework. In: Friedman, G.M., Krumbein, W.E. (Eds.), Hypersaline ecosystems. The Gavish Sabkha. Ecological Studies: Analysis and Synthesis 53, pp. 39-71.

Garfunkel, Z., 1970. The tectonics of the western margins of the Southern Arava. PhD-Thesis, Dep. Geol., The Hebrew University of Jerusalem, Israel, pp. 204.

Garfunkel, Z., Bartov, Y., Eyal, Y., Steinitz, G., 1974. Raham Conglomerate-new evidence for Neogene tectonism in the sourthern part of the Dead Sea Rift. Geol. Mag. 111, 55-64.

Garfunkel, Z., Zak, I., Freund, R., 1981. Active faulting in the Dead Sea Rift. Tectonophys. 80, 1-26.

Grant, J.A., Schreiber, R., 1990. Modern swath sounding and sub-bottom profiling technology for research applications: the Atlas Hydrosweep and Parasound systems. Mar. Geophys. Res. 12, 9-19.

Guallier, V., Bellaiche, G., 1998. Near-bottom sedimentation processes revealed by echo-character mapping studies, northwestern Mediterranean Basin. AAPG Bulletin 82, 1140-1155.

Hall, J., Ben-Avraham, Z., 1978. New bathymetric map of the Gulf of Aqaba. Tenth Int. Congr. on Sedimentology 1, 285.

Jacobi, R.D., 1976. Sediment slides on the northwestern continental margin of Africa: Mar. Geol. 82, 157-173.

Loncke, L., Gaullier, V., Bellaiche, G., Mascle, J., 2002. Recent depositional patterns of the Nile deep-sea fan from echo-character mapping. AAPG Bull. 86, 1165-1186.

Mechie, J., El-Isa, Z.H., 1988. Upper lithospheric deformations in the Jordan-Dead Sea transform regime. Tectonophys. 153, 153-159.

Richards, M., Bowman, M., Reading, H., 1998. Submarine-fan systems I: characterization and stratigraphic prediction. Mar. Petrol. Geol 15, 689-717.

Rostek, F., Spieß, V., Bleil, U., 1991. Parasound echosounding: Comparison of analogue and digital echosounder records and physical properties of sediments from the Equatorial South Atlantic. Mar. Geol. 99, 1-18.

Shanmugam, G., Moiola, R.J., 1982. Eustatic control of turbidites and winnowed turbidites. Geology 80, 192-223.

Shepard, F.P., 1981. Submarine canyons: Multiple causes and long term persistence. Bull. Am. Assoc. Petrol. Geol. 65, 1062-1077.

Spieß, V., 1993. Digitale Sedimentechographie - Neue Wege zu einer hochauflösenden Akustostratigraphie. Berichte Fachbereich Geowissenschaften, Universität Bremen 35, 1-199.

Stow, D.A.V., Howell, D.G., Nelson, C.A., 1985. Sedimentary, tectonic, and sea-level controls. In: Bouma, A.H., Normark, W.R., Barnes, N.A., (Eds.), Submarine Fans and Related Turbidite Systems, Springer, New York, pp. 15-22.

Uenzelmann-Neben, G., Spieß, V., Bleil, U., 1997. A seismic reconnaissance survey of the northern Congo fan. Mar. Geol. 140, 283-306.

Wessel, P. and Smith, W.H.F., 1998. New, improved version of Generic Mapping Tools released. EOS trans. Amer. Geophys. Un. 79, 579.

CHAPTER THREE

Growth and development of the submarine prolongation of Wadi Watir alluvial fan into the Gulf of Aqaba, Red Sea, deduced from high-resolution multi-channel seismic reflection data

(To be submitted to Marine Geophysical Researches)

M. Salem[1], S. Krastel[1], C. Hübscher[2], V. Spieß[1]

[1]*Department of Geosciences, University of Bremen, PO Box 33 04 40, D-28334 Bremen, Germany.*

[2]*Institute of Geophysics, Hamburg University, Bundesstr. 55, 20146 Hamburg.*

msalem@uni-bremen.de

Growth and development of the submarine prolongation of Wadi Watir alluvial fan into the Gulf of Aqaba, Red Sea, deduced from high-resolution multi-channel seismic reflection data

M. Salem[1], S. Krastel[1], C. Hübscher[2], V. Spieß[1]

[1]*Department of Geosciences, University of Bremen, PO Box 33 04 40, D-28334 Bremen, Germany. Email:* msalem@uni-bremen.de

[2]*Institute of Geophysics, Hamburg University, Bundesstr. 55, 20146 Hamburg.*

Abstract

The submarine prolongation of Wadi Watir alluvial fan is formed at the mouth of Wadi Watir, which delivers its load from the rocky desert of the Sinai Peninsula to the sea during sporadic rainy seasons and periods of humid climate. The submarine fan covers an area of ~25 km by ~7 km, and can be traced down to a water depth of ~1000 m. The morphology and sedimentary structure of this fan have been studied using a Hydrosweep multibeam system and high-resolution multi-channel seismic reflection data, which were used to map different seismic facies in the fan, ranging from continuous parallel high-amplitude reflections to chaotic reflection patterns. Unchannelized sediment transport significantly contributes to the buildup of the submarine prolongation resulting in decreasing grain size with increasing distance from the coast. Small faults reflect the ongoing tectonic activity. Several canyons up to ~130 m deep and ~1.5 km wide are carved into the fan. Most of the canyons are accompanied by graben faults. Large amounts of sediments are transported through these canyons to the most distal part of the fan and the basins. Abundant slide and slump deposits indicate the importance of mass wasting during the evolution of the submarine fan.

3.1 Introduction

Submarine fans may form at any time when sediment gravity flows transport sediments across the slope to the basin floor (Posamentier et al., 1991). Such submarine fans are called turbidite systems by Mutti and Normark (1991), fan sequences by Feeley et al. (1985), and fan-lobes by Bouma et al. (1985).

The general classification by Richards et al. (1998) of submarine fan/turbidite systems is based on grain size and feeder system. The grain size components include mud-rich, mud/sand-rich, sand-rich, and gravel-rich. The feeder systems are divided into point-source, multiple-source submarine ramp, and linear-source slope apron. From a possible polyaxial system, two grain size systems are selected as end members: mud-rich and sand-rich, both with point-source feeding, but being variable with respect to texture.

Stelting et al. (2000) stated that the differences between coarse-grained systems and fine-grained turbidite systems could be fully appreciated. The principal characteristics of the two systems are summarized as follows (Bouma, 2000): Coarse-grained, sand-rich turbidite systems typically occur in small basins on continental crust, have short terrestrial transport distances, narrow shelves, canyon-sources, nonefficient basin transport, progradational depositional styles, and decreasing ratios of gravels with increasing distances to the sediment pathways. Fine-grained, mud-rich turbidite systems, by contrast, are found in large basins on passive margins, have long terrestrial transport distances and broad shelves, delta-sources, efficient basin transport resulting in bypassing of a high percentage of sands to the outer fan, and spatially variable net-to-gross ratio patterns. Another group can be classified as fine-grained, sand-rich turbidite systems as found in the west Texas Permian Basin (Carr and Gardener, 2000).

The submarine prolongation of Wadi Watir alluvial fan (Fig. 3.1) is one of the largest elongated submarine fans, which have developed at the western side of the Gulf of Aqaba. The fan is located off the mouth of Wadi Watir and extends for about 7 km offshore to ~1000 m water depth. The surface of the fan is dissected by straight and V-shaped canyons (Salem et al., this thesis). Seismic Data in the Gulf of Aqaba are sparse. The only published data were collected in 1976 on R/V Ramona (Ben-Avraham et al., 1979). Signals for these data were generated by a 4.9 liter (300 cu. in.) airgun resulting in frequencies between 20-60 Hz, hence not resolving the fine structure of near-surface fan sediments.

In this paper, we present an interpretation of the seismic facies distribution of the fan based on newly collected high-resolution multi-channel seismic data of Wadi Watir submarine fan. The aim of this study is to answer the following questions: 1) What types of

sediments occur in the fan and how are they distributed? 2) What are the main processes during the evolution of the fan? This includes a detailed analysis of the importance of tectonic activity and mass wasting events. These results, in combination with previously published geological and geophysical data, are used for a structural analysis of the submarine prolongation of Wadi Watir alluvial fan.

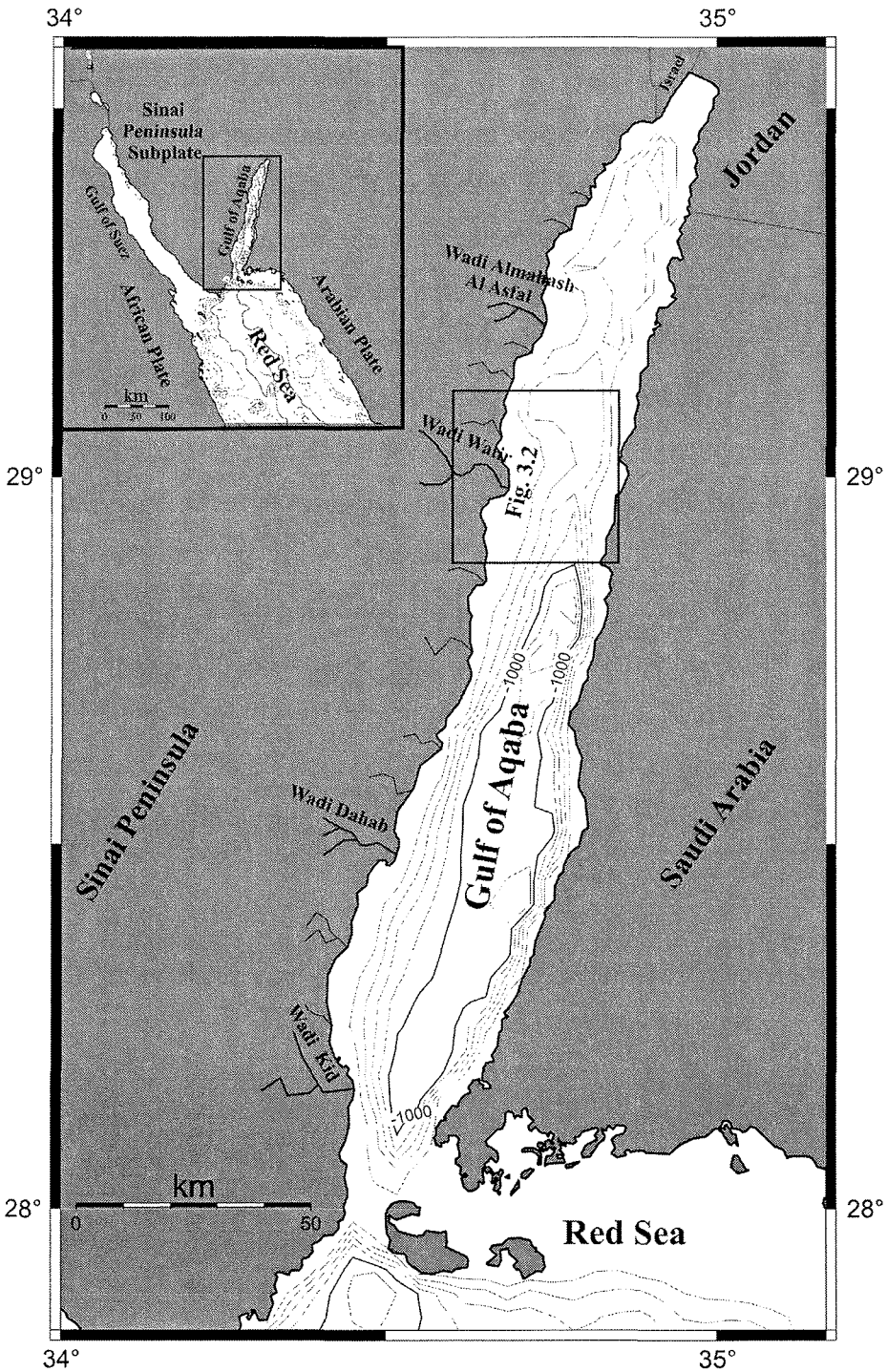


Fig. 3.1: *Overview map of the Gulf of Aqaba. The location of the study area is shown by the box.*

3.2 Geological setting, previous studies

The Gulf of Aqaba is the eastern extension of the Red Sea (Fig. 3.1). The Red Sea, which forms the boundary between the African Plate and the Arabian Plate, bifurcates into two branches. The Gulf of Suez follows the main trend of the Red Sea and forms the boundary between the African Plate and the Sinai Subplate. The Gulf of Aqaba, trending N-S and being 160 km long, forms the southern part of the 1100 km long Dead Sea Rift that separates the Arabian Plate from the Sinai Subplate and extends up to the collision zone at the Taurus-Zagros mountain range (Garfunkel, 1970). The Dead Sea Rift was formed in the Cenozoic by breakup of the once continuous Arabian-African platform, which had been a tectonically stable area since the end of the Precambrian (Ben-Avbraham et al., 1979). Geomorphic, geologic, and seismic studies show that the strike slip motion of the faults along the Dead Sea rift is still active (Zak and Freund, 1966; Garfunkel, 1970; Freund and Garfunkel, 1976; Ben-Menahem et al., 1976).

Badawy and Horvath (1999) studied the tectonic evolution of the northern Red Sea region, and stated that the Gulf of Aqaba can be characterized by a left-lateral displacement of about 107 km active since the Middle Miocene. They also concluded that the earthquake activity in the Gulf of Aqaba and Gulf of Suez regions is a direct consequence of the relative motion between the African Plate, the Arabian Plate, and the Sinai Subplate.

The bathymetric map of the Gulf of Aqaba, which was prepared by Hall and Ben-Avraham (1978), shows that almost no continental shelves are bordering the Gulf of Aqaba; coastal plains are absent or very narrow. On the western side of the Gulf of Aqaba, the Sinai Mountains rise steeply, generally being delimited by coastal faults. Large alluvial fans were built in front of these fault scarps. The fans extend as submarine cones on which many canyons are carved.

Previous seismic studies showed that the marginal slope areas are underlain by coarse-grained stratified sediments (Ben-Abraham et al., 1979). The individual reflectors are undulating, patchy, irregular and rough, often discontinuous, and may cause diffractions. Local minor unconformities were observed. As a whole, these series resemble the morphologically defined alluvial fans. The thickness recorded is 1-1.5 sec, which was the maximal penetration of the seismic signals. The observed dips are in part depositional, but tectonic warping and faulting is also present. Correlation between seismic profiles is difficult due to the great lateral variability (Ben-Avraham et al., 1979).

3.3 Methods

Seismic data were recorded with the high-resolution multi-channel reflection seismic system of Bremen University. A Generator/Injector Gun with a volume of 0.4 l was used as primary source. The frequencies of this source range from 50 and 500 Hz with a peak value around 150-200 Hz. The data were recorded with a 24-channel 300–m long streamer. The midpoint distance between individual channels was 12.5 m. In order to optimize the frequency response of the streamer at higher inclination angles in shallow water, hydrophone groups of only 2 hydrophones at a distance of ~0.30 m were used. The data were processed in a combination of in-house software of Bremen University and the public domain package SEISMIC UN*X (Stockwell, 1997). Processing included a static correction for streamer variations, binning, spherical divergence correction, velocity-analysis, stacking, frequency filtering, and time migration. A bin-distance of 10 m was chosen resulting in 10-fold sections.

The seismic profiling activity was accompanied by bathymetric measurements with a Hydrosweep multibeam system operating at a frequency of 15.5 kHz (Grant and Schreiber, 1990). Depth values are generated for 59 beams with an angular coverage of 90° resulting in a coverage of twice the water depth. Typical accuracies of the system are 0.25% of water depth reduced to 1% in areas of steep slopes. The location of the profiles gives a complete bathymetric coverage of the central area of Wadi Watir submarine fan (Fig. 3.2). The data were processed with the mb-system software package (Caress and Chayes, 1996) and finally gridded with a grid-size of 70 m. The data were displayed using the Generic Mapping Tools (GMT) software (Wessel and Smith, 1998).

3.4 Results

3.4.1 Description of seismic reflection profiles

A network of 26 seismic profiles was collected across the submarine prolongation of Wadi Watir alluvial fan. Figure 3.2 only shows the location of profiles presented in this manuscript but all collected profiles were used for an analysis of depositional patterns, sediment deformation, and faulting and facies distribution in order to study the evolution of the submarine fan in space and time. Following, the seismic data are described in detail for the different objectives and results are integrated for interpretation of fan depositional processes.

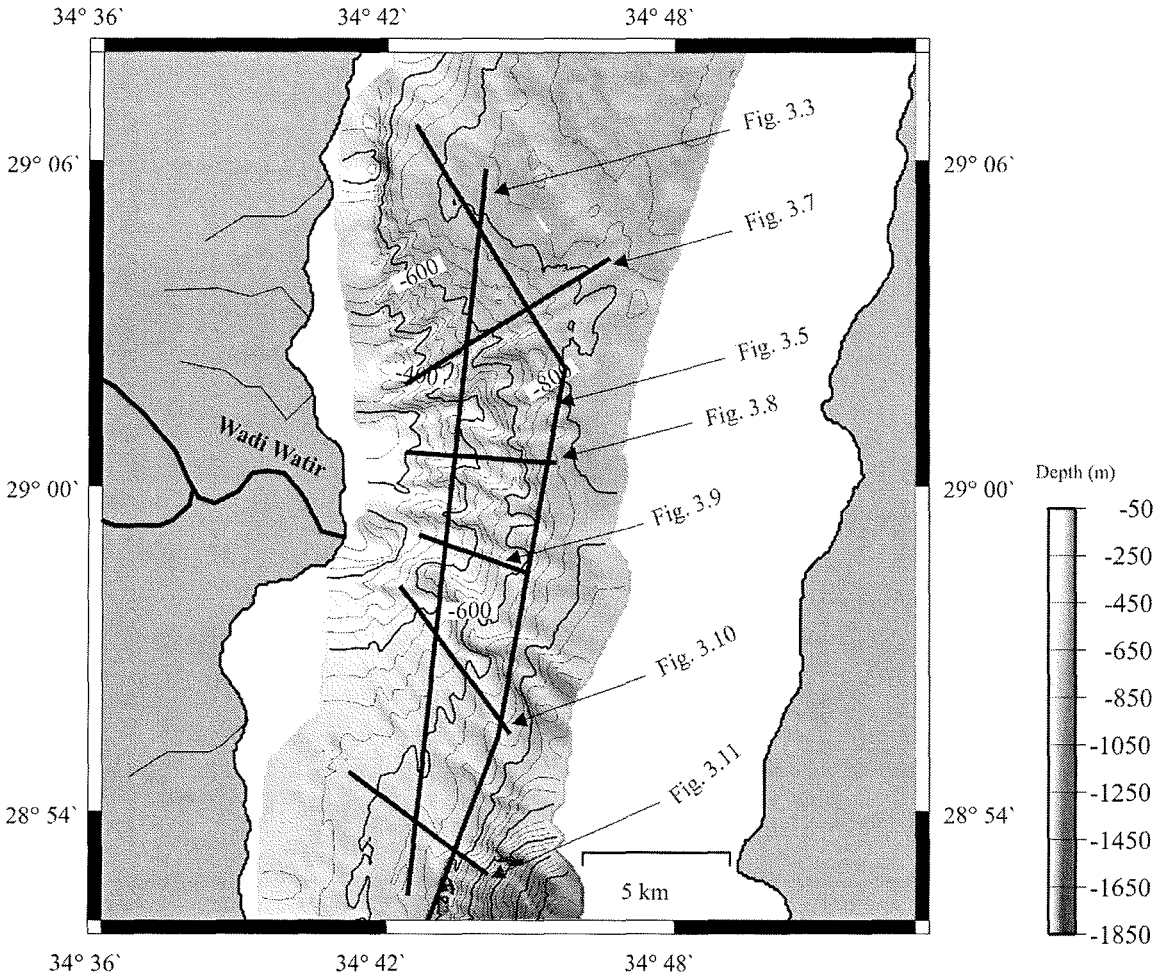


Fig. 3.2: *Bathymetric map of the submarine prolongation of Wadi Watir alluvial fan. The black lines show the location of the profiles presented in this manuscript. The location of the map is shown in Fig. 3.1.*

3.4.1.1 Seismic reflection profiles running parallel to the coast of the Gulf of Aqaba

Seismic Line GeoB99-057 running in S-N direction (Fig. 3.3) can be subdivided into three parts according to seismic reflection patterns. The first part, which extends from the northern end of the profile to CMP 1900, shows an irregular reflection pattern characterized by discontinuous hummocky reflectors. Several indications for slumping were found in this part of the profile. The second part of the profile reaches from CMP 1100-1900. It is characterized by low-amplitude reflections and partially transparent intervals. The penetration of the seismic energy is with 300 ms two-way traveltine (TWT) relatively low compared to the northern and southern parts, which reveal up to 1000 ms TWT penetration. The central part of the profile is dissected by deep V-shaped and a single U-shaped canyon; the canyons are up to 130 m deep and 1.5 km wide. They appear to be

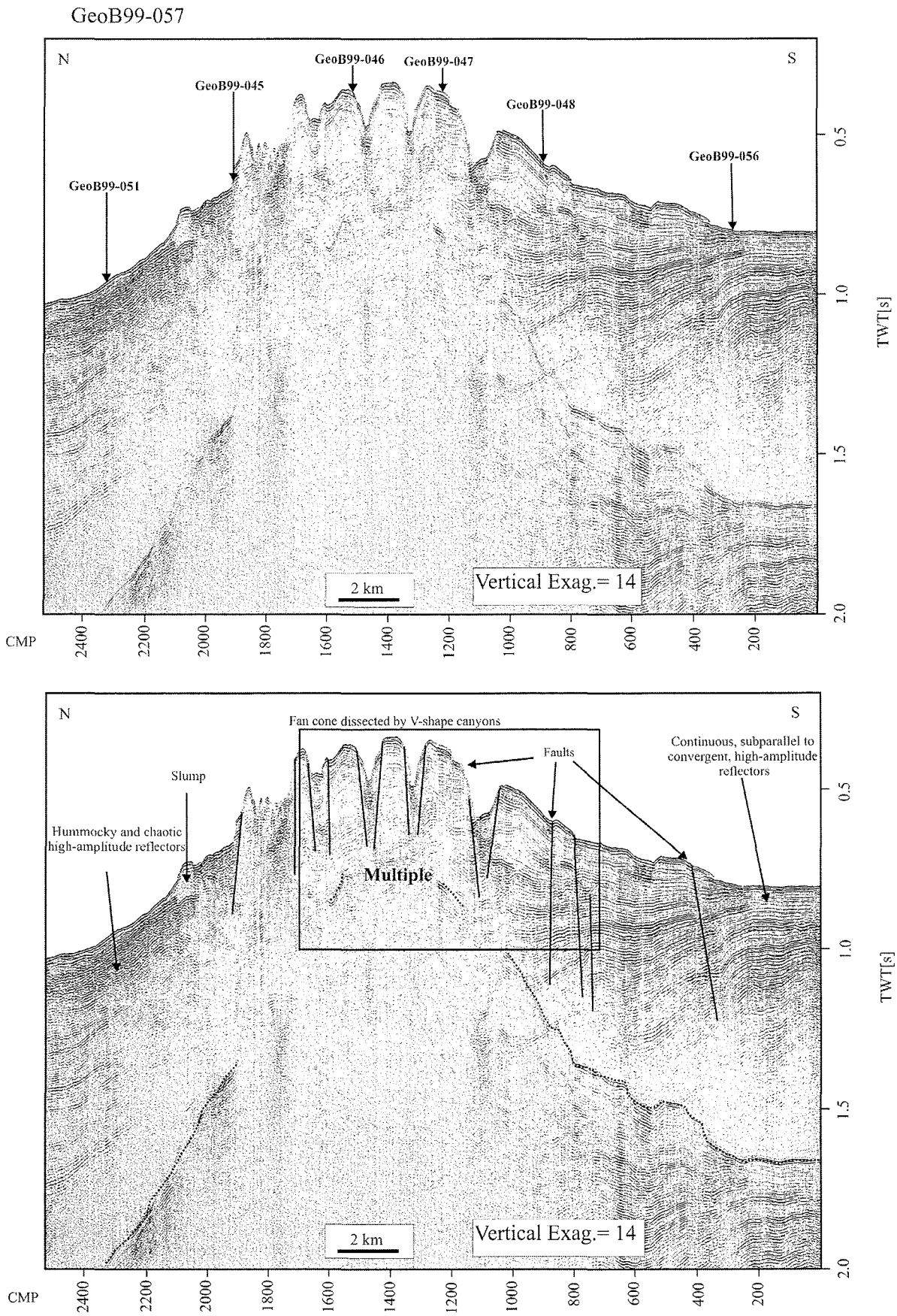


Fig. 3.3: *Seismic image and interpretation of Line GeoB99-057. The location of the profile is shown in Fig. 3.2.*

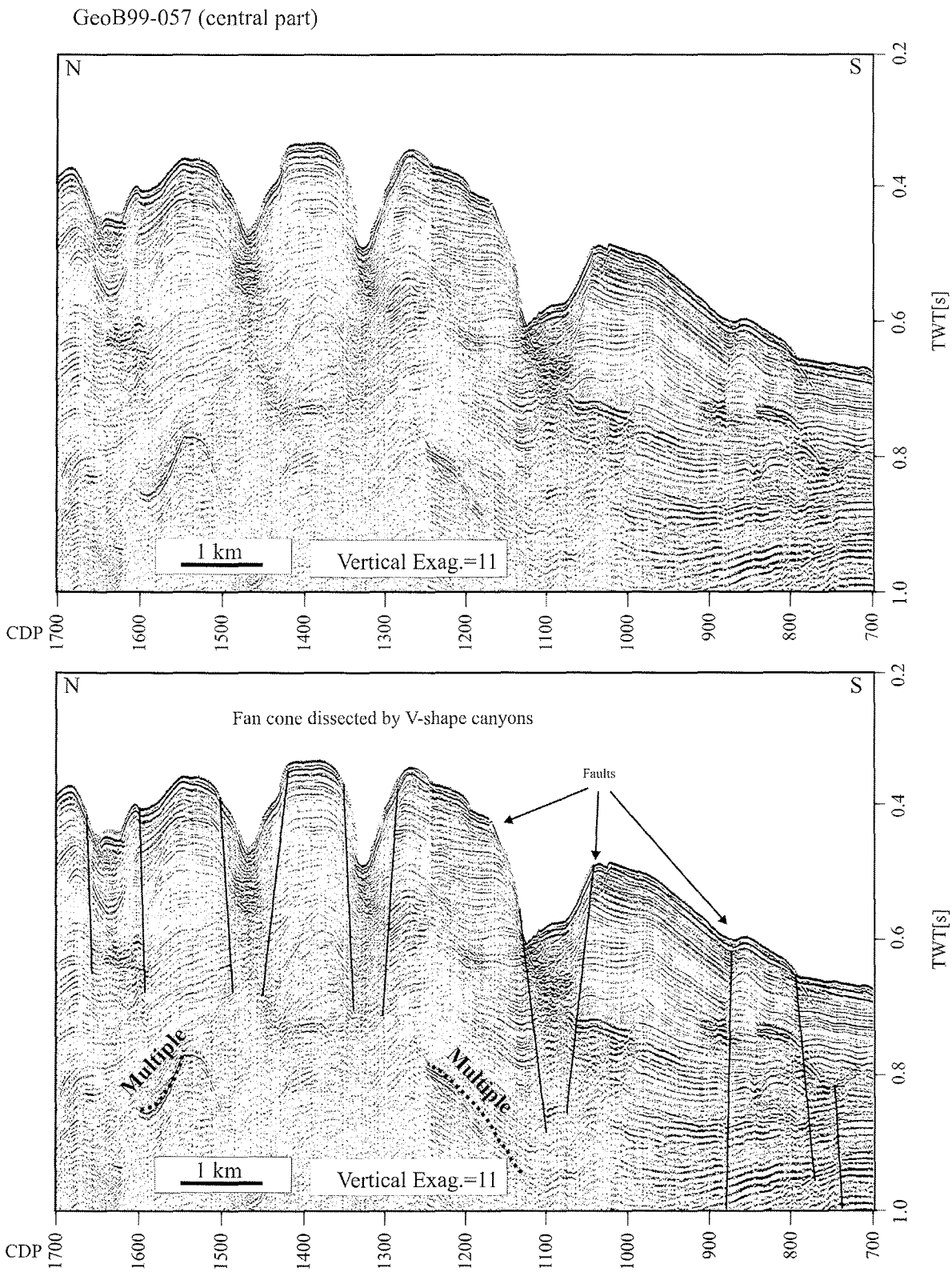


Fig. 3.4: *Closeup of the central part of Line GeoB99-057. The location of the closeup is shown in Fig. 3.3.*

associated with graben faults, though the faults cannot be traced to depth (Fig. 3.4). The canyons are partially filled with deposits showing a chaotic character, and moderate to high-amplitude reflection patterns. This part of the profile represents the central part of the submarine fan, which we designate to the cone of the fan. The third part, extending from CMP 1100 to the southern end of the profile, shows reflectors which are well stratified but disrupted by faults. The locations of the faults were inferred from reflection termination and changes in reflector dips (Fig. 3.3). The subparallel reflectors are characterized by high-amplitudes and a good continuity, converging towards the basin. Reflector amplitudes decrease gradually towards the central part of the fan.

The second longitudinal seismic reflection Line GeoB99-051 (Fig. 3.5) with a course changes in the northern and southern part exhibits a predominance of subparallel, undulating, discontinuous reflectors of moderate to high-amplitudes alternating with low amplitude to transparent intervals. These reflectors gradually change to a more chaotic pattern towards the northwestern and southwestern end of the line. This pattern is clearly interrupted by a dense distribution of faults (Fig. 3.6), which results in discontinuity of these reflectors especially in the central part of the fan (CMP 1200-2600). In addition, numerous V-shaped canyons up to 120 m deep were identified on the seismic image. The canyons seem to be related to the above-described faults.

In summary, discontinuous, undulating, irregular, and rough reflectors characterize the profiles parallel to the coast. The seismic pattern of the distal profile differs from the character of the upslope profile through average higher reflection amplitudes. An increase in amplitude with increasing distance to the coast is also seen on the profiles perpendicular to the coast (see below).

3.4.1.2 Seismic reflection profiles running perpendicular to the coast of the Gulf of Aqaba

Several seismic profiles were shot perpendicular to the coast in the vicinity of the mouth of Wadi Watir. All lines show reflectors, which dip towards the basin, but major differences were observed between the different profiles. The lines are incised by a few faults; the reflectors have generally discontinuous, moderate-amplitudes and a subparallel internal structure.

Seismic Profile GeoB99-045 (Fig. 3.7) is located on the northern side of the depositional cone (Fig. 3.2). It shows low to moderate amplitudes. The continuity of the reflectors generally enhances towards the basin. The irregular subparallel reflectors, which

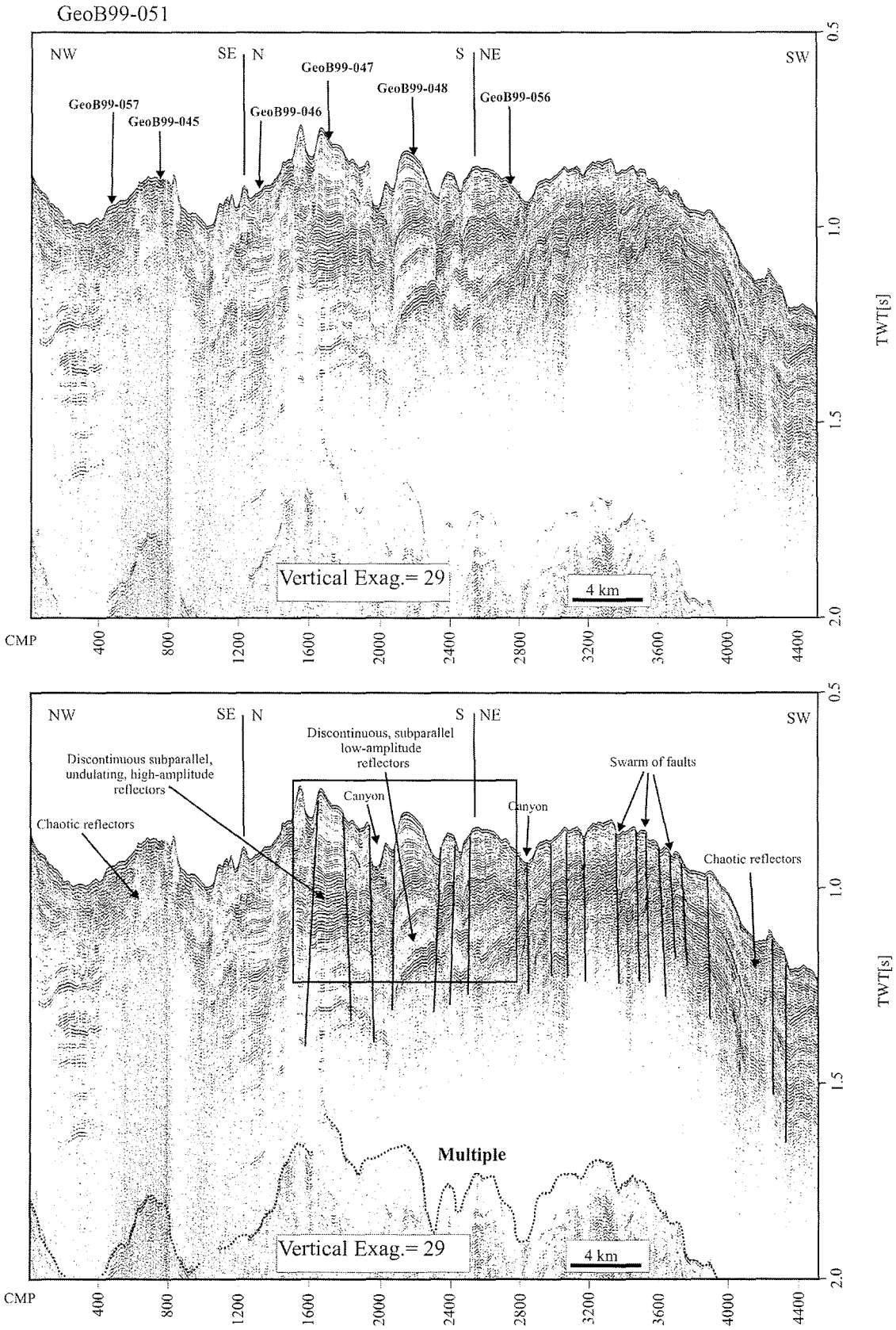


Fig. 3.5: *Seismic image and interpretation of Line GeoB99-051. The location of the profile is shown in Fig. 3.2. Note that the profile is not straight.*

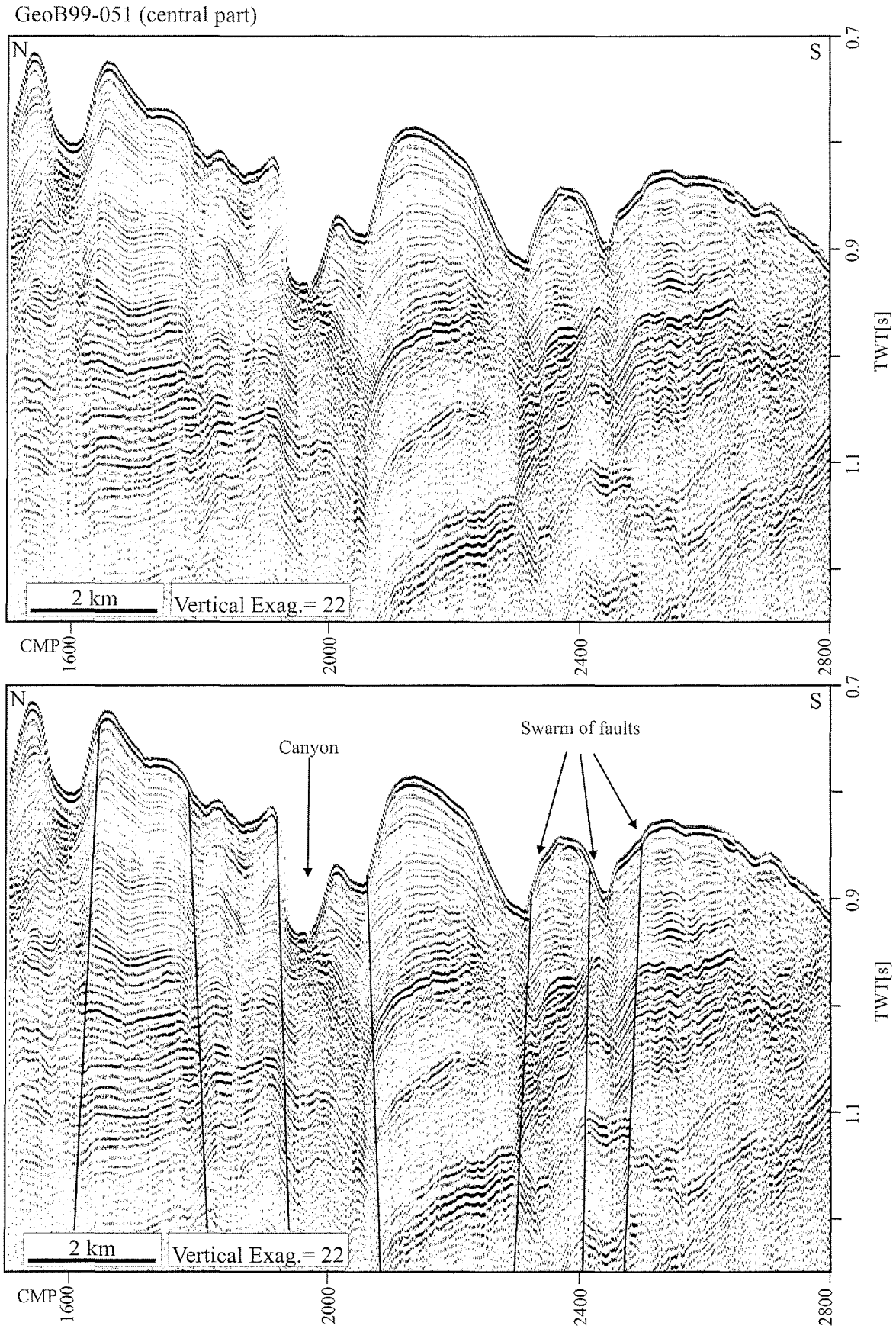


Fig. 3.6: *Closeup of the central part of Line GeoB99-051. The location of the closeup is shown in Fig. 3.5.*

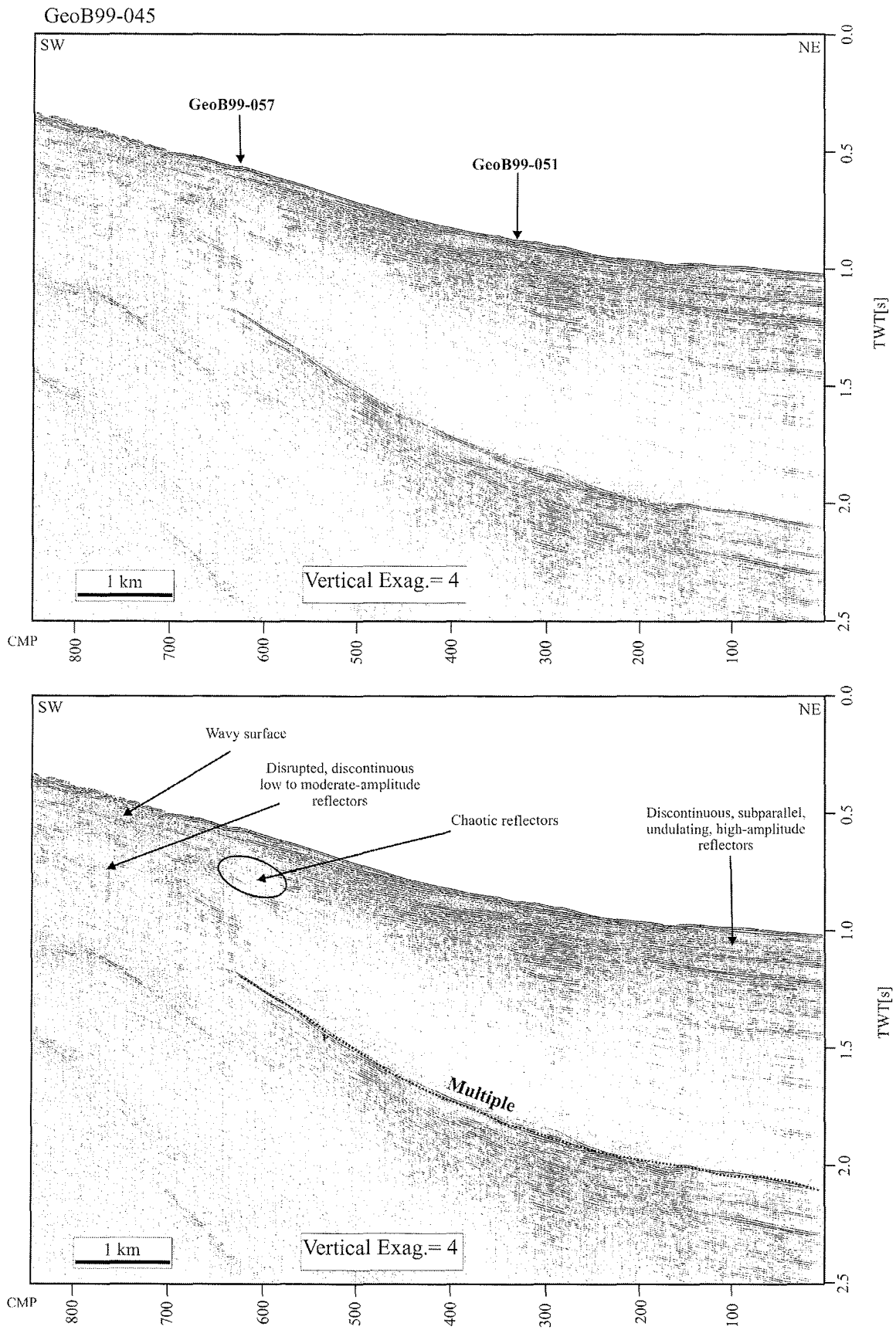


Fig. 3.7: *Seismic image and interpretation of Line GeoB99-045. The location of the profile is shown in Fig. 3.2.*

incline towards the basin, are intercalated with transparent or low-amplitude chaotic reflectors. The southwestern part of the line reveals an irregular surface.

The seismic reflection Line GeoB99-046 (Fig. 3.8) is located further to the south and closer to the center of the fan but still north of the mouth of the wadi. It shows continuous to discontinuous reflectors of low to moderate-amplitude at the western side; amplitudes and the continuity increase towards the basin. The reflectors diverge towards the basin and are interrupted by faults, which are associated with a wider zone of low reflectivity, possibly indicative of a small angle between the fault plane and the strike of the seismic line. Some slumps, characterized by a chaotic reflection pattern, are identified on this profile.

The seismic reflection Profile GeoB99-047 (Fig. 3.9) is located close to the mouth of the wadi, though it is not located in direct continuation of the wadi, but on a ridge located slightly to the north (Fig. 3.2). This profile shows continuous to discontinuous moderate-amplitude reflectors but in some places, groups of moderate to strong reflectors can be observed especially towards the basin. The upper reflectors show pinch-out and onlap structures. Truncation of the reflectors at the sea floor is found between CM 150 and 200 upslope of the onlap structure. The reflectors might be truncated due to a recent slide with a slide plane now exposed at the sea floor. The transparent zone between CMPs 200 and 350 about 150 ms beneath the sea floor is probably caused by an older buried slump. The base of the slump could not be identified due to interference with the multiple but its thickness is at least 200 ms TWT corresponding to 160 m when using a sediment velocity of 1600 m/s. Minor indications for faulting were found in this profile.

The seismic reflection Line GeoB99-048 (Fig. 3.10) also starts very close to the mouth of the wadi, but its orientation is NW-SE, hence most of the profile is clearly south of the wadi mouth (Fig. 3.2). This profile shows a vertical variation of the reflection patterns, which can be used to infer possible lithofacies types. According to the character of the reflectors, we can divide it vertically into two units. The lower unit is characterized by discontinuous low-amplitude reflections and is separated from the upper unit by a conformable surface. In contrast, the upper unit comprises parallel continuous, moderate to high-amplitude reflectors at its base, grading vertically into moderate-amplitude reflectors with varying continuity. Chaotic sediments can be identified at the northwestern end of the profile. The amplitudes are generally higher in the more distal parts of the profile.

Seismic reflection Profile GeoB99-056 (Fig. 3.11) is located south of the central fan area. It shows irregular subparallel to contorted and low to moderate-amplitude reflectors.

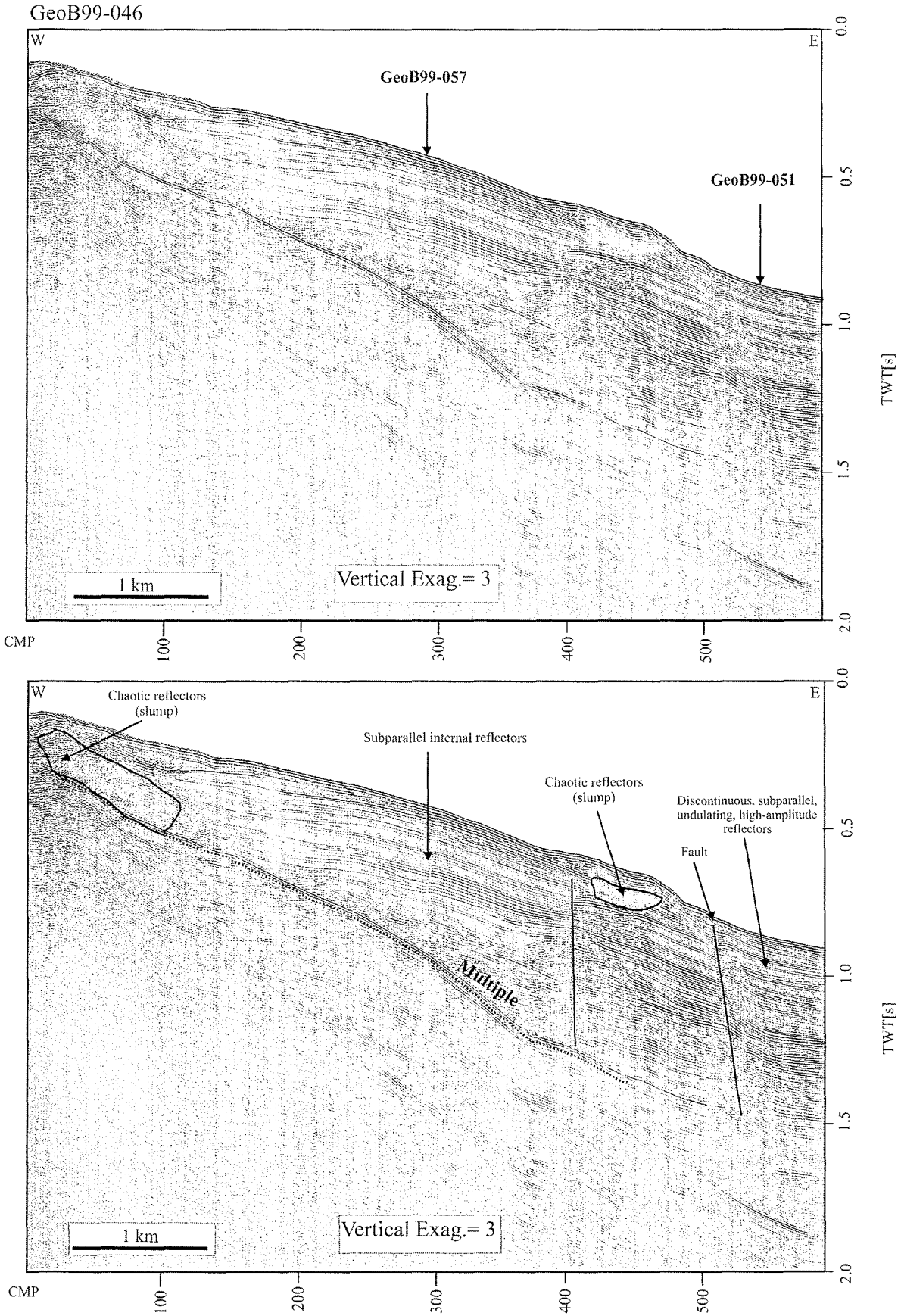


Fig. 3.8: *Seismic image and interpretation of Line GeoB99-046. The location of the profile is shown in Fig. 3.2.*

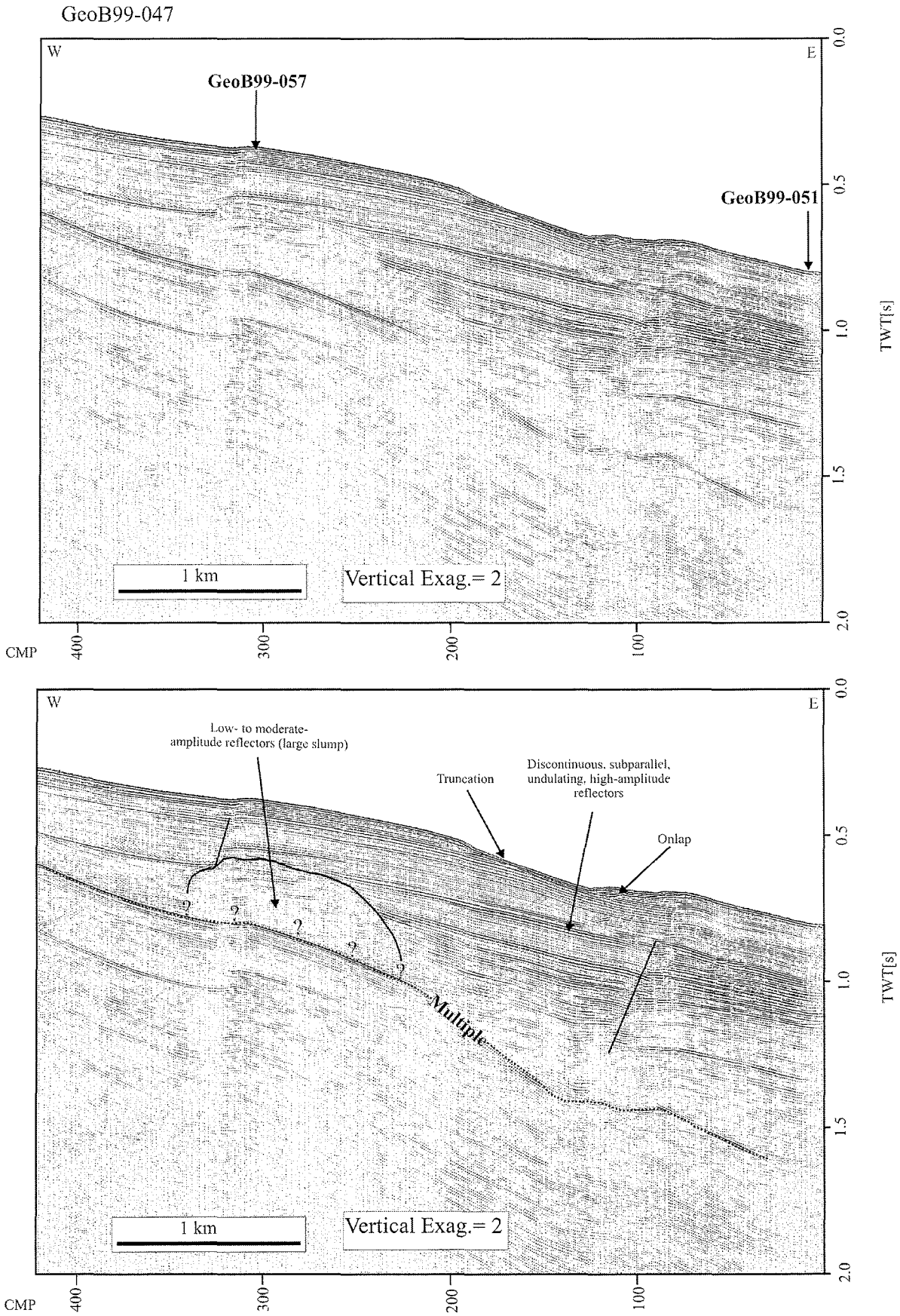


Fig. 3.9: *Seismic image and interpretation of Line GeoB99-047. The location of the profile is shown in Fig. 3.2.*

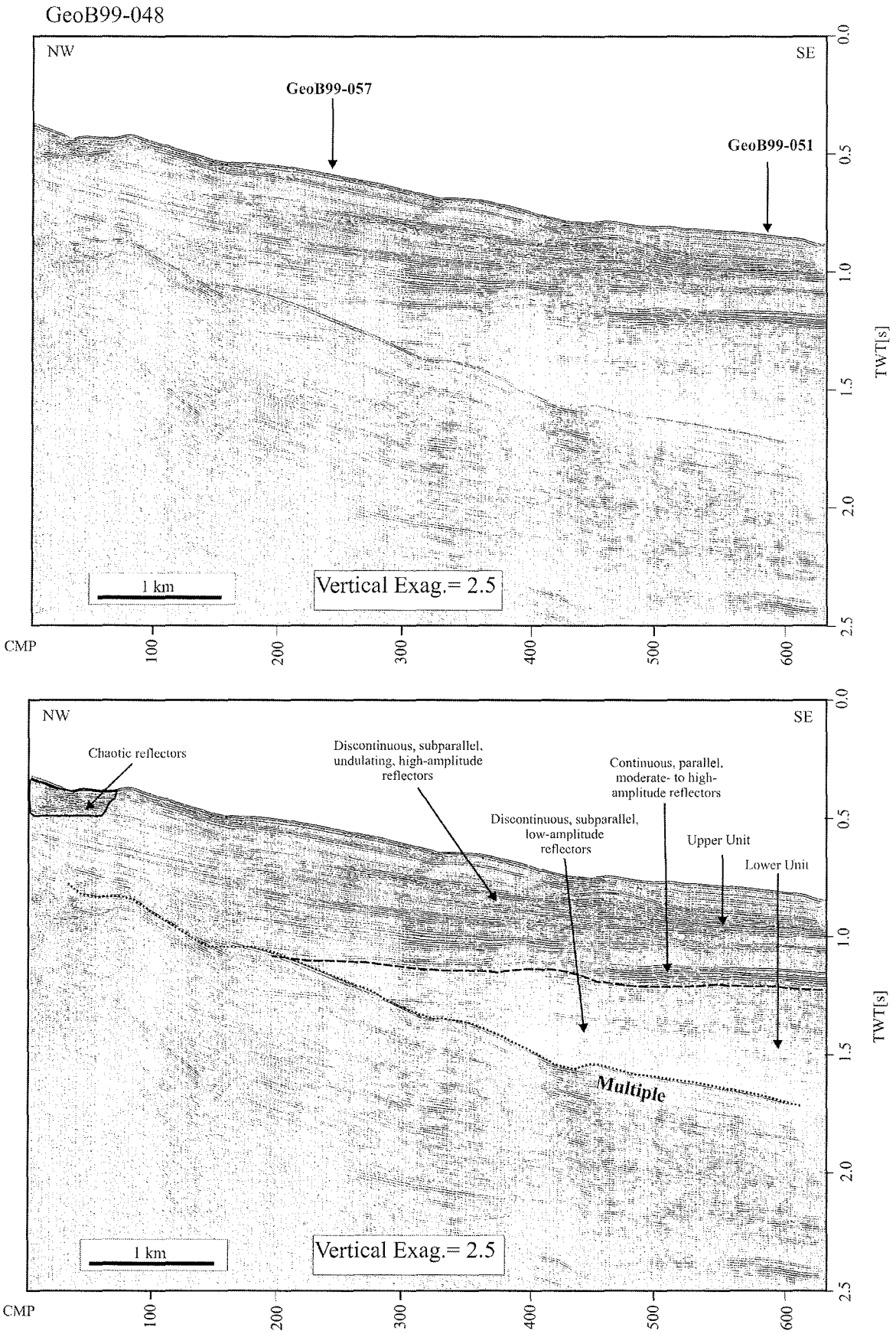


Fig. 3.10: *Seismic image and interpretation of Line GeoB99-048. The location of the profile is shown in Fig. 3.2.*

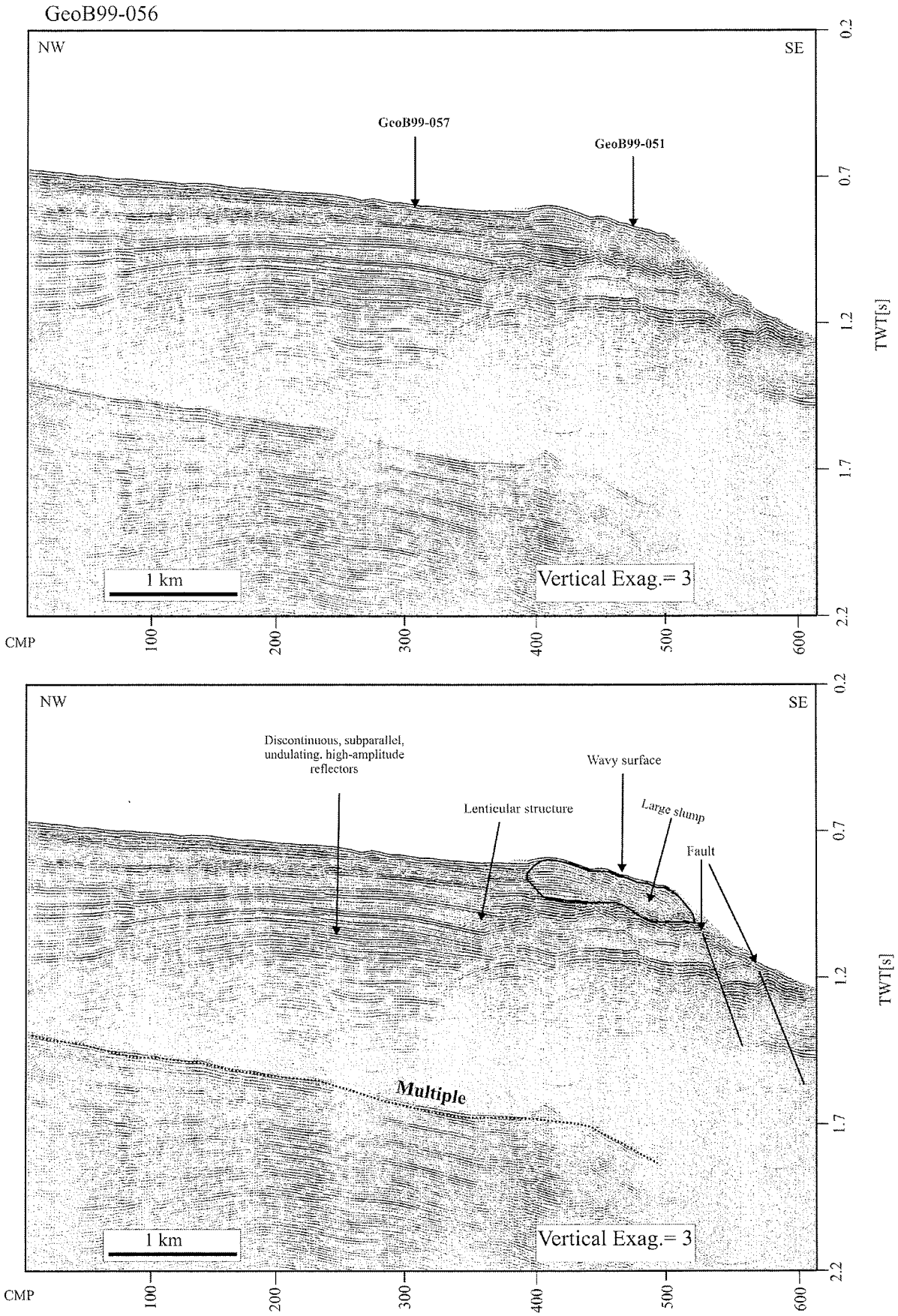


Fig. 3.11: *Seismic image and interpretation of Line GeoB99-056. The location of the profile is shown in Fig. 3.2.*

These reflectors increase in amplitude towards the upper slope. The upper part of the profile is composed of moderate amplitude reflectors intercalated with low-amplitude (transparent) reflectors. The relative large slope angle at the southeastern side of the profile marks the transition to one of the deep basins of the Gulf of Aqaba (Fig. 3.2). This transition is accompanied by faults. It is interesting to notice that a large slump block is located at the transition between the relative flat sea floor and the steeper slope. The cross-profile GeoB99-051 (Fig. 3.5) indicates that this slump block is related to a canyon located south of Line Geob99-056 and not to the transition to the deep basin.

It is difficult to correlate reflectors between the profiles because large canyons are located between them, and the reflection patterns are different on the different profiles. A common feature on all profiles, however, is the increasing continuity and amplitude of the reflectors towards the basin.

3.4.2 Definition and distribution of seismic facies

The seismic survey of the submarine prolongation of Wadi Watir alluvial fan provides a relatively clear picture of the growth pattern of the fan and the different seismic reflection facies. The seismic data show different types of seismic facies, which were defined using parameters such as reflection configuration, amplitude, and external form of each seismic sequence. The definition of seismic facies follows the classification by Mitchum et al. (1977) and Piper et al. (1999). The following seismic facies were identified in the study area:

Facies 1: Disrupted, discontinuous, low to moderate-amplitude reflections. This facies is visible on Fig. 3.7, but also on all others profiles running perpendicular to the coast. This facies is predominant in the proximal fan and changes gradually into discontinuous, subparallel, undulating, high-amplitude reflections (Facies 2) towards the distal part of the fan.

Facies 2: Discontinuous, subparallel, undulating, high-amplitude reflections. Examples of this facies are shown on Figures 3.5 and 3.7. This facies is predominant in the distal part of the fan. Discontinuous, subparallel, low-amplitude reflections (Facies 3) are intercalated into this facies.

Facies 3: Discontinuous, subparallel, low-amplitude reflections. An example of this facies is the lower unit (LU) in Figure 3.10. This facies can also be identified in the more distal parts of the fan on Line GeoB99-051 (Fig. 3.5), where it is intercalated between discontinuous, undulating, subparallel, high-amplitude reflectors (Facies 2).

Facies 4: Continuous parallel, moderate to high-amplitude reflections. This facies is found at the base of the upper unit of Fig. 3.10. The distribution of this facies is small.

Facies 5: Continuous, subparallel to convergent, high-amplitude reflections. This facies is found on the southern flank of the fan (Fig. 3.3).

Facies 6: Hummocky high-amplitude reflections. This facies characterizes the northern flank of the fan (Fig. 3.3).

Facies 7: Chaotic reflections. Lenses of chaotic reflectors can be found all over the fan, especially close to the surface and in areas of steep slopes. They vary in amplitude from low-amplitude (Fig. 3.8) to high-amplitude (Fig. 3.10).

The submarine prolongation of Wadi Watir alluvial fan shows a very complex structure. The lateral and vertical changes are very abrupt but we see a general trend of the seismic facies as a function of distance from the coast. The proximal fan mainly consists of low to moderate-amplitude reflections with a chaotic to wavy geometry. This pattern gradually changes to discontinuous, subparallel reflections with moderate-amplitudes in the middle part of the fan. Discontinuous, undulating, subparallel, high-amplitude reflectors mainly characterize the distal part of the fan, though areas of low-amplitudes were identified as well. A clear change of seismic facies is also seen in a north-south direction parallel to the coast (Fig. 3.3, Profile GeoB99-057). The northern flank of the fan is characterized by hummocky to chaotic high amplitude reflections, while the southern flank shows continuous, subparallel to convergent, high-amplitude reflectors. The middle part of Profile GeoB99-057 (Fig. 3.3) making up the central part of the fan is characterized by subparallel, moderate-amplitude reflections which are dissected by deep canyons. The fan also shows vertical changes, as illustrated in Fig. 3.10, in which low-amplitude reflectors with varying continuity of the lower unit are overlain by moderate to high-amplitude internal reflectors with a good continuity at the base of the upper unit, which in turn gradually change to discontinuous subparallel reflectors with moderate to high-amplitudes in the upper part of the upper unit. Such changes, however, cannot be traced over a larger area, and therefore illustrate the great complexity of the fan.

3.5 Discussion

3.5.1 Seismic facies interpretation of the fan

Seven seismic facies were recorded in the survey area based on the reflection configuration, amplitude, and external form of each seismic package: 1) disrupted, discontinuous, low to moderate-amplitude reflections, 2) discontinuous, subparallel,

undulating, high-amplitude reflections, 3) discontinuous, subparallel, low-amplitude reflections, 4) continuous parallel, moderate to high-amplitude reflections, 5) continuous, subparallel to convergent, high-amplitude reflections, 6) hummocky high-amplitude reflections, and 7) chaotic reflections. We attempt to interpret these seismic facies by comparing our results with those of sediment deposits with similar depositional settings, because of the lack of stratigraphic and core data in our study area.

The most prominent seismic facies in the proximal part of the fan is Facies 1, characterized by disrupted, discontinuous, low to moderate-amplitude reflections. We interpret this facies as consisting of gravel and coarse sands. Sediments eroded in the rocky hinterland of the Sinai Peninsula are transported through the wadis during periodic flash floods. The transport energy in the wadis is very high and therefore is able to carry gravel and coarse sand to the coast. Once the sediments reach the coast, the transport energy is reduced and the coarse sediments are deposited in the proximal part of the fan, covering an area of limited spatial extent during a single flooding event. These coarse sediments cause the disrupted, discontinuous reflectors. The seismic facies in the proximal parts of the fan gradually changes to Facies 2, characterized by discontinuous, subparallel, undulating, high-amplitude reflections. The continuity of the seismic reflectors is increased in this facies, which we attribute to a fining of the sediments and their more widespread deposition. The high amplitudes, however, indicate the predominance of a relatively coarse fraction, either exclusively or by a graded bedding within turbiditic sequences. Facies 3, characterized by subparallel, low-amplitude reflections, is intercalated in the sediments of the distal fan. This facies indicates hemipelagic sedimentation and fine-grained distal turbidites (Laberg and Vorren, 1996), which is supported by previous studies of sediments close to the center of the Gulf of Aqaba (Ben-Avraham et al., 1979). The turbidites develop out of the sediments transported through the wadis into the submarine fan, but turbidity currents may also result from earthquake induced failures.

Continuous parallel, moderate to high-amplitude reflections (Facies 4) were only identified on seismic Line Geob99-048 (Fig. 3.10). The continuous, parallel reflectors indicate an undisturbed deposition of sediments, but since undisturbed deposition is an exception in Wadi Watir fan, this is probably related to local conditions. Continuous, parallel reflectors could also reflect a depositional lobe deposited by a major canyon and consisting out of stacked graded beds but we did not find a correlation between continuous parallel, moderate to high-amplitude reflections and major canyons. We would expect depositional lobes in greater distance to the coast further down the slope because most of

our profiles are recorded in areas of relatively large gradients where erosion and not deposition is the predominant process in the canyons.

The southern and northern flanks of the fan differ significantly from each other. The southern flank is characterized by continuous, subparallel to convergent, high-amplitude reflections (Facies 5), while hummocky high-amplitude reflections (Facies 6) predominate the northern flank. These differences are probably caused by the different morphology of the flanks. The southern flank of the fan is characterized by relatively low slope angles allowing undisturbed sedimentation. The sedimentation rates are increased close to the coast as clearly shown by the thickening of units towards the coast on Profile GeoB99-56 (Fig. 3.11). The northern flank of the fan is characterized by large slope angle of ~5° causing disturbance of the sediments through little slumps and slides. The difference in morphology of the slopes might be the result of the regional tectonic setting though individual processes remain unclear.

The chaotic facies (Facies 7) represents slump and slide deposits. Slumps and slides have been identified all over the fan (see below).

The analysis of the seismic facies shows that the bulk of the Wadi Watir submarine fan sediments are composed of coarse clastic materials (gravels and sand); fine sediments are rare. This indicates that the sediment source is close to the shore, and the distance and time of terrestrial transport is relatively short, hence reducing the chance for active disintegration of particles. This character enables us to classify this fan under the category of coarse-grained, sand-rich submarine systems following the scheme of Richards et al. (1998).

3.5.2 Slides and slumps in the Wadi Watir fan

The chaotic facies (Facies 7) is found all over the fan, especially close to the sea floor, and in areas of steep slopes. We interpret this facies as slope failure deposits, i.e., slides, slumps and debris flows. The largest slope failure deposit was found on Profile GeoB99-047 (Fig. 3.9) with a length of ~1.5 km and a thickness >150 m on this seismic line (see results). The sizes of most slope failure deposits, however, are much smaller and their thicknesses are significantly less than 100 m. The areal extent cannot be determined without 3D control but most slope failures cannot be traced for more than 1 km on the 2D-seismic lines (e.g. Fig 3.8). It is not possible to correlate slope failure deposits between the individual profiles. We think that slope failures occur relatively frequent, but the individual events are small.

The potential causes for instability and slope failures are numerous but not well understood. Mechanisms include, among others, erosion, sedimentation, earthquake activity, diapirism, sea level fluctuations, and wave action (Locat, 2001). We assume sedimentation, erosion and earthquakes as being the most important causes for the slides and slumps in the submarine prolongation of Wadi Watir alluvial fan.

The Gulf of Aqaba is located in a tectonically active area, where frequent small and large earthquakes occur (Ambraseys and Melville, 1989). The direct link between earthquakes and submarine slope instabilities and/or turbidity current emplacement has been widely described (Prior and Coleman, 1984; Keefer, 1994). Earthquakes have two effects on the sediments (Hampton et al., 1978). First, they induce horizontal and vertical acceleration stresses, which produce direct loading on the sediment, and second, they induce a potential buildup of fluid pressure in the sediment (Egan and Sangrey, 1978). Both factors may cause slope failures in Wadi Watir submarine fan.

Depositional and erosional processes are important for the generation of mass wasting events as well. Sediment supply is provided by few events during rainy seasons, but transport of large volume of material during these events may result in rapid loading. Such rapidly accumulated sediments associated with a lack of compaction remain relatively unstable and submarine slides or slumps may result. Erosion in the fan mainly occurs along the deeply incised canyons, where the canyon flanks become subject of failure and mass wasting due to oversteepening.

Sea level fluctuations can also be important for slope instability. Large slope failures of continental margins often occur during rising or falling sea level (Weaver et al., 1998) but slides and slumps in Wadi Watir submarine fan are small events probably not related to a changing sea level. Due to the absence of a shelf in the Gulf of Aqaba no significant amounts of sediments, which possibly could be destabilized, are exposed during sea level low stands. Therefore, sea level fluctuations can not play an important role for the generation of slope failures in the Gulf of Aqaba.

It is difficult to estimate the importance of the different causes for instability and slope failures from our data alone. The relatively small sizes of slope failure deposits suggest that most major mass wasting events are a direct result of the infrequent but rapid sediment loading, but a high proportion of mass movements probably result in initiation of channelized or unchannelized turbidites, which contribute to the distal, layered units of the fan deposits, which are indistinguishable from normal fan sedimentary sequences. Earthquakes probably play an important role in triggering the slope failures.

3.5.3 Faults and tectonic activity

Wadi Watir fan is located on the western side of the Gulf of Aqaba, which is the southern part of the Dead Sea rift, a plate boundary of the transform type. The Dead Sea rift connects the sea floor-spreading center of the Red Sea with the Zagros zone of continental collision.

Abdel Khalek et al. (1993) stated that the area occupied by the Gulf of Aqaba underwent several different deformational phases, and mentioned four tectonic stages: 1) Aquitainian-Burdigalian phase, 2) Late Middle-Late Miocene Phase, 3) Pliocene Phase, and 4) Post Pliocene-Late Holocene Phase. The first three phases were important for the initiation of the Gulf of Aqaba, while the opening of the Gulf occurred in the last phase. During the opening of the Gulf, three pull-apart basins developed along its trough and normal faults formed along its periphery. Abdel Khalek et al. (1993) also suggested that the tectonic environment prevailing during the different stages of Aqaba rifting, was caused by a transtensional movement between the Sinai and Arabian Continents. Ben-Avraham (1979) suggested that the faults in the Gulf of Aqaba are the dominant structural element being the product of rifting and continental breakup. These faults are pronounced as small and large N-S to NNE faults, cutting the Quaternary and older rock units (Abdel Khalek et al., 1993). In addition, faults are locally developed parallel to the still active strike-slip faults.

Several faults have been identified in Wadi Watir submarine fan on the new seismic data. The faults are usually inferred from reflection terminations and dip changes of reflectors. A few of the faults might show evidence of repeated movements (Fig. 3.3). Faults, which were identified at the flanks of incisions, show very small offsets of a few meters and the limited resolution of the seismic data would alternatively associate these zones with flexural deformation from beginning mass failures. Several of these vertical faults (normal and reverse) seem to be related to form graben and horst systems (Fig. 3.4).

Since the grid of seismic lines was not collected to study the tectonics of the Gulf of Aqaba, their use is limited to identify fault tectonics in particular because the fault movements are probably masked by the massive sediment input within the sedimentary fan. However, the faults identified on our profiles, may provide some insight into the mechanisms of sediment mobilization and remobilization within the fan.

Numerous submarine canyons incise the surface of the submarine fan, which are up to 130 m deep and 1.5 km wide. According to Fricke and Landmann (1983), the canyons in the Gulf of Aqaba formed during periods of glaciation, and their formation continues via

sediment-laden flows, which enter the sea during periodic flash floods. It seems that most of the canyons are associated with normal faults on both flanks (Figs. 3.4 and 3.6). If the faults were related to the regional tectonic setting, their morphological expressions at the sea floor, particularly small grabens, would be preferred pathways for the sediment-laden streams. Erosion by sediment-laden streams deepens the graben and the canyon floor is therefore the graben of a pre-defined fault system. Another explanation might be that faulting and canyon formation are contemporaneous processes due to erosion at the canyon floor and slope failures of the canyon walls. In this case the canyons accompanying the canyons would not be related to the regional tectonic. A more detailed discussion of the interaction of faults in canyons is given in Salem et al. (this thesis). Regardless of the origin of the canyons, they act as major conduits for sediment transport between the subaerial wadis and the distal parts of the submarine prolongations of the alluvial fans.

3.5.4 Evolution of the fan

The submarine prolongation of Wadi Watir alluvial fan is mainly characterized by coarse sediments, numerous small slides and slumps, and deep canyons. The distribution of the seismic facies indicates a close interaction between deposition and erosion.

The analysis of our new high-resolution multi-channel seismic and bathymetric data significantly improved the knowledge of depositional and erosional processes during the formation of the submarine prolongation of Wadi Watir alluvial fan. Our new results in combination with previous studies (Abdel Khalek et al., 1993; Ben-Abraham et al., 1979) allow to draw a picture of the major events during the growth of the submarine fan. Beginning in Pleistocene time (Ben-Avraham et al., 1979), the fan was fed through Wadi Watir which delivered its deposits from basement and sedimentary rocks eroded on the Sinai Peninsula. The sediments, which were collected in Wadi Watir, mainly consist of gravel and coarse sand. Due to short transport distances, the grain sizes were not significantly reduced during transportation to the coast. Parts of the sediments were deposited on subaerial alluvial fans, but most sediments entered the sea and built up the submarine prolongation of the alluvial fan.

The sediments of the proximal part of the submarine fan mainly consist of coarse gravels and sands. Sediment transport in submarine fans might be channelized or unchannelized. Channelized transport traps the sediments in the canyons. Such a mechanism results in bypassing of coarser sediments in an energy-efficient mode into the distal fan and basins while finer sediments spill over during transport resulting in

widespread deposition of the finer sediments from the upper slope down the distal fan. Bypassing of coarser sediments is observed for many large deep-sea fans, e.g. Amazon and Bengal fan (e.g. Hiscott et al., 1997; Weber et al., 2003; Schwenk et al., 2003). Unchannelized flows spread over a larger area and the coarsest sediments were deposited first when the transport energy decreases (Normark and Piper, 1991). The setting at the submarine prolongation of Wadi Watir alluvial fan is different compared to large deep-sea submarine fans, i.e. slope angles are larger and transport distances are shorter, but we think that the general processes are the same. In principle, we observe two different transport mechanisms of equal importance building up slope and fan sediments, i.e. unchannelized and channelized transport of terrigenuous material. Unchannelized flow of sediments is probably important for the buildup of the proximal fan mainly composed of coarse sand and gravel. Accumulation rates from this process decrease with increasing transport distance. Finer proportions of the transported sediments may generate turbiditic flows. Channelized transport causes bypassing of coarse sediments and bring significant amounts of coarse sediment into the deeper fan. In addition, the proportion of fine material from channelized and unchannelized turbidites increases, which is consistent with our observations that the average grain size decreases with increasing distance to the coast. Hemipelagic sediments are intercalated into coarser fan deposits in the distal fan.

Sedimentation rates slightly increase on the lower slope as illustrated by a thickening of sedimentary units on the seismic lines perpendicular to the coast (e.g. Figs 3.8, 3.9) but a significant amount of the sediments is deposited on the upper slope. Based on the thickness of the seismic units, we estimate that deposition of sediments on the upper slope by unchannelized flow make up ~30-40% of the fan sediments. The canyons are the preferred pathways for sediment mass flows into the lower fan and the basins. We assume that turbidity currents form in the canyons and efficiently transport both fine and coarse sediments into the distal part of the fan and in the basins, most likely producing graded bedding and associated high reflection amplitudes and significant reflector continuity.

Small slumps and slides were identified all over the fan. Most of the mass wasting events are probably a direct result of the rapid sediment loading. Earthquakes may play an important role for the triggering of mass wasting events, although direct indication is lacking due to the limited coverage of the seismic data in the region. The key features of the submarine prolongation of the Wadi Watir alluvial fan are summarized in Fig. 3.12.

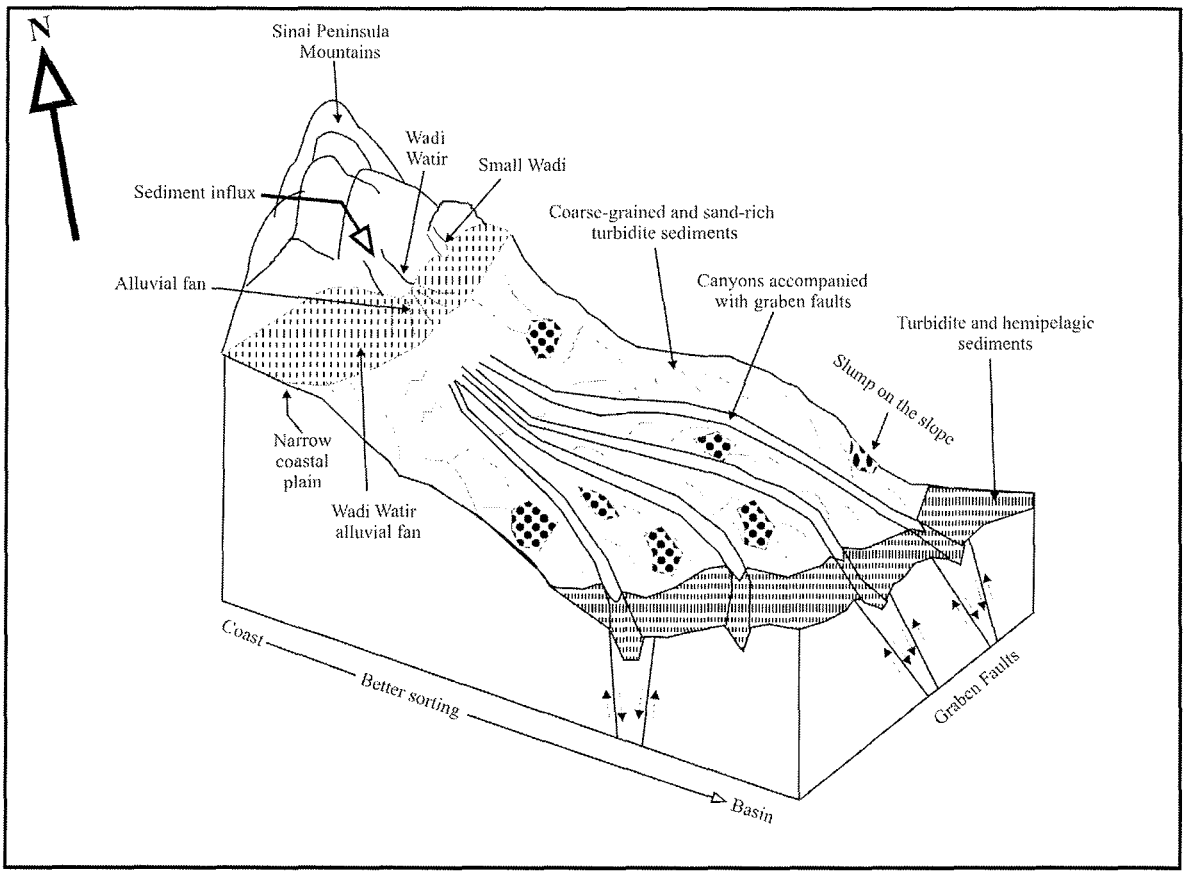


Fig. 3.12: *Schematic model showing the Pleistocene-Quaternary processes in the submarine prolongation of Wadi Watir alluvial fan.*

The amount of sediments transported through Wadi Watir to the submarine fan is basically controlled by climate. The present climate is dry, but occasional heavy rains result in flash-floods, which carry sediments to the submarine prolongation of the alluvial fan. During glacial times, the climate used to be wetter (Herman, 1965) and more sediments were transported to the fan. Some of the seismic lines indicate a cyclicity of the reflectors between stronger and weaker amplitudes, and it might be speculated that they are the result of such climatic changes, although stratigraphic and age control through drill holes is lacking. Sea level fluctuations probably play only a minor role for sediment transport into the submarine fan. No shelf or major coastal plain exists in the Gulf of Aqaba and sediment transport from land to the sea is probably not strongly influenced by changes in the sea level.

3.6 Conclusion

- Newly collected bathymetric and high-resolution seismic data allowed studying the sedimentary structure and evolution of the submarine prolongation of Wadi Watir alluvial fan.
- Wadi Watir fan is built up by sediments, which were eroded in the rocky hinterland of the Sinai peninsula and transported through Wadi Watir into the submarine fan during periodic flash floods or periods of wetter climate.
- The fan is mainly composed of coarse gravel and sand. The grain size decreases with increasing distance from the coast. The submarine Wadi Watir fan system can be characterized as coarse-grained, sand-rich turbidite system.
- Unchannelized sediment transport significantly contributes to the buildup of the submarine prolongation of Wadi Watir alluvial fan. We estimate that deposition of sediments on the upper slope by unchannelized flow make up ~30-40% of the fan sediments.
- Numerous V-shaped canyons are the most prominent morphological feature of the fan. The canyons are bounded by graben faults. The canyons are important pathways for coarse and fine sediment transported from land into the distal parts of the fan and the deep basins in the center of the Gulf.
- Abundant small slides and slumps were identified in the submarine fan. Most of the slides and slumps are a direct result of the infrequent but rapid sediment loading. Earthquakes probably play an important role in triggering the slope failures.

Acknowledgements

We wish to thank the Crew of R/V Meteor Cruise M44/3. We are grateful to our colleagues from the Bremen University - Marine Technology/Environmental Research, for fruitful discussions and the most valuable help. The work is part of the Red Sea Program (RSP II), funded by the Ministry of Higher Education of Egypt.

References

Abdel Khalek, M.L., Abdel Wahed, N. and Sehim, A.A., 1993, Wrenching deformation and tectonic setting of the northwestern part of the Gulf of Aqaba. Geological Society of Egypt Special Publication, 1, 409-444.

Alves, T.M., Gawthorpe, R.L., Hunt, D., Hunt, D.W. and Monteiro, J.H., 2002, Cenozoic tectono-sedimentary evolution of the western Iberian margin. Marine Geology, 3267, 1-34.

Ambraseys, N.N., and Melville, C.P., 1989, Evidence for interplate earthquakes in northwest Arabia. Bulletin of the Seismological Society of America, 79, 1279-1281.

Badawy, A. and Horvath, F., 1999, The Sinai subplate and tectonic evolution of the northern Red Sea region. Geodynamics, 27, 433-450.

Bayer, H.J., Hötzl, H., Jado, A.R., Roscher, B., and Voggenreiter, W., 1988, Sedimentary and structural evolution of the northwest Arabian Red Sea margin. Tectonophysics, 153, 137-151.

Ben-Avraham, Z., Almagor, G. and Garfunkel, Z., 1979, Sediments and structure of the Gulf of Aqaba - Northern Red Sea. Sedimentary Geology, 23, 239-267.

Ben-Menahem, A., Nur, A. and Vered, M., 1976, Tectonics, seismicity and structure of the Afro-Eurasian junction-the breaking of an incoherent plate. Physical of the Earth and Planetary Interiors, 12, 1-50.

Bouma, A.H., 2000, Fine-grained, mud-rich turbidite systems: model and comparison with coarse-grained, sand-rich systems. In: Bouma, A.H. and Stone, C.G. (eds.), Fine-Grained Turbidite Systems. Americal Association of Petroleum Geologists Memoir, 68, 9-20.

Bouma, A.H., Normark, W.R. and Barnes, N.E., 1985, Submarine fans and related turbidite systems. Springer, New York, pp 351.

Caress, D.W. and Chayes, D.N., 1996, Improved processing of Hydrosweep DS multibeam data on the R/V Maurice Ewing, Marine Geophysical Researches, 18, 631-650.

Carr, M. and Gardener, M.H., 2000, Portrait of a basin-floor fan for sandy deepwater systems, Permian lower Brushy Canyon formation, west Texas. In: Bouma, A.H. and Stone, C.G. (eds.), Fine-Grained Turbidite Systems, Americal Association of Petroleum Geologists Memoir, 68, 215-232.

Feeley, M.H., Buffler, R.T. and Bryant, W.R., 1985, Depositional units and growth pattern of the Mississippi fan. In: Bouma, A.H., Normark, W.R. and Barnes, N.E. (eds.), Submarine Fans and Related Turbidity Systems. Springer, New York, pp 253-257.

Freund, R. and Garfunkel, Z., 1976, Guide book to excursion along the Dead Sea rift. Department of Geology, Hebrew University of Jerusalem, pp 43.

Fricke, H.W. and Landmann, G., 1983, On the Origin of Red Sea Submarine Canyons. Naturwissenschaften, 70, 195.

Garfunkel, Z., 1970, The tectonics of the western margins of the Southern Arava. Department of Geology, Hebrew University of Jerusalem, pp 204.

Grant, J.A. and Schreiber, R., 1990, Modern swath sounding and sub-bottom profiling technology for research applications: the Atlas Hydrosweep and Parasound systems. Marine Geophysical Researches, 12, 9-19.

Hall, J. and Ben-Avraham, Z. 1978, New bathymetric map of the Gulf of Aqaba. 10th International Congress on Sedimentology, 1: 285.

Hampton, M.A., Bouma, A.H., Carlson, P.R., Molnia, B.F., Clukey, E.C. and Sangrey, D.A., 1978, Quantitative study of slope instability in the Gulf of Alaska. Proceedings Offshore Technology Conference, 10, 2307-2318.

Herman, Y., 1965. Evidence of climatic changes in Red Sea cores. In: Means of correlation of Quaternary successions. Int. Assoc. Quaternary Research, 7th Cong. Proc. 8, 325-348.

Hiscott, R.N., Hall, F.R. and Pirmez, C., 1997, Turbidity current overspill from the Amazon channel: Texture of the silt/sand load, paleoflow from anisotropy of magnetic susceptibility and implications for flow processes. In: Flood, R.D., Piper, D.J.W., Klaus, A. and Peterson, L.C. (eds.), Proceedings of the ODP, Scientific Results, 155, Ocean Drilling Program, College Station, TX, pp. 53-78.

Keefer, D.K., 1994, The importance of earthquake-induced landslides to long-term slope erosion and slope-failure hazards in seismically active regions. Geomorphology, 10, 265-284.

Laberg, J.S. and Vorren, T.O., 1996, The Middele and Late Pleistocene evolution of the Bear Island Trough Mouth Fan. Global and Planetary change, 12, 309-330.

Locat, J., 2001, Instabilities along ocean margins: a geomorphological and geotechnical perspective. Marine Petroleum Geology, 18, 503-512.

Mitchum, R.M. Jr., Vail, P.R. and Sangree, J.B., 1977, Stratigraphic interpretation of seismic reflection patterns in depositional sequences. In: Payton, C.E. (ed.), Seismic Stratigraphy-Application to Hydrocarbon Exploration. American Association of Petroleum Geologists, 26, 117-134.

Mutti, E. and Normark, W.R., 1991, An integrated approach to the study of turbidite systems. In: Weimer, P. and Link, M.H. (eds.), Seismic Facies and Sedimentary Processes of Submarine Fans and Turbidite Systems. Springer, New York, pp. 75-106.

Normark, W.R. and Piper, D.J., 1991, Initiation processes and flow evolution of turbidity currents: implications for the depositional record. In: Osborne, H.R. (ed.), From shoreline to abyss: contributions in marine geology in honor of Francis Parker Shephard, SEPM Special Publication, 46, 207-230.

Piper, D.J.W., Hiscott, R.N. and Normark, W.R., 1999, Outcrop-scale acoustic facies analysis and latest Quaternary development of Hueneme and Dume submarine fans, offshore California. Sedimentology, 46, 47-78.

Posamentier, H.W., Erskine, R.D. and Mitchum Jr, R.M., 1991, Models for submarine fan deposition within a sequence stratigraphic framework. In: Weimer, P. and Link, M.H. (eds.), Seismic Facies and Sedimentary Processes of Submarine Fans and Related Turbidite Systems. Springer, New York, pp. 127-136.

Prior, D.B. and Coleman, J.M., 1984, Submarine slope instability. In: Brundsen, D. and Prior, D.B. (eds.), Slope Instability. Wiley, New York, pp. 419-455.

Richards, M., Bowman, M., and Reading, H., 1998, Submarine-fan systems I: characterization and stratigraphic prediction. Maraine Petroleum Geology, 15, 689-717.

Salem, M., Krastel, S., Spieß, V., Hübscher, C., 2003. Influnce of tectonics on the origin of canyons in submarine prolongations of alluvial fans into the Gulf of Aqaba-Red Sea, this thesis.

Schwenk, T., Spieß, V. Hübscher, C., Breitzke, M., 2003, Frequent channel avulsions within the active channel-levee system of the middle Bengal Fan-an exceptional channel-levee development derived from Parasound and Hydrosweep data. Deep-Sea Reseacrh, 50, 1023-1045.

Stelting, C.E., Bouma, A.H. and Stone, C.G., 2000, Fine-grained turbidite systems. In: Bouma, A.H. and Stone, C.G. (eds.), Fine-grained turbidite systems. Americal Association of Petroleum Geologists, 68, 1-8.

Stockwell, J.W., 1997, Free software in education: A case study of CWP/SU: Seismic Un*x, Leading Edge, 16, 1045-1049.

Weaver, P.P E., Jarvis, I., Lebreiro, S.M., Alibés, B., Baraza, J., Howe, R., and Rothwell, R.G., 1998, Neogene turbidite sequence on the Madeira Abyssal Plain: Basin filling and diagenesis in the deep ocean. In: Waever, P:P:E:, Schincke, H.-U., Firth, J:V:, Duffield, W. (eds.), Proceedings of the ODP, Scientific Results, 157, Ocean Drilling Program, College Station, TX, 619-634.

Weber, M.E., Wiedecke-Hombach, M., Kudrass, H.R., and Erlenkeuser, H., 1997, Bengal Fan sediment transport activity and response to climate forcing inferred from sediment physical properties. Sedimentary Geoleology, 155, 361-381.

Wessel, P. and Smith, W.H.F., 1998, New, improved version of Generic Mapping Tools released. EOS Transactions. Amrican Geophysical Union, 79, 579.

Zak, I. and Freund, R., 1966, Recent strike-slip movement along the Dead Sea rift. Israel Journal of Earth Science, 15,33-37.

CHAPTER FOUR

Influence of tectonics on the origin of canyons in submarine prolongations of alluvial fans in the Gulf of Aqaba-Red Sea

(To be submitted to Geo-Marine Letters)

M. Salem[1], S. Krastel[1], V. Spieß[1], C. Hübscher[2]

[1]*Department of Geosciences, University of Bremen, PO Box 33 04 40, D-28334 Bremen, Germany.*

[2]*Institute of Geophysics, Hamburg University, Bundesstr. 55, 20146 Hamburg. Germany.*

msalem@uni-bremen.de

Influence of tectonics on the origin of canyons in submarine prolongations of alluvial fans in the Gulf of Aqaba-Red Sea

M. Salem[1], S. Krastel[1], V. Spieß[1], C. Hübscher[2]

[1]*Department of Geosciences, University of Bremen, PO Box 33 04 40, D-28334 Bremen, Germany. Email:* msalem@uni-bremen.de

[2]*Institute of Geophysics, Hamburg University, Bundesstr. 55, 20146 Hamburg.*

Abstract

The submarine prolongations of alluvial fans along the western side of the Gulf of Aqaba are dissected by numerous canyons which differ in size and number from fan to fan. Bathymetric, Parasound and multichannel seismic reflection profiling data enable us to understand the morphology and the origin of these canyons. The canyons are up to ~130 m deep and ~1.5 km wide, and have mainly V-shaped cross-sections with steep slopes; only a few canyons reveal an U-shaped cross-section. The canyons are straight without any major sinuosity. We postulate that the canyons develop along small depressions, which might be of tectonic origin. The depressions became deepened by further erosion during sporadic heavy rains or in periods of more humid climate. The combination of tectonics and submarine erosional processes plays an important role in the formation and evolution of the canyons and, therefore, for the evolution of the submarine prolongations of alluvial fans in the Gulf of Aqaba.

4.1 Introduction

This work aims to study the canyons which dissect the surface of the submarine prolongations of alluvial fans in the Gulf of Aqaba (Fig. 4.1). Main focus will be put on the processes being responsible for the origin and development of these canyons. We will use bathymetric maps of the submarine prolongation of Wadi Watir and Wadi Dahab alluvial fans, as well as Parasound and multichannel seismic reflection profiles crossing the canyons, to study the significant processes.

Previously, the canyons on the fans were mentioned briefly by a few authors, e.g., Ben-Abraham et al. (1979) who stated that the fans are dissected by canyons. The canyons reach depths up to 150 m, and widths up to 1.5 km. The canyons usually have V-shaped cross-section, but may rarely have flat bottoms. Reches et al. (1987) stated that the canyons of the Gulf of Aqaba may have formed during the Late Pleistocene (glacial time), when the sea level was 90 to 130 m below the present sea level, but a detailed analysis of the origin and development of the canyons has not been carried out until now.

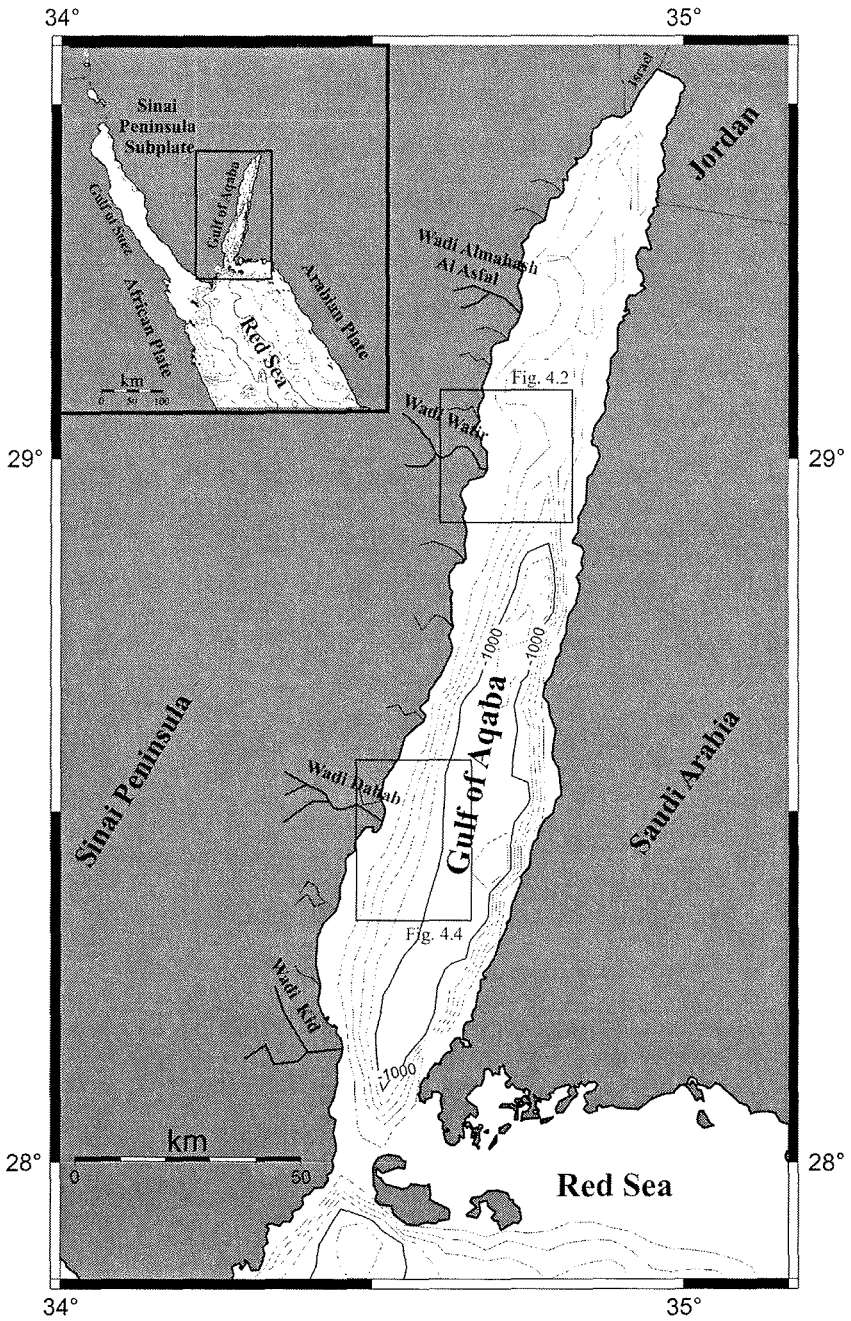


Fig. 4.1: *Overview map of the Gulf of Aqaba. The locations of the survey areas are shown by black boxes.*

4.2 Geologic setting of the Gulf of Aqaba

The Gulf of Aqaba is essentially a branch of the Red Sea (Fig. 4.1), trending N30°E. The structure of the Gulf of Aqaba is extremely complex. It is the southern part of the 1100 km long Dead Sea rift (Garfunkel, 1970). The Dead Sea rift is a plate boundary of the transform type, which connects the Red Sea where sea-floor spreading occurs, with the Zagros zone of continental collision. The fault zone is known to have produced several relatively large historical earthquakes. However, the historical events are unequally distributed along the fault (Klinger et al., 2000). The history of movement along the Dead Sea suggests that two principal phases of movement occurred. Freund and Garfunkel (1976) suggested that the first stage of slip along the Dead Sea occurred in the Early Miocene or earlier and that the second stage began in the Late Miocene or in the Pliocene. Major parts of the Dead Sea Rift are characterized by prominent morpho-tectonic depressions. The present tectonic pattern of the Dead Sea rift and its surroundings has been shaped mainly in the Late Tertiary and Quaternary periods (Eyal et al., 1981). The stratigraphy around the Gulf of Aqaba appears to lack sedimentary rocks older than the Pliocene, and is essentially bordered by shield rocks (Abdel-Gawad, 1970).

Ben-Avraham et al. (1979) stated that submarine prolongations of alluvial fans were constructed on the western coast of the Gulf of Aqaba. These fans are dissected by V-shaped steep canyons. Ben-Avraham et al. (1979) also noted that the analysis of seismic profiles in the Gulf of Aqaba appears to be very complicated, reflecting the complex tectonics of the region.

4.3 Methods

The submarine prolongations of Wadi Watir and Wadi Dahab alluvial fans in the Gulf of Aqaba were surveyed by high-resolution reflection seismics and the hydro-acoustic systems, Parasound and Hydrosweep, during R/V Meteor Cruise M44/3 in 1999. A GI-Gun (0.4 L) was used as seismic source. The signals were recorded by means of a 300-m-long streamer with 24 channels. The distance between the channels was 12.5 m; each channel consisted of only two hydrophones placed at a distance of ~0.30 m. A common mid-point (CMP) distance of 10 m was chosen for the processing of the data. Stacking of the data was followed by time migration.

All seismic profiling activities during R/V Meteor Cruise M44/3 included continuous operation of a Parasound sediment echosounder and a Hydrosweep swath sounder to determine the sea floor morphology as well as to characterize and analyze sediment

deposition processes and sediment structures. Both hydro-acoustic data sets were acquired digitally. The general purpose of the Hydrosweep system is to survey topographic features of the seafloor. A sector of 90° is covered by a swath of 59 pre-formed beams. Thus, a stripe with the width of twice the water depth is mapped perpendicular to the ship track. The data were processed with the mb-system software package (Caress and Chayes, 1996) and finally gridded with a grid-size of 70 m. The data were displayed using the Generic Mapping Tools (GMT) software (Wessel and Smith, 1991).

The Parasound system surveys the uppermost sedimentary layers of the seafloor. Due to the high signal frequency of 4 kHz, the short signal length of two sinusoidal pulses, and the narrow beam angle of 4°, a very high vertical and lateral resolution is achieved. An optimized succession of generated signals allows the resolution of small horizontal variations. The ParaDigma system (Spieß, 1993) converts the analog to digital data and stores them in a SEG-Y like format.

4.4 Results

Many canyons were identified on the submarine prolongations of Wadi Watir and Wadi Dahab alluvial fans by means of bathymetric maps and Parasound and air-gun reflection profiles. These canyons are the most prominent features shaping the upper surface of the fans. The canyons are generally straight and show no sinuosity although some of them show angular curvatures.

4.4.1 Wadi Watir canyons

The surface of the submarine prolongation of Wadi Watir alluvial fan (Fig. 4.2) is intensively dissected by canyons. The canyons are unevenly spaced and have a radial distribution. Some canyons can be traced from close to the coast to the most distal part of the mapped area. Other canyons only appear for a short stretch, and disappear where the general slope angles get small. Most canyons are V-shaped in cross section; some are up to 1.5 km wide and 130 m deep as illustrated by Parasound and seismic profiles (Fig 4.3). The largest canyon is found directly off the mouth of the present Wadi and runs in a WNE-ESE direction. Only some smaller canyons were identified south of this major canyon, but the area north of this canyon is also intensively dissected by a large number of canyons of different sizes.

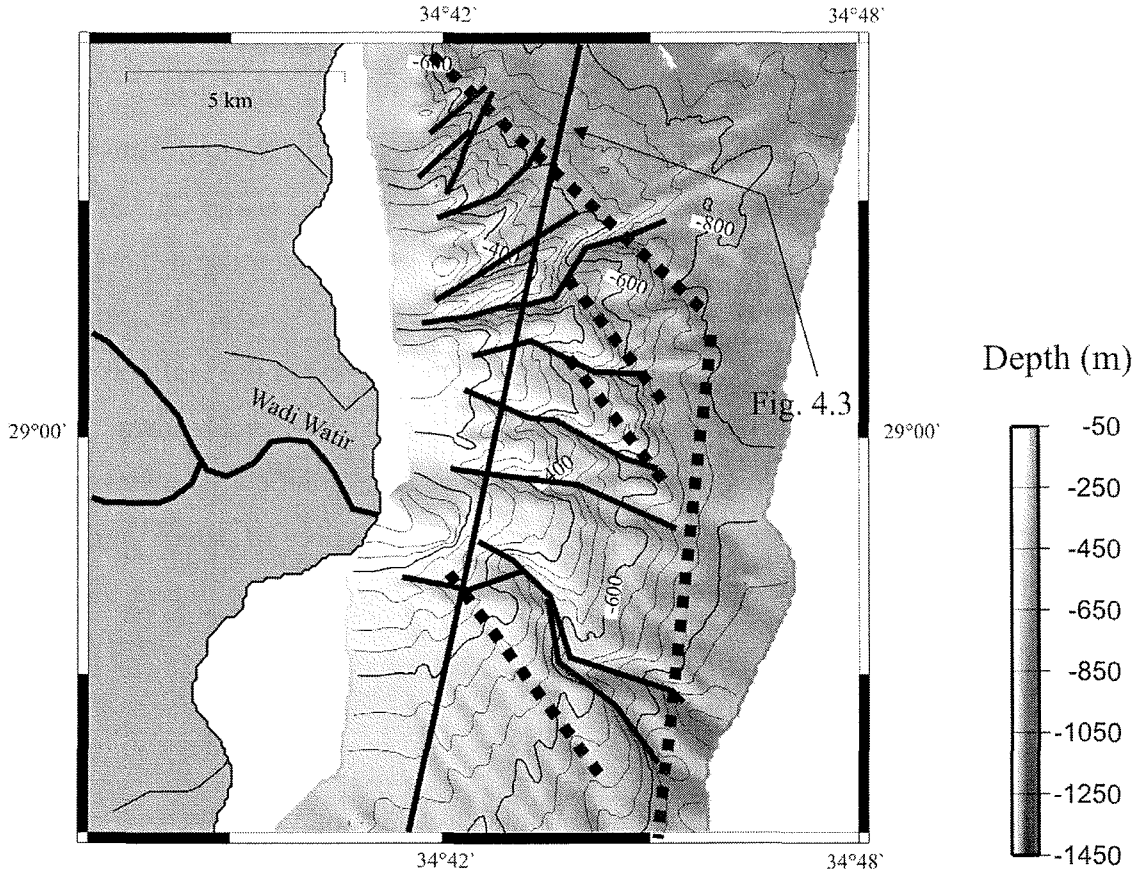


Fig. 4.2: *Bathymetric map of the central part of the submarine prolongation of Wadi Watir alluvial fan. The canyons are shown by black lines. Structural trends are indicated by dashed black lines.*

Cross sections of the canyons and sedimentary structures associated with them were imaged by Parasound and seismic profiles (Fig. 4.3). The Parasound profile show the V-shaped cross-section of the canyons. The canyons are carved in sediments characterized by a discontinuous bedded echo type. Only some short stretches of strong reflectors were imaged on the canyon floors. The seismic data (Fig. 4.3) show the deeper structure of the canyons and the surrounding sediments. The sediments between the main canyons are characterized by sub-parallel low- to moderate-amplitude reflection with varying continuity. Some transparent zones indicate the occurrence of slumps and slides. The canyons are carved into these sediments. The canyons are partially filled with deposits showing a chaotic character, but these canyon fills cannot be traced deeper. Several small faults were identified on the seismic profiles, particularly in the central part of the fan. Most of the major canyons seem to be bounded by graben faults.

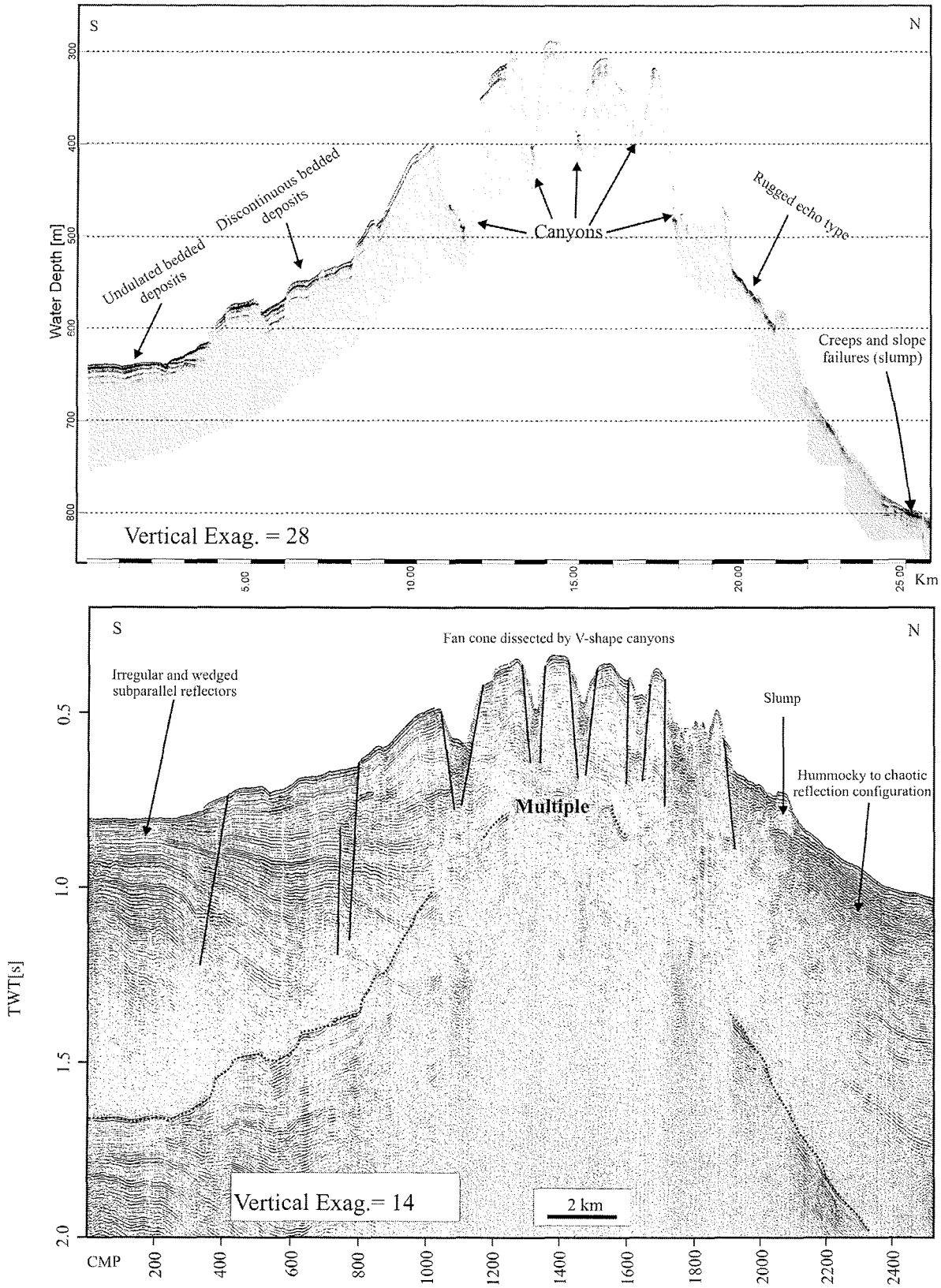


Fig. 4.3: *Parasound (top) and seismic (bottom) line Geob99-057. The location of the profile is shown in Fig. 4.2.*

4.4.2 Wadi Dahab canyons

The surface of the submarine prolongation of Wadi Dahab alluvial fan (Fig. 4.4) is also dissected by numerous canyons, but the number and the size of the canyons are smaller compared to Wadi Watir. The canyons mainly occur in a relatively small area off the wadi mouth resulting in a rough morphology. They are usually characterized by a V-shaped cross-section, and are up to 1 km wide and 100 m deep. The canyons can be traced down to a water depth of ~950 m. Nothing can be said for the area close to the coast in water depths shallower then 400 m due to the missing coverage with profiling data.

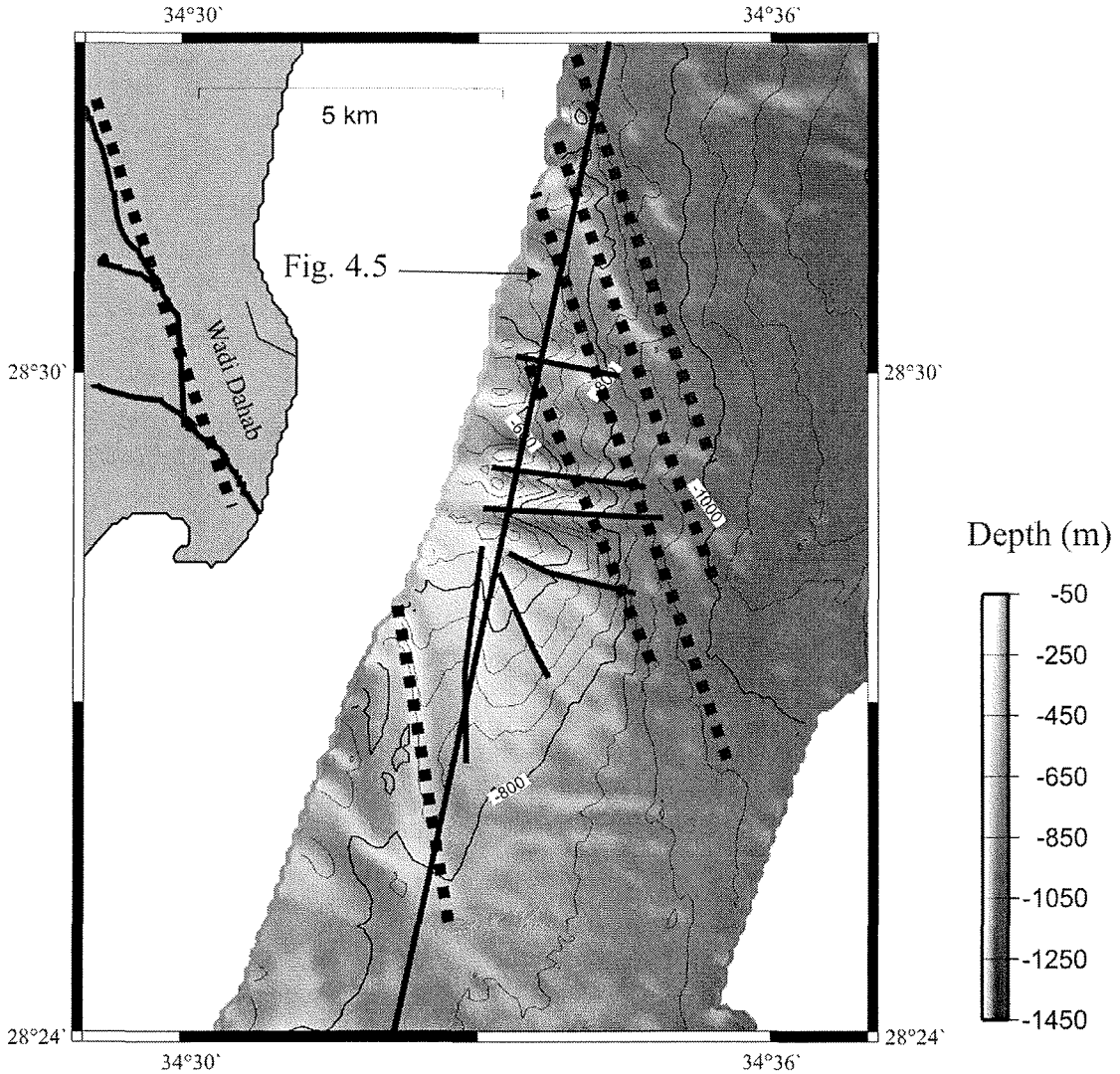


Fig. 4.4: *Bathymetric map of the central part of the submarine prolongation of Wadi Dahab alluvial fan. The canyons are shown by black lines. Structural trends are indicated by dashed black lines.*

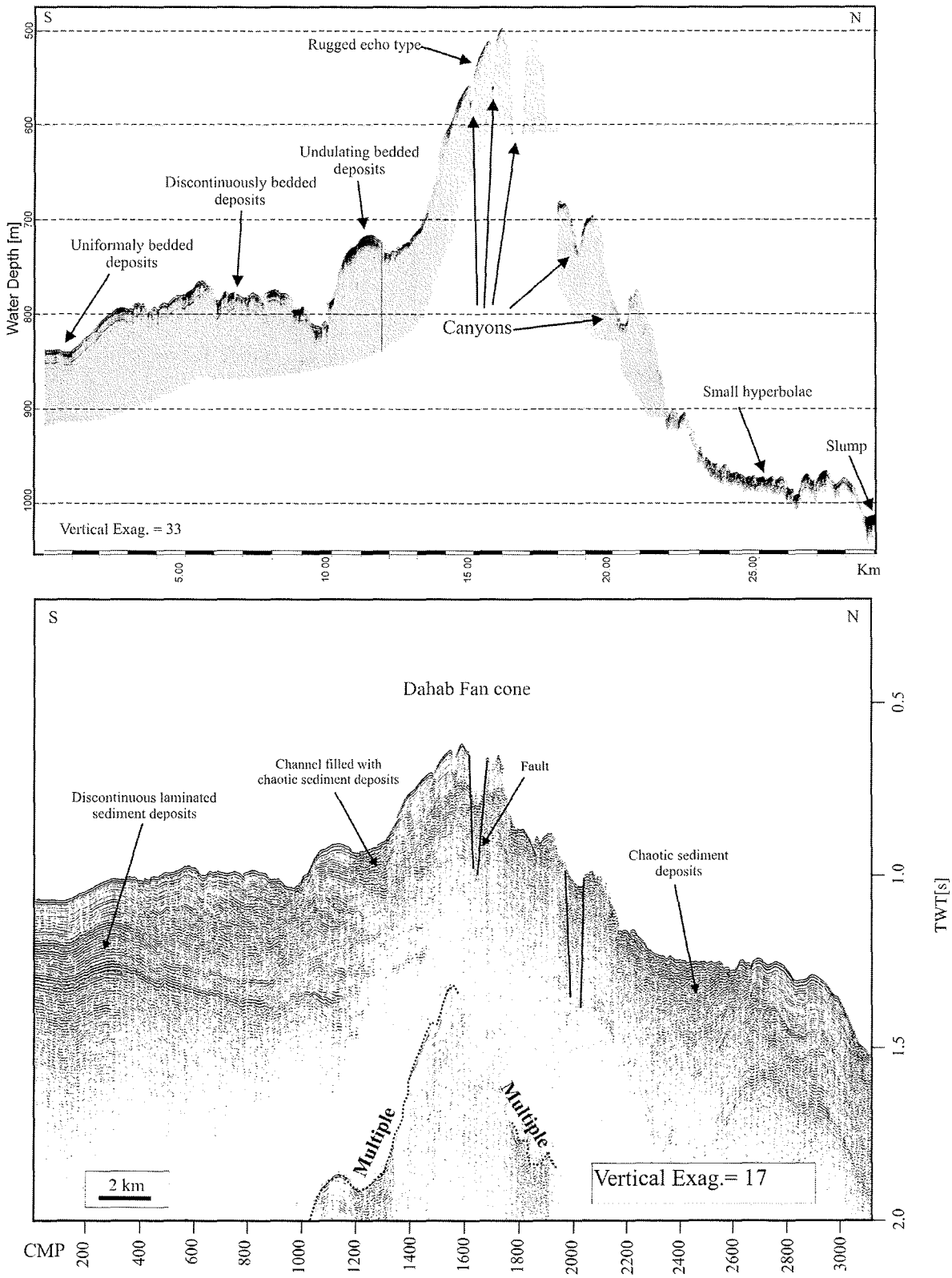


Fig. 4.5: *Parasound (top) and seismic (bottom) line Geob99-065. The location of the profile is shown on Fig. 4.4.*

The Parasound profile (Fig. 4.5) shows that the canyons are carved into sediments characterized by a rugged echo type. A single strong reflector can be seen at the base of some of the canyons. The seismic profile (Fig. 4.5) mainly shows moderate-amplitude reflections with low continuity. The canyons are partially filled with chaotic deposits. The major canyon seems to be bounded by a graben fault, but similar structures were not imaged for the smaller canyons. A canyon, almost filled with chaotic sediments, was identified around CMP 1200 on the seismic profile.

4.5 Discussion

4.5.1 Canyon forming processes

The understanding of the evolution of submarine canyons has advanced to a composite origin with various processes operating in sequence or simultaneously (Shepard, 1981; May et al., 1983). Generally, the origin of submarine canyons can be related to river incision, subaerial erosion, turbidity currents erosion, structural movements (faulting, diapirism, etc.), and biological activities. Laursen and Normark (2002) concluded that the position and configuration of submarine canyons are controlled by multiple factors, including structural fabric, tectonics, sea level variation, sediment supply, and the underlying rock type.

Multiple factors probably also controlled the formation of the canyons in the Gulf of Aqaba, and are closely related to the evolution of the fans themselves. All fans are located off major wadis. During sporadic rainy seasons or periods of wetter climate, large amounts of sediments were eroded in the hinterland of the Sinai Peninsula and collected in the wadis and transported to the coast. These sediments build up the submarine prolongations of the alluvial fans. Sediment-laden streams, developing in the wadis, probably play a key-role in the formation of the canyons.

El-Asmar (1997) stated that there are at least four major oscillations in the sea level of the Gulf of Aqaba forming four climatic periods over the Middle to Late Quaternary age, as revealed from the study of the Quaternary isotope stratigraphy and paleoclimate of coral reef terraces. These periods are of warm-wet climatic conditions, which would result in larger amounts of sediments to be transported into the submarine fans. Sea level fluctuations might be visible in the seismic data, which show a cyclic pattern at the southern side of Fig. 4.5. This pattern may indicate an alternating stratification between coarse and fine sediment deposits.

The canyons in the Gulf of Aqaba may be the result of the sea level oscillations especially during the unusual conditions that prevailed during the late Würm glaciation about 11,000 years ago. Sea level is considered to have been 130 m lower worldwide at that time; a considerable volume of water went into the formation of glacial ice (Gvirtzman et al., 1977), and therefore the base level of erosion was lowered. The climate is considered to have been more humid. The net effect of the lower base level and increased precipitation was a rejuvenation of the erosive power of running water along the Gulf.

Our investigations show that the major canyons are bounded by graben faults (Figs. 4.3 and 4.5). Two possible scenarios exist for the origin of the faults. 1) The faults might be related to the regional tectonics in the Gulf of Aqaba and predates the canyon formation. The grabens form small depressions (proto-canyons), which are the preferred pathways for sediment-laden streams. The erosive power of sediment mass flows and turbidity currents deepen the proto-canyons resulting in deep submarine canyon-systems. The location of the canyons would therefore be defined by the graben faults. 2) Depressions are formed by erosive downslope bedload transport of coarse material. Once these depressions exist, they are focusing sediment transport subsequently, and canyons evolve through erosion of the canyon floor and failures of the flanks. These processes might be accompanied by the development faults, which follow the canyon axis.

An interaction of tectonics and submarine erosion as a cause for the formation of canyons was previously interpreted for large scale canyons in several areas. For example, a tectonic control in the origin and development of a submarine canyon system was assumed by Nagel et al. (1986), who described the Ascension Submarine Canyon located along a strike-slip continental margin off central California. Liu et al. (1993) showed evidence for a combination of submarine erosional and tectonic processes being responsible for the origin and evolution of Kaoping Canyon System, southern Taiwan. Also, Monterey Canyon was shown to be influenced by the San Gregorio fault zone which diverts the canyon axis (McHugh et al., 1998) in a similar way as described by Algan et al. (2002) for the Sakarya Delta in the southern Black Sea shelf.

The canyons in the submarine prolongations of alluvial fans in our study area are much smaller, but at least some of them might have formed in a similar way, i.e., the locations of the canyons are determined by faults. Grabens and folds, with different sizes and trends, are recognized in several areas around the Dead Sea and the Gulf of Aqaba. Abdel Khalek et al. (1993) stated that many folds are associated with faults of different trends on the western side of the Gulf of Aqaba. These folds principally develop in response to the shear

stress associated with adjoining faults. The folds have planar limbs and hinges, which are mostly rounded, but may be occasionally sharp. The tight hinges are often crossed by en echelon radial fractures. The locations of the wadis are mainly controlled by the tectonics (Abdel Khalek et al., 1993).

The analysis of our new bathymetric maps of the submarine prolongations of alluvial fans reveals structural trends mainly in a NW-SE direction (Fig. 4.2 and 4.4). These trends are orientated at a 45° angle to the main strike-slip movement, which is a direction of extension in the Gulf of Aqaba (Beyer et al., 1988). If extension occurs in the fan area, we would expect the development of graben faults, which might guide the submarine canyons. A comparison of the structural trends in the fans with the orientation of the canyons show that four of the six canyons in Wadi Dahab are located almost perpendicular to the structural trends in this fan, which may be supportive for a tectonic control of the location of the canyons. Structural trends are more difficult to identify in Wadi Watir due to a thicker sediment cover, but tectonic control in this fan seems to be less pronounced. Therefore, the distribution of canyons may be a result of several factors; both structural lineation and typical radial transport and erosion pattern from sediment transport seems to be important. We think that the sediment-laden streams, traveling through the wadis, spread over a larger area close to the coast as soon as they are not constrained by the wadis. Once the sediments enter the sea, they were preferably transported downslope along pre-existing depressions, as e.g. tectonically controlled zones of weakness. A comparison with the main structural trends in the region may reveal similarities, which could well explain some of the canyon orientations to be controlled by tectonics, whereas others may just indicate an orientation along the maximum slope angle.

It is interesting to note that only very small canyons exist south of the main canyon of Wadi Watir, but several large canyons were identified further to the north. Geological maps (Geological Maps of Sinai, Arab Republic of Egypt, 1994) show that the area directly south of the Wadi is constructed by basement rocks, which are difficult to erode, while the northern part is bordered by sedimentary rocks which are more easily erodable. Sediment input in the northern submarine fan is therefore probably higher than in the south resulting in the uneven distribution of canyons off Wadi Watir. Another reason might be a second small wadi located immediately to the north of Wadi Watir. This wadi also delivers sediments into the sea, though its catchment area is much smaller.

4.5.2 Scenario for the canyon evolution

The discussion above shows that an interaction of tectonics and submarine erosion is the key factor for the evolution of the canyons on the submarine prolongations of the alluvial fans. Based on these observations, we postulate the following scenario for the origin and evolution of the canyons (Fig. 4.6):

(1) The still active tectonics, especially faulting activities, might play an important role in the origin of the canyons. Due to extension, graben faults produced small surface depressions, which can form proto-canyons.

(2) Flash floods through major and small wadis during sporadic heavy rains or during periods of wetter climate on the Sinai Peninsula transport large amounts of material from the catchment area (rocky desert of the Sinai Peninsula) into the Gulf of Aqaba. Sediment-laden streams with high erosion potential originate and develop in subaerial canyons.

(3) The sediment-laden streams spread over a larger area close to the coast as soon as they are not constrained by the wadi. These streams enter the Gulf and accelerate on the steep submarine slopes. Their preferred pathways are pre-existing depressions, such as the surface expressions of graben faults, thereby deepening these proto-canyons. Thereafter, several processes become important for continued erosion, e.g., sea level fluctuation during the Quaternary age. The activity within the incisions increased during the sea level lowstand of the Late Pleistocene (glacial time). Being the preferred path for subsequent sediment discharge, the canyon deepens to the point of oversteepened canyon walls. Failures of the canyon walls and/or floors result in sediment slides.

(4) Besides these processes, the buildup of an upper slope apron allows also a radial pattern of sediment transport pathways, following the maximum gradient, to develop and interfere with existing canyon systems.

(5) Sliding/slumping features on the canyon walls, associated with inward oriented normal or growth faults, resulted in the widening of the canyons and in the formation of U-shaped canyons.

4.5.3 Significance of the canyons

Submarine prolongations of alluvial fans were formed on the western side of the Gulf of Aqaba off major wadis. Several submarine canyons, carved into the fan, are their main morphological feature. We think that most of the canyons are active otherwise the canyons would be filled with sediments in a relatively short period of time. The canyons probably play a key-role during the evolution of the submarine fans.

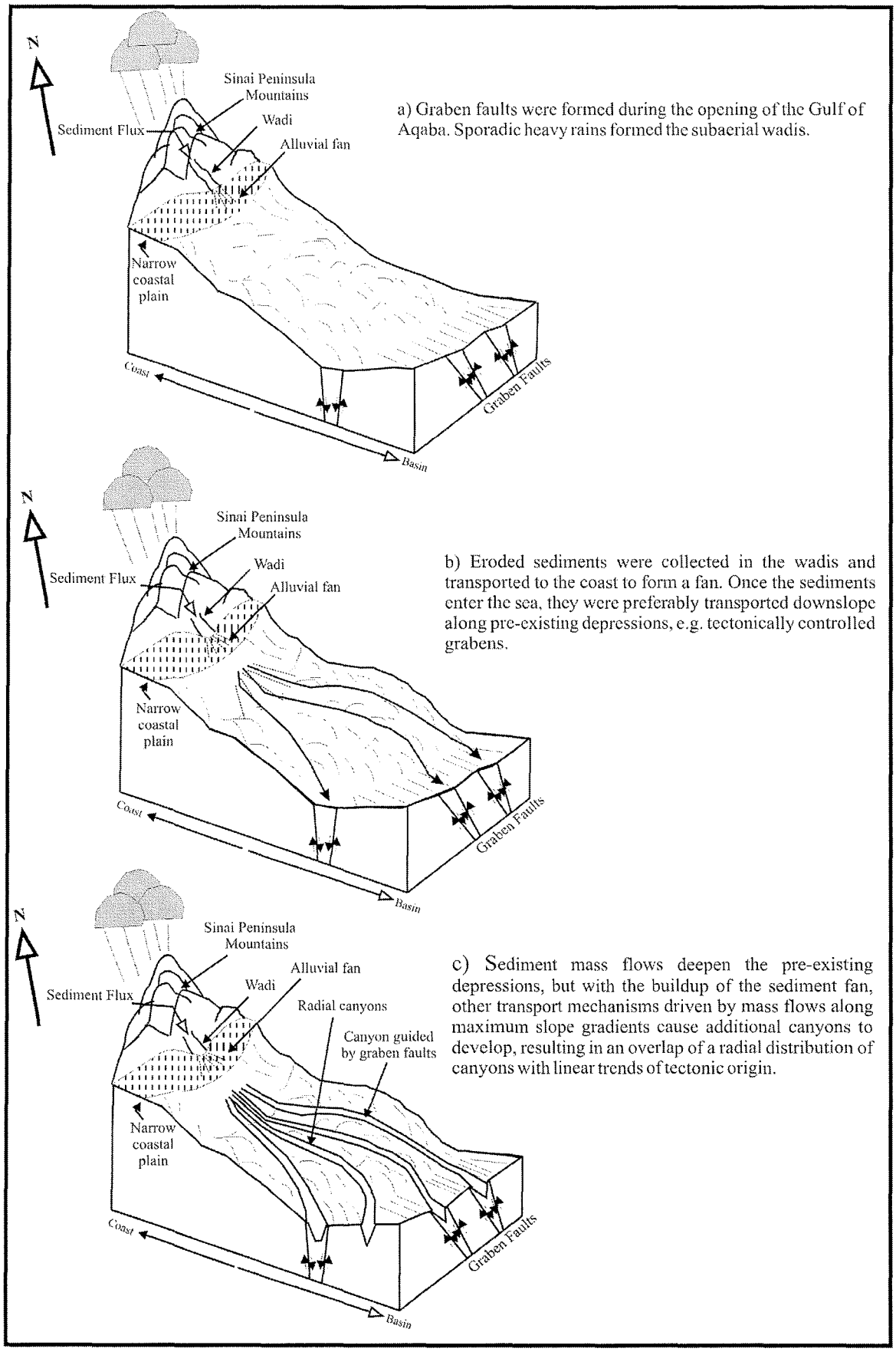


Fig. 4.6: *Sketch illustrating the origin and development of canyons in submarine prolongations of alluvial fans in the Gulf of Aqaba.*

The fans are constructed by material eroded in the hinterland of the Sinai Peninsula and transported through major wadis to the coastline. Parts of the sediments are deposited as subaerial alluvial fans but the larger part of the sediments enter the sea. The submarine slope angles are relatively large and attain average angles of 16° in the steepest parts but the shallower parts usually have average slopes of 7-11° (Ben-Avraham et al., 1979); the submarine prolongations of the alluvial fans are therefore unstable. Sediment transportation typically occurs along the submarine canyons and as individual slides and slumps. Several individual slides and slumps were identified in submarine fans of the Gulf of Aqaba, but the size of these mass wasting events is relatively small. The submarine canyons provide direct pathways for sediments and particle dispersal from the coast to the more distal parts of the fans. We are not able to identify any lobes, but we assume that relatively coarse material is concentrated at the end of the canyons, though this assumption remains speculative without additional data such as sidescan sonar images or sea floor samples. Oversteepened canyon walls are also a preferred location for sediment slumps and slides. The widening of the canyons by such mass movement is another important process for sediment transport in the submarine prolongations of alluvial fans.

In summary, we consider the canyons to play a key role for sediment transport in the submarine fans in the Gulf of Aqaba. Sediment transport mainly characterizes the evolution of all the fans. The formation of the canyons is, therefore, of highest significance for the evolution of the submarine prolongations of alluvial fans in the Gulf of Aqaba.

4.6 Conclusions

The submarine prolongations of alluvial fans in the Gulf of Aqaba are dissected by numerous V-shaped and few U-shaped canyons. The most important factor for the initiation and evolution of these canyons is an interaction of tectonics and sedimentary processes. Graben faults form zones of weakness, which in turn are forming proto-canyons. These proto-canyons are the preferred pathways for subsequent sediment mass flows, which develop in the wadis in rainy seasons and enter the sea. The sediment mass flows deepen and widen possible proto-canyons, but with the buildup of the sediment fan, other transport mechanisms driven by mass flows along maximum slope gradients, cause additional canyons to develop, resulting in an overlap of a radial distribution of canyons with linear trends of tectonic origin. Oversteepened canyon walls may cause slides/slumps and occasionally convert the cross-section of the canyons into an U-shape. The erosional power of the sediment-laden streams, developing in the wadis, is highest during periods of

wet climate and sea level low stands. The submarine canyons provide direct pathways for sediments and particle dispersal from the coast to the more distal parts of the fans, hence playing an important role during the evolution of the submarine prolongations of alluvial fans in the Gulf of Aqaba.

Acknowledgements

This study was carried out as part of the PhD thesis of M. Salem at Bremen University. Many thanks to the Crew of the R/V Meteor during Leg 3 of Cruise M44/3. We are grateful to our colleagues from the Bremen University - Marine Technology/Environmental Research, for fruitful discussions and the most valuable help. The work was funded by the Ministry of Higher Education, Egypt.

References

Abdel Khalek ML, Abdel Wahed N, Sehim AA, (1993) Wrenching deformation and tectonic setting of the northwestern part of the Gulf of Aqaba. Geological Soceity of Egypt 1: 409-444.

Abdel-Gawad M (1970) Interpretation of satellite photographs of the Red Sea and Gulf of Aden. Philosophycal Transactions, Royal Soceity, Lond 267: 23-40.

Algan O, Gökasan E, Gazioglu C, Yücel ZY, Alpar B, Güneysu C, Kirci E, Demirel S, Sari E, Ongan D (2002) A high-resolution seismic study in Sakarya Delta and submarine canyon, southern Black Sea shelf. Continental Shelf Research 22: 1511-1527.

Bayer HJ, Hötzl H, Jado AR, Roscher B, Voggenreiter W (1988) Sedimentary and structural evolution of the northwest Arabian Red Sea margin. Tectonophysics, 153: 137-151.

Ben-Avraham Z, Almagor G, Garfunkel Z (1979) Sediments and structure of the Gulf of Aqaba - Northern Red Sea. Sedimentary Geology 23: 239-267.

Caress DW, Chayes D.N (1996) Improved processing of Hydrosweep DS multibeam data on the R/V Maurice Ewing, Marine Geophysical Research 18: 631-650.

El-Asmar HM (1997) Quaternary isotope stratigraphy and paleoclimate of coral reef terraces, Gulf of Aqaba, South Sinai, Egypt. Quaternary Science Reviews 16: 911-924.

Eyal M, Eyal Y, Bartov Y, Steinitz G (1981) The tectonic development of the western margin of the Gulf of Elat (Aqaba) rift. Tectonophysics 80: 39-66.

Freund R, Garfunkel Z (1976) Guide book to excusion along the Dead Sea rift. Department of Geology, Hebrew University of Jerusalem, Israel, p.43.

Garfunkel Z (1970) The tectonics of the western margins of the Southern Arava. Thesis, Department og Geology, Hebrew University of Jerusalem, Israel, p. 204.

Gvirtzman G, Buchbinder B, Sneh A, Nir Y, Friedman GM (1977) Morphology of the Red Sea fringing reefs: a result of the erosional pattern of the last-glatial low-stand sea level and the following Holocene recolonization. Second Int. Fossil Coral Reef Symposium, Paris, Bureau de recherches géologiques et minières, 89: 480-491.

Klinger Y, Avouac JP, Dorbath L, Abou Karaki N, Tisnerat N, (2000) Seismic behavior of the Dead Sea fault along Araba Valley, Jordan. Geophysical Journal International 142 (3): 769-782.

Laursen J, Normark WR (2002) Late Quaternary evolution of the San Antonio Submarine Canyon in the central Chile forearc (~33°S). Marine Geology 188: 365-390.

Liu C, Lundberg N, Reed D, Huang, Y (1993) Morphological and seismic characteristics of the Kaoping submarine canyon. Marine Geology 111: 93-108.

May JA, Warme JE, Slater RA, (1983) Role of submarine canyons on shelfbreak erosion and sedimentation: modern and ancient examples. In: The Shelfbreak: Critical Interface on Continental Margins. Stanley DJ, Moore GT (ed), SEPM Special Publication 33: 315-332.

McHugh CMG, Ryan, WB, Eittreim, S, Reed D, (1998) The influence of the San Gregorio fault on the morphology of Monterey Canyon. Marine Geology 146: 63-91.

Nagel D, Mullins, HT, Greene G (1986) Ascension submarine canyon, California-evolution of a multi-head canyon system along a strike slip continental margin. Marine Geology 37: 285-310.

Reches Z, Erez J, Garfunkel Z (1987) Sedimentary and tectonic features in the northwestern Gulf of Aqaba. Tectonophysics 141: 169-180.

Shepard FP (1981) Submarine canyons: Multiple causes and longterm persistence. Bull. Am. Assoc. Petroleum Geology 65: 1062-1077.

Spieß V (1993) Digitale Sedimentechographie - Neue Wege zu einer hochauflösenden Akustostratigraphie. Berichte, Fachbereich Geowissenschaften, Universität Bremen 35: 1-199.

Wessel P, Smith WHF (1991) The Generic Mapping Tools technical reference and cookbook, Version 3.1, 90p.

CHAPTER FIVE

Final conclusions

and

future perspectives

5. Final conclusions and future perspectives

5.1 Final conclusions

The seismic and hydroacoustic data analyzed in this thesis document the first detailed study of the main processes that control the formation of the submarine prolongations of alluvial fans in the Gulf of Aqaba. The fans are fed by wadis, which transport eroded sediments from the Sinai Peninsula to the coast during sporadic rainy seasons or during periods of wetter climate. The confined channel flows expand as they leave the wadis and then gradually build the alluvial fans. Most of the sediments, however, enter the sea and construct the submarine prolongations of the alluvial fans. The sediments of the submarine prolongations of the alluvial fans mainly consist of coarse gravels and sands. The grain size decreases with increasing distance from the coast. Unchannelized and channelized transport of terrigenuous material is of equal importance for the buildup of the fan. Sediments transported by unchannelized flows were mainly deposited at the upper fan, while channelized flow brings significant amounts of fine and coarse sediments into the deeper fan. The channelized flows travel through several large canyons which are carved into the submarine fans. The canyons are formed by the interaction of tectonic and submarine erosional processes. Several small slumps and slides were identified all over the fan, which are most likely the results of the infrequent, but rapid, sediment loading and earthquake activity.

The main conclusions of this thesis can be summarized as follows:

(1) Submarine prolongations of alluvial fans in the Gulf of Aqaba are formed at the mouths of major wadis which deliver their deposits from eroded basement and sedimentary rocks of the Sinai Peninsula into the sea. Newly acquired seismic, sediment echosounder, and bathymetric data provided a detailed picture of the morphology and sedimentary structures of Wadi Watir, Wadi Dahab, and Ras El Burka submarine fans for the first time.

(2) Bathymetric data show that the fans extend to water depths greater than 1000 m. Slope angles in the proximal fans are large exceeding 5°. The varying volumes of the fans between <5 km^3 and ~15 km^3 are a direct result of the different sizes of the corresponding catchment area.

(3) Numerous deep canyons constitute the most prominent morphological features of the fans. The canyons are mainly characterized by steep V-shaped cross-sections. A few isolated canyons have an U-shaped cross-section. The canyons are up to 1.5 km wide

and 130 m deep. The courses of the canyons are generally straight, and show no significant meanders. The canyons are usually accompanied by faults on both flanks.

(4) Based on the combined interpretation of bathymetric, Parasound, and high-resolution seismic data a model for the canyon initiation and evolution was developed. The canyons start to evolve along small pre-existing depressions, which might be of tectonic origin. Subsequent sediment mass flows deepen and widen these depressions, but with the buildup of the sediment fan, other transport mechanisms driven by mass flows along maximum slope gradients cause additional canyons to develop, resulting in an overlap of a radial distribution of canyons with linear trends of tectonic origin. Oversteepened canyon walls may cause slides/slumps and occasionally convert the V-shaped cross-section of the canyons into an U-shape.

(5) The Parasound data allowed to identify four echo characters (rugged, hyperbolic, bedded, and partially transparent/discontinuously bedded echo characters). All echo characters are characteristic of fan sediments, except the uniformly bedded echo type which represents the basin deposits.

(6) The high-resolution seismic reflection data allowed a detailed study of the sedimentary structures in the fans. Seven seismic facies were identified: A seismic facies characterized by disrupted, discontinuous, low- to moderate-amplitude reflections is typical for the proximal part of the fan. The continuity of the seismic reflectors gradually increases with increasing distance to the coast. The seismic facies changes to subparallel, undulating, high-amplitude reflections in the distal part of the fans. The analysis of the echo and seismic facies revealed that the sedimentary deposits of the submarine prolongations of alluvial fans in the Gulf of Aqaba essentially consist of clastic material, which slightly decreases in grain size towards the basins of the gulf. Therefore, the submarine prolongations of alluvial fans in the Gulf of Aqaba can be classified as sand-rich, point-source turbidite systems.

(7) Two different transport mechanisms of equal importance were observed building up slope and fan sediments: unchannelized and channelized transport of terrigenuous material. Unchannelized flow of sediments is probably important for the buildup of the proximal fan mainly composed of coarse sand and gravel. Accumulation rates from this process decrease with increasing transport distance. Channelized transport causes bypassing and brings significant amounts of fine and coarse sediment into the deeper fan. In addition, the proportion of fine material from channelized and unchannelized

turbidites increases in the deeper fan, which is consistent with our observations that the average grain size decreases with increasing distance to the coast.

(8) Several slumps and/or slides were identified in the study areas. These deposits demonstrate frequent gravitational transport along the steep slopes. The most likely reason for slope failures in the fans is the rapid but infrequent sediment loading, which also might have caused oversteepening of the slope. Earthquakes probably acted as the main trigger mechanism for the slope failures.

(9) The growth patterns of the submarine prolongations of alluvial fans in the Gulf of Aqaba suggest that deposition is mainly influenced by the rate of erosion of rocks from the hinterland and tectonics. The rate of erosion is mainly dependent on the climate. Climate used to be wetter during glacial times resulting in an increased sediment supply into the fans. Tectonics might control the courses of the canyons, which are important for sediment transport into the fan. Earthquakes are an important trigger for slope failures in the fans. Sea-level fluctuations probably have not played a major role during fan development because of very narrow coastal plains and the absence of a continental shelf.

5.2 Future perspectives

The data presented in this thesis are the first results of a detailed analysis of submarine prolongations of alluvial fans in the Gulf of Aqaba. Several questions, however, remain open. Future studies should include the following aspects:

(1) Wadi Kid alluvial fan on the southwestern side of the Gulf of Aqaba is the largest alluvial fan in the Gulf of Aqaba. A geophysical survey of the submarine prolongation of this fan would allow to characterize the tectonic and sedimentary history of this fan. A study of the growth patterns of this large submarine fan might shed more light on the impact of sea level and climatic fluctuations on sediment input and depositional processes in the Gulf of Aqaba.

(2) The sampling of marine surface sediments and drilling long sediment cores for palaeoceanographic studies would provide stratigraphic control for the seismic data. Cores should be taken from several locations because sedimentary processes might be expressed by different types of echo characters. For example, transparent echo characters and small hyperbolic echo characters may both represent mass-flow deposits and, in turn, some echo types may also indicate different types of sediments generated by different kinds of sedimentary processes. The availability of cores would

improve the reconstruction of the fan history and the determination of distinct growth episodes.

(3) A detailed investigation of the submarine terraces in the Gulf of Aqaba would provide information about sea level fluctuations and tectonically-driven uplift/subsidence, which might have influenced sediment deposition. A survey with hydroacoustic systems close to the coast, on both sides of the Gulf, would be necessary for such an approach.

(4) Deep seismic data and/or earthquake studies would improve our understanding of the tectonic evolution of the Gulf of Aqaba. Such data would allow a better assessment of the importance of tectonic processes in the evolution of the submarine fans.

(5) The construction of a detailed structural map of the coastline prepared from aerial photos and satellite images would allow a better correlation between the subaerial and submarine features in the fans.

Acknowledgments

I would like to express my deep gratitude to my advisor, Prof. Dr. Volkhard Spiess, for giving me the opportunity to carry out this PhD work at the University of Bremen, and also for his supervision, continuous fruitful support and guidance throughout my study. Special thanks are also due to Dr. Jürgen Pätzold for agreeing to be a referee to this thesis.

Special thanks and deep appreciation are due to my co-advisor, Dr. Sebastian Krastel, for his encouragements, useful advice, critical review and fruitful discussions. Without his support, this work would not have been possible. I wish also to thank Dr. Christian Hübscher for his sincere criticisms and comments during and after the data acquisition.

I am grateful to my PhD colleagues, Tilmann Schwenk, Felix Heidersdorf, Andrew Akwasi Antobreh and Florian Meier, for their support, encouragement and friendship that helped me to complete this thesis.

Sincere gratitude is also owed to Dr. Hanno Von Lom-Keil, Dr. Lars Zühldorff, and Andrea Gerriets for kindly providing useful information and comments, which greatly improved the thesis. Special thanks also to my colleagues, Martin Gutowski, Wolfgang Böke and Angelika Rinkel for general help and their generosity in providing information, especially, during my early days in Germany.

I would like also to thank all my colleagues in the student homes encouragement and brotherhood greatly helped me during my study in Germany.

I wish to acknowledge the crew and the technical team of the R/V Meteor Cruise M44/3. This research is part of the Red Sea Program (RSP II) in marine sciences, and the PhD thesis was funded by the Ministry of Higher Education of Egypt.

Lastly, but certainly not the least, I owe special thanks to my beloved parents, wife and kids (Riham, Nihal and Dina) for their help, patience and moral support during my education and my stay in Germany, and for making a very hectic life fun.

Publications of this series:

No. 1 **Wefer, G., E. Suess and cruise participants**
Bericht über die POLARSTERN-Fahrt ANT IV/2, Rio de Janeiro - Punta Arenas, 6.11. - 1.12.1985.
60 pages, Bremen, 1986.

No. 2 **Hoffmann, G.**
Holozänstratigraphie und Küstenlinienverlagerung an der andalusischen Mittelmeerküste.
173 pages, Bremen, 1988. (out of print)

No. 3 **Wefer, G. and cruise participants**
Bericht über die METEOR-Fahrt M 6/6, Libreville - Las Palmas, 18.2. - 23.3.1988.
97 pages, Bremen, 1988.

No. 4 **Wefer, G., G.F. Lutze, T.J. Müller, O. Pfannkuche, W. Schenke, G. Siedler, W. Zenk**
Kurzbericht über die METEOR-Expedition No. 6, Hamburg - Hamburg, 28.10.1987 - 19.5.1988.
29 pages, Bremen, 1988. (out of print)

No. 5 **Fischer, G.**
Stabile Kohlenstoff-Isotope in partikulärer organischer Substanz aus dem Südpolarmeer (Atlantischer Sektor). 161 pages, Bremen, 1989.

No. 6 **Berger, W.H. and G. Wefer**
Partikelfluß und Kohlenstoffkreislauf im Ozean.
Bericht und Kurzfassungen über den Workshop vom 3.-4. Juli 1989 in Bremen.
57 pages, Bremen, 1989.

No. 7 **Wefer, G. and cruise participants**
Bericht über die METEOR - Fahrt M 9/4, Dakar - Santa Cruz, 19.2. - 16.3.1989.
103 pages, Bremen, 1989.

No. 8 **Kölling, M.**
Modellierung geochemischer Prozesse im Sickerwasser und Grundwasser.
135 pages, Bremen, 1990.

No. 9 **Heinze, P.-M.**
Das Auftriebsgeschehen vor Peru im Spätquartär. 204 pages, Bremen, 1990. (out of print)

No. 10 **Willems, H., G. Wefer, M. Rinski, B. Donner, H.-J. Bellmann, L. Eißmann, A. Müller, B.W. Flemming, H.-C. Höfle, J. Merkt, H. Streif, G. Hertweck, H. Kuntze, J. Schwaar, W. Schäfer, M.-G. Schulz, F. Grube, B. Menke**
Beiträge zur Geologie und Paläontologie Norddeutschlands: Exkursionsführer.
202 pages, Bremen, 1990.

No. 11 **Wefer, G. and cruise participants**
Bericht über die METEOR-Fahrt M 12/1, Kapstadt - Funchal, 13.3.1990 - 14.4.1990.
66 pages, Bremen, 1990.

No. 12 **Dahmke, A., H.D. Schulz, A. Kölling, F. Kracht, A. Lücke**
Schwermetallspuren und geochemische Gleichgewichte zwischen Porenlösung und Sediment im Wesermündungsgebiet. BMFT-Projekt MFU 0562, Abschlußbericht. 121 pages, Bremen, 1991.

No. 13 **Rostek, F.**
Physikalische Strukturen von Tiefseesedimenten des Südatlantiks und ihre Erfassung in Echolotregistrierungen. 209 pages, Bremen, 1991.

No. 14 **Baumann, M.**
Die Ablagerung von Tschernobyl-Radiocäsium in der Norwegischen See und in der Nordsee.
133 pages, Bremen, 1991. (out of print)

No. 15 **Kölling, A.**
Frühdiagenetische Prozesse und Stoff-Flüsse in marinen und ästuarinen Sedimenten.
140 pages, Bremen, 1991.

No. 16 **SFB 261 (ed.)**
1. Kolloquium des Sonderforschungsbereichs 261 der Universität Bremen (14.Juni 1991):
Der Südatlantik im Spätquartär: Rekonstruktion von Stoffhaushalt und Stromsystemen.
Kurzfassungen der Vorträge und Poster. 66 pages, Bremen, 1991.

No. 17 **Pätzold, J. and cruise participants**
Bericht und erste Ergebnisse über die METEOR-Fahrt M 15/2, Rio de Janeiro - Vitoria,
18.1. - 7.2.1991. 46 pages, Bremen, 1993.

No. 18 **Wefer, G. and cruise participants**
Bericht und erste Ergebnisse über die METEOR-Fahrt M 16/1, Pointe Noire - Recife,
27.3. - 25.4.1991. 120 pages, Bremen, 1991.

No. 19 **Schulz, H.D. and cruise participants**
Bericht und erste Ergebnisse über die METEOR-Fahrt M 16/2, Recife - Belem, 28.4. - 20.5.1991.
149 pages, Bremen, 1991.

No. 20 **Berner, H.**
Mechanismen der Sedimentbildung in der Fram-Straße, im Arktischen Ozean und in der Norwegischen See. 167 pages, Bremen, 1991.

No. 21 **Schneider, R.**
Spätquartäre Produktivitätsänderungen im östlichen Angola-Becken: Reaktion auf Variationen im Passat-Monsun-Windsystem und in der Advektion des Benguela-Küstenstroms. 198 pages, Bremen, 1991. (out of print)

No. 22 **Hebbeln, D.**
Spätquartäre Stratigraphie und Paläozeanographie in der Fram-Straße. 174 pages, Bremen, 1991.

No. 23 **Lücke, A.**
Umsetzungsprozesse organischer Substanz während der Frühdiagenese in ästuarinen Sedimenten. 137 pages, Bremen, 1991.

No. 24 **Wefer, G. and cruise participants**
Bericht und erste Ergebnisse der METEOR-Fahrt M 20/1, Bremen - Abidjan, 18.11.- 22.12.1991. 74 pages, Bremen, 1992.

No. 25 **Schulz, H.D. and cruise participants**
Bericht und erste Ergebnisse der METEOR-Fahrt M 20/2, Abidjan - Dakar, 27.12.1991 - 3.2.1992. 173 pages, Bremen, 1992.

No. 26 **Gingele, F.**
Zur klimaabhängigen Bildung biogener und terrigener Sedimente und ihrer Veränderung durch die Frühdiagenese im zentralen und östlichen Südatlantik. 202 pages, Bremen, 1992.

No. 27 **Bickert, T.**
Rekonstruktion der spätquartären Bodenwasserzirkulation im östlichen Südatlantik über stabile Isotope benthischer Foraminiferen. 205 pages, Bremen, 1992. (out of print)

No. 28 **Schmidt, H.**
Der Benguela-Strom im Bereich des Walfisch-Rückens im Spätquartär. 172 pages, Bremen, 1992.

No. 29 **Meinecke, G.**
Spätquartäre Oberflächenwassertemperaturen im östlichen äquatorialen Atlantik. 181 pages, Bremen, 1992.

No. 30 **Bathmann, U., U. Bleil, A. Dahmke, P. Müller, A. Nehrkorn, E.-M. Nöthig, M. Olesch, J. Pätzold, H.D. Schulz, V. Smetacek, V. Spieß, G. Wefer, H. Willems**
Bericht des Graduierten Kollegs. Stoff-Flüsse in marinen Geosystemen. Berichtszeitraum Oktober 1990 - Dezember 1992. 396 pages, Bremen, 1992.

No. 31 **Damm, E.**
Frühdiagenetische Verteilung von Schwermetallen in Schlicksedimenten der westlichen Ostsee. 115 pages, Bremen, 1992.

No. 32 **Antia, E.E.**
Sedimentology, Morphodynamics and Facies Association of a mesotidal Barrier Island Shoreface (Spiekeroog, Southern North Sea). 370 pages, Bremen, 1993.

No. 33 **Duinker, J. and G. Wefer (ed.)**
Bericht über den 1. JGOFS-Workshop. 1./2. Dezember 1992 in Bremen. 83 pages, Bremen, 1993.

No. 34 **Kasten, S.**
Die Verteilung von Schwermetallen in den Sedimenten eines stadtbremischen Hafenbeckens. 103 pages, Bremen, 1993.

No. 35 **Spieß, V.**
Digitale Sedimentographie. Neue Wege zu einer hochauflösenden Akustostratigraphie. 199 pages, Bremen, 1993.

No. 36 **Schinzel, U.**
Laborversuche zu frühdiagenetischen Reaktionen von Eisen (III) - Oxidhydraten in marinen Sedimenten.189 pages, Bremen, 1993.

No. 37 **Sieger, R.**
CoTAM - ein Modell zur Modellierung des Schwermetalltransports in Grundwasserleitern. 56 pages, Bremen, 1993. (out of print)

No. 38 **Willems, H. (ed.)**
Geoscientific Investigations in the Tethyan Himalayas. 183 pages, Bremen, 1993.

No. 39 **Hamer, K.**
Entwicklung von Laborversuchen als Grundlage für die Modellierung des Transportverhaltens von Arsenat, Blei, Cadmium und Kupfer in wassergesättigten Säulen. 147 pages, Bremen, 1993.

No. 40 **Sieger, R.**
Modellierung des Stofftransports in porösen Medien unter Ankopplung kinetisch gesteuerter Sorptions- und Redoxprozesse sowie thermischer Gleichgewichte. 158 pages, Bremen, 1993.

No. 41 **Thießen, W.**
Magnetische Eigenschaften von Sedimenten des östlichen Südatlantiks und ihre paläozeanographische Relevanz. 170 pages, Bremen, 1993.

No. 42 **Spieß, V. and cruise participants**
Report and preliminary results of METEOR-Cruise M 23/1, Kapstadt - Rio de Janeiro, 4.-25.2.1993. 139 pages, Bremen, 1994.

No. 43 **Bleil, U. and cruise participants**
Report and preliminary results of METEOR-Cruise M 23/2, Rio de Janeiro - Recife, 27.2.-19.3.1993 133 pages, Bremen, 1994.

No. 44 **Wefer, G. and cruise participants**
Report and preliminary results of METEOR-Cruise M 23/3, Recife - Las Palmas, 21.3. - 12.4.1993 71 pages, Bremen, 1994.

No. 45 **Giese, M. and G. Wefer (ed.)**
Bericht über den 2. JGOFS-Workshop. 18../19. November 1993 in Bremen. 93 pages, Bremen, 1994.

No. 46 **Balzer, W. and cruise participants**
Report and preliminary results of METEOR-Cruise M 22/1, Hamburg - Recife, 22.9. - 21.10.1992. 24 pages, Bremen, 1994.

No. 47 **Stax, R.**
Zyklische Sedimentation von organischem Kohlenstoff in der Japan See: Anzeiger für Änderungen von Paläoozeanographie und Paläoklima im Spätkänozoikum. 150 pages, Bremen, 1994.

No. 48 **Skowronek, F.**
Frühdiagenetische Stoff-Flüsse gelöster Schwermetalle an der Oberfläche von Sedimenten des Weser Ästuares. 107 pages, Bremen, 1994.

No. 49 **Dersch-Hansmann, M.**
Zur Klimaentwicklung in Ostasien während der letzten 5 Millionen Jahre: Terrigener Sedimenteintrag in die Japan See (ODP Ausfahrt 128). 149 pages, Bremen, 1994.

No. 50 **Zabel, M.**
Frühdiagenetische Stoff-Flüsse in Oberflächen-Sedimenten des äquatorialen und östlichen Südatlantik. 129 pages, Bremen, 1994.

No. 51 **Bleil, U. and cruise participants**
Report and preliminary results of SONNE-Cruise SO 86, Buenos Aires - Capetown, 22.4. - 31.5.93 116 pages, Bremen, 1994.

No. 52 **Symposium: The South Atlantic: Present and Past Circulation.**
Bremen, Germany, 15 - 19 August 1994. Abstracts. 167 pages, Bremen, 1994.

No. 53 **Kretzmann, U.B.**
^{57}Fe-Mössbauer-Spektroskopie an Sedimenten - Möglichkeiten und Grenzen. 183 pages, Bremen, 1994.

No. 54 **Bachmann, M.**
Die Karbonatrampe von Organyà im oberen Oberapt und unteren Unteralb (NE-Spanien, Prov. Lerida): Fazies, Zyklo- und Sequenzstratigraphie. 147 pages, Bremen, 1994. (out of print)

No. 55 **Kemle-von Mücke, S.**
Oberflächenwasserstruktur und -zirkulation des Südostatlantiks im Spätquartär. 151 pages, Bremen, 1994.

No. 56 **Petermann, H.**
Magnetotaktische Bakterien und ihre Magnetosome in Oberflächensedimenten des Südatlantiks. 134 pages, Bremen, 1994.

No. 57 **Mulitza, S.**
Spätquartäre Variationen der oberflächennahen Hydrographie im westlichen äquatorialen Atlantik. 97 pages, Bremen, 1994.

No. 58 **Segl, M. and cruise participants**
Report and preliminary results of METEOR-Cruise M 29/1, Buenos-Aires - Montevideo, 17.6. - 13.7.1994
94 pages, Bremen, 1994.

No. 59 **Bleil, U. and cruise participants**
Report and preliminary results of METEOR-Cruise M 29/2, Montevideo - Rio de Janiero 15.7. - 8.8.1994. 153 pages, Bremen, 1994.

No. 60 **Henrich, R. and cruise participants**
Report and preliminary results of METEOR-Cruise M 29/3, Rio de Janeiro - Las Palmas 11.8. - 5.9.1994. Bremen, 1994. (out of print)

No. 61 **Sagemann, J.**
Saisonale Variationen von Porenwasserprofilen, Nährstoff-Flüssen und Reaktionen in intertidalen Sedimenten des Weser-Ästuars. 110 pages, Bremen, 1994. (out of print)

No. 62 **Giese, M. and G. Wefer**
Bericht über den 3. JGOFS-Workshop. 5./6. Dezember 1994 in Bremen.
84 pages, Bremen, 1995.

No. 63 **Mann, U.**
Genese kretazischer Schwarzschiefer in Kolumbien: Globale vs. regionale/lokale Prozesse.
153 pages, Bremen, 1995. (out of print)

No. 64 **Willems, H., Wan X., Yin J., Dongdui L., Liu G., S. Dürr, K.-U. Gräfe**
The Mesozoic development of the N-Indian passive margin and of the Xigaze Forearc Basin in southern Tibet, China. – Excursion Guide to IGCP 362 Working-Group Meeting "Integrated Stratigraphy". 113 pages, Bremen, 1995. (out of print)

No. 65 **Hünken, U.**
Liefergebiets - Charakterisierung proterozoischer Goldseifen in Ghana anhand von Fluideinschluß - Untersuchungen. 270 pages, Bremen, 1995.

No. 66 **Nyandwi, N.**
The Nature of the Sediment Distribution Patterns in ther Spiekeroog Backbarrier Area, the East Frisian Islands. 162 pages, Bremen, 1995.

No. 67 **Isenbeck-Schröter, M.**
Transportverhalten von Schwermetallkationen und Oxoanionen in wassergesättigten Sanden. - Laborversuche in Säulen und ihre Modellierung -. 182 pages, Bremen, 1995.

No. 68 **Hebbeln, D. and cruise participants**
Report and preliminary results of SONNE-Cruise SO 102, Valparaiso - Valparaiso, 95.
134 pages, Bremen, 1995.

No. 69 **Willems, H. (Sprecher), U.Bathmann, U. Bleil, T. v. Dobeneck, K. Herterich, B.B. Jorgensen, E.-M. Nöthig, M. Olesch, J. Pätzold, H.D. Schulz, V. Smetacek, V. Speiß. G. Wefer**
Bericht des Graduierten-Kollegs Stoff-Flüsse in marine Geosystemen.
Berichtszeitraum Januar 1993 - Dezember 1995.
45 & 468 pages, Bremen, 1995.

No. 70 **Giese, M. and G. Wefer**
Bericht über den 4. JGOFS-Workshop. 20./21. November 1995 in Bremen. 60 pages, Bremen, 1996. (out of print)

No. 71 **Meggers, H.**
Pliozän-quartäre Karbonatsedimentation und Paläozeanographie des Nordatlantiks und des Europäischen Nordmeeres - Hinweise aus planktischen Foraminiferengemeinschaften.
143 pages, Bremen, 1996. (out of print)

No. 72 **Teske, A.**
Phylogenetische und ökologische Untersuchungen an Bakterien des oxidativen und reduktiven marinen Schwefelkreislaufs mittels ribosomaler RNA. 220 pages, Bremen, 1996. (out of print)

No. 73 **Andersen, N.**
Biogeochemische Charakterisierung von Sinkstoffen und Sedimenten aus ostatlantischen Produktions-Systemen mit Hilfe von Biomarkern. 215 pages, Bremen, 1996.

No. 74 **Treppke, U.**
Saisonalität im Diatomeen- und Silikoflagellatenfluß im östlichen tropischen und subtropischen Atlantik. 200 pages, Bremen, 1996.

No. 75 **Schüring, J.**
Die Verwendung von Steinkohlebergematerialien im Deponiebau im Hinblick auf die Pyritverwitterung und die Eignung als geochemische Barriere. 110 pages, Bremen, 1996.

No. 76 **Pätzold, J. and cruise participants**
Report and preliminary results of VICTOR HENSEN cruise JOPS II, Leg 6,
Fortaleza - Recife, 10.3. - 26.3. 1995 and Leg 8, Vítoria - Vítoria, 10.4. - 23.4.1995.
87 pages, Bremen, 1996.

No. 77 **Bleil, U. and cruise participants**
Report and preliminary results of METEOR-Cruise M 34/1, Cape Town - Walvis Bay, 3.-26.1.1996.
129 pages, Bremen, 1996.

No. 78 **Schulz, H.D. and cruise participants**
Report and preliminary results of METEOR-Cruise M 34/2, Walvis Bay - Walvis Bay, 29.1.-18.2.96
133 pages, Bremen, 1996.

No. 79 **Wefer, G. and cruise participants**
Report and preliminary results of METEOR-Cruise M 34/3, Walvis Bay - Recife, 21.2.-17.3.1996.
168 pages, Bremen, 1996.

No. 80 **Fischer, G. and cruise participants**
Report and preliminary results of METEOR-Cruise M 34/4, Recife - Bridgetown, 19.3.-15.4.1996. 105 pages, Bremen, 1996.

No. 81 **Kulbrok, F.**
Biostratigraphie, Fazies und Sequenzstratigraphie einer Karbonatrampe in den Schichten der Oberkreide und des Alttertiärs Nordost-Ägyptens (Eastern Desert, N'Golf von Suez, Sinai). 153 pages, Bremen, 1996.

No. 82 **Kasten, S.**
Early Diagenetic Metal Enrichments in Marine Sediments as Documents of Nonsteady-State Depositional Conditions. Bremen, 1996.

No. 83 **Holmes, M.E.**
Reconstruction of Surface Ocean Nitrate Utilization in the Southeast Atlantic Ocean Based on Stable Nitrogen Isotopes. 113 pages, Bremen, 1996.

No. 84 **Rühlemann, C.**
Akkumulation von Carbonat und organischem Kohlenstoff im tropischen Atlantik: Spätquartäre Produktivitäts-Variationen und ihre Steuerungsmechanismen. 139 pages, Bremen, 1996.

No. 85 **Ratmeyer, V.**
Untersuchungen zum Eintrag und Transport lithogener und organischer partikulärer Substanz im östlichen subtropischen Nordatlantik. 154 pages, Bremen, 1996.

No. 86 **Cepek, M.**
Zeitliche und räumliche Variationen von Coccolithophoriden-Gemeinschaften im subtropischen Ost-Atlantik: Untersuchungen an Plankton, Sinkstoffen und Sedimenten. 156 pages, Bremen, 1996.

No. 87 **Otto, S.**
Die Bedeutung von gelöstem organischen Kohlenstoff (DOC) für den Kohlenstoffffluß im Ozean. 150 pages, Bremen, 1996.

No. 88 **Hensen, C.**
Frühdiagenetische Prozesse und Quantifizierung benthischer Stoff-Flüsse in Oberflächensedimenten des Südatlantiks. 132 pages, Bremen, 1996.

No. 89 **Giese, M. and G. Wefer**
Bericht über den 5. JGOFS-Workshop. 27./28. November 1996 in Bremen. 73 pages, Bremen, 1997.

No. 90 **Wefer, G. and cruise participants**
Report and preliminary results of METEOR-Cruise M 37/1, Lisbon - Las Palmas, 4.-23.12.1996. 79 pages, Bremen, 1997.

No. 91 **Isenbeck-Schröter, M., E. Bedbur, M. Kofod, B. König, T. Schramm & G. Mattheß**
Occurrence of Pesticide Residues in Water - Assessment of the Current Situation in Selected EU Countries. 65 pages, Bremen 1997.

No. 92 **Kühn, M.**
Geochemische Folgereaktionen bei der hydrogeothermalen Energiegewinnung. 129 pages, Bremen 1997.

No. 93 **Determann, S. & K. Herterich**
JGOFS-A6 "Daten und Modelle": Sammlung JGOFS-relevanter Modelle in Deutschland. 26 pages, Bremen, 1997.

No. 94 **Fischer, G. and cruise participants**
Report and preliminary results of METEOR-Cruise M 38/1, Las Palmas - Recife, 25.1.-1.3.1997, with Appendix: Core Descriptions from METEOR Cruise M 37/1. Bremen, 1997.

No. 95 **Bleil, U. and cruise participants**
Report and preliminary results of METEOR-Cruise M 38/2, Recife - Las Palmas, 4.3.-14.4.1997. 126 pages, Bremen, 1997.

No. 96 **Neuer, S. and cruise participants**
Report and preliminary results of VICTOR HENSEN-Cruise 96/1. Bremen, 1997.

No. 97 **Villinger, H. and cruise participants**
Fahrtbericht SO 111, 20.8. - 16.9.1996. 115 pages, Bremen, 1997.

No. 98 **Lüning, S.**
Late Cretaceous - Early Tertiary sequence stratigraphy, paleoecology and geodynamics of Eastern Sinai, Egypt. 218 pages, Bremen, 1997.

No. 99 **Haese, R.R.**
Beschreibung und Quantifizierung frühdiagenetischer Reaktionen des Eisens in Sedimenten des Südatlantiks. 118 pages, Bremen, 1997.

No. 100 **Lührte, R. von**
Verwertung von Bremer Baggergut als Material zur Oberflächenabdichtung von Deponien - Geochemisches Langzeitverhalten und Schwermetall-Mobilität (Cd, Cu, Ni, Pb, Zn). Bremen, 1997.

No. 101 **Ebert, M.**
Der Einfluß des Redoxmilieus auf die Mobilität von Chrom im durchströmten Aquifer. 135 pages, Bremen, 1997.

No. 102 **Krögel, F.**
Einfluß von Viskosität und Dichte des Seewassers auf Transport und Ablagerung von Wattsedimenten (Langeooger Rückseitenwatt, südliche Nordsee). 168 pages, Bremen, 1997.

No. 103 **Kerntopf, B.**
Dinoflagellate Distribution Patterns and Preservation in the Equatorial Atlantic and Offshore North-West Africa. 137 pages, Bremen, 1997.

No. 104 **Breitzke, M.**
Elastische Wellenausbreitung in marinen Sedimenten - Neue Entwicklungen der Ultraschall Sedimentphysik und Sedimentechographie. 298 pages, Bremen, 1997.

No. 105 **Marchant, M.**
Rezente und spätquartäre Sedimentation planktischer Foraminiferen im Peru-Chile Strom. 115 pages, Bremen, 1997.

No. 106 **Habicht, K.S.**
Sulfur isotope fractionation in marine sediments and bacterial cultures. 125 pages, Bremen, 1997.

No. 107 **Hamer, K., R.v. Lührte, G. Becker, T. Felis, S. Keffel, B. Strotmann, C. Waschkowitz, M. Kölling, M. Isenbeck-Schröter, H.D. Schulz**
Endbericht zum Forschungsvorhaben 060 des Landes Bremen: Baggergut der Hafengruppe Bremen-Stadt: Modelluntersuchungen zur Schwermetallmobilität und Möglichkeiten der Verwertung von Hafenschlick aus Bremischen Häfen. 98 pages, Bremen, 1997.

No. 108 **Greeff, O.W.**
Entwicklung und Erprobung eines benthischen Landersystemes zur *in situ*-Bestimmung von Sulfatreduktionsraten mariner Sedimente. 121 pages, Bremen, 1997.

No. 109 **Pätzold, M. und G. Wefer**
Bericht über den 6. JGOFS-Workshop am 4./5.12.1997 in Bremen. Im Anhang: Publikationen zum deutschen Beitrag zur Joint Global Ocean Flux Study (JGOFS), Stand 1/1998. 122 pages, Bremen, 1998.

No. 110 **Landenberger, H.**
CoTReM, ein Multi-Komponenten Transport- und Reaktions-Modell. 142 pages, Bremen, 1998.

No. 111 **Villinger, H. und Fahrtteilnehmer**
Fahrtbericht SO 124, 4.10. - 16.10.199. 90 pages, Bremen, 1997.

No. 112 **Gietl, R.**
Biostratigraphie und Sedimentationsmuster einer nordostägyptischen Karbonatrampe unter Berücksichtigung der Alveolinen-Faunen. 142 pages, Bremen, 1998.

No. 113 **Ziebis, W.**
The Impact of the Thalassinidean Shrimp *Callianassa truncata* on the Geochemistry of permeable, coastal Sediments. 158 pages, Bremen 1998.

No. 114 **Schulz, H.D. and cruise participants**
Report and preliminary results of METEOR-Cruise M 41/1, Málaga - Libreville, 13.2.-15.3.1998. Bremen, 1998.

No. 115 **Völker, D.J.**
Untersuchungen an strömungsbeeinflußten Sedimentationsmustern im Südozean. Interpretation sedimentechographischer Daten und numerische Modellierung. 152 pages, Bremen, 1998.

No. 116 **Schlünz, B.**
Riverine Organic Carbon Input into the Ocean in Relation to Late Quaternary Climate Change. 136 pages, Bremen, 1998.

No. 117 **Kuhnert, H.**
Aufzeichnug des Klimas vor Westaustralien in stabilen Isotopen in Korallenskeletten. 109 pages, Bremen, 1998.

No. 118 **Kirst, G.**
Rekonstruktion von Oberflächenwassertemperaturen im östlichen Südatlantik anhand von Alkenonen. 130 pages, Bremen, 1998.

No. 119 **Dürkoop, A.**
Der Brasil-Strom im Spätquartär: Rekonstruktion der oberflächennahen Hydrographie während der letzten 400 000 Jahre. 121 pages, Bremen, 1998.

No. 120 **Lamy, F.**
Spätquartäre Variationen des terrigenen Sedimenteintrags entlang des chilenischen Kontinentalhangs als Abbild von Klimavariabilität im Milankovi- und Sub-Milankovi-Zeitbereich. 141 pages, Bremen, 1998.

No. 121 **Neuer, S. and cruise participants**
Report and preliminary results of POSEIDON-Cruise Pos 237/2, Vigo – Las Palmas, 18.3.-31.3.1998. 39 pages, Bremen, 1998

No. 122 **Romero, O.E.**
Marine planktonic diatoms from the tropical and equatorial Atlantic: temporal flux patterns and the sediment record. 205 pages, Bremen, 1998.

No. 123 **Spiess, V. und Fahrtteilnehmer**
Report and preliminary results of RV SONNE Cruise 125, Cochin – Chittagong, 17.10.-17.11.1997. 128 pages, Bremen, 1998.

No. 124 **Arz, H.W.**
Dokumentation von kurzfristigen Klimaschwankungen des Spätquartärs in Sedimenten des westlichen äquatorialen Atlantiks. 96 pages, Bremen, 1998.

No. 125 **Wolff, T.**
Mixed layer characteristics in the equatorial Atlantic during the late Quaternary as deduced from planktonic foraminifera. 132 pages, Bremen, 1998.

No. 126 **Dittert, N.**
Late Quaternary Planktic Foraminifera Assemblages in the South Atlantic Ocean: Quantitative Determination and Preservational Aspects. 165 pages, Bremen, 1998.

No. 127 **Höll, C.**
Kalkige und organisch-wandige Dinoflagellaten-Zysten in Spätquartären Sedimenten des tropischen Atlantiks und ihre palökologische Auswertbarkeit. 121 pages, Bremen, 1998.

No. 128 **Hencke, J.**
Redoxreaktionen im Grundwasser: Etablierung und Verlagerung von Reaktionsfronten und ihre Bedeutung für die Spurenelement-Mobilität. 122 pages, Bremen 1998.

No. 129 **Pätzold, J. and cruise participants**
Report and preliminary results of METEOR-Cruise M 41/3, Vitoria, Brasil – Salvador de Bahia, Brasil, 18.4. - 15.5.1998. Bremen, 1999.

No. 130 **Fischer, G. and cruise participants**
Report and preliminary results of METEOR-Cruise M 41/4, Salvador de Bahia, Brasil – Las Palmas, Spain, 18.5. – 13.6.1998. Bremen, 1999.

No. 131 **Schlünz, B. und G. Wefer**
Bericht über den 7. JGOFS-Workshop am 3. und 4.12.1998 in Bremen. Im Anhang: Publikationen zum deutschen Beitrag zur Joint Global Ocean Flux Study (JGOFS), Stand 1/ 1999. 100 pages, Bremen, 1999.

No. 132 **Wefer, G. and cruise participants**
Report and preliminary results of METEOR-Cruise M 42/4, Las Palmas - Las Palmas - Viena do Castelo; 26.09.1998 - 26.10.1998. 104 pages, Bremen, 1999.

No. 133 **Felis, T.**
Climate and ocean variability reconstructed from stable isotope records of modern subtropical corals (Northern Red Sea). 111 pages, Bremen, 1999.

No. 134 **Draschba , S.**
North Atlantic climate variability recorded in reef corals from Bermuda. 108 pages, Bremen, 1999.

No. 135 **Schmieder, F.**
Magnetic Cyclostratigraphy of South Atlantic Sediments. 82 pages, Bremen, 1999.

No. 136 **Rieß, W.**
In situ measurements of respiration and mineralisation processes – Interaction between fauna and geochemical fluxes at active interfaces. 68 pages, Bremen, 1999.

No. 137 **Devey, C.W. and cruise participants**
Report and shipboard results from METEOR-cruise M 41/2, Libreville – Vitoria, 18.3. – 15.4.98. 59 pages, Bremen, 1999.

No. 138 **Wenzhöfer, F.**
Biogeochemical processes at the sediment water interface and quantification of metabolically driven calcite dissolution in deep sea sediments. 103 pages, Bremen, 1999.

No. 139 **Klump, J.**
Biogenic barite as a proxy of paleoproductivity variations in the Southern Peru-Chile Current. 107 pages, Bremen, 1999.

No. 140 **Huber, R.**
Carbonate sedimentation in the northern Northatlantic since the late pliocene. 103 pages, Bremen, 1999.

No. 141 **Schulz, H.**
Nitrate-storing sulfur bacteria in sediments of coastal upwelling. 94 pages, Bremen, 1999.

No. 142 **Mai, S.**
Die Sedimentverteilung im Wattenmeer: ein Simulationsmodell. 114 pages, Bremen, 1999.

No. 143 **Neuer, S. and cruise participants**
Report and preliminary results of Poseidon Cruise 248, Las Palmas - Las Palmas, 15.2.-26.2.1999. 45 pages, Bremen, 1999.

No. 144 **Weber, A.**
Schwefelkreislauf in marinen Sedimenten und Messung von *in situ* Sulfatreduktionsraten. 122 pages, Bremen, 1999.

No. 145 **Hadeler, A.**
Sorptionsreaktionen im Grundwasser: Unterschiedliche Aspekte bei der Modellierung des Transportverhaltens von Zink. 122 pages, 1999.

No. 146 **Dierßen, H.**
Zum Kreislauf ausgewählter Spurenmetalle im Südatlantik: Vertikaltransport und Wechselwirkung zwischen Partikeln und Lösung. 167 pages, Bremen, 1999.

No. 147 **Zühlsdorff, L.**
High resolution multi-frequency seismic surveys at the Eastern Juan de Fuca Ridge Flank and the Cascadia Margin – Evidence for thermally and tectonically driven fluid upflow in marine sediments. 118 pages, Bremen 1999.

No. 148 **Kinkel, H.**
Living and late Quaternary Coccolithophores in the equatorial Atlantic Ocean: response of distribution and productivity patterns to changing surface water circulation. 183 pages, Bremen, 2000.

No. 149 **Pätzold, J. and cruise participants**
Report and preliminary results of METEOR Cruise M 44/3, Aqaba (Jordan) - Safaga (Egypt) – Dubá (Saudi Arabia) – Suez (Egypt) - Haifa (Israel), 12.3.-26.3.-2.4.-4.4.1999. 135 pages, Bremen, 2000.

No. 150 **Schlünz, B. and G. Wefer**
Bericht über den 8. JGOFS-Workshop am 2. und 3.12.1999 in Bremen. Im Anhang: Publikationen zum deutschen Beitrag zur Joint Global Ocean Flux Study (JGOFS), Stand 1/ 2000. 95 pages, Bremen, 2000.

No. 151 **Schnack, K.**
Biostratigraphie und fazielle Entwicklung in der Oberkreide und im Alttertiär im Bereich der Kharga Schwelle, Westliche Wüste, SW-Ägypten. 142 pages, Bremen, 2000.

No. 152 **Karwath, B.**
Ecological studies on living and fossil calcareous dinoflagellates of the equatorial and tropical Atlantic Ocean. 175 pages, Bremen, 2000.

No. 153 **Moustafa, Y.**
Paleoclimatic reconstructions of the Northern Red Sea during the Holocene inferred from stable isotope records of modern and fossil corals and molluscs. 102 pages, Bremen, 2000.

No. 154 **Villinger, H. and cruise participants**
Report and preliminary results of SONNE-cruise 145-1 Balboa – Talcahuana, 21.12.1999 – 28.01.2000. 147 pages, Bremen, 2000.

No. 155 **Rusch, A.**
Dynamik der Feinfraktion im Oberflächenhorizont permeabler Schelfsedimente. 102 pages, Bremen, 2000.

No. 156 **Moos, C.**
Reconstruction of upwelling intensity and paleo-nutrient gradients in the northwest Arabian Sea derived from stable carbon and oxygen isotopes of planktic foraminifera. 103 pages, Bremen, 2000.

No. 157 **Xu, W.**
Mass physical sediment properties and trends in a Wadden Sea tidal basin. 127 pages, Bremen, 2000.

No. 158 **Meinecke, G. and cruise participants**
Report and preliminary results of METEOR Cruise M 45/1, Malaga (Spain) - Lissabon (Portugal), 19.05. - 08.06.1999. 39 pages, Bremen, 2000.

No. 159 **Vink, A.**
Reconstruction of recent and late Quaternary surface water masses of the western subtropical Atlantic Ocean based on calcareous and organic-walled dinoflagellate cysts. 160 pages, Bremen, 2000.

No. 160 **Willems, H. (Sprecher), U. Bleil, R. Henrich, K. Herterich, B.B. Jørgensen, H.-J. Kuß, M. Olesch, H.D. Schulz,V. Spieß, G. Wefer**
Abschlußbericht des Graduierten-Kollegs Stoff-Flüsse in marine Geosystemen. Zusammenfassung und Berichtszeitraum Januar 1996 - Dezember 2000. 340 pages, Bremen, 2000.

No. 161 **Sprengel, C.**
Untersuchungen zur Sedimentation und Ökologie von Coccolithophoriden im Bereich der Kanarischen Inseln: Saisonale Flussmuster und Karbonatexport. 165 pages, Bremen, 2000.

No. 162 **Donner, B. and G. Wefer**
Bericht über den JGOFS-Workshop am 18.-21.9.2000 in Bremen:
Biogeochemical Cycles: German Contributions to the International Joint Global Ocean Flux Study.
87 pages, Bremen, 2000.

No. 163 **Neuer, S. and cruise participants**
Report and preliminary results of Meteor Cruise M 45/5, Bremen – Las Palmas, October 1 – November 3, 1999. 93 pages, Bremen, 2000.

No. 164 **Devey, C. and cruise participants**
Report and preliminary results of Sonne Cruise SO 145/2, Talcahuano (Chile) - Arica (Chile), February 4 – February 29, 2000. 63 pages, Bremen, 2000.

No. 165 **Freudenthal, T.**
Reconstruction of productivity gradients in the Canary Islands region off Morocco by means of sinking particles and sediments. 147 pages, Bremen, 2000.

No. 166 **Adler, M.**
Modeling of one-dimensional transport in porous media with respect to simultaneous geochemical reactions in CoTReM. 147 pages, Bremen, 2000.

No. 167 **Santamarina Cuneo, P.**
Fluxes of suspended particulate matter through a tidal inlet of the East Frisian Wadden Sea (southern North Sea). 91 pages, Bremen, 2000.

No. 168 **Benthien, A.**
Effects of CO_2 and nutrient concentration on the stable carbon isotope composition of C37:2 alkenones in sediments of the South Atlantic Ocean. 104 pages, Bremen, 2001.

No. 169 **Lavik, G.**
Nitrogen isotopes of sinking matter and sediments in the South Atlantic. 140 pages, Bremen, 2001.

No. 170 **Budziak, D.**
Late Quaternary monsoonal climate and related variations in paleoproductivity and alkenone-derived sea-surface temperatures in the western Arabian Sea. 114 pages, Bremen, 2001.

No. 171 **Gerhardt, S.**
Late Quaternary water mass variability derived from the pteropod preservation state in sediments of the western South Atlantic Ocean and the Caribbean Sea. 109 pages, Bremen, 2001.

No. 172 **Bleil, U. and cruise participants**
Report and preliminary results of Meteor Cruise M 46/3, Montevideo (Uruguay) – Mar del Plata (Argentina), January 4 – February 7, 2000. Bremen, 2001.

No. 173 **Wefer, G. and cruise participants**
Report and preliminary results of Meteor Cruise M 46/4, Mar del Plata (Argentina) – Salvador da Bahia (Brazil), February 10 – March 13, 2000. With partial results of METEOR cruise M 46/2. 136 pages, Bremen, 2001.

No. 174 **Schulz, H.D. and cruise participants**
Report and preliminary results of Meteor Cruise M 46/2, Recife (Brazil) – Montevideo (Uruguay), December 2 – December 29, 1999. 107 pages, Bremen, 2001.

No. 175 **Schmidt, A.**
Magnetic mineral fluxes in the Quaternary South Atlantic: Implications for the paleoenvironment.
97 pages, Bremen, 2001.

No. 176 **Bruhns, P.**
Crystal chemical characterization of heavy metal incorporation in brick burning processes.
93 pages, Bremen, 2001.

No. 177 **Karius, V.**
Baggergut der Hafengruppe Bremen-Stadt in der Ziegelherstellung. 131 pages, Bremen, 2001.

No. 178 **Adegbie, A. T.**
Reconstruction of paleoenvironmental conditions in Equatorial Atlantic and the Gulf of Guinea Basins for the last 245,000 years. 113 pages, Bremen, 2001.

No. 179 **Spieß, V. and cruise participants**
Report and preliminary results of R/V Sonne Cruise SO 149, Victoria - Victoria, 16.8. - 16.9.2000.
100 pages, Bremen, 2001.

No. 180 **Kim, J.-H.**
Reconstruction of past sea-surface temperatures in the eastern South Atlantic and the eastern South Pacific across Termination I based on the Alkenone Method. 114 pages, Bremen, 2001.

No. 181 **von Lom-Keil, H.**
Sedimentary waves on the Namibian continental margin and in the Argentine Basin – Bottom flow reconstructions based on high resolution echosounder data. 126 pages, Bremen, 2001.

No. 182 **Hebbeln, D. and cruise participants**
PUCK: Report and preliminary results of R/V Sonne Cruise SO 156, Valparaiso (Chile) - Talcahuano (Chile), March 29 - May 14, 2001. 195 pages, Bremen, 2001.

No. 183 **Wendler, J.**
Reconstruction of astronomically-forced cyclic and abrupt paleoecological changes in the Upper Cretaceous Boreal Realm based on calcareous dinoflagellate cysts. 149 pages, Bremen, 2001.

No. 184 **Volbers, A.**
Planktic foraminifera as paleoceanographic indicators: production, preservation, and reconstruction of upwelling intensity. Implications from late Quaternary South Atlantic sediments. 122 pages, Bremen, 2001.

No. 185 **Bleil, U. and cruise participants**
Report and preliminary results of R/V METEOR Cruise M 49/3, Montevideo (Uruguay) - Salvador (Brasil), March 9 - April 1, 2001. 99 pages, Bremen, 2001.

No. 186 **Scheibner, C.**
Architecture of a carbonate platform-to-basin transition on a structural high (Campanian-early Eocene, Eastern Desert, Egypt) – classical and modelling approaches combined. 173 pages, Bremen, 2001.

No. 187 **Schneider, S.**
Quartäre Schwankungen in Strömungsintensität und Produktivität als Abbild der Wassermassen-Variabilität im äquatorialen Atlantik (ODP Sites 959 und 663): Ergebnisse aus Siltkorn-Analysen. 134 pages, Bremen, 2001.

No. 188 **Uliana, E.**
Late Quaternary biogenic opal sedimentation in diatom assemblages in Kongo Fan sediments. 96 pages, Bremen, 2002.

No. 189 **Esper, O.**
Reconstruction of Recent and Late Quaternary oceanographic conditions in the eastern South Atlantic Ocean based on calcareous- and organic-walled dinoflagellate cysts. 130 pages, Bremen, 2001.

No. 190 **Wendler, I.**
Production and preservation of calcareous dinoflagellate cysts in the modern Arabian Sea. 117 pages, Bremen, 2002.

No. 191 **Bauer, J.**
Late Cenomanian – Santonian carbonate platform evolution of Sinai (Egypt): stratigraphy, facies, and sequence architecture. 178 pages, Bremen, 2002.

No. 192 **Hildebrand-Habel, T.**
Die Entwicklung kalkiger Dinoflagellaten im Südatlantik seit der höheren Oberkreide. 152 pages, Bremen, 2002.

No. 193 **Hecht, H.**
Sauerstoff-Optopoden zur Quantifizierung von Pyritverwitterungsprozessen im Labor- und Langzeit-in-situ-Einsatz. Entwicklung - Anwendung – Modellierung. 130 pages, Bremen, 2002.

No. 194 **Fischer, G. and cruise participants**
Report and Preliminary Results of RV METEOR-Cruise M49/4, Salvador da Bahia – Halifax, 4.4.-5.5.2001. 84 pages, Bremen, 2002.

No. 195 **Gröger, M.**
Deep-water circulation in the western equatorial Atlantic: inferences from carbonate preservation studies and silt grain-size analysis. 95 pages, Bremen, 2002.

No. 196 **Meinecke,G. and cruise participants**
Report of RV POSEIDON Cruise POS 271, Las Palmas - Las Palmas, 19.3.-29.3.2001. 19 pages, Bremen, 2002.

No. 197 **Meggers, H. and cruise participants**
Report of RV POSEIDON Cruise POS 272, Las Palmas - Las Palmas, 1.4.-14.4.2001. 19 pages, Bremen, 2002.

No. 198 **Gräfe, K.-U.**
Stratigraphische Korrelation und Steuerungsfaktoren Sedimentärer Zyklen in ausgewählten Borealen und Tethyalen Becken des Cenoman/Turon (Oberkreide) Europas und Nordwestafrikas. 197 pages, Bremen, 2002.

No. 199 **Jahn, B.**
Mid to Late Pleistocene Variations of Marine Productivity in and Terrigenous Input to the Southeast Atlantic. 97 pages, Bremen, 2002.

No. 200 **Al-Rousan, S.**
Ocean and climate history recorded in stable isotopes of coral and foraminifers from the northern Gulf of Aqaba. 116 pages, Bremen, 2002.

No. 201 **Azouzi, B.**
Regionalisierung hydraulischer und hydrogeochemischer Daten mit geostatistischen Methoden.

108 pages, Bremen, 2002.

No. 202 **Spieß, V. and cruise participants**
Report and preliminary results of METEOR Cruise M 47/3, Libreville (Gabun) - Walvis Bay (Namibia), 01.06 - 03.07.2000. 70 pages, Bremen 2002.

No. 203 **Spieß, V. and cruise participants**
Report and preliminary results of METEOR Cruise M 49/2, Montevideo (Uruguay) - Montevideo, 13.02 - 07.03.2001. 84 pages, Bremen 2002.

No. 204 **Mollenhauer, G.**
Organic carbon accumulation in the South Atlantic Ocean: Sedimentary processes and glacial/interglacial Budgets. 139 pages, Bremen 2002.

No. 205 **Spieß, V. and cruise participants**
Report and preliminary results of METEOR Cruise M49/1, Cape Town (South Africa) - Montevideo (Uruguay), 04.01.2000 - 10.02.2000. 57 pages, Bremen, 2003.

No. 206 **Meier, K.J.S.**
Calcareous dinoflagellates from the Mediterranean Sea: taxonomy, ecology and palaeoenvironmental application. 126 pages, Bremen, 2003.

No. 207 **Rakic, S.**
Untersuchungen zur Polymorphie und Kristallchemie von Silikaten der Zusammensetzung $Me_2Si_2O_5$ (Me:Na, K). 139 pages, Bremen, 2003.

No. 208 **Pfeifer, K.**
Auswirkungen frühdiagenetischer Prozesse auf Calcit- und Barytgehalte in marinen Oberflächen-sedimenten. 110 pages, Bremen, 2003.

No. 209 **Heuer, V.**
Spurenelemente in Sedimenten des Südatlantik. Primärer Eintrag und frühdiagenetische Überprägung. 136 pages, Bremen, 2003.

No. 210 **Streng, M.**
Phylogenetic Aspects and Taxonomy of Calcareous Dinoflagellates. 157 pages, Bremen 2003.

No. 211 **Boeckel, B.**
Present and past coccolith assemblages in the South Atlantic: implications for species ecology, carbonate contribution and palaeoceanographic applicability. 157 pages, Bremen, 2003.

No. 212 **Precht, E.**
Advective interfacial exchange in permeable sediments driven by surface gravity waves and its ecological consequences. 131 pages, Bremen, 2003.

No. 213 **Frenz, M.**
Grain-size composition of Quaternary South Atlantic sediments and its paleoceanographic significance. 123 pages, Bremen, 2003.

No. 214 **Meggers, H. and cruise participants**
Report and preliminary results of METEOR Cruise M 53/1, Limassol - Las Palmas – Mindelo, 30.03.2002 - 03.05.2002. 81 pages, Bremen, 2003.

No. 215 **Schulz, H.D. and cruise participants**
Report and preliminary results of METEOR Cruise M 58/1, Dakar – Las Palmas, 15.04..2003 - 12.05.2003. Bremen, 2003.

No. 216 **Schneider, R. and cruise participants**
Report and preliminary results of METEOR Cruise M 57/1, Cape Town – Walvis Bay, 20.01. – 08.02.2003. 123 pages, Bremen, 2003.

No. 217 **Kallmeyer, J.**
Sulfate reduction in the deep Biosphere. 157 pages, Bremen, 2003.

No. 218 **Røy, H.**
Dynamic Structure and Function of the Diffusive Boundary Layer at the Seafloor. 149 pages, Bremen, 2003.

No. 219 **Pätzold, J., C. Hübscher and cruise participants**
Report and preliminary results of METEOR Cruise M 52/2&3, Istanbul – Limassol – Limassol, 04.02. – 27.03.2002, Bremen, 2003.

No. 220 **Zabel, M. and cruise participants**
Report and preliminary results of METEOR Cruise M 57/2, Walvis Bay – Walvis Bay, 11.02. – 12.03.2003, 136 pages, Bremen 2003.

No. 221 **Salem, M.**
Geophysical investigations of submarine prolongations of alluvial fans on the western side of the Gulf of Aqaba-Red Sea. 100 pages, Bremen, 2003.