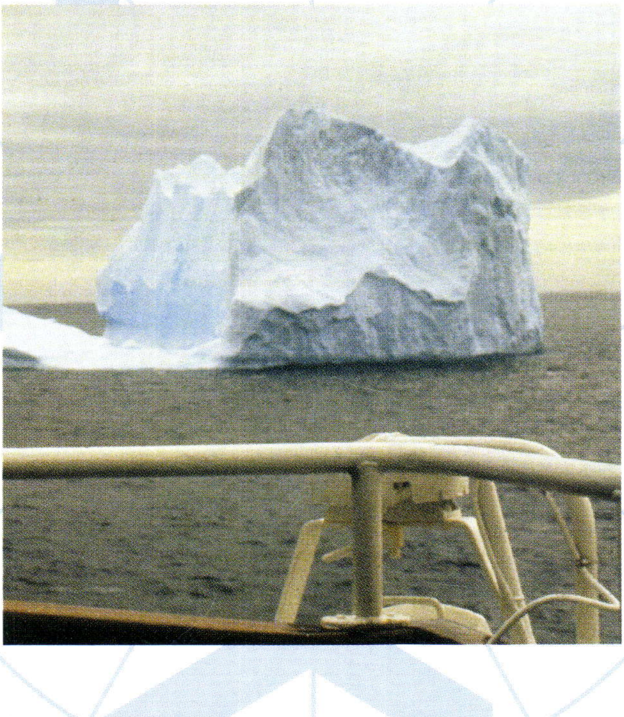
BELGIAN SCIENTIFIC RESEARCH PROGRAM
ON THE ANTARCTIC

SCIENTIFIC RESULTS OF PHASE TW
(10/1988 - 05/1992)

VOLUME II

MARINE GEOPHYSICS

EDITED BY S. CASCHETTO



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FOREWORD

In 1985, the Belgian government decided to launch a research programme to give tangible form to Belgium's desire to make an active contribution towards the international scientific effort on the Antarctic. This programme was designed as a coordinated thematic action targeting scientific problems identified by the Antarctic Treaty System as top-level priorities in pursuance of two objectives: protection of the Antarctic environment and ecosystems, and the role played by Antarctica and the Southern Ocean in global climate mechanisms. Particular attention was given to the complementarity of the different research projects, all covering a period of three years.

Development of the Belgian research effort continued between 1988 and 1992 during the Second Phase of the Programme, following the same general strategy and options. In particular, the same four fields of research were retained: (i) Plankton Ecology, (ii) Marine Biogeochemistry, (iii) Marine Geophysics and (iv) Glaciology-Climatology.

This volume sets out the results of the research projects carried out during the Second Phase of the Programme, on Marine Geophysics.

The results of the research conducted in the other fields within the Programme are the subject of two separate volumes (Volume I: Plankton Ecology and Marine Biogeochemistry and Volume III: Glaciology-Climatology).

At present, Belgium's involvement in scientific research on the Antarctic is covered by the Third Phase of the Programme, which commenced in the summer of 1992.

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M. De Batist, J.-P. Henriet, H. Miller, A. Moons, B. Dennielou, N. Kaul, E. Maes, W. Jokat, B. Schulze, G. Uenzelmann-Neben, W. Versteeg and the GRAPE TEAM (Geophysical Research of the Antarctic Peninsula)

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HIGH-RESOLUTION SEISMIC INVESTIGATION OF THE EVOLUTION (STRATIGRAPHY AND STRUCTURE) OF THE CONTINENTAL MARGINS OF THE EASTERN WEDDELL SEA AND OF THE ANTARCTIC PENINSULA

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ABSTRACT

During the ANTARKTIS VIII/5 cruise (December 1989 - March 1990), which was jointly carried out by AWI and RCMG, the seismic grid already available in the Weddell Sea could be expanded with up to 4100 km of high-resolution reflection seismic profiles.

The Meso-Cenozoic seismostratigraphic model, originally defined on ODP Site 693 (Leg 113), was extended throughout the existing seismic database along the entire eastern Weddell Sea continental margin. This correlation effort provides some closer time constraints on different stratigraphic units elsewhere in the Weddell Sea, a.o. within the Crary Fan depositional system. A major unconformity (WO4) reflects important erosive and tectonic events at the Meso-Cenozoic boundary, which could be attributed to the existence of a structurally controlled Late Mesozoic Transantarctic seaway. Such implies a paleoceanographic control on the development of at least some of the Mesozoic Weddell Sea unconformities. The Cenozoic unconformities are well controlled by paleoclimatic factors.

A structural analysis of the seismic data provides new insights in the possible origin of the Explora Escarpment and the associated Outer High, as well as in the development of the Wegener Canyon. The "Polarstern Bank" is a major structural feature that has been discovered during the ANTARKTIS VIII/5 cruise. Its presence is evaluated in view of the prevailing models for the initial break-up of Gondwana, which assume a major structural lineament throughout the Weddell Sea, connecting the Explora Escarpment and the Andenes Chain.

The high-resolution seismic database in the southeastern Weddell Sea yields new insights in the detailed and fine-scale sequence stratigraphic structure and build-up of the entire Crary Fan depositional system, from the proximal parts on the continental slope to the more distal parts in the Polarstern Bank area. Sedimentary processes, such as channel-levee deposition and depocentre migration, are discussed, as well as the fan system's development through time and as a response to eustatic sea-level fluctuations. On base of a good-quality seismic profile, connecting the shelf deposits (off Halley Bay) with the fan area, a climatic-eustatic controlled sedimentation model is advanced, explaining the development of the entire southeastern Weddell Sea continental margin since mid-Oligocene times.

Further interpretation has also been carried out of the seismic data of the northwestern Antarctic Peninsula, which are covering the rift basin of Bransfield Strait, an elongated sediment-filled trough interpreted as a fore-arc basin, accretional and progradational slopes, recent and ancient trench environments and the facing oceanic domain.

In this oceanic domain, different fracture zones have highly contrasting morphological and geophysical expressions. The subduction of a fracture zone like Hero F.Z., characterized by a significant relief possibly related to the presence of buoyant (serpentinite) ridges, may have been a factor of subduction

termination for the last segment of the Aluk (Drake) plate. It may also have played a role in the separation of a blueschist-bearing fragment (Smith Island) from the base of the accretionary plate margin and in its lift to the surface.

The magnetic anomaly pattern of the oceanic slabs facing the northwestern Peninsula margin shows evidence of an intriguing spreading acceleration, which apparently preceded ridge-trench collision. The same anomaly pattern provides a clue to the stratigraphic interpretation of the oceanic sediment cover and of the frontal part of the prograding, now passive margin south of the South Shetland Island Arc.

An apparently broken and tilted oceanic plate fragment, squeezed between the South Shetland Trench and Schackleton F.Z., may argue for the role of transpression associated with the oblique convergence of the Antarctic and Scotia plates.

GENERAL INTRODUCTION

Within the framework of the first phase (1986-1988) of the Belgian Antarctic Research Programme, the Seismostratigraphy Unit of the Renard Centre of Marine Geology (RCMG) at the University of Gent participated in two marine geophysical surveys organised by the Alfred-Wegener-Institut für Polar- und Meeresforschung (AWI - Bremerhaven, GER) : the ANTARKTIS V/4 expedition (December 1986 - March 1987) in the Weddell Sea and the ANTARKTIS VI/2 expedition (October - December 1987) along the western margin of the Antarctic Peninsula. The latter study was carried out jointly with the Geophysical Institute of the University of Kiel (GER). Both the data acquisition, the digital processing and the interpretation have formed a cooperative exercise between the Belgian and both German research partners.

The first results of these seismic investigations were presented in HENRIET *et al.* (1989). They comprised :

- a newly defined Meso-Cenozoic seismostratigraphic model for the northeastern Weddell Sea (ODP Site 693 - Leg 113), accepted by the main investigators (RCMG, AWI, BGR and University of Bergen) studying the area ;
- a reassessment of the main structural and morphological features of the northeastern Weddell Sea, such as the Explora Escarpment and the Wegener Canyon ;
- new insights in the local dynamics of spreading and subduction along the northern Antarctic Peninsula and on the segmentation history of the western margin of the northern Antarctic Peninsula.

Since then, the interpretation of the acquired data has steadily proceeded and a number of key-areas were selected for hypotheses-testing investigations during a third joint Antarctic cruise in the Weddell Sea : ANTARKTIS VIII/5 (December 1989 - March 1990). Acquisition, processing and interpretation of this additional data set and its integration in the already available data base was carried out in the framework of the second phase (1989-1991) of the Belgian Antarctic Research Programme.

The main goals of this study were to eventually obtain an integrated geological-geophysical insight into the long-term evolution of the investigated Antarctic margins (the northern Antarctic Peninsula and eastern Weddell Sea margins) and peri-Antarctic basins (the Bransfield and Weddell Sea basins), hereby focussing a.o. on their sequence and seismic stratigraphic architecture, their structural evolution, their subsidence history and on the role of eustacy.

PART 1 : THE WEDDELL SEA

1 . 1 RESEARCH OBJECTIVES AND PROGRESS

The general objectives of the Belgian marine geophysical research efforts in the Weddell Sea are to obtain a sound insight in the long-term geological evolution of this major sedimentary basin and of its surrounding continental margins. To this end, a large amount of new high-resolution reflection seismic data has been acquired, processed and interpretated in previous years. This could be achieved thanks to the successful collaboration between the Renard Centre of Marine Geology (RCMG) and the Alfred-Wegener-Institut für Polar- und Meeresforschung (AWI) in Bremerhaven (GER).

A first joint survey along the eastern margin of the Weddell Sea was carried out on board of R.V. "Polarstern" from December 1986 to March 1987 : the ANTARKTIS V/4 survey. This survey partly coincided with the drilling operations of R.V. "Joides Resolution" in the Weddell Sea in the framework of Leg 113 of the "Ocean Drilling Program" (ODP), which yielded a unique opportunity to integrate seismic and high-quality borehole data. During this first cruise, a total of some 2850 km of multi-channel seismic profiles were acquired in two areas : the area around ODP Sites 692 and 693, off Cape Norvegia, and an area off Halley Bay.

On the ODP site, particular attention was paid to questions concerning the nature of the Explora Escarpment and the Wegener Canyon, as well as to a seismostratigraphic stratotype definition of the Meso-Cenozoic sequences encountered during the drilling operations. In the Halley Bay study area, channel-levee complexes of the upper and middle Crary Fan overlying major erosional unconformities could be examined in high detail. The results of these seismic investigations were presented in HENRIET *et al.* (1989).

As the interpretation of the available data evolved, the acquisition of additional seismic lines was deemed essential for addressing a few major problems with respect to the overall basin evolution. This could be achieved during a second joint AWI/RCMG survey in the Weddell Sea on board of R.V. "Polarstern" from December 1989 to March 1990 : the ANTARKTIS VIII/5 survey. Exceptionally favourable weather and ice conditions lead to the acquisition of over 4100 km of reflection seismic profiles, 1300 km of refraction seismic profiles and 19 sonobuoy measurements in and between the two previously selected key-areas and in some blank parts of the southern Weddell Sea.

These additional data provided new arguments in the discussion on the complex structure of the continent-to-ocean boundary in the eastern Weddell Sea and in the general tectonic and structural evolution of this major sedimentary basin (section 1.4), while the stratotypes previously defined on the ODP site could now be used for a comprehensive stratigraphic correlation of all depositional sequences in the eastern Weddell Sea (section 1.3). The new data also allowed to complete our insight in the general structure of the Crary Fan and in its evolution as a response to eustatic sea level fluctuations which are possibly climate-induced (section 1.5).

The AWI/RCMG seismic data have been acquired and interpreted in close coordination with the Bundesanstalt für Geowissenschaften und Rohstoffen (BGR - Hannover, GER) and Bergen University (NOR), who have kindly put their data at our disposal. The seismostratigraphic results have also been integrated with all available geophysical (refraction seismics, gravity and magnetics) and geological (sedimentology, age dating, etc.) data.

1.2 METHODS

12.1 High-resolution reflection seismic data acquisition

The seismic tracks surveyed by AWI/RCMG during the ANTARKTIS V/4 (prefix 87) and ANTARKTIS VIII/5 (prefixes 89 or 90) cruises are shown on figure 1. The identification numbers of the V/4-profiles, as used in HENRIET *et al.* (1989), have been revised for reasons of uniformity in nomenclature.

The acquisition configuration used on the ANTARKTIS V/4 cruise has already been described in HENRIET *et al.* (1989) and basically remained the same during the ANTARKTIS VIII/5 cruise. Most of the new reflection profiles have however been recorded with a tuned array of three BOLT airguns with volumes of 1.2 l, 2.0 l and 2.5 l. With this source, fired at an average pressure of 130-140 bar, an penetration of over 3000 ms below sea-floor could be achieved with a minimal bubble effect. For some combined reflection-refraction profiles the much more powerful 32 l BOLT airgun was deployed.

All data have been recorded with a PRAKLA-SEISMOS streamer with an active length of 600 m, configured into 24 channels with 32 hydrophones each. 5 remote-controllable SYNTRON cable levellers provided the required depth control and regulation of the active streamer section. The digital data acquisition system consisted of an EG&G GEOMETRICS ES 2420 seismograph, the high sampling capacity of which guaranteed the required resolution. Data was stored in SEGD format (417 field tapes) on two STORETEK tape drives (6250 Bpi). Excellent quality analog monitor records on different scales have been obtained on two EPC recorders after adequate bandpass filtering and time variant gain amplification.

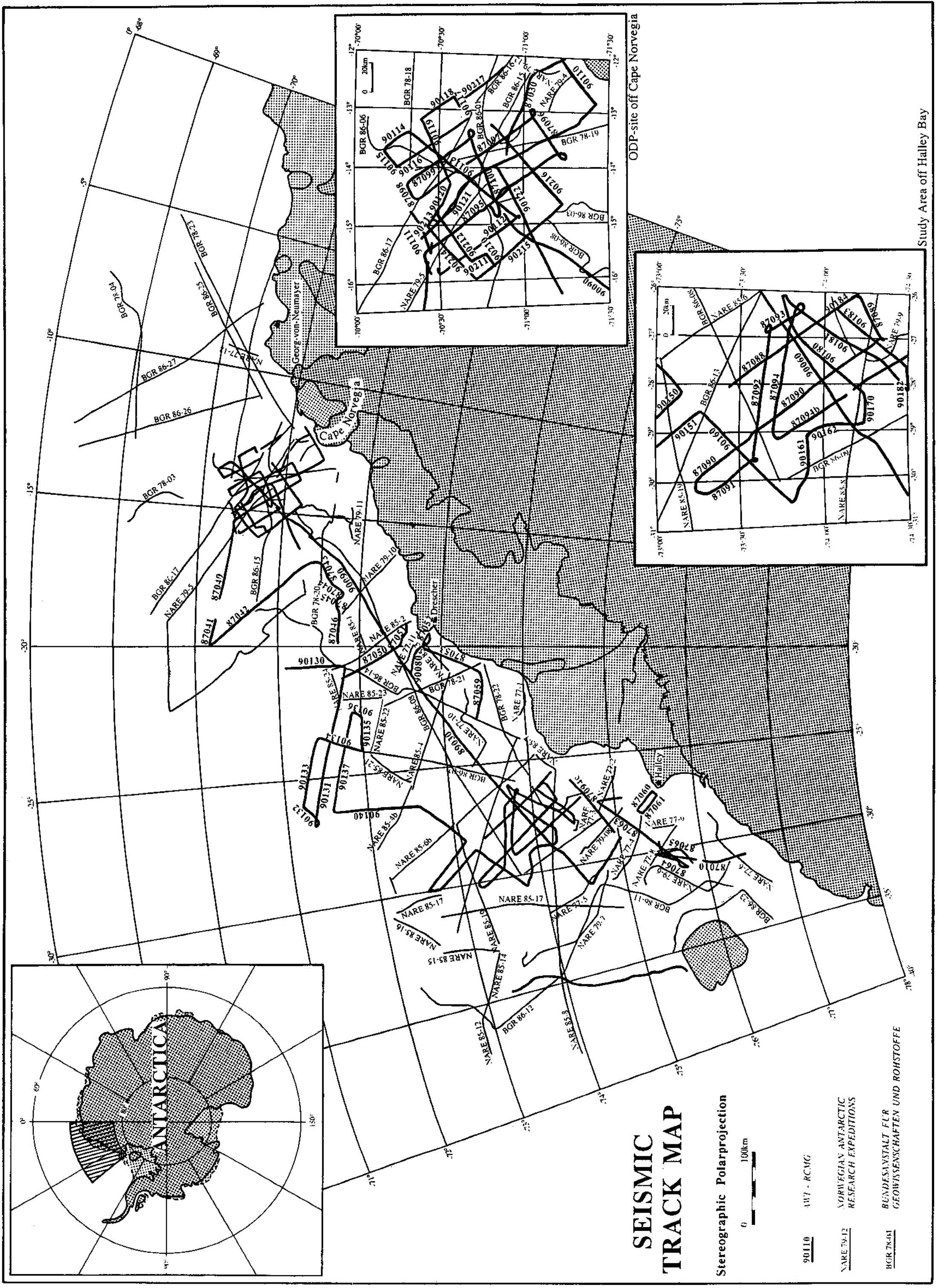


Figure 1. Track map of all AWI/RCMG reflection seismic profiles and of former seismic investigations of RCMG's research partners in the eastern Weddell Sea.

12.2 Reflection seismic data processing

At the time R.V. "Polarstern" sailed out for the ANTARKTIS VIII/5 expedition, routine seismic processing of the ANTARKTIS V/4 profiles had not yet been fully completed. One of the main objectives of the ANTARKTIS VIII/5 cruise was therefore to process all profiles - old as well as new ones - in order to avoid further accumulation of processing delays in the future. With this respect a CONVEX mini-supercomputer with DISCO 7.2 (COGNISEIS) seismic processing software was leased and installed on board by AWI. It was equipped with two additional STORETEK tape drives and a 12" VERSATEC V-80 plotter. Through an intense cooperative effort of the entire Marine Geophysics Group on board and around-the-clock processing shifts the objective could eventually be achieved.

The basic processing routines applied to all reflection profiles consisted of the following sequence:

CONVERSION MULTIPLEX-TO-DEMULTIPLEX AND SEGD-TO-DISCO FORMATS
SIGNAL ANALYSIS
POWER SPECTRUM DETERMINATION
COMMON OFFSET PLOT
    FIRST CHANNEL ; BANDPASS FILTERING
GEOMETRY DEFINITION ON BASE OF SHOTPOINT COORDINATES
STATIC CORRECTION FOR MISTRIGGERS
COMMON DEPTH POINT SORTING
VELOCITY ANALYSIS ON STACKED
VELOCITY ANALYSIS ON UNSTACKED DATA
VELOCITY FUNCTION DEFINITION
NORMAL MOVE-OUT CORRECTION
NORMAL STACKING
    12 TO 24 FOLD ; AGC
PLOTTING
    BANDPASS FILTERING ; AGC ; AUTOMATIC MUTE

A major handicap for data enhancement by digital processing is the limited velocity information, which is due to the relatively short streamer length when compared to the investigated depths. Notwithstanding this limitation, the applied basic processing steps already yield a significant increase in data quality, without drastic loss of resolution, when compared to the analog sections. It appears however that stacked sections and the analog monitor records may display significantly different expressions of e.g. seismic facies, which makes them both highly complementary for geological interpretation (figure 2).

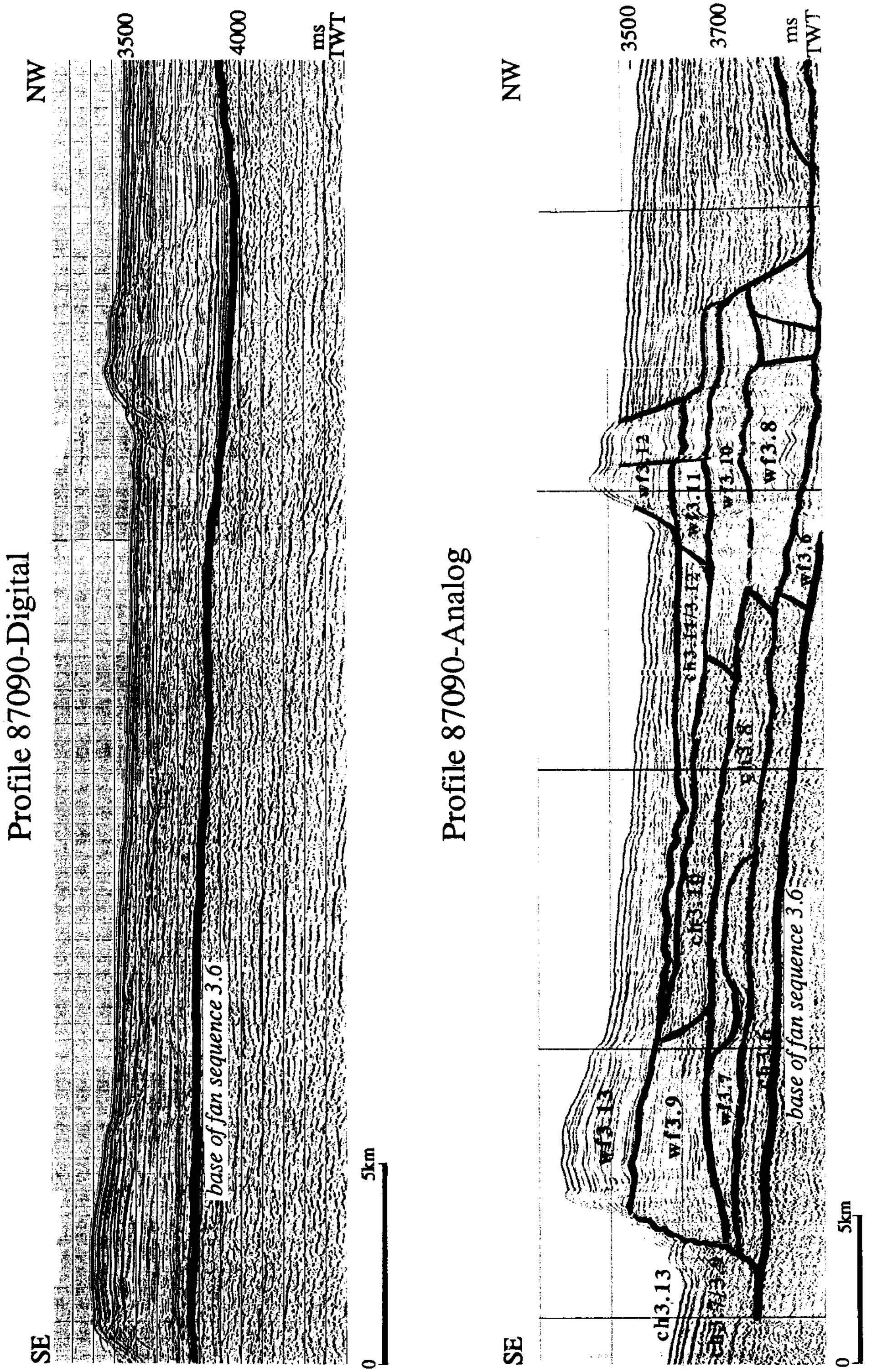


Figure 2. Comparison of two versions of AWI/RCMG profile 87090, once recorded and processed digitally and once as analog monitor section. Remark the difference in seismic facies and resolution.

In addition to the routine processing, a number of seismic sections were selected for the testing of some additional and more advanced - but also time-consuming - processing routines :

DECONVOLUTION FILTERING
SPIKING ; GAP ; ZCROSS
MULTIPLE ATTENUATION
MIGRATION AFTER STACKING

The deconvolution routines were applied to most of the ANTARKTIS V/4 data in order to reduce the rather strong and disturbing bubble effect. During the ANTARKTIS VIII/5 cruise such bubble effects could mostly be avoided or attenuated by adequate tuning of the individual airguns in each array.

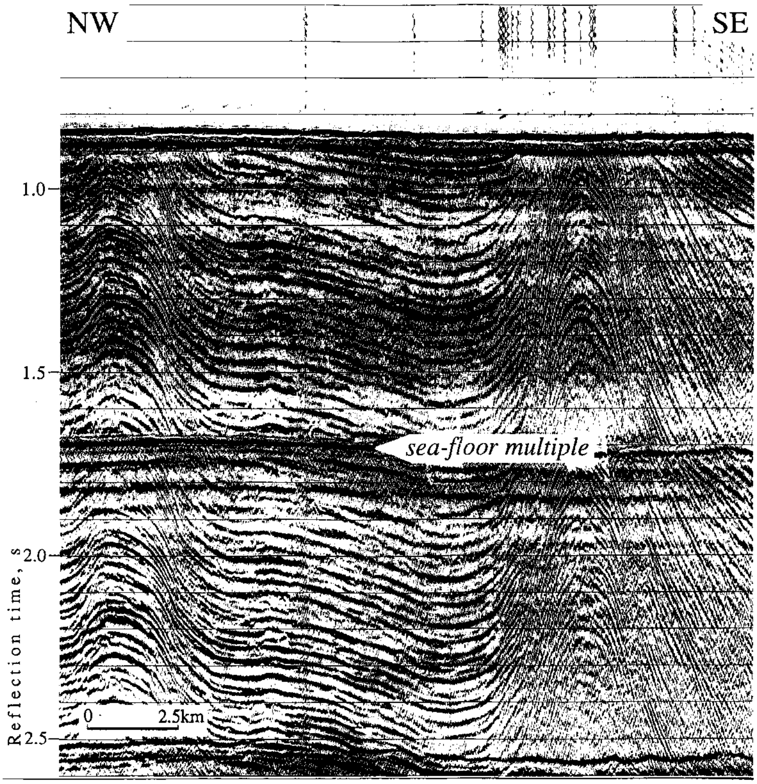


Figure 3. Part of AWI/RCMG profile 90200 (stacked section) at the extreme southwestern edge of the Weddell Sea at the transition of the West Antarctic tectonic units and the Weddell Sea sedimentary basin. Strong sea-floor multiples, also reported by HINZ & KRISTOFFERSEN (1987), mask all information below 1.7 s TWT.

Most of the shelf profiles, both from the ANTARKTIS V/4 and the VIII/5 cruises, are characterized by extremely strong sea-floor multiples, masking a large part of the primary reflections (figure 3). Some multiple attenuation routines have been applied to these profiles, but they could not adequately enhance the quality of the data.

On a few seismic sections topographic irregularities cause many disturbing diffraction hyperbolae. Migration-after-stacking routines could to a certain extent eliminate the diffractions, but a.o. the poor velocity control impeded any significant enhancement in data quality .

12.3 Refraction seismics

As already mentioned, the relatively short streamer lengths required for operations in heavy sea-ice conditions do not yield sufficient velocity information for optimal data enhancement by seismic processing. Refraction seismic profiles can however to a certain extent provide additional velocity information. Refraction seismic measurements by means of sonobuoys have

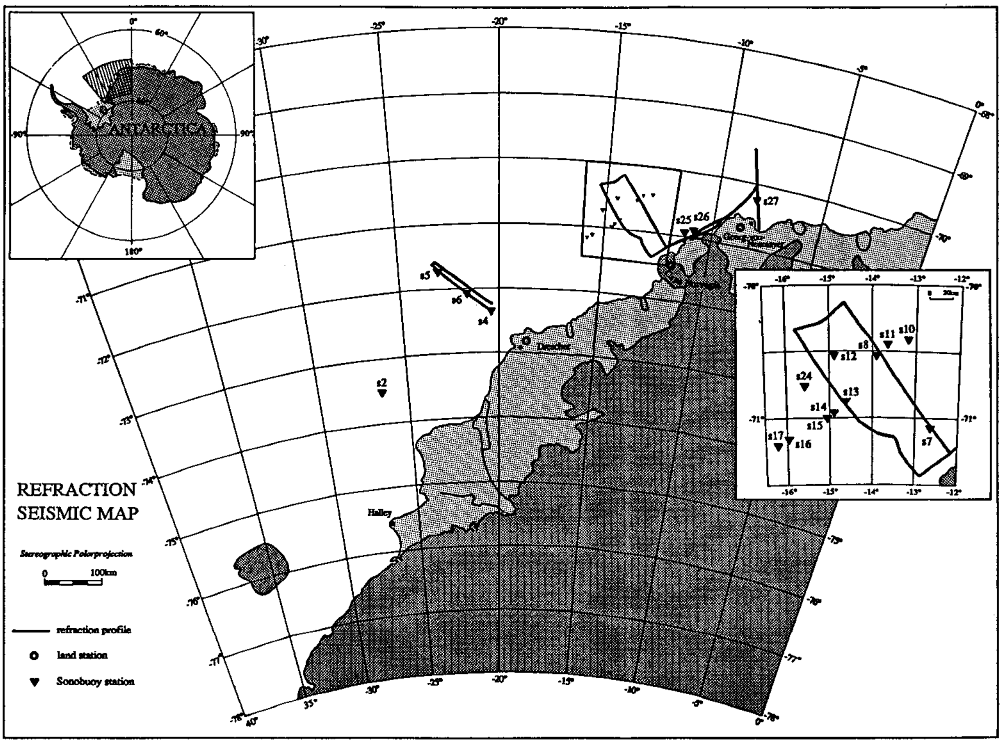


Figure 4. Localisation map of all AWI/RCMG refraction seismic profiles and sonobuoy stations in the eastern Weddell Sea.

the advantage that they can be run simultaneously with normal reflection seismic data acquisition.

With this objective a number of FAIRCHILD SB87 sonobuoys have been released by the AWI partners on some selected sites during the ANTARKTIS VIII/5 cruise. The location of the sonobuoy stations is indicated on figure 4. The data have been digitally recorded on the EG&G GEOMETRICS ES 2420 seismograph (auxiliary channels) and stored on tape, in order to enable further processing.

The preliminary interpretation of a sonobuoy measurement (S1) in the southernmost Weddell Sea, in a shelf environment with a water depth of about 330 m. (KAUL & UENZELMANN-NEBEN, personal information) yields the identification of 4 refractors up to a depth of about 2200 m. Interval velocities in the sediments range from 2270 m/s in the upper layer to 3048 m/s in the lower one. The velocity of the top layer is remarkably high, but comparable velocities were obtained by other sonobuoy analyses (KAUL, 1991) and were also measured by means of ocean bottom streamer experiments in Atka Bay, during the ANTARKTIS V/4 cruise (HENRIET *et al.*, 1989). Such high velocities can presumably account for the very strong sea-floor multiples observed on most reflection profiles recorded on the Weddell Sea shelves (figure 3), and argue for an important degree of overconsolidation of the shelf sediments by glacial loading, probably under advancing ice shelves.

1.3 THE WEDDELL SEA UNCONFORMITIES

13.1 The Weddell Sea stratotype definition and unconformity correlation

The study area off Cape Norvegia, centered around ODP Sites 692 and 693, is of fundamental importance for all stratigraphic work in the Weddell Sea. It is the only locality in this large sedimentary basin where seismostratigraphy can be unambiguously fitted into a chrono- and lithostratigraphic framework.

HENRIET *et al.* (1989) and MILLER *et al.* (1990) proposed a stratotype definition for the Mesozoic and Cenozoic sequences encountered on ODP Sites 692 and 693 and on the AWI/RCMG seismic sections in the area. This seismostratigraphic nomenclature is currently in use with all involved research partners (AWI, BGR, Bergen University, RCMG). The stratigraphic correlation effort, already initiated in HENRIET *et al.* (1989) and building out from these ODP sites, has been continued and intensified, leading to some closer time constraints on some sedimentary units elsewhere in the Weddell Sea (figure 5). This exercise involves a continuing integration of all available seismic information. Most of the analog AWI/RCMG profiles used in the first interpretation phase did not show sufficient penetration to trace all important unconformities along the entire continental margin. Therefore, the relevant seismostratigraphic information provided by deeper BGR and NARE profiles were also taken into account. In addition, the digital processing of the AWI/RCMG data during the ANTARKTIS VIII/5 survey revealed useful information concerning the deeper horizons.

It was already indicated in HENRIET *et al.* (1989) that a number of the hiatuses identified on the ODP site actually correspond to major regional onlap surfaces or sequence boundaries on the seismic sections (hence labelled as "WO - Weddell Sea Onlap" surfaces).

A regional onlap surface of major importance is WO4, representing a hiatus of 60 My between Aptian-Albian and early Late Oligocene deposits. This WO4 unconformity has been traced further south along the AWI/RCMG seismic grid, where it becomes increasingly erosive and eventually truncates all underlying sequences over a depth of more than 2000 m in the area of the Crary Fan (figure 5). Here, it is onlapped by a previously unidentified sequence with a thickness of up to 3000 m. These in their turn are truncated by another important unconformity, which merges with the lower one in northern and eastern directions, and which is directly overlain by the thick stack of Crary Fan deposits in the southern Weddell Sea (figure 5) (see also section 1.5).

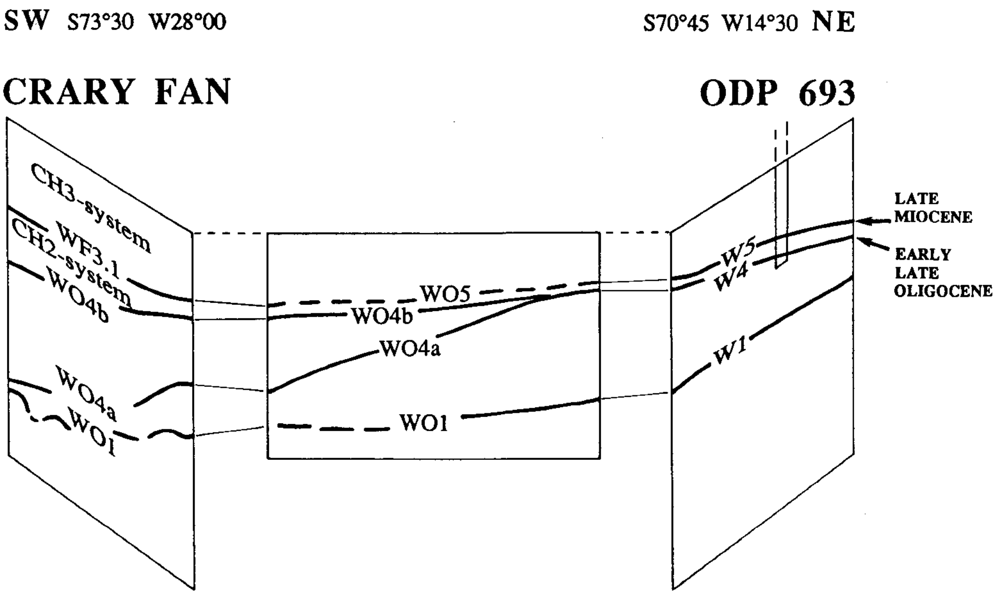


Figure 5. Schematic fence diagram illustrating the distribution of the most important basin-wide unconformities throughout the eastern Weddell Sea, as identified on the AWI/RCMG data.

Since both unconformities merge towards the northeast where they can be laterally correlated with WO4, they are respectively labelled WO4a for the lower and WO4b for the upper one.

Hence the conviction grows that the 60 My gap at Site 693 might in fact represent at least two major erosive events, with coalescing unconformities. If on the basis of the chronostratigraphic data provided by ODP Sites 692-693, a post-Early Cretaceous age is assigned to the WO4a unconformity, and if for similar reasons a pre-Late Oligocene age is assumed for unconformity WO4b, than it follows that the intermediate sequences may include Upper Cretaceous to Early Oligocene deposits.

On Site 693, the post-WO4 sequences consist largely of glaciomarine deposits of Neogene age. An initiated correlation effort of these sequences with sequences further south remains for the time being still somewhat elusive. During the ANTARKTIS VIII/5 survey, a long correlation profile has been shot parallel to the BGR 86-08 line but closer to the ice edge, but correlation along the entire continental margin is highly speculative due to active erosion to a level beneath WO5 by the numerous sea-floor channels and canyons.

Nevertheless, KUVAAS & KRISTOFFERSEN (1991), in an attempt to extend the ODP site seismostratigraphy towards the southern Weddell Sea in the Crary Fan area (figure 5), propose a correlation of the WO5 unconformity, the origin of which is attributed to a major expansion of the East Antarctic ice sheet, with one of the major intra-fan discontinuities they identified on the Norwegian lines. Although the proposed correlation would fit our Crary Fan stratigraphic model (see also section 15.2), the AWI/RCMG data don't allow to confirm it unambiguously.

13.2 Origin of the Weddell Sea unconformities

132.1 The WO4a-WO4b unconformities

Both the increasingly truncating nature of WO4a towards south, as observed on the AWI/RCMG profiles, and the thick wedge of possibly Upper Cretaceous to Eocene sediments are intriguing and raise questions with regard to their origin. Especially the fact that the truncating character of the WO4a unconformity apparently increases towards the most confined part of the Weddell Sea may support the hypothesis that the southern Weddell Sea has not always been a confined area.

HUBER (1988) has advanced micropaleontological arguments in favour of a Late Cretaceous Transantarctic marine seaway between the Ross and the Weddell Seas, more specific in Campanian through Maastrichtian times. WEBB (1991) even advocates a recurrent marine connection between the Ross and Weddell Sea during the Cenozoic. Basically, a deep gateway is not required for allowing a migration of planktonic species. HUBER's (1988) and WEBB's

(1991) observations by themselves therefore don't explain the observed truncating character of WO4a.

A study of STERN & TEN BRINK (1989) confirms the extensional nature of the Transantarctic Mountain range. In the Ross Sea embayment, this major structural line is marked by rift-like structures (COOPER *et al.*, 1987). Hence, a structurally controlled shallow gateway reactivated in Late Cretaceous times - connecting the southern Weddell Sea, interpreted as dominated by rift structures by MASOLOV *et al.* (1981), with the Victoria Land basin in the Ross Sea - might have been deep enough for allowing significantly erosive currents and eddies in the Weddell Sea. One might expect a more vigorous erosion closer to the mouth of such a gateway, in the southernmost part of the Weddell Sea. Such a scenario would also explain why ANDERSON *et al.* (1991) fail to retrieve marine Cretaceous palynomorphs south of 76° S in the Weddell Sea, an observation they interpreted as an indication that marine incursions did not occur in that area until some time in the Tertiary.

The closure of such a seaway could have occurred e.g. in response to the uplift of the Transantarctic Mountains, some 50 My ago. Recent AWI/RCMG data, acquired during the ANTARKTIS VIII/5 expedition, suggest that a major tectonic event also affected parts of the Weddell Sea basin itself. The seismic profiles show that the newly discovered Polarstern Bank (see also section 14.5) apparently has been uplifted shortly after the development of the WO4a unconformity - possibly still in Late Cretaceous times. Such a tectonic event could perhaps be attributed to an initial pulse of the Transantarctic Mountains uplift. The actual uplift in turn might have been the source for the thick sequence of sediments which accumulated on top of the WO4a unconformity in the southern Weddell Sea.

Alternative hypotheses which do not imply the existence of a seaway in Late Cretaceous times could be advanced e.g. by considering erosive processes enhanced by Coriolis force along the southwestern margin of the Weddell Sea in early Cenozoic times.

132.2 The post-WO4 unconformities

On the ODP site, the influence of expanding East Antarctic ice sheets was identified from Oligocene times onwards (SHIPBOARD SCIENTIFIC PARTY, ODP LEG 113, 1988). This implies that direct climatic influences might have contributed significantly in the development of certain stratigraphic signatures from that period onwards.

With respect to the possible origin of the post-WO4 unconformities identified on the seismic sections near the ODP-site, the idea of an important climatic influence had already been advanced in HENRIET *et al.* (1989), on base of the observation of a striking coincidence of major rises in composite benthic foraminiferal $\delta^{18}O$ for Atlantic DSDP sites (MILLER *et al.*, 1987 ; MILLER & KENT, 1987) with most of the Cenozoic unconformities identified in the Weddell Sea.

This hypothesis of a significant climatic influence on the development of unconformities and on the distribution pattern of sediments in the Weddell Sea will be dealt with in full detail in section 15.4.

1.4 THE TECTONIC STRUCTURE OF THE WEDDELL SEA BASIN

14.1 The HINZ-KRISTOFFERSEN model

A first comprehensive model of the tectonic structure (figure 6) and evolution of the Weddell Sea basin and of its position and role in the early break-up history of Gondwana was presented by KRISTOFFERSEN & HAUGLAND (1986) and HINZ & KRISTOFFERSEN (1987), after combining the results of the first German (BGR) and Norwegian seismic reconnaissance surveys in the area.

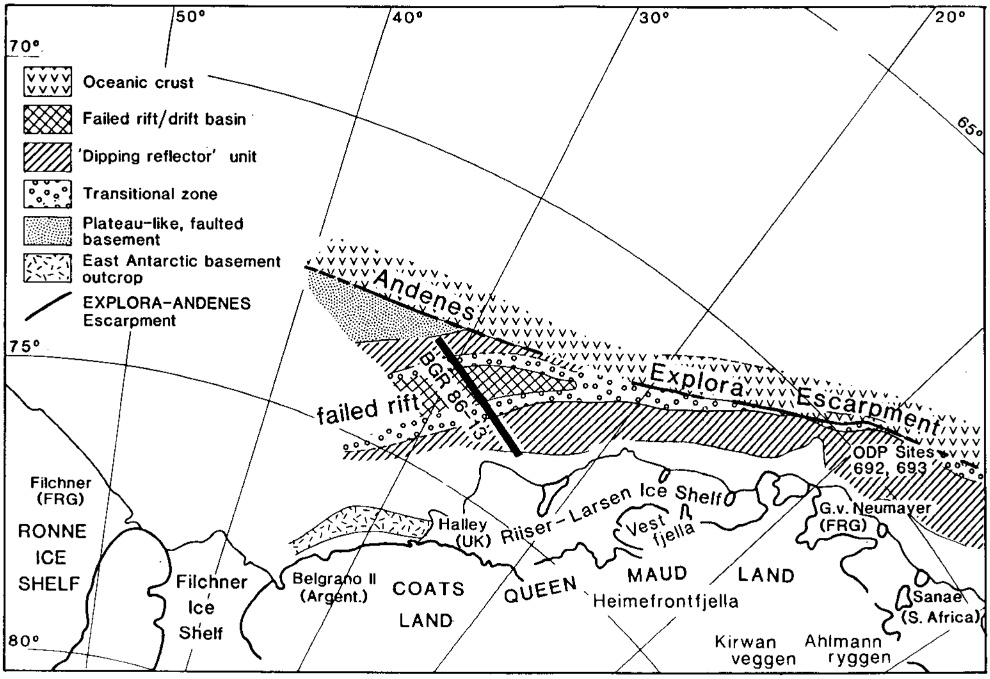


Figure 6. Major geological structures of the East Antarctic continental margin between 0° and 40° W, based on BGR and NARE seismic profiles (from KRISTOFFERSEN & HINZ, 1991). Bold line indicates location of figure 7.

In the southeastern Weddell Sea, under a thousands of metres thick stack of undisturbed sediments, HINZ & KRISTOFFERSEN (1987) identified a N50°E-trending failed rift-drift basin, symmetrically bordered by wedge-shaped basement units with a typical pattern of divergent reflectors (figures 6-7). The seismic characteristics (seismic facies and velocity) and the analogy with similar wedge-like structures identified in drill holes of ODP Leg 104 on the Vøring Plateau in the Norwegian Sea (HINZ *et al.*, 1987) suggest that these wedges consist of volcanic rocks overlying thinned continental crust (HINZ, 1981). The observed structure therefore probably represents an initial phase of continental rifting in the break-up history of Gondwana, which was accompanied by prolific volcanism and took place already in Middle Jurassic times.

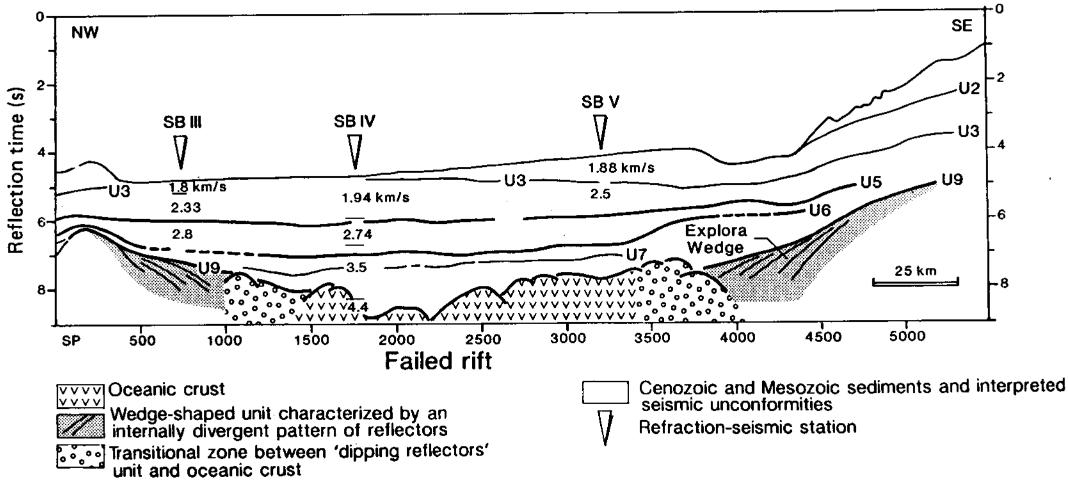


Figure 7. Geoseismic section of profile BGR 86-13 (from KRISTOFFERSEN & HINZ, 1991). Remark the fundamental differences in interpretation with figure 19, representing our interpretation of the same profile, which was put at our disposal by BGR.

Further to the northeast, the failed rift-drift basin apparently vanishes and only one of the volcanic wedges can be recognized and traced along the eastern coast of the Weddell Sea : the so-called "Explora Wedge" (HINZ & KRAUSE, 1982). A few other remarkable structures can however be observed affecting the basement morphology : the "Explora Escarpment" (HINZ & KRAUSE, 1982) and the buried "Andenes Chain" (ORHEIM, 1985).

KRISTOFFERSEN & HAUGLAND (1986) and later KRISTOFFERSEN & HINZ (1991) proposed that both features are part of one major structural alignment, the Explora-Andenes Escarpment, cutting through the initial rift structures (figure 6) and representing the actual continent-ocean boundary - a rifted margin - as formed during the opening of the Weddell Sea by oblique sea-floor spreading, from Late Jurassic times onwards.

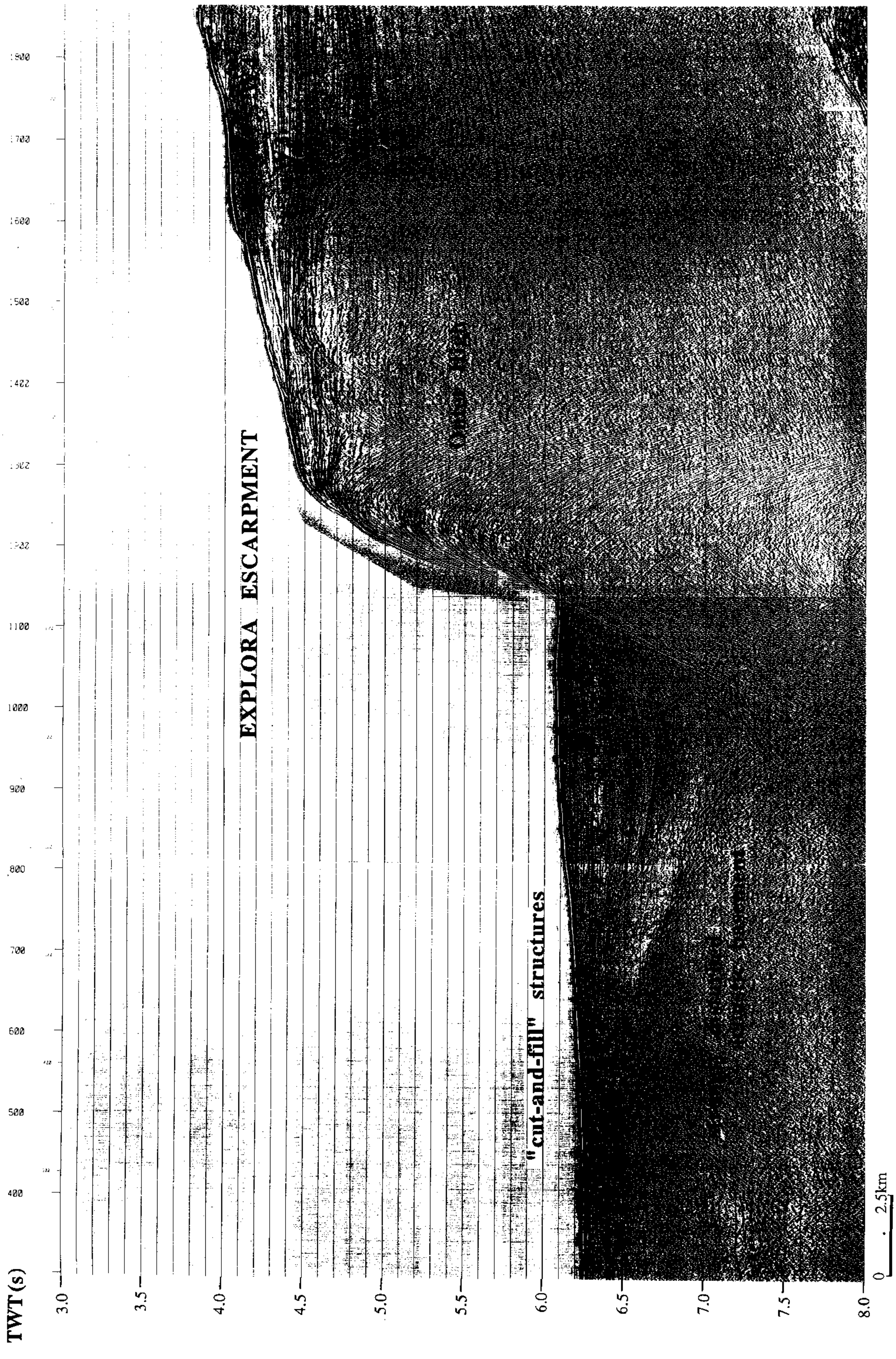


Figure 8. Stacked section of AWI/RCMG profile 90112, showing the Explora Escarpment, the Outer High and the basement structures at the foot of the escarpment.

Since this model was advanced, many new seismic sections have been acquired in the Weddell Sea by AWI/RCMG. They provided new and detailed information, which throw new light on the structural evolution of this area with respect to the reconstruction of the initial Gondwana break-up and the development of the Weddell Sea as an ocean basin. These new observations are presented below and their possible implications are shortly discussed.

14.2 The Explora Escarpment

The "Explora Escarpment", first defined by HINZ & KRAUSE (1982), is a steep scarp separating the lower continental slope (depths of 1500 to 3000 m) and the continental rise (depths over 4000 m) in the area off Cape Norvegia, between 10 and 17°W, and undoubtedly constitutes one of the most striking structural features in the entire Weddell Sea (figure 8). As a morphological feature however, it remains rather local as it fades out fairly quickly towards the south and the north. This was confirmed by a detailed bathymetric survey, that was carried out during the AWI/RCMG ANTARKTIS VIII/5 survey, in an attempt to map in detail the sea-floor topography along the escarpment between 13° and 19°W, with the use of a HYDROSWEEP sonar system.

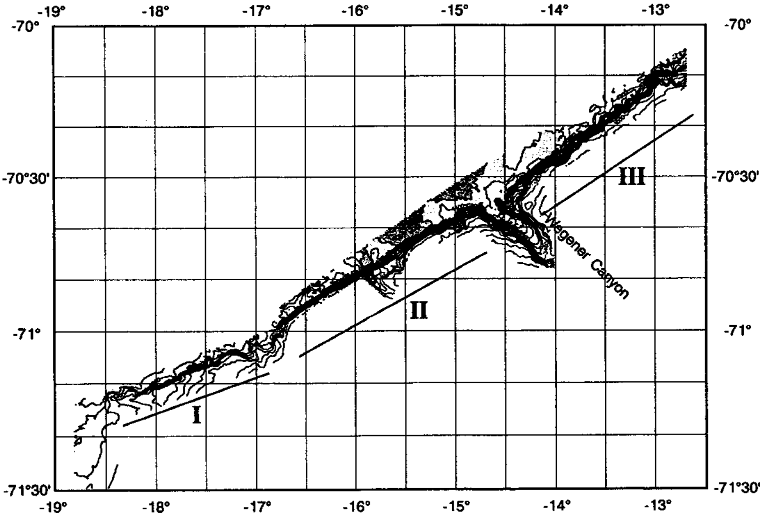


Figure 9. Bathymetric map of the Explora Escarpment (from MILLER *et al.*, 1991), showing the three differently striking segments (I = 70° strike, II = 60° strike, III = 55° strike).

These bathymetric data also show that the escarpment in fact is built up of 3 segments, each characterized by slightly different strike directions (figure 9). Each change in strike is associated with the occurrence of a canyon, cut at right angles to the strike of the escarpment, and among which the "Wegener Canyon", at about 14°W, is certainly the most pronounced.

The exact nature of the Explora Escarpment as an outspoken morphological feature still remains a point of considerable debate, although most authors regard it to be marking the boundary - of whatever nature - between oceanic and continental crust. The AWI/RCMG data don't provide any conclusive evidence in this matter (MILLER *et al.*, 1991).

A vague similarity in the northward rotation of the 3 Explora Escarpment segments and of the strike directions of magnetic anomalies M29 to M0 in the northern Weddell Sea (LABRECQUE & BARKER, 1981) could indicate a direct relationship between a number of different rifting stages and the observed segmentation of the continental margin along the escarpment. In this new model of the Wegener Canyon, the location of which has always been attributed to the presence of faults (SHIPBOARD SCIENTIFIC PARTY, ODP LEG 113, 1988), is interpreted as the morphological expression of the edge of a tilted and rotated basement block, constituting the last continental fragment of the rifted margin. The same consideration holds for the canyon at 17°W. This model would therefore to a certain extent confirm the obliquely rifted margin hypothesis of KRISTOFFERSEN & HAUGLAND (1986) and KRISTOFFERSEN & HINZ (1991), but does not really explain the scarp morphology. Moreover, it should not be ruled out that the observed segmentation is an inherited feature, when after initial rifting the margin developed into a transform fault boundary, as was already proposed in an early model (NORTON & SCLATER, 1979) and is strongly supported by recent kinematic reconstructions.

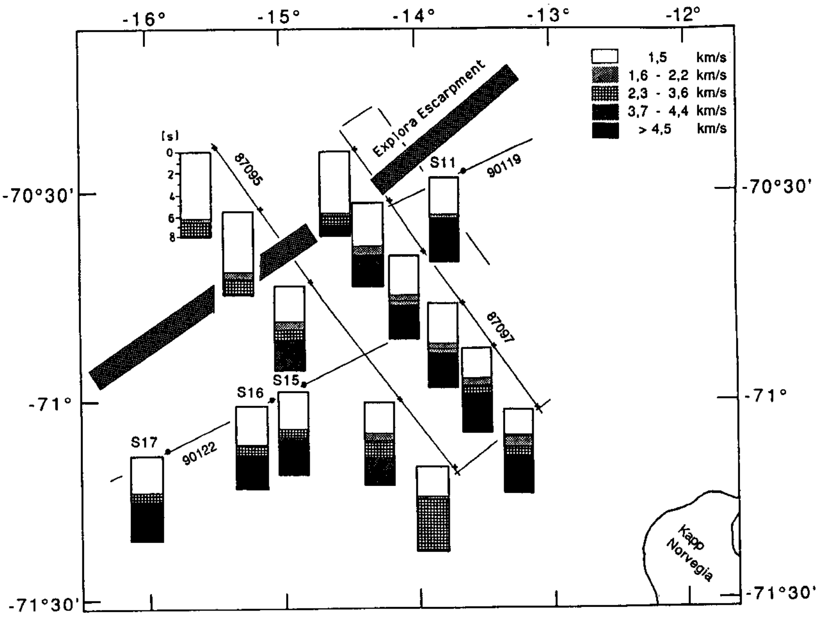


Figure 10. Seismic velocity structure of the ODP site (from KAUL, 1991) on base of sonobuoy data S11, S15, S16, S17 (location indicated by dots) and velocity analyses of the AWI/RCMG multi-channel seismic profiles 87095, 87097, 90119, 90122 (location of selected CDP's indicated by cross marks). The vertical axis of each of the velocity sections ranges from 0 to 8 s TWT.

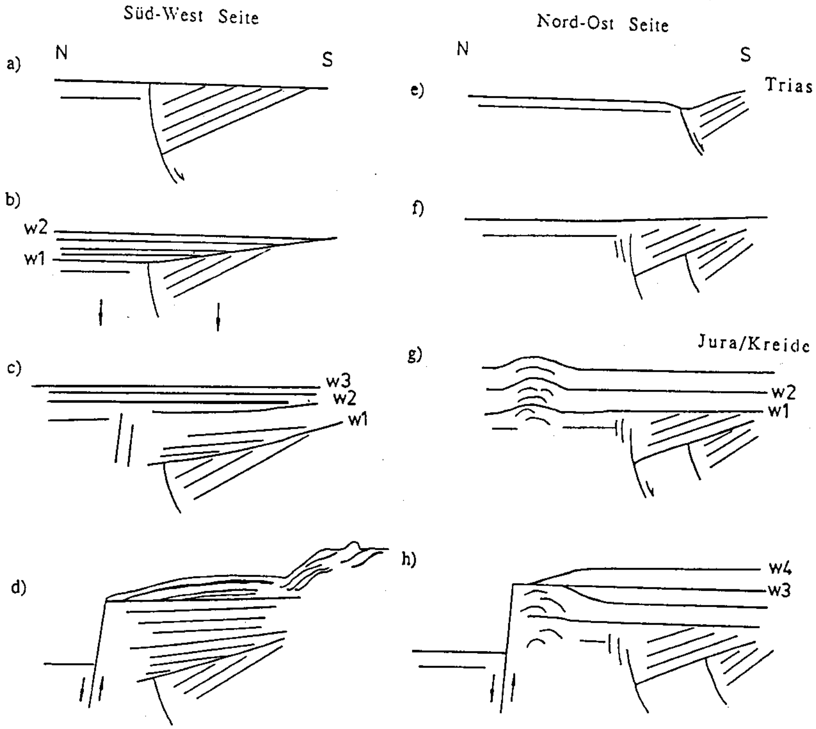


Figure 11. Evolution of the continental margin at both sides of Wegener Canyon as derived from the AWI/RCMG seismic sections (from KAUL, 1991). The fundamental difference lies in the development of barrier reef carbonates on the northeastern side, around the Jurassic-Cretaceous boundary.

In another, early interpretation HINZ & KRAUSE (1982) suggested that the impressive scarp morphology could have been caused by a subsurface basement high. On most AWI/RCMG seismic sections through the Explora Escarpment a mound-like structure can indeed be observed, characterized by numerous diffraction hyperbolae and by a structureless, completely reflection-free seismic facies (figure 8). This so-called "Outer High" was assumed by HINZ & KRAUSE (1982) to be of magmatic origin and to be closely associated with the second phase of the rifting process. This interpretation has never been corroborated by any really conclusive evidence, such as geological samples, and has already been commented upon by HENRIET *et al.* (1989).

In order to obtain some additional information a.o. on the velocity structure of the escarpment and the 'Outer High' a number of sonobuoy measurements (figure 10), as well as a dense grid of additional multi-channel seismic profiles have been performed by AWI/RCMG during the ANTARKTIS VIII/5 expedition. The preliminary interpretation of these data seems to indicate that the association of the "Outer High" with the actual scarp face, as observed on all previous sections, appears to be only local. Towards the north an "Outer High"-like structureless mound can be observed at a considerable distance behind the scarp face itself. Here reflectors with a clearly "sedimentary" appearance are cut by the scarp face, which exhibits a terrace-like morphology, as observed by a detailed bathymetric mapping (AWI BATHYMETRIC GROUP, personal communication). Also the seismic facies of the Outer High-like structure changes considerably towards north, with the appearance of some reflector elements in the otherwise structureless mass. In a new model (KAUL, 1991), partly based on these observations and on the elaborated velocity structure, the "Outer High" is re-interpreted to consist of barrier-type carbonate reefs. The escarpment itself is regarded in this model to be the result of purely vertical tectonic movements, dating from Cretaceous times (figure 11).

In HENRIET *et al.* (1989) and in HENRIET & MILLER (1990) yet another interpretation has been proposed for the nature of the Outer High, taking into account the seismic observations and the coincidence of the most pronounced morphology with a curved section of the structural lineament, here interpreted as the abovementioned transform fault. The Outer High could then represent a strongly disturbed, accretionary wedge-like sedimentary unit, associated with some overthrusting in a dextral transpressional regime. This hypothesis seems to be confirmed by a re-interpretation of profile BGR 86-15 (HINZ, personal communication), where some very typical 'Popeye'-structures, observed in close association with the Outer High itself, may also be interpreted as the result of transpressional movements.

14.3 The continental rise at the foot of the Explora Escarpment

Another remarkable feature has been observed by HINZ (personal communication) on a number of BGR profiles crossing the continental rise at the foot of the Explora Escarpment. Locally, a structurally strongly disturbed acoustic basement is characterized by some typical seismic facies aspects. These suggest that this acoustic basement could be formed by a very strongly deformed sedimentary sequence, rather than by oceanic crust as would be expected. 'Normal' oceanic crust facies can be observed only much further to the north.

It should be stated, that at present no evidence can be put forward for the suggested sedimentary nature of the acoustic basement, and also the recent ANTARKTIS VIII/5 profiles in the area add no real new information to this. They do however reveal some remarkable 'basement' structures, associated with important unconformities in the sedimentary cover and indicating a history of important compressive tectonic stresses or stress components (figure 8).

Some unconformities at the foot of the Explora Escarpment were interpreted in HENRIET *et al.* (1989) as cut-and-fill structures, witnessing either successive episodes of scouring and deposition of turbiditic sediments in basin floor fans, associated with the periodic activity of slope-edge canyons, or climatically controlled episodic variations in long slope currents, induced by variations of bottom water flux. Our recent observations however indicate that an important structural influence has to be taken into consideration, both with respect to the nature of the acoustic basement and to the origin of the overlying unconformities.

14.4 The Wegener Canyon

As had already been suggested by the SHIPBOARD SCIENTIFIC PARTY, ODP LEG 113 (1988), the location of Wegener Canyon is most likely structurally controlled. This assumption is based on an offset, observed at the oceanward scarp of the Outer High. Moreover, the presence of a number of faults in the strata underlying Wegener Canyon was observed during the ANTARKTIS V/4 survey, by e.g. profile 87100 as reported by HENRIET *et al.* (1989).

This hypothesis of a fault control of Wegener Canyon therefore remained one of the prime research objectives of the ANTARKTIS VIII/5 seismic survey in this area. A set of reflection profiles has been shot parallel and perpendicular to the canyon, as well as in the canyon axis. Interpretation of these data again clearly indicates the presence of faults associated with the canyon and also strong differences in the stratigraphic structure and build-up at either side of the canyon (KAUL, 1991). On basis of these observations, Wegener Canyon as well as the canyon at 17°W are now interpreted as the morphological expression of the edge of some tilted and rotated basement blocks, constituting the last continental fragment of the rifted margin, as was already argued for above.

An additional observation can be made at the oceanward prolongation of Wegener Canyon, where a major structural event can be observed. The 'basement' - whatever it's nature - is here affected by a steep flexure with a throw of up to 1 s. This certainly argues in favour of a structural control on the canyon development.

14.5 The Andenes Chain and the Polarstern Bank

Further southwest in the Weddell Sea, an important linear basement high, completely covered with sediments, was discovered by a Norwegian team in 1985 and named the "Andenes Chain" (ORHEIM, 1985).

The remarkable alignment of this Andenes Chain with the Explora Escarpment lead KRISTOFFERSEN & HAUGLAND (1986), HINZ & KRISTOFFERSEN (1987) and KRISTOFFERSEN & HINZ (1991) to propose a continuity between both structures, which hence may have formed part of a giant "Andenes-Explora Escarpment" (> 1000 km long), although earlier seismic sections as well as recently shot reflection profiles never provided any really conclusive evidence for such an east-west trending alignment of basement highs throughout the eastern Weddell Sea. The hypothesis is therefore often disputed, a.o. by LAWVER *et al.* (1991).

During the ANTARKTIS VIII/5 survey, an important part of the marine geophysical activity was focused on verifying the existence of this proposed structural connection between the Andenes Chain and the Explora Escarpment. As mentioned before, a detailed bathymetric survey suggests that towards the SW the Explora Escarpment fades away as a topographic feature or bends to the south as a highly-reduced sea-floor irregularity. With regard to the supposed continuation of the basement structure beneath the sedimentary cover no definite answer could be obtained.

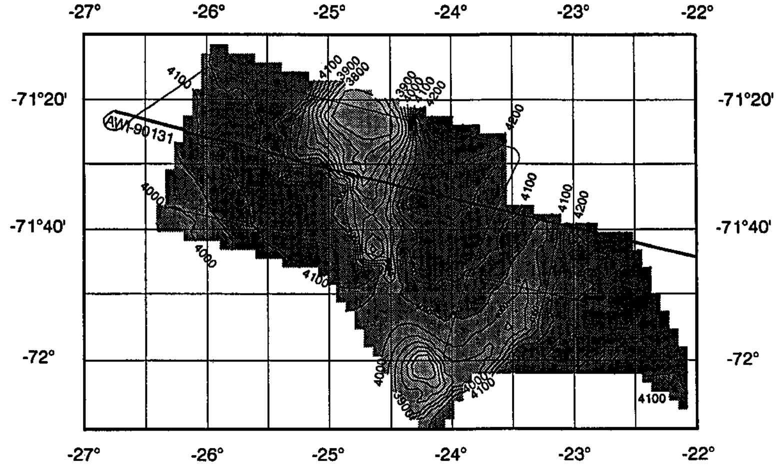


Figure 12. Bathymetry map of Polarstern Bank, acquired during the AWI/RCMG ANTARKTIS VIII/5 survey (from MILLER *et al.*, 1991).

In order to investigate a possible continuation of the vanished Explora Escarpment into the Andenes structures, a number of seismic profiles were shot by AWI/RCMG between 19° and 23°W, the proposed onset of the Andenes Chain (KRISTOFFERSEN & HAUGLAND, 1986). These new data disclosed a hitherto unknown structural feature in the sea-floor morphology, at approximately 71°20'S-25°W : the "Polarstern Bank". HYDROSWEEP sonar data reveal the isolated character and limited size of the structure : the maximum E-W width is 15 km, the elevation above the sea-floor reaches 400 m (figure 12). Heavy ice conditions unfortunately prevented to investigate it north of 71°20'S.

The structure is also characterized by a seismic basement - obviously of oceanic nature as indicated by its seismic character - rising nearly up to the sea-floor. This is particularly striking, considering that elsewhere in the area it is only slightly disturbed and mostly occurs

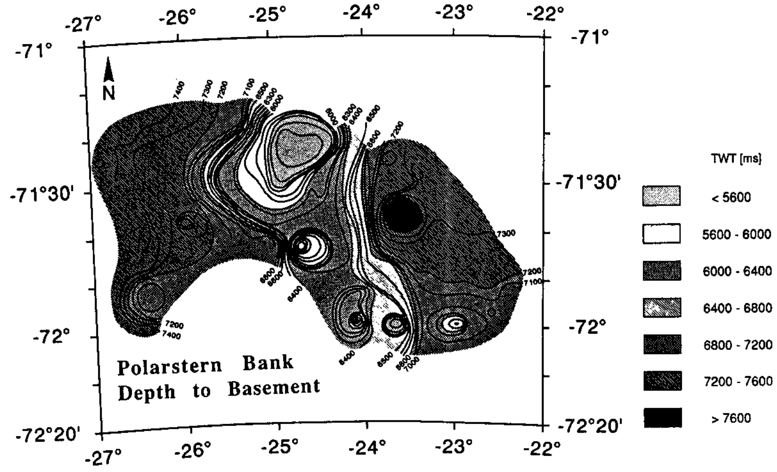


Figure 13. Structural contour map of acoustic basement around Polarstern Bank, based on the seismic profiles acquired during the AWI/RCMG ANTARKTIS VIII/5 survey (from MILLER *et al.*, 1991).

at a depth of 7000 m. Structural mapping of this basement high confirms the narrow E-W extension and the apparently N-S trending strike derived from the bathymetric data (figure 13). The gravity data show a smooth, positive free-air anomaly with a maximum value of 20 mgal. All characteristics of this Polarstern Bank, derived from seismic, gravity and bathymetric data, suggest that it is not structurally or morphologically connected with either the Explora or the Andenes Escarpment.

On the seismic data it can also be observed that the oceanic Polarstern Bank basement has apparently been uplifted with part of its initial sedimentary cover. These early sediments are onlapped on the flanks of the bank by younger sediments, which reach thicknesses of about 1.5-2.5 km. Through correlation across the existing set of interconnected seismic lines in the Weddell Sea it was possible to identify and date this onlap surface. Within the frame of the agreed seismostratigraphic terminology for the Weddell Sea (MILLER *et al.*, 1990) it has been identified as the WO.4a unconformity and thus provides a lower age limit of late Lower Cretaceous (Albian) for the development of this structure (figure 14).

The originating event is therefore probably not related to either of the two proposed rift phases, which are regarded to date from respectively Middle and Late Jurassic times. Therefore, the uplifting of the Polarstern Bank most likely results from post-rift intra-plate tectonics or from some delayed deep crustal intrusion in the northerly continuation of the mid-Jurassic failed rift basin axis.

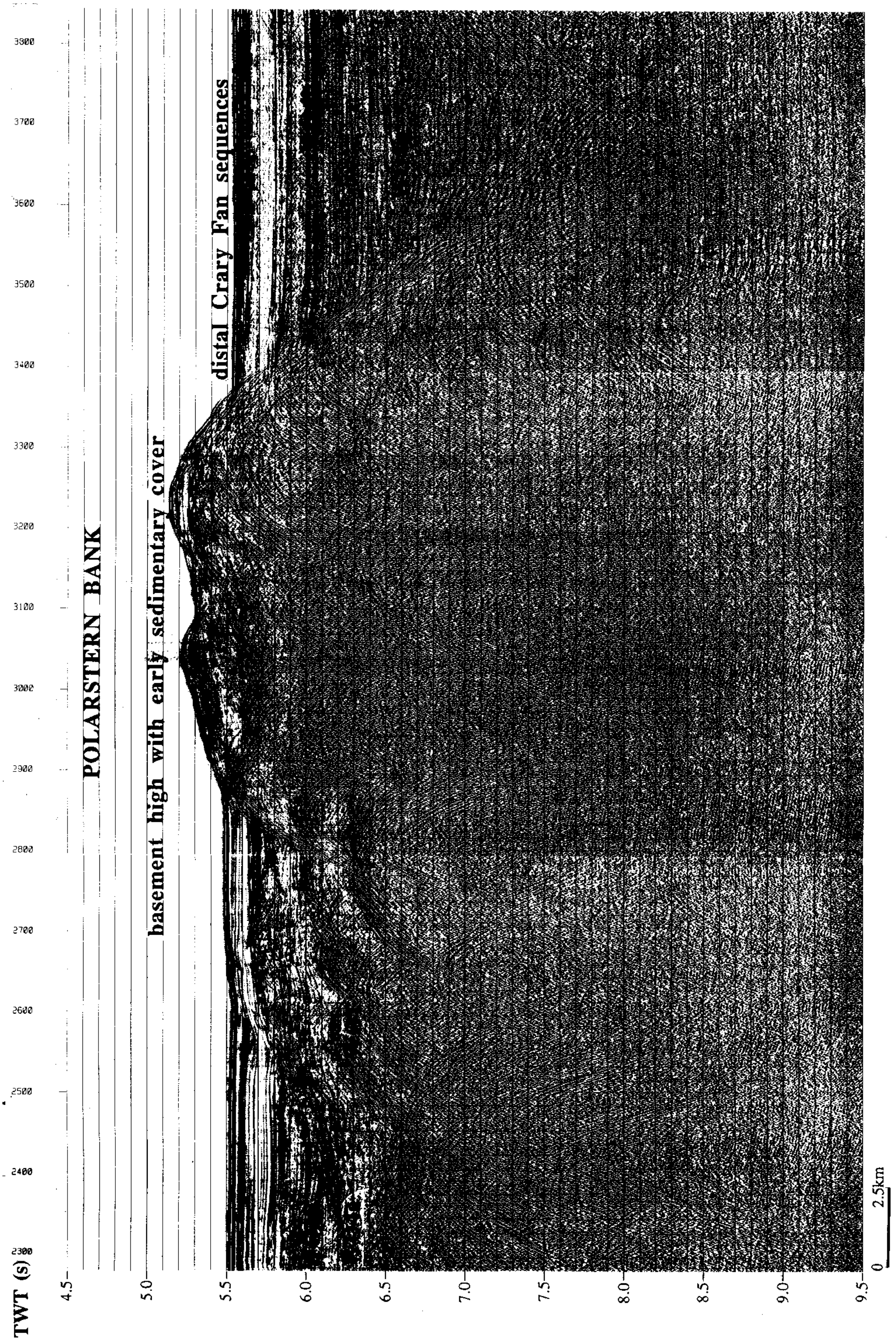


Figure 14. Stacked section of AWI/RCMG profile 90131, showing the Polarstern Bank with its sedimentary cover.

14.6 The AWI/RCMG data versus the HINZ-KRISTOFFERSEN model

Although the AWI/RCMG seismic data seem to confirm that the Explora Escarpment represents an initial Antarctic plate boundary - be it an original rifted margin or one subsequently developed into a transform boundary - the same cannot be concluded for the Andenes Chain. Moreover, on our data no indication whatsoever has been found for a basement structural link between the Explora and Andenes structures. The only structural feature that can be observed between both basement structures is the newly discovered Polarstern Bank, the development of which is clearly of a younger age than what was postulated by HINZ & KRISTOFFERSEN (1987) for the Explora-Andenes Escarpment. The existence of a mega-structural connection between both features is therefore very unlikely.

Nevertheless, recent satellite magnetic investigations (GHIDELLA *et al.*, 1991) reveal the presence of a major structural lineament connecting both the Explora Escarpment and the Andenes Chain, and even extending further south under the Filchner Ice Shelf.

It is clear that with the available combined (reflection-refraction seismics, magnetics and gravimetry) geophysical data-set it is not yet possible to advance a solid model for the early structural evolution of the Weddell Sea basin. A main task for the AWI/RCMG geophysical group on board of R.V. "Polarstern" during the ANTARKTIS X/2 expedition will therefore lie in the acquisition of additional data in well-selected target regions.

1.5 DETAILED SEQUENCE STRATIGRAPHY OF THE CRARY FAN

15.1 General structure of the Crary Fan

Large parts of sea-floor in the southeastern Weddell Sea are overlain by an important submarine fan, the "Crary Fan", which was already identified in former studies (HAUGLAND, 1982 ; HAUGLAND *et al.*, 1985 ; ANDERSON *et al.*, 1986) and has been the subject of recent, detailed investigations by HENRIET *et al.* (1989), KUVAAS & KRISTOFFERSEN (1991) and MOONS *et al.* (1992).

Up to now, the fan deposits have been identified on seismic records in an area between 71-75°S and 22-40°W (an extension of the fan further to the west could as yet not be ascertained). They cover the continental slope and basin floor in front of the Crary Trough, a glacially eroded depression with a maximum observed water depth of 1140 m near the Filchner Ice Shelf and scoured some 630 m into the outer part of the southern Weddell Sea continental shelf. This feature suggests that the Filchner Ice Shelf must have been once some 800 m thicker than at present (ELVERHØI & MAISEY, 1983).

The bathymetric map of the continental margin in this area shows oceanward convex isobath contours in front of the Crary Trough, outlining the position of the accumulated sediments within the fan (figure 15). The upper continental slope is more gentle here than on the eastern side of the fan, where it is characterized by numerous submarine incisions or canyons (JOHNSON *et al.*, 1981) and very coarse debris-like slope deposits.

The Crary Fan exhibits a number of classical structural characteristics of submarine fans, such as the occurrence of different stacked fan lobes and channel-levee complexes (NORMARK, 1970 ; NORMARK, 1978 ; NELSON, 1983 ; STOW *et al.*, 1985). Nevertheless, this is somewhat

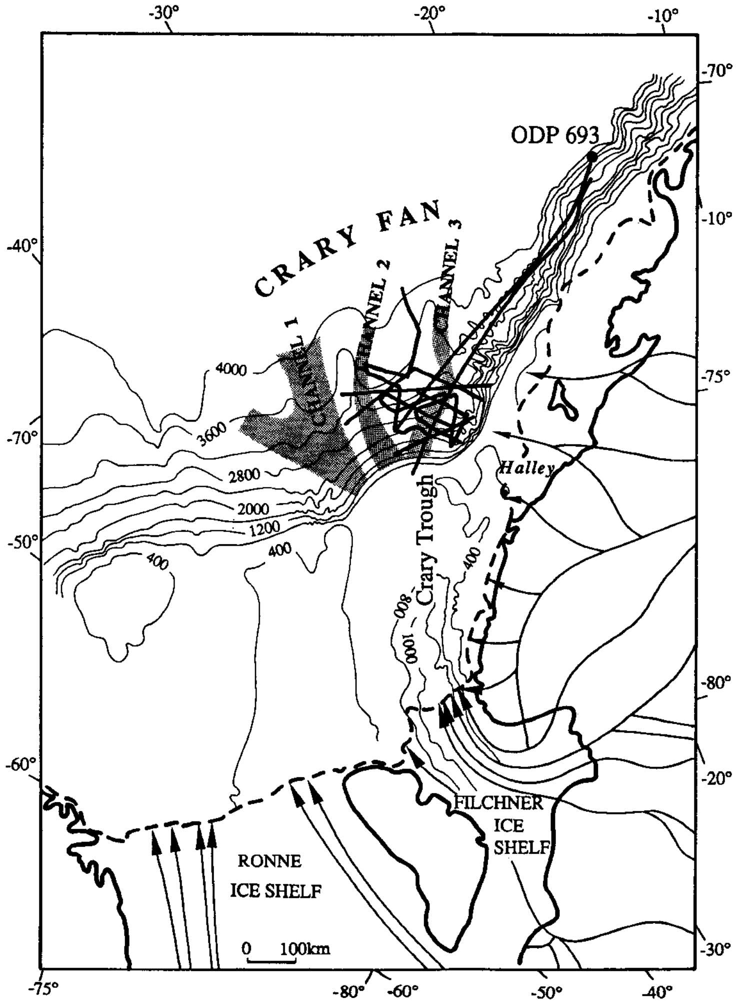


Figure 15. Outline bathymetry of the eastern and southeastern Weddell Sea and location of the AWI/RCMG seismic profiles. Location of the three channel systems of the Crary Fan (channel system I after KUVAAS & KRISTOFFERSEN, 1991). Major recent ice flow lines shown with arrows (after FÜTTERER & MELLES, 1990).

in contradiction with what is generally observed in high-latitude deep-sea fan systems, e.g. in the Barents Sea (VORREN *et al.*, 1989) and in Baffin Bay (AKSU & PIPER, 1987).

The general structure of the fan, as first revealed by KUVAAS & KRISTOFFERSEN (1991) and as confirmed by the AWI/RCMG data, is remarkably simple. It is composed of three major elongate fan systems consecutively deposited one on top of the other, from W to E and from old to young (figures 16-17). Each of these fan systems is characterized by an axial channel, with lengths of more than 200 km and widths of several tens of kilometres. These channels gradually fade out towards the north, towards the distal parts of the fan, located in the Polarstern Bank area. In the area off Halley Bay, the channels are flanked by up to 1500 m thick stacks of levee and overbank deposits, indicating a middle to upper fan context.

The three fan systems are directly overlying the WO4b unconformity in the entire area (figure 4). This implies that the emplacement of the Crary Fan depositional system was probably initiated already from mid-Oligocene times.

15.2 Stratigraphy of the channel-levee systems I to III

Where KUVAAS & KRISTOFFERSEN (1991) identified three fan systems, which were numbered I to III from old to young, the high resolution of the seismic data acquired by AWI/RCMG allowed a much more detailed analysis. Unfortunately however, the AWI/RCMG profiles don't extend as far to the west as the data studied by KUVAAS & KRISTOFFERSEN (1991), but are essentially restricted to fan systems II and III.

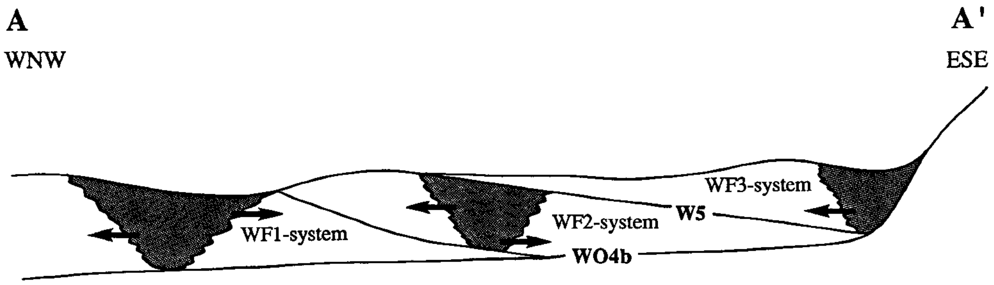


Figure 16. Schematic cross-section through the Crary Fan, illustrating the three stacked fan systems on top of the WO4b unconformity. Arrows indicated direction of levee-outbuilding.

Up to 20 fan sequences ("lobes") could be identified on the AWI/RCMG data. Their boundaries on the seismic records are all more or less important onlap/downlap surfaces or erosional unconformities, which are best observed within the levee and overbank deposits. These

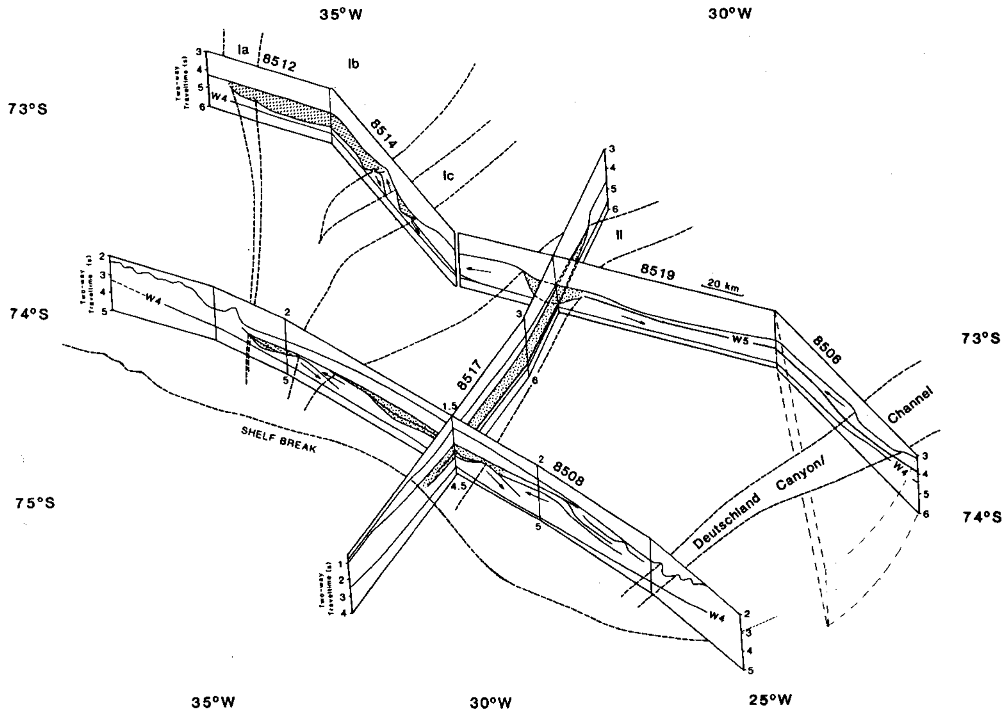


Figure 17. Cartoon showing the interpreted hierarchy of channel-levee complexes forming the Crary Fan (from KUVAAS & KRISTOFFERSEN, 1991).

sequences have been assigned the wf (Weddell Sea Fan) symbol (WF for the entire system), while their associated channel is labelled with the ch (Weddell Sea Fan Channel) symbol (CH for the entire channel complex). The first digit behind this symbol refers to the main fan system (1 to 3, corresponding to systems I to III of KUVAAS & KRISTOFFERSEN (1991)), while the second rank digit determines the depositional sequence itself.

Figure 18a-b-c illustrates the mapped distribution of the different fan sequences within the fan area, and their genetic relationship with the associated channels.

152.1 The wfO sequence

The base of all presently observed fan deposits consists of a set of irregular and discontinuous reflectors, which has a variable thickness, with a maximum between 200 and 300 ms TWT. This unit can be traced in the entire study area and rests directly on top of the WO4b unconformity. It most likely represents a sequence - here provisionally named wf0 - which is formed in a pre-fan period or in an initial phase of fan outbuilding, followed by a period of important erosion.

152.2 The WF1 system

The first true fan sequence on top of these pre-fan deposits is associated with the fan system I of KUVAAS & KRISTOFFERSEN (1991). It is denominated wf1 (without rank number as only 1 sequence can be identified). This sequence can only be observed in the westernmost part of the area covered by the AWI/RCMG data and on some of the available NARE and BGR profiles. The upper boundary of wf1 is an erosion surface, which forms the base of the WF2 system and which is clearly associated with an important migration of the channel complex as the main sediment source towards the east.

152.3 The WF2 system

The overall structure of the overlying fan system WF2 and its associated channel complex CH2, which has a roughly N-S to NNE-SSW orientation, can clearly be recognized on figure 19. It is strongly asymmetrically built, with much better developed and higher stacked levee-deposits at the western side of the channel system. This phenomenon must undoubtedly be attributed to the Coriolis-effect, which in the southern hemisphere tends to diverge all sediment particle to the west.

With this fan system WF2, of which the AWI/RCMG data only cover the eastern levee deposits, up to 5 sequences can be associated : wf2.1 to wf2.5. Sequences wf2.1 to wf2.4 are all on- or downlapping in a southeastern direction against the erosional surface on top of the basal wf0 unit. Some of these levee and overbank sequences attain thicknesses of up to 400 m. Sequence wf2.5 seems to be largely removed by erosion in the eastern levee - which is the reason why it has not been included in figure 18a - while it is very well developed in the western one (figure 19).

The associated channel complex CH2 shows 5 distinct phases of channel migration : ch2.1 to ch2.5. The channels are essentially vertically stacked on top of each other and show very little lateral displacement (figure 18a). The channel system keeps a roughly linear course, and only during deposition of the wf2.3 sequence bifurcation can be observed. On figure 19 the channel complex shows a general tendency to broaden upwards.

The upper boundary of the WF2 system is characterized by a major erosional/onlap surface, which also forms the lower boundary of the WF3 system and thus actually separates the fan systems 2 and 3.

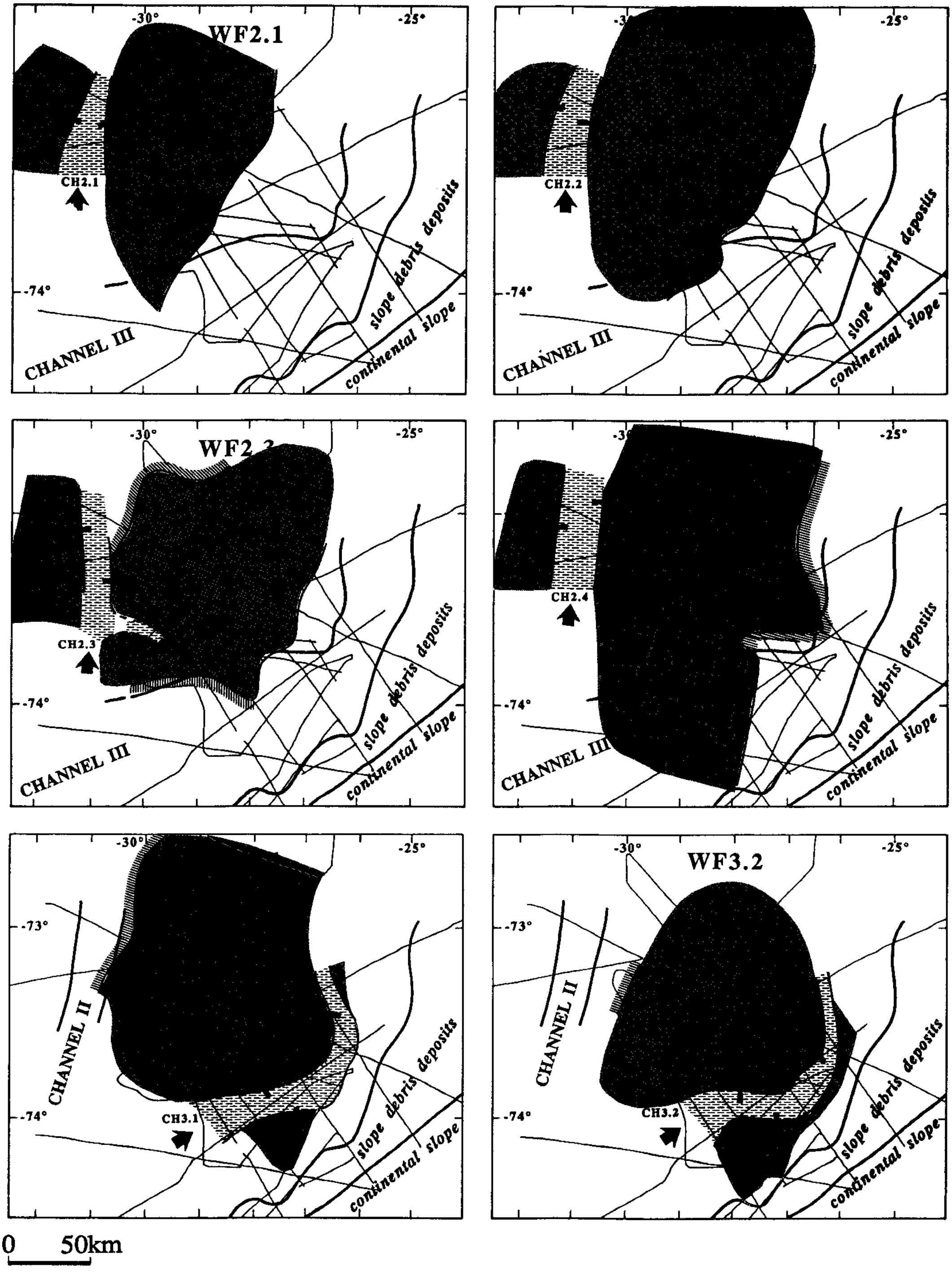


Figure 18a. Mapped distribution of Crary Fan sequences wf2.1 to wf3.2 (plain grey fill) and associated channel system (dashed fill). Arrows indicate derived direction of main sediment transport and levee-outbuilding. Levees terminate either by truncation (hatched limits) or by depositional pinch-out (tick-marked limits).

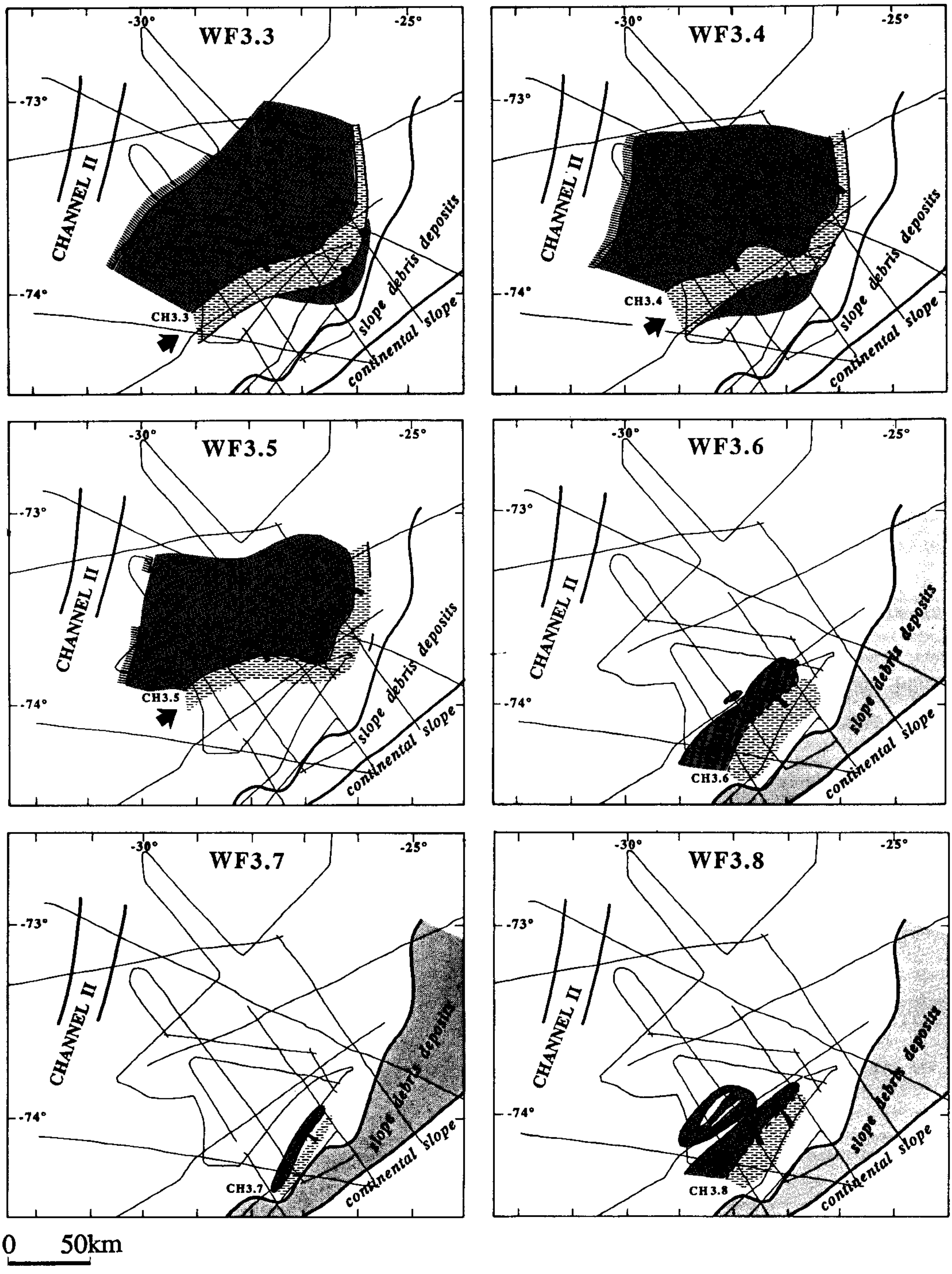


Figure 18b. Mapped distribution of Crary Fan sequences wf3.3 to wf3.8 (plain grey fill) and associated channel system (dashed fill). Arrows indicate derived direction of main sediment transport and levee-outbuilding. Levees terminate either by truncation (hatched limits) or by depositional pinch-out (tick-marked limits).

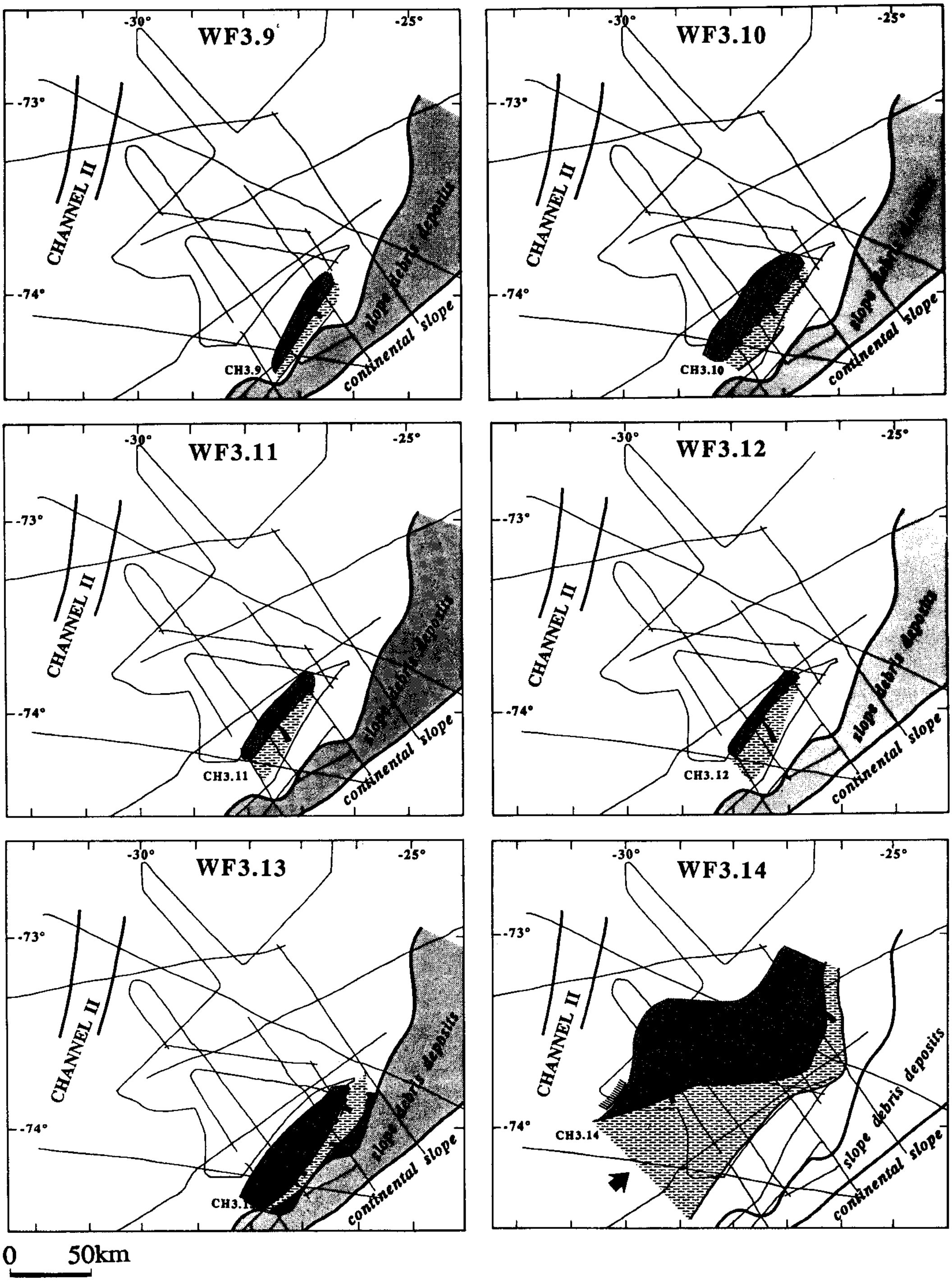
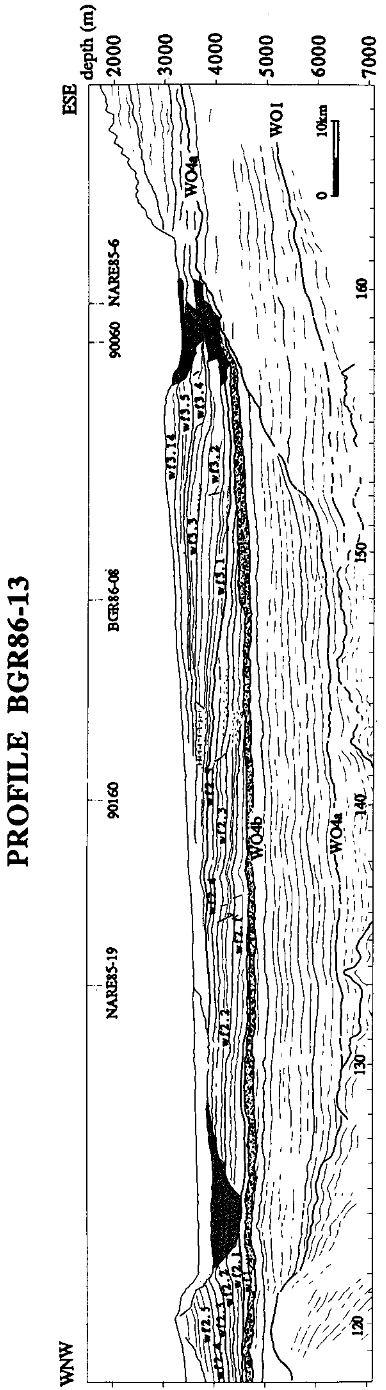


Figure 18c. Mapped distribution of Crary Fan sequences wf3.9 to wf3.14 (plain grey fill) and associated channel system (dashed fill). Arrows indicate derived direction of main sediment transport and levee-outbuilding. Levees terminate either by truncation (hatched limits) or by depositional pinch-out (tick-marked limits).



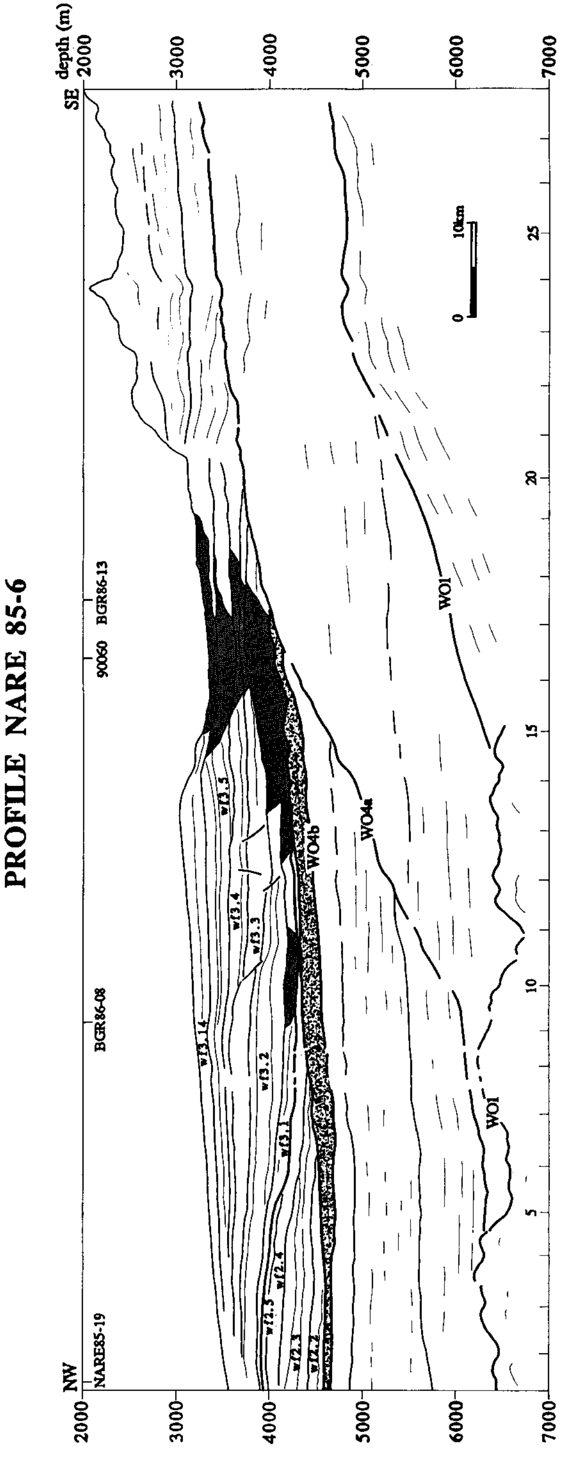
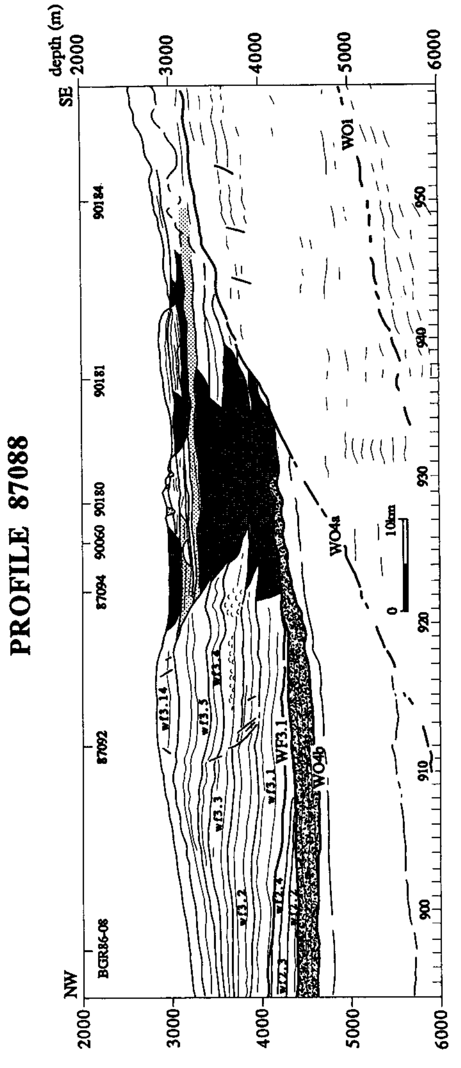


Figure 19. AWI/RCMG line-drawing of profile BGR 86-13. Channel fill deposits indicated by plain dark grey fill.

Figure 20. AWI/RCMG line-drawing of profile NARE 85-6.



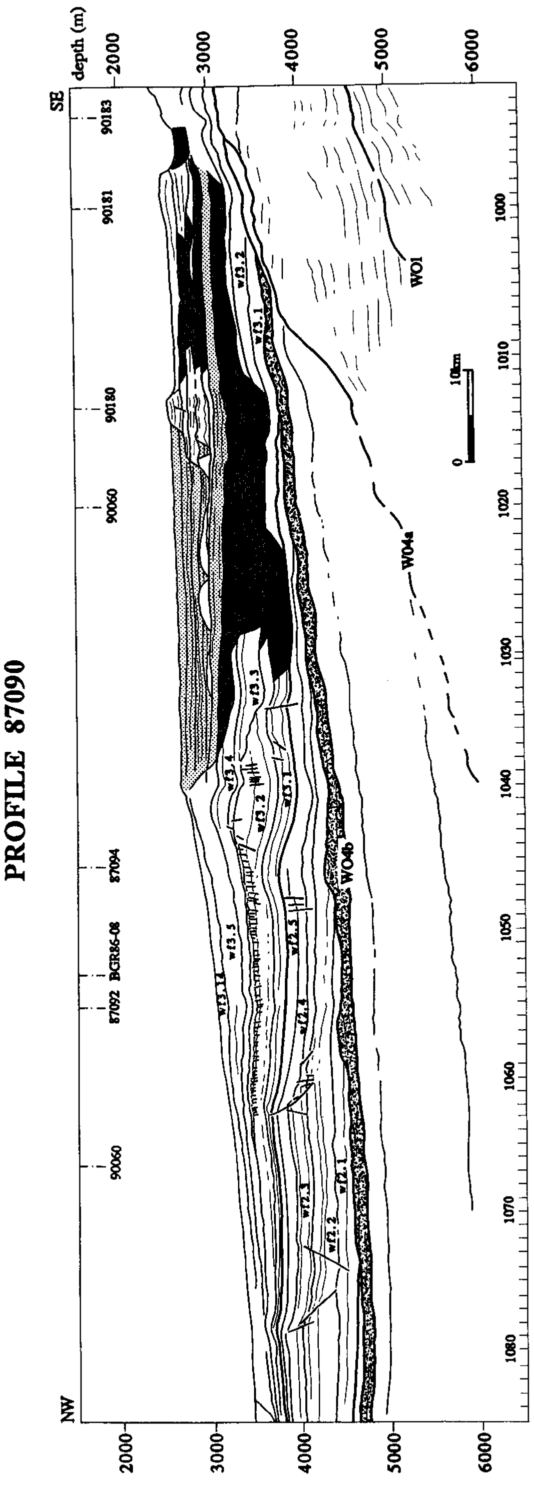


Figure 21. Interpreted line-drawing of AWI/RCMG profile 87090. Channel fill deposits indicated by plain dark grey fill ; continental shelf/slope deposits indicated by plain light grey fill.
Figure 22. Interpreted line-drawing of AWI/RCMG profile 87088.

152.4 The WF3 system

The WF3 system is situated at the foot of the eastern Weddell Sea continental slope and witnesses another major migration to the east of the entire sedimentary system (figures 18a-19-20). WF3 has an outspoken asymmetric structure - even more pronounced than in WF2 - with the channels systematically located at the eastern and the levee and overbank deposits essentially at the western side. This can probably best be observed on figure 19.

Additionally, within WF3 a remarkable change in overall fan outbuilding can be observed. The system can be divided into 2 subsystems : a lower one with sedimentary and structural features comparable to those observed in WF1 and WF2, and an upper one characterized by very high-frequent channel switching processes (figure 18bc).

With the first subsystem 5 sequences can be associated : wf3.1 to wf3.5. Their associated migrating channels (ch3.1 to ch3.5) are fairly large, having widths ranging from 10 to 60 km. They have a meandering course roughly following the foot of the continental slope (figures 18bc-20), characterized by chaotic slope debris deposits. This most likely has prevented the development of continuous levee deposits at the eastern side of the channels, as can be observed on e.g. figure 20.

The well-developed levee deposits towards the west are characterized by a series of strong, continuous and subparallel reflectors, which are locally - essentially in sequences wf3.2 and wf3.3 - interrupted by mass movement features or compaction-related deformations (figures 21-22-23), which are characterized by numerous diffraction hyperbolae.

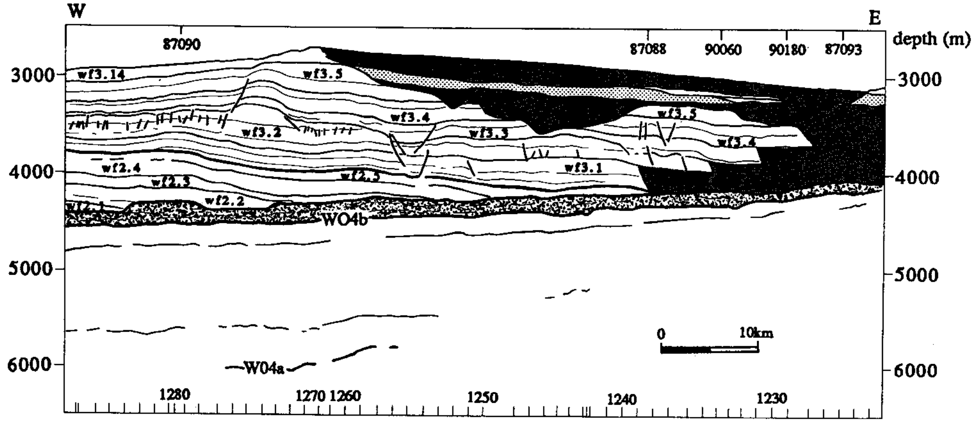
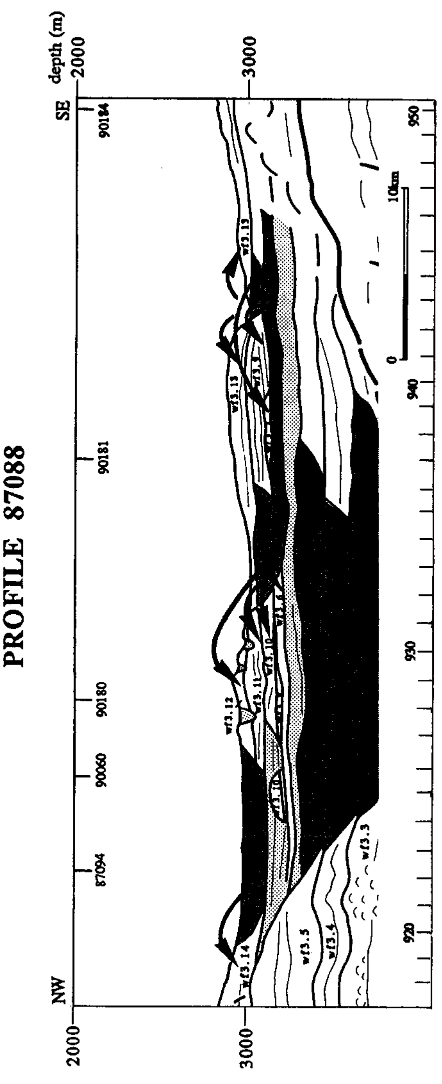


Figure 23. Interpreted line-drawing of AWI/RCMG profile 87094. Channel fill deposits indicated by plain dark grey fill ; continental shelf/slope deposits indicated by plain light grey fill.



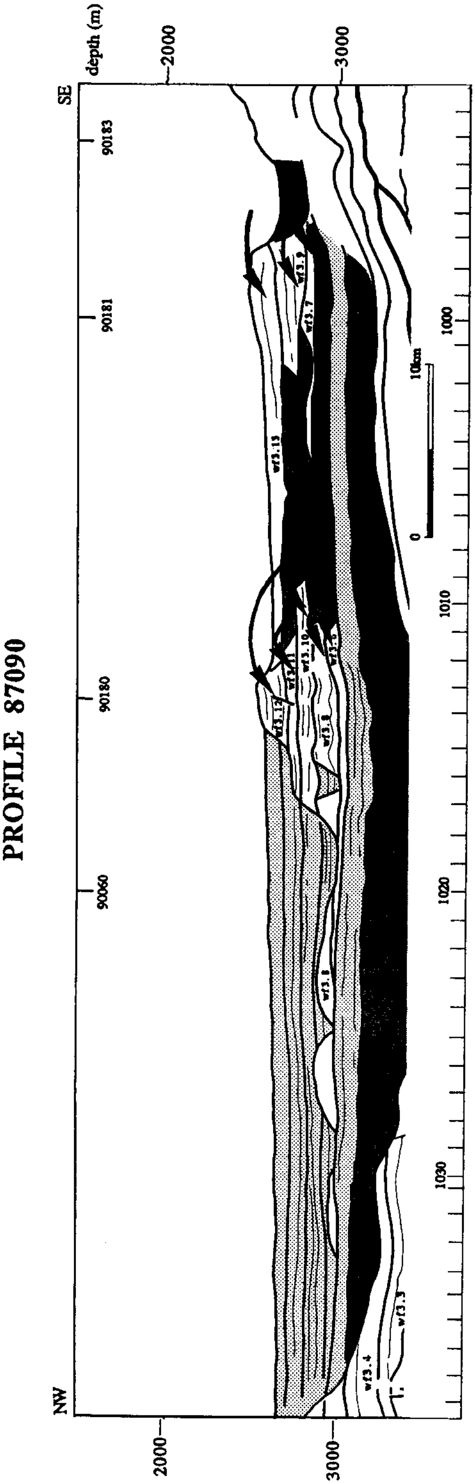


Figure 24. Interpreted line-drawing of AWI/RCMG profile 87090 (enlargement of figure 21). Channel fill deposits indicated by plain dark grey fill ; continental shelf/slope deposits indicated by plain light grey fill ; arrows indicate channel-levee relationship.

Figure 25. Interpreted line-drawing of AWI/RCMG profile 87088 (enlargement of figure 22).

Almost completely incorporated within what appears to be all WF3 channel-fill deposits some remarkable seismic units can be observed (figures 21-22). They exhibit a totally different seismic facies than the surrounding sediments and have initially been interpreted as large olistoliths, partly on base of a striking basal disharmonic folded structure and on an affinity in seismic facies with the levee deposits flanking the channel (HENRIET *et al.*, 1989). These units have been the subject of an detailed survey and integrated interpretation exercise during the ANTARKTIS VIII/5 expedition, which included superficial gravity core sampling, detailed bathymetric mapping (HYDROSWEEP), subbottom profiling (PARASOUND) and high-resolution reflection seismics.

The bathymetric data reveal that these 'floating' sediment bodies actually show up as 2 elongated ridges in the present-day sea-floor morphology, while reflection seismic profiles indeed identify them as continuous structures with a general NE-SW orientation, parallel to the main channel axis (figure 26) (DENNIELOU, 1991). The analog recordings of a.o. profiles 87088 and 87090 (figures 24-25) allow to interprete these sequences as partly eroded levees, deposited in at least 9 phases (wf3.6 to wf3.14) and associated with important successive lateral channel migrations (figure 18bc). The recentmost phase (wf3.14) is characterized by an outspoken broadening of the channel system, with deposition of an extensive western levee.

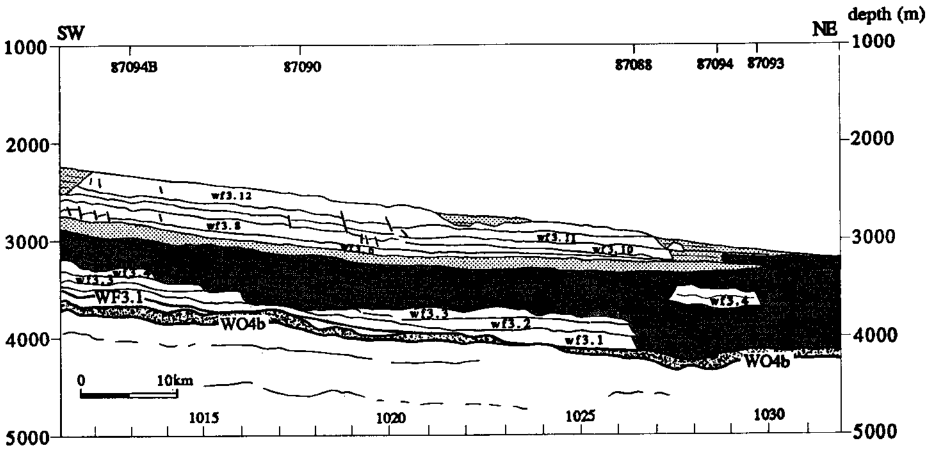


Figure 26. Interpreted line-drawing of AWI/RCMG profile 90180. Channel fill deposits indicated by plain dark grey fill ; continental shelf/slope deposits indicated by plain light grey fill.

A detailed analysis of the responsible sedimentary processes points to a multi-phased, high-frequent back-and-forth switching channel activity, leading to the formation of a complex, funnel-shaped CH3 channel system.

As a whole these remnant levee deposits and the associated channel fills represent the second subsystem of WF3. Additionally, and interbedded between the channel-levee deposits of WF3 the distal parts of some of the continental slope deposits can be observed.

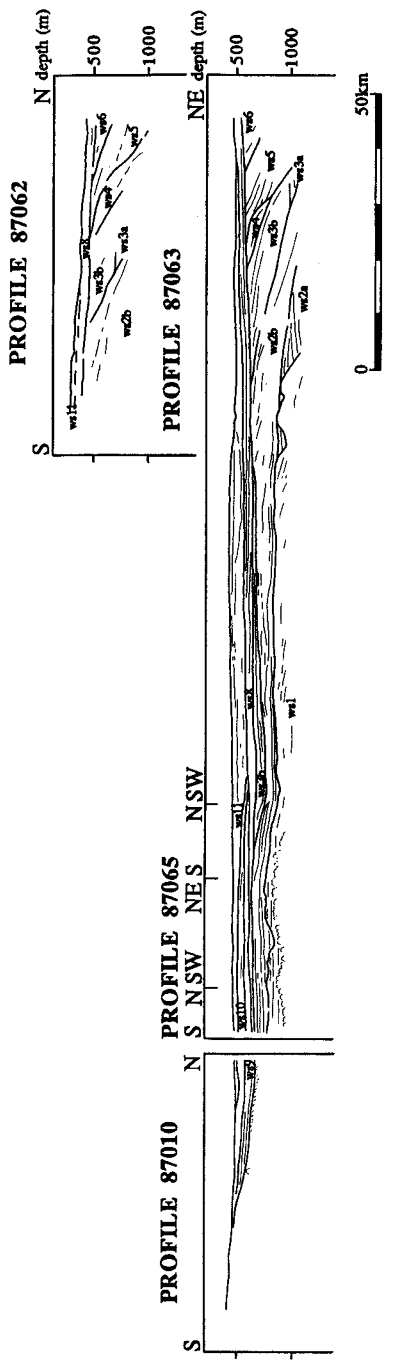
15.3 Stratigraphy of the associated shelf deposits

The Cenozoic deposits, which build up the southern Weddell Sea continental shelf, attain a thickness of more than 5000 m in front of the Filchner Ice Shelf and are characterized by a distinct obliquely prograding internal structure (HAUGLAND, 1982 ; ELVERHØI & MAISEY, 1983 ; HAUGLAND *et al.*, 1985). These deposits, which have also been described by HENRIET *et al.* (1989), HINZ & KRISTOFFERSEN (1987) and COOPER *et al.* (1991), indicate a high rate of sediment input and deposition, presumably in a deltaic environment on a subsiding continental shelf.

The seismic processing of the AWI/RCMG data from the ANTARKTIS V/4 expedition, profiles 87062 to 87065 (figure 27), and the acquisition of the new shelf profile 90060 during the ANTARKTIS VIII/5 expedition (figure 28) has yielded a better insight in the exact configuration and facies of these prograding units and of the cut-and-fill structures associated with them. It is however clear that the structure of the continental shelf is not simple : on top of the basement, composed of cristalline rocks of the East Antarctic Craton (ELVERHØI & MAISEY, 1983), at least 11 sequences with a complex prograding internal structure can be observed, although the interpretation is heavily impeded by the strong sea-floor multiples and the steep slope.

The observed prograding units have been assigned the ws (Weddell Sea Shelf) symbol, followed by a ranking number from 1 to 11. All are separated by major erosional unconformities, which become increasingly important towards the paleo-shelf break, where the sequences are often abruptly truncated. The most important erosion appears to have taken place between the deposition of units ws7 and ws8 (figure 27), as the base of ws8 truncates all underlying units. Some sequences (ws9 and ws10) occur only in a limited area high on the shelf, whereas other sequences extend much further into the basin : ws7, ws8 and ws11 pinch out against the remnant levee deposits in CH3 and ws6 even completely covers the ch3.5 channel deposits (figure 28).

Within some of the prograding wedges a lower sub-unit can be distinguished, which is characterized by a distinct coastal onlap and apparent truncation pattern. Both sub-units - the onlapping basal unit and the prograding upper unit - therefore most likely represent two fundamentally different episodes in the process of shelf outbuilding.



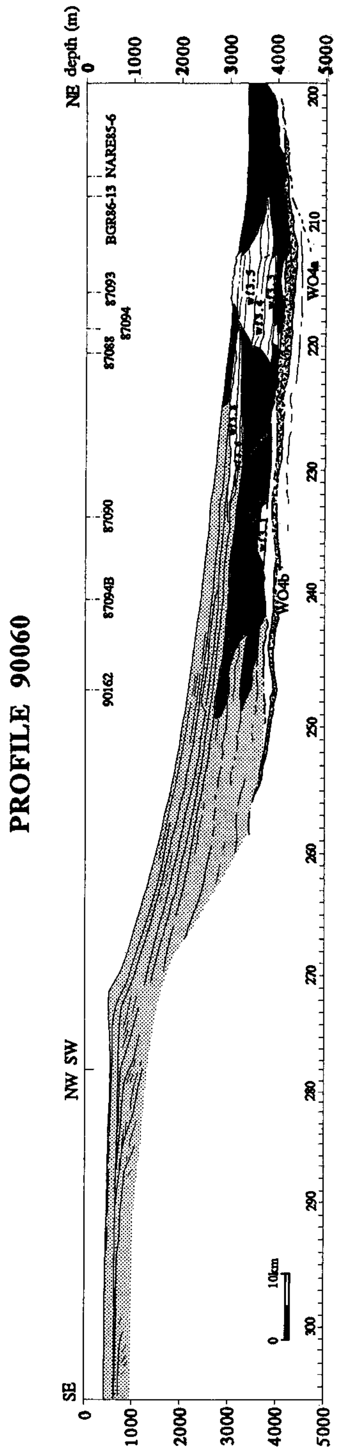


Figure 27. Interpreted line-drawing of AWI/RCMG profiles 87010, 87062, 87063 and 87065.
Figure 28. Interpreted line-drawing of AWI/RCMG profile 90060. Channel fill deposits indicated by plain dark grey fill ; continental shelf/slope deposits indicated by plain light grey fill.

The succession of prograding wedges, observed on the AWI/RCMG data (figures 27-28), indicates a shelf progradation of a least 70 km since the deposition of ws1 on top of the cristalline basement. KUVAAS & KRISTOFFERSEN (1991) also inferred a shelf edge progradation of about 70-80 km, since the onset of fan growth (mid-Oligocene), among which 35 km during the last 15 my (mid-Miocene).

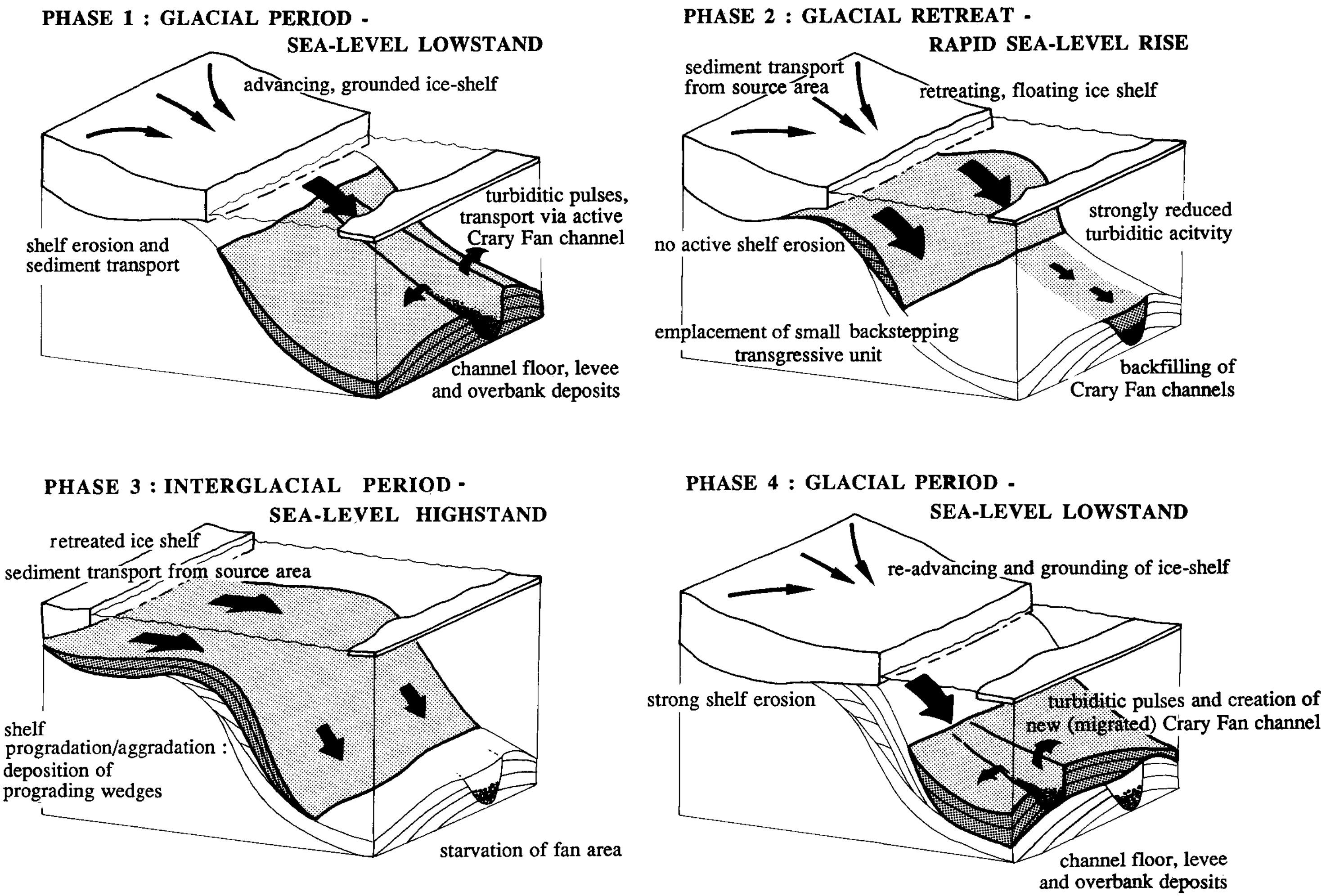
15.4 The eustatically controlled sedimentation model for the Crary Fan

154.1 Eustatic and climatical controls on the sequence stratigraphic framework

It is a basic concept that changes in eustatic sea-level play a key role in the spatial organization of submarine fan systems (BOUMA *et al.*, 1985 ; WEIMER & LINK, 1991). Highstands of sea-level commonly coincide with relatively inactive phases, while lowstands result in active fan growth in many well described fans, e.g. in the Indus Fan (KOLLA & COUMES, 1987) and in the Mississippi Fan (FEELEY *et al.*, 1990 ; WEIMER, 1990). Submarine fan sequences therefore most likely entirely consist of lowstand systems tracts, the so-called basin-floor fan and lowstand wedge deposits (VAN WAGONER *et al.*, 1988). During periods of rising sea-level the fan gradually starves and the depocentres shift towards the coast, thus creating the typical backstepping, onlapping deposits of the transgressive systems tracts (VAN WAGONER *et al.*, 1988). In a later phase, during sea-level highstands, shelf edge outbuilding processes dominate with the instalment of the aggradational and/or prograding wedges of the highstand systems tracts (VAN WAGONER *et al.*, 1988).

Nevertheless, it has always remained a point of debate whether individual fan sequences - as identified by stratal pattern analysis on seismic sections - actually result from autocyclic processes, such as sediment bypassing due to channel blocking (DROZ & BELAICHE, 1985) or channel meandering, or wether they are externally induced, e.g. by eustatic sea-level changes or tectonic processes. It is AWI/RCMG profile 90060 across the Crary Fan (figure 28) that could give a conclusive answer to this question. On this profile the distal parts of the transgressive and highstand wedges are interbedded in between the lowstand fan sequences, indicating that each of these fan sequences is deposited during one particular lowstand period and followed by a sea-level rise. Each of the fan sequences therefore indeed corresponds to a different eustatic cycle.

Eustatic sea level variations in the recentmost geological times are known to be in phase with glacial/interglacial fluctuations (HAQ *et al.*, 1987), at least on a world-wide scale. Therefore deep-sea fan growth most probably occurs during glacial periods, while the fans are essentially sediment starved during the interglacials, when sedimentation is shifted to the shelf and upper continental slope.



PHASE 1 : GLACIAL PERIOD - SEA-LEVEL LOWSTAND

PHASE 2 : GLACIAL RETREAT - RAPID SEA-LEVEL RISE

PHASE 3 : INTERGLACIAL PERIOD - SEA-LEVEL HIGHSTAND

PHASE 4 : GLACIAL PERIOD - SEA-LEVEL LOWSTAND

Figure 29. The Weddell Sea continental margin sedimentation model.

154.2 The Weddell Sea continental margin sedimentation model

On the grounds of the above considerations a cyclic 4-phased climatic-eustatically controlled sedimentation model can be advanced : Phase 1 representing a glacial period, Phase 2 a period of glacial retreat, Phase 3 an interglacial period and Phase 4 a new glacial period. This model is also illustrated in figure 29.

Phase 1 : Glacial period - Sea-level lowstand - Active fan growth

Global cold climate or glacial periods correspond to eustatic sea-level lowstands. They are also characterized by advancing and eroding grounded ice sheets, covering the entire continental shelf, where they are believed to be responsible for erosion, basal till deposition, deposition of water-lain tills at the grounding line and deposition of dropstone diamictons in regions of basal melting (KUVAAS & KRISTOFFERSEN, 1991). On profile 87065 (figure 27), the ubiquitous erosion scars within the shelf sequences clearly illustrate the erosive effect and the extent of the grounded ice sheets.

Such ice sheets can mobilize large amounts of sediments and transport them from the hinterland. Especially the Filchner and Ronne Ice Shelves function as sediment discharge funnels for a huge catchment area (figure 15) (FÜTTERER & MELLES, 1990). As the ice sheet reaches the shelf edge, these sediments are deposited on the upper continental slope. Slumping of these rapidly deposited sediments can generate mass flows and turbidite sedimentation, which could account for the lens-shaped deposits in front of the Crary Trough observed by HAUGLAND *et al.* (1985) and by KUVAAS & KRISTOFFERSEN (1991).

Subglacial meltwater streams, possibly channelized by subglacial scour features such as the Crary Trough, supply sediment directly to channels or canyons incised in the slope by means of turbidity currents. These are responsible for typical turbiditic sedimentation features such as channel-levee complexes in a fan-type setting, with coarse lag deposits on the channel floor and well-sorted fine-grained levee and overbank deposits radially downlapping from the channel outwards. This characteristic channel-levee configuration is obvious on all AWI/RCMG profiles, while seismic facies analysis confirms the coarse nature of the channel deposits and the finer-grained levees.

Widespread distribution of thick turbiditic sands on the continental slope and abyssal plain in the eastern Crary Fan area has indeed been described by WRIGHT & ANDERSON (1982). As a result of the Coriolis-effect, the western levees generally tend to be higher and better developed (figure 19), a phenomenon which has a major effect on the longer-term development of the fan.

Phase 2 : Glacial retreat - Rapid sea-level rise - Fan starvation

During periods of global climate warming the grounded ice shelves gradually retreat, while eustatic sea-level responds with a rapid rise. Such a sea-level rise induces further basal melting and eventually floatation of the ice sheets. On the continental shelf, where subglacial erosion has now ceased, this results in the deposition of dropstone diamictons in regions of basal melting and in the winnowing of shelf sediments by cold bottom water flows (HAASE, 1986).

These cold-water bottom currents however still supply large amounts of sediment to the upper continental slope and shelf margin. Here, they are deposited as small, rapidly backstepping and onlappping transgressive units (e.g. unit ws2a on figure 27), the sedimentation of which is keeping pace with the fast sea-level rise. The development of small transgressive systems tracts is typical for a rapid sea-level rise in an environment with a large sediment supply (BOWMAN & VAIL, 1992).

As the areas of main deposition are gradually backstepping up-slope as a response to the rising sea-level, rapid sedimentation on the continental slope is strongly reduced. This implies a marked decrease in the turbiditic activity and hence a gradual starvation of the fan proper. However, direct sediment supply to the fan area can to a certain extent be maintained by sediment charged cold bottom water flows, channelized through the existing continental slope channels or canyons. This phenomenon could account for the gradual backfilling of the fan channels with badly sorted and relatively fine-grained sediments, covering the coarser lag deposits on the channel floor (KOLLA & COUMES, 1987).

Phase 3 : Interglacial period - Sea-level highstand - Shelf progradation

Global warm climate or interglacial periods correspond to eustatic sea-level highstands. These are characterized by a maximal retreat of the floating ice sheets, which hereby disclose large parts of the continental shelf. The shelf deposits undergo further winnowing by cold bottom water flows.

The sediments imported from the hinterland and transported over the continental shelf as suspension loads in the cold meltwater from underneath the ice shelves, are freely deposited on the shelf and upper slope, hereby forming the typical aggradational or progradational wedges (e.g. ws3b on figure 27). Indeed, as the continental margin channels and canyons have been gradually infilled during the sea-level rise, they no longer act as preferentially pathways for these sediment-charged cold bottom water flows.

High-velocity cold and dense meltwater currents flow vigorously downslope and mainly cause erosion (KUHN, 1992 ; KUHN & WEBER, in press). Such flows are most likely responsible for the development of the present-day sea-floor channels, such as the "Deutschland Canyon Channel" and "Cold Water Channel" identified by KUVAAS & KRISTOFFERSEN (1991). In this way, small amounts of sediments may have been supplied to the fan area by winnowing from the shelf and upper slope. However, except for a small amount of hemipelagic sedimentation (WEIMER, 1990) and for re-sedimentation processes, due to channel wall or levee instabilities, the fan area can now be considered as essentially sediment starved.

Phase 4 : Glacial period - Sea-level lowstand - Shelf erosion and active fan growth

As a new glacial period starts, eustatic sea-level will fall and the Filchner and Ronne ice sheets will re-advance onto the southern Weddell Sea continental shelf and become grounded. This will obviously cause severe erosional truncation of the shelf and upper slope sequence that was deposited during the previous sea-level highstand.

As a result of this renewed ice sheet expansion, turbiditic activity will increase with the re-development of canyons or channels in the continental slope and the deposition of a new channel-levee fan sequence. This sequence will be deposited in that area providing the most accommodation space and simply vertical stacking of channel-levee complexes through time is therefore very unlikely. This implies that at a certain moment in time the depocentre - and consequently the course of the channel - will be shifted. As a result of the strongly developed western levees, the channel will in this case be forced to migrate to the E, which explains the development of the fan by stacking of fan lobes from W to E.

The above model is completely in accordance with the classic sequence stratigraphy concepts along passive continental margins, in which shelf and slope progradation take place during relative sea-level highstands. However, the situation is believed to be much more complex along glaciated margins, where it has been observed that shelf progradation could very well occur during periods of maximal glaciation, thus during periods of global eustatic lowstand (BOULTON, 1990). In such a setting, the isostatic effect of the advancing ice is regarded to exceed the eustatic response to ice sheet expansion, hereby creating relative sea-level highstands during periods of global eustatic lowstand. Future research work of RCMG's Seismostratigraphic Unit will therefore focus on evaluating the above fan sedimentation model in the light of BOULTON's (1990) glaciated margin progradation model.

154.3 The evolution of the Crary Fan through time

The stratigraphic models obtained through the interpretation of the seismic data covering the Crary Fan deposits and of those on the southeastern Weddell Sea continental shelf could up until now hardly be correlated. Only HAUGLAND *et al.* (1985) made an early attempt to this end. Consequently, it remained still highly speculative to assign precise ages to the prograding shelf margin sequences as well as to the deep-sea Crary Fan sequences. AWI/RCMG profile 90060, providing the 'missing link' between the lower continental slope and the continental shelf (figure 28), allows the formulation of a time-controlled sedimentation model for the southeastern Weddell Sea continental margin, in a classic sequence stratigraphic framework.

Considering that in the above model the development of the fan sequences is restricted to periods of eustatic sea-level lowstand and taking into account the probable initiation of fan growth in mid-Oligocene times, it is tempting to associate the 20 Crary Fan sequences with the known 3rd order hierarchy eustatic cycles of HAQ *et al.* (1987) and the 3 major Crary Fan systems, bounded by the most outspoken unconformities, with the second order cycles TB1 to TB3 (figure 30).

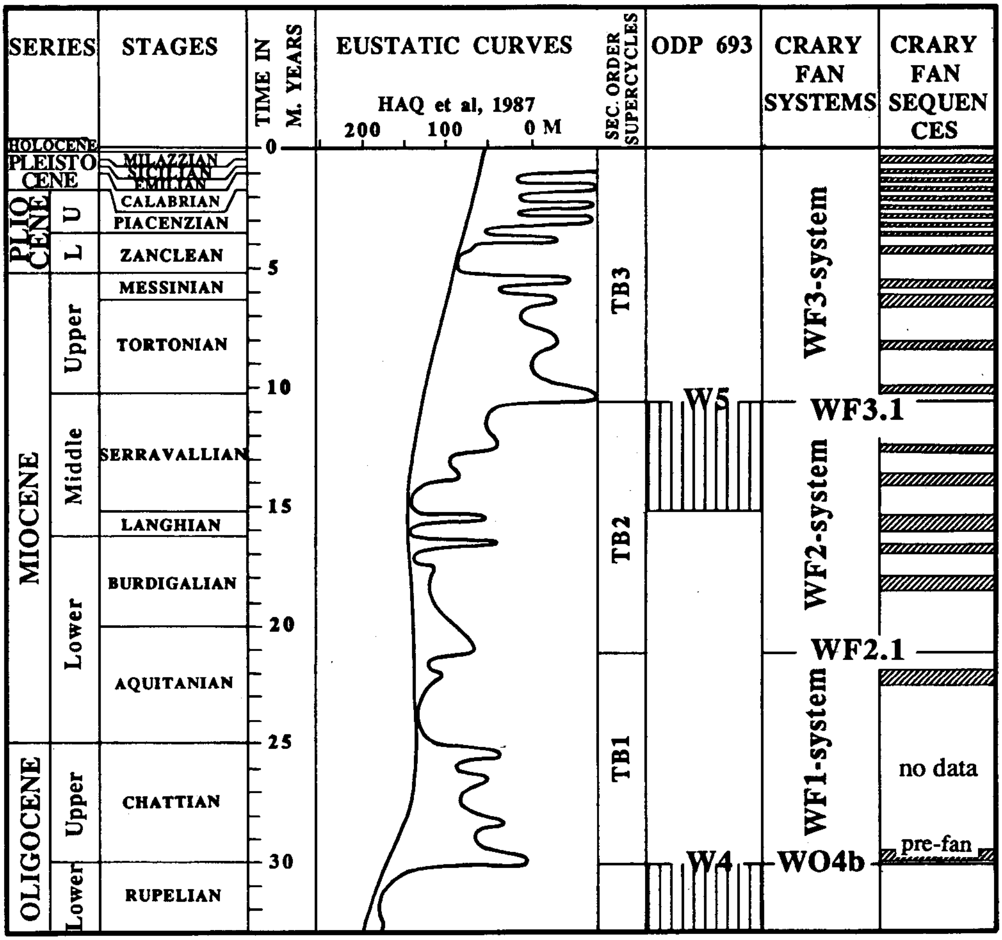


Figure 30. Tentative correlation of the Crary Fan sequences and systems with the eustatic sea-level curve of HAQ *et al.* (1987).

The boundary between fan systems WF1 and WF2 therefore probably corresponds to the Lower Miocene sea level drop. The unconformity at the base of the WF3 system would then most likely correspond to the important Middle Miocene sea level drop. This boundary was already correlated by KUVAAS & KRISTOFFERSEN (1991) with the Middle Miocene unconformity W5, identified on ODP site 693.

Linking each of the 20 individual fan sequences with the 3rd order cycles may however be less obvious. Nevertheless, it is a striking observation to see that the number of sequences within each of the fan systems and the frequency of depositional changes more or less correspond to those of the eustatic cycles. In particular the striking change in fan behaviour observed within WF3, with the sudden instalment of a quickly changing sedimentation pattern, seems to reflect the clearly climatically induced, rapid and relatively high-amplitude sea-level fluctuations that occurred during Late Pliocene to Quaternary times (figure 30).

The proposed sedimentation model and its tight link to the well-dated sea-level curve of HAQ *et al.* (1987) certainly deserves further attention, as high-resolution stratigraphic analysis of high-latitude submarine fans might prove an ideal tool for better understanding the history of sea level fluctuations and of the associated glacial/interglacial climatic changes.

PART 2 : THE ANTARCTIC PENINSULA

2.1 RESEARCH OBJECTIVES AND PROGRESS

In HENRIET *et al.* (1989) the preliminary interpretation was presented of some seismic data from the northwestern part of the Antarctic Peninsula. These data were acquired during the ANTARKTIS VI/2 expedition, which took place on R.V. "Polarstern" from November to December 1987, and during which the marine geophysical programme was carried out jointly by the Renard Centre of Marine Geology (RCMG), the Alfred-Wegener-Institut für Polar- und Meeresforschung (AWI) in Bremerhaven (GER) and the Institut für Geophysik of the Christian-Albrechts-Universität in Kiel (GER).

In this interpretation special attention was paid to the analysis of the interaction between the essentially glacially-marine controlled sedimentation and the active margin evolution along this part of the Antarctic Peninsula. As a result of the subsequently released new literature and of numerous discussions with fellow researchers working on the Antarctic Peninsula, some new insights were obtained in the evolution of this margin and the interpretation was slightly further developed. Those concepts which have evolved since publication of HENRIET *et al.* (1989) are summarized below.

2. 2 ACTIVE MARGIN HISTORY

The Pacific margin of the Antarctic Peninsula is characterized by a complex subduction history, which lasted from long before the break-up of Pangea up to recent times. The older subduction history has left its scars in the ancient accretionary wedge structures and magmatic rocks exposed on the islands and on the mainland, while the more recent Cenozoic active margin dynamics are well reflected in the magnetic anomaly pattern and the bathymetry of the ocean floor. An updated map of isochrons, derived from magnetic anomalies by using a standard magnetostratigraphic scale (COX & HART, 1986), and including interpreted plate-tectonic features is shown in figure 31.

A comprehensive analysis of these magnetic anomaly patterns around the Antarctic Peninsula in terms of plate tectonic processes has been presented by BARKER (1982), who described the sequence of successive ridge-trench collisions, which probably started in the south of the peninsula some 50 Ma ago. After each collision, which progressively migrated in northward direction, subduction and spreading both stopped in the concerned plate segment ; the trench topography disappeared and the margin became a passive margin. According to BARKER (1982),

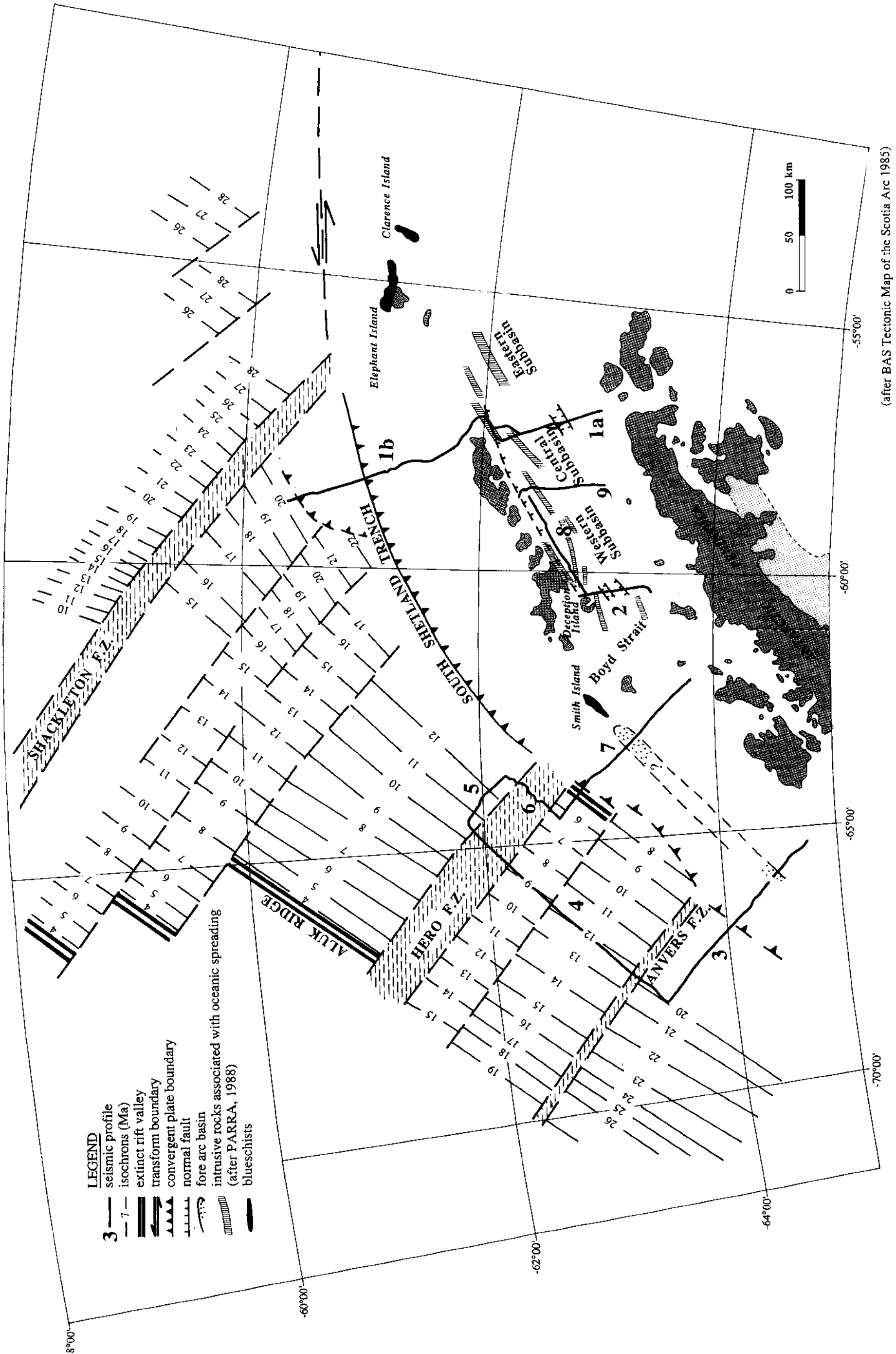


Figure 31. Sea-floor isochron map, interpreted from the Tectonic Map of the Scotia Arc (BRITISH ANTARCTIC SURVEY, 1985), and structural elements identified during the ANTARKTIS VI/2 expedition.

this process went on up to 6.5 to 4 Ma ago, when the last ridge segment would have collided, just south of Hero F.Z.

As discussed further on and in contrast with the hypotheses put forward in HENRIET *et al.* (1989), it is now believed by most authors that the ridge-trench collision which occurred in the segment just north of Anvers F.Z. some 6.5 Ma ago (anomaly 4) actually could have been the last one. It seems, however, to be well established that spreading stopped at the northernmost ridge sections between Hero and Shackleton F.Z. about 4 Ma ago, well before the last ridge segments had reached the trench (BARKER, 1982). The "Drake" plate segment between Hero and Shackleton F.Z. (BRITISH ANTARCTIC SURVEY, 1985) is consequently the last major remnant of the subducted Aluk plate.

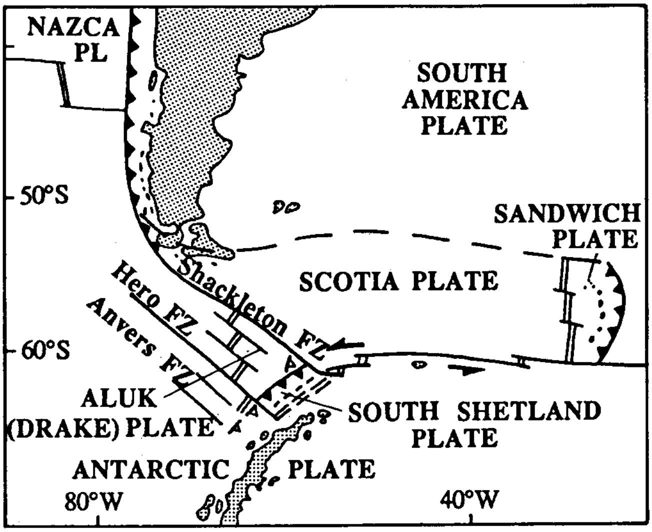


Figure 32. Plate tectonic setting of the study area (modified after BARKER, 1982).

The chronology of the extension of Bransfield Strait seems to be in accordance with the above ridge-trench collision model. Rifting may have started in Early Pliocene times (JEFFERS *et al.*, 1991), while the opening of the basin apparently started some 2 Ma ago (WEAVER *et al.*, 1982 ; GONZALEZ-FERRAN, 1991). The opening of Bransfield Strait generated a new microplate, the South Shetland plate (figure 32), bounded by a postulated back-arc spreading axis in Bransfield basin, by the South Shetland Trench, Shackleton F.Z. and a left-lateral transform fault in the extension of Hero F.Z. along Boyd Strait, decoupling the South Shetland volcanic arc and Bransfield basin from the continental margin further south. Present-day rifting is substantiated by the tensional stress regime, which finds its expression in the earthquake fault plane solutions for the southwestern Bransfield Strait and the South Shetland Trench (BRITISH ANTARCTIC SURVEY, 1985 ; PELAYO & WIENS, 1989).

The coinciding length and parallelism of Bransfield Strait, the South Shetland Trench and the desactivated spreading ridges between Hero and Shackleton F.Z. suggest a close relationship. BARKER (1982) has proposed that Bransfield Strait opened because of the cessation of spreading, as a result of the continuing sinking of the remnant plate at the trench : the "trench suction" of FORSYTH & UYEDA (1975). JEFFERS *et al.* (1991) attribute a possible relationship between the segmentation of Bransfield basin and its fan-shaped opening - with the northern sub-basin displaying the characteristics of early sea-floor spreading, while the southwestern one is still in a stage of incipient rifting - to differing rates of sinking of the subducted slab : the older, denser slab fragment below the northeastern sub-basin could sink faster, driving extension more rapidly than further to the south.

However, the opening of Bransfield Strait may not uniquely be a simple rollback or response to trench suction. The left-laterally moving Scotia Plate which obliquely impinges upon the northern edges of the Shetland and Drake platelets (figure 32) may be responsible for a westward movement with possibly a counter-clockwise rotation of the South Shetland microplate. The progressive shift from a subduction-controlled stress regime towards a larger control by the left-lateral convergence between the South American and Antarctic plates is also supported both by the stress field evolution reflected in the succession of joint patterns on King George Island (TOKARSKI, 1991) and by the present observation of a fragment of the Drake Plate which, squeezed between Shackleton F.Z. and the South Shetland Arc, apparently chipped off and got tilted under probably highly transpressional stresses.

2.3 CONVERGENCE RATES

The rate of plate convergence is an important factor which not only controls the morphology of trench and accretionary wedge, but also the thermal regime of the sinking plate, and consequently the possible development of metamorphic mineral assemblages.

The intraplate setting of the Aluk Plate within the Antarctic Plate constrains in a very effective way the local convergence rates, which up to the cessation of spreading amounted to exactly twice the half-spreading velocities. The convergence rates, averaged over the past 25 Ma, are in the order of magnitude of 4-5 cm/year.

A closer look at the evolution of these velocities as a function of time however reveals a remarkable and systematic acceleration shortly preceding ridge-trench collision. This observation is illustrated by figure 33, displaying the convergence rates for the margin segments immediately west of Anvers F.Z., between Anvers and Hero F.Z. and between Hero and Shackleton F.Z. This figure differs from that presented in HENRIET *et al.* (1989), as it takes into account the slightly revised concept of last ridge-trench collision and spreading stop.

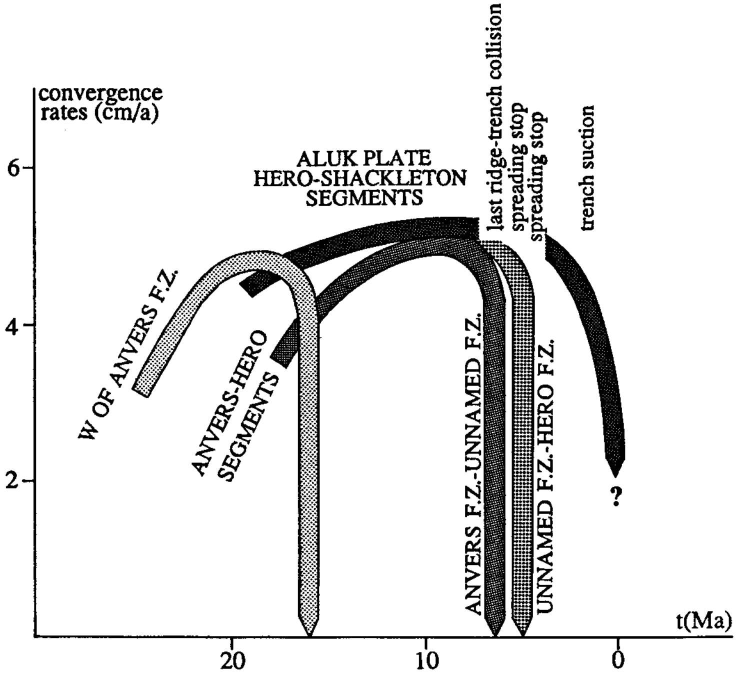


Figure 33. Evolution of the convergence rates along the Pacific margin of the northeastern Antarctic Peninsula, possibly by slab-pull induced acceleration.

Additional observations are, however, needed for justifying an argumentation about the possible causes of such an apparent pre-collision gain in momentum.

The collision of a ridge and a trench may be a factor of margin uplift and development of a fore-arc high and fore-arc basin (CLOOS & SHREVE, 1988). Both the elevation of the ridge and the isostatic response of the partly subducted young oceanic lithosphere which got decoupled from the sinking slab may account for this margin uplift. Some other factors could, however, also play a role. In theory, a terminal acceleration of the convergence rate may contribute to such an uplift by increasing the sediment influx in the accretionary wedge (influx = the product of sediment thickness, corrected for compaction, and the subduction speed). This effect, however, may on its turn be attenuated by the decrease in sediment thickness on the younger oceanic lithosphere flanking a spreading ridge. However, where terrigenic supply and longitudinal slope foot transport (hence not controlled by the age of the oceanic basement) is a significant factor of trench fill, an acceleration of the rate of convergence may effectively be a factor of margin uplift. Processes of terminal margin uplift after a ridge-trench collision deserve attention along the Antarctic Peninsula, e.g. in view of the observaton of a fore-arc high and fore-arc basin on the margin south of Hero F.Z.

A quantification of the convergence at the South Shetland Trench after the last ridge-trench collision is still relatively speculative. THOMSON *et al.* (1983) considered that the South Shetland Islands had been displaced to the northwest by about 65 km. Some 20 km of stretching has been assumed from an offset component of the "West Coast Magnetic Anomaly" by GARRETT & STOREY (1987). A recent estimate of the width of the igneous material injected during rifting and spreading amounts to 5-15 km (GONZALEZ-FERRAN, 1991). The latter figure would argue for convergence rates of maximum 0.25-0.75 cm/year for the past 2 Ma, which is only a fraction of the convergence rate during the spreading of Aluk Ridge. Whether this residual convergence by trench migration still really goes on in recent times is a point of debate (LARTER & HENRIET *et al.*, 1991)

2.4 THE OCEANIC DOMAIN AND THE FRACTURE ZONES

AWI/RCMG profile 4 (figure 34), shot over the oceanic crust parallel to the margin, is quite informative about the nature and setting of Hero F.Z. and Anvers F.Z., which have very different geophysical, structural and morphological expressions. It is also the only profile which shows prominent structures deep in the magmatic oceanic crust, even directly visible on the analog sections. On this profile also a third fracture zone, here referred to as the Unnamed F.Z., could be identified.

The segments of oceanic crust between the fracture zones are found at different depths below sea level, which is basically in accordance with their age and the laws of thermal subsidence (PARSONS & SCLATER, 1977). Very locally, the changes in crustal depth are quite substantial and the question arises how much of this jump can really be attributed to the sole age difference. For this purpose, depths to ocean crust have been measured at regular intervals and compared to the predicted depth using PARSONS & SCLATER's theoretical relationship (HUWS, 1989). Assumptions have been made for rock density, expected temperature contrast vertically through the crust, coefficient of thermal expansion and thermal diffusivity of the crust, in accordance with data proposed in TURCOTTE & SCHUBERT (1982). The results presented in HENRIET *et al.* (1989) have been kept virtually unchanged.

2.5 FRACTURE ZONE PROCESSES AND MODELS

The southward dipping reflectors discovered in the oceanic crust where profile 4 intersects the Anvers and Hero F.Z. (figure 34), together with the morphology of the oceanic lithosphere abutting against these surfaces might be diagnostic for the processes which have shaped these fracture zones.

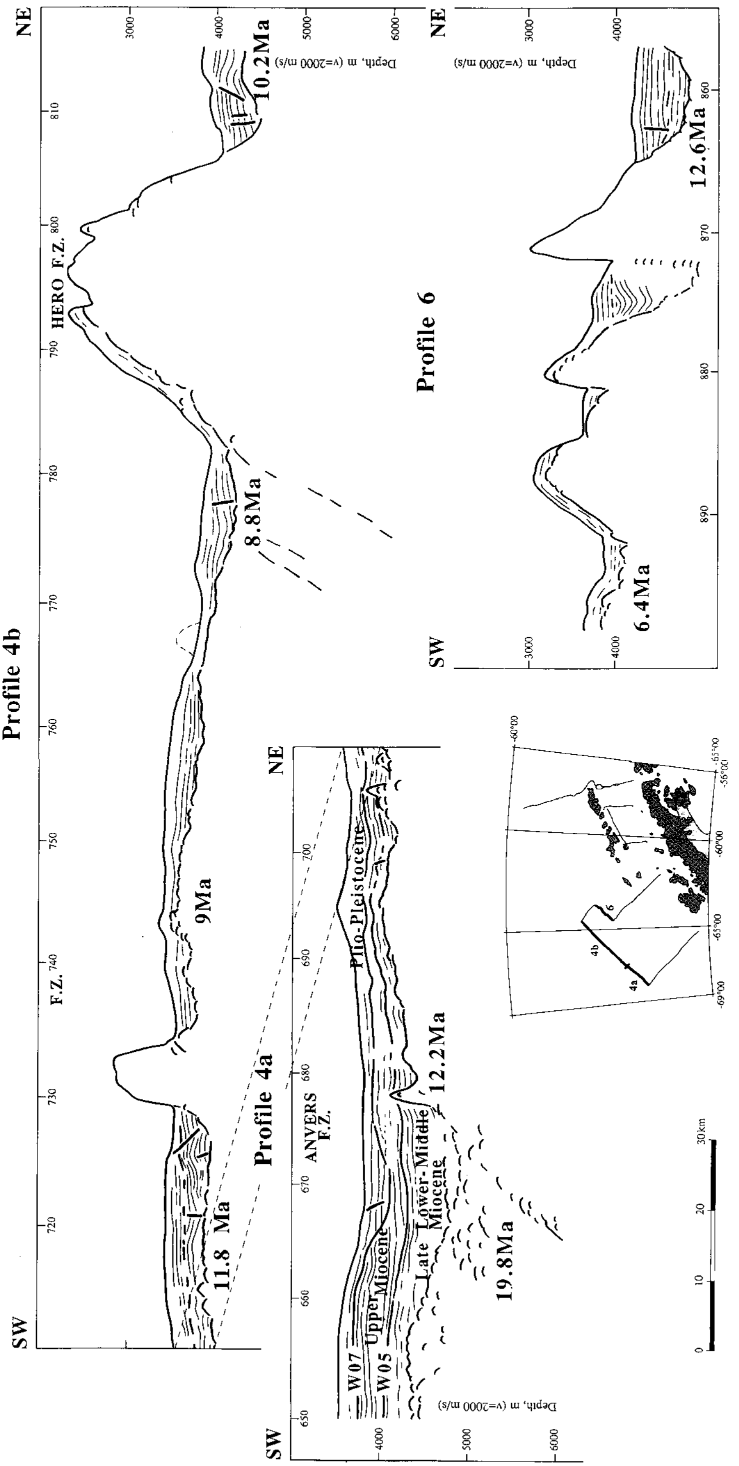


Figure 34. Interpreted profiles 4 and 6, crossing the Hero and Anvers F.Z.

At Anvers F.Z., the tensional stresses, resulting from the cooling of the lithospheric slab moving away from the spreading ridge, seem to have been accommodated by a component of downward slip along a major dipping fault plane.

At Hero F.Z. the main oblique fault clearly forms the flank of a huge intrusion-like body, rising high above the sea-floor. The observation of a crustal reflector in continuity with the southern flank of Hero Ridge may argue for the hypothesis of a diapiric intrusion of hydrated upper mantle material like serpentinite, at least where profile 4 crosses the ridge. The presence of basaltic flows associated with such a ridge on other places can certainly not be ruled out. Gravity and magnetic modelling of this ridge and dredging along the flanks of Hero F.Z. in a future research programme should allow to test this hypothesis.

The hypothesis inferring the presence of serpentinite ridges along Hero F.Z. may have far-reaching consequences for the interpretation of the segmentation of the convergent margin along the Antarctic Peninsula, as discussed later.

2.6 THE OCEANIC SEDIMENTARY COVER

Both the thickness and the lithological composition (and hence mechanical properties) of an incoming sedimentary pile approaching a continent on top of a subducting slab have an influence on the build-up and deformation of an accretionary wedge (CLOOS & SHREVE, 1988). A renewed attention has consequently been paid to the seismic-stratigraphic analysis of the sedimentary cover on the oceanic plate and in the paleotrench.

The thickest sedimentary cover shown on profile 4a south of Anvers F.Z. (figure 34) is situated on oceanic crust with an age of about 20 Ma, which means late Early Miocene. There are consequently arguments in favour of assigning a late Early Miocene age to the basal beds of the depositional sequence, filling the depression south of the fracture zone.

Across Anvers F.Z., the oceanic plate is about 12 Ma old, which means Middle Miocene. This implies that the lower depositional sequence directly resting on this plate segment might be assigned a (late) Middle Miocene age. This sequence is absent across the Unnamed F.Z., on oceanic crust which is some 9 Ma old, which suggests that its top horizons are virtually older than Late Miocene. The upper boundary of the sequence is erosional and seems to reflect a (minor) hiatus at the end of Middle Miocene times. We are inclined to identify this hiatus here with the U4 event (HINZ & KRISTOFFERSEN, 1987) which is clearly defined in the eastern Ross Sea and for which an age of some 10 Ma has been advanced. This event is attributed to a world-wide cooling and might correlate with the late Middle Miocene hiatus on ODP Site 693 in the Weddell Sea (SHIPBOARD SCIENTIFIC PARTY, ODP LEG 113, 1988), and hence also with the prominent WO5 unconformity identified on seismograms along the eastern margin of the Weddell Sea (MILLER *et al.*, 1990). As shown by the latter authors, this hiatus correlates with the Mid-Miocene cooling event which is well documented in the oxygen isotope record of Atlantic benthic foraminifera (MILLER *et al.*, 1987 ; MILLER & KENT, 1987) and which probably heralded a major advance of ice sheets in Late Miocene times.

The Mid-Miocene hiatus is also known on DSDP Site 325, some 500 km further southeast (SHIPBOARD SCIENTIFIC PARTY, DSDP LEG 35, 1976). On this site it separates a lower unit of coarser clastic rocks of Early Miocene age from a upper unit essentially consisting of Late Miocene and Pliocene claystones.

Plio-Pleistocene deposits can probably be identified on profile 4 (figure 34) as those resting on the upper major unconformity, which deeply ravinates the underlying sequence. On profile 3 (figure 36), the sequence of supposed Plio-Pleistocene age at the foot of the continental slope is at least 600 m thick and possibly includes slope-fan deposits.

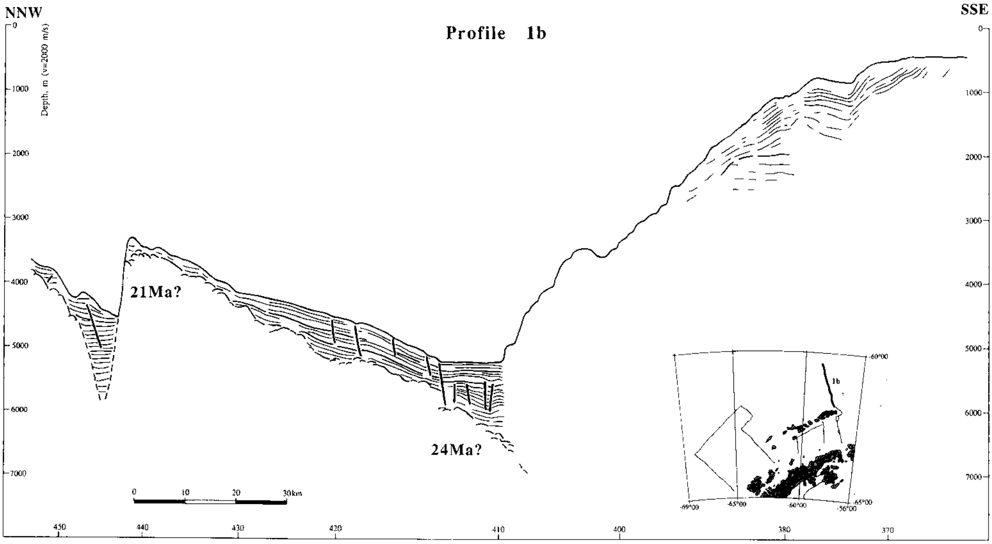


Figure 35. Interpreted profile 1b over South Shetland Trench, showing the apparently broken and tilted slab of oceanic lithosphere.

2.7 TRENCH, SLOPE AND FORE-ARC ENVIRONMENT

Profiles 3, 7 (figure 36) and 1 (figure 35) present three different images of the South Shetland trench and slope environment. Profile 3 shows the sedimentary wedge and paleotrench deposits on a 16 Ma ridge-trench collision site ; profile 1 shows a classic image of a recent

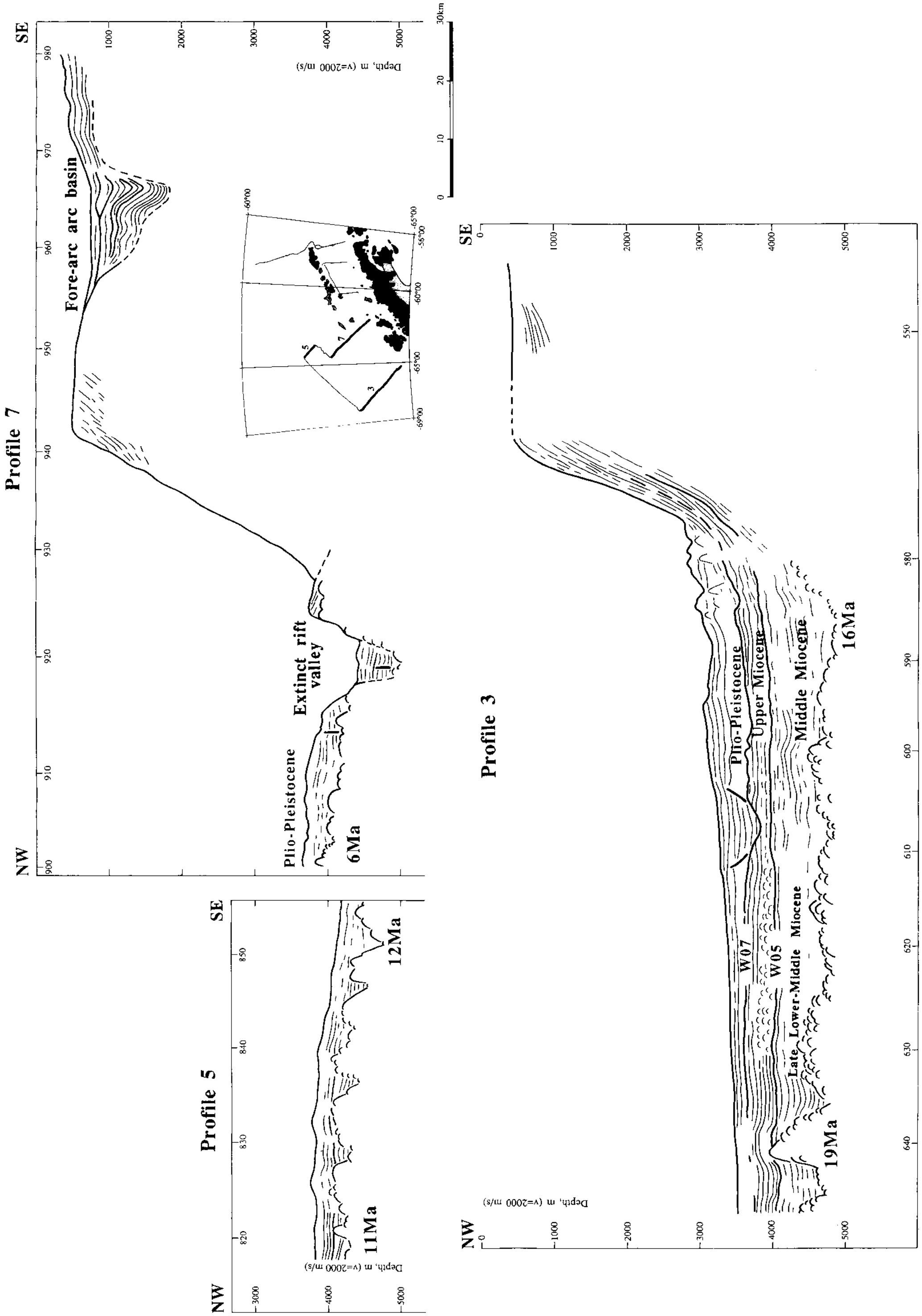


Figure 36. Interpreted profiles 3, 5 and 7, crossing the continental slope on former sites of subduction and ridge-trench collision.

trench and profile 7 shows a transitional section, with a possible relict rift valley. As will be discussed, there are some striking analogies between the structural and morphological features shown on these sections and those observed in a present-day site of ridge-trench collision, off southern Chile (CANDE & LEWIS, 1988).

27.1 Paleotrench and progradational margin

The sedimentary wedge at the foot of the continental slope on profile 3 shows the same three depositional sequences as described on profile 4 south of Anvers F.Z., however here with larger thicknesses, suggesting not only the probable presence of basal paleotrench deposits, but also suggests fan deposition. The stratigraphic interpretation put forward in HENRIET *et al.* (1989) is maintained in its broad lines. Some additional attention is paid below to the slope morphology.

The lower beds of turbidites are deposited on top of an unconformity, which is correlated with the mid-Miocene WO5 unconformity of the Weddell Sea (MILLER *et al.*, 1990). Plio-Pleistocene deposits at the foot of the slope, deposited on top of the erosional WO7 unconformity, are at least 600 m thick.

An interesting remark is that the ridge-trench collision occurred here at the boundary between Early and Middle Miocene times (16 Ma). From this time onwards, this margin behaved as a normal passive margin. It apparently vigorously built out under the Middle-Late Miocene and Plio-Pleistocene ice sheet advances with a continuous progradation of deposits over shelf, slope and continental rise, as clearly shown on profile 3 (figures 36-37), and also on profile 9 of KIMURA (1982) and on the data of LARTER & BARKER (1989). Downlap structures can be identified on top of the WO5 unconformity.

The progradational shelf slope on profile 3 (figure 36) turns out to be steeper than the slope observed on a site closer to a recent ridge-trench collision (profile 7, figure 36), and certainly steeper than the shelf slope in front of a recent trench (profile 1b, figure 35). Some authors have already described the progressive steepening of an active margin slope when a ridge crest approaches, both along the Antarctic Peninsula (BARKER, 1982) and the southern Chile margin (HERRON *et al.*, 1981 ; CANDE & LEWIS, 1988). They generally proposed a process of tectonic erosion to explain a 'slope maximum' at the ridge-crest subduction site. What is observed here and is confirmed by the bathymetric maps is that the continental slope further steepens south of the site of recentmost ridge-trench collision. This steepening seems to be primarily bound to the important progradation of the shelf in glacial times and apparently proceeded until an equilibrium profile was reached, in function of the slope sediment type, grade and cohesion. Although the idea of tectonic erosion at a ridge-trench collision site is basically not invalidated by this observation, it is clear that the study of bathymetric profiles

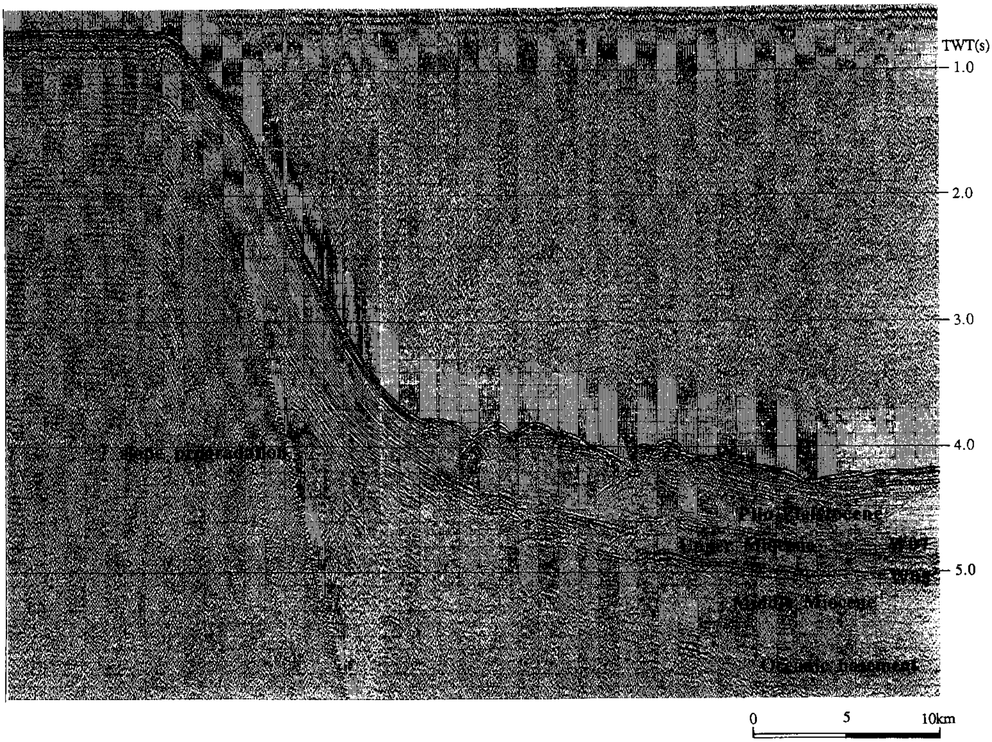


Figure 37. Near-trace profile of the prograding continental slope on the site of a 16 Ma ridge-trench collision (profile 3).

only is not sufficient for an analysis of morphogenetic processes along active margins which have known important terrigenous sediment fluxes. Due control of the nature and structure of the slope by reflection seismic profiling is always required.

27.2 Ridge-trench approach site

Profile 7 (figure 36), located just south of Hero F.Z., shows a slope foot setting much different from that on profile 3. The sedimentary cover on the oceanic plate is thin and probably not older than Plio-Pleistocene, considering the young age of the oceanic crust (6 Ma). A typical trench structure or even a buried paleotrench is absent, as well as any significant fan or other slope foot deposit.

A most intriguing feature at the foot of the continental slope is a fault-bounded trough, some 6 km wide and 600 m deep (figure 36). The accretionary prism encroaches on its eastern flank, which is tilted, possibly by a rotational movement under the load of the accretionary wedge resting on its buried part.

BARKER (1982) considered this site to have witnessed the last ridge-trench collision, some 4 Ma ago. The graben we observe is found close where the axial rift valley north of the Unnamed F.Z. should have been at the moment of the last ridge-trench collision south of it (6.5 Ma ago ; BARKER, 1982). To be exact, this graben is observed where the rift valley should have been if plate convergence had locally been frozen some 5 Ma ago (figure 31). There is also a remarkable analogy between the observed structure and cross sections through a known rift valley in the on-going collision zone off southern Chile (CANDE & LEWIS, 1988). A main but not unexpected difference is that the active rift along the Chile margin is barren of sediments.

These observations may support the idea that the ridge-trench collision which occurred north of Anvers F.Z. some 6.5 Ma ago was actually the last one, and that spreading in the segment between the Unnamed F.Z. and Hero F.Z. slowed down and stopped some 5 Ma ago, shortly before the ridge collided with the trench. Further evidence and the interpretation of the processed section is, however, needed for identifying this trough unambiguously as a fossil rift valley. Ideally, this sloop foot should also become the target of a multi-beam bathymetric survey, which should help in eliciting the morphological context in greater detail.

27.3 Fore-arc basin

The top edge of the continental margin on profile 7 shows again an important set of seaward prograding sediments. In contrast with those on profile 3, they do not drape the slope but on the contrary seem to be possibly in part truncated by slope processes. Their stratigraphic pattern shows some analogy with a sequence of obliquely prograding glacial-marine sediments described further south by ANDERSON & MOLNIA (1989), but here they are barren of any cover sediments and their top also seems to have been truncated, probably by advancing grounded ice sheets.

A most interesting feature on the shelf part of profile 7 is the prominent sedimentary basin, characterized on this profile by a sediment thickness of more than thousand metres (figure 36-38). A structure recognized as an old fore-arc basin and bearing a very strong similitude with that on profile 7 has also been observed on a high-resolution profile off Adelaide Island (ANDERSON & MOLNIA, 1989).

Considering both the position and structure of this basin on profile 7 and the above arguments found in literature, we are inclined to identify this basin with a typical fore-arc basin. Its genesis has probably been closely related to the growth and rotational uplift of the accretionary wedge, and in particular with the margin uplift which probably occurred at the time of ridge-trench approach. The relationship and relative timing between margin uplift, fore-arc basin development, outbuilding of the progradational slope cover and erosion by grounded ice sheets is no doubt a key question for the seismic-stratigraphic analysis of this margin, which however cannot be satisfactorily answered for the time being by the given profile alone.

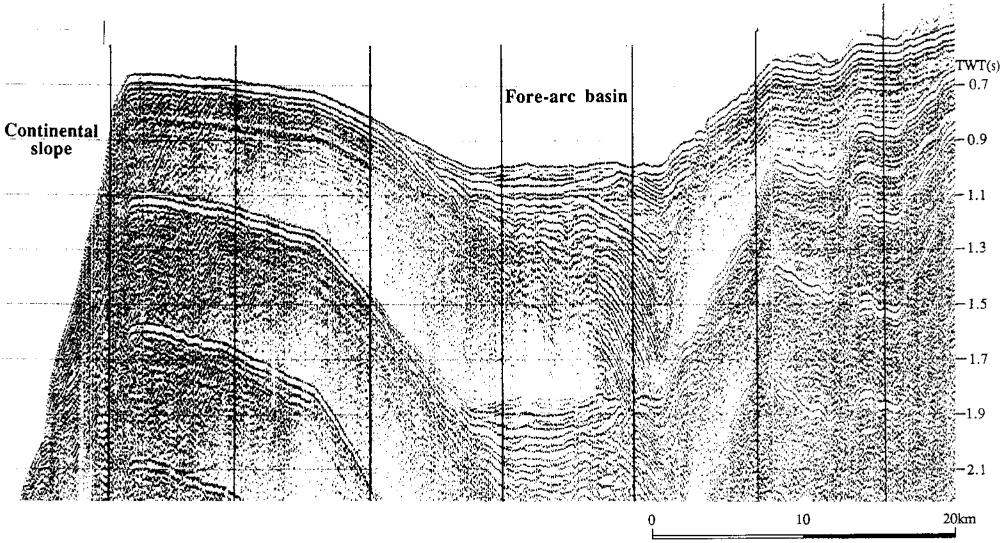


Figure 38. Analog monitor profile over a basinal structure interpreted as a fore-arc basin W of Smith Island (profile 7).

2.8 THE RIFT BASIN OF BRANSFIELD STRAIT

The three transverse profiles 2, 9 and 1a (figure 39) convey an excellent impression of the succession - in space and time - of the rifting and drifting phases which generate an oceanic domain. Spreading propagated from north to south. Profile 2 has been shot in the western subbasin, while profiles 9 and 1a have been recorded in the central subbasin (figure 31).

Since publication of HENRIET *et al.* (1989) some new observations have been made along profile 1a (figure 39), which shows a clearly oceanic domain close to King George Island, with a distinct ridge structure or seamount, also marked by an anomaly on the aeromagnetic data. The crust with an oceanic-type morphology would have been generated in the last 2 Ma (GONZALEZ-FERRAN, 1991). The sediment thickness of some 300 to 400 m on the oceanic crust reflects relatively high accumulation rates. Bransfield Strait is still nowadays characterized by one of the highest sedimentation rates along the Antarctic margins. The main components of the modern basin floor deposits are ash-bearing diatomaceous muds and oozes ; downslope transport from the volcanic islands and seamounts and from what could be an axial ridge produces graded volcaniclastic units (ANDERSON & MOLNIA, 1989). Deeper units of Pleistocene age may include significant amounts of turbidites, sourced from prograding trough-outlet wedges in lowstand/glacial maximum conditions.

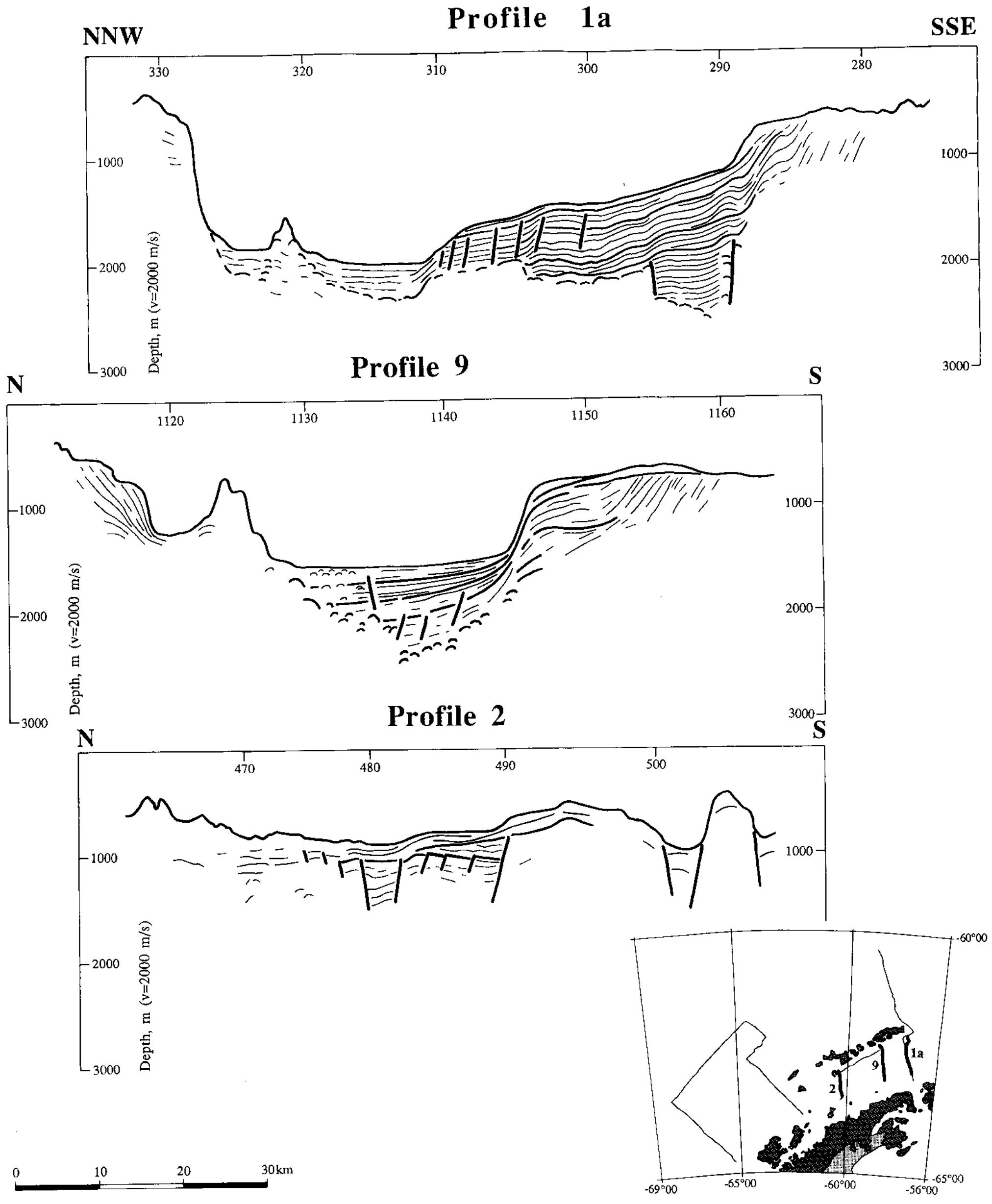


Figure 39. Interpreted profiles 2, 9 and 1a through the western and central sub-basins of Bransfield Strait.

The prograding sediment wedge on the southern rim of the basin (profile 1a) seems to bury an ancient, still relatively ill-defined graben structure with a possible Plio-Pleistocene synrift sediment fill of some 1000 m. Such a graben, bounded in seaward direction by a basement high and topped by a major unconformity, has also been described by GAMBOA & MALDONADO

(1990). The overlying prograding sequences, some 800 to 1000 m thick, are probably composed of mixed volcaniclastic/siliciclastic deposits, transported from the Trinity Peninsula by glacial-marine and submarine slope processes. They build out a two-step platform, with a first level at a depth of some 750 to 900 m and characterized by toplap reflector terminations, and a second level forming the top of a prograding lobe at some 1200 to 1600 m depth. The toe deposits of this lobe, strongly affected by listric faults and slumps, encroach upon the oceanic crust where they grade into the turbiditic and hemipelagic basin floor sediments.

On profile 2, four major depositional sequences can very clearly be identified in the basin floor fill, probably reflecting major climatological episodes in Pleistocene times. The lower two units have a pronounced transparent seismic facies, which could confirm their turbiditic nature. The third and fourth sequences are characterized by a number of onlapping, even, parallel reflectors, probably reflecting an increased hemipelagic input.

2.9 FRACTURE ZONES AND TECTONIC SEGMENTATION

Hypotheses about tectonic segmentation of the Antarctic Peninsula margin by oceanic fracture zones have already been advanced by several authors (e.g. HAWKES, 1981 ; GARRETT & STOREY, 1987). In particular, several tectonic lineaments, discontinuities and remarkable geological structures line up along the landward prolongation of Hero F.Z. :

- the offset of the West Coast Magnetic Anomaly (GARRETT & STOREY, 1987) ;
- the seismically active left-lateral fault which forms the southern boundary of the extensional domain of Bransfield Strait and of the South Shetland volcanic arc ;
- the probable northern termination of the fore-arc basin described above ;
- the northern boundary of Gerlache Strait, a possible de-activated rift structure ;
- the trough-like morphology of Boyd Strait, in the axis of Hero F.Z. ;
- the active volcanism of Deception Island, close to the intersection between the tensional axis of Bransfield basin and the extension of Hero F.Z. ;
- Smith Island, a blueschist terrane showing evidence of considerable uplift and located exactly in front of Hero F.Z.

Although strictly speaking any seamount penetrating a subduction channel is an asperity which may disrupt the crystalline hanging wall and hence is a potential source of segmentation, it may be expected that the presence of serpentinite ridges characterized by a high buoyancy would enhance this process. Some first-order effects of a collision of a buoyant ridge with a margin are (BOUYSSE & WESTERCAMP, 1988) the temporary blocking of the subduction process, a change in the back-arc volcanic activity and a major uplift of the marginal front by underplating.

It is a fact that some 4 Ma ago, spreading stopped at Aluk Ridge and subduction along the South Shetland Trench faded out. No satisfactory explanation has been advanced yet for this phenomenon of spreading stop. However, if the ridge crossed by profile 4 proves to be of a buoyant nature, its proximity to the trench suggests that a number of similar seamounts or ridge fragments have already been dragged into the subduction channel. In this hypothesis, a subduction stop partly caused by this phenomenon cannot be ruled out.

In this context, one might wonder to what extent and how long the subduction of ridges and seamounts belonging to Hero F.Z. may have acted on the margin. In other words, if the subducted fracture zone has acted as a saw-blade scouring the base of the continental lithosphere, what was the length of the blade before subduction ?

BARKER (1982) has estimated that Hero F.Z. has been subducted for at least some 12 Ma and possibly some 16 Ma. A subduction lasting some 12 Ma (between 16 and 4 Ma) with an average convergence rate of 4-5 cm/year represents a length of 500 to 600 km. This length is that of the landward aseismic ridge segment of Hero F.Z., measured from the proximal spreading rift axis (the one which nearly collided, cfr. profile 7). The distance between the proximal rift axis and the distal one, on the opposite side of the fracture zone, amounts to about 250 km. We now observe on a map of the deflection of the vertical derived from GEOSAT data for the Scotia Arc (SANDWELL, in DALZIEL, 1989) that Hero F.Z. coincides with a very extensive linear anomaly, stretching over a distance of about 1100 km from the South Shetland Trench. This means that structures and bodies which generate significant gravity anomalies line up over a length of about 850 km (1100 - 250 km) along the northwestern aseismic ridge of Hero F.Z. Such a figure may thus also be considered a reasonable guess for the length of the subducted section. With the given subduction rates this would correspond with a subduction time span of 16-20 Ma, i.e. from 4 Ma ago, the time of spreading stop, to 20 or 24 Ma ago. The occurrence of ridges and seamounts along the subducted aseismic ridge should logically image the occurrence of such bodies along its northwestern counterpart, which is marked by the significant gravity anomalies. Hence the probability that the subducted fracture zone was characterized by a string of well-pronounced morphological features is not negligible.

Wether buoyant or not, elements dragged in the subduction channel and scouring the hanging wall of the margin for some 20 Ma must have left important scars in the continental lithosphere and may be regarded as a significant factor in the segmentation of the margin.

2.10 BLUESCHIST TERRANE EMPLACEMENT

The presence of the blueschist terrane of Smith Island in the frontal part of the shelf just in the axis of Hero F.Z. (BRITISH ANTARCTIC SURVEY, 1985) deserves some attention. As already pointed out by other authors, it is probably not merely fortuitous that the only other similar blueschist terranes in this region are found further north on Elephant and Clarence Islands, exactly in the prolongation of Shackleton F.Z. (figure 31).

Blueschists are the product of metamorphic recrystallization occurring at pressures above 300 to 500 MPa (corresponding to depths of some 12 to 20 km) but at temperatures of 250 to 450 °C, which are abnormally low for such depths. These conditions are virtually only met at convergent boundaries, where cold lithosphere causes a depression of the geotherms. Their preservation after cessation of subduction, however, requires an uplift to depths shallower than 10 km, otherwise the blueschists would alter to greenschists or amphibolite-facies mineral assemblages.

Smith Island seems to be one large blueschist terrane, essentially built of blueschists, light green schists, metacherts and carbonates (DALZIEL, 1989). The original rocks appear to have been ocean-floor basalts and hemipelagic sediments, with minor manganiferous chert and limestone. The mineral assemblages in the blueschists suggest burial down to pressure conditions of 600-800 MPa (24-30 km depth) and temperatures of 350-400 °C. They may have been formed by underplating beneath the margin of Gondwanaland before break-up, beneath a subsequently accreted terrane or beneath the Pacific margin of the Antarctic Peninsula after break-up. Most radiometric age determinations on rocks of the Elephant Island Group and Smith Island, by both K-Ar and Rb-Sr methods, have yielded ages in the range 80-120 Ma (TROUW, 1988). An age of 47 Ma obtained by $^{40}Ar/^{39}Ar$ analysis on a single white mica suggests that the blueschists were buried deeply at least until Eocene times, or else it could imply early Tertiary re-heating. DALZIEL (1989) proposes that the final uplift of this massive in Tertiary times probably resulted from a disruption of the accretionary prism caused by the subduction of Hero F.Z.

One might wonder if the subduction of Hero F.Z. could not only be responsible for the final upward 'push' of the Smith Island terrane, but also for its primary 'plucking' from the margin base and for its full uplift. A possible onset of subduction of significant morphological features of Hero F.Z. some 20 to 24 Ma ago has been argued above. Smith Island is presently situated some 60 km from the trench axis. The logical place where the blueschists could have been disrupted from the overriding plate is the 'control point' of the subduction channel (*sensu* CLOOS & SHREVE, 1988), where the channel capacity decreases and where any 'clogging' can develop an upward backflow of subduction mélange. CLOOS & SHREVE (1988) have proposed that the upwelling of subduction mélange may exert a trenchward-directed drag on the hanging wall of the overriding plate that may fracture and transport previously accreted rocks, including blueschist fragments, to the surface. They consider that flow gyres may be common at depths of 30-40 km within subduction shear zones, which thus should be regarded as 'two-way streets'.

If the control point under the considered site was situated at a depth of some 24-30 km, the probable depth of origin of the Smith Island blueschists, it means that the first significant morphological features of Hero F.Z. may have reached this point after a subduction track of some 70 km, which would have required some 1.5 Ma at the proposed convergence rates. This still leaves some 14 to 18 Ma for an early blueschist 'knocker' to reach the surface during the subduction process, which implies minimum flow velocities of a few millimetres per year. We believe such velocities are not improbable in an upwelling mélange most likely characterized by undercompaction and pore water overpressure.

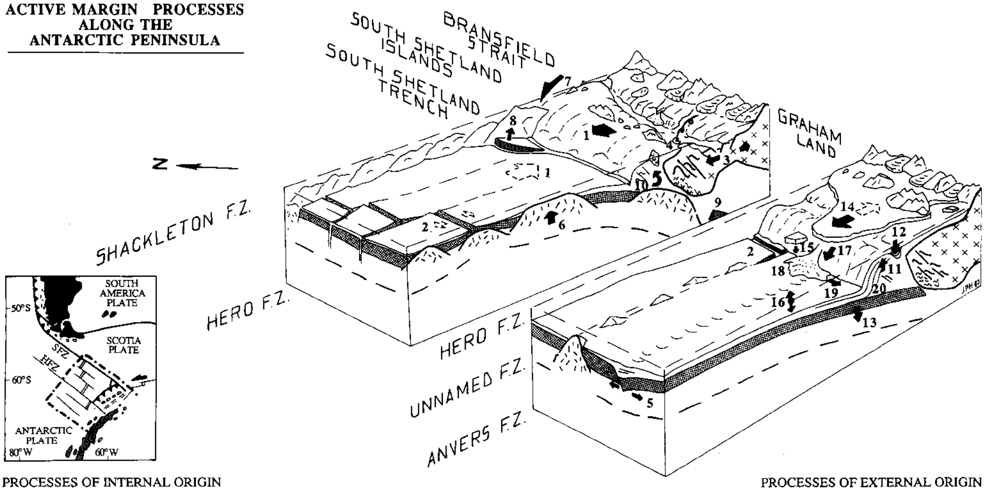
If the hypothesis regarding the presence of buoyant elements like serpentinite ridges along Hero F.Z. would be confirmed, one may expect that such elements caught in the subduction channel would enhance the clogging and disruption processes. In a way, the observation that blueschist fragments are lacking in actively subducting margins (CLOOS & SHREVE, 1988) but frequently observed in outcropping ancient convergent domains may possibly be conciliated by stating that both subduction stop and blueschist terrane fragmentation and uplift might often have a common cause : the collision of an active margin and a buoyant ridge, or at least a ridge with a considerable relief.

2.11 CONCLUSIONS

The Antarctic Peninsula is an outstanding area for the study of active margin processes and their fate on the wane of subduction. The AWI/RCMG data acquired during the ANTARKTIS VI/2 expedition allowed to elicit or further define some of these processes. A synopsis of these processes is shown in a conceptual way on figure 40.

During the ANTARKTIS VI/2 survey, new data were gathered over the oceanic domain, in particular those revealing or suggesting thermal bending and diapiric intrusion phenomena along fracture zones. The hypothesis about the possible identification of serpentinite ridges along Hero F.Z. deserves further control during future surveys ; if this hypothesis would be supported by other evidence, it could possibly clarify some aspects of the tectonic segmentation of the Antarctic Peninsula margin, of the termination of subduction and of the emplacement of blueschist bodies in front of the fracture zone apices. The AWI/RCMG data provide arguments suggesting that the subduction of Hero F.Z. might account for the 'plucking' and full uplift of blueschist terranes such as those of Smith Island, and not only for their final uplift.

The high quality of the seismic data over the sedimentary cover allowed a first stratigraphic analysis, well constrained by the interpretation of known patterns of sea-floor magnetic anomalies. The results of this stratigraphic interpretation correlate with those of DSDP well 325 and the profiles of fellow researchers. Also the structure of the prograding slope deposits on the now passive margin south of Hero F.Z. could be well defined. The possible identification of an extinct rift valley at the foot of the slope just south of Hero F.Z. is supported by a striking analogy with the site of on-going ridge-trench collision in southern Chile. This hypothesis - subject to further control - would imply a re-assessment of the date of the last ridge-trench collision along the Antarctic Peninsula, here tentatively set at 6.5 Ma.



ACTIVE MARGIN PROCESSES ALONG THE ANTARCTIC PENINSULA

PROCESSES OF INTERNAL ORIGIN
1. Convergence and subduction, trench suction.
2. Spreading and spreading stop.
3. Lithospheric stretching and back-arc spreading.
4. Back-arc volcanism.
5. Thermal contraction stresses at fracture zones.
6. Diapirism at leaky fracture zones.
7. Transpression at transform boundary.
8. Plate chipping and tilting.
9. Decoupling of subducting plate, termination of slab pull.
10. Plucking of blueschist fragments and uplift by backflow of accretional mélange.
11. Margin uplift at ridge-trench collision.
12. Fore-arc basin development.
13. Thermal subsidence of passive margin.

PROCESSES OF EXTERNAL ORIGIN
14. Waxing and waning of ice sheets.
15. Glacial marine sedimentation.
16. Eustatic sea level changes.
17. Slope transport, slumping.
18. Fan development.
19. Longitudinal slope foot transport.
20. Margin progradation.

Figure 40. Conceptual model of the processes of both internal and external origin which contributed in shaping the convergent margin of the Antarctic Peninsula.

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