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**REFLECTION SEISMIC  
INVESTIGATIONS IN THE  
WEDDELL SEA AND ALONG THE  
ANTARCTIC PENINSULA**

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J.P. Henriet<sup>(\*)</sup>, H. Miller<sup>(+)</sup>, R. Meissner<sup>(o)</sup>,  
A. Moons<sup>(\*)</sup>, D. Huws<sup>(\*)</sup>, W. Jokat<sup>(+)</sup>,  
N. Kaul<sup>(+)</sup>, E. Van Heuverswyn<sup>(\*)</sup>  
and W. Versteeg<sup>(\*)</sup>

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<sup>(\*)</sup>RENARD CENTRE OF MARINE  
GEOLOGY  
RIJKSUNIVERSITEIT GENT  
KRIJGSLAAN 281  
B-9000 GENT (BELGIUM)

---

<sup>(+)</sup>ALFRED WEGENER INSTITUT FUR  
POLAR- UND MEERESFORSCHUNG  
COLUMBUSSTRASSE  
D-2850 BREMERHAVEN (F.R.G.)

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<sup>(o)</sup>INSTITUT FUR GEOPHYSIK  
CHRISTIAN ALBRECHTS UNIVERSITAT  
ZU KIEL  
OLSHAUSENSTRASSE 40  
D-2300 KIEL (F.R.G.)

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## Reflection seismic investigations in the Weddell Sea and along the Antarctic Peninsula

### Abstract

Within the framework of the first phase of the Belgian Antarctic Research Programme (1986-1988), the Renard Centre of Marine Geology (RCMG) at the State University of Ghent has participated in two cruises organized by the Alfred-Wegener-Institut für Polar- und Meeresforschung (Bremerhaven).

Both cruises addressed different marine geological domains: the passive margin of the eastern Weddell Sea (cruise Antarktis V/4) and the active western margin of the Antarctic Peninsula (cruise Antarktis VI/2).

In the Weddell Sea some 2650 km of high-resolution reflection seismic profiles have been shot, partly in connection with the drilling operations of ODP Leg 113 off Cape Norvegia. This site has been used as a stratotype for an integrated seismic-stratigraphic reassessment of the Weddell Sea Basin, a joint venture of German, Norwegian and Belgian research teams. The study off Cape Norvegia also allowed to propose a new tectonic model for the origin of the Explora-Andenes Escarpment and the associated outer high.

Another study region in the eastern Weddell sea was the distal part of Cray Fan, off Halley Bay. The very high resolution achieved there over the fan units allowed a detailed analysis of sediment deformations and mass transport. Large unconformities, calibrated by tentative long-range correlations to ODP Site 693, might yield some clues about the paleoceanography of the Mesozoic and Cenozoic South Atlantic domain. They seem to support the hypothesis of a Late Mesozoic Transantarctic initiation of an early Antarctic Circumpolar Current. Cenozoic unconformities are well controlled by paleoclimatic factors.

The Antarctic Peninsula survey involved the recording of some 1800 km of reflection data with larger penetration, both in Bransfield Strait and along the Bellingshausen margin. The reassessment of the seafloor magnetic anomalies helped to constrain the seismic-stratigraphic analysis and also yielded some new insight in the local dynamics of spreading and subduction, e.g. suggesting phenomena like a slab pull induced spreading acceleration preceding ridge-trench collision. The seismic-stratigraphic interpretation of the oceanic sediments is in good agreement with the results found at DSDP well 325 and with those proposed by Japanese studies further to the west.

Seismic profiles across Anvers and Hero Fracture Zones illustrate different aspects of thermal plate contraction, including thermal bending and magmatic diapirism. The seismic evidence that the submarine ridge of Hero F.Z. might be a diapiric serpentinite body, similar to the situation at Vema F.Z. in the central Atlantic, has several implications for the segmentation of the western margin of the Antarctic Peninsula. One new aspect about this segmentation confirmed by the present study is the presence of a fore-arc basin on the shelf south of Hero F.Z..

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The merits of this study are shared by many partners in this research. Possible errors in this report, a normal ingredient of any learning process, are the sole responsibility of the undersigned.

Ghent, December 1988

Jean-Pierre Henriët

## **Introduction**

Within the framework of the first phase of the Belgian Antarctic Research Programme (1986-1988), the Seismostratigraphy Unit of the Renard Centre of Marine Geology (RCMG) at the State University of Ghent participated in two cruises organized by the Alfred-Wegener-Institut für Polar- und Meeresforschung (Bremerhaven) : the Antarktis V/4 cruise (December 1986 - March 1987) in the Weddell Sea and the Antarktis VI/2 cruise (October - December 1987) along the western margin of the Antarctic Peninsula (fig. 2). The latter study was jointly promoted by the AWI and the Geophysical Institute of the University of Kiel.

Both the data acquisition and the interpretation of the data carried out in a cooperative effort yield fresh insights in the geological evolution of the Antarctic margins in the Southern Atlantic domain. These insights have been acquired by carefully blending seismic stratigraphic interpretations with the analysis of related geophysical, sedimentological, paleoceanographic and paleoclimatic data. Preliminary results of this joint study are presented in this report.

## **Part 1 : the Weddell Sea**

### **1.1 Research objectives**

A basic objective of the marine geophysical research effort in the Weddell Sea within the framework of the Belgian Research Programme on Antarctica is to carry out high-resolution reflection seismic investigations, which possibly could yield a better insight in the structure and history of this important sedimentary basin. A particular attention is hereby paid to the identification of paleoceanographic and paleoclimatological signals locked in the sedimentary record of the Antarctic continental margins, both in the fine-scale stratigraphy of the depositional sequences and in the patterns of sediment erosion and deformation.

These objectives could be achieved through a collaboration of the Renard Centre of Marine Geology (RCMG) with the Alfred-Wegener-Institut für Polar- und Meeresforschung (AWI) in Bremerhaven. A joint survey was carried out on board of R.V. "Polarstern" from December 1986 to March 1987 along the eastern margin of the Weddell Sea (fig.1). This survey coincided with the drilling operations of "Joides Resolution" in the Weddell Sea in the framework of Leg 113 of the "Ocean Drilling Program" (ODP). "Polarstern" hence was the first vessel to shoot high-resolution reflection seismic profiles over boreholes 692 and 693, immediately after their completion. The

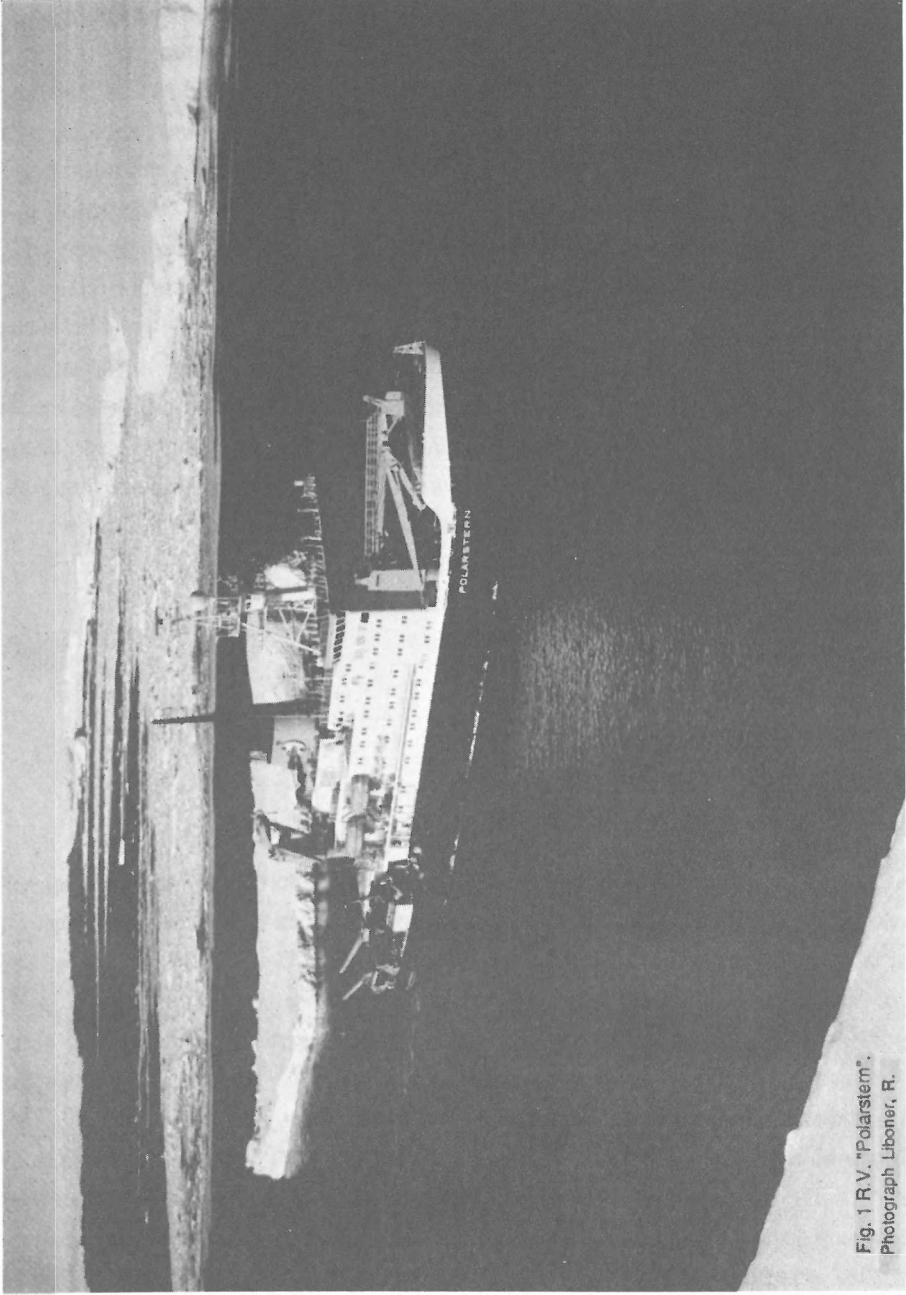


Fig. 1 R.V. "Polarstern".  
Photograph Liboner, R.



Fig. 2 Survey area during the Antarktix V/4 and VI/2 cruises

integration of the seismic and borehole data does not only prove a valuable asset for the valorization of the seismic results, but also significantly broadens the output of the ODP operations in this basin.

Some preliminary results of this joint research have been presented at the National Colloquy on the Belgian Scientific Research Programme in Antarctica in Brussels (Miller e.a. 1988) and at the NATO Advanced Research Workshop "Geologic History of the Polar Oceans : Arctic versus Antarctic" in Bremen (Miller e.a. 1989 and Henriët e.a. 1989). A number of data and figures in this report have been borrowed from the above mentioned publications.

## 1.2 Previous research

The geological and geophysical reconnaissance of the continental margins of the Weddell Sea has steadily progressed in the past ten years. A review of multichannel seismic investigations hitherto carried out in the Weddell Sea basin is presented in Table 1.

Year	Institution	Country	Vessel	Profile length
1977	Bergen University	Norway	Polarsirkel	1000 km
1978	Bundesanst. Geow. Rohst.	Germany	Explora	5850 km
1978	Lamont-Doherty Geol. Obs.	U.S.A.		
1979	Bergen University	Norway	Polarsirkel	1010 km
1983	Nat. Oil Corporation	Japan	Hakurei-Maru	1500 km
1985	Bergen University	Norway	Andenes	2600 km
1986	Bundesanst. Geow. Rohst.	Germany	Polarstern	6260 km
1987	Alfr. Weg. Inst., RCMG	Germany, Belgium	Polarstern	2850 km

Table 1: multichannel seismic investigations in the Weddell Sea  
(after Hinz e.a. 1987 and Fütterer 1988)

Only few of these surveys could penetrate into the southwestern part of the Weddell Sea, where severe ice conditions prevail throughout the seasons. Only a few isolated profiles have been recorded there by Bergen University (1977), Soviet scientists (1982) and BGR (1986), in front of the Ronne and Filchner ice shelves. In contrast, the eastern and southeastern margins of the Weddell Sea are now relatively well documented. A map of the seismic tracks recorded with German and Norwegian vessels in this region is shown on fig. 3.

A first coherent geological picture of the eastern margin of the Weddell Sea resulted from the extensive surveys of BGR, partly carried out as a reconnaissance for ODP Leg 113. The 1978 survey shed light on a remarkable wedge-like structure with seaward dipping reflectors : the "Explora Wedge". By analogy with similar wedge-like structures identified in drillholes of Leg 104 on the Voring Plateau in the Norwegian Sea, these dipping layers are considered to be of

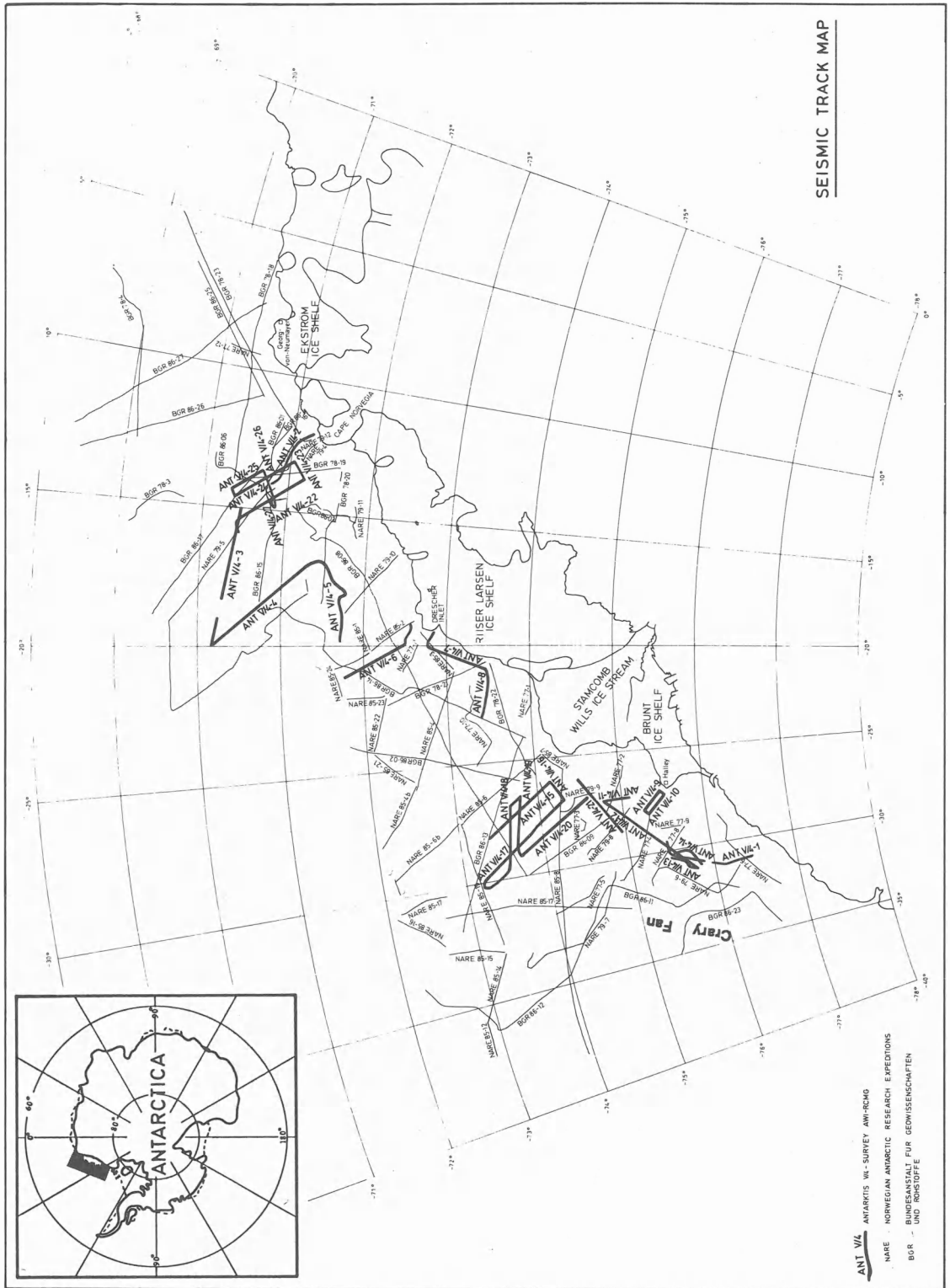


Fig. 3 Seismic track map of the Antarktiss V/4 cruise and of former seismic investigations in the eastern Weddell Sea.

volcanic origin. Off the northeastern part of the Weddell Sea margin, the lower continental slope at depths of 1500 to 3000 m was found to be abruptly bounded by a steep escarpment, leading to the continental rise at depths over 4000 m. This scarp, named the "Explora Escarpment" (Hinz and Krause 1982), could later be traced further south by the Norwegian scientists in 1985 and was consequently named the "Explora-Andenes Escarpment".

The 1986 survey of BGR led to the discovery of a conjugate set of dipping reflectors further south. Both sets frame a central basin with oceanic crust, identified as a failed rift-drift basin (Hinz and Kristoffersen 1987). This basin, probably an early witness of the fragmentation of Gondwanaland, is obliquely transected by the Explora-Andenes Escarpment, which is probably the surface morphological expression of a large transcurrent fault.

The seismic stratigraphy of the sedimentary cover in the Weddell Sea Basin was first approached by Hinz and Krause (1982), Haugland, Kristoffersen and Velde (1985) and Hinz and Kristoffersen (1987).

Hinz and Krause (1982) identified two major units, separated by the distinct "Weddell Sea continental margin unconformity" ("U9"). The upper, tectonically undisturbed unit could be subdivided into four depositional sequences. The lower unit consisted of the volcanic Explora Wedge sequence. Circum-Antarctic correlations between the Weddell Sea unconformities and some major ones identified in the Ross Sea, off Terre Adélie and in the Tasman Sea have been proposed by Hinz and Block (1984) and Hinz and Kristoffersen (1987).

Haugland, Kristoffersen and Velde (1985) mainly documented the seismic stratigraphy of the Crary Fan, a large submarine fan complex in the southeastern Weddell Sea off Filchner and Ross ice shelves, and proposed a tentative correlation with fan sequences in the Eastern Basin of Ross Sea.

All time connotations of the seismic stratigraphic interpretations in the Weddell Sea however remained highly speculative until the ODP wells of Leg 113 had provided the first ground truth.

### 1.3 Methods

#### 13.1 High-resolution reflection seismic data acquisition

The seismic tracks surveyed by AWI and RCMG during the Antarktis V/4 cruise (1986-1987) are shown on fig. 3.

Out of the 27 profiles recorded in the Weddell Sea Basin, 21 have been shot with an array of PRAKLA-SEISMOS airguns with volumes of 0.5 l, 2.5 l and 5 l, totalizing a capacity generally not exceeding 10 l. The guns were powered by 6 JUNKERS type 4FK 115 compressors, delivering each 2 cubic metres per minute of air compressed at 14 MPa (140 bars). With this source

configuration, data of excellent definition have been recorded down to two thousand metres below the sea-floor.

In the shallower shelf zone off Halley Bay and on ODP Site 693, 7 profiles have been shot with high-resolution sources such as a 12-electrode sparker fired at 4.5 kJ or a SODERA S-15 watergun, with a volume of 0.25 l. On Site 693 in water depths of about 2400 m, the watergun yielded a resolution better than 5 m over the whole depth of drilling (some 500 m).

Most data have been recorded with a PRAKLA-SEISMOS streamer with an active length of 600 m and 96 hydrophone groups, clustered into a 24-channel configuration. Some shallow shelf profiles shot in difficult ice conditions have been recorded with an 8-channel TELEDYNE streamer with an active length of 100 m. The digital data acquisition system consisted of an EG&G GEOMETRICS ES 2420 seismograph with data storage on two CIPHER tape drives. Analog monitor records of excellent quality and different scale have been obtained on two EPC recorders after adequate bandpass filtering and time variant gain amplification.

## 13.2 Reflection data processing

Due to the limited computer capacity presently available at RCMG, the bulk of the processing of the more than thousand magnetic tapes of the Weddell Sea survey is being carried out on the CONVEX computer with DISCO seismic software at AWI in Bremerhaven. Examples of stacked sections are shown on figs. 10 and 12.

## 13.3 Reflection data interpretation

### 133.1 Profile interpretation and display

A large part of the interpretation has been carried out on the analog monitor records, in parallel with the digital data processing. This was not only a matter of time gain, but also a question of resolution, as very fine structures are usually better preserved on the single channel analog records than on stacked sections. Several examples of analog reflection records are shown on figs. 9, 15, 19, 20, 21, 22, 23 and 26.

Significant reflectors identified on the sections have been digitized and introduced into RCMG's seismic databank "NORFILE", which performs the transformation of the variable horizontal scale into a linear one in function of the true coordinates recorded on fix points, as well as the conversion of two-way reflection time into depth, in accordance with a selected velocity model. Other routines in NORFILE are used for preparing track maps in different scales and projections, posted depth maps, contoured maps (isobath and isopach maps) and three-dimensional representations.

### 133.2 Seismic-stratigraphic analysis

The early analysis of the seismic stratigraphy of the eastern Weddell Sea by the BGR has led to the identification of a number of major breaks in the sedimentary record, labeled U9, U7, U6, U5, U3 and U2 (Hinz e.a. 1987). This subdivision is inherent to a model of the evolution of the oceans of the Earth, where the major unconformities are interpreted in terms of geodynamic, oceanologic or climatologic events of global relevance. Such an approach proved its value in the earliest attempts to fit the emerging geological picture of the Antarctic continental margins into a global context and to orient further exploration, in particular in the framework of the Ocean Drilling Program.

However, as exploration progresses and more factual evidence about the age of local unconformities becomes available, this approach with a time-bound terminology proves inconvenient. Any reassessment of the age of an unconformity compels to change its name on profiles and maps, which may lead to confusion in literature. In order to avoid this problem, four seismic research teams<sup>1</sup> meeting at the Bremen Workshop in 1988 decided to strive for a common, horizon- and sequence-bound seismic-stratigraphic nomenclature for the Weddell Sea.

In this approach, profile ANT V/4-22 which passes over ODP Site 693 is used as a seismic-stratigraphic stratotype section, on which a basic series of depositional sequences are identified and named. The capital character *W* followed by a rank digit is assigned both to a major depositional sequence and to its basal unconformity identified on the stratotype section<sup>2</sup>. The rank of the digits increases from lower (older) units to higher (younger) units, as in standard stratigraphic practice. Further subdivisions of sequences as a consequence of the introduction of an increased resolution can be accommodated by adding more digits behind the main label, separating them from it by a decimal point (e.g. *W 1.1*, *W 1.2*, *W 11.1*, etc.).

It should be mentioned that the concept of depositional sequence is used here in its original seismic stratigraphic definition, being *any* "stratigraphic unit composed of a relatively conformable succession of genetically related strata, bounded at its top and base by unconformities or their correlative conformities" (Mitchum, Vail and Thompson III 1977). The term "unconformity" in this definition is taken in its broadest sense, encompassing both subaerial and submarine surfaces of erosion or nondeposition. In the more recent sequence stratigraphic approach (Vail e.a. 1987), the term "sequence" is used in a more restrictive sense. A sequence in this definition is bound by "unconformities" which are surfaces marked by subaerial exposure on their landward portions. A sequence is then the highest order unit, grouping all "systems tracts" associated with one major relative sea level movement. Systems tracts (sensu Brown and Fisher 1977) are linked and contemporaneous depositional systems which are also usually

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<sup>1</sup> The Alfred-Wegener Institut für Polar- und Meeresforschung (Bremerhaven), the Bundesanstalt für Geowissenschaften und Rohstoffe (Hannover), the University of Bergen (Norway) and the Renard Centre of Marine Geology of the State University of Ghent (Belgium)

<sup>2</sup> only the sequence symbol is noted in italic characters

intergradational (for example linked fluvial, delta, shelf and slope systems). Systems tracts take a well defined position within the sequence and are characterized by the stacking pattern of "parasequence sets" and "parasequences", the fundamental building blocks of sequences.

The sequence stratigraphic approach being much more interpretative is difficult to apply at the level of basin reconnaissance, which still is the status of the Weddell Sea investigation. At the present level of analysis, the main objective is the unifying use of a common and unbiased communication tool between the cooperating teams. Once all stratigraphic units are adequately analysed both in their areal extent and their genetic context, a possible move towards a sequence stratigraphic approach can be envisaged.

Coming back to the naming procedure here adopted for sequences and bounding unconformities, it should be noted that a problem arises in using the same symbol for a sequence and its basal unconformity when it turns out that different depositional sequences lap out on the same basal surface. The approach initially proposed in the agreement between the four aforesaid teams and outlined in the paper presented at the Bremen workshop (Miller e.a. 1989) was to keep unaltered the name of the basal unconformity which has been defined on the stratotype section, as this might facilitate long-range correlations along the continental margin (e.g. here with W1 and W4, which seem to be tracable over the larger part of the continental margin). However, there are some strong arguments in favour of assigning a separate symbol (differing from that of any depositional sequence) to such complex onlap surfaces. One argument is the presently emerging evidence of the presence of additional major onlap surfaces, which is the result of the ongoing joint reassessment of former interpretations (e.g. of BGR lines BGR 86-08 and BGR 86-13, courtesy K. Hinz). Such complex onlap surfaces will consequently be referred to in this paper with the symbol WO (Weddell Sea Onlap Surface), which is a higher level symbol : a complex onlap surface will catenate the basal reflectors of successive onlapping depositional sequences, as illustrated on fig. 4.

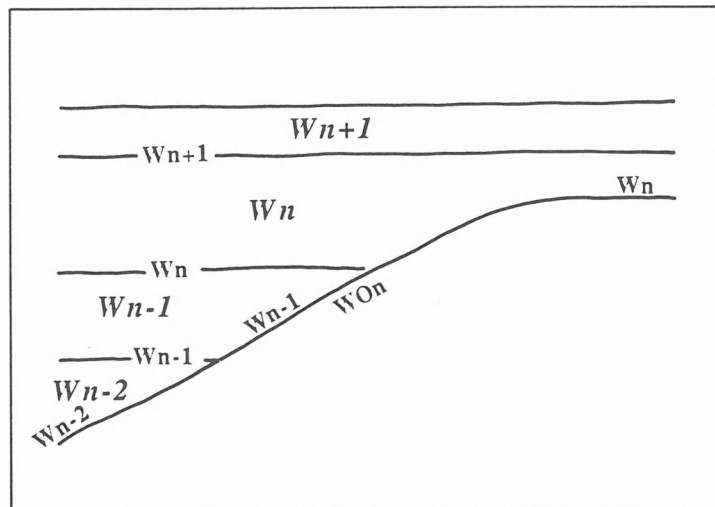


Fig. 4 Seismic stratigraphic terminology in the Weddell Sea.



Table 2 gives an overview of the sequences and unconformities discussed in this report, their present identification and their tentative correlation with former definitions found in literature, in particular the "WS" units and the bounding "U" unconformities defined by Hinz e.a. (1982) and Hinz e.a. (1987). It should be noted that this table simply technically translates the names used for seismic marker horizons on figures in both aforementioned papers into the new marker terminology : e.g. the marker labeled U6 on fig. 28 in Hinz e.a. 1987, which also forms the boundary between the WS-3A and WS-3B units on fig. 3 in Hinz e.a. 1982, now reads as W2.

In addition to the definition of depositional sequences by the analysis of the nature of their boundaries, due attention has also been paid to the diagnostic value of the internal seismic facies of the sequences, which shows to full advantage on the high-resolution profiles. These facies characteristics do reflect both the depositional and the early compaction history of the Weddell Sea sediments. The latter evolution is vividly illustrated by spectacular aspects of sediment flowage and internal slumping, which have been put into evidence in various sequences.

#### 13.4 Refraction seismics

Very strong multiple reflections have been observed on the shelf of the southern Weddell Sea, both during the BGR survey of 1986 and the AWI-RCMG survey. Such multiples are extremely resistant to any form of processing. They argue for the presence of a shallow, hard horizon, which could be explained by two processes :

- overconsolidation of shelf sediments by glacial loading, a phenomenon well documented in the Norwegian Sea and Barents Sea (Elverhoi e.a. 1989) ;
- submarine permafrost, as reported in the Beaufort Sea, Alaska (Rogers and Morack 1983).

Considering the importance of this problem both for geophysical and geotechnical applications in polar regions, a refraction configuration consisting of a single-electrode sparker as sound source and a 16-channel streamer has been lowered and stretched on the sea bottom on two shelf sites, one in Atka Bay (near Georg von Neumayer Station) and one in heavy pack-ice south of Halley Bay. Water depth on both sites ranged between 220 and 270 m, and the water temperature measured above the sea bed was  $-1.9^{\circ}$  C.

The results of Atka Bay are shown on figs. 5 (record) and 6 (interpretation). This record clearly shows a two-layer case with a 1.9 m thick top layer with a velocity of 1460 m/s above a substratum with a velocity of 2140 m/s. The velocity of the top layer is very similar to the velocity measured in water (1420 m/s with the refraction array when pulled up, 1444 m/s calculated from CTD measurements), and thus probably corresponds with water-logged unconsolidated mud. The velocity of the bottom layer, which could be well reproduced on neighbouring sites, is high. However, it does not allow for the time being to discriminate unambiguously between non-frozen coarse sediments and frozen silty clays, which display a similar range of velocities (King and Pandit 1981). Additional information will be needed in such

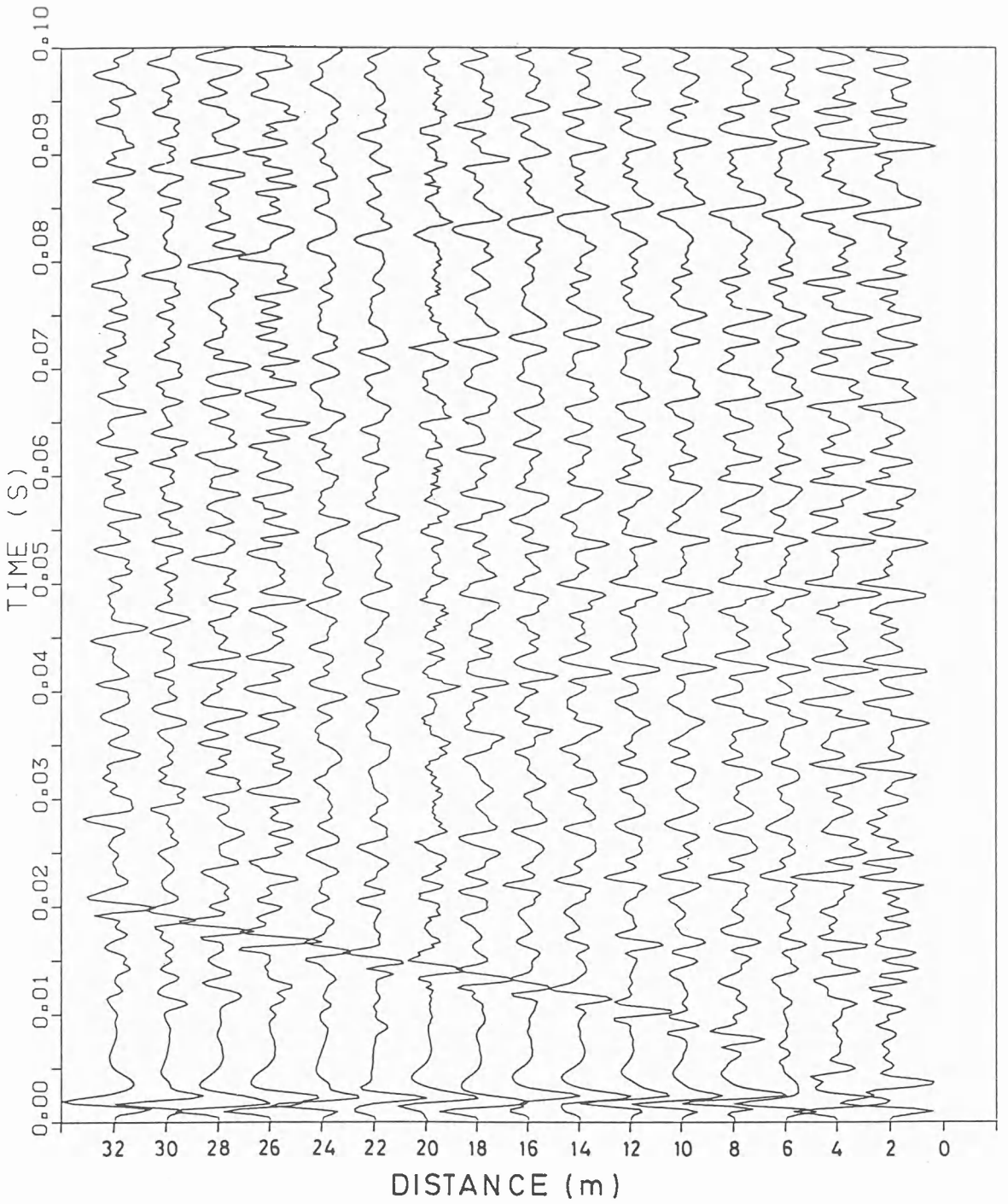


Fig. 5 Refraction record.

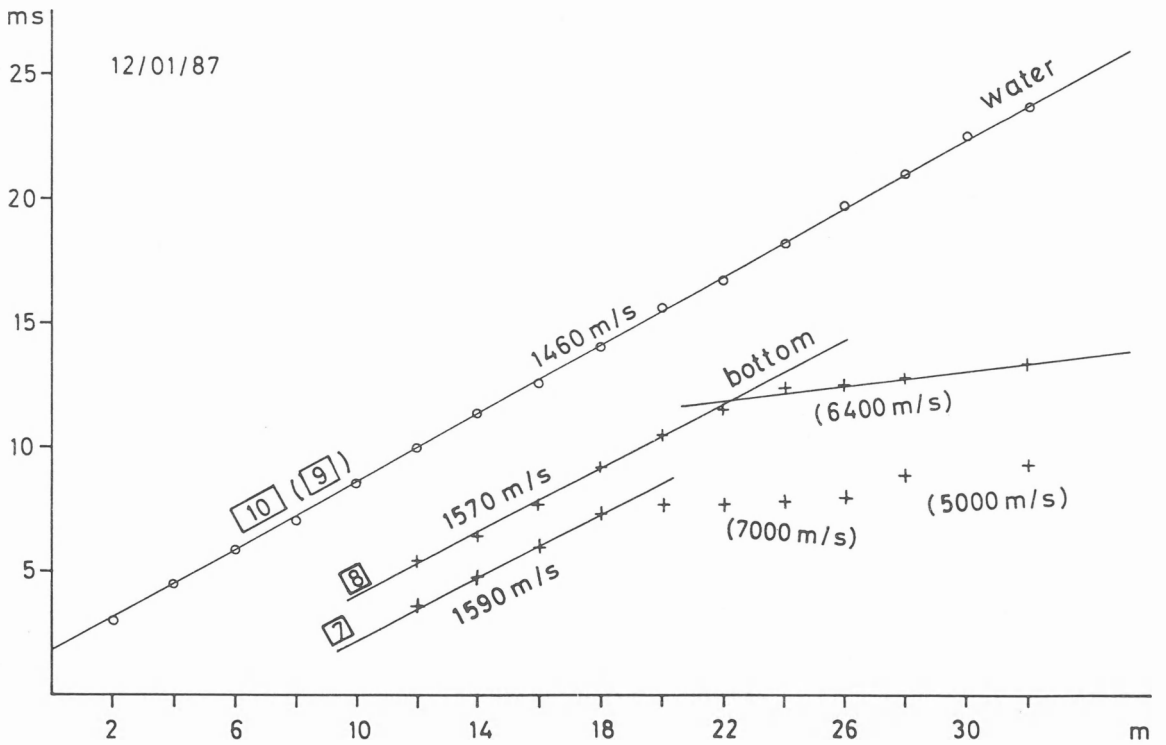
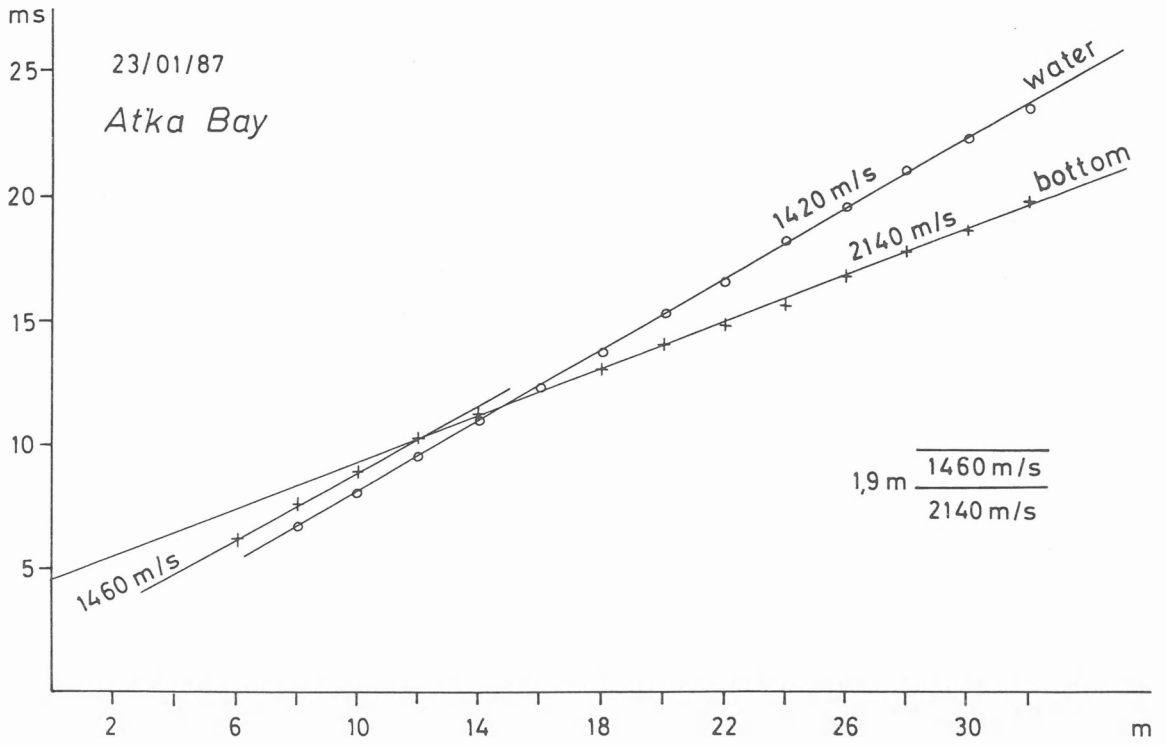


Fig. 6 Interpreted refraction profile.

an analysis. Time constraints did unfortunately not allow to multiply such experiments on a wider range of shelf sites.

#### 1.4 Geological interpretation

Two main survey areas are discussed in this report :

- a) a seismic grid shot off Cape Norvegia in the area of the ODP Sites 692 and 693, framing an important submarine canyon (Wegener Canyon) and exploring the local geological setting of the Explora Escarpment ;
- b) a high-resolution seismic transect and grid covering the continental shelf, slope and rise north of Halley Bay and yielding a very fine-scale picture of the distal part of the Cray Fan deposits.

##### 14.1 Sedimentary sequences off Cape Norvegia

###### 14.1.1 Survey structure

The target area for the ODP drillholes 691 to 693 off Cape Norvegia presents a remarkable marine morphological and structural setting. The results of the seismic stratigraphic analysis and of the well control are however not less rewarding.

The survey area shows the Explora-Andenes Escarpment, bordering the lower continental slope at depths between about 2000 and 3000 m and the continental rise at a depth of more than 4000 m. This prominent structural feature is a large transcurrent fault, considered to mark the boundary between oceanic crust of not yet well defined age and subsided continental crust. It shows in the seabed morphology as a steep scarp, locally deeply incised by canyons. "Wegener Canyon", stretching between the ODP Sites 692 and 693, has been mapped in detail with "Polarstern" 's SEABEAM system (figs. 7 and 8).

A sparker line (ANT V/4-2) has been shot in the early part of the seismic survey from the shelf edge at Cape Norvegia down to the upper part of Wegener Canyon, close to the site where the "Joides Resolution" had started drilling wells 691 and 692. After all wells had been spud, "Polarstern" shot a tie line across Wegener Canyon over Sites 692 and 693 (ANT V/4-26), as well as three parallel dip lines running from the lower continental slope down to the rise, at more than 4500 m depth (ANT V/4-22, 24 and 25). The survey was completed with a short watergun profile with shallow penetration but very high resolution over Site 693 (ANT V/4-27).

An analog monitor record of profile ANT V/4-22, selected as seismic-stratigraphic stratotype section, is presented on fig. 9, while a horizontally expanded digital section is shown on fig. 10. Both figures have been annotated with the information from well 693. The results of the velocity analyses performed at BGR and AWI are also presented on fig. 10. An interpretation of line

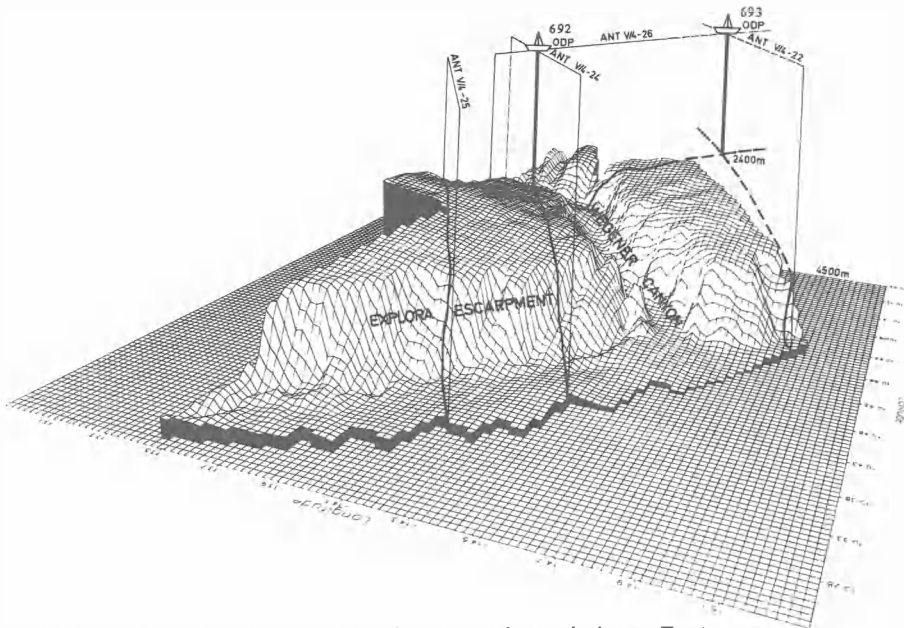


Fig. 7 Three-dimensional view of the lower continental slope, Explora Escarpment and continental rise in the region of Wegener Canyon, with localisation of the ODP sites and the seismic tracks (SEABEAM plot, AWI).

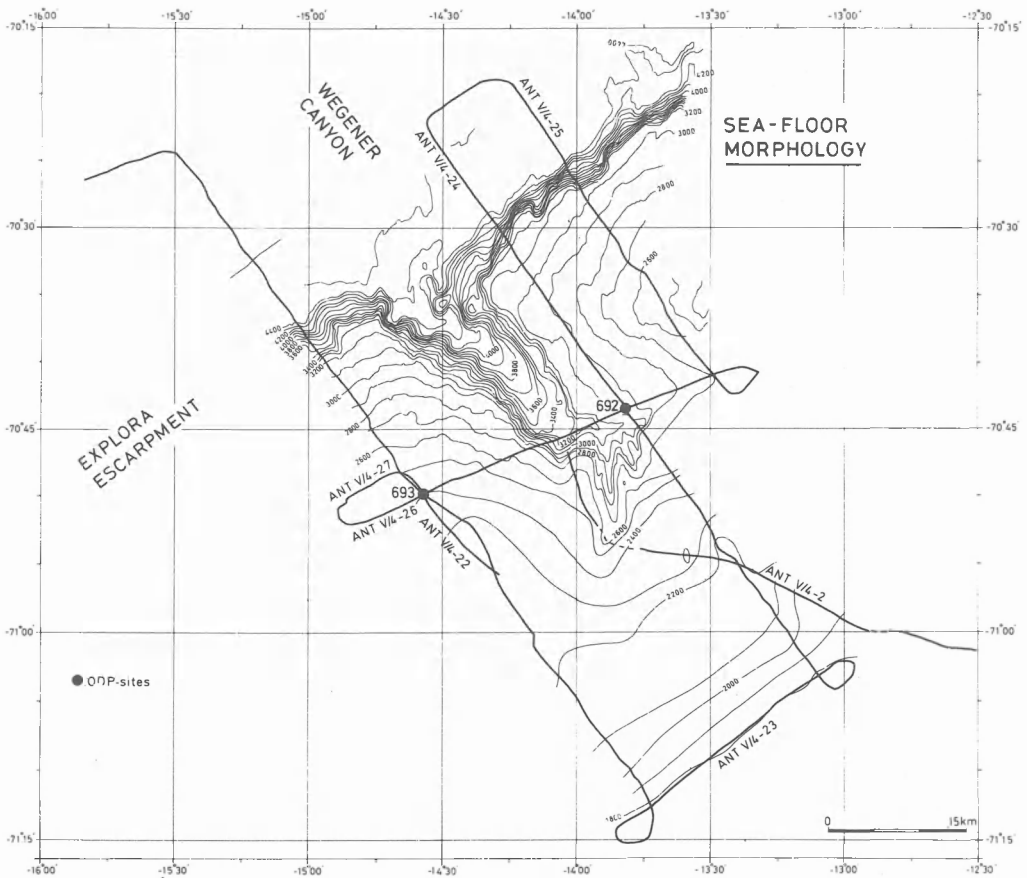
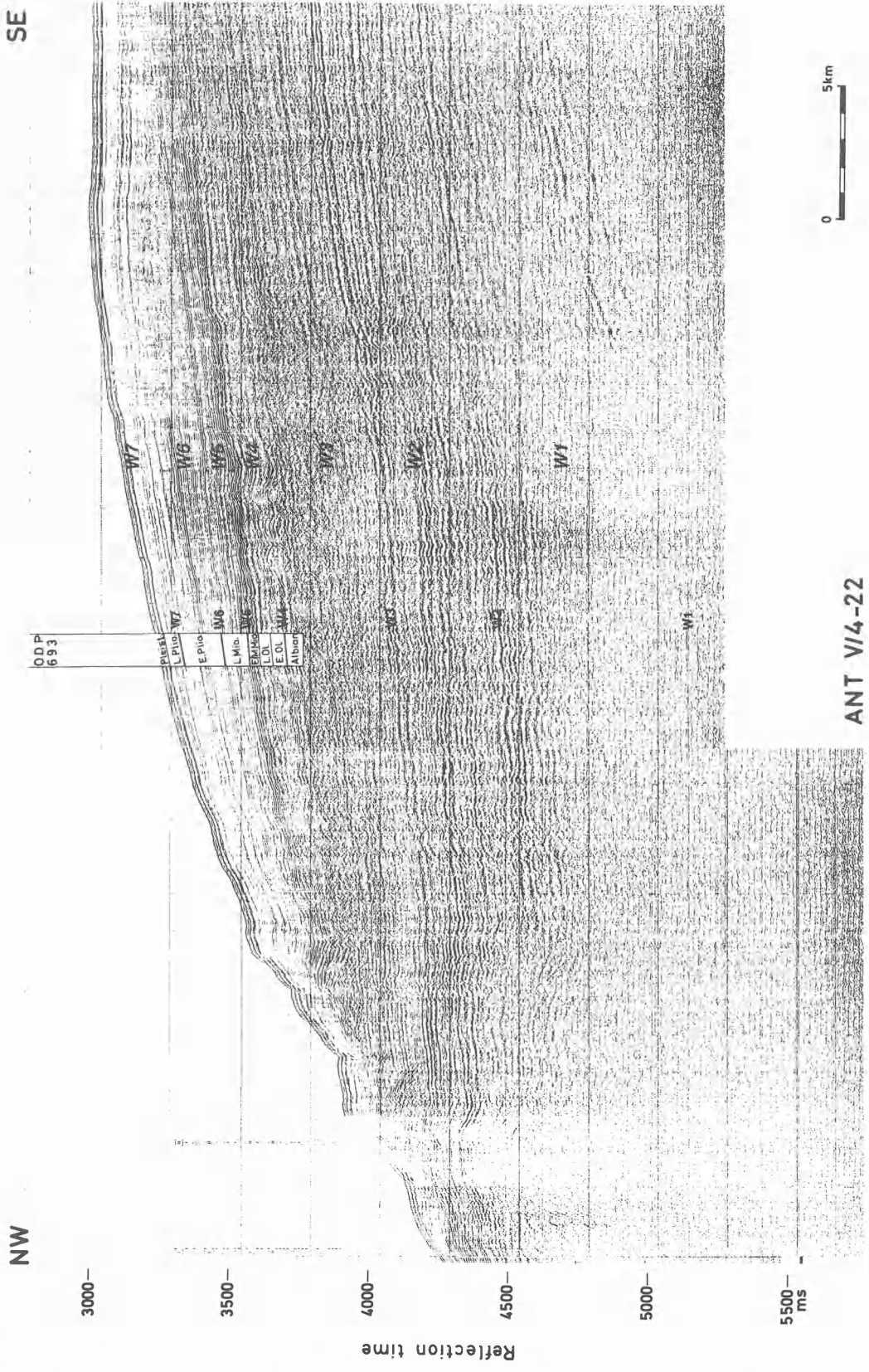


Fig. 8 Map of the seismic tracks framing Wegener Canyon.



ANT V14-22

Fig. 9 Analog monitor record of the seismic stratigraphic prototype profile (ANT V/4-22) through ODP Site 693.



22 with a larger vertical scale exaggeration for a better resolution of the stratigraphy of the Cenozoic cover is shown on fig. 11.

A digital profile of the tie line between both wells is shown on fig. 12. This profile bears clear evidence of a fault control of Wegener Canyon. Interpreted sections of the full set of airgun profiles in the considered area are shown on fig. 13.

#### 141.2 Mesozoic stratotype sequences

The Mesozoic depositional sequences identified in the vicinity of Wegener Canyon are the *W1*, *W2* and *W3* sequences. The basal unconformity *WO1* corresponds with the "Weddell Sea Continental Margin Unconformity" *U9*, postulated of Late Middle Jurassic age (Hinz and Kristoffersen 1987). *WO1* is best defined on fig. 8, where the lower frequency seismic events are better preserved. The underlying diverging set of oceanward dipping reflectors of the "Explora Wedge" (unit *WS-4* in Hinz and Krause 1982), of probable volcanic origin, is but faintly visible on the AWI-RCMG records, due to the limited power of the used airgun array.

Sequence *W1*, which onlaps on the basal surface *WO1* in landward direction, has a thickness of about 1000 to 1200 m below Site 693 (700 ms two-way time, interval velocity 3000 to 3400 m/s). It is characterized by some low-frequency events in the basal interval ; these are less obvious on profile ANT V/4-22 but show up as a good marker horizon (*W1.2*) on neighbouring BGR profile 86-08. Above *W1.2*, there is a reflection-poor interval followed by a distinct but discontinuous reflector, which can also be traced some distance further south on BGR 86-08. Sequence *W1* can be physically correlated with sequence *WS-3A* defined by Hinz and Krause (1982), which was also described by those authors as a landward onlapping unit, suggesting deposition on a subsiding base (ref. : profile BGR 78-19, crossing profile ANT V/4-24).

Sequence *W2* is a stack of continuous, sub-parallel reflectors, affected by faulting in the vicinity of the "outer high", the apparently structureless wall bordering the plateau at the Explora-Andenes Escarpment. According to Hinz and Krause (1982), the boundary between *WS-3A* and *WS-3B* (here surface *W2*) is an erosional unconformity. Sequence *W2* is about 500 to 600 m thick below Site 693. On profiles ANT V/4-24 and 25, it wedges out in a landward diverging reflection configuration against the back of the outer high. Both the diverging pattern and the slight buckling of these layers visible on profiles 24 and 25 suggest a layer emplacement which was contemporaneous with a rotational uplift of the outer high (cfr. 142.3 and Henriët e.a. 1989). Sequence *W2* includes unit *WS-3B* and the basal interval of unit *WS-2* (Hinz and Krause 1982), as shown on table 2.

Sequence *W3* is characterized by a sub-parallel to wavy reflection pattern with moderate coherency. As these deposits have been identified as Lower Cretaceous organic mudstones in the ODP well, shale tectonic deformations which are quite common in organic-rich shales are a possible cause of the wavy reflection pattern. The basal reflector *W3* is a clearly defined erosional

Fig.11 Interpreted stratotype profile showing the detail of the Cenozoic sequences. Profile ANT V/4-22.

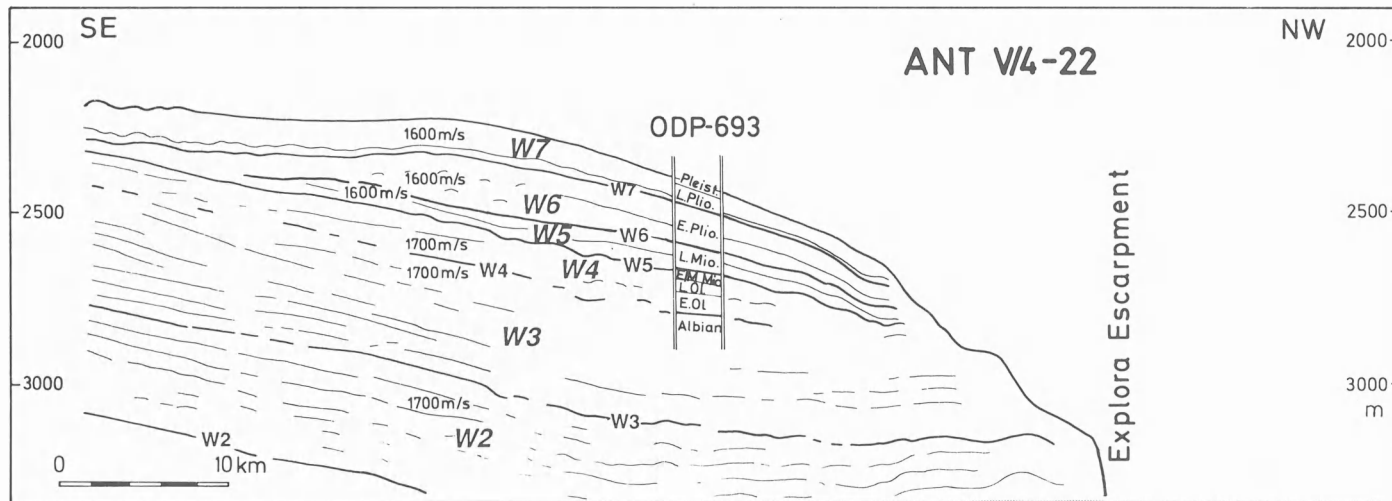




Fig. 12 Processed tying line ANT V/4-26 through ODP Sites 692 and 693.

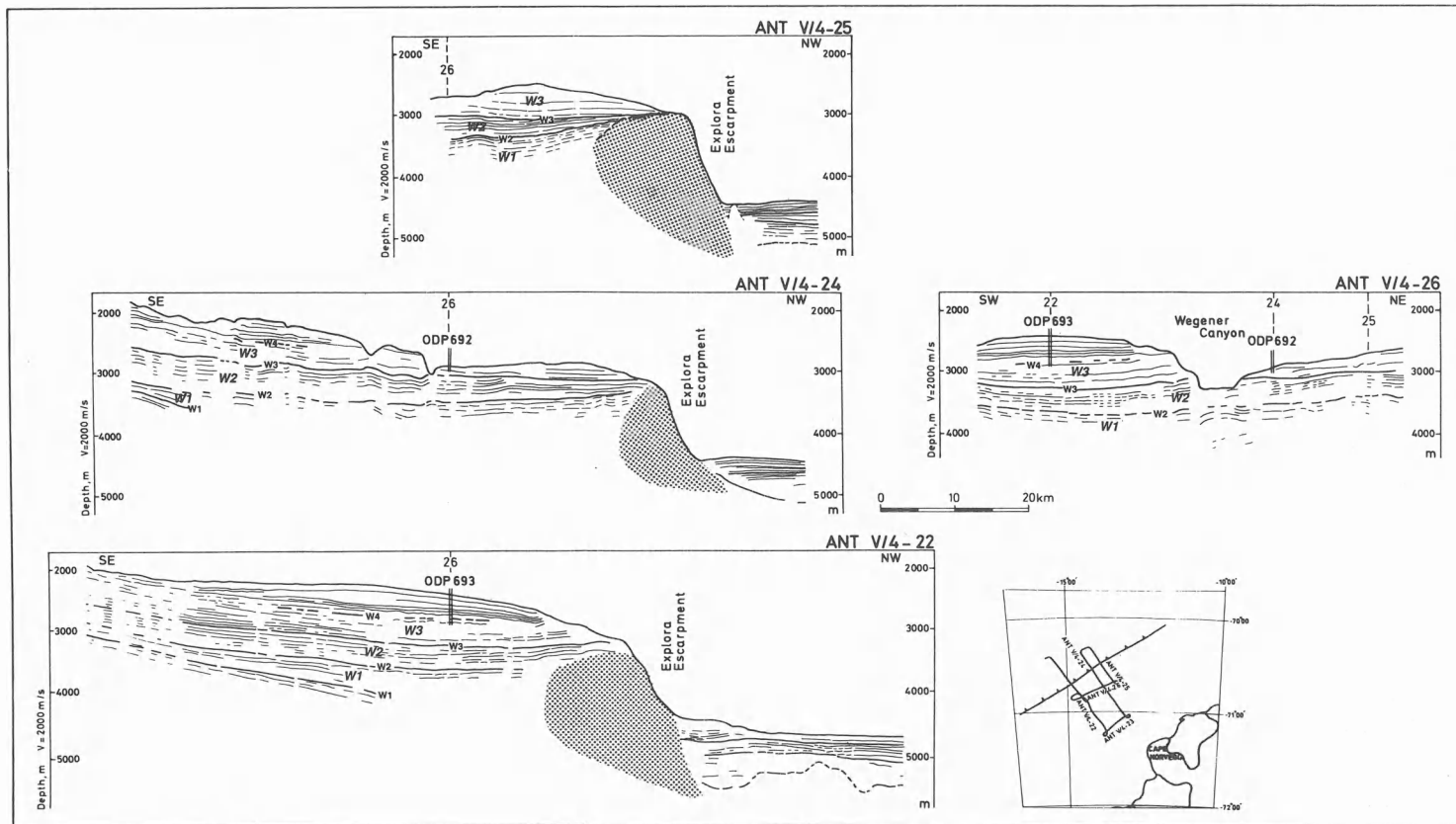


Fig. 13 Interpreted sections of the Wegener Canyon area. Profiles ANT V/4-22, 24, 25 and 26.

unconformity, truncating both the underlying *W2* sequence and the top of the outer high (profiles ANT V/4-24 and 25, fig. 8). The thickness of *W3* on Site 693 is about 400 m. It has been penetrated over a depth of 75 m in the cored section. The relative absence of continuous reflections in this sequence has also been reported by Hinz and Krause (1982), who noted only some low-amplitude sub-parallel bedding in the lower part of sequence WS-2. Sequence WS-2 should in our opinion be correlated with *W3* and the top interval of *W2*, above a prominent reflector defined as U5 by Hinz and Kristoffersen (1987) (table 2).

The top interval of *W3* was found to be of Aptian to Albian age at Site 693, while the lower interval of organic-rich claystones drilled at Site 692, about 150 m above *W3*, showed possible age associations ranging between upper Tithonian and late Hauterivian, depending upon the studied fossil assemblage (Shipboard Scientific Party 1988). If WO1 is indeed of late Middle Jurassic age, as proposed by Hinz and Kristoffersen (1987), this implies the presence of about 1500 to 1800 m of sediments of probably late Middle Jurassic to Upper Jurassic age below Site 693 (sequences *W2* and *W1*). Such a thickness suggests long-term average sedimentation rates of 20 to 40 m/Ma in the Jurassic and Early Cretaceous (Shipboard Scientific Party Leg 113, 1988), which are similar to the rates found for shorter intervals on the Falkland Plateau, at that time not far away. There is however evidence that larger thicknesses and additional sequences - probably also of Mesozoic age - are found in the interval between WO1 and WO4 when moving further south. Deposition apparently may have been more continuous and generous on the Weddell Sea margin than on the Falkland Plateau in Late Mesozoic times.

#### 141.3 Cenozoic stratotype sequences

The seismic stratigraphy of the Cenozoic deposits on the stratotype section is straightforward : most stratigraphic boundaries identified in well 693 have distinct reflection responses on the high-resolution profiles.

The deposits of sequence *W4* show a characteristic draping configuration, arguing for continuing shale tectonic deformations in the underlying Lower Cretaceous after emplacement of the new sediment load. In well 693, sediments mainly consisting of nannofossil-bearing clayey mud and diatom silty to clayey mud have been assigned an Early to Late Oligocene and Early to Middle Miocene age (lithostratigraphic units IIIc, IV and V, Shipboard Scientific Party 1988). This implies that the WO4 unconformity here represents a local hiatus of about 60 Ma. The basal reflection WO4 is very weak and discontinuous, especially on the analog record (fig. 9). In fact the whole seismic facies of *W4* looks rather noisy, with many diffractions and very weakly defined subparallel discontinuous reflections. In this context it should be noted that slumping has been reported in much of the Early Oligocene sediment in hole 693B. Above a basal slumped section, some 40 m thick, there is a 5-6 Ma hiatus around the boundary between Early and Late Oligocene in the borehole log, which cannot be resolved from the basal WO4 reflection on seismic sections but

which seems possibly to correlate with a climatic signal, like the other Cenozoic unconformities (cfr. 15.3).

In contrast to the noisy facies of this sequence, the top boundary WO5 is a very strong, continuous and locally wavy reflection. This prominent reflector WO5 corresponds to another - though minor- hiatus in well 693, where most of the Middle Miocene is lacking. Directly above the hiatus is a thin nannofossil mudstone, which possibly significantly contributes to the reflection response. Horizon WO5 heralds a dramatic change in seismic facies, well visible on the high-resolution profile of fig.9. All units above WO5 display a regular and thin-bedded pattern of parallel, continuous reflections, only affected downslope by some incipient slumping phenomena. This change in seismic facies no doubt reflects the increasing role played by glacial marine sedimentation, related to the renewed cooling and major expansion of the East Antarctic ice sheet from Middle Miocene times onwards. This event is also well documented in the oxygen isotope records of benthic foraminifera in Atlantic DSDP Sites (fig. 30).

Notwithstanding the relatively homogeneous seismic facies and also lithologic composition of the deposits above WO5 (lithostratigraphic units IIIA, II and I), the very high resolution of the records allows a further seismic stratigraphic subdivision to be made : two sequences named *W5* and *W6* are truncated upslope and covered by a continuous top sequence *W7*. The boundary between *W5* and *W6* is a well defined reflector (fig. 9), possibly related to the jump in velocity observed on the P-wave velocity log at a depth of 190 m below sea floor in well 693 (from 1600 to 1680 m/s, fig. 10). Sequence *W5* would thus correlate with Late Miocene silty and clayey diatom-bearing muds, with a P-wave velocity of 1680 m/s. Sequence *W6* then corresponds with Early Pliocene deposits of similar composition, but with a velocity of 1600 m/s. Upslope the unit becomes chaotic and is truncated by *W7*. The passage from Early Pliocene to Late Pliocene and Pleistocene sedimentation is thus locally marked by an erosional unconformity. This observation might support the results of Ledbetter and Ciesielski (1982), who have advanced a Late Pliocene to Early Pleistocene hiatus of regional significance in the northeastern Weddell Basin. Again this unconformity clearly seems to correlate with a significant drop in the  $\delta^{18}\text{O}$  record, as illustrated on fig. 30.

#### 141.4 Continental rise deposits

The sediments at the foot of the Explora-Andenes Escarpment are characterized by cut and fill structures, as shown for instance on profile ANT V/4-4 (fig. 14). Such structures may bear witness of successive episodes of scouring and deposition of turbiditic sediments in basin floor fans, associated with the periodic activity of slope-edge canyons like Wegener Canyon. Alternatively, these structures could be explained by episodic variations in longslope currents induced by variations of bottom water flux, with an implicit climatic control.

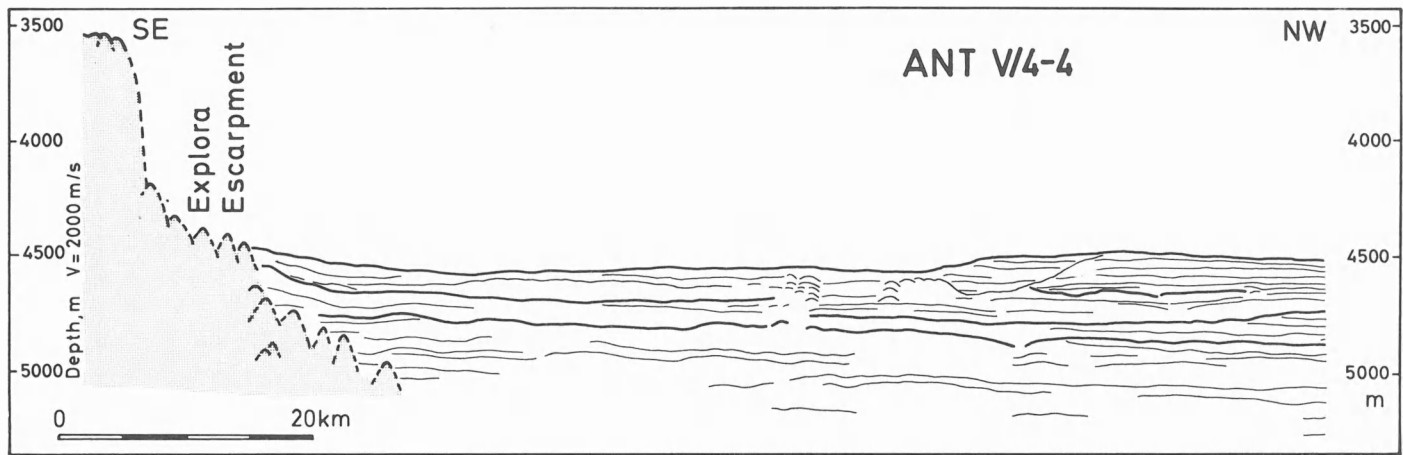


Fig. 14 Cut and fill structures at the foot of the Explora Escarpment. Profile ANT V/4-4

## 14.2 The nature of the Explora-Andenes Escarpment

The seismic observations made over the Explora-Andenes Escarpment during the Antarktis V/4 cruise have triggered a critical re-evaluation of existing geophysical data, which might possibly lead to some new insights in the origin of this prominent feature in the seafloor morphology of the eastern Weddell Sea.

### 14.2.1 The outer high

The apparently volcanic sequence of oceanward dipping reflectors known in the eastern Weddell Sea as the Explora Wedge abuts in oceanward direction against the so-called "outer high", a mound-like structure which is characterized on many seismic profiles by numerous diffraction hyperbolae and the virtual absence of continuous reflectors. This outer high was initially regarded as a basement high by Hinz and Krause (1982), essentially on the basis of the observation of refraction seismic velocities of 5 km/s to more than 7 km/s in their refraction profile S 22. The oceanward flank of the outer high shapes the Explora-Andenes Escarpment, which as already stated is thought of being caused by a large transcurrent fault, obliquely transecting the failed rift basin identified by K. Hinz (Hinz and Kristoffersen 1987).

The assumption of the presence of an outer high of magmatic origin which would have acted as a retaining sill for the sediments overlying the dipping reflectors of the Explora Wedge along the Dronning Maud Land margin has subsequently been taken over by the Shipboard Scientific Party of ODP Leg 113 (1988, p. 316). These authors moreover refer to such an outer high as a common feature of seaward-dipping reflector provinces (citing e.g. Roberts e.a. 1985) ; such a high would be located where oceanic basalt has erupted at shallow depth. In the model advanced by the ODP Leg 113 Scientific Party, the erosion of Wegener Canyon would have followed a two-step evolution. By the early Late Miocene or before, a gently sloping canyon floor covered by a coarse gravel lag would have developed at the level of the shoulder of ODP Site 692. Subsequently, a steep inner canyon would have formed (Site 691) and cut rapidly headward through the sediments on its landward side once the basaltic sill had been breached. This rejuvenation of the canyon probably began in the late Middle Miocene, as the East Antarctic glaciation deepened and the supply of sediment to the margin started to increase. The ODP Leg 113 Scientific Party already suggested a fault control on the location of the canyon, on basis of an offset of the oceanward scarp of the outer high. The presence of faults in the basement strata of Wegener Canyon has been confirmed by profile ANT V/4-26, tying ODP wells 692 and 693 across the canyon (fig. 12).

### 142.2 Some comments

A first comment to be made is that the hypothesis of a magmatic outer high bordering the Explora-Andenes scarp in the region of Wegener Canyon has not yet been supported by any fully conclusive evidence. Refraction profile S 22 referred to by Hinz and Krause (1982) and situated some 350 km south of Wegener Canyon in water depths of 3900 m proves the presence of high-velocity rocks (5.4 to 7.7 km/s), however below about 3000 m of sediments with velocities of 2.33 to 4.15 km/s (Hinz and Krause 1982, Table 2). Magnetic profiles measured over the escarpment both by BGR and during the Antarktis V/4 survey are characterized by long-wave anomalies, suggesting deep-seated causative bodies rather than a towering magmatic high.

It should further be remarked that the two phases of erosion of Wegener Canyon proposed by the ODP Leg 113 Shipboard Scientific Party might very well reflect a climatic control rather than a prolonged resistance to submarine scouring offered by a magmatic sill.

### 142.3 New observations

The detailed SEABEAM bathymetric mapping of Wegener Canyon, carried out during the Antarktis V/4 cruise, does not give a conclusive morphological evidence of the presence of rocks with strongly contrasting resistance in the lower canyon reaches (figs. 7 and 8). One might expect that the breach of a magmatic wall in such a canyon would have been marked by a narrowing of the valley and a steepening of the slopes, which is not the case.

A processed seismic section shot by R.V. "Polarstern" in the area of ODP Sites 691 to 693 shortly after their completion (Miller e.a., 1989) showed a first evidence of a reflector which can be followed some distance below the otherwise structureless outer high, without any noticeable velocity pull-up.

Another observation on the high-resolution seismic records is that sedimentary units leaning upon the landward flank of the outer high display a characteristic pattern of diverging and slightly buckling reflectors, which might suggest a layer emplacement which was contemporaneous with a rotational uplift of the outer high (cfr. the analog monitor records of profiles ANT V/4-24 and 25, shown on fig. 15).

Finally it should be mentioned that grab sampling carried out by "Polarstern" along the flanks of Wegener Canyon after the seismic survey yielded a range of shallow-water sandstones with glassy inclusions, but not a single basalt sample<sup>1</sup>.

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<sup>1</sup> Personal communication G. Kuhn, Alfred-Wegener-Institut für Polar- und Meeresforschung

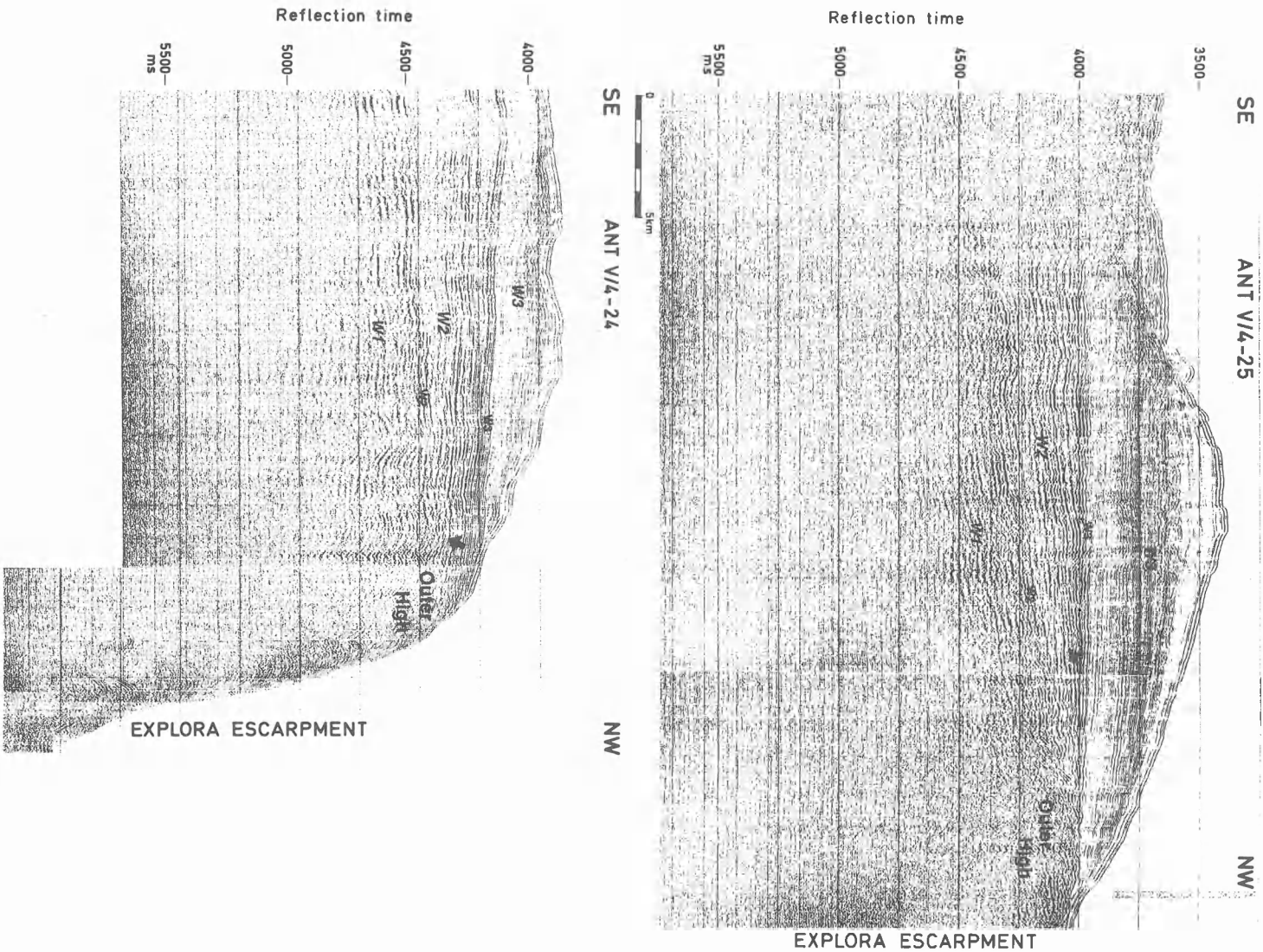


Fig. 15 Analog seismic profiles (ANT V/4-24 and 25) across the sedimentary cover on the landward flank of the "outer high", Explora Escarpment.

#### 142.4 A new hypothesis

The scarcity of conclusive evidence about the nature and origin of the Explora-Andenes Escarpment found in literature leaves space for some conjectures, which can be nourished by the above mentioned observations.

If the transcurrent fault supposed to mark the escarpment has operated in a right-lateral sense, the regional displacement sense in the separation between Antarctica and Africa, the slightly arcuate northerly segment of the fault must have been subject to compressive stress components, in addition to the major shear component associated with the strike-slip motion (fig. 16). Such a situation is not likely to generate large leaks of magmatic material, but on the contrary might result in some underplating.

In this hypothesis, the scarp wall known as the outer high may to some extent consist of a stack of material of sedimentary nature, scraped off the early oceanic crustal plate by the overthrusting continental plate. The lithologic nature of the dredged samples is not in contradiction with this hypothesis : the coarse sands including volcanic glass grains could well fit into a model of shallow sea sedimentation on the early oceanic crust of Middle to Late Jurassic age. Any presence of minor inclusions of crustal or other magmatic origin amid the sediment stack is certainly not ruled out in this model.

The observation of the diverging set of slightly buckling deposits (of apparently sedimentary nature), abutting against the landward flank of the outer high, might confirm this hypothesis, arguing for a progressive build-up of the sediment stack on the overthrusting plate edge, possibly in a similar way as accretionary wedges are formed along converging margins. Similar structures are indeed known on the back of typical accretionary stacks such as that associated with the Barbados Ridge complex ( Westbrook e.a. 1988).

The above hypothesis is in no way proposed as an ultimate one. It can easily be tested by further magnetic, gravity and seismic experiments, supported by meticulously planned geological sampling. Such work will probably be scheduled in the forthcoming geophysical programmes to be carried out with "Polarstern" in the Weddell Sea (season 1989-1990).

### 14.3 Sedimentary sequences off Halley Bay

#### 143.1 Survey structure

The study area north of Halley Bay can be subdivided into two parts (fig. 17) : a shelf area south of 74°30'S, with water depths of 300 to 500 m, and a continental slope and rise area north of 74°30'S, in water depths ranging from 2000 to 3500 m. With exception of lines ANT V/4-1, 9 and 10, shot with the 4.5 kJ sparker or the 0.25 l watergun and of refraction line ANT V/4-21 (recorded with full available airgun power and two ocean bottom seismographs), all profiles have

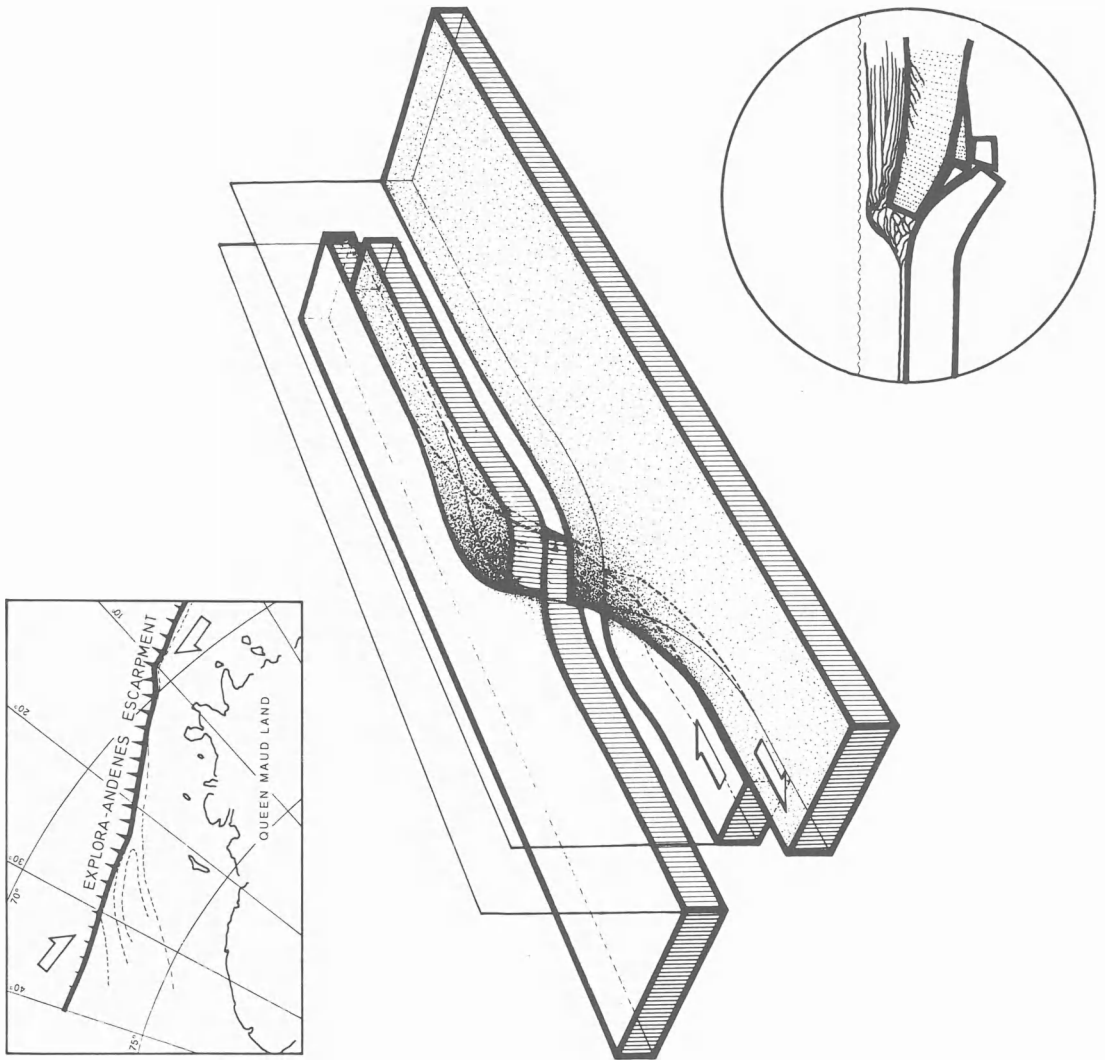


Fig. 16 Underthrusting along the Explora Escarpment as a consequence of the arcuate shape of the transcurrent fault.

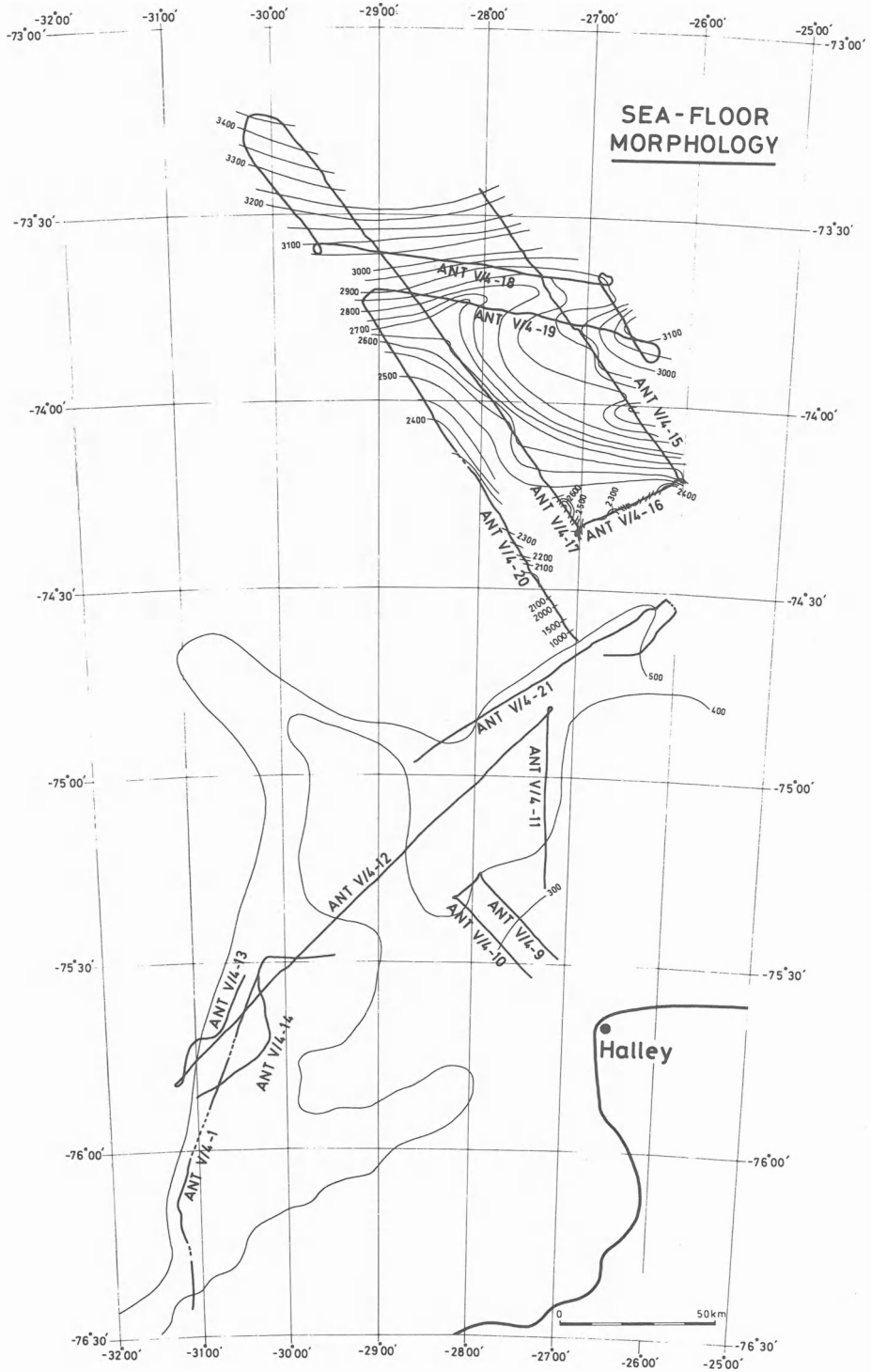


Fig.17 Sea-floor morphology and track map of the seismic survey over the continental shelf, slope and rise north of Halley (distal fan sequences, Cray Fan).

been shot with the above described airgun array (13.1), optimally trimmed for high-resolution acquisition.

#### 143.2 Shelf sequences

The shelf profiles have been shot along the edge of the pack ice. Line ANT V/4-1, starting from a nearshore outcrop of the East Antarctic basement (fig. 18), has been extended by line ANT V/4-14 and 12 with the purpose of tying the Norwegian lines NARE 77-6, 8, 4, and 2 and NARE 79-6 and 8. These profiles show the top sequences of the obliquely prograding wedges, already described by Haugland (1982), Haugland e.a. (1985) and Hinz e.a. (1987). The deltaic progradation and associated submarine fan evolution have caused the important northward migration of the shelf edge in the southern Weddell Sea, probably in relatively recent Cenozoic times.

The sections on fig. 18 show at least five depositional sequences, which provisionally have not yet been named, as this will be done in agreement with the Norwegian partners. Most sequences show a rather complex internal bedding, with downlap and other lateral pinchout patterns and channel cut and fill structures.

The lowermost two sequences are both up-building in an onlap pattern on the cratonic basement and out-building in basinward direction. Channel erosion scars on top of the lower unit and a clear onlap of the overlying unit on the progradational front of the lower unit argue for a sea level lowering between both depositional phases. The second sequence also displays buried channels in its upper interval, visible for instance on profile ANT V/4-13 (figs. 18 and 19). Its top surface is also an erosional unconformity, which moreover truncates a third sequence at the far northeastern end of the profile. This erosional surface can possibly be regarded as the product of a prograding grounded ice sheet. The two last mentioned units are both covered by a relatively thin sequence (about 50-80 m thick) which on its turn overlies on the basement surface. The most superficial unit (100-150 m thick) is of limited lateral extent on the considered profile.

Assigning an age to these sequences is still highly speculative. The correlation with the SWS units defined by Haugland e.a. (1985) still has to be worked out. According to these authors, the younger SWS shelf sequences (SWS-A to D) in the Weddell Embayment might correlate with strongly prograding shelf sequences of postulated Early Miocene to Pliocene age (Hinz and Krause 1984).

#### 143.3 Slope fan sequences

Profiles ANT V/4-15, 17 and 20 and their tie lines ANT V/4-16, 18 and 19 (fig. 17) show a very high resolution picture of the distal units of Cray Fan and of a large associated buried channel, which trends in northeastern direction along the foot of the upper continental slope.

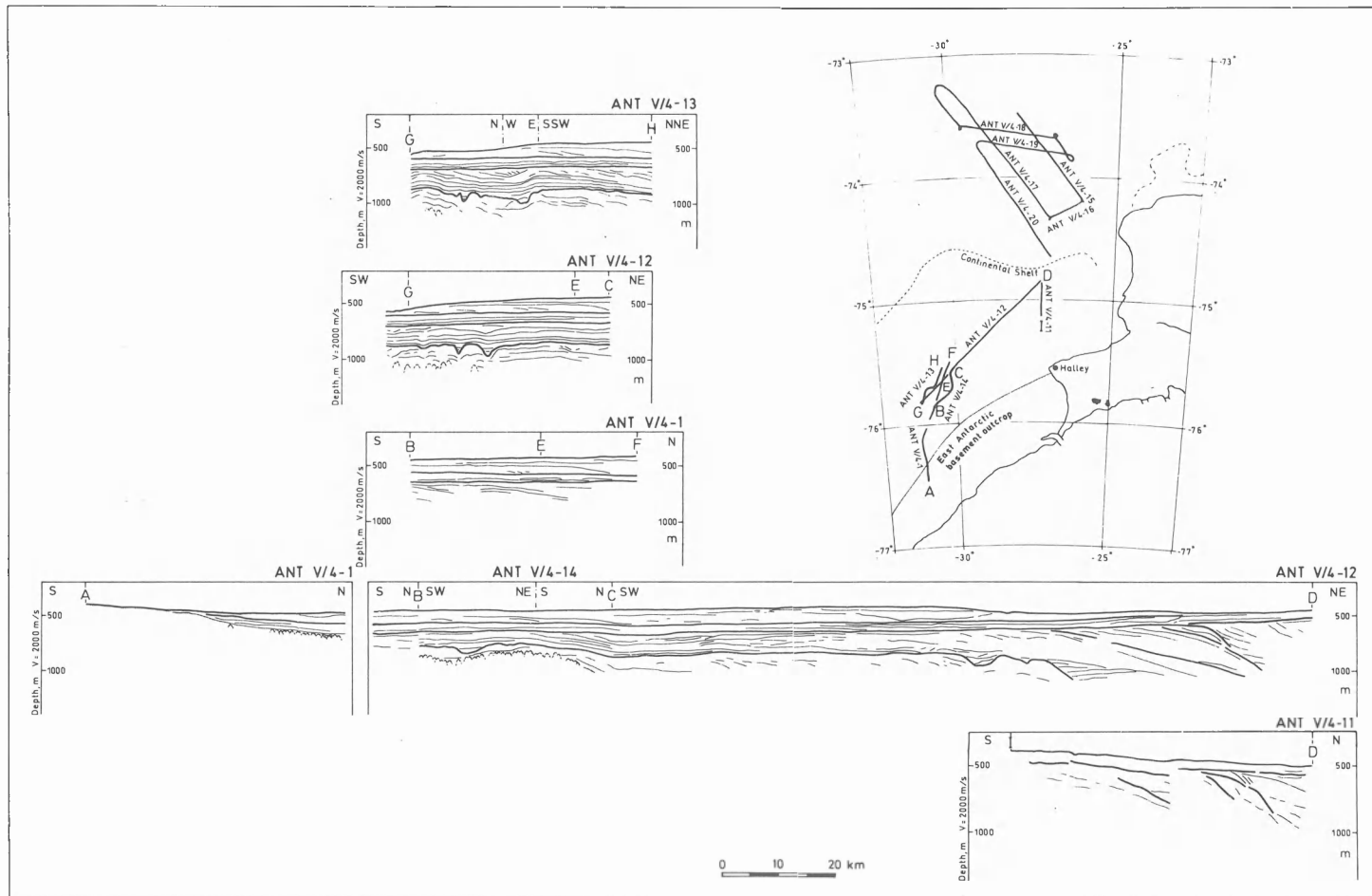


Fig. 18 Interpreted shelf profiles with prograding wedges north of Halley Bay. Profiles ANT V/4-1, 11, 12, 13 and 14.

ANT V/4-13

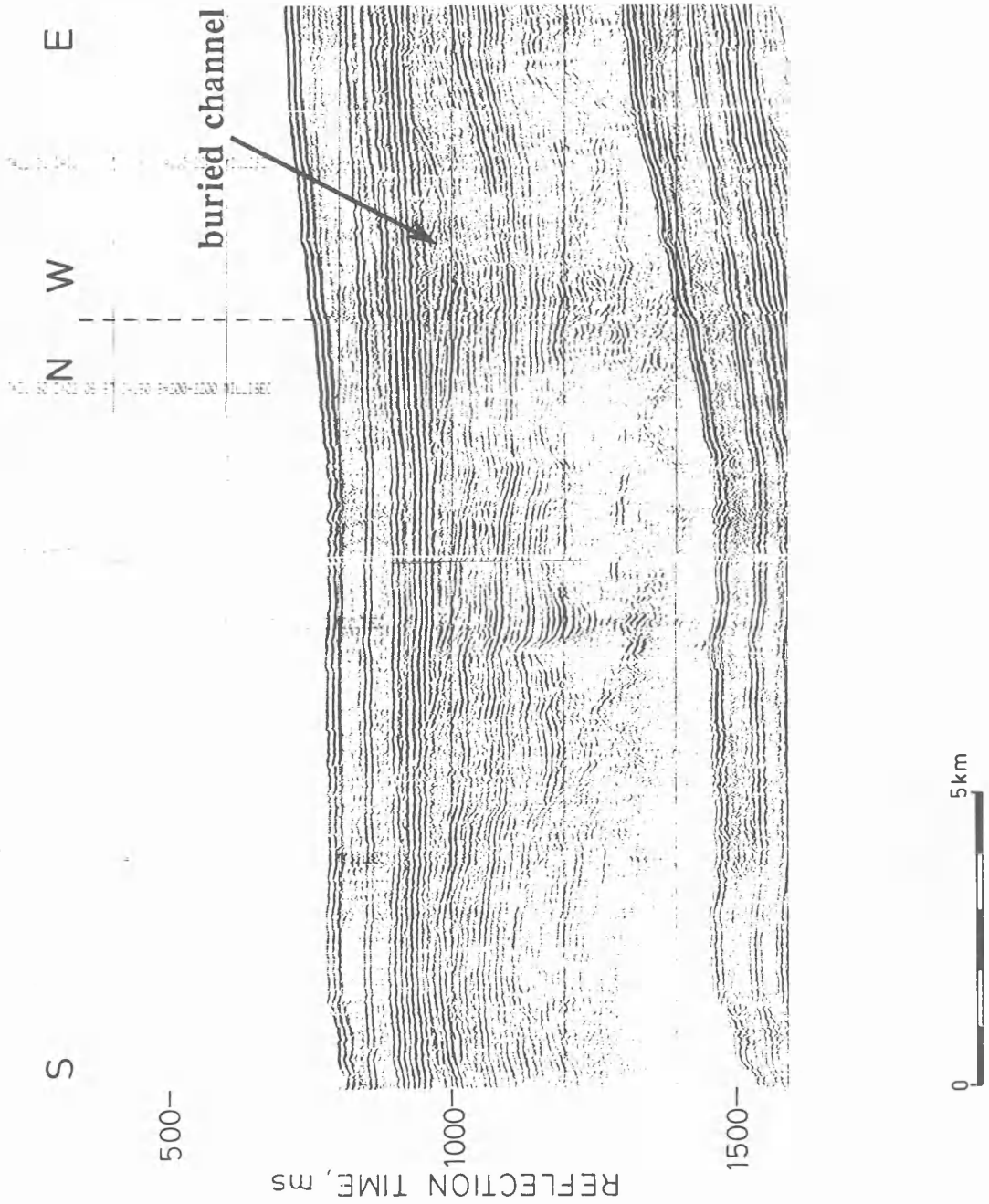


Fig. 19 Detail of the shelf wedge deposits with buried channel at the top of a depositional sequence. Profile ANT V/4-13.

Four major fan sequences can be identified, all downlapping or onlapping on a sloping erosional surface. It looks as if this erosional surface can be followed on BGR profile 86-08 over the whole length of the continental margin of the eastern Weddell Sea up to ODP Site 693, where it matches unconformity WO4 at the base of sequence *W4*. For reasons related with an observation reported below, this unconformity at the base of the fan deposits off Halley Bay will for the time being be called WO4b. This surface acts as an acoustic basement on the AWI-RCMG profiles (figs. 20, 21, 22, 23), due to the limited power of the seismic sources.

BGR lines across this area (e.g. BGR 86-08 and BGR 86-13) however confirm the presence of more than 3000 m of sediments below WO4b. In fact it appears that two practically adjacent major supersequences can be identified below the level of WO4b on profile BGR 86-13, both about 2 s thick (which corresponds with thicknesses of about 3000 m each, taking into consideration velocities between 2.8 and 3.5 km/s at that depth, Hinz e.a. 1987). Both supersequences locally rest on the unconformity WO1 and are separated by a major erosional unconformity which obliquely truncates the lower supersequence. This lower supersequence essentially rests on continental crust topped by the Explora Wedge. The upper supersequence is essentially resting on oceanic crust and onlaps on the sloping unconformity, provisionally named WO4a.

An important remark is that the WO4b unconformity merges with WO4a when followed along the intersecting line BGR 86-13 in landward direction, hence forming again one single unconformity WO4, a situation remembering that on Site 693. It is not excluded that a similar merging would occur along line BGR 86-08, but it has not yet been demonstrated in a conclusive way. We cannot exclude either the hypothesis that WO4b would correlate with WO5, which would imply a Late Miocene to Pliocene age of the onlapping fan sequences. This preliminary interpretation will be further discussed among the Weddell Sea research partners before interpretative profiles can be presented.

The submarine fan sequences observed north of Halley Bay clearly belong to a completely different systems tract than the Cenozoic stratotype sequences overlying surface WO4 at Site 693, which obviously complicates any correlation effort. Hence the fan sequences have been provisionally named *WF 1*, *WF 2*, *WF 3* and *WF 4* in this study. This terminology is subject to revision when forthcoming correlation work with Norwegian and BGR data has been completed, as mentioned above.

Sequence *WF 1* is characterized by weak, sub-parallel reflectors. It has a thickness of about 500 m in the westernmost part of the study area (profile ANT V/4-19, fig. 23) and rapidly wedges out in landward direction. The lapout pattern of sequences *WF 1* to *WF 3* shown on the map on fig. 24 is probably to be regarded as the lateral wedge-out of northeasterly prograding fan lobes.

Sequence *WF 2*, characterized by weak, discontinuous reflectors, keeps a fairly constant thickness of about 200 m until it also wedges out against WO4. Its basal unconformity *WF 2* clearly truncates the underlying sequence on profiles ANT V/4-17 and 19 (figs. 21 and 22).

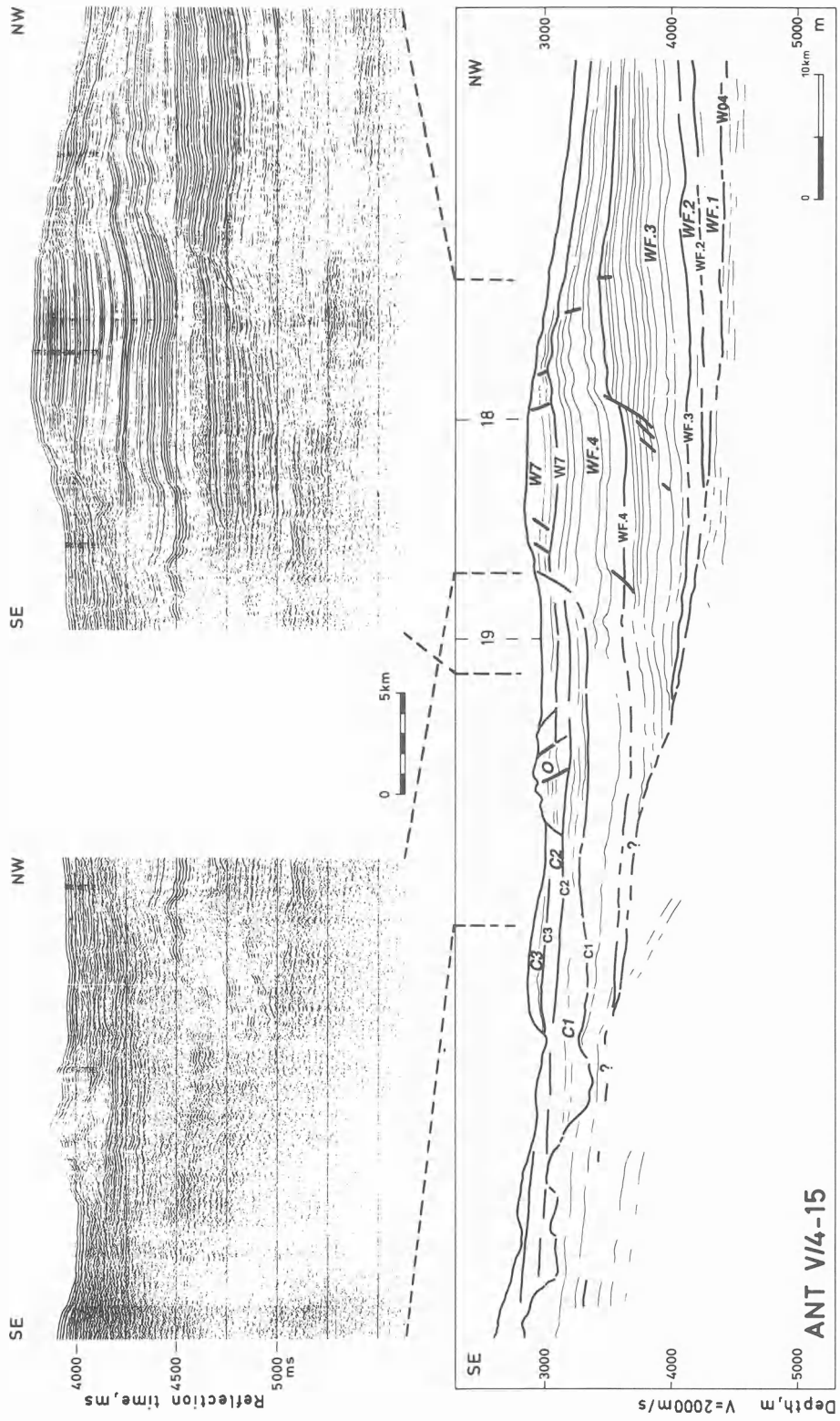


Fig. 20 Distal fan sequences onlapping on unconformity W4. Channel sequences (C) and olistoliths (O). Profile ANT V/4-15.

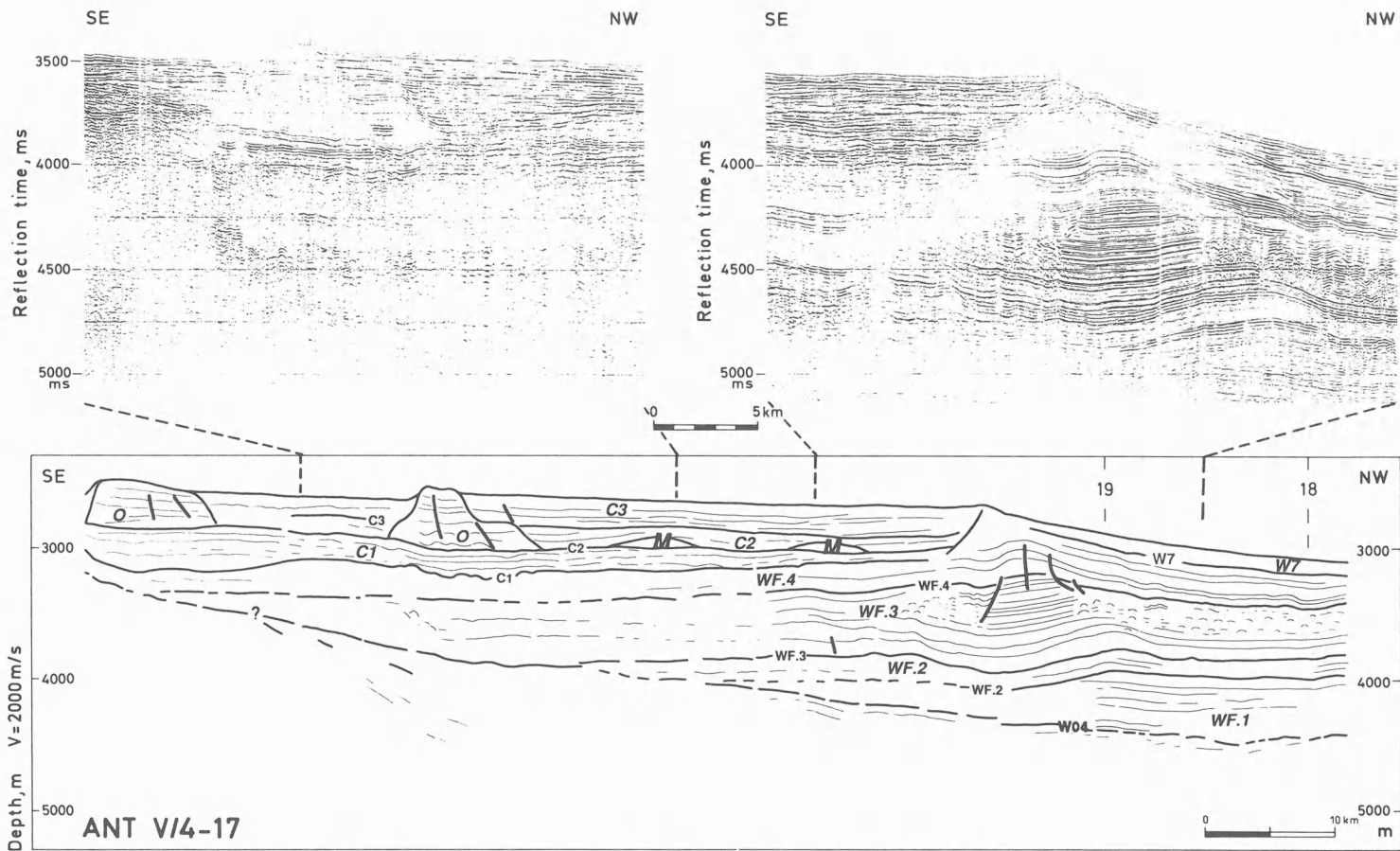


Fig. 21 Distal fan sequences onlapping on unconformity W4. Channel sequences (C) and olistoliths (O). Profile ANT V/4-17.

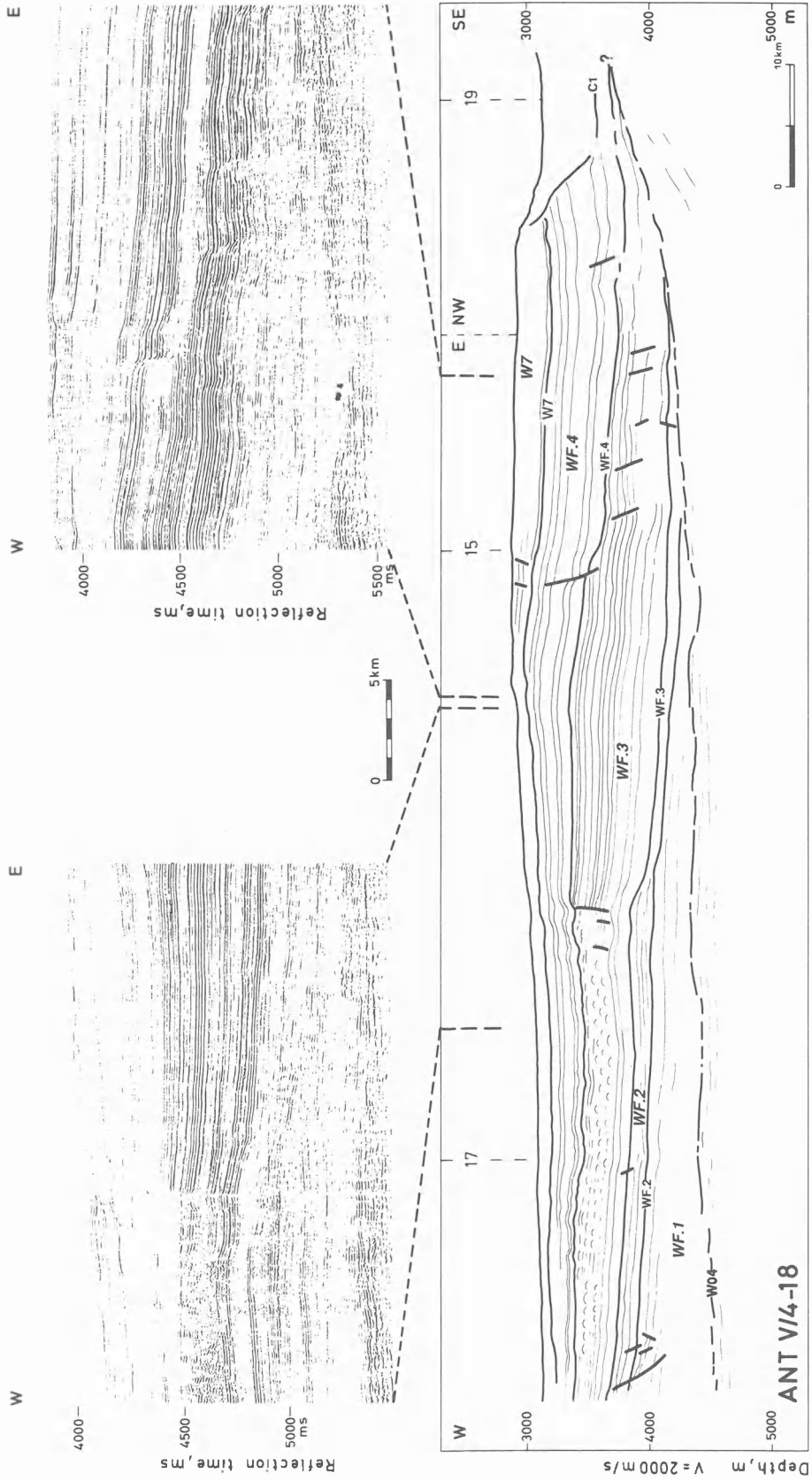


Fig. 22 Distal fan sequences downlapping on unconformity W4. Profile ANT V/4-18.

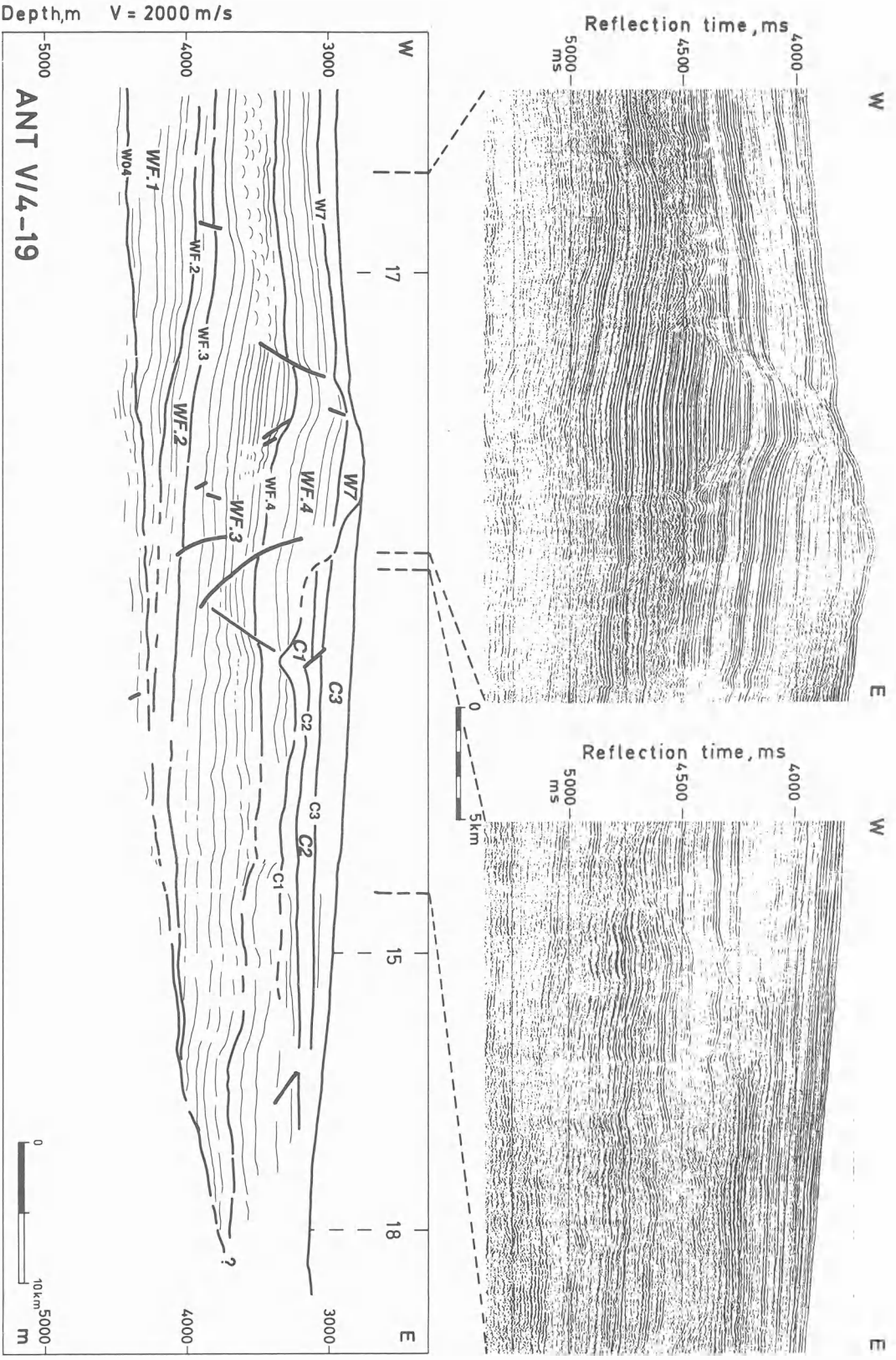


Fig. 23 Downlapping fan sequences with detail of buried erosional ridge flanked by slumped deposits. Profile ANT V/4-19.

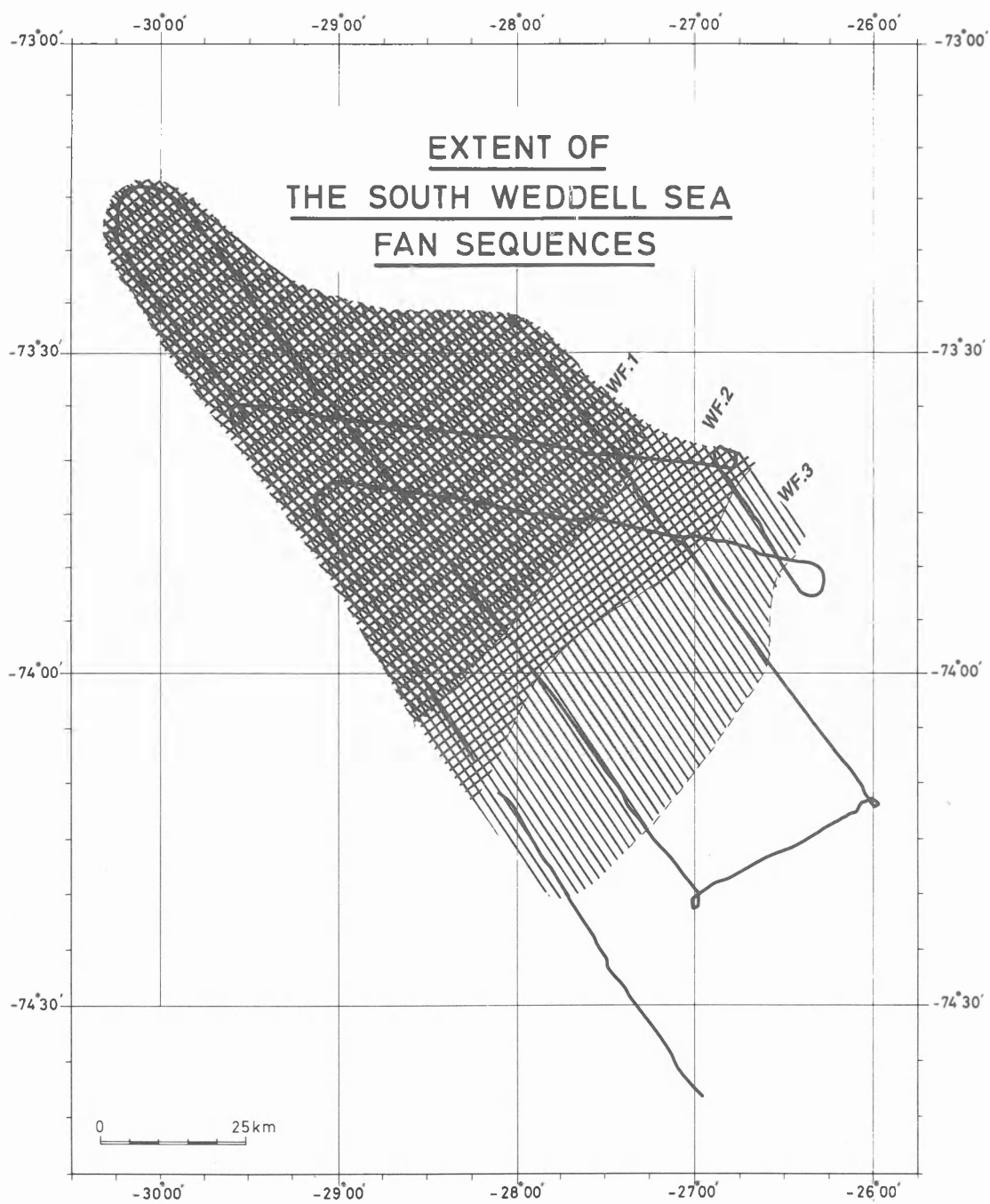


Fig. 24 Lateral onlap pattern of distal fan lobes on the W4 unconformity.

The basal unconformity of sequence *WF 3* erodes the distal part of sequence *WF 2*, as observed on profile 18 (fig. 22). Sequence *WF 3* is no doubt the most striking unit in this part of the study area. It reaches a maximal thickness of 700 m in the considered area and thins out both in southeasterly and northwesterly directions. Its facies is characterized by a series of strong, continuous and parallel reflections, locally disturbed by remarkable sediment-tectonic features. Some of the listric faults observed also affect the overlying sequence, but none of them can be traced down in the underlying unit. The origin of these deformations should consequently be sought in sequence *WF 3* itself and is most probably related to a shear strength reduction in temporarily overpressured horizons. This hypothesis seems to be corroborated by the observation of extensive sediment fluidization and slumping phenomena, affecting the footwall of some major listric faults. The slumped horizons are marked by an undulating to chaotic seismic facies, with numerous diffraction hyperbolae (figs. 21, 22, 23). The hanging wall of the considered listric faults displays a larger stratigraphic thickness, building up a prismatic paleoridge. The areal extent of faults, slumped areas and paleoridge are shown on fig. 25. The fact that some stratigraphic units disappear across the faults might argue for an early slumping activity, which would have caused the remobilization and removal of the upper part of the slumped sediment sections (shortly after deposition but before burial by the following sequence). In an alternative interpretation, such paleoridges might be seen as sedimentary drift structures formed by bottom currents (K. Hinz, 1989, pers. communication).

The paleoridge structure and the slumped areas described above are draped by sequence *WF 4*, where the deformations initiated in the underlying sequence progressively fade out. This unit is itself covered by a draping, continuous sequence with relatively constant thickness. By virtue of affinities in emplacement, seismic facies and thickness with the top sequence on ODP Site 693, this unit has been named sequence *W7*.

Close to the foot of the upper continental slope, which has a very rough topography, the fan sequences and especially sequence *WF 4* have been deeply ravinated by a broad longslope channel, which shows different sequences of sediment infill named *C1* to *C3*. The seismic facies of the valley fill sequences is very different from that of the fan deposits: quite striking are the high-amplitude, discontinuous reflections, suggesting a high-energy depositional environment, probably turbiditic.

Very large olistolith-like structures, some of them characterized an internal seismic facies displaying striking analogies with that of sequence *WF 4*, are resting on top of the lower fill sequence (fig. 21). A major argument for the identification of such sediment bodies as olistoliths is this analogy in facies with *WF 4* and the observation of remarkable basal disharmonic folds, suggesting the presence of a slip surface (fig. 26). An alternative interpretation, as advanced by some sedimentologists, is that these sediment bodies should be identified as leveed channel deposits. The facies characteristics of these sediment units however seems to contradict this hypothesis. The occurrence of the olistolith-like structures has been mapped and represented on fig. 21. The

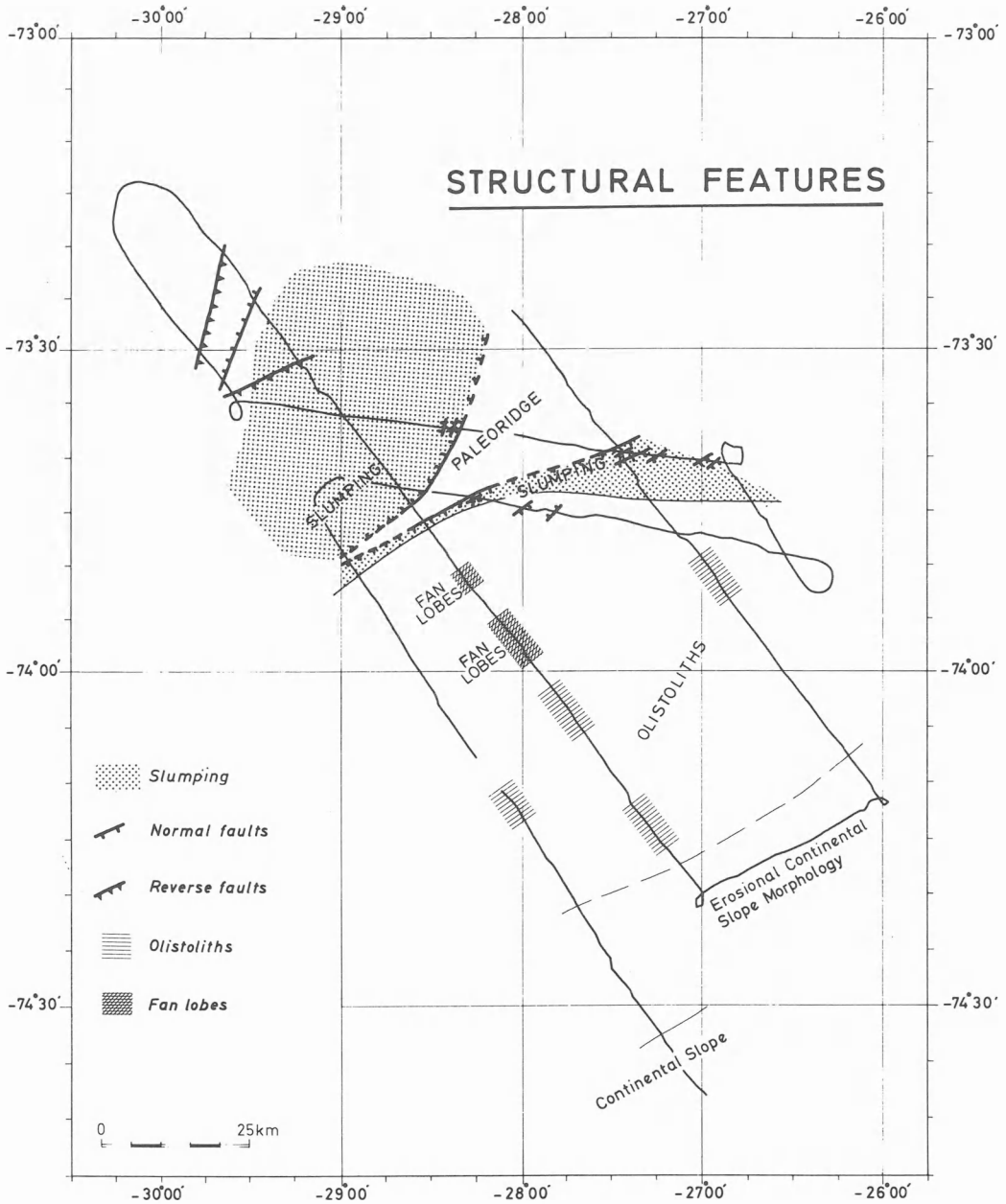


Fig. 25 Sediment-tectonic features in fan sequence *WF 3* and areal distribution of olistolith-like structures in the buried channel at the foot of the upper continental slope.

ANT V/4-17

SE

NW

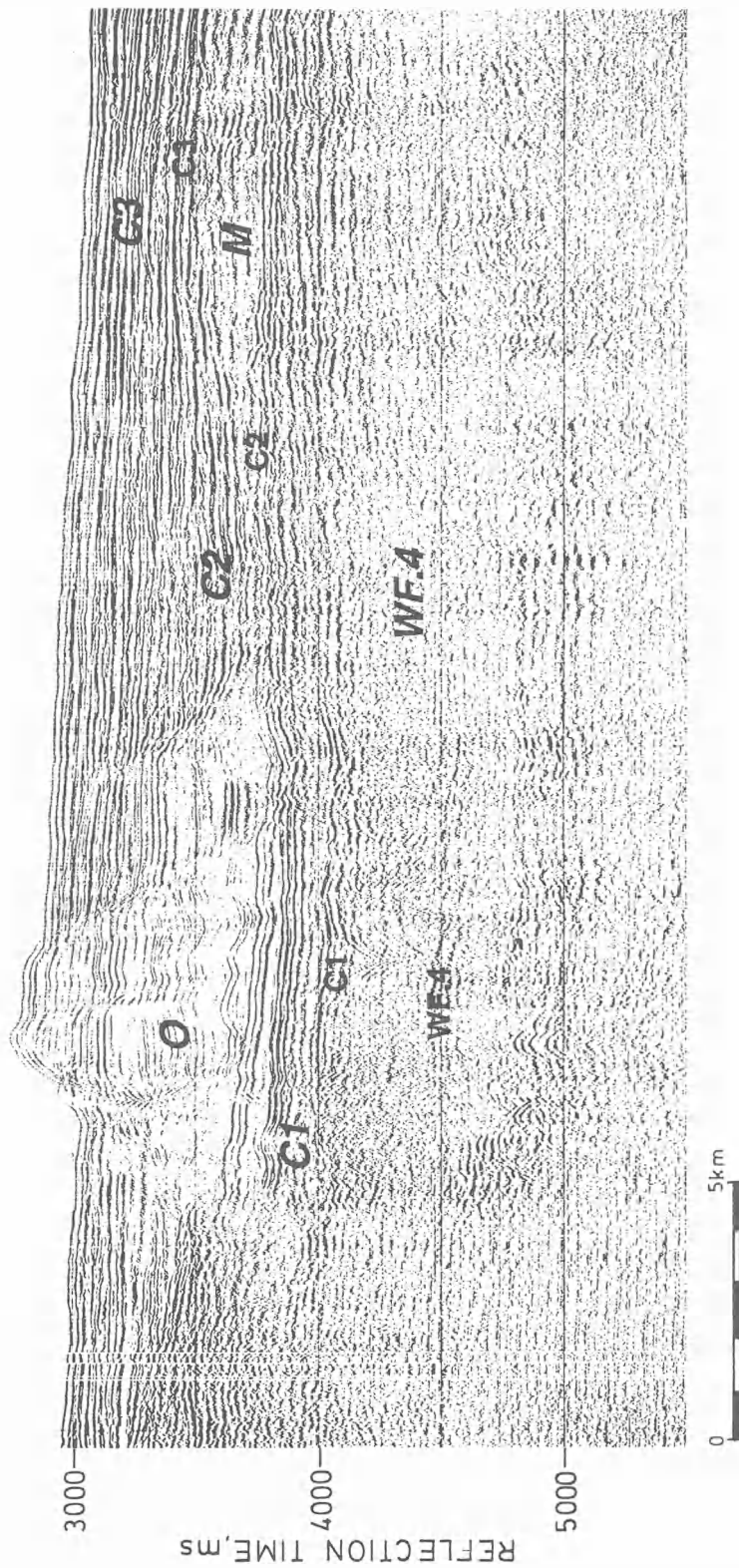


Fig. 26 Detail of an olistolith-like structure, showing the disharmonic folding above the supposed slip plane. Profile ANT V/4-17.

apparent alignment of three of these structures on parallel profiles might be used as an argument for identifying them as one single leveed channel, but this appearance of an alignment might simply be fortuitous.

The detachment and sliding of large slabs of sequence *WF 4* from flanks of the valley (here most probably from upper reaches of the valley) should not be utterly surprising, considering the emplacement of this unit on top of a sloping fan sequence itself characterized by extensive areas of sediment fluidization and slumping. Also the locally observed very steep valley flank with a height of about 750 m (on the southeastern end of profile ANT V/4-18, fig. 22) may bear witness of past large-scale sliding events, which might have fed large sediment slabs into the lower reaches of the valley. These sediment bodies have subsequently been buried beneath the apparently high-energy deposits of sequences *C2* and *C3*.

Another characteristic form of sediment deposits also mostly resting on surface *C2* are the mound-shape fan lobes (*M*). Such depositional structures are quite frequent in basin floor fans (P. Vail 1989, pers. communication) and are usually built up of coarse grained sediments.

## 1.5 Broadening the picture

### 15.1 New insights in the Mesozoic South Atlantic sedimentary province

The identification of the *W 3* sequence with Lower Cretaceous black shales on ODP sites 692 and 693 sheds some new light on the importance of the Mesozoic sequences and the extent of the Cretaceous anoxic event on the southern margin of the early South Atlantic sedimentary province. The southernmost representatives of these sediments were hitherto only known from the DSDP boreholes on the Falkland Plateau (DSDP Site 511), the marginal Magallanes Basin and the Cape Basin (DSDP Site 361).

Although the true extent and stratigraphical importance of these sequences is not yet fully elucidated, there is little doubt that the southeastern Weddell Sea margin is characterized by comprehensive Late Jurassic to Early Cretaceous sequences. Whether the sequences below the *WO4b* unconformity in the southeastern Weddell Sea (off Halley Bay) do include Upper Cretaceous, Paleocene and/or Eocene sequences is difficult to evaluate at the present time.

The confirmation of an oxygen deficiency in the Late Jurassic to Early Cretaceous sediments of the Antarctic margin of the incipient South Atlantic Ocean is in itself not surprising. The important corollary of this observation however is that it possibly puts an additional constraint on the plausible paleocirculation models of the early Weddell Sea, a constraint which can be added to the analysis of the sequence of depositional phases and erosional events as observed on seismic sections.

There are indeed two fundamental models which address the problem of the widespread preservation of organic-rich sediments in the Cretaceous ocean, a key problem of paleoceanography (Zimmerman *e.a.* 1987). One is the preservational model, which implies a very low flux of dissolved oxygen to the site of deposition and consequently a very low vertical circulation. The other one is the productivity model, based on a greatly increased surface productivity which overwhelms the oxygen content of the water column ; the ocean dynamic corollary of this model is an enhanced vertical circulation (Southam *e.a.* 1982).

The preservational model with its restricted vertical circulation seems to apply to tectonically isolated basins such as the Black Sea or also the Late Jurassic to Lower Cretaceous South Atlantic (McCoy *e.a.* 1977, Natland 1978, Arthur *e.a.* 1979, de Graciansky *e.a.* 1984, Zimmerman *e.a.* 1987). Palinspastic reconstructions of the Late Jurassic to Cretaceous Southern Atlantic Ocean, shown on fig. 27 (after Zimmerman *e.a.* 1987), illustrate its confined setting.

If the preservational model holds, there are few reasons for expecting vigorous erosional events in such an environment. Such a situation most probably persisted at least up to Albian times in the Weddell Sea, considering the discovery of Albian black shales on Site 693. This reasoning thus possibly settles a lower boundary for the age of the major erosional unconformities observed on seismograms in the Weddell Sea above the WO1 unconformity.

## 15.2 Paleoceanographic control of Weddell Sea unconformities

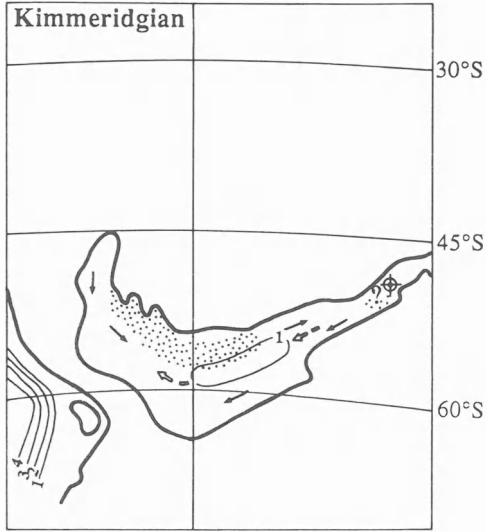
Of all major unconformities identified in the Weddell Sea, only one has a purely tectonic control : the basal unconformity WO1, corresponding with the Middle Jurassic event U9 of Hinz and Kristoffersen (1987), which here along the Antarctic margin separates the sedimentary cover from the underlying magmatic crust. In a way it is unfortunate that the name "Weddell Sea Continental Margin Unconformity" has been introduced for this unconformity, considering that it certainly has the least significance in terms of paleoceanography or paleoclimatology.

Far more intriguing is the WO4 unconformity, constrained in age by the ODP drillhole data of Leg 113, as well as its possibly correlative and strongly erosive counterpart WO4a, identified off Halley (WO4b is a clear onlap surface at the base of Cray Fan deposits but it does not significantly truncate lower sequences). In view of the above considerations, it should normally fit into the interval from Late Albian to Early Oligocene.

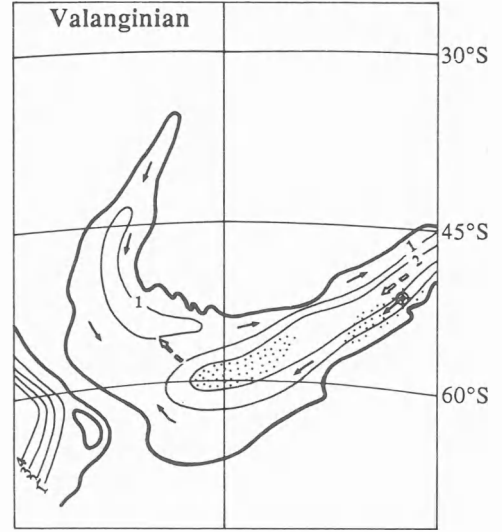
According to Zimmerman *e.a.* (1987), the anoxic episode was terminated in the Southern Atlantic by a generalized erosional event in Cenomanian - Early Turonian times, associated with the establishment of the deep connection between the North and South Atlantic. This erosional event results in a generalized Cenomanian - Early Turonian hiatus, immediately following Albian times (fig. 28).

The onset of the hiatus on top of the Albian deposits on Site 693 might thus correlate with this event, although the dramatic influence of such a remote event in the Weddell Sea is

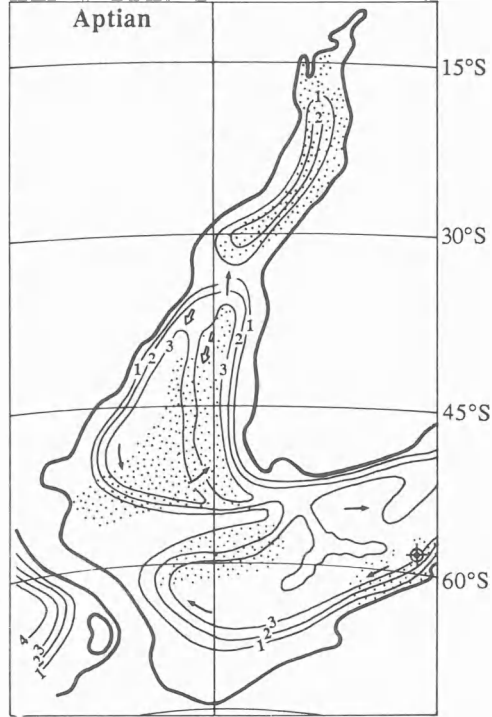
LATE JURASSIC



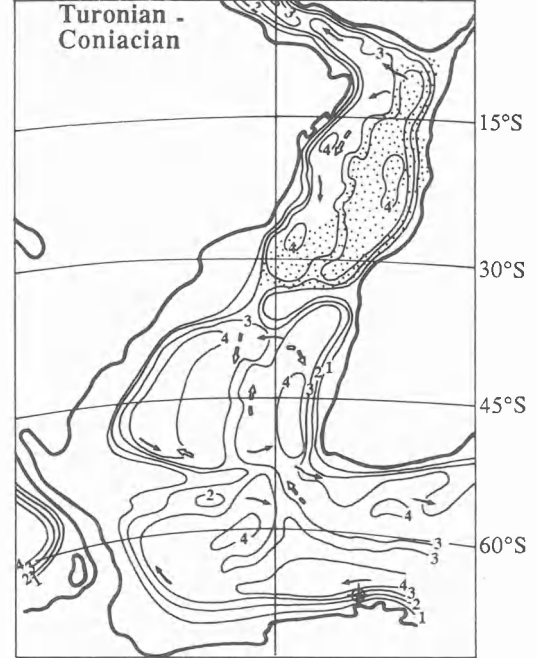
LOWER CRETACEOUS



LOWER CRETACEOUS



UPPER CRETACEOUS



(after Zimmerman, H.B. e.a. 1987)

- 3— paleobathymetry in km
- surface currents
- ⇨ deepwater current flow
- ⊕ ODP Leg 113 692/693
- ⋯ distribution of black shales

Fig. 27 Palinspatic reconstruction of the Late Jurassic to Cretaceous Southern Atlantic.

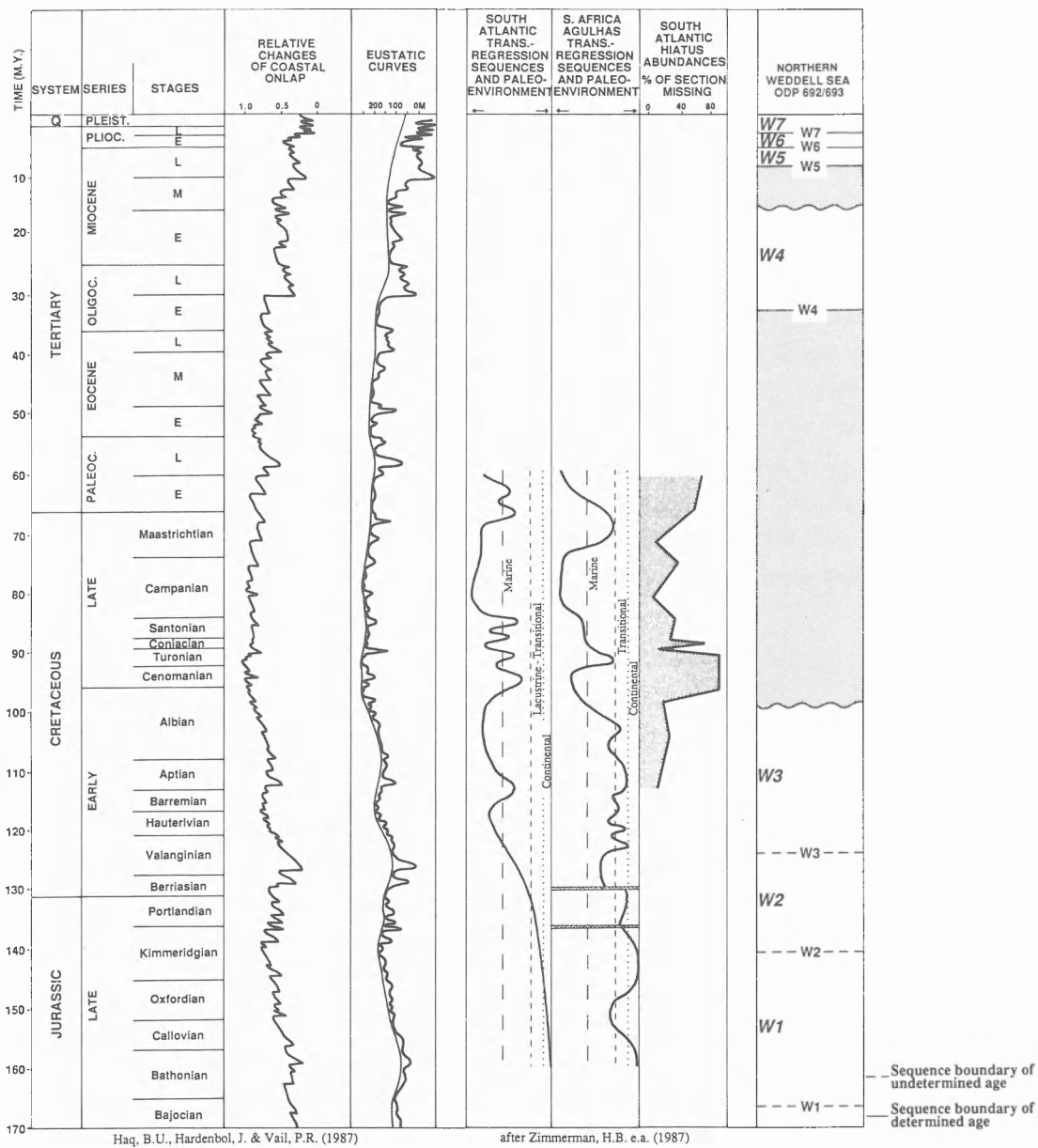


Fig. 28 Tentative correlation of the depositional sequences of the Weddell Sea with South Atlantic and global chronostratigraphy, sea level changes and hiatus occurrence.

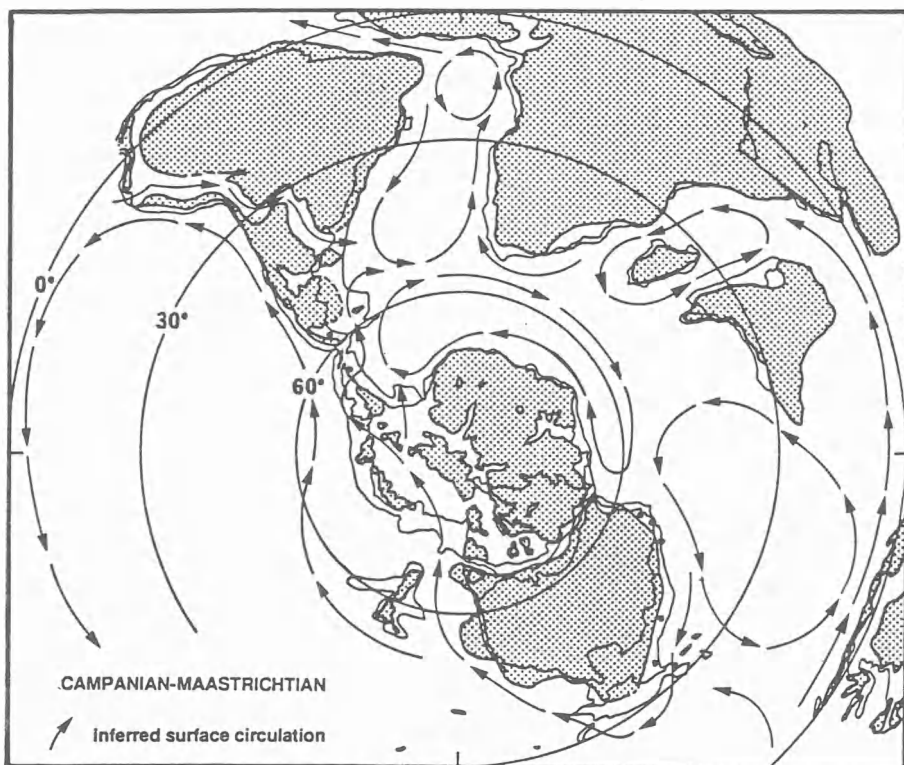
questionable. One might therefore also pay some closer attention to more proximate factors, which has led to scrutinize the fate of the Transantarctic region in those times.

A recent study of the dispersion of Upper Cretaceous planctonic and benthic foraminifera by B. Huber (1988, unpublished thesis) shows evidence of a Transantarctic marine seaway in Campanian-Maastrichtian times (fig. 29). Such a gateway might have caused vigorous bottom currents and countercurrents in the Weddell Sea Embayment, and hence erosion. One might expect a most vigorous erosion closer to the mouth of such a gateway, in the southern Weddell Sea, which could explain the strongly truncating unconformity off Halley (WO4a) and the more mildly erosional unconformity WO4 off Cape Norvegia. Further north, on Maud Rise, a full sequence of Late Campanian/Maastrichtian to Paleocene, Eocene, Oligocene and Miocene to Plio-Pleistocene sediments has been drilled in ODP boreholes 689 and 690 of Leg 113, arguing for an undisturbed sedimentation environment.

The closure of this seaway could have occurred in mid-Eocene times, after about 50 Ma ago, as a consequence of the uplift of the Transantarctic Mountains (Gleadow e.a., in press, cited by B. Huber 1988). This uplift could at the same time have created a significant source of sediment supply towards the Weddell Sea Embayment, which possibly could have contributed to the huge sediment sequence of the supersequence off Halley Bay, bracketed by the WO1 and WO4b unconformities and overlapping on WO4a.

The seismic-stratigraphic study of the Weddell Sea hence seems to provide an independent support to Huber's hypothesis of a Late Cretaceous and possibly Early Cenozoic Transantarctic seaway. Such a seaway may have initiated a current system encircling East Antarctica and Australia (in Late Cretaceous times). Later, after the rifting between Antarctica and Australia, it might have evolved into an early circumantarctic current. According to Mutter e.a. (1985), the breakup between Antarctica and Australia may have started at 85 Ma B.P., however at a very low spreading rate. Considering that there is considerable speculation about the possible causal relationship between the progressive isolation of Antarctic landmass by a circling current and a climatic cooling effect, it will be evident that a hypothesis of an early ACC will also deserve attention in terms of a possible paleoclimatological impact. One should however bear in mind that both a Transantarctic current and any initial current between Antarctica and Australia had to circulate over shallow sills (e.g. the Tasman ridge in the latter seaway). This situation -if it occurred- is consequently not to be compared with the present ACC, involving deep water circulation, strongly affecting the Southern Ocean circulation pattern.

The onset of the present Antarctic Circumpolar Current is related to the opening of another seaway, caused by the spreading of Drake Passage, between the Antarctic Peninsula and South America. There is some evidence that shallow marine channels connecting the Pacific and South Atlantic Oceans developed in the earliest rifting phase of Drake Passage, around 30 Ma ago. A major argument is the westward migration of planctonic foraminifera of the genus *Guembeletria* from the Australian province into South African waters (Bearman, ed., 1989). Coherent sea-floor



(Huber B. 1988)

Fig. 29 Inferred patterns of surface circulation for the Southern Hemisphere during the Campanian through Maastrichtian.

spreading in Drake Passage began at 29 Ma, but a deep gap could not develop until the ends of submarine ridges along Shackleton Fracture Zone fully cleared, which happened about 23 Ma ago (Barker and Burrell 1977), about at the Oligocene-Miocene boundary.

A clear evidence of a direct erosional response to the onset of the ACC is lacking in the ODP logs off Cape Norvegia, except for the presence of a local hiatus in the Late Oligocene of hole 693, above the horizon of slumped Oligocene deposits at the base of sequence *W4*. There is yet no conclusive causal relationship between this hiatus and the onset of a gyre current, but on the contrary it seems to reflect a possible ice growth pulse, as discussed below.

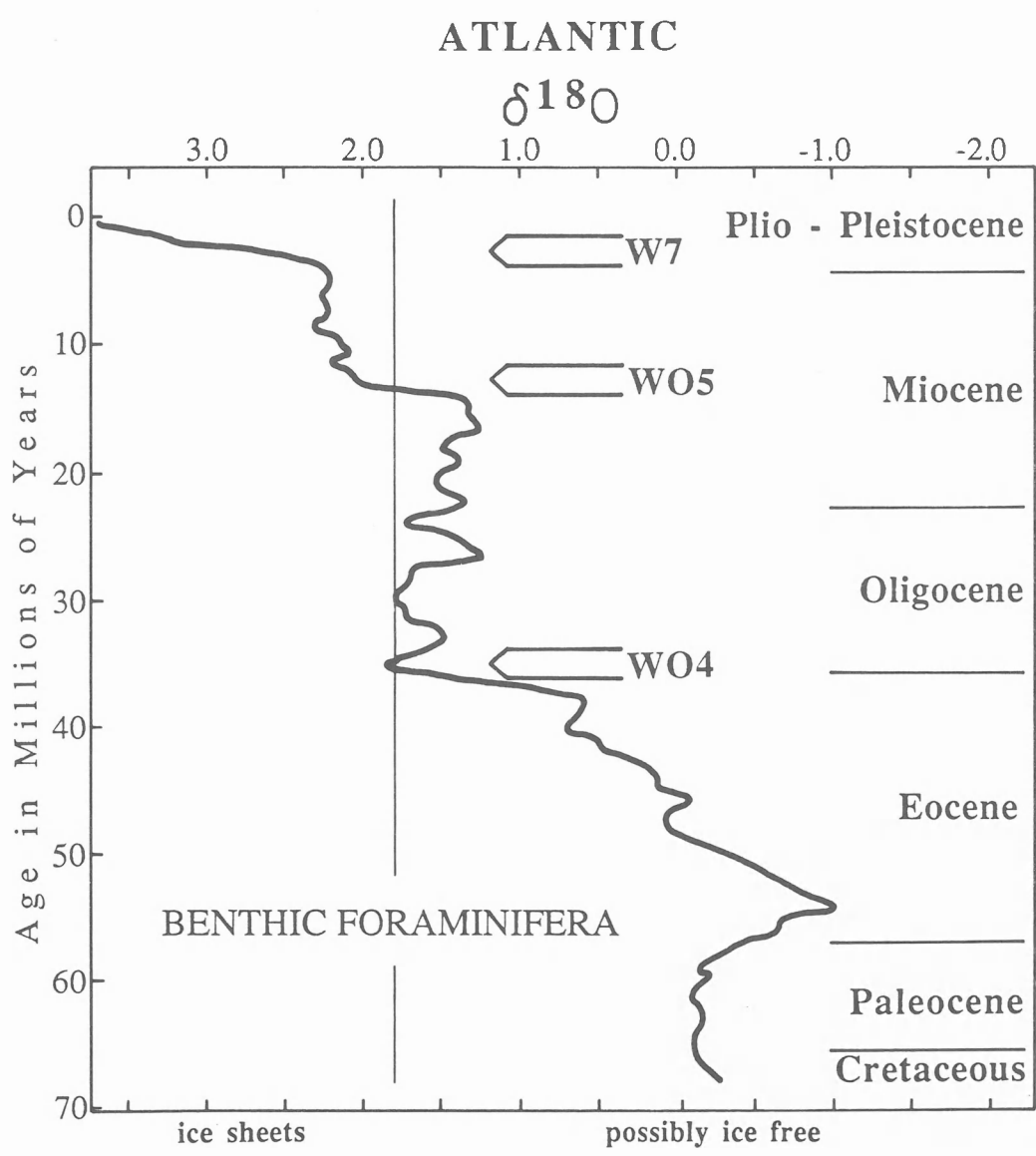
Barker and Burrell (1977) already remarked that, although the isolation of the Antarctic landmass and its engirdling by the ACC is generally accepted as the onset of a major climatic deterioration, there is no striking coincidence between ACC onset (at 23 Ma) and the renewed cooling, which apparently started at about 16 Ma ago. There is however a close temporal agreement between the inferred onset of the ACC and the emergence in Early Miocene times of that siliceous biofacies which today dominates sedimentation between the Antarctic Convergence and the Antarctic Divergence.

### 15.3 Paleoclimatic control of Cenozoic Weddell Sea unconformities

It has been noted in the precedent chapter that the opening of Drake Passage apparently has caused little erosional response in the stratigraphic record of the eastern Weddell Sea margin. In fact it appears that erosional unconformities in this area do more directly lock in on climatological signals in Cenozoic times, as illustrated on fig. 30.

This figure represents a composite benthic foraminiferal  $\delta^{18}\text{O}$  record for Atlantic DSDP sites, corrected to *Cibicidoides* and reported to PDB standard (Miller e.a. 1987). Most of the observed variation of  $\delta^{18}\text{O}$  in benthic foraminiferal skeletons during the young Cenozoic is due to the enhanced differential incorporation of  $^{16}\text{O}$  into the ice of the polar ice caps during glacial periods, leaving the oceans relatively enriched in the heavy isotope  $^{18}\text{O}$ . Accordingly, the isotopic ratio of benthic foraminifera can be taken as a measure of the amount of ocean water held in ice-sheets at any given time. The vertical line is drawn through 1.8 per mil; values greater than this provide evidence for significant continental ice sheets.

If the isotopic ratio of benthic foraminifera can be taken as a measure of the amount of ocean water locked in ice sheets, it is also an indicator of global sea level. Comparisons of the oxygen-isotope composition of foraminiferans at the peak of the last glaciation with the composition of modern ones led to the observation that a difference in  $\delta^{18}\text{O}$  of 0.1 per mil is equivalent to a 10 m change in sea-level, a relationship valid for changes in the past two million years (Bearman, ed. 1989). If the  $\delta^{18}\text{O}$  curve reflects sea-level changes and ice sheet dynamics, which along Antarctic margins invariably means variations in cold bottom water flux, in coastal plain and shelf erosion and in sediment flux, it should not be surprising to find some agreement



(after Miller K.G. e.a. 1987)

Fig. 30 Coincidence of Weddell Sea unconformities with rises in the composite benthic foraminiferal  $\delta^{18}O$  record for Atlantic DSDP sites.

between striking features of this curve and the occurrence of major Cenozoic unconformities. As can be seen on fig. 30, this proves to be the case.

The W4 unconformity coincides with the first ice growth event identified on the isotopic ratio curve, at 35 Ma. Also the small hiatus above the slumped Early Oligocene sediments in the base interval of sequence W4 (cfr. 15.2) seems to coincide with a significant event at 32-28 Ma. The coincidence of W4 with a significant glacial advance suggests that the 60 Ma hiatus on Site 693 has a complex origin, with the possible superposition of at least two erosional processes, one in the Upper Cretaceous to Early Cenozoic (related to the breaching of a Transantarctic seaway) and one in the Early Oligocene, of glacial origin.

The very prominent reflector WO5 marking a Mid-Miocene hiatus (16 to 9 Ma) and heralding a pronounced change in seismic facies also perfectly fits with a major ice growth signal on the  $\delta^{18}\text{O}$  curve starting at 16 Ma. This unconformity fits the U5 event in Hinz and Kristoffersen (1987), dated 16-13 Ma .

A similar observation also holds for the very conspicuous unconformity W 7 showing on high-resolution seismograms and identified in ODP hole 693 as the base of the Late Pliocene-Pleistocene glacial marine sediment cover. This fully coincides with the recent major ice growth event at about 3-4 Ma, named U2 by Hinz and Kristoffersen (1987).

The excellent fit between these observations turns the isotopic ratio curve into a first order interpretation tool in the seismic-stratigraphic analysis of peri-Antarctic basins.

## 1.6 Conclusions and perspectives

### 16.1 The detailed picture of the Weddell Sea sediments and their dynamics

The Antarktis V/4 cruise with its acquisition of more than 2800 km of high quality reflection seismic profiles no doubt takes a special position in the record of the geological reconnaissance of the eastern Weddell Sea. A major reason is the very high resolution achieved both in single channel and in multichannel data over the larger part of the eastern Weddell Sea margin, thus highlighting a hitherto unknown stratigraphic and structural detail. This detail provides among other aspects a valuable information about the role of sediment mass movements in Antarctic deepsea fan deposits, such as those studied in front of Halley Bay. Features like the extensive sediment flow structures observed in sequence WF 3 and the giant olistolith-like sediment bodies in buried channels along the continental slope had eluded previous investigations, essentially due to a lack of resolution.

### 16.2 Towards a unified stratigraphic model of the Weddell Sea

The high-resolution multichannel data collected by "Polarstern" helped to bridge the gap between the detailed stratigraphic and lithologic log of the ODP boreholes and the reflection picture of former surveys with deep penetration, such as the BGR profiles. The AWI-RCMG survey and interpretation consequently catalyses a new effort towards a unified approach in the seismic-stratigraphic analysis of the Weddell Sea Basin, a venture jointly undertaken by German, Norwegian and Belgian research teams. This effort involves the exchange of information and the compilation of all data sets pertinent to common research areas, which contributed to an agreement about a common seismic-stratigraphic interpretation and sequence naming procedure. The critical confrontation of interpretations on intersecting lines shot by different partners already yielded stimulating new insights in the geological structure of the eastern Weddell Sea.

### 16.3 Clues for a precursor of the Antarctic Circumpolar Current

The new joint interpretation effort progressively sheds some new light on the evolution of the sedimentary environment of the South Atlantic and the Weddell Sea Basin through Mesozoic and Cenozoic times. These ongoing efforts directly benefit from the recently released ODP results, which are fully integrated in the emerging model. Some new arguments seem to support the hypothesis of a Late Cretaceous initiation of a precursor of the Antarctic Circumpolar Current through a Transantarctic seaway, a concept which has obvious and stimulating paleoceanographical and paleoclimatological implications. The critical further analysis of this hypothesis will no doubt be a major line of research in the forthcoming programme.

### 16.4 Underplating as origin of the Explora-Andenes Escarpment

The interpretation of seismic and geological observations around Wegener Canyon and the critical reassessment of former geophysical data leads to a new and relatively straightforward geodynamic model for the origin of the Explora-Andenes Escarpment. This involves underplating and the build-up of an accretionary sediment stack in a local compressional context, bound to a sigmoid bend of the involved transcurrent fault. Forthcoming geophysical programmes could easily check the validity of this hypothesis.

### 16.5 Extracting the climatic signals from seismic data

The availability of very high-resolution seismic data calibrated on well-documented ODP wells provides a major opportunity to analyse the climatic information locked in the reflection seismograms. A remarkable observation hereby is the excellent match of erosional unconformities

identified on high-resolution reflection seismic profiles collected on the eastern margin of the Weddell Sea with the record of continental ice growth events, reflected in the Atlantic oxygen isotopic ratio log determined for benthic foraminifera. If such a correlation can be confirmed on other Antarctic margins, it can prove a valuable support for the analysis of the paleoclimate records from seismic investigations of the peri-Antarctic sedimentary wedges.

#### 16.6 Forging a European cooperation in the Weddell Sea Basin research

The spirit of international cooperation strongly promoted by the Alfred-Wegener-Institut für Polar- und Meeresforschung in all levels of the geological study of the Weddell Sea Basin, from joint data acquisition to processing and interpretation, certainly has to be acknowledged as a major achievement. It is presently forging a joint European expertise in polar marine geological research, which certainly faces new opportunities and scientific perspectives.

## **Part 2 : the Antarctic Peninsula**

### 2.1 Research objectives

The second marine geophysical cruise in the framework of the Belgian Research Programme about the Antarctic took again place in cooperation with the Alfred-Wegener-Institut für Polar- und Meeresforschung and this time also in cooperation with the Institut für Geophysik of the Christian-Albrechts Universität zu Kiel. Prof. H. Miller from AWI and Prof. R. Meissner from Kiel were the promoters of a study programme of the structure and evolution of the Antarctic Peninsula, sponsored by the Deutsche Forschungsgemeinschaft (DFG).

During the Antarktis VI/2 cruise of R.V. "Polarstern", some 1400 km of reflection profiles have been recorded, in addition of two refraction profiles (resp. 345 and 65 km long) and magnetic and gravimetric profiles. These profiles primarily addressed the deeper structure of the back-arc spreading basin of Bransfield Strait and the South Shetland Trench with its converging plate boundary environment. The reflection seismic parameters could however be trimmed in such a way that valuable information could also be acquired about the sedimentary cover.

When comparing the Antarctic Peninsula research with the Weddell Sea investigation, one might state that the Antarctic Peninsula Basins involve sedimentation processes not only controlled by paleoceanographic and paleoclimatic factors (as is the case along the passive continental margins of the eastern Weddell Sea) but also by geodynamic processes characteristic of active

margins, such as subduction, back-arc spreading with associated magmatism and, as has been shown by this cruise, by the development of a fore-arc basin. The Antarctic Peninsula is in addition one of the very few geodynamic environments in the world where such well developed converging margin features coexist with nearby mid-oceanic spreading ridge segments, which have been active until a relatively recent geological past.

When such unique geodynamic features are blended with not less exceptional paleoclimatic processes (the proximity of the Antarctic glacial regime) and paleoceanographic events (the opening of Drake Passage in Oligo-Miocene times, initiating the presently known Antarctic Circumpolar Current), it is clear that this area forms an outstanding marine-geological study domain, which in addition is a key element for the understanding of the Cenozoic evolution of the South Atlantic and of the Weddell Sea.

Getting an insight in the structure and evolution of this domain and acquiring some new data in hitherto unexplored parts of this domain was a prime objective of the present research. The processing and interpretation of the results of this recent cruise are still in progress, which means that the results presented below have a preliminary character.

## 2.2 Previous research

Bransfield Strait and adjacent areas have been a focus of marine geophysical and geological research in the past ten years, with main programmes deployed by the British Antarctic Survey, the Polish Academy of Sciences (1979-1980), the Alfred-Wegener-Institut für Polar- und Meeresforschung and Kiel University (ANT II/3), Brazil (PETROBRAS survey, 1987) and various U.S. cruises. Japanese marine geophysical investigations have been carried out in the Bellingshausen Sea over DSDP drill site 325, linking this important reference borehole to the paleotrench along the continental margin off Adelaide Island (Kimura 1982).

The crustal structure of the marine basins along the northern Antarctic Peninsula has mainly been documented by deep refraction studies carried out by British and Polish investigators (Ashcroft 1972, Guterch e.a. 1985).

The sedimentary cover has mainly been analysed by reflection seismics. Some 1100 km of reflection seismic profiles have been shot by the Polish expedition, essentially in Bransfield Strait and around King George Island. The German ANT II/3 expedition (F.Theilen, Kiel) recorded several high-resolution lines with a single airgun in an area confined to Bransfield Strait. The Brazilian survey, carried out with oil industry standards (8 guns, 72-channels recording), is certainly the most extensive one recorded until now in this region: more than 5000 km of high quality reflection seismic profiles have been shot over Bransfield Strait and the continental shelf as far south as Adelaide Island. This survey is the first to report the presence of a long sedimentary basin on the continental shelf of the Bellingshausen margin, informally named "Câmara Basin".

This basin has also been crossed later in the same year by the Antarktis VI/2 cruise of AWI/Kiel/RCMG and is interpreted in the present report as a typical fore-arc basin. The Brazilian expedition also mentioned the presence of a large submarine fan down-dip of the Câmara Basin, stretching over oceanic crust. The results of this cruise have to our knowledge not yet been published.

## 2.3 Methods

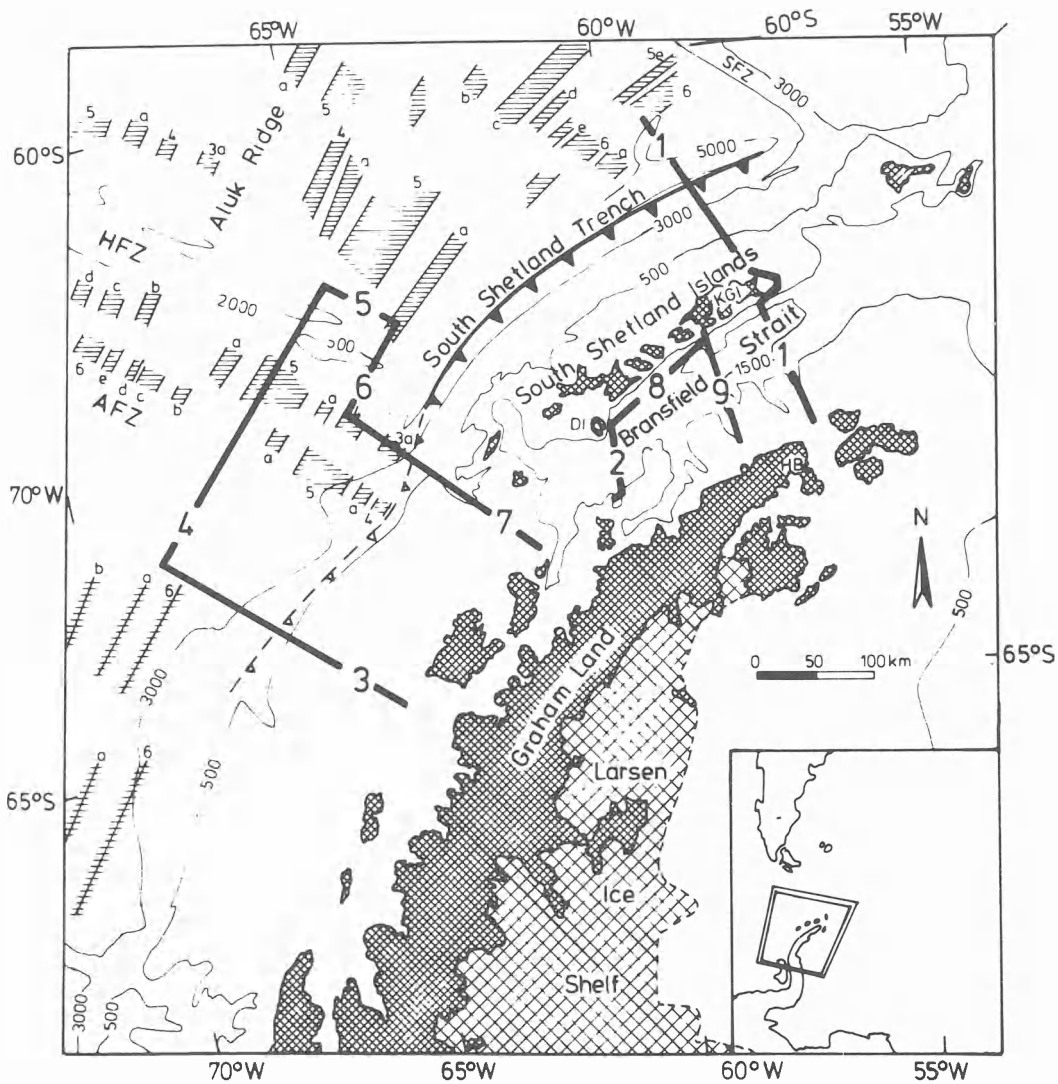
### 23.1 Reflection data acquisition

The reflection data set recorded during the Antarktis VI/2 cruise is shown on fig. 31. Profile 1, about 338 km long, ran from Hope Bay across Bransfield Strait, along King George Island and then across the South Shetland Trench. Another two profiles (9 and 2) crossed Bransfield Strait further southwest, while one longitudinal profile has been shot along the southern margin of the South Shetland Islands (profile 8). The oceanic domain with the prominent Hero and Anvers Fracture zones and the ridge-trench collision area off Brabant and Anvers Islands have been investigated with a large seismic loop (lines 3, 4, 5, 6 and 7).

Most reflection profiles have been shot with four BOLT PAR 1500 C airguns from IFREMER, with air chamber volumes of 9 l. Some reflection profiling has also been carried out during refraction shooting with the same guns fitted with 16 l air chambers (refraction line 1), which however did not yield any apparent additional deep crustal information. As the information about the sedimentary cover was poor with these powerful guns, this experiment was not repeated on other lines. A part of profile 3 (fig. 31) has been shot with the same AWI PRAKLA-SEISMOS airguns (2 x 2 l and one of 5 l) which had successfully been used in the Antarktis V/4 cruise in the Weddell Sea the previous year, but they proved too weak in the storm-swept environment of the western Antarctic Peninsula. There was consequently no hope of acquiring in this spring season any meaningful high-resolution data with RCMG's 0.25 l watergun.

The major part of the reflection data has been detected with AWI's 24-channel streamer with an active length of 600 m, built by PRAKLA-SEISMOS. Whenever the deployment of this larger streamer was not possible (e.g. for short lines recorded in between fishery research activities), data could still be recorded with RCMG's manually deployed 100 m streamer with 8 channels.

All digital acquisition took place on RCMG's EG&G ES 2420 seismograph, with data written out on two CIPHER tape drives. Two EPC recorders with different recording scale have been used for analog monitoring.



(Meissner R. e.a. 1988)

Fig. 31 Seismic track map of the Antarktis VI/2 cruise.

### 23.2 Reflection data processing

For the same reasons cited sub 13.2, the bulk of the magnetic tapes recorded during the Antarktis VI/2 cruise are processed at the German partner institutions : at AWI some first processing has taken place on the CONVEX minisupercomputer with DISCO software (COGNISEIS), while Kiel University is processing the data on twinned MicroVAX computers with PHOENIX software (SSL).

### 23.3 Reflection data interpretation

The present status of all seismic profiles is that a first interpretation has been carried out, with the identification of major depositional sequences but without any formal naming of unconformities or sequences. To our knowledge no sequence naming has been published yet for the Bransfield sequences or the Bellingshausen continental margin. We consequently should start "from scratch". All time to depth conversions on the profiles shown on figs. 35, 38, 39 and 40 have been carried out with a preliminary model assuming a water velocity of 1500 m/s and a sediment velocity of 2000 m/s. Corrections to these depth conversions will be made as more data are available, both by the compilation of published data and by the processing of the multichannel data.

A basic concern before introducing a seismic-stratigraphic nomenclature is to frame the possible geological age of these units, thus trying to establish possible conceptual links with other peri-Antarctic areas such as the Weddell Sea or the Ross Sea sequences and unconformities. In contrast with the eastern Weddell Sea, there is no DSDP or ODP borehole which could be used as calibration well directly in the survey area. The nearest reference well, DSDP hole 325, is more than 500 km further west. The only presently available age information available in this area is locked in the magnetic anomaly pattern of the oceanic crust, which consequently deserves some prior attention.

### 23.4 Magnetic data interpretation

The pattern of magnetic anomalies of the oceanic plates around the Antarctic Peninsula is well documented by the studies of British Antarctic Survey. The basic document used in our interpretation is BAS Tectonic Map of the Scotia Arc at scale 1:3 000 000 (1985). Another map which has been consulted is the Antarctica Sheet of the Plate-Tectonic Map of the Circum-Pacific Region at scale 1:10 000 000 (Circum-Pacific Council for energy and Mineral Resources 1983). The latter map, probably drafted from the same data base in the considered area, is less convenient for magnetostratigraphic interpretations, but presents some alternative structural interpretations.

A recent aeromagnetic coverage of the Antarctic Peninsula (Parra e.a. 1988) also includes the oceanic plate area northwest of the South Shetland Islands but is - for the oceanic part - taken with some reserve, considering that the lineations offsetting sea-floor anomalies and hence suggesting the presence of fracture zones flagrantly cross the seafloor ridges (e.g. Hero Fracture Zone). It is not excluded that the flight pattern introduced some bias in the contouring of this part of the map. The structural interpretation of the Bransfield Strait part of this magnetic survey has been added as background on fig. 32.

The first step in the interpretation of the sea-floor anomalies in terms of geological age was the translation of the magnetic anomaly patterns of the oceanic crust into isochrons, hereby using a standard magnetostratigraphic scale (e.g. Cox and Hart 1986). The result of this analysis is presented on fig. 32.

This isochron map does not only constrain the possible age range of the sedimentary cover on the oceanic plates, but it also offers a full record of the spreading and subduction history of the considered area, thus giving an insight in its geodynamic history.

## 2.4 Geological interpretation

### 24.1 Active margin history

A comprehensive analysis of the magnetic anomaly patterns around the Antarctic Peninsula in terms of plate tectonic processes has been published by Barker (1982). We refer to this author for previous literature references dealing with the interpretation of oceanic magnetic anomalies in the southeast Pacific.

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 left its traces 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 anomalies and the bathymetry of the ocean floor.

Quite striking is 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. This process proceeded up to about 6 to 4 Ma ago, when the last ridge segment collided just south of Hero Fracture Zone. At this moment, spreading apparently stopped at the northernmost spreading sections, between Hero and Shackleton F.Z., hence before the last ridge segments had reached the trench. The plate segment between Hero and Shackleton F.Z. is hence the last remnant of the subducted Aluk plate.

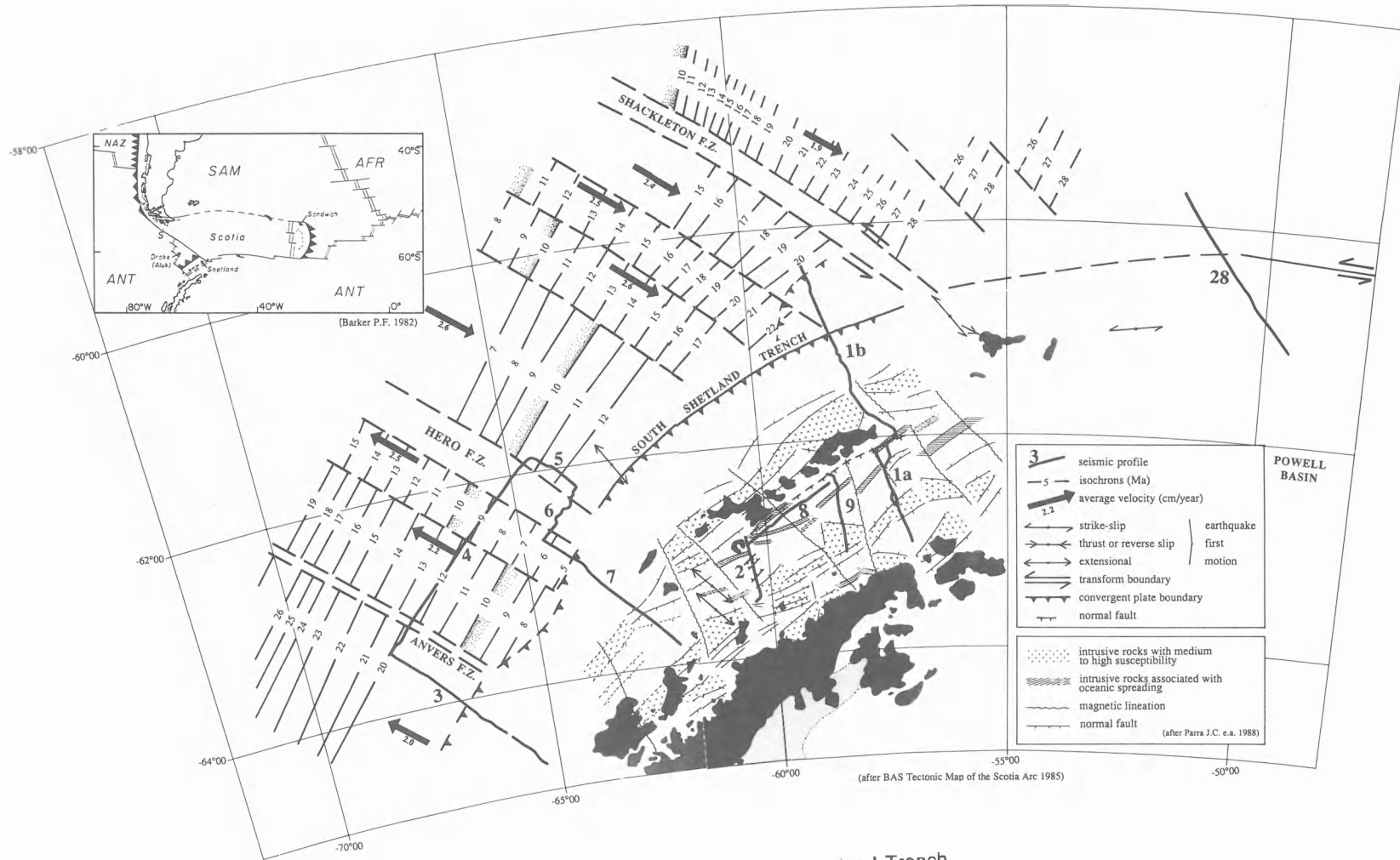


Fig. 32 Structural and aeromagnetical interpretation map around South Shetland Trench.

It has been pointed out by Barker (1982) that the chronology of Bransfield Strait extension seems to be in accord with this process : the back-arc spreading apparently started some 1.3 Ma ago (Roach 1978) but the rifting would have started in part in Late Pliocene times. Also the coinciding length and parallelism of Bransfield Strait, the South Shetland Trench and the deactivated 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 and Uyeda 1975).

#### 24.2 Analysis of the spreading velocities

Half-spreading velocities of the approaching ridge segments south of Shackleton F.Z., averaged over the past 25 Ma, are in the order of magnitude of 20 to 25 mm/a. A closer look at the evolution of these velocities as a function of time however reveals a systematic acceleration, shortly preceding the collision. This observation can be made on fig.33, displaying the half-spreading rate evolution for the plate segments south of Anvers F.Z. (lower left), between Anvers and Hero F.Z. (lower right), between Hero and Shackleton F.Z. (upper right) and northeast of Shackleton F.Z., the Scotia plate (upper left).

The acceleration before the ridge-trench collision south of Hero F.Z. seems to have started about 16 Ma ago, the probable age of the ridge-trench collision southwest of Anvers F.Z.. The gain of momentum acquired by a subducting plate when the ridge approaches the trench might in our opinion reflect an increased net slab pull effect, due among other factors to the decrease in horizontal basal friction force exerted on the (decreasing) basal surface of the subducting slab (fig. 34). The analogy of a sheet of paper slowly pushed over a table's edge, which finally accelerates before falling might be an oversimplified but nevertheless not completely invalid model. This mechanism has possibly been enhanced along this margin by the fact that the ridges migrated in a direction rigorously perpendicular to the trenches, which means that the decoupling of a sinking slab segment from the collided one took place in an abrupt way, hence possibly generating an additional momentum on the adjacent, still partly superficial limb. Such processes possibly might not occur where ridges approach a trench in an oblique way, where the slab pull forces act in a more continuous way, but this hypothesis still has to be controlled (e.g. along the margin of South Chile).

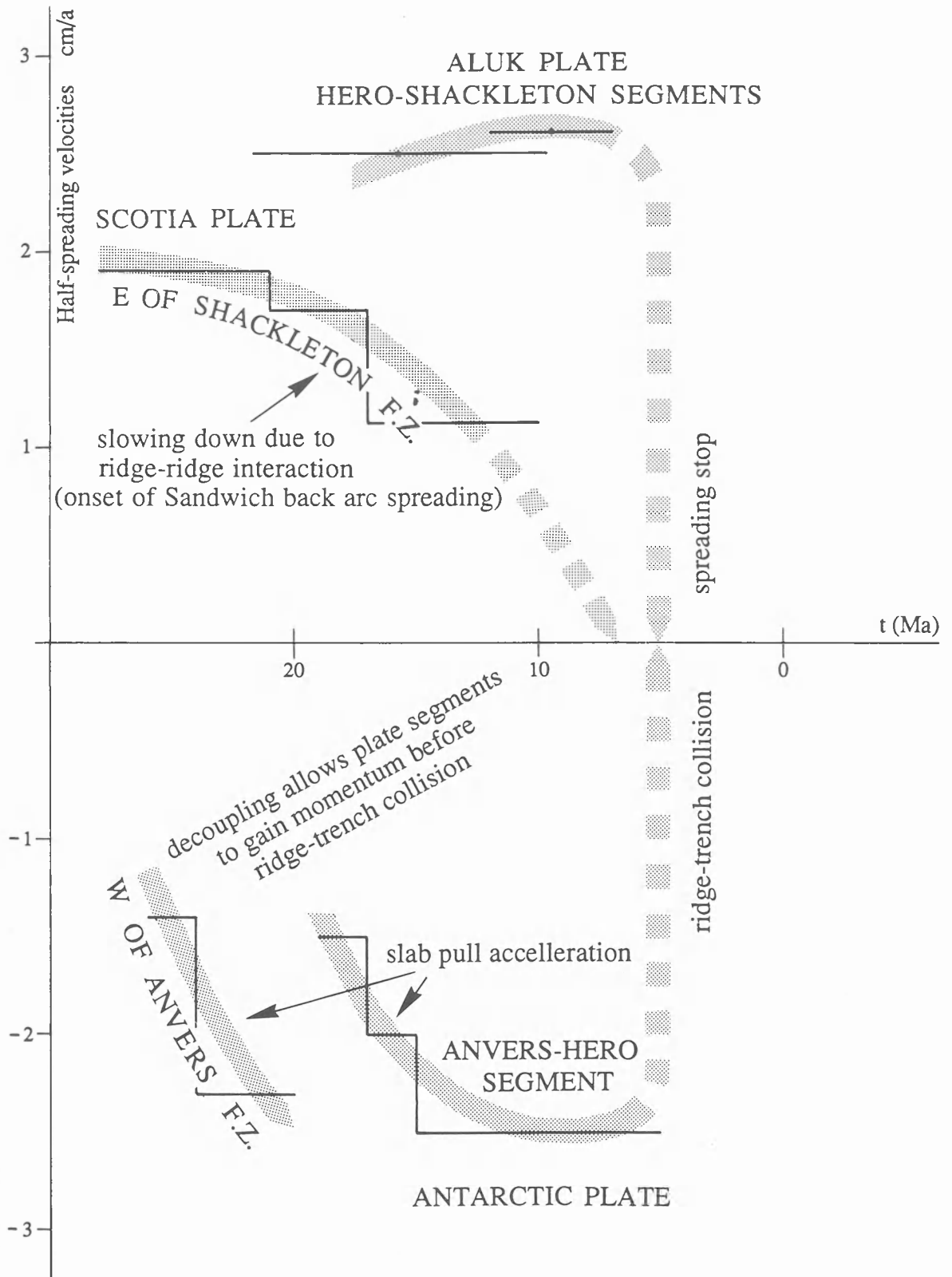


Fig. 33 Evolution of the half-spreading velocities as a function of time.

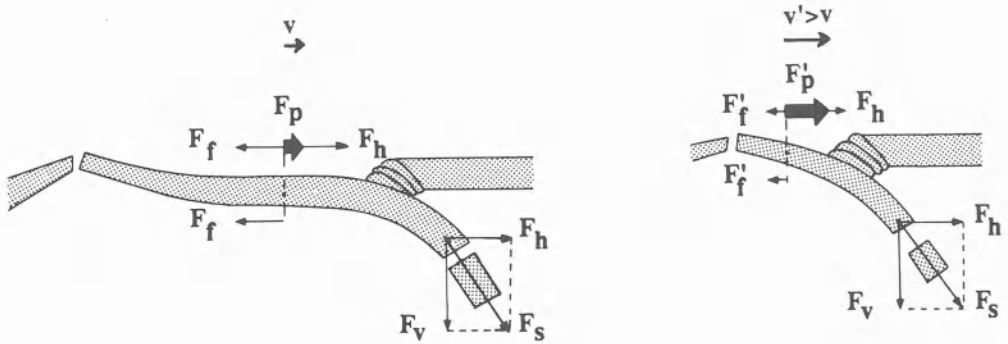


Fig. 34 The gain of momentum acquired by a subducting plate when the ridge approaches the trench might reflect an increased net slab pull effect.

$F_s$  = slab pull force

$F_v$  = vertical component

$F_h$  = horizontal component

$F_f, F'_f$  = basal frictional drag force

$F_p, F'_p$  = net slab pull force

$v, v'$  = slab velocity (half-spreading)

#### 24.3 The oceanic domain and the fracture zones

Profile 4 (fig. 35) is quite informative about the nature and setting of Hero and Anvers Fracture Zones, which have very different geophysical, structural and morphological expressions. It is also the only profile which shows very prominent structures deep in the magmatic oceanic crust, even directly visible on the analog sections.

Anvers F.Z., which is the southernmost one on this profile, is absolutely not reflected in the seafloor topography, except for a faint depression. It separates two segments of oceanic crust of quite different geological age : the southern crust has an age of 19.8 Ma, while the northern one is about 12.2 Ma old (fig.32). The older, cooler oceanic lithosphere has sunk deeper, in accordance with the laws of thermal subsidence (Parsons and Sclater 1977). The vertical offset of the top of the magmatic oceanic lithosphere as a result of the age difference of 7.6 Ma is about 300 m. As a consequence of the age and depth differences across Anvers F.Z., there is also a considerable difference in thickness of the sedimentary cover on both sides : about 900 m south of Anvers F.Z., versus some 500 m north of it (assuming an average sediment velocity of 2000 m/s ; better constrained values should result from the ongoing velocity analyses on the multichannel seismic data). A most conspicuous feature marking the presence of the F.Z. is the alignment of diffraction hyperbolae in the magmatic crust, dipping south. A possible explanation of this feature will be proposed in the following chapter.

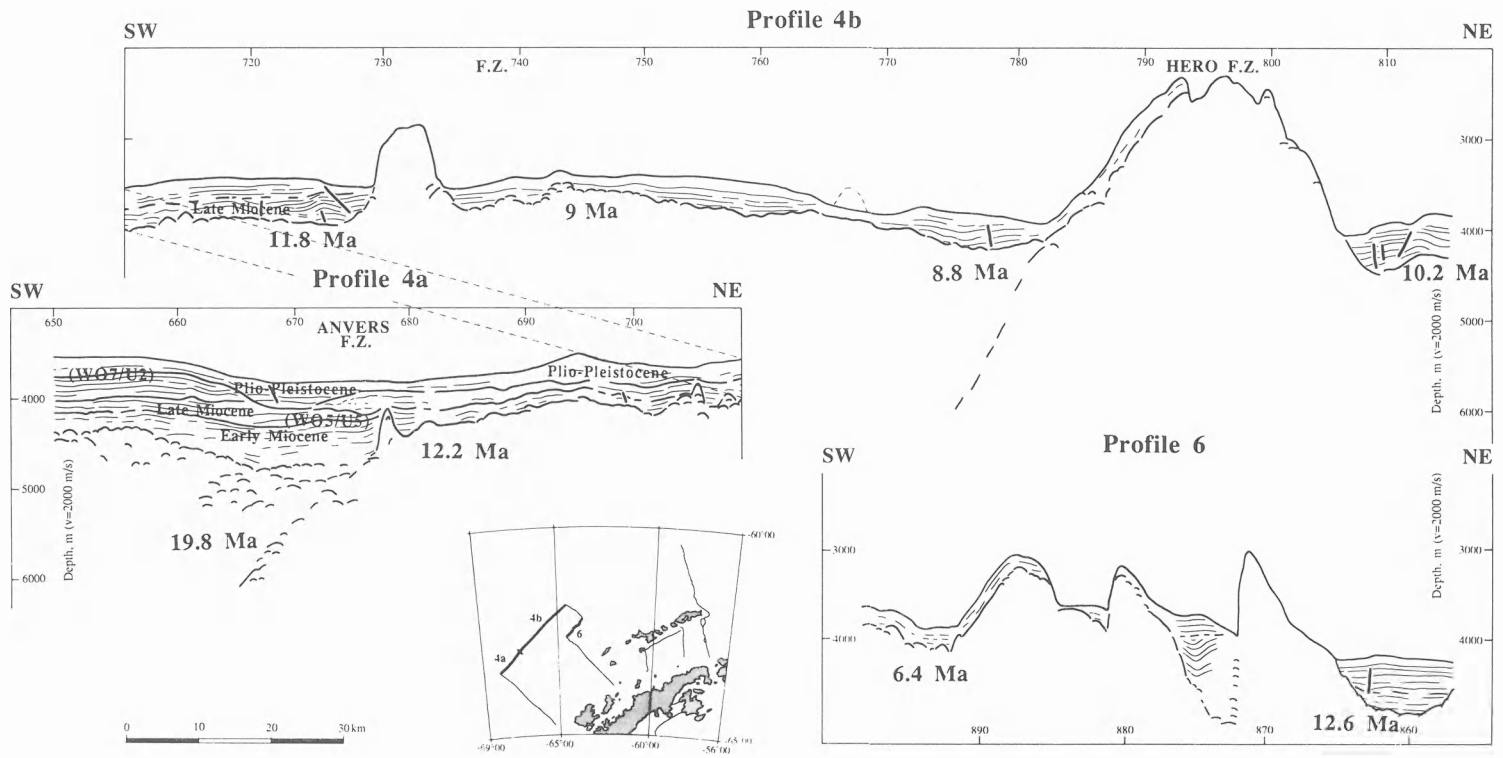


Fig. 35 Interpreted reflection profiles (4 and 6) crossing the Hero and Anvers Fracture Zones.

A second fracture zone, characterized by a much smaller age jump (2.8 Ma), is seen on the central part of profile 4 (4b). The vertical offset of the top of the oceanic lithosphere is consequently smaller, and also the difference in thickness is smaller but nevertheless obvious. A small seamount or ridge is visible, somewhat south of the location of the fracture zone which would be derived from the magnetic anomaly map. One should be careful in interpreting sediment thicknesses across fracture zones characterized by seafloor highs, as increased current velocities at the foot of the ridges might have impeded sedimentation or caused erosion (Davies and Laughton 1972). Such moats have frequently been observed along the continental slope and the Explorandenes Escarpment in the Weddell Sea.

The third and most impressive fracture zone on this profile is no doubt the Hero F.Z., characterized by a mighty ridge, towering more than 1500 m above the surrounding seafloor. Its southern flank is covered by a sedimentary layer which is only slightly thinner than that on the southern oceanic plate, suggesting that the ridge emplacement has occurred relatively shortly after the plate segment had spread away from the ridge.

The age contrast across Hero F.Z. is not impressive (1.4 Ma), but one should keep in mind that this contrast is purely fortuitous and changes if we move along the ridge, as the lithospheric segments on both sides did belong to different plates, on either side of a spreading ridge (fig. 32). Strictly speaking, Hero F.Z. should be regarded as a recently extinct transform fault, deactivated when spreading stopped after the last ridge-trench collision, while the preceding two fracture zones were aseismic ridges before subduction stopped. Hero F.Z. was up to the last ridge-trench collision a true plate boundary, separating the Aluk plate from the Antarctic plate to the south just like Shackleton F.Z. separated Aluk plate from Scotia plate to the north.

A most intriguing feature again is the dipping reflector in the magmatic oceanic crust, plunging in southward direction in continuation of the southern ridge flank. This reflector, also well visible on the analog profile, might yield a clue to the nature of the Hero F.Z. ridge, as discussed in 24.4.

On profile 6 further south, the ridge marking Hero F.Z. is segmented into three ridges. The southwest flank of the southernmost ridge is covered by a thin layer of sediments, which is clearly in continuity with the sedimentary cover of the oceanic plate, as was the case further north. This sedimentary cover is somewhat thinner than in the north, which is not in contradiction with the younger age of the underlying oceanic lithosphere. The sedimentary fill ponded between the two northernmost ridge segments on profile 6 is rather impressive and is composed of a lower, folded sequence truncated by an erosion surface and covered by a younger sedimentary cover. The thickness of the lower sequence is intriguing, as it looks as if this sequence has been deposited in a relatively early stage of the ridge development, before being deformed, eroded and buried by a sequence which seems to have been deposited in a similar context as the sedimentary cover of the southern ridge segment.

North of the northern ridge on profile 6, another small sedimentary basin shows up. The difference in elevation of the top of the oceanic crust in comparison with that on the other side of Hero F.Z. seems to be at least qualitatively in agreement with the difference in age (6.2 Ma). An analysis of the sediment thickness close to this ridge should however here too be carried out with utmost reserve. As shown on tying profile 5 (fig. 38), parallel to the fracture zone, this little basin forms part of a very peculiar sequence of highs and lows in the magmatic oceanic crust, draped by a sediment cover of quickly changing thickness. Even the magnetic interpreter should be aware of the potential pitfall : the observed sequence of basement highs is likely to generate at the sea surface a rithmically banded anomaly pattern which purely reflects the magmatic bedrock morphology but which possibly could confuse the observation of polarity reversal patterns.

#### 24.4 Fracture zone processes

The two southward dipping reflectors discovered in the oceanic crust where profile 4 intersects the Anvers and Hero Fracture Zones, together with the morphology of the oceanic lithosphere abutting against these surfaces might well be diagnostic for the processes which have shaped the Anvers and Hero F.Z..

As a lithospheric slab moves away from a spreading ridge, it slowly cools. This cooling does not only result in vertical thermal contraction of the lithosphere, but also in horizontal contraction. While vertical thermal contraction is expressed in the subsidence of seafloor with age (Parson and Sclater 1977), horizontal thermal contraction can produce large internal stresses. It is convenient to separate thermal stresses into two parts, the first due to lateral changes in the vertically averaged temperature (thermal contraction stresses s.s.) and the second due to changes in the temperature variation with depth. The latter are referred to as thermal bending stresses (Haxby and Parmentier 1988).

Thermal contracting stresses s.s. may have a variety of important consequences. They may in some way contribute to the formation (Sandwell 1986) and opening of transform faults and fracture zones, where they consequently may contribute in a significant way to magmatic and

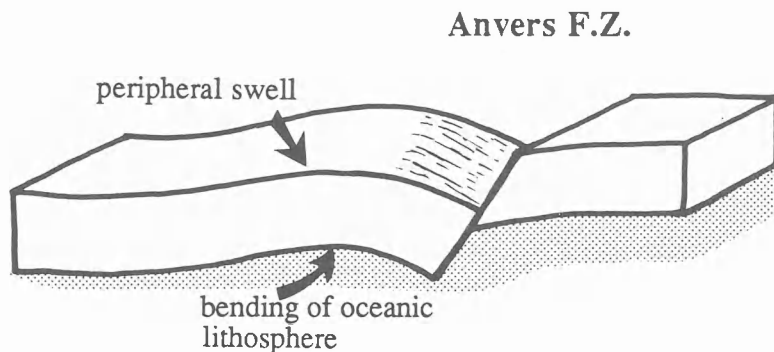


Fig. 36 Model of Anvers F.Z., illustrating the possible thermal bending on the old side of the F.Z., in accordance with the model of Haxby and Parmentier (1988).

hydrothermal processes. Thermal bending stresses are responsible for the flexure of oceanic lithosphere at fracture zones. This process has been described in detail and modelled by Haxby and Parmentier (1988).

At Anvers F.Z., the tensional thermal stresses seem to have been accommodated by a component of downward slip along the dipping fault plane. The bending of the lithosphere against this dipping plane probably occurred in response to the thermal bending stresses described above, in accordance with Haxby and Parmentier's model (fig. 36)

At Hero F.Z., there is clearly more than simple normal faulting and flexural bending against a dipping fault. Here this fault clearly forms the flank of a huge intrusion, which rose high above the seafloor. Two types of intrusion and extrusion at ("leaky") fracture zones are known (Kastens 1987) : the effusive extrusion of basalts or the diapiric extrusion of serpentinite bodies, or a combination of both. Considering the continuity of the crustal reflector with the southern flank of Hero ridge, we are inclined to opt for the hypothesis of a diapiric intrusion of hydrated upper mantle material like serpentinite, at least where our profile crosses the ridge. The presence of basaltic flows associated with such a ridge on other places can certainly not be ruled out.

The diapiric intrusion of a serpentinite body into the fracture zone, opened by the thermal contracting stresses, probably finds its early origin in the hydrothermal circulation of sea water deep in the fracture zones, resulting in serpentinization of upper mantle peridotite. The lowering of the density of these ultramafic rocks by serpentinization generates a buoyancy relative to deep crustal rocks such as gabbros. This buoyancy and the low strength of serpentinite at a temperature of a few hundred degrees Celsius can force the serpentinite body into the fracture zone and create a huge diapiric ridge. A model of such an intrusion in the Vema F.Z. (central Atlantic) is shown on fig. 37 (after Bonatti and Honnorez 1976).

Dredging along the flanks of Hero F.Z. in a future research programme should allow to test this hypothesis.

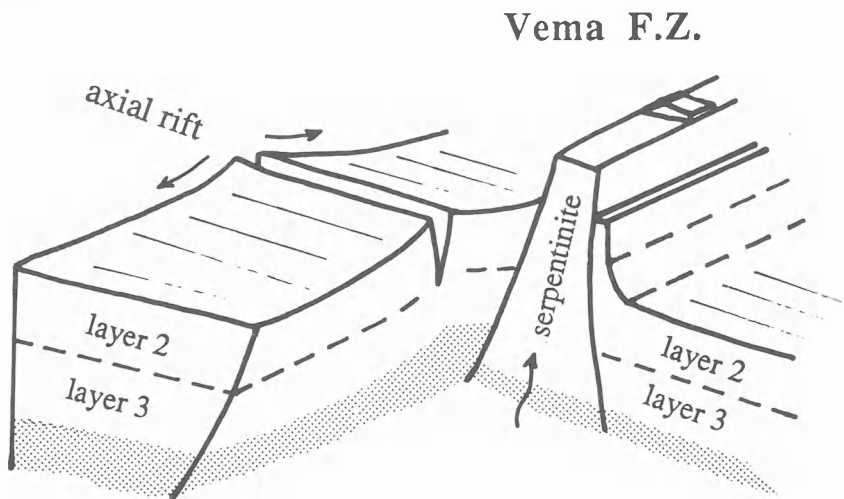


Fig. 37 Model of Vema F.Z. (Central Atlantic, after Bonatti and Honnorez 1976), a possible analog of Hero F.Z. in front of the Antarctic Peninsula.

#### 24.5 Age of the oceanic sedimentary cover

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

Across Anvers F.Z. on the same profile, the oceanic plate is about 12 Ma old, which locates it in the late Middle Miocene. This means that the lower depositional sequence directly resting on this plate segment might largely be assigned a Late Miocene age. The basal level of this sequence seems to correlate laterally with a prominent unconformity south of Anvers F.Z., which hence suggests a possible hiatus in Middle Miocene times. We are consequently inclined to correlate this event with the U5 event of Hinz and Kristoffersen (1987), dated 16-13 Ma, and thus also with the prominent WO5 unconformity identified on seismograms and on Site 693 along the eastern margin of the Weddell Sea.

The Mid-Miocene hiatus which seems to reflect a major ice advance (cfr. 15.3) is also known from DSDP Site 325, some 500 km further to the southeast (DSDP Leg 35 Shipboard Scientific Party, 1976). On this site it separates a lower unit of coarser clastic rocks of Early Miocene age, drilled over a length of 150 m (down to the bottom of the 720 m deep hole), from a 570 m thick upper unit essentially consisting of Late Miocene and Pliocene claystones, with minor siltstones and sandstones. The whole sedimentary sequence seemed to be of turbiditic origin, except for a few thin beds with mainly biogenic components. The oldest ice-rafted debris occurred in Lower Miocene claystone. The thickness of the Late Miocene -Pliocene unit in DSDP Site 325 (570 m) is in perfect agreement with the thickness of the supposed Late Miocene to Plio-Pleistocene sequences in the vicinity of Anvers F.Z. on profile 4 (about 500 m).

On this profile we still see another unconformity, deeply ravinating the underlying (Late Miocene ?) sequence. We are inclined to identify this unconformity with the base of the Plio-Pleistocene deposits. On Site 325, Pliocene deposits are particularly thick (about 400 m out of the 570 m of the upper unit). The high accumulation rates (120-150 m/Ma) of the Early to Middle Pliocene recorded both in well 325 and in other wells in the Bellingshausen Sea (DSDP Sites 322 and 323) suggest vigorous continental erosion and sediment flux during this time. On profile 3 (fig. 38), the sequence of supposed Plio-Pleistocene age at the foot of the continental slope is up to 600 m thick.

#### 24.6 Trench, slope and fore-arc environment

Profiles 3, 7 and 1 (figs. 38 and 39) present three different images of the South Shetland trench and slope environment. Profile 3 shows the sedimentary wedge on top of the collided

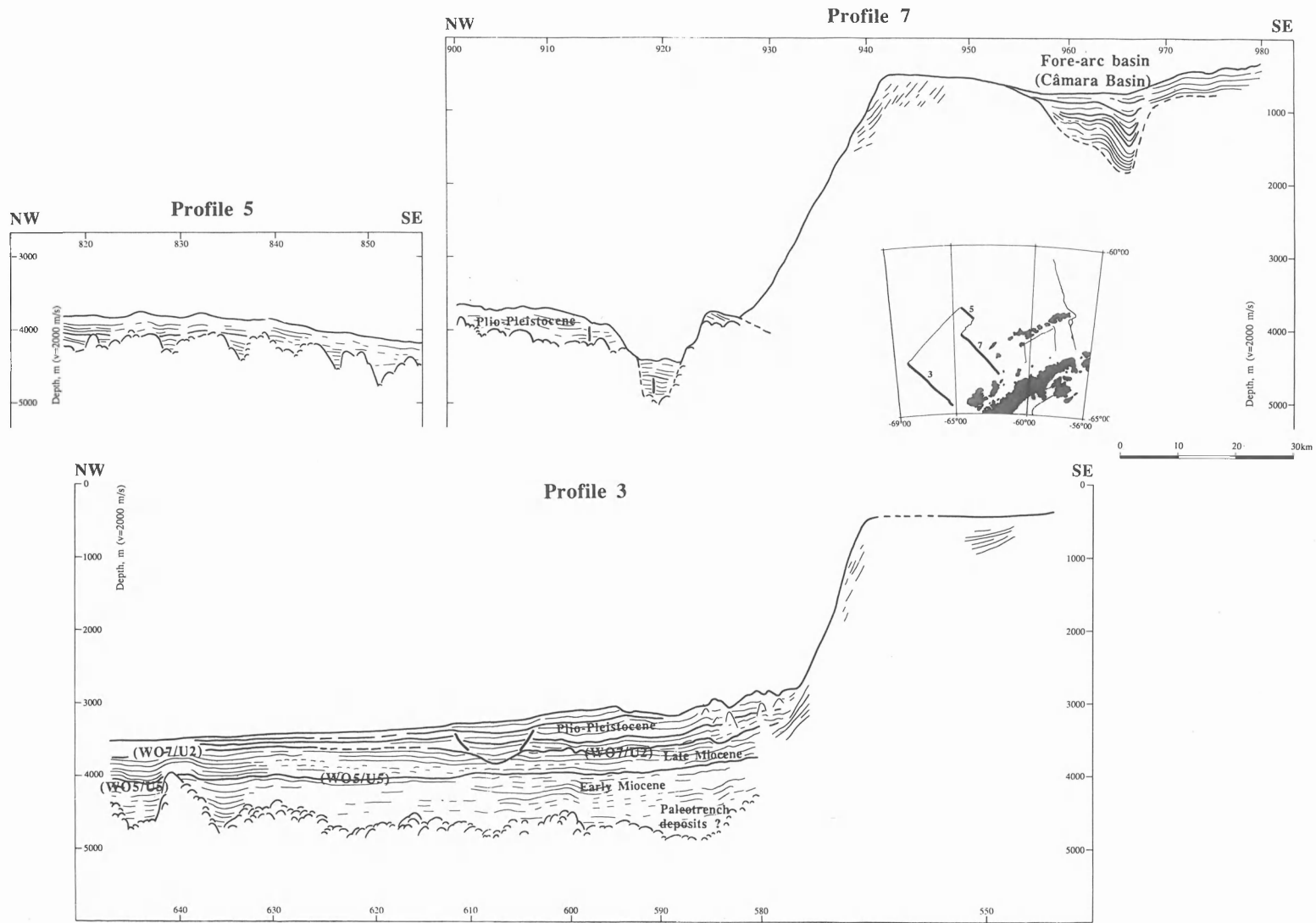


Fig. 38 Interpreted reflection profiles (3, 5 and 7) crossing the South Shetland Trench.

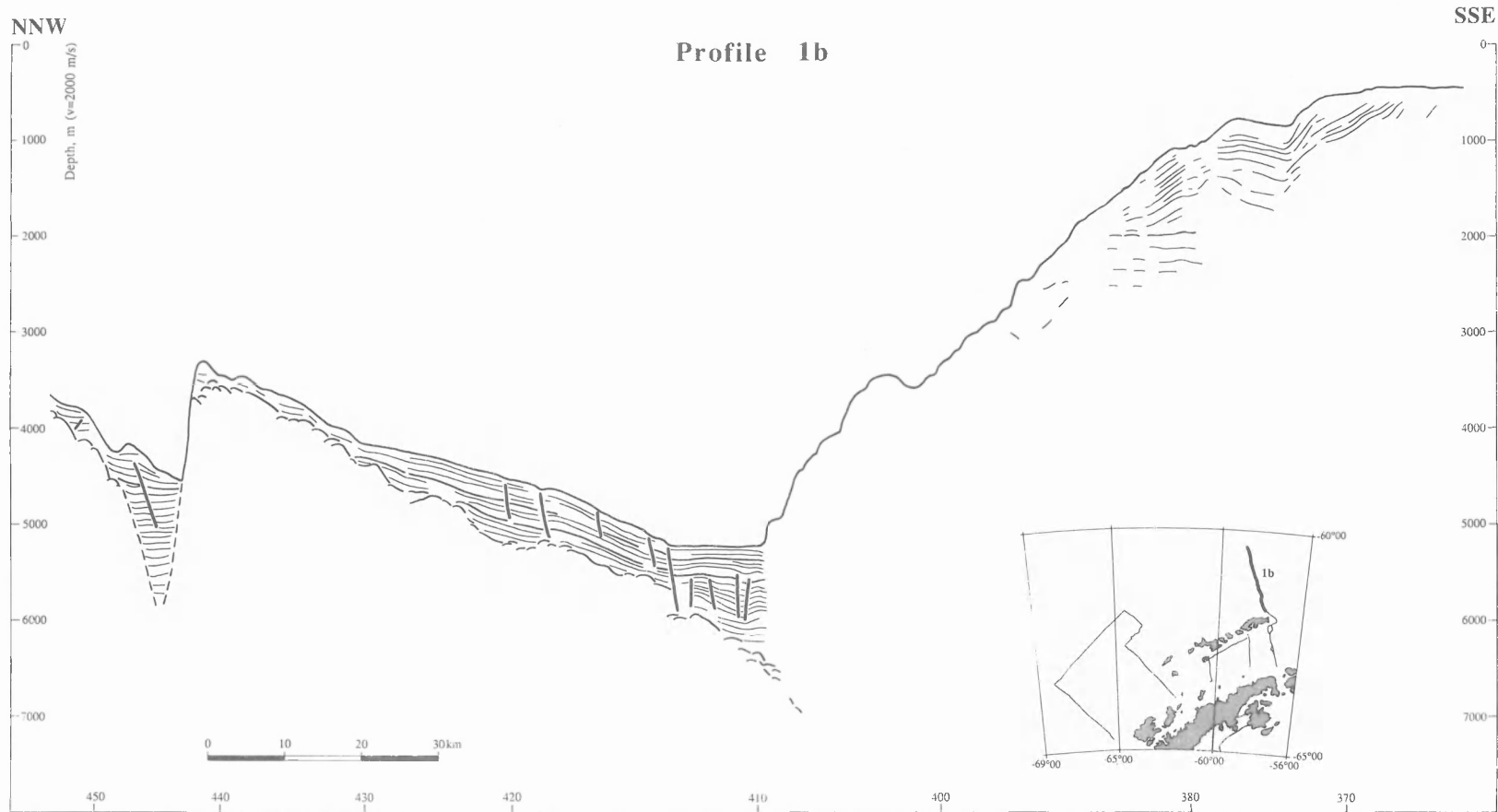


Fig. 39 Interpreted reflection profile (1b) crossing the South Shetland Trench.

Antarctic plate segment, profile 1 shows a classical image of a trench and profile 7 shows a transitional stage between both.

#### 246.1 The paleotrench

The sedimentary wedge at the foot of the continental slope on profile 3 shows the same three depositional sequences as described on the tying profile 4 south of Anvers F.Z. (24.5), however with larger thicknesses. This threefold structure has also been described by Kimura (1982) on his profile 9, linking Site 325 to the continental slope. Kimura's units C, B and A respectively correspond with the Early Miocene, the Late Miocene and the Plio-Pleistocene terrigenous turbidites, identified in well 325. In accordance with Kimura's observation, we cannot rule out that the lower unit on our profile also includes a basal wedge of paleotrench deposits, characterized by a slightly chaotic reflection configuration.

The large thickness of sediments observed at the foot of this slope (in total about 2000 m, taking into consideration that the lower units will most probably have velocities higher than 2000 m/s), might suggest the proximity of a sediment fan. The initial report of the PETROBRAS cruise (unpublished note presented at the 5th Int. Symp. on Antarctic Earth Sciences, Cambridge 1987) mentions the presence of a large submarine fan on the oceanic basement off Câmara Basin.

An interesting remark is that the age of the unconformity, which we here too would correlate with the WO5 unconformity in the Weddell Sea (the U5 event), is about the same as the age of the local ridge-trench collision (16 Ma). From this time onwards this margin behaved as a normal passive margin. This implies a continuity of deposition over shelf, slope and continental rise, as clearly shown on profile 3 and also on Kimura's profile 9. On our profile, it is possible to identify clear downlap structures on top of the WO5 unconformity. Kimura (1982) already reported that units B and A become strongly prograding east of 80° W.

The lower beds of the Late Miocene turbidites on top of WO5 locally show a wavy to hummocky and chaotic reflection pattern, quite similar to that observed in the slumped horizons of sequence *WF 3* of the Crary Fan off Halley Bay in the Weddell Sea. Both the sedimentary and time context of these sediment deformations could possibly be quite similar.

The erosional nature of unconformity WO7 with local valley incisions, which had already been observed on profile 3, is confirmed on this profile. Normal faults due to differential compaction have developed in the Plio-Pleistocene cover above the buried valley flanks.

#### 246.2 The transitional trench and the Câmara fore-arc basin

Profile 7 (fig. 38), still located south of Hero F.Z. and thus on a site of former ridge-trench collision but at the very edge of the paleotrench extension, shows a structure already quite different from that on profile 3. It should be mentioned that the collision on this segment of the

Antarctic plate occurred in much more recent geological times, about 4 to 5 Ma ago, which might have played a role in the preservation of some trench characteristics.

Considering the young age of the collided plate segment (5-6 Ma), the sedimentary cover of the oceanic plate cannot be much older than Plio-Pleistocene. A most peculiar feature at the foot of the continental slope is a basal step, covered by some sediments. Such inner walls have already been observed in many other trenches, in particular along the Japanese Islands and in the Middle America Trench (DSDP Sites 488 and 494). It might represent a fragment of a subducted crustal slab, bound at its top by a thrust plane. This features might hence represent a late witness of the accretionary processes which no doubt substantially have contributed to the growth of the continental margin on this site.

The top edge of this continental margin shows an important set of obliquely prograding sediments, most of which have probably been deposited and truncated by the advancing grounded ice sheets in the recent Plio-Pleistocene glacial period.

The most interesting feature on this profile however is no doubt the very prominent sedimentary basin met on the continental shelf, characterized on this profile by a sediment thickness of more than thousand metres. The discovery of a long basin on the Bellingshausen shelf had been reported in 1987 by PETROBRAS (cfr. 2.2) and informally named Câmara Basin. Looking at the zig-zag tracks of the PETROBRAS cruise on this part of the shelf, there is little doubt that the basin seen on profile 7 is the Câmara Basin. The only description given in the Brazilian preliminary report however is that the upper sequences of this basin are represented by prograding sediments, which is not obvious on this profile.

Considering both the position and structure of this basin, we believe it is a typical fore-arc basin, previously unknown in literature. This hypothesis is corroborated by the observation of similar basin structures on many other active margins, both recent (e.g. along Western Luzon, Philippines, Lewis and Hayes 1985) and fossil. The genesis of this basin on the back of the accretionary wedge must have been closely related to the growth and rotational uplift of this wedge.

If such an elongated basin has not been reported on the shelf further north, which has been crossed by Brazilian and Polish reflection lines and also by the Antarktis VI/2 profile 1, it may indicate that it is not present north of Hero F.Z., which would yield another clue for the strong segmentation of the continental margin by Hero F.Z. .

### 246.3 The South Shetland Trench

The northern part of reflection line 1, off King George Island, shows a classical trench profile, however with some puzzling problems.

A first problem is the sedimentary cover of the plunging oceanic plate, which shows a distinct onlap in seaward direction, by which it quickly thins out. A second problem is the steep fault in the northern part of the profile, shaping a kind of secondary, filled trench. This trench-

like feature can easily be followed in the seafloor morphology as a depression, which further south merges with the main trench (fig. 32). A third problem is the fact that the sediments in both trench depressions are barely deformed, which seems in contradiction with a "trench suction" mechanism (24.1) : if Bransfield Strait has been spreading in recent geological times, why is there no apparent compressional deformation in the trench? In other words, where is the space accommodation for the opening created in Bransfield Strait, as it is unlikely that any space accommodation would have been created east of Bransfield Strait, at the side of the peninsular mainland. There is at the present time little conclusive evidence answering these questions.

The problem of the sediment cover is certainly not elucidated by indications of the plate age, as no datable magnetic anomalies have been identified yet. Extrapolating magnetic information from plate segments west of the small secondary trench would suggest an age of 21 to 24 Ma (fig. 32), which means the lowest Lower Miocene. The thickness of the sediments on such a relatively old plate segment is consequently very modest, at least in seaward direction and especially on top of the faulted scarp. There are few arguments for postulating a sedimentary environment starved from sediment supply, considering the proximity of the shelf. We consequently have no explanation for this observation yet, also due to a lack of reference profiles on the Aluk plate further west.

The conspicuous onlap in a way evokes a thermal onlap on a spreading ridge flank, a model certainly difficult to fit into the local tectonic context. Still the relatively large onlap angle clearly does suggest a deposition against a sloping surface, which might argue for a deposition after the generation of the faulted scarp. But why should a relatively old plate segment have remained largely bare of sediments until it got tilted, for whatever reason? Such an argumentation hence also moves the problem of the sediment cover to the problem of the origin and time of origin of the scarp.

The close association of the "secondary trench" with the main one, with which it seems to merge further west in a kind of triple junction, evokes in a first approach an incipient trench backstepping. There is however no evidence of accretionary wedge building along the northern fault scarp. The most plausible explanation seems to be that the small triangular plate fragment, squeezed between the subduction zone of the South Shetland Trench and the still active Shackleton F.Z., chipped off the main Aluk plate and got tilted. One factor which possibly could have contributed to an increase of the stress field in this corner is the fan-shaped opening of Bransfield Strait (24.7). The two-dimensional velocity field analysis presently in development at RCMG, aiming at the reconstruction of relative plate motion velocities and of triple junction migration paths at selected times in the past, will possibly shed some light on this problem. The most straightforward solution will anyhow also be the collection of more field data in this F.Z.-trench triple junction area.

#### 24.7 The back-arc basin of Bransfield Strait

The analysis of the Bransfield data is still in a very initial phase. Literature dealing with gravimetric, magnetic and refraction seismic surveys in this basin is vast and should be carefully evaluated for a sound insight in the structure and geodynamic history of this basin. The Antarktis VI/2 data should also be matched with the former high-resolution data acquired by Kiel University and possibly also other reflection data sets, in a joint effort comparable with the one in action in the Weddell Sea. In the meantime a preliminary interpretation of the seismic profiles has been carried out, presented on fig. 40. The lay-out of the profiles is shown on fig. 32, where the structural interpretation of the aeromagnetic data from Parra e.a. (1988) has been added as background, for illustrative purposes. Elements of this map deemed of lesser relevance for our interpretation will be deleted in a later phase.

The three transverse profiles 2, 9 and 1a (fig. 40) 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 which started from the presently active volcano of Deception Island shows a characteristic graben and horst province, with tilted blocks and rotational fault development in a regime of continental extension. The maximal sediment thickness (600 m) has been found in a central graben, also drawn on fig. 32. The faults do not seem to reach the surface, which rises some doubts about any continuing activity in recent geological times. The focal analysis of earthquakes however still gives evidence of actual normal faulting (fig. 32).

Profile 9, located centrally in Bransfield Strait, probably shows a first phase of development of oceanic crust, possibly constrained to the northern flank of the basin, with a ridge structure which clearly shows on the aeromagnetic interpretation map (fig. 32). The initial rift has developed into an asymmetric basin, with sediment thicknesses of 800 to 1000 m in the axial zone. The prograding sedimentary wedge infilling the basin from the south probably reaches thicknesses larger than 1000 m.

The northernmost profile shows a truly oceanic domain, in the northern part of the profile. Again there is a distinct ridge structure in this domain, marked by an anomaly on the aeromagnetic data. The oceanic crust has been assigned an age of 1.3 Ma by Roach (1978). The sediment thickness of some 300 to 400 m on the oceanic crust reflects high accumulation rates.

The prograding sediment wedge on the southern rim of the basin buries an ancient rift and probably impinges further north on the oceanic crust. The maximal sediment thickness of the prograding sequences amounts to some 800 to 1000 m, while the sediment fill of the buried graben could be rated at another 1000 m.

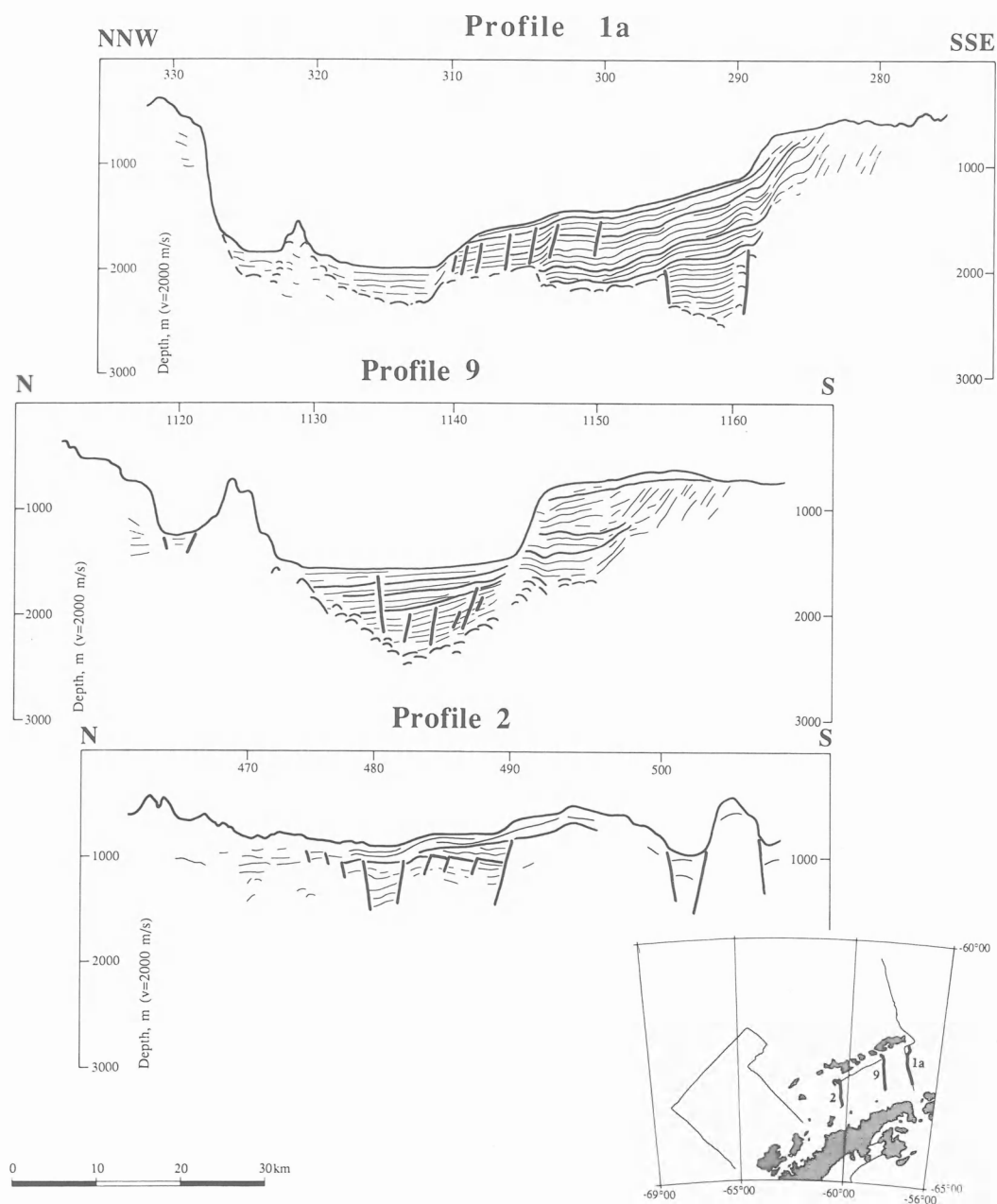


Fig. 40 Interpreted reflection profiles (2, 9 and 1a) crossing Bransfield Strait.

#### 24.8 The transform boundary north of Powell Basin

On the return route of cruise Antarktis V/4 in the Weddell Sea, a profile has been shot over the transform boundary between the Scotia plate in the north and the Antarctic plate with Powell Basin in the south. This profile (ANT V/4-28 shown at far right on fig. 32) crossed a 5300 m deep trench, flanked by huge ridges (fig. 41). A small axial ridge flanked by a very symmetric set of diverging reflectors has been discovered in the deepest part of the trench (B-B'). The main shear zone has apparently been crossed north of the northern ridge on the profile (A-A').

This profile still has to be framed in the regional geodynamic and stratigraphic context, after which a detailed interpretation of the sedimentary sequences and structural features will be carried out. The recently released data from wells 695, 696 and 697 of ODP Leg 113 might provide supporting data.

#### 2.5 Conclusions and perspectives

Although the analysis of the Antarktis VI/2 cruise is still in a preliminary phase, a number of interesting results are already emerging, both in the domain of the geodynamic evolution of the western margin of the Antarctic Peninsula and in the domain of the stratigraphy of the sedimentary basins. The joint analysis of both domains is essential in an active margin area where sedimentation and tectonics are closely linked.

##### 25.1 Dynamics of the converging plate boundary

The acquisition of seismic profiles over some hitherto seismically unexplored oceanic regions off the Antarctic Peninsula motivated a reassessment of the spreading and subduction history from available magnetic data. This analysis has shed some light on the possible role of the slab pull effect on the terminal acceleration of the spreading, recorded shortly before ridge-trench collision. The present reassessment forms the base of a two-dimensional velocity field analysis, which possibly could yield a better insight in the complex Shackleton F.Z.-South Shetland Trench triple junction. It might also help to explain the origin of a secondary trench-like structure, crossed by a reflection profile.

##### 25.2 Thermal contraction effects and magmatic diapirism at fracture zones

The profiles shot over Anvers and Hero F.Z. present to our knowledge the first reflection seismic evidence of thermal bending and magmatic diapirism along these important fracture zones. The fracture planes themselves can be followed deep in the oceanic crust. At Hero F.Z., such a plane

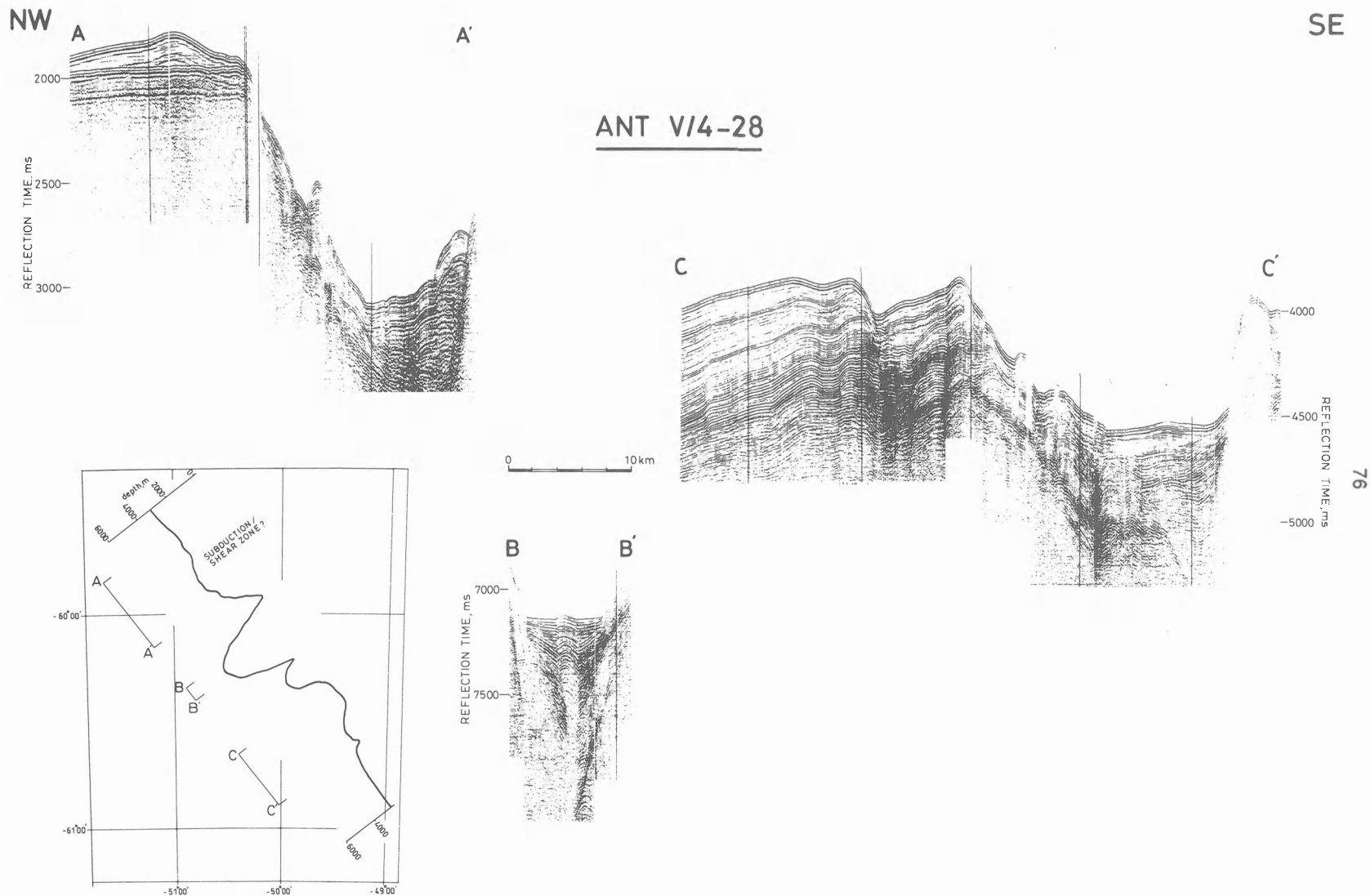


Fig. 41 Reflection profile (ANT V/4-28) recorded across the transform boundary between the Scotia plate and the Antarctic plate

in the oceanic crust can be followed in full continuity with the flank of the ridge, arguing for a diapiric origin of the ridge rather than an effusive one. The most likely nature of the Hero F.Z. ridge on the investigated profile is a serpentinite body, created by deep hydrothermal metamorphism of upper mantle peridotites, in analogy with e.g. Vema F.Z..

### 25.3 Oceanic seismic stratigraphic analysis

The deficiency of direct borehole control for the analysis of the seismic stratigraphy in the oceanic domain could be mended by a careful constraint of the age of the sedimentary cover through the above mentioned analysis of the magnetic anomaly patterns and their translation into a plate isochron map. The success of this approach was proved by the convergence of the results with those obtained by Japanese investigators further south, by direct shooting over a DSDP reference well: both the structure and the chronostratigraphic interpretation of the margin deposits which are in a similar geodynamic and sedimentary setting yield results in close agreement.

This approach allowed to identify stratigraphic unconformities at geological times which correlate in a very coherent way with some identified in the Weddell Sea. Both domains were in the considered period (Miocene to Plio-Pleistocene times) in open connection through Drake Passage, but the dominant control seems to be again rather climatic than paleoceanographic.

Sediment deformation features in slope foot deposits of Late Miocene age display striking similarities with the sediment flowage and slumping observed in fan deposits in the Weddell Sea, possibly in a similar time context and sedimentary environment.

### 25.4 Segmentation of the trench, slope and margin

The huge Hero F.Z. seems to have played a major role in the segmentation of the western margin of the Antarctic Peninsula. The hypothesis of the serpentinite nature of this ridge has a profound impact, as the degree of buoyancy of a ridge meeting a trench controls the type and extent of the structural, geochemical and petrological segmentation of that margin. Huge buoyant ridges even can stop subduction, as is known in the Lesser Antilles (Bouysse and Westercamp 1988). Whether such a phenomenon might have played a role in the stop of the subduction after the last ridge-trench collision at the western Peninsula margin deserves due attention.

The segmentation of the margin anyhow is not only expressed in the already well known difference in slope of the continental slope and the areal extent of the South Shetland trench and Bransfield Strait, but also possibly in the areal extent of an elongated basin on the outer shelf south of Hero F.Z., in our study interpreted as a fore-arc basin.

### 25.5 The rift-drift structure of Bransfield Strait

The sequence of profiles recorded in Bransfield Strait yield additional data about the fan-shaped opening of this back-arc basin and about its sedimentary infill. These data will be as much as possible integrated in the already recorded data set of previous studies in order to contribute to a general seismic-stratigraphic and geodynamic analysis of this remarkable basin. The more general geodynamic analysis of this area will also benefit from the analysis of a reflection profile recorded further west in the axis of Bransfield Strait, across the transform boundary between the Scotia plate and the Antarctic plate.

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