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4. WEGENER CANYON BATHYMETRY AND RESULTS FROM ROCK DREDGING NEAR ODP SITES 691–693, EASTERN WEDDELL SEA, ANTARCTICA[1]

Dieter Karl Fütterer,[2] Gerhard Kuhn,[2] and Hans Werner Schenke[2]

ABSTRACT

Systematic bathymetric surveys to map the Wegener Canyon with the multibeam sonar system SEABEAM, were carried out during the *Polarstern* cruises in 1985, 1986, and 1987. Wegener Canyon is one of the larger canyon systems along the Antarctic continental margin of the eastern Weddell Sea, and its vicinity. The swath survey covers an area of more than 10,000 km^2 off Kapp Norvegia and stretches from the upper continental slope (500 mbsl) to the Weddell Abyssal Plain (4,400 mbsl).

Wegener Canyon represents a prominent northwest-trending system of deep incisions of variable depth, extending over about 85 km from the shelf break to the continental rise. On the lower continental slope the canyon has been cut to a depth of about 1200 m. It has a width of 4 km at the bottom and 10 km between its shoulders, and measures about 25 km in length. It cuts through the northeast-trending, morphologically very prominent steep slope of the Explora Escarpment. The main topographic features of the lower Wegener Canyon are three cliff-like scarps, which are most prominently developed along the southwestern flank of the canyon where the slope inclination may be as steep as 24°.

On the gently inclined platform of the middle slope the canyon diverges into several morphologically less prominent tributaries, only one of which cuts into the upper slope and shelf.

Mesozoic sediments were dredged at eight stations on the scarps on the southwestern flank of Wegener Canyon. Volcaniclastic sandstones and mudstones, nannofossil oozes, and claystones rich in organic matter were recovered. Physiographic and structural settings interpreted from seismic data, together with preliminary results from the lithologies recovered, clearly indicate that the beds cropping out in the upper scarp are as old as the Early Cretaceous sediments drilled at ODP Sites 692 and 693. The middle and lower scarps consist of lowermost Cretaceous to Upper Jurassic sediments, which were not reached by drilling, providing additional information for the interpretation of the pre-Valanginian/Aptian sedimentary environment in the Weddell Sea.

INTRODUCTION

The Antarctic continental margin of the eastern Weddell Sea off Kapp Norvegia (Fig. 1) in western Dronning Maud Land shows an apparent subdivision into three major characteristic morphological units (Fig. 2). A very steep and narrow upper continental slope changes abruptly into a gently sloping mid-slope bench, about 80 km wide. Its transition to the continental rise at depths of more than 4000 m and further down to the Weddell Abyssal Plain is characterized by the steep and narrow Explora Escarpment (Hinz and Krause, 1982). The Explora Escarpment, with its distinct morphology, is the most prominent structural feature along the northeastern margin of the Weddell Sea, and was initially regarded as a magmatic outer basement high (Hinz and Krause, 1982). Toward the southwest it becomes more subdued, extending as a major sediment-covered basement structure, the Andenes Escarpment (Kristoffersen and Haugland, 1986).

The linear structure of the Explora-Andenes Escarpment is interpreted as representing a transtensional plate boundary between Africa and Antarctica (Hinz and Kristoffersen, 1987). New seismic reflection data (Miller et al., in press) show evidence of seismic reflectors which can be followed below the otherwise structureless outer high. New ideas regarding the nature of the Andenes-Explora-Escarpment, based upon these observations (Henriet and Miller, in press), lead to the interpretation that the escarpment formed as a compressional zone during

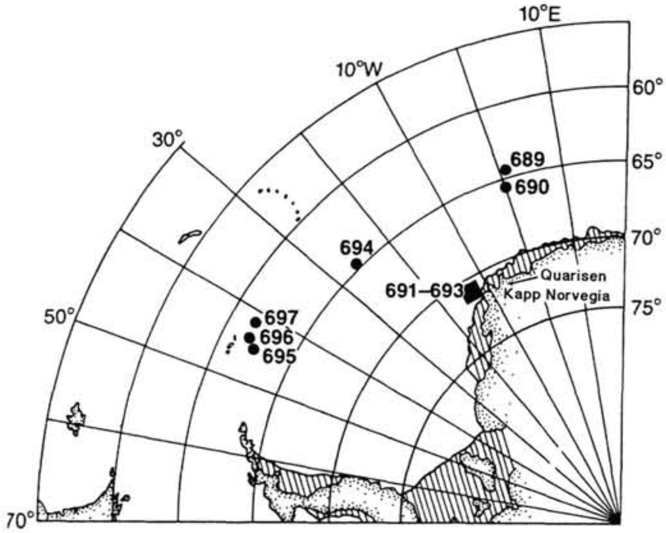

Figure 1. ODP Leg 113 drill sites in the Weddell Sea. Solid square = area of the Wegener Canyon near Sites 691–693 off Kapp Norvegia shown in Figure 2. Ice-shelf areas are hatched.

strike-slip motion connected with underthrusting and stacking of predominantly sedimentary material.

An alternative interpretation to explain the structure and morphology of the Explora Escarpment is based on the observation of several large, parallel, normal faults in the hinterland of Kapp Norvegia to the south. These faults define a half-graben structure in a rifted continental margin setting (Spaeth and Schüll, 1987). The Explora Escarpment in this model would

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[2] Alfred Wegener Institute for Polar and Marine Research, Columbusstraße, D-2850 Bremerhaven, Federal Republic of Germany.

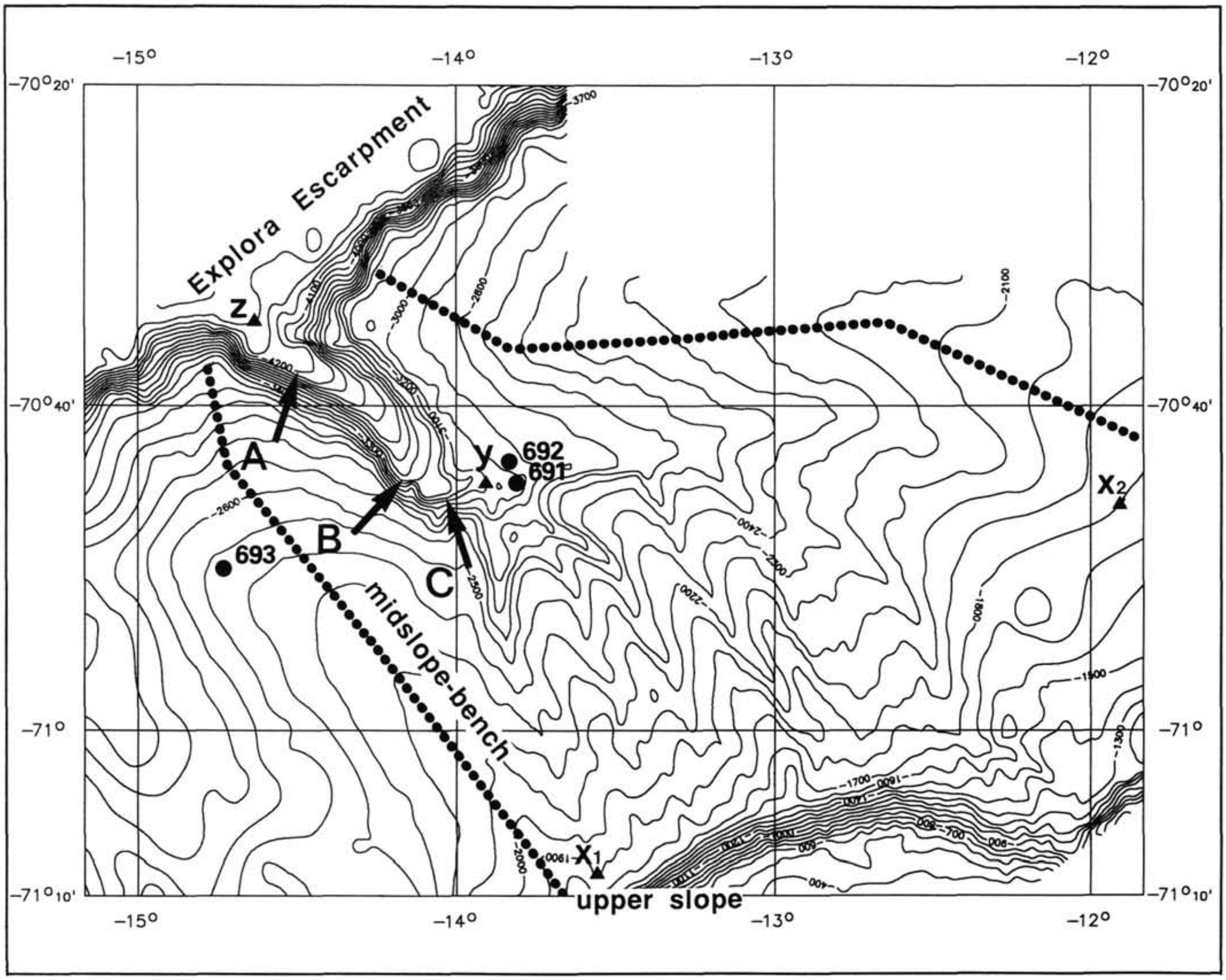

Figure 2. Bathymetry of the Wegener Canyon system and major morphologic units of the continental margin off Kapp Norvegia, eastern Weddell Sea, from multibeam echo-sounding data. Bathymetric contours in meters; dotted line circumscribes area of the Wegener Canyon system; A, B, and C refer to profiles shown in Figure 5A and *Polarstern* dredge sites (A = hauls PS-1592-1, PS-1634-1, PS-1644-1, PS-1644-2; B = hauls PS-1503-1, PS-1630-1; C = hauls PS-1633-1, PS-1646-1). Detailed information for each dredge haul is given in Table 1; 691, 692, and 693 refer to ODP Leg 113 drill site locations; x_1, x_2, y, z mark points for calculation of thalweg gradients.

simply represent the offshore edge of a tilted basement block (Henriet and Miller, in press).

Off Kapp Norvegia, the Andenes-Explora Escarpment is deeply incised by the Wegener Canyon which continues into the mid-slope bench and up to the shelf break.

The area of the mid-slope bench and the Wegener Canyon off Kapp Norvegia were chosen for drilling by Leg 113 of the Ocean Drilling Program (ODP Sites 691–693; Fig. 1; Barker, Kennett, et al., 1988) in order to: (1) examine the Cenozoic history of the Antarctic ice-sheet and climate of the continent by drilling the upper sedimentary sequence on the canyon shoulders, and (2) to test the nature and age of the oceanward-dipping reflectors of the Explora Wedge by drilling the floor of the canyon. This structural feature of northward-dipping seismic reflectors forms the basement of the thick Mesozoic-Cenozoic sedimentary sequence of the mid-slope bench. It is interpreted as representing a massive sequence of volcanic and volcaniclastic rocks erupted in an intracontinental rift-axis setting. Eruptions took place in a subaerial to shallow-marine environment onto highly distended continental crust (Hinz, 1981; Hinz and Kristoffersen, 1987) during the initial phase of plate tectonic break-up between Africa and Antarctica. The most likely age for the formation of the Explora Wedge has been assumed to be Middle Jurassic (Hinz and Krause, 1982; Hinz and Kristoffersen, 1987) on the basis of potassium-argon ages of subaerially extruded and intruded tholeiitic lavas from Vestfjella (Furnes and Mitchell, 1978; 169–154 Ma) and Heimefrontfjella (Rex, 1972; 173–156 Ma) in the hinterland of Kapp Norvegia.

At ODP Site 691, which is located in a water depth of 3036 m in the axis of the topographically complex mid-slope area of the branching Wegener Canyon system (Fig. 2), it was not possible to spud in because of a hard seafloor, probably comprising a thick lag sediment cover of ice-rafted and/or turbidity current transported boulders.

Hole 692B, in 2875 m water depth on the canyon shoulder to the north (Fig. 2), penetrated 97.9 m below seafloor (mbsf), i.e., to a depth of 2972.9 m below sea level (mbsl; meters below sea level are used through this study as reference to correlate drilled sequences to seismic reflectors and topographic features). The oldest sediments recovered at this site comprise nannofossil claystones with a considerable amount of volcaniclastic components of Early Cretaceous, probably middle Valanginian age (Mohr, this volume, chapter 29; Valanginian to Hauterivian according to Barker, Kennett, et al., 1988).

Site 693 is located on the mid-slope bench some 10 km southwest of the outer rim of the Wegener Canyon, at 2359 m water depth. Hole 693A penetrated 483.9 mbsf (2842.9 mbsl) and yielded dark, organic-rich, terrigenous claystones and mudstones with substantial quantities of volcaniclastic material from the base of this hole. These sediments have been dated by nannofossils and dinoflagellate cyst assemblages as early Aptian to early Albian (Mutterlose and Wise, this volume; Mohr, this volume, chapter 29).

Multichannel seismic reflection data (Hinz and Krause, 1982; Hinz et al., 1986) and high-resolution profiling by *Polarstern* during the austral summer of 1986/87 (Miller et al., in press), in the area of the Wegener Canyon and ODP drill sites, revealed that sub-bottom reflection horizons have a very low dip and can be followed from Site 692 to Site 693. The deepest beds recovered at ODP Sites 692 (middle Valanginian, 2972.9 mbsl) and 693 (late Aptian, 2842.9 mbsl), as well as deeper seismic stratigraphic sequences (Hinz and Kristoffersen, 1987; Miller et al., in press), would therefore be expected to form outcrops on the steep walls of the lower Wegener Canyon at corresponding depths. A detailed survey of the Wegener Canyon bathymetry and morphology, including subsequent dredging of pronounced cliffs on the canyon walls, thus became a promising means of extending the sedimentary record below the 2972.9 mbsl level penetrated at Site 692 at 98.9 mbsf, to a depth of about 4400 mbsl represented at the canyon base.

BATHYMETRIC SURVEY OF THE WEGENER CANYON AREA

Methods

The bathymetric survey of the Wegener Canyon system and its vicinity was carried out during *Polarstern* expeditions ANT-IV/3 (ODP Site Survey 1985/86; Fütterer, 1987), ANT-V/4 (1986/87; Miller and Oerter, 1990), and ANT-VI/3 (1987/88; Fütterer, 1988) using the multibeam sonar system SEABEAM.

SEABEAM is a bathymetric swath survey system allowing a two-dimensional mapping of the seafloor topography with high horizontal resolution. Even small features with a lateral extension of 150 m can be detected in water depths of about 3000 m (Schenke and Ulrich, 1987).

Precise positioning of the ship is the main prerequisite for compilation of the final bathymetric chart. The lack of land-based reference stations for radio navigation systems in the Antarctic, and the presence of heavy sea-ice in the area surveyed made it extremely difficult to realize a systematic box-survey with parallel profiles. The navigation of *Polarstern* was mainly based on an integrated navigation system (INDAS-V, Prakla-Seismos Co.), with Doppler Sonar and TRANSIT satellite fixes. The period between satellite fixes in the eastern Weddell Sea varies from 20 to 30 min. With a sophisticated correction procedure, the achievable accuracy with the integrated navigation system, under high latitude conditions, is of the order of + 200 m. In addition, the GPS/NAVSTAR navigation system, with an accuracy of less than ± 50 m (Wells et al., 1986) was available 10–13 hr/day. Both types of navigation data were integrated and used for final processing. Swath-plots of the SEABEAM survey were used to check the navigation data, areal coverage, and the survey quality. Furthermore, they can be used as a tool to continuously plan the running survey in order to achieve complete areal coverage with the necessary swath overlays.

The swath-width from SEABEAM profiles depends directly on the water depth under the vessel and is usually equal to 3/4 of it. In an area of rugged seafloor topography, as in the Wegener Canyon, planning of an economically and scientifically efficient survey grid is difficult, and track lines must be adjusted to the rapidly changing water depths.

The irregular movements of the vessel while surveying ice-covered areas cause a large number of incorrect SEABEAM-measurements. These errors have to be excluded using redundant information from overlapping survey tracks when available, or filtered by an extensive post-processing procedure using special interpolation techniques.

Besides accuracy in positioning and SEABEAM measurements, there are other principal problems involved concerning vertical resolution and precision. Our map compilation is based on uncorrected SEABEAM depth measurements calculated by using a nominal sound velocity of 1500 m/s. A comparison of water depths derived from drill-pipe measurements at Sites 691, 692, and 693 and water depths at these drill sites taken from processed SEABEAM maps yields deviations of 60–100 m. After correction of SEABEAM depths following Matthew's echo-sounding correction tables (Carter, 1980) a deviation of 7–46 m (compared to drill-pipe measurements at the drill sites) still exists.

The final bathymetric chart of the Wegener Canyon area (Fig. 2) was compiled on the basis of 9000 km of continuous SEABEAM profiling with a mean areal overlap of 10%. The chart covers an area of more than 10,000 km^2 between 70°20′S and 71°10′S and 11°50′W and 15°10′W.

RESULTS

The bathymetric chart of the continental margin off Kapp Norvegia presents a striking morphological pattern which apparently comprises three depth units (Figs. 2 and 4).

Below a distinct shelf break at about 600 mbsl a relatively smooth but steep upper slope extends down to 1700 mbsl. Over large areas it shows a slope inclination of 12°–16° (Fig. 4). From our shallow seismic records, sub-bottom profiling and sediment sampling, it is evident that this steep slope is covered by a coarse gravelly residual sediment. At 12°W, in the transition zone between Kapp Norvegia and the Quarisen ice shelf to the east (Fig. 1), the base of the upper slope shoals to a depth of 1200 mbsl, indicating a general rise of 500 m (Fig. 2).

A gently oceanward-sloping (about 1.5°) mid-slope bench that is over 80 km wide stretches from 1700 mbsl to about 3100 mbsl. Its landward portion is subdivided into several elongated ridges by the slight incisions of the distributary gully system of the upper Wegener Canyon. The flatter seaward portion is characterized by the deep incision of the lower Wegener Canyon. The oceanward edge of the mid-slope bench is formed by the steep cliff-like wall of the Explora Escarpment (Figs. 2 and 4), which descends from about 3100 m water depth through more than 1300 m to the abyssal plain at 4400 m. Northeast of Wegener Canyon the Explora Escarpment is distinctly steeper than to the southwest of it (Fig. 2), locally showing maximum slope inclinations of 30°. Directly at the mouth of Wegener Canyon the western part of the escarpment shows a slight but distinct offset of 3–4 km to the north.

The southwest-to-northeast trending Explora Escarpment and the mid-slope bench are cut by the Wegener Canyon system which is deeply incised into the escarpment and lower bench and shows a rather linear trend toward the southeast (Fig. 2). Here, the canyon walls are at least 1000 m in height with mean slope inclinations ranging from 10° to 15°. At the bottom, the canyon is rather uniformly 4 km wide, whereas the upper edges generally are about 10 km apart, giving rise to an unusual U-shaped cross-section. A faint indication of a gorge-like narrowing may exist near to the canyon mouth (Fig. 2 near arrow A). The southwestern canyon wall is locally up to 300 m higher and generally shows steeper slopes (12°–16°) than the northeastern canyon flank (6°–12°). The reason for this is not clear, although from seismic reflection data there is some evidence for a structural origin. The length of the deeply incised lower canyon is about 35 km. Between positions y and z (Fig. 2) at 3100 mbsl and 4400 mbsl respectively, the canyon axis shows a rather uniform gradient of 2.2° over a distance of 33 km.

The main characteristic of the lower Wegener Canyon, besides its deeply incised character and its U-shaped cross-section, is the occurrence of three cliff-like scarps, separated by distinct breaks in slope inclination. However, they are clearly recognizable only on large-scale maps (Fig. 3). Two of the scarps, the lower one at 3900–4100 mbsl and the middle one at 3100–3300 mbsl, surround the whole canyon at constant depths. The upper scarp between 2750 and 2950 mbsl is morphologically less prominent and represented only on the southern and southwestern flanks of the canyon (Fig. 3). On the northern flank of the canyon it cannot be detected probably because of extensive erosion, an assumption supported by the drilling results from ODP Hole 692B. The middle scarp (3100–3300 mbsl) especially but also the lower scarp (3900–4100 mbsl) form pronounced cliff-like protrusions showing slope inclinations ranging locally from 25° to 30° along the southwestern flank of the canyon.

In the center of the mid-slope bench, the Wegener Canyon branches into several morphologically less-prominent tributary valleys, and loses its deeply incised, steep-walled character. This occurs where the middle scarp (3100–3300 mbsl) crosses the canyon floor (Fig. 3) and where the axis of the canyon turns to the east by some 50°, to continue as a gently-sided valley roughly parallel to the upper continental slope (Figs. 2 and 3). A system of five deep tributary gullies, which originate at the base of the upper slope, enters from a southeasterly direction (Figs. 2 and 4). Only the easternmost gully cuts the upper slope and continues across the shelf and underneath the ice shelf where it has not been surveyed to date. All the tributaries to the west neither cut into the upper slope nor into the shelf. The tributary gullies are less deeply incised, up to 200 m only, and are more than 1 km wide, showing a typically V-shaped cross-section. Slope inclination never exceeds 6°. The average thalweg inclination of the tributary gullies of about 1°–1.5° is clearly less than that of the deeply incised lower Wegener Canyon to the north. However, there is an apparent change in thalweg inclination from 1.5° between positions x_1 and y at 1900 mbsl and 3100 mbsl, respectively, over a distance of 48 km in the westernmost tributary (Fig. 2), to 1° between positions x_2 and y at 1800 mbsl and 3100 mbsl, respectively, in the main valley immediately to the east. This change reflects the fact that all tributaries are cut to grade with the west-east-trending main branch of the canyon. There is no indication of a preferential erosion activity in any of the gullies.

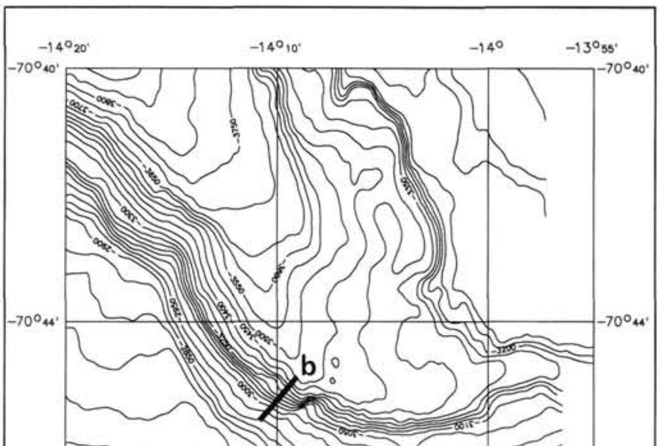

Figure 3. Large scale bathymetric chart of deeply incised central part of the Wegener Canyon showing prominent cliff-like middle scarp at 3100–3300 mbsl surrounding the canyon at a regular depth; b and solid line mark middle scarp dredged along profile B of Fig. 5. Broken line and c mark morphologically less prominent upper scarp dredged along profile C of Fig. 5.

ROCK DREDGING SURVEY IN THE LOWER WEGENER CANYON

From the detailed bathymetric survey of the deeply incised lower part of Wegener Canyon, it can be seen that the slopes of this northern canyon area are subdivided by several steep cliff-like scarps, each about 200 m in height (Fig. 3). It was assumed (Miller and Oerter, 1990) that these scarps, each lying in nearly constant water depths (2750–2950 mbsl, 3100–3300 mbsl, 3900–4100 mbsl; Fig. 5), comprised flat-lying sedimentary sequences more resistant to erosion and could represent outcrops of Mesozoic strata.

For this reason, dredging three main sites on the steeper southwestern slope (Figs. 2 and 4) was selected as a simple but efficient and inexpensive method (von Rad et al., 1979) to supplement the lithological and stratigraphical rock sequence recovered at ODP Sites 692 and 693, and to obtain more information for seismic interpretation. Determination of the lithology, age, and paleoenvironment of samples collected by eight dredge hauls (Table 1) along the canyon walls will be the objective of further investigations.

Technique of Rock Dredging

One dredge station (PS-1503) was taken during *Polarstern* cruise ANT-V/4 (1986/87). All other dredges were taken during ANT-VI/3 in 1987/88 (Fütterer, 1988). We used a heavy chain bag dredge with a frame opening of 100 × 35 cm. Every dredge haul was depth controlled and its location reconstructed as precisely as possible (Fig. 5, Table 1) by using the ship's position and speed, water depth, amount of wire paid out, wire tension, and time (Wiedicke, 1987; von Rad et al., 1979). All dredge hauls except PS-1592-1 contained variable quantities of sedimentary rocks with freshly broken surfaces, clearly indicating their detachment from outcropping strata, in addition to ice-rafted dropstones. The largest haul with about 500 kg of rocks was obtained at station PS-1503. The weight of rocks in other dredge hauls varied from approximately 20 to 100 kg. The dredge became stuck at station PS-1592 and the haulage rope broke. It was recovered empty using the safety rope.

Preliminary Results from Rock Dredging

The deepest scarp at 3900–4100 mbsl was successfully dredged with hauls PS-1644-1 and PS-1644-2. Mainly pebbly and coarse-grained, poorly sorted impure volcaniclastic sandstones (dark brown to green-olive) with a mixture of well to poorly rounded components and fine-sandy siltstones were recovered. Large pyroxenes, grains of volcanic glass, and pumice shards were common. Only rarely indefinable fossil molds (mollusks?) were found.

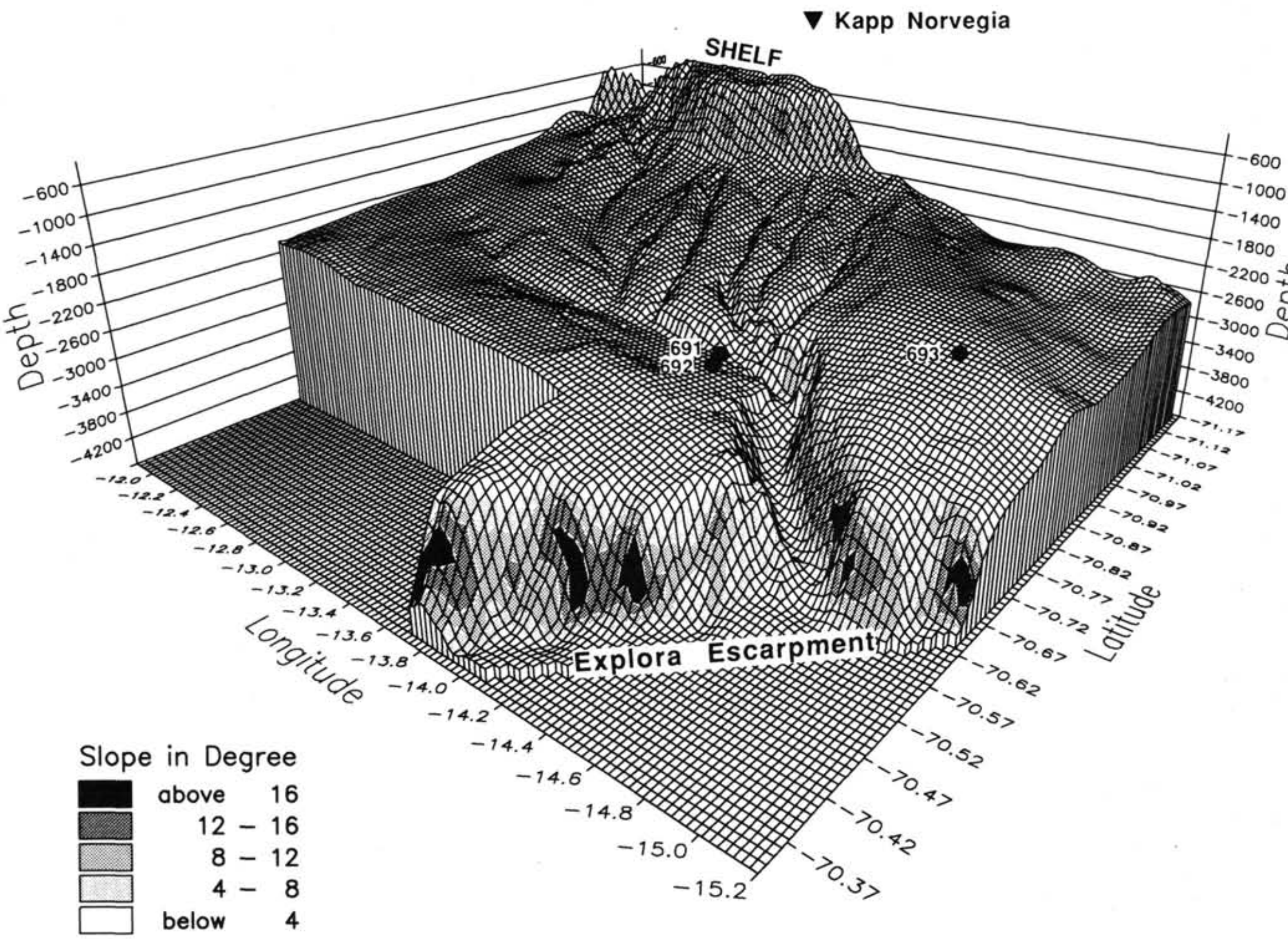

Figure 4. Three-dimensional view of the Antarctic continental margin off Kapp Norvegia from multibeam echo-sounding showing main morphologic patterns of the Wegener Canyon system and ODP Sites 691–693. Slope inclination is indicated by various shadings.

Table 1. Position and data of Wegener Canyon dredge hauls. Profiles A, B, and C refer to Figures 2 and 5.

Dredge haul	Profile	Position: Dredged from	Position: Dredged to	Water depth: At start	Water depth: At end	Maximum wire out	Maximum wire tension	Remarks
PS-1503-1	B	70°45.1′S 14°10.5′W	70°46.0′S 14°10.9′W	3270 m	2700 m	4100 m	6.5 t	Full haul.
PS-1592-1	A	70°38.8′S 14°26.0′W	70°39.9′S 14°27.1′W	4100 m	3440 m	5000 m	9.4 t	Empty, haulage rope broke.
PS-1630-1	B	70°43.9′S 14°10.7′W	70°45.2′S 14°14.8′W	3540 m	2720 m	4300 m	7.0 t	
PS-1633-1	C	70°45.7′S 14° 3.2′W	70°46.4′S 14° 2.6′W	3350 m	3000 m	5000 m	10.4 t	
PS-1634-1	A	70°40.3′S 14°27.0′W	70°41.7′S 14°27.0′W	3370 m	3070 m	4800 m	10.0 t	
PS-1644-1	A	70°38.2′S 14°28.4′W	70°39.2′S 14°29.4′W	4170 m	3480 m	5200 m	8.7 t	
PS-1644-2	A	70°38.2′S 14°28.4′W	70°39.4′S 14°29.5′W	4180 m	3420 m	5380 m	7.9 t	
PS-1646-1	C	70°46.7′S 14° 1.5′W	70°47.6′S 14° 0.3′W	2930 m	2630 m	4100 m	6.7 t	

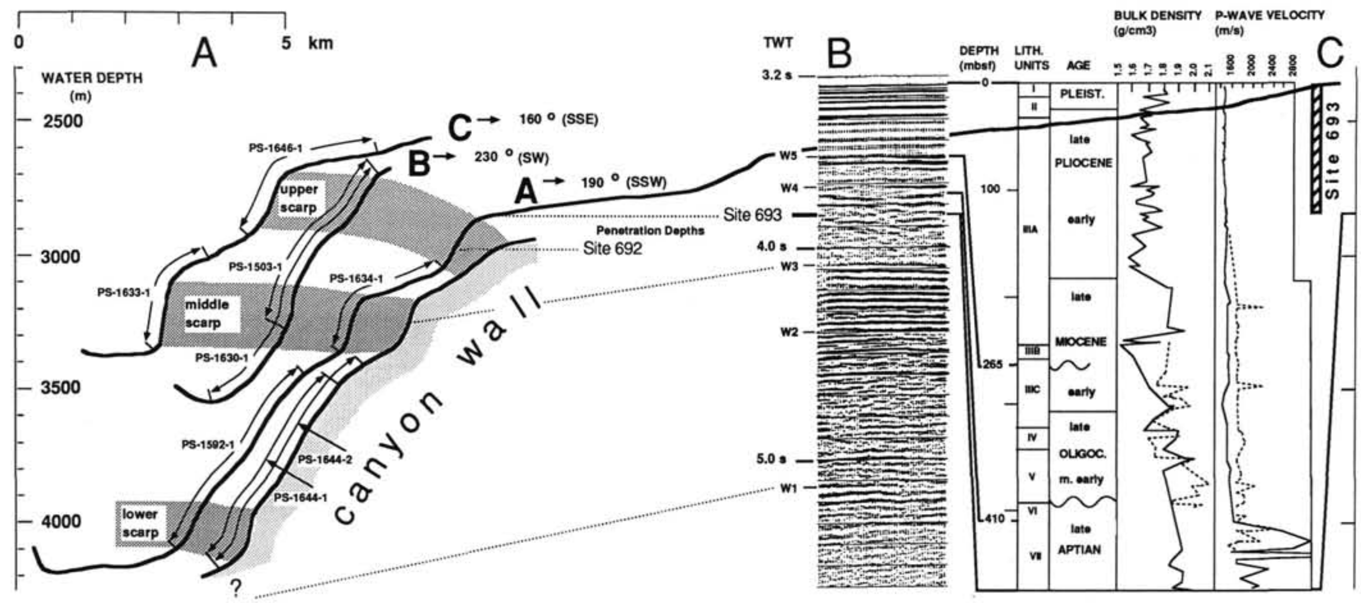

Figure 5. Correlation of Wegener Canyon topography, high resolution seismic stratigraphy pattern at ODP Site 693 from Miller et al. (in press), and lithologic units and ages at ODP Site 693 (Barker, Kennett, et al., 1988). **A.** Bathymetric profiles (A, B, C) and cliff-like scarps at the southwestern slope of the lower Wegener Canyon where several dredge hauls (PS-; for details see Table 1) were carried out along profiles A, B, and C. Profile A directly correlates the upper scarp of Wegener Canyon and ODP Site 693 (distance and height in scale). **B.** Detail of high-resolution seismic reflection pattern at ODP Site 693 with regional unconformities W1 through W5; W1 and W3 are tentatively correlated with the outcropping strata on the walls of the lower Wegener Canyon. **C.** Lithologic units and bulk density of Hole 693A (solid line) and Hole 693B (broken line); *P*-wave velocity is from physical properties measurements of Hole 693A (solid line) and from sonic log (broken line).

The intermediate scarp at 3100–3300 mbsl was sampled by dredges PS-1503-1, PS-1630-1, PS-1633-1, and PS-1634-1. The dominant lithologies are compact, brown to green-olive and gray, homogeneous or finely layered mudstones, impure siltstones and coarse, poorly consolidated sandstones. Gastropod and bivalve shells and molds are common in the siltstones. The sandstones and siltstones also contain volcanic components but in distinctly minor quantities compared with the sediments from the lower scarp. In dredge haul PS-1503 a few chunks of light gray-brown nannofossil ooze were recovered. Some claystones and siltstones contain trace fossils, mostly open and unfilled burrows which show thin Fe-Mn coatings on their inner walls. Dark organic-rich layers were found in the claystones. The few analyses made to date show that one sample had an organic carbon content of 7.7%. A belemnite fragment of probable Early Cretaceous age was found in material from dredge PS-1503-1, and a poorly preserved ammonite fragment, which may allow a rough age determination, was recovered in a sandstone from dredge PS-1633-1. Besides these macrofossils, further investigations on calcareous nannofossils and/or other microfossils may allow a better dating of the sediments in the future.

The upper scarp is sufficiently developed only at the southern wall of the central canyon area between 2750 and 2950 m water depth (Figs. 2 and 3, areas C). Here the steeper slope was sampled by dredge haul PS-1646-1. Some material from hauls PS-1503-1 and PS-1630-1 may have originated as down-fall material from this uppermost scarp. Sediments recovered by dredge PS-1646-1 were green-olive to brown, poorly consolidated, bedded or finely laminated, sandy siltstones and homogeneous claystones.

DISCUSSION

Stratigraphic Correlation

The geological and structural development of the continental margin of the eastern Weddell Sea were first described by Hinz and Krause (1982). They identified a seismic stratigraphic sequence pattern which was later extended by introducing a circum-Antarctic seismic stratigraphic concept (Hinz and Block, 1984; Hinz and Kristoffersen, 1987). This scheme has recently been redefined by the introduction of a fine-scale seismic stratigraphy for the eastern Weddell Sea continental margin (Miller et al., in press). The new approach uses a seismic line passing over ODP Site 693 as a seismic-stratigraphic stratotype section, and ties the existing seismic patterns to the biostratigraphy and lithostratigraphy of ODP Sites 693 and 692 (see Table 2). This scheme was used in our attempt to correlate the outcrops dredged at Wegener Canyon and the sediment sequences recovered from ODP sites.

A correlation of the physiographic setting of the lowermost scarp at 3900–4100 mbsl with the sub-bottom depth of the seismic stratigraphic units (Figs. 5B and 6), reveals that the volcaniclastic sandstones and siltstones dredged at station PS-1644, have to be placed in the upper part of seismic stratigraphic sequence *W1* which is still well above the horizon of the seismic reflector W1 at a sub-bottom depth of 1.9 s TWT (two-way travel time; Table 2) or about 4800 mbsl (Fig. 6). This horizon was first identified by Hinz and Krause (1982) as a regional unconformity and named the "Weddell Sea continental margin unconformity". Unconformity W1 (formerly U9 according to Hinz and Kristoffersen, 1987) is interpreted as representing the upper boundary of the Explora Wedge, which consists of a thick oceanward-dipping reflector sequence most probably of volcanic and volcaniclastic origin. It is supposed to be of late Middle Jurassic age which would imply a probable Late Jurassic age for the overlying volcaniclastic sandstones and siltstones dredged from the lower scarp of the Wegener Canyon.

The sediments cropping out on the middle scarp at 3100–3300 mbsl lie approximately 100–300 m deeper stratigraphically than the oldest deposits recovered in Hole 692B (2972.9 mbsl) which have been dated as middle Valanginian (Mohr, this volume, chapter 29). A Late Jurassic to earliest Cretaceous age for

Table 2. Overview of existing seismic stratigraphic sequences and unconformities and their correlation with lithologic units at ODP Site 693 and the dredged Wegener Canyon outcrops.

Hinz and Krause (1982)	Hinz and Kristoffersen (1987)	Miller et al., (in press)	Site 693 TWT (sbsf)	Site 693 Estimated (mbsf)	Hole 693A lithologic units	Wegener Canyon
		W7			I	
					II	
		W7	0.08	65	↑	
		W6				
		W6	0.20	190	IIIA	
WS-1						
		W5			↓	
					IIIIB	
		W5	0.30	255		
					IIIC	
		W4			IV	
					V	
	U3	W4	0.48	398		
					VI	
				484*	VII	upper
		W3		615**		scarp
WS-2						
		W3	0.82	ca. 900		
						middle scarp
	U5	*W2*	0.94			
WS-3B						
	U6	W2	1.22	ca. 1350		
						lower scarp
WS-3A		*W1*				
	U9	W1	1.90	ca. 2450		
Weddell Sea continental margin unconformity						
WS-4 "Explora Wedge"						

Note: Data at Site 693 are given as two-way travel times (TWT) in seconds below seafloor (sbsf) and estimated meters below sea floor (mbsf); * = maximum penetration depth at Site 693; ** = maximum penetration depth at Site 692 projected into Site 693 (modified from Miller et al., in press).

the sediments dredged from the middle scarp is therefore most likely. These sediments are provisionally correlated with the lowermost seismic sequence *W3* and uppermost sequence *W2* thereby, as indicated in Figure 6, placing unconformity W3 somewhere in the middle of the scarp. The organic-rich claystones from dredge haul PS-1503-1 (dredged interval 3270–2700 mbsl), if dredged from a rock outcrop of the middle scarp, indicate that the equivalent organic-rich claystone facies recovered from the middle Valanginian in Hole 692B at 2973 mbsl, continues down into the middle scarp. It is assumed that this facies extends down as far as unconformity W3 at about 3150 mbsl. This would imply that the organic-rich claystone facies, present in the Aptian of Hole 693A at 2757–2843 mbsl and in the Valanginian of Hole 692 at 2875–2973 mbsl, were part of a succession that accumulated throughout most of Early Cretaceous time to a thickness of about 400 m. Alternatively, these claystones could represent rock fall debris derived from further up the slope. In this case the claystones would correlate with the upper Aptian organic-rich claystone sequence recovered from Hole 693A, and which most probably crop out in the upper scarp.

According to the observations from the high resolution seismic records, that show the seismic reflectors of the area to have only very low or no dip, the lowermost strata drilled at Sites 692 (2972.9 mbsl) and 693 (2843 mbsl) should be exposed in the uppermost scarp at 2750–3000 mbsl (Fig. 5). By simple depth correlation from the bottom of Hole 693A, and taking into account the seismic stratigraphy pattern and water depth (Fig. 5), the upper scarp edge may comprise the upper Aptian claystones. This assumption corresponds with an increase of *P*-wave velocities in the lowermost sediments from Hole 693A (Barker, Kennett, et al., 1988), which indicates a more consolidated lithology firm enough to form a cliff. At least 45 m of organic-rich claystones and mudstones and clayey muddy nannofossil chalk of Valanginian age as recovered from Hole 692B, should crop out in the lower part of the upper scarp. However, more detailed petrographical and paleontological analyses are needed to determine whether the few sediment chunks recovered by dredge haul PS-1646-1 from the area of the upper scarp can definitely be related to the oldest sediments recovered from Holes 692B (middle Valanginian) and/or 693A (late Aptian).

From dredge profile A in Fig. 5A, and by fitting it into the seismic stratigraphy pattern of Fig. 5B, it may be speculated that the slight step in the slope profile between 2650 and 2700 mbsl correlates with the prominent reflector W5. This significant reflector is assumed to represent a minor Miocene hiatus, and an overlying thin sequence of diatom-nannofossil ooze of Lithologic Unit III at Site 693 (Barker, Kennett, et al., 1988; Miller et al., in press).

Evolution of the Wegener Canyon System

The formation of the Wegener Canyon system in its principal morphologic pattern is assumed to have been mainly structurally controlled, although unequivocal arguments are lacking. However, the process that is now widely accepted as being the principal agent of canyon erosion is turbidity current activity; masses of sediment-laden water that can flow at high speed down the continental slope (Emery and Uchupi, 1984). Today, the continental margin of the eastern Weddell Sea is sediment-starved, and as a consequence the Wegener Canyon system is considered to be inactive. Some support for this assumption comes from oceanographic data and sediment sampling in the Wegener Canyon system. Active erosion is assumed to occur

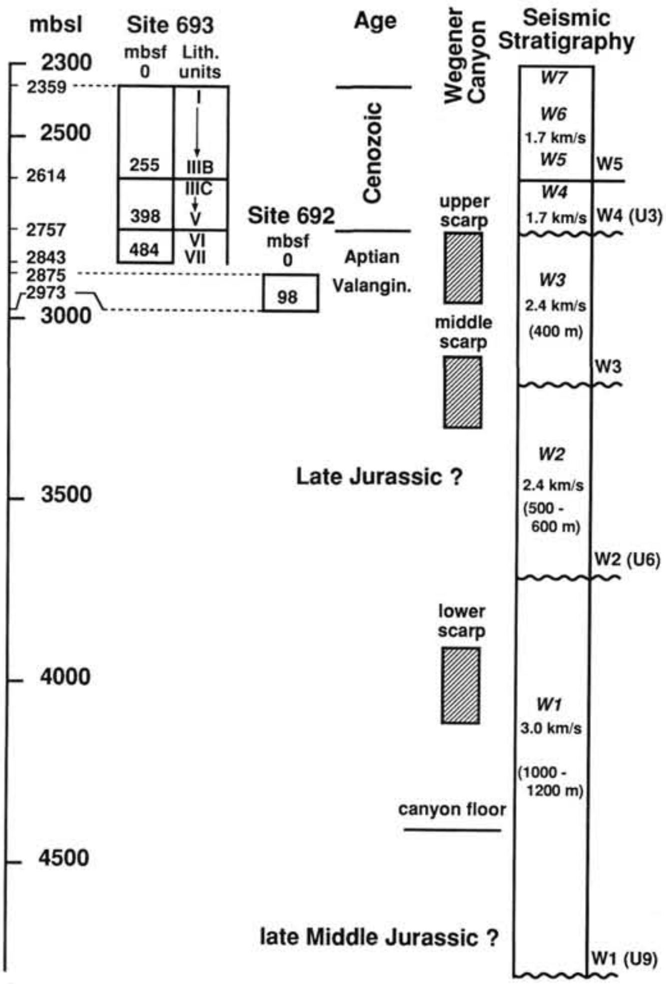

Figure 6. Correlation of seismic stratigraphic sequences and unconformities, lithologic units of ODP Sites 692 and 693 (Barker, Kennett, et al., 1988), and outcropping beds dredged at Wegener Canyon. Seismic stratigraphy data are from Miller et al. (in press); seismic sequences *W1–W7* show integrated velocity in km/s and estimated thickness in m; wavy lines mark erosional unconformities.

predominantly during glacial periods when grounded ice-sheets reach the shelf edge and make abundant sediment available for turbidity currents. Such a transport and sedimentation pattern on the margin would explain why most tributary gullies are not cut into the upper slope and shelf but start to form at about 1700 mbsl. It further implies a direct coupling with respect to time of glacial cyclicity and periods of active canyon erosion.

The morphologically prominent feature of the Explora Escarpment, disregarding its structural importance as an outer "volcanic" (Hinz and Kraus, 1982) or "sedimentary/structural" high (Miller et al., in press), would have acted as an oceanward retaining sill for the Mesozoic/Cenozoic sediments that accumulated above the dipping reflector sequence of the Explora Wedge. Once the sill depth has been reached, a spill-over of sediments occurs and the initial stage of "canyon" formation can start. From the uniform seismic pattern throughout all sequences, showing very low dip of reflectors over long distances and their abrupt truncation at the canyon walls, it is assumed that the sill depth was rather high and near to the present day edge of the Explora Escarpment at about 3100 mbsl. There is no indication of a less pronounced escarpment edge in the area of the canyon mouth. However, this area of the escarpment can represent a structurally weak domain.

The offset and northward displacement of the western part of the escarpment, where the Wegener Canyon has cut through the Explora Escarpment, most probably indicates a structural origin. Additionally, there is much evidence from high resolution seismic records that the western wall of the Wegener Canyon, which is morphologically much more pronounced than the opposite wall, follows a major dextral strike-slip fault (H. Miller, pers. comm., 1988). Whether this fault cuts the Explora Escarpment to cause the offset of 3–4 km, needs further investigation, as does its age. Tracing of the morphological scarps along the canyon walls (Fig. 3), as well as correlation of high resolution seismic stratigraphy, however, makes a major vertical displacement of the Cretaceous and Cenozoic sequences unlikely. Another argument for a structural control is the absence of tributary valleys on the sides of the lower Wegener Canyon, a feature common to other fault-controlled submarine canyons (Shepard, 1981).

The analysis of the modern thalweg gradients shows remarkable variations: 2.2° in the oceanward, steeply-walled, lower canyon; 1.5° in the western tributary; and 1° in the main valley in the east (Fig. 2). These variations indicate that the canyon system has not yet reached a dynamically balanced state. An extrapolation of the gradients from positions x_1 and x_2 to the canyon mouth at position z at 4400 mbsl (Fig. 2) yield ancient sill depths at the escarpment of 4000 mbsl and 3700 mbsl, respectively. The apparent differences in thalweg inclination imply at least two stages of the erosion process of the Wegener Canyon system, as similarly discussed by the Leg 113 Shipboard Scientific Party (Barker, Kennett, et al., 1988). In the first stage a gently sloping canyon system, covered along its axis by a coarse gravel and boulder lag, developed on the mid-slope bench. Steady cutting down of this system occurred in balance with the sill depth at the escarpment until the depth level of the canyon shoulder at Site 692 was reached, which roughly corresponds to the calculated sill depth of 3700 mbsl. Subsequently, the sill at the escarpment collapsed or was rapidly breached and a deep and steeply walled lower canyon was formed that rapidly cut headward.

Regarding the timing of these two phases of erosion of the Wegener Canyon, the older Phase I is assumed to be documented in the less steep tributary system of the upper mid-slope bench, whilst the younger Phase II is probably evident from the lower canyon deeply incised into the oceanward lower mid-slope bench. However, we presently do not have any age information from the sediments to fix an age estimation for the periods of canyon erosion. This important but problematic question needs further attention with additional sampling and studies in the area.

The conclusion made by the Leg 113 Shipboard Scientific Party (Barker, Kennett, et al., 1988), that, by early late Miocene time or even before, the canyon had been cut down to the present shoulder at Site 692, may need revision. This conclusion is based on small sediment chips from the drill cuttings of Sample 113-692B-3R-1, 38–42 cm, at 21.3 mbsf (= 2896.4 mbsl), which indicate an earliest Pliocene to Miocene diatom age. The sediment chips were recovered from above a cobble layer and were considered to have been in place. This assumption, which is questioned here, would assign an early late Miocene or older age for the development of the cobble layer as also for Phase I of the canyon-cutting process. A much younger, post Miocene age is favored here which, however, is only poorly supported by unambiguous observations.

Patterns from sub-bottom profiling at 3.5 kHz at Site 692 show a strong bottom reflector underlain by a thin layered sequence, but with poor penetration below that from about 10–20 mbsf where irregular echo characters occur. It is more likely that the upper 50 m drilled at Site 692 represent a poorly stratified lag deposit of cobbles, boulders, and various allochthonous components, including Miocene and Pliocene sediments, from rock fall further upslope. The *in situ* Miocene-Pliocene transition was penetrated at Site 693 at about 185 mbsf which corresponds to 2545 mbsl. This is 380 m above the base of the Miocene-Pliocene diatom dated lag deposit which was drilled at Site 692 at about 50 mbsf or 2925 mbsl respectively. If this is in place it would mean that the post Miocene sediment sequence (nearly 200 m in thickness at Site 693) was accumulated on a morphologically rugged canyon-cut surface. From high resolution seismics and sub-bottom profiling no indication can be derived to support this.

CONCLUSIONS

The bathymetric investigation of the Wegener Canyon system at the eastern Weddell Sea continental margin off Kapp Norvegia reveals a remarkable subdivision into two morphologically distinct regions.

1. Oceanward is a deeply incised canyon, steep-walled, and U-shaped in cross-section, cutting through the Explora Escarpment and continuing into the lower mid-slope bench. The steep canyon walls show distinct cliff-like scarps comprising outcrops of sedimentary strata of probably Late Jurassic to Early Cretaceous age.
2. On the mid-slope the canyon system branches abruptly into several less deeply incised distributary gullies, distinctly V-shaped in cross-section and extending into the upper slope.

The formation of Wegener Canyon, in its overall pattern, is structurally controlled by the sill of the Explora Escarpment. It is assumed to have developed predominantly as a result of erosion by turbidity currents coupled to the cycles of sediment supply arising from glacial activity. From the thalweg gradient two phases of canyon erosion can be differentiated, the timing of which is presently pure speculation. A post-Miocene age is considered as most likely.

The sediments cropping out in the three cliff-like scarps along the steep slopes of Wegener Canyon were sampled by dredging and are correlated with the sedimentary sequences drilled at ODP Sites 691–693 and tied to the existing seismic stratigraphy.

Coarse-grained, impure volcaniclastic sandstones and fine-sandy siltstones of probable Late Jurassic age were recovered from the lower scarp at 3900–4100 mbsl.

Homogeneous and finely layered mudstones, impure siltstones with abundant mollusk shells and poorly consolidated sandstones were recovered from the uppermost Jurassic to lowermost Cretaceous strata of the middle scarp at 3300–3100 mbsl.

Homogeneous claystones and bedded or finely laminated sandy siltstones were dredged from the upper scarp at 2750–2950 mbsl. Horizons cropping out here can be correlated with Valanginian to Aptian organic carbon-rich sediments recovered from the base of ODP Holes 692B and 693A.

The portion of volcaniclastic sediment components, clearly dominating the Late Jurassic sediments near the canyon base, decreases up the sequence indicating a decrease in magmatic activity toward the Early Cretaceous.

Although only preliminary results are currently available from sediment descriptions made on board *Polarstern,* it is evident that analyses of dredged samples from deposits older than those drilled at ODP Sites 692 and 693 will provide further information concerning the depositional environment of the opening Weddell Sea during Late Jurassic and Early Cretaceous time.

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