OCEAN DRILLING PROGRAM

LEG 104 SCIENTIFIC PROSPECTUS

NORWEGIAN SEA

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INTRODUCTION

Leg 104 of the Ocean Drilling Program will drill targets in the Norwegian Sea during July and August 1985. The drillship JOIDES RESOLUTION is scheduled to leave Bremerhaven, FRG on June 25 and to be in the general drilling area after four days of transit. The Leg will end with a port call in Stavanger, Norway on August 11. This timing falls within the operational weather window for the Norwegian Sea, with moderate wind conditions and mean air and sea temperatures between 8-10°C.

The Norwegian Sea has been targeted for drilling during ODP Leg 104 to answer questions relative to the structural and geologic evolution of Voring Plateau, paleoceanography of the Norwegian Current and northern hemisphere glaciation, and evolution of polar floras and faunas, among others. The target drill sites are located on the outer Voring Plateau and in the Voring Basin (Figure 1).

ORIGIN OF DIPPING REFLECTORS

Numerous seismic studies reveal a sequence of seaward-dipping reflectors underlying the margin of the outer Voring Plateau (Figure 2), the tectonic origin of which is disputed. Multichannel seismic records such as that shown in Figure 2 across the outer Voring Plateau reveal an acoustic stratigraphy which can be subdivided into the following units:

1) Seafloor ~2.5 sec.: Horizontally layered sedimentary unit (Unit 1).

2) ~2.5 - up to 4.5 sec.: Arcuate continuous reflectors with seaward dips (Unit 2).

3) Below unit 2: Acoustic basement with homogeneous seismic character and no internal reflectors.

The geologic interpretation of these three units, aided by DSDP drilling results from Leg 38 (Talwani, Udintsev et al., 1976) suggests that Acoustic Unit 1 is composed of primarily hemipelagic siliceous muds. Units 1 and 2 are separated by a strong reflector believed to be a basalt flow such as drilled by Leg 38. As drilling on Leg 38 ended in tholeitic basalts found toward the base of Unit 1, the compositions of Units 2 and 3 remain uncertain. Multichannel seismics and Leg 38 drilling suggest that Unit 2 may consist of interbedded basalts and sediments.

The origin of dipping reflectors on passive margins represents a fundamental question concerning the mechanisms involved during early basin rifting and initiation of seafloor spreading. Dipping reflector sequences have been identified throughout the Norwegian margin from the Faeroes Platform to the Lofoten Islands (Talwani et al., 1982). Hinz (1981) identified similar sequences in numerous passive margins around the world. Dipping reflector sequences are limited to the structural edges of ocean basins, generally under continental rise or lower slope sediments. In addition, they are associated with the oldest mappable magnetic anomalies. Their geologic setting and implied age suggest that the origin of these reflectors is intimately tied to rifting and/or early seafloor spreading events. However, the depositional mechanism that emplaced the material forming these reflectors and the tectonic events that create the observed arcuate geometry are a matter of considerable debate.

Several hypotheses have been advanced to explain the origin and development of dipping reflector sequences. Mutter et al., (1982) proposed that the production of volcanic material during the earliest stages of seafloor spreading is so great that it is possible for the spreading center to build an edifice up to sea level (Figure 3). Having gained a subaerial exposure, lavas erupted at the spreading center flow considerable distances away from the ridge axis. Successive eruptions occur by the intrusion of feeder dikes at the spreading center as the crust moves apart, and successive flows overlay and load existing flows. Bodvarsson and Walker (1964) describe such a scheme for the development of lava sequences in eastern Iceland. As spreading at the exposed eruption center progresses with time, new lavas load the underlying units causing them to subside and rotate toward the site of eruption, as described from Icelandic data by Bodvarsson and Walker (1964) and Palmason (1973, 1980). Cann (1974) proposed models for the formation of normal oceanic crust that incorporate the effects of the volcanic load in this way. After a few million years a structure develops that consists of a set of laterally stacked, seaward dipping lavas. As long as the eruption rate is high and the eruption center remains emergent, this type of structure will continue to develop.

Suites of dipping reflectors are present on the Norwegian margin only beneath the outer Voring Plateau and other regions underlain by the very oldest sea floor in the Norway and Lofoten Basins (Figure 4). Spreading at an exposed eruption center was, therefore, a transient phenomenon affecting the crustal structure only during the first few million years of spreading. After this time the eruption rate must have decreased, the spreading center fell below sea level, and the length of lava outflows erupted at the spreading center decreased abruptly. The normal chaotic structure of the upper parts of the oceanic crust would then develop. Hence, a transition from oceanic crust developed at a subaerial eruption center to crust formed at a submerged spreading center occurred.

An alternate explanation for the dipping sequences has been suggested by Hinz (1981) and is illustrated in Figure 5. He proposed that extension and attenuation of the continental crust is accompanied by the development of linear zones of dike injections from which lavas are extended onto the attenuated crust in a subaerial environment. As eruption continues the weight of lavas results in crustal subsidence. Since the model proposes a localized fissure zone from which the lavas emerge at the surface, the regions closest to the fissure acquire the largest build-up of lavas (as occurs in a central volcano). These regions are more heavily loaded and hence are depressed by a greater amount. Therefore, lavas acquire dips toward the fissure zone much as described by Mutter et al., (1982). The fissure zone then becomes the site at which new oceanic crust first forms, splitting the pile of subaerially erupted lavas centrally, leaving one half on each of the continental margins. The dips on these lavas, acquired by loading of the volcanic pile onto the attentuated continental crust, will occur in a seaward direction, i.e., toward the spreading center.

Smythe (1983) has put forward a third model for the dipping reflectors that attributes them to subaerial seafloor spreading like Mutter et al., (1982). The principal difference between Smythe and Mutter is that Smythe considers the oldest (most landward) of the dipping sequences to have flowed over continental crust. The continent-ocean boundary occurs at the lower (most seaward) end of the oldest of the dipping sequences.

These three hypotheses concur regarding the loading mechanism leading to the deformed, arcuate pattern seen in seismic profiles. Similarly, all three suggest a subaerial extrusion of lavas. The primary differences are in the nature of basement underlying the dipping reflectors and the association of their emplacement to rifting or seafloor spreading.

Hinz (1981) pointed out a particularly interesting correlation. He noted that on margins where dipping reflector suites can be recognized, there is no evidence for extensional faulting occurring in the adjacent margin basin near the time of the initiation of spreading. The converse observation seems also to be true; that margins exhibiting extensional faulting lack evidence of dipping reflector suites. It is, therefore, possible that the structure represented by the dipping reflectors forms at margins that do not experience a major extensional episode prior to the initiation of spreading. They may be characteristic of a "nonextensional" end member of passive margin evolutionary types.

None of the drilling results to date have reached the base of the dipping reflectors, and none have sampled the reflectors sufficiently to characterize their spatial and temporal lithologic changes, their physical properties, or geochemistry. Our present knowledge is inadequate even to determine what gives rise to the reflecting interfaces themselves, much less the origin of the structure as a whole.

Drilling at target sites VOR 2A and 2B (alternates are VOR 3A, VOR 3B, and VOR 1) is planned to answer many of the questions surrounding the origin and nature of the dipping reflectors and the evolution of these types of passive margins. Sites VOR 2A and 2B are situated in approximately 1300 meters of water, on the outer Voring Plateau slope (Figures 1 and 2). Penetration at Site VOR 2A is expected to recover Cenozoic sediments to approximately 430 meters sub-bottom, and then to sample the dipping reflector sequence to about 1000 meters sub-bottom. The sedimentary section at this site will be double HPC cored for proper sampling, and the entire sequence will be logged. Site VOR 2B will penetrate roughly the same lithology; however, full penetration to 1000 meters sub-bottom is expected to sample Horizon K, a major reflector believed to be marking the base of the reflector sequence. The total time for these sites depends a great deal on the drilling conditions and lithologies encountered. The range of estimated times on each site is listed on the site occupation schedule.

NORWEGIAN SEA PALEOCEANOGRAPHY

Another major topic that will be addressed by Leg 104 drilling concerns the paleoceanographic history of the Norwegian-Greenland Sea. Studies from this area will yield important climatic and oceanic information for the northern subpolar environment.

At present the water masses of the Indian and Pacific Oceans have virtually no exchange with the northern polar region but are wide open to the Southern Ocean. It is only through the Atlantic Ocean and the Norwegian-Greenland Sea that the cold realms of the northern and southern hemispheres are allowed to exchange surface and deep water masses. This fact has important consequences for global oceanography, both for deep and shallow hydrography and circulation patterns.

This area, however, has a relatively short geological history; it evolved only over the past 55-60 my when the Norwegian-Greenland Sea began to open (Talwani and Eldholm, 1977). True deep-water passages developed even later; about 36 m.y.b.p. in the area of the Fram Strait and only during late Miocene or Pliocene times in the region of the Greenland-Scotland Ridge (Eldholm and Thiede, 1980; Thiede and Eldholm, 1983). Since that time the North Atlantic temperate waters flow northward, most probably as a relatively warm current along the NW European continental margin; cool to cold waters from the Arctic Ocean flow southward following the East Greenland continental margin (Figure 6).

Based on studies of Quaternary sediments the entire current regime is assumed to have disappeared during glacial times. This disappearance probably resulted from the movement of the northern polar front southward to latitudes between northern North America and southwestern Europe. As such, this is the oceanic area of the most extreme climatic changes during the Quaternary (CLIMAP, 1976). The modern temperate NW European climate depends strongly upon the existence of the warm water influx into the Norwegian-Greenland Sea. A detailed understanding of the impact and history of the North Atlantic Drift and of the Norwegian Current is of high interest.

Another paleoceanographic and climatic topic of interest is the assumed early and middle Cenozoic climatic asymmetry between the southern and northern hemispheres. In the southern hemisphere, a glacial-type climate started approximately 40 m.y.b.p. whereas in the northern hemisphere a glacial influence can be documented only for the past 2.4 my (maybe for the past 5-6 my). It is important to discover whether this apparent asymmetry is real or if it represents an artifact of the presently available sample material.

Since Early Tertiary times the polar oceanic water masses of both hemispheres have cooled from about 10-15^{o}C to near 0^{o}C. Marine faunas and floras had to adapt and evolve under the influences of the changing hydrography and climate of the polar realms. In both polar ocean regions biocoenoses have evolved which are specialized to live under very cold conditions. Northern and southern hemisphere polar marine faunas and floras display characteristic similarities (e.g. in their plankton), but also typical differences (e.g. in the type of end member of the marine food webs). Studies of the evolution of these polar oceanic floras and faunas will be included in the paleoceanographic objectives of ODP Leg 104.

The Norwegian-Greenland Sea is surrounded by passive margins. Worldwide, they probably represent the best surveyed subpolar to polar continental margins. From recent investigations it is well known that major aspects of sediment distribution and morphology of these margins are controlled by giant slumping and mass wasting which have occurred despite morphologically shallow gradients over many margin segments. High sedimentation rates and lithology probably play key roles in these processes. The physical properties of the very fine-grained, dominantly terrigenous sediments covering these margins are not well known, but have probably contributed considerably to the potential of these margins for slumping. A detailed physical properties program combined with sedimentologic studies will identify events of mass wasting and characterize the features associated to such occurrences.

Other problems that will be addressed by drilling in the Norwegian Sea include subsidence history related to glacial events, dating of erosional pulses of the Norwegian Caledonides (believed to have occurred primarily during the Tertiary), and the sedimentology of polar to sub-polar climates.

The second and third priority drilling targets for ODP Leg 104 should provide answers to the paleoceanographic questions regarding the Norwegian-Greenland Sea. The operational plan is to form a transect of sites, VOR 2A-2B, VOR 4 and VOR 5, across the Voring Plateau and into the Voring Basin (Figure 1). The principal drilling objective of VOR 4 and 5 is to sample the Cenozoic sedimentary section. The seismic sections showing the location of the targeted sites are presented in Figures 7 and 8. The transect of sedimentary sections obtained at sites VOR 2A-2B, 4 and 5 will yield paleontologic, sedimentary, geochemical, physical properties and magnetic studies from areas in different water depths and at a variable distance from shore.

SPECIAL EXPERIMENTS

Two sites, probably VOR 2A and 2B, will be used for vertical seismic profile (VSP) experiments. The tests will require approximately one full day after drilling and logging have been completed at the site. A hydrophone tool will be lowered down the drillstring and raised in 10-15 meter increments while shot to from the surface. The resulting seismic information should provide a valuable tie between drilling, logging, and regional seismic survey results.

LEG 104 OCEAN DRILLING PROGRAM

Norwegian Sea

Location of Proposed Sites

Site Number	Latitude	Longitude	Water Depth	Max. Penetr.	Operations	Objectives
VOR 2A	67°15.6'N	02°55.2'E	1335m	1000m	HPC/reentry Logging	Sample a type section of dipping reflectors and its base; sediment paleoenvironment.
VOR 2B	67°10.2'N	02°58.8'E	1265m	1000m	HPC/reentry Logging	Sample basement and Horizon "K" underlying the landward part of dipping reflectors; paleoenvironment.
VOR 4	67°42.6'N	01°03.6'E	2700m	1100m	HPC or single bit Logging	Sample sedimentary section for Cenozoic paleoenvironment of Norwegian Sea.
VOR 5	66°40.2'N	04°34.2'E	1200m	200m	HPC	Sample young Cenozoic sedimentary section for Norwegian Sea paleoenvironment.
VOR 1*	67°13.2'N	02°57.0'E	1305m	1250m	HPC/reentry Logging	Sample a type section of dipping reflectors and its base; sediment paleoenvironment.
VOR 3A*	68°12.6'N	03°17.4'E	1615m	1300m	HPC/reentry Logging	Sample a type section of dipping reflectors; sediment paleoenviron.
VOR 3B*	67°54.0'N	03°13.2'E	1350m	500m	HPC/reentry Logging	Sample base of dipping reflectors, Horizon "K" and paleoenvironment.

* Alternate sites.

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SITE OCCUPATION SCHEDULE

Site	Location	Travel Time (Days)	Drilling Time (Days)[1] Min.	Max.	Departure Date (Approximate)
	Depart: Bremerhaven				25 June 1985
	Underway	3.8			
VOR 2A[2]	67°15.6'N 02°55.2'E		22	24	21 July 1985
VOR 2B[2]	67°10.2'N 02°58.8E		19	25	8-9 August 1985
VOR 4[3]	67°42.6'N 01°03.6'E		5	11	9 August 1985
VOR 5	66°40.2'N 04°34.2'E		1		9 August 1985
	Underway	1.8			
	Arrive: Stavanger				11 August 1985
		5.6	41.4		47 days
Alternate Sites:					
VOR 1	67°13.2'N 02°57.0'E		33		
VOR 3A	68°12.6'N 03°17.4'E		22		
VOR 3B	67°54.0'N 03°13.2'E		5.5-11[4]		

[1]Minimum and maximum estimated times are shown since drilling progess will be defined by lithologies encountered.

[2]One day for VSP experiments added to each site.

[3]Minimum and maximum times shown reflect the difference in coring with HPC or single-bit to refusal.

[4]Estimates vary depending on single-bit or multiple re-entry option.

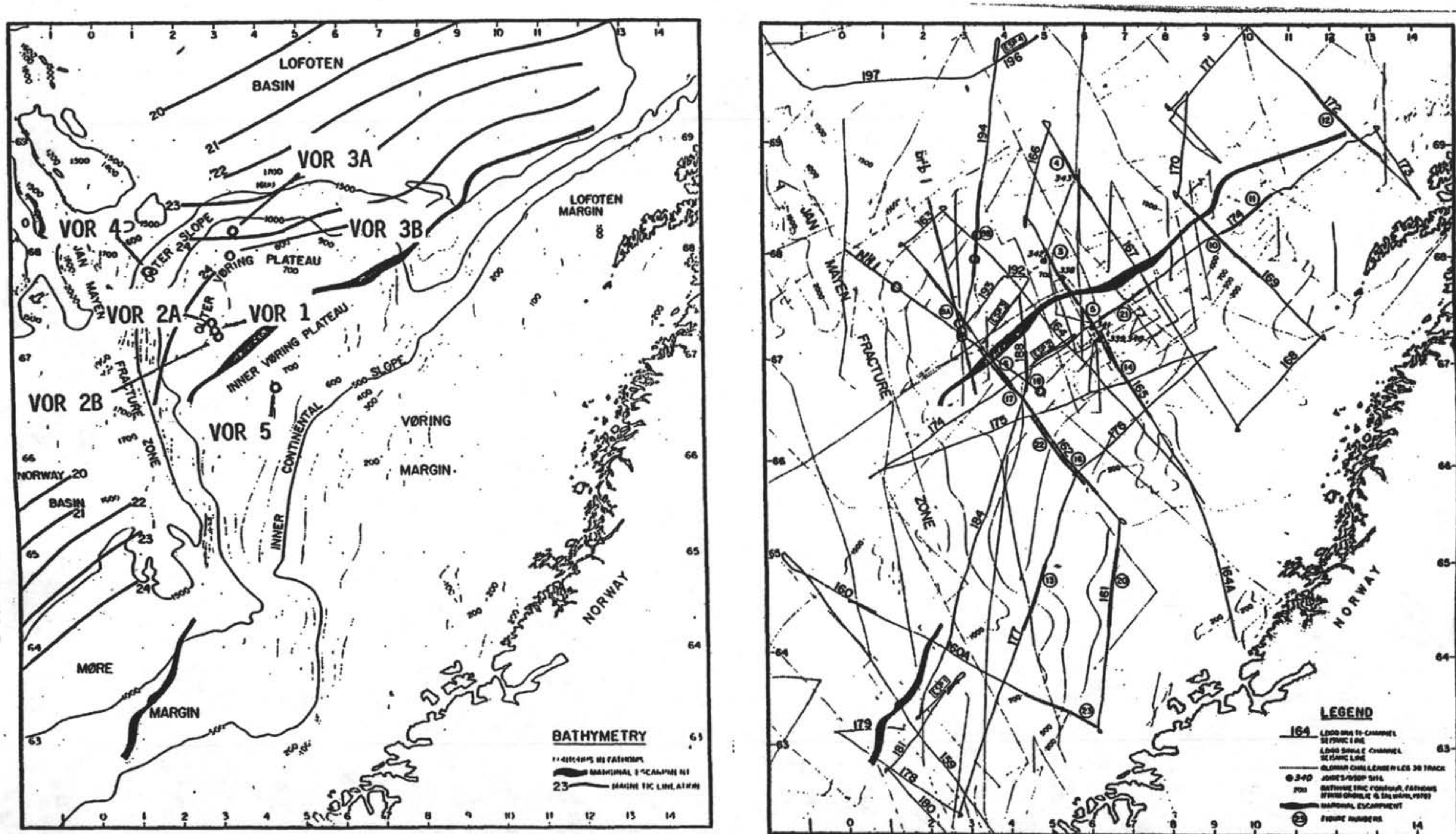

FIGURE 1. Bathymetry (left) and location of seismic profile lines (right) of the Norwegian margin between 60°N and 70°N. Both maps show locations of targeted ODP Leg 104 drill sites (map from Mutter et al., 1983).

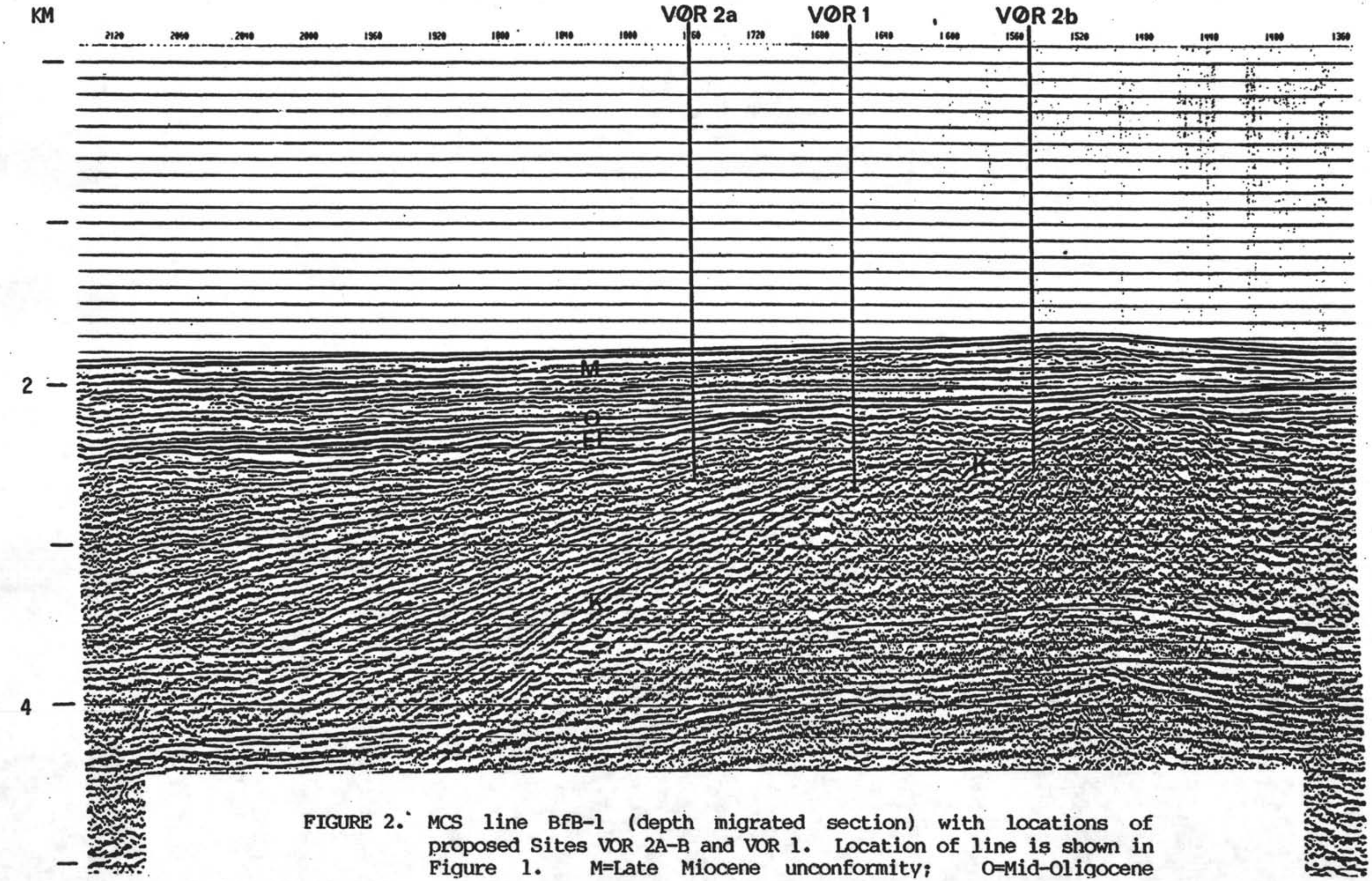

FIGURE 2. MCS line BfB-1 (depth migrated section) with locations of proposed Sites VOR 2A-B and VOR 1. Location of line is shown in Figure 1. M=Late Miocene unconformity; O=Mid-Oligocene

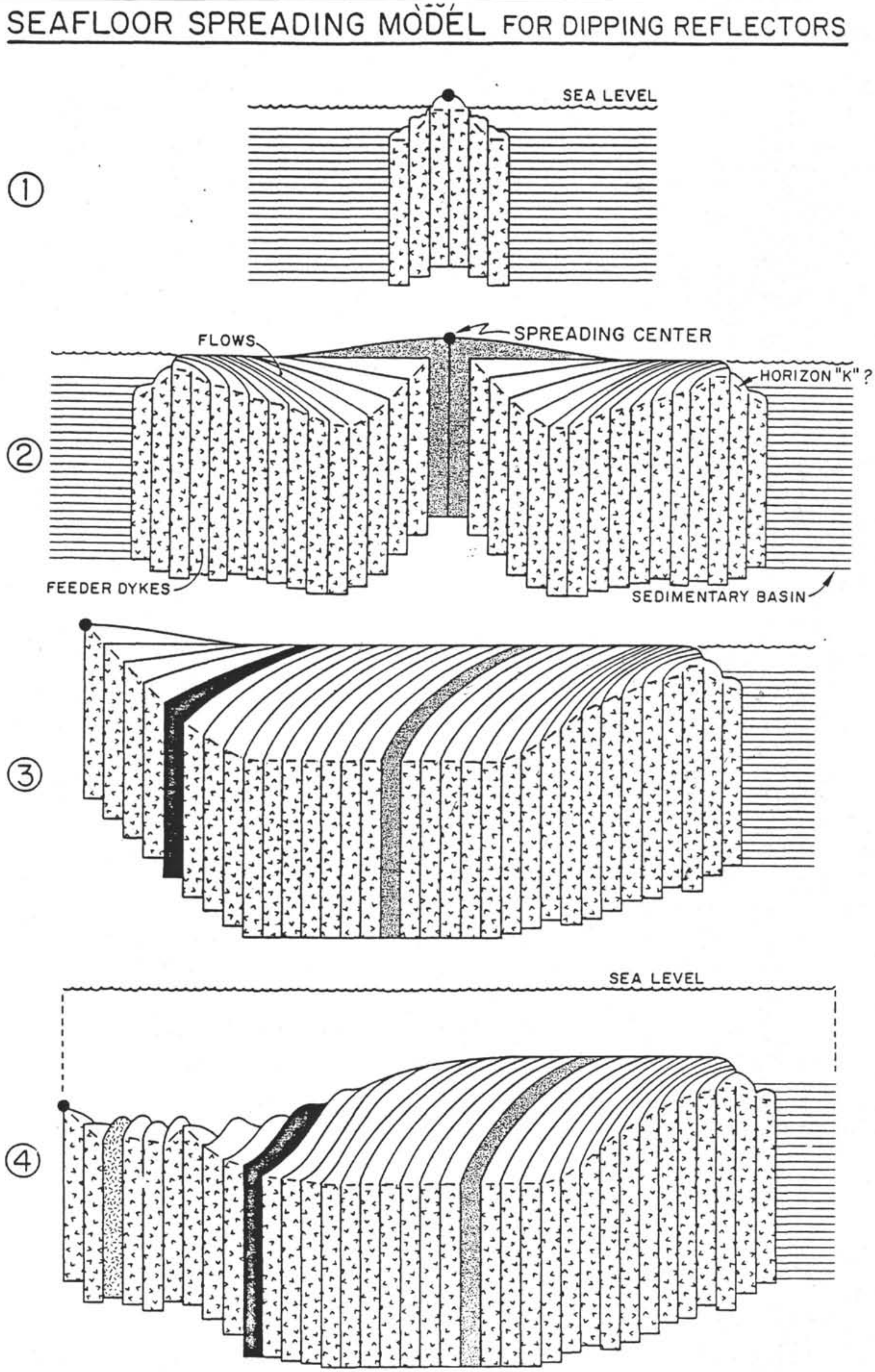

FIGURE 3. Mutter et al. (1982) model of formation of dipping reflector sequences.

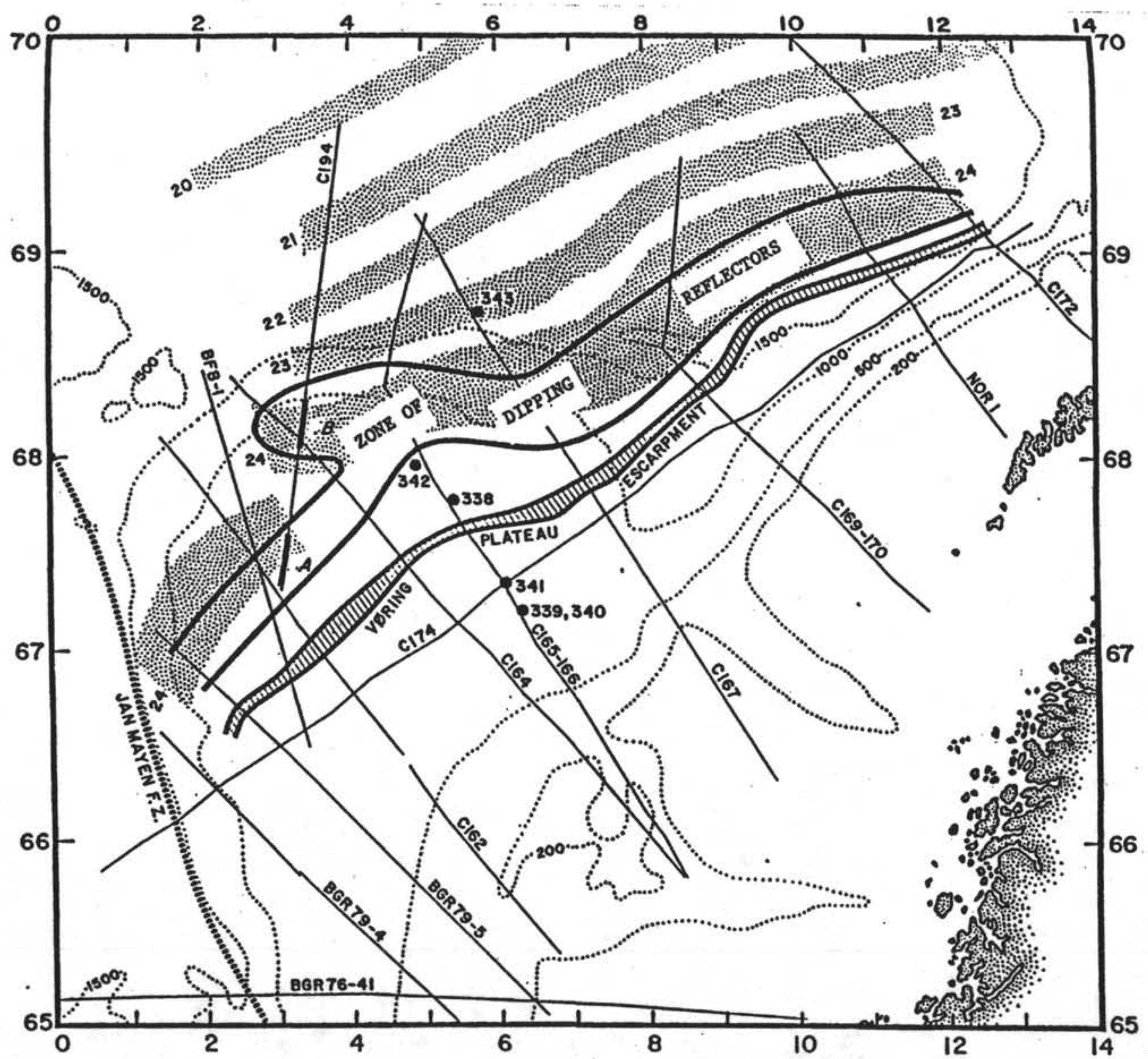

FIGURE 4. Location of magnetic anomaly patterns with respect to the region of dipping reflector sequences on the Norwegian margin (from Mutter et al., 1982).

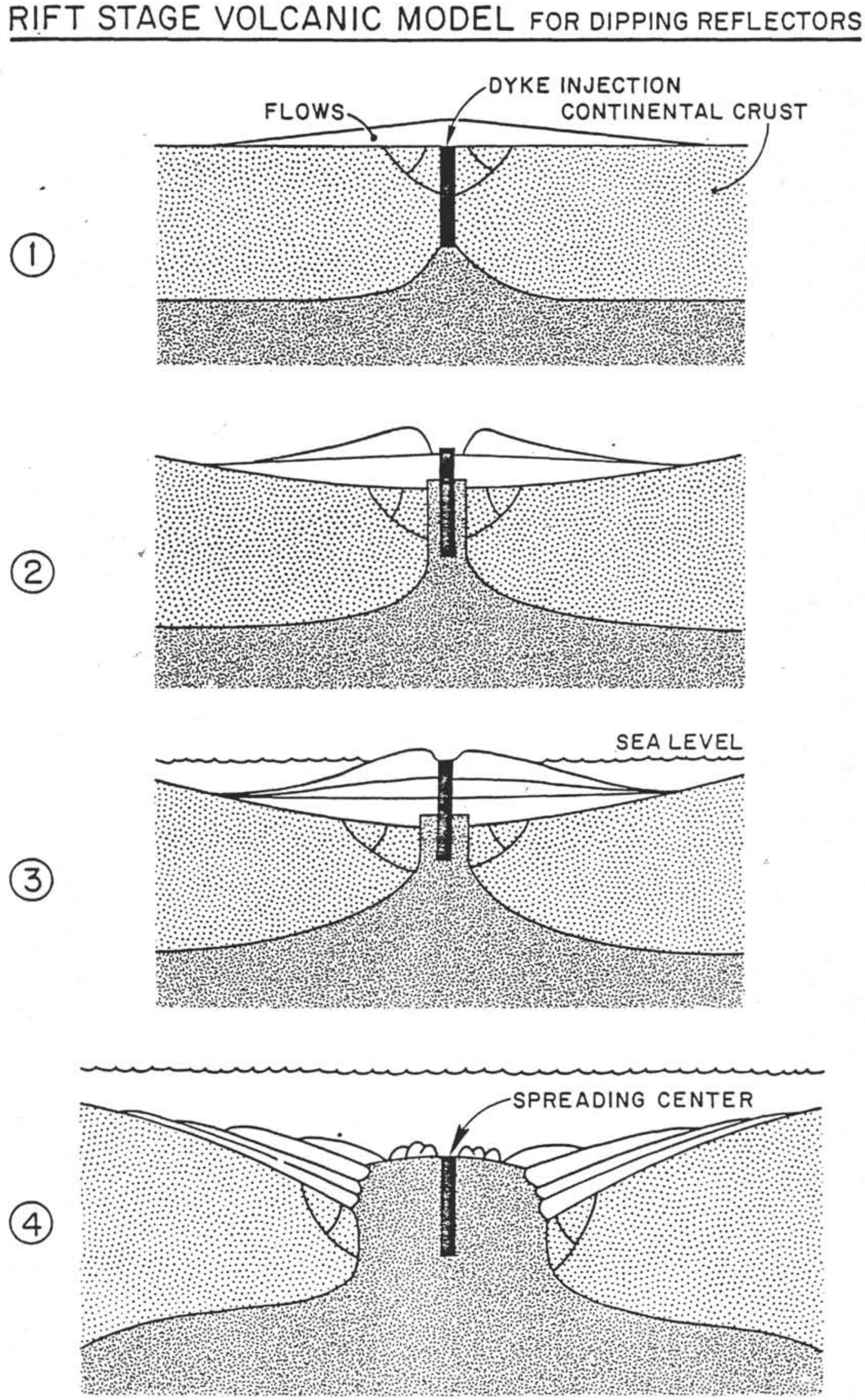

FIGURE 5. Hinz (1981) model of formation of dipping reflector sequences.

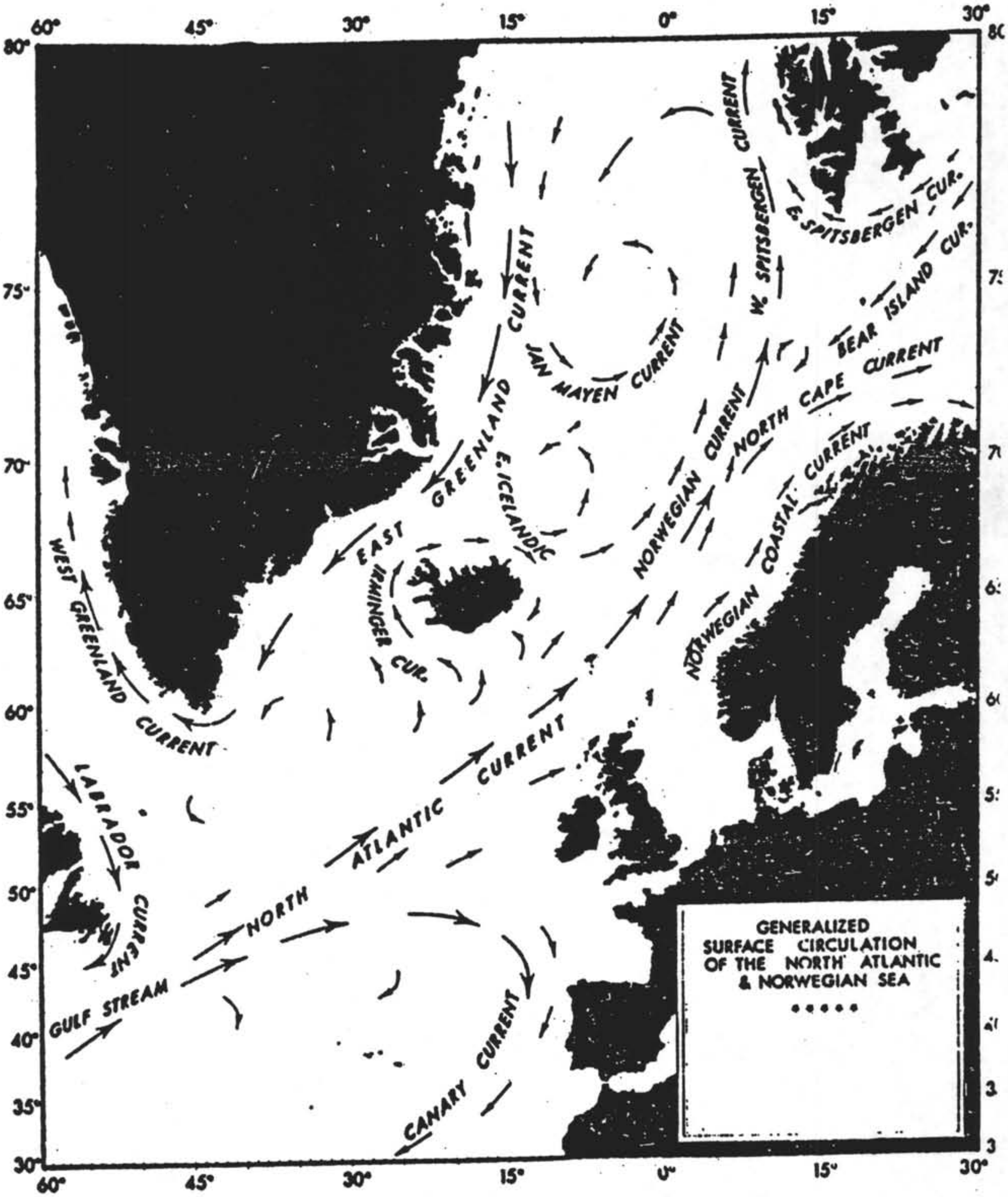

FIGURE 6. Present-day surface current patterns in the North Atlantic and Norwegian Sea (from Kellogg, 1975).

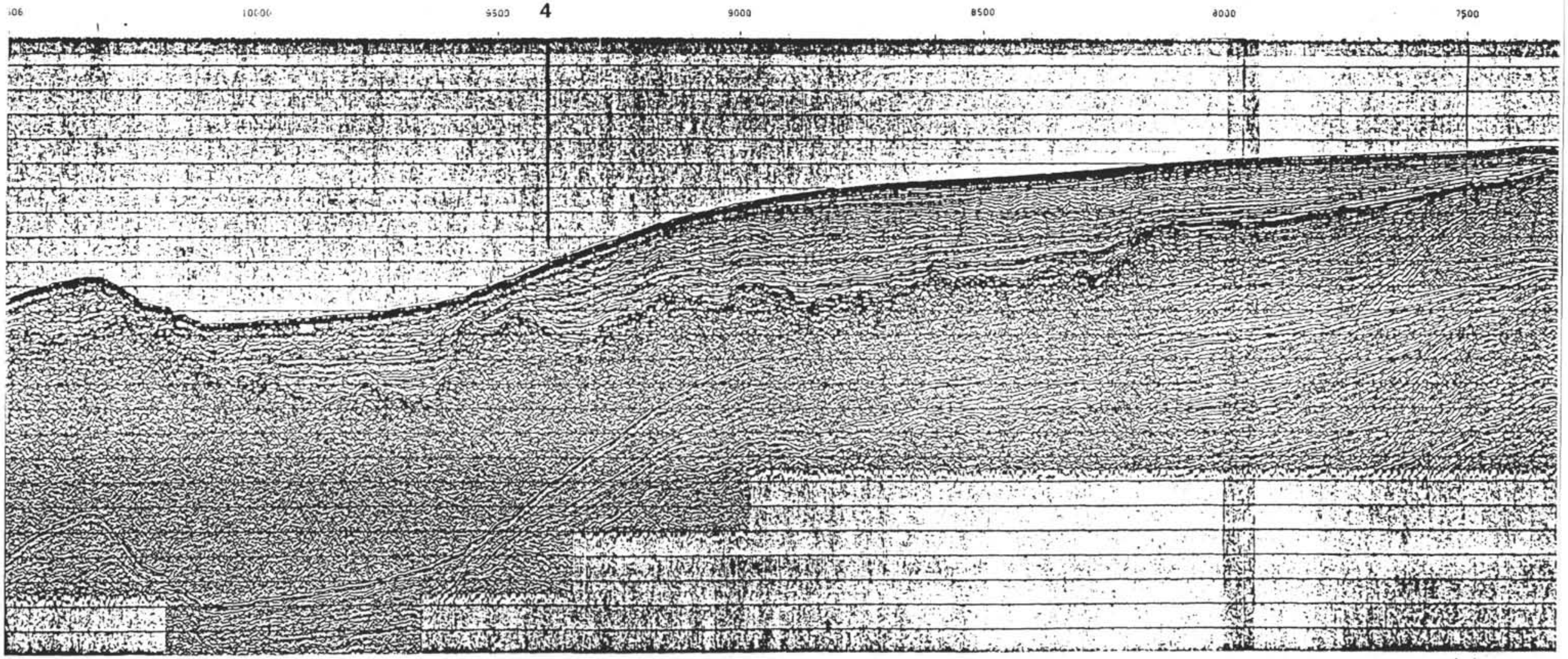

FIGURE 7. MCS line NH-1 with location of proposed Site VOR 4. Location of line is shown in Figure 1.

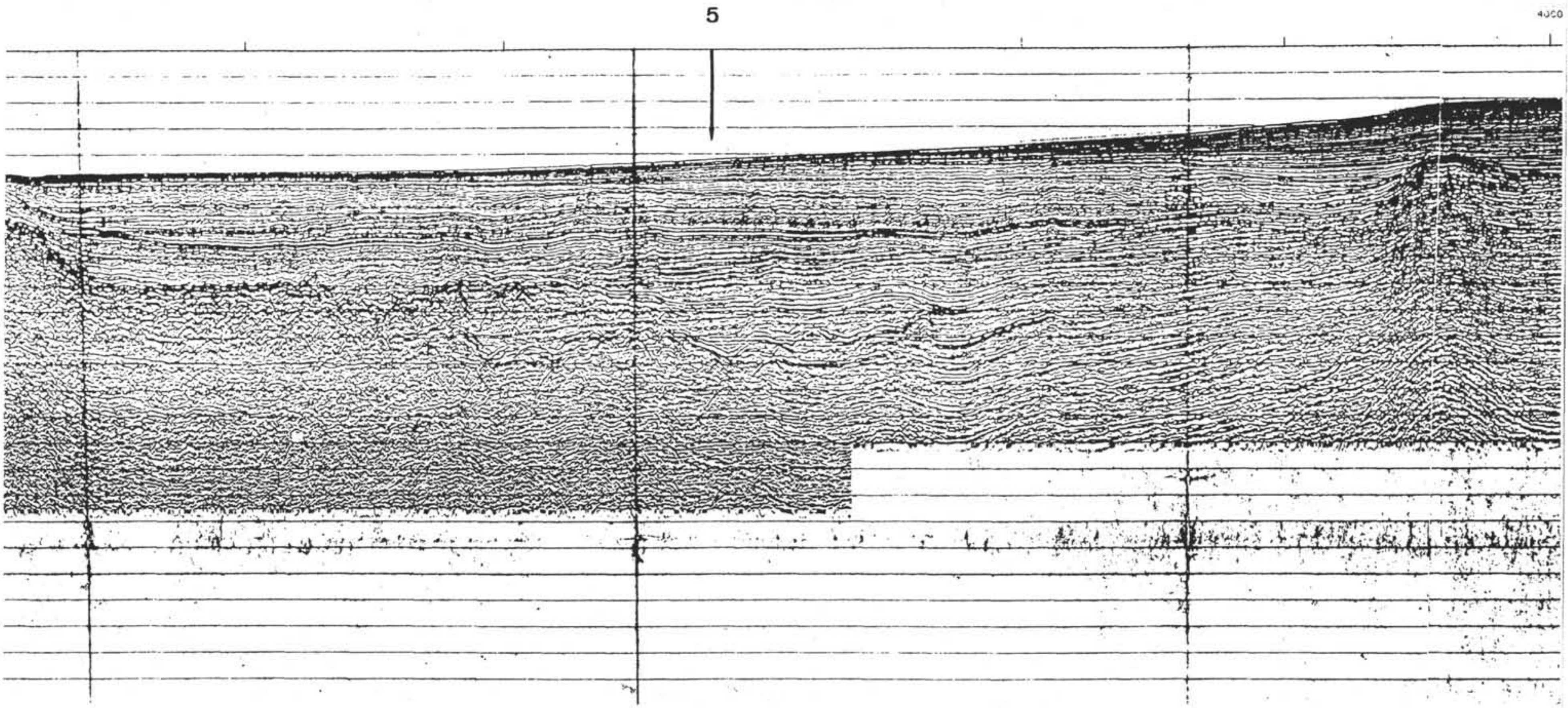

FIGURE 8. MCS line NH-1 with location of proposed Site VOR 5. Location of line is shown in Figure 1.

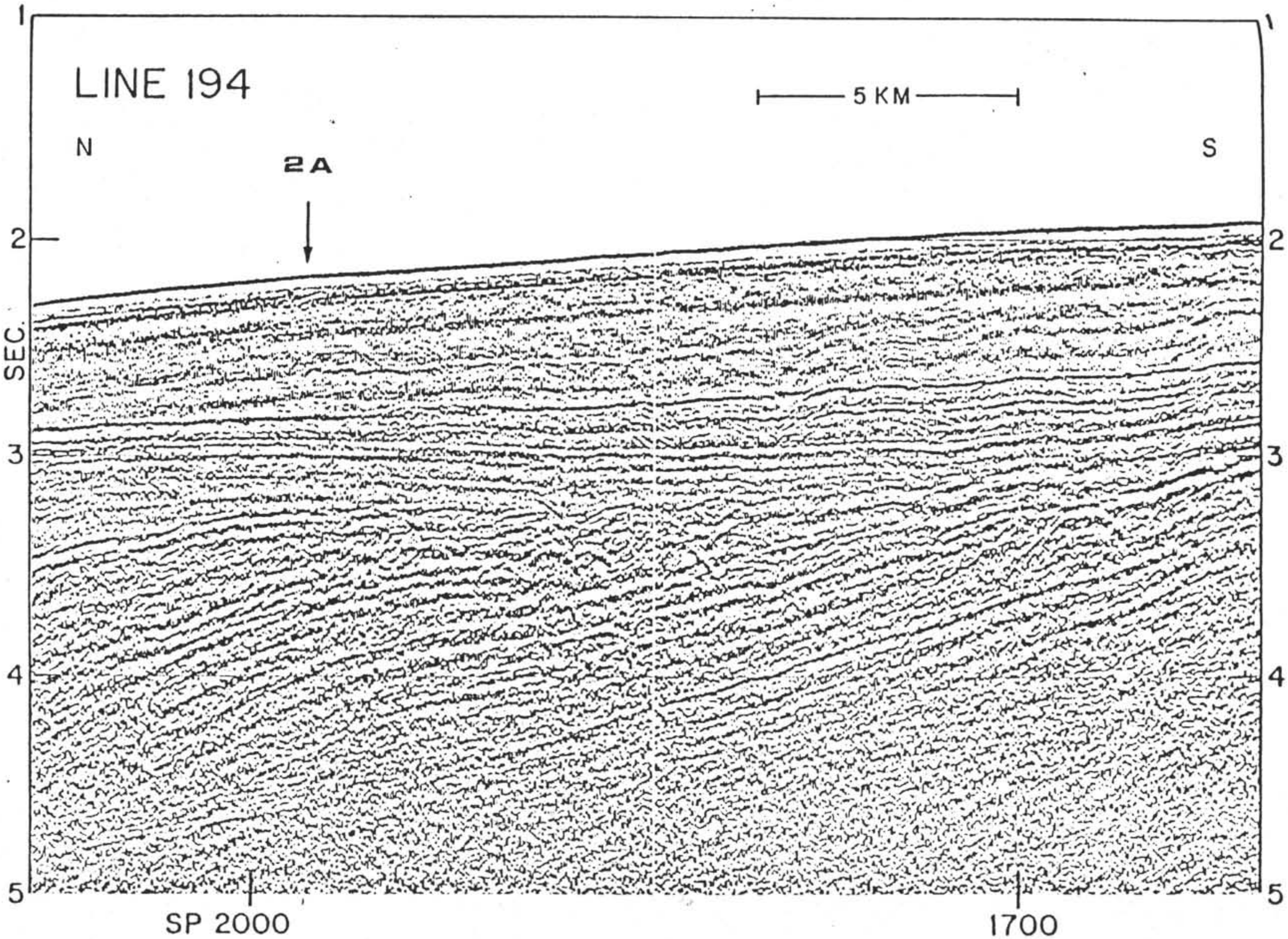

FIGURE 9. Detailed profile of proposed Site VOR 2A (MCS line BfB-1 time section).

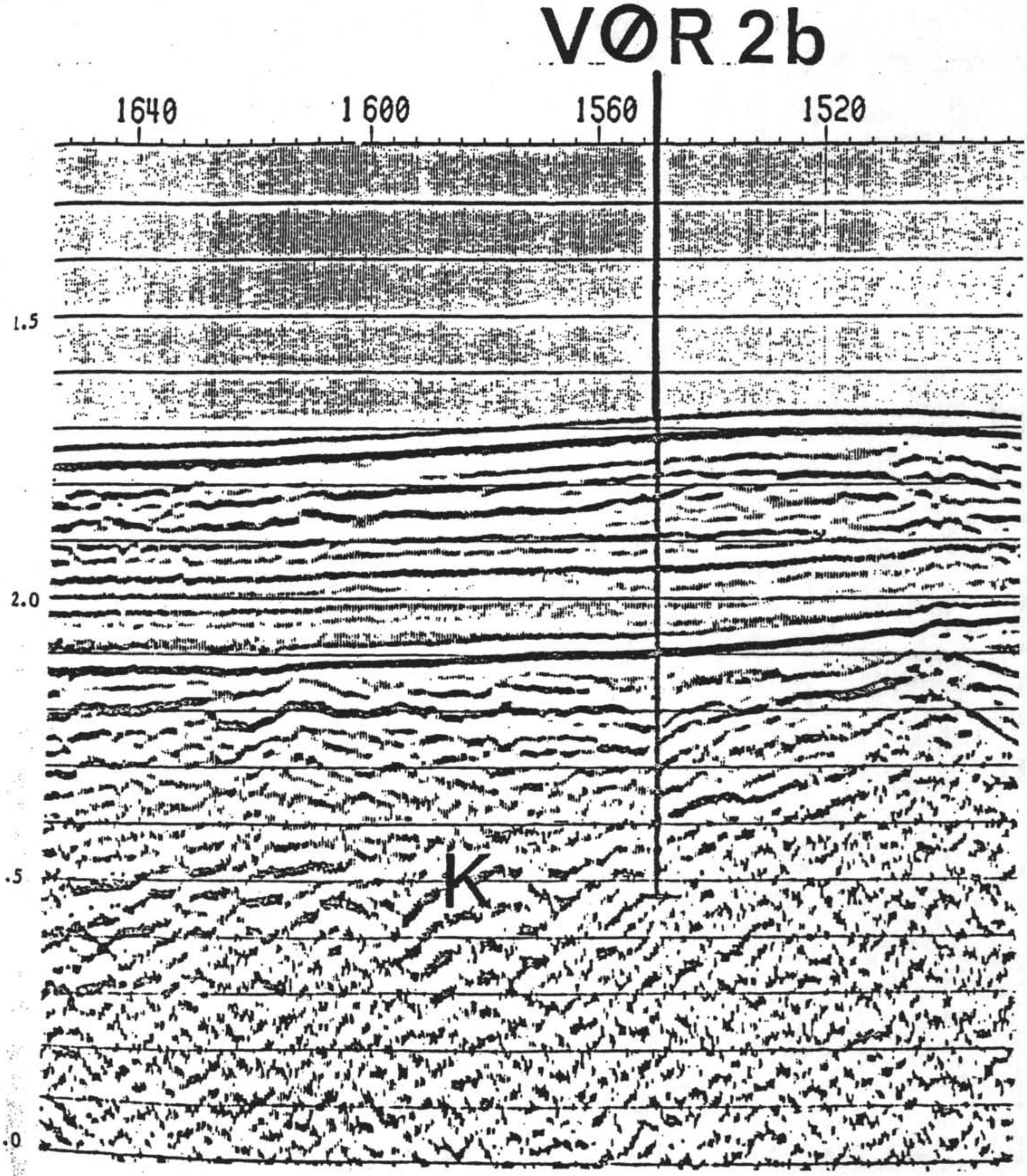

FIGURE 10. Detailed profile of proposed Site VOR 2B (MCS line BfB-1 time section).

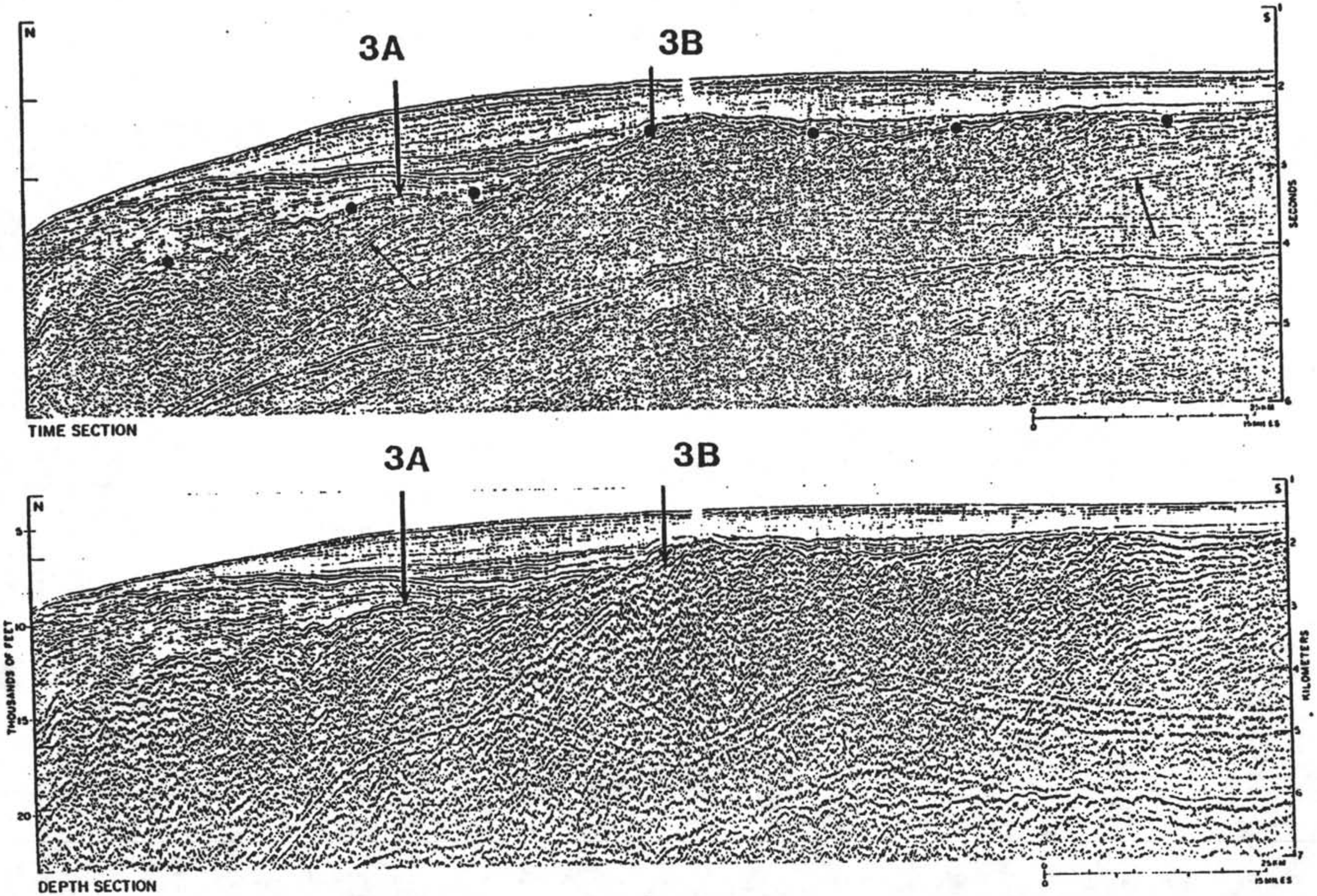

FIGURE 11. MCS line C-194 with locations of proposed alternate Sites VOR 3A

SITE NUMBER: VOR 2A (Outer Voring Plateau)

POSITION: $67^{o}15.6'N$ $02^{o}55.2'E$ **SEDIMENT THICKNESS:** 430m

WATER DEPTH: 1335m **PRIORITY:** 1

PROPOSED DRILLING PROGRAM:

HPC/reentry: 430m of sediment, 570m of "basement."

SEISMIC RECORD: BfB-1, S.P. 1760.

HEAT FLOW: yes

LOGGING: yes

VERTICAL SEISMIC PROFILING: yes

OBJECTIVES:

1) Sample a type section of dipping reflectors sequence and establish relative stratigraphic positions of the various lithologies;

2) Test models for origin of dipping reflector sequence: (a) subsided and rotated stack of subaerial lavas that formed from a zone of oceanic injection dikes; (b) subsided stack of subaerial lavas formed at a localized fissure in extended, attenuated continental crust; (c) subsided and rotated stack of subaerial lavas formed first on continental crust and continuing onto oceanic crust;

3) Determine paleomagnetic sequence of volcanic pulses;

4) Characterize physical properties and geochemistry of lithologies involved in the sequence;

5) Obtain and document paleocirculation of Norwegian current;

6) Document the history of Glacials and Interglacials;

7) Determine the isostatic movements of the Norwegian continental margin during Neogene glaciations; and

8) Document the erosional episodes of the Paleozoic Norwegian Caledonides.

SEDIMENT TYPE:

0-430m: Calcareous and diatomaceous oozes with sands and ice-rafted debris.

430-1000: Intercalated Paleogene sediments, flood basalts and pyroclastic sediments, igneous rocks and/or Mesozoic-Paleozoic rocks.

SITE NUMBER: VOR 2B (Outer Voring Plateau)

POSITION: 67°10.2'N 02°58.8'E SEDIMENT THICKNESS: 450m

WATER DEPTH: 1265m PRIORITY: 1

PROPOSED DRILLING PROGRAM:

HPC/reentry: 450m of sediment, 550m of "basement."

SEISMIC RECORD: BfB-1; S.P. 1550.

HEAT FLOW: no

LOGGING: yes

VERTICAL SEISMIC PROFILING: yes

OBJECTIVES:

Same as for VOR 2A; however, the primary target is Horizon K, the base of the reflectors.

SEDIMENT TYPE:

Same as for VOR 2A.

SITE NUMBER: VOR 4 (Outer Voring Plateau)

POSITION: 67°42.6'N 01°03.6'E SEDIMENT THICKNESS: 1100m

WATER DEPTH: 2700m PRIORITY: 2

PROPOSED DRILLING PROGRAM:

HPC/XCB to refusal or single bit to 1100m.

SEISMIC RECORD: NH-1, S.P. 9400.

HEAT FLOW: no

LOGGING: yes

VERTICAL SEISMIC PROFILING: no

OBJECTIVES:

1) Sample Cenozoic (Quaternary to Eocene or older) sedimentary section;

2) Investigate paleontologic variations reflecting changes of the Norwegian Current and northern hemisphere sub-polar paleoceanography;

3) Document influxes of ice-rafted debris and their petrology;

4) Determine the physical properties of polar to sub-polar sediments and their relationship to widespread mass wasting or slumping;

5) Study the evolution of polar oceanic floras and faunas of the last 40-50 my;

6) Describe the sedimentary facies relationship to polar climate;

7) Define vertical movements along this margin related to isostatic adjustments of glacial events and loading; and

8) Obtain material reflecting erosional episodes of the Norwegian Caledonides.

SEDIMENT TYPE:

Hemipelagic and siliceous deposits. Ice-rafted debris in the upper section. Sediments should range from Recent to Eocene.

SITE NUMBER: VOR 5 (Voring Basin)

POSITION: 66°40.2'N 04°34.2'E **SEDIMENT THICKNESS:** 3000m

WATER DEPTH: 1200m **PRIORITY:** 3

PROPOSED DRILLING PROGRAM:

HPC to 200m.

SEISMIC RECORD: NH-1, S.P. 5600.

HEAT FLOW: no

LOGGING: no

VERTICAL SEISMIC PROFILING: no

OBJECTIVES:

Same as VOR 4; penetration of young Cenozoic section.

SEDIMENT TYPE:

Hemipelagic and siliceous deposits. Ice-rafted debris in the upper section. Sediments should range from Recent to mid-Oligocene.

SITE NUMBER: VOR 1 (Outer Voring Plateau)

POSITION: $67^{o}13.2'N$ $02^{o}57.0'E$ SEDIMENT THICKNESS: 390m

WATER DEPTH: 1305m PRIORITY: (Alternate)

PROPOSED DRILLING PROGRAM:

HPC/reentry: 390m of sediment, 860m of "basement."

SEISMIC RECORD: BfB-1, S.P. 1660.

HEAT FLOW: no

LOGGING: yes

VERTICAL SEISMIC PROFILING: yes

OBJECTIVES:

Same as VOR 2A-2B.

SEDIMENT TYPE:

0-400m: Calcareous and diatomaceous oozes with sands and ice-rafted debris.

400-1250m: Intercalated Paleogene sediments, flood basalts and pyroclastic sediments, igneous rocks and/or Mesozoic-Paleozoic rocks

SITE NUMBER: VOR 3A (Outer Voring Plateau)

POSITION: 68°12.6'N 03°17.4'E SEDIMENT THICKNESS: 900m

WATER DEPTH: 1615m PRIORITY: (Alternate)

PROPOSED DRILLING PROGRAM:

HPC/reentry: 900m of sediment, 400m of "basement."

SEISMIC RECORD: C-194, S.P. 1980.

HEAT FLOW: no

LOGGING: yes

OBJECTIVES:

Same as for VOR 2A-2B.

SEDIMENT TYPE:

Same as for VOR 2A-2B.

SITE NUMBER: VOR 3B (Outer Voring Plateau)

POSITION: 67°54.0'N 03°13.2'E

SEDIMENT THICKNESS: 300m

WATER DEPTH: 1350m

PRIORITY: 2

PROPOSED DRILLING PROGRAM:

HPC/reentry: 300m of sediment, 200m of "basement."

SEISMIC RECORD: C-194, S.P. 1320.

HEAT FLOW: no

LOGGING: yes

OBJECTIVES:

Same as for VOR 2A-2B.

SEDIMENT TYPE:

Same as for VOR 2A-2B.

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