

# 1. THE NORWEGIAN CONTINENTAL MARGIN: TECTONIC, VOLCANIC, AND PALEOENVIRONMENTAL FRAMEWORK<sup>1</sup>

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## INTRODUCTION

A major goal of both the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP) has been to elucidate the temporal and spatial geologic history of the birth of an ocean. This fundamental objective can only be seriously addressed by sampling the sedimentary and underlying basement rocks at the passive continental margin. Rock samples shed light and place constraints on models of the geodynamic processes acting during the important phase of transition from continental rifting to continental drifting. However, most of the world's passive margins are Mesozoic in age and covered by thick sedimentary sequences requiring deep drilling to reach basement. Drilling of this kind has generally been unattainable with the technology available during DSDP and the initial phase of ODP.

During the last 20 yr the Norwegian–Greenland Sea (Fig. 1) has been surveyed extensively; in particular, a large number of high-quality seismic profiles cover the eastern continental margin. The investigations have proven that the ocean is an excellent laboratory to study a number geological events associated with the creation and evolution of an ocean basin. Because it is a relatively young ocean, about 57 Ma, the sediment thickness at the outer margin is locally quite small. Thus, basement drilling is achievable using a vessel like *JOIDES Resolution*. This was demonstrated on ODP Leg 104 when we drilled a characteristic segment of the Norwegian continental margin at the Vøring Plateau in the summer of 1985.

A particularly important observation in the seismic records is the existence of buried structural highs along regions of the outer margins in the Norwegian–Greenland Sea (Fig. 1). These features are often locally underlain by sequences of seaward-dipping reflectors also described along many other passive margins (Hinz, 1981). It is generally accepted that the marginal highs are related to the initial formation of the Norwegian–Greenland Sea during the early Eocene; however, a number of diverging models have been proposed for the high's evolution and the relationship with the continent/ocean boundary.

Throughout most of the Cenozoic period the Norwegian–Greenland Sea has acted as a major pathway for the influx of cold polar water into the North Atlantic Ocean as well as the advection of warm water from the North Atlantic to the polar deep-sea basin (Fig. 2). The temporal and spatial evolution of this water exchange has had profound paleoenvironmental effects on the world's ocean as a whole. During this period both the surface- and bottom-water circulations were governed by

two major tectonic events, the break-through of a deep-water passage between northeast Greenland and Svalbard, and the submergence of the Greenland–Scotland transverse ridge complex. Furthermore, the location of the ocean within the realm of the late Neogene Northern Hemisphere glaciations has also left its detailed imprint in the marine sedimentary record. Thus, the Norwegian–Greenland Sea is expected to yield paleoceanographic and paleoclimatological data having fundamental influence on a far larger region.

During DSDP Leg 38 a series of holes was drilled in several geological provinces in the Norwegian–Greenland Sea (Talwani, Udintsev et al., 1976). That drilling program was primarily designed to test and put constraints on the plate tectonic evolutionary history. The fact that most sites were placed in locations of condensed sediment sections and were discontinuously cored precluded high-resolution studies of the paleoenvironment. Moreover, the sub-basement structure of the marginal highs was unknown prior to the advent of deep penetration multichannel seismic data. When such data arrived, however, a new drilling leg focusing on the Vøring Plateau and the Jan Mayen Ridge was proposed. Unfortunately, because of problems in obtaining a research license the drilling had to be abandoned.

As more geophysical data became available, it was recognized that drilling at the outer Vøring Plateau might provide insight into the history of a passive margin in general and that primary sub-basement features were within reach of the drillstring. The Norwegian margin drilling proposal remained as a high-priority target with the DSDP Passive Margin Panel and was carried over to the initial phase of ODP. A Norwegian Sea Working Group\* under the Atlantic Regional Panel was charged with formulating a drilling program. The working group suggested a two-component drilling scenario. The primary objective was to drill a deep hole into the basement and the dipping reflectors, whereas addressing the Cenozoic paleoenvironment problems formed the secondary objective. This proposal was subsequently accepted as the scientific rationale for the ODP Leg 104 drilling program at the Vøring Plateau continental margin.

*D/V JOIDES Resolution* set out from Bremerhaven June 24, 1985, drilled eight holes at three sites at the Vøring Plateau, and returned to Stavanger, Norway, on August 12, 1985. The detailed results and preliminary interpretations of that successful coring program were presented by Eldholm, Thiede, Taylor, et al. (1987). This volume of scientific results contains more complete analyses, interpretations, and syntheses. We stress, however, that difficulties in stratigraphic correlations and time demands on many ship and shore-based investigators have made the syntheses less comprehensive than anticipated. Therefore, we expect additional results to appear in the scientific literature over the next few years.

<sup>1</sup> Eldholm, O., Thiede, J., Taylor, E., et al., 1989. *Proc. ODP, Sci. Results*, 104: College Station, TX (Ocean Drilling Program).

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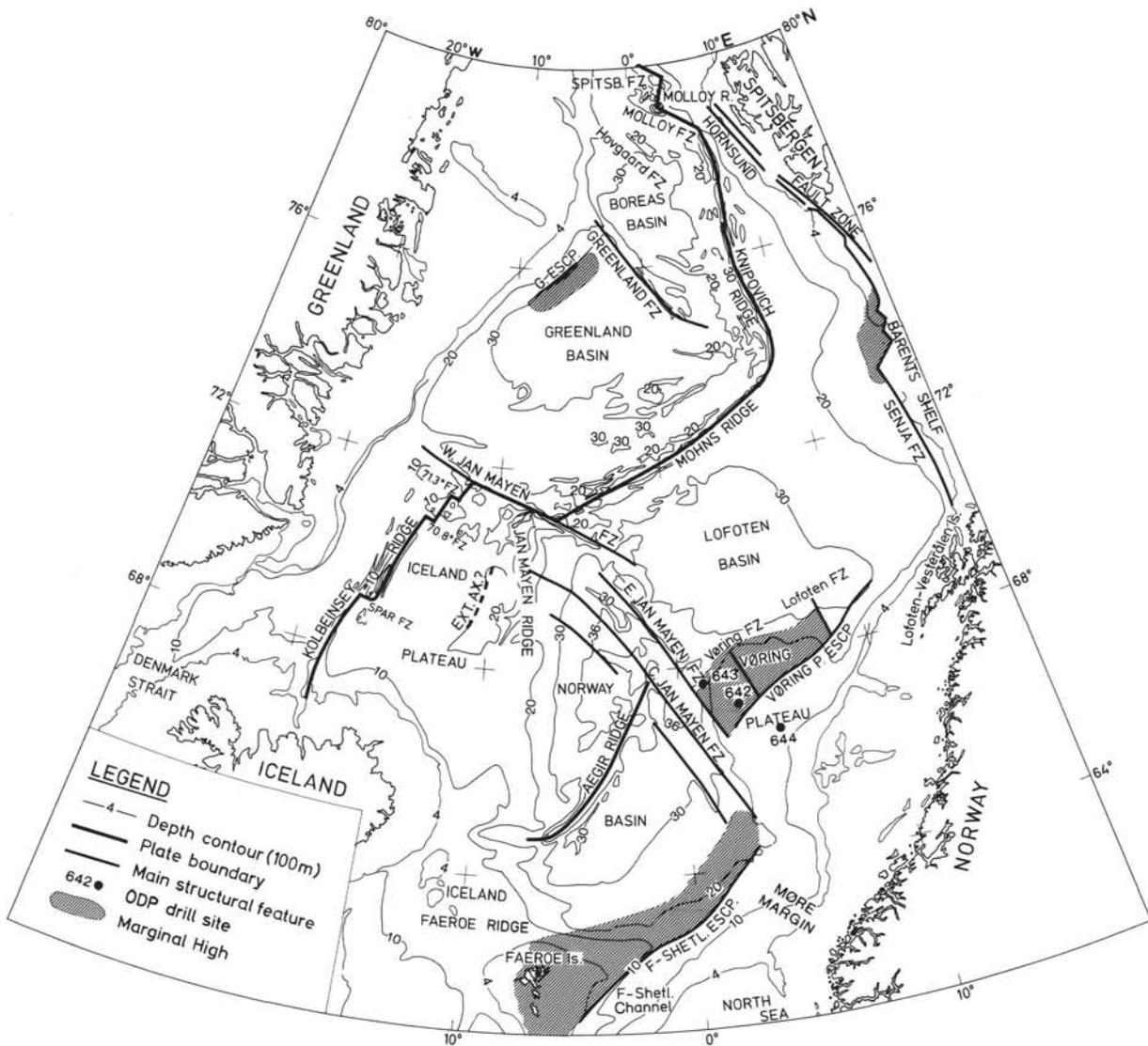


Figure 1. Physiography and structural features in the Norwegian-Greenland Sea, slightly updated from Eldholm et al. (in press). Simplified bathymetry from Perry et al. (1980).

**THE NORWEGIAN CONTINENTAL MARGIN**

The outer Norwegian continental margin between 62° and 70°N is prominently offset by the Jan Mayen Fracture Zone system separating the Møre Margin to the south from the region to the north comprising the Vøring Plateau Margin and the Lofoten-Vesterålen Margin (Fig. 1). These margin segments, which have distinct bathymetric, physiographic, and structural features, are generally thought to form separate geologic provinces.

North of the Jan Mayen Fracture Zone a spectacular marginal plateau, the Vøring Plateau, protrudes from the continental slope distinguishing the central part of the Norwegian margin. The Vøring Plateau Margin consists of a wide, relatively deep shelf and an inner, moderately grading slope interrupted by the plateau, defined by the 1200- and 1600-m contours. Farther seaward, the plateau is bounded by an outer steep slope, at water depths between 1600 and 3000 m, toward the Lofoten and Norway basins (Figs. 1, 3).

**Structural Framework**

The East and Central Jan Mayen fracture zones (Figs. 1, 3) define the southwestern extent of the plateau whereas no obvious structural boundaries have been recognized under the western or northwestern flanks.

Beneath the outer margin off Norway, there are two large buried basement highs which are elevated with respect to the adjacent oceanic crust (Fig. 1). The highs at the Møre and Vøring margins mark the western termination of large pre-Cenozoic regional sedimentary basins extending toward the coast of Norway in the east. Two first-order geologic structures, the Faeroe-Shetland and Vøring Plateau escarpments, separate the marginal highs and the pre-opening Møre and Vøring basins on the landward side (Fig. 3). In the north, the Vøring Basin rises toward the structurally elevated Lofoten-Vesterålen shelf.

Globally, the most thoroughly investigated marginal high is probably that at the Vøring Plateau. We refer to Hinz et al.

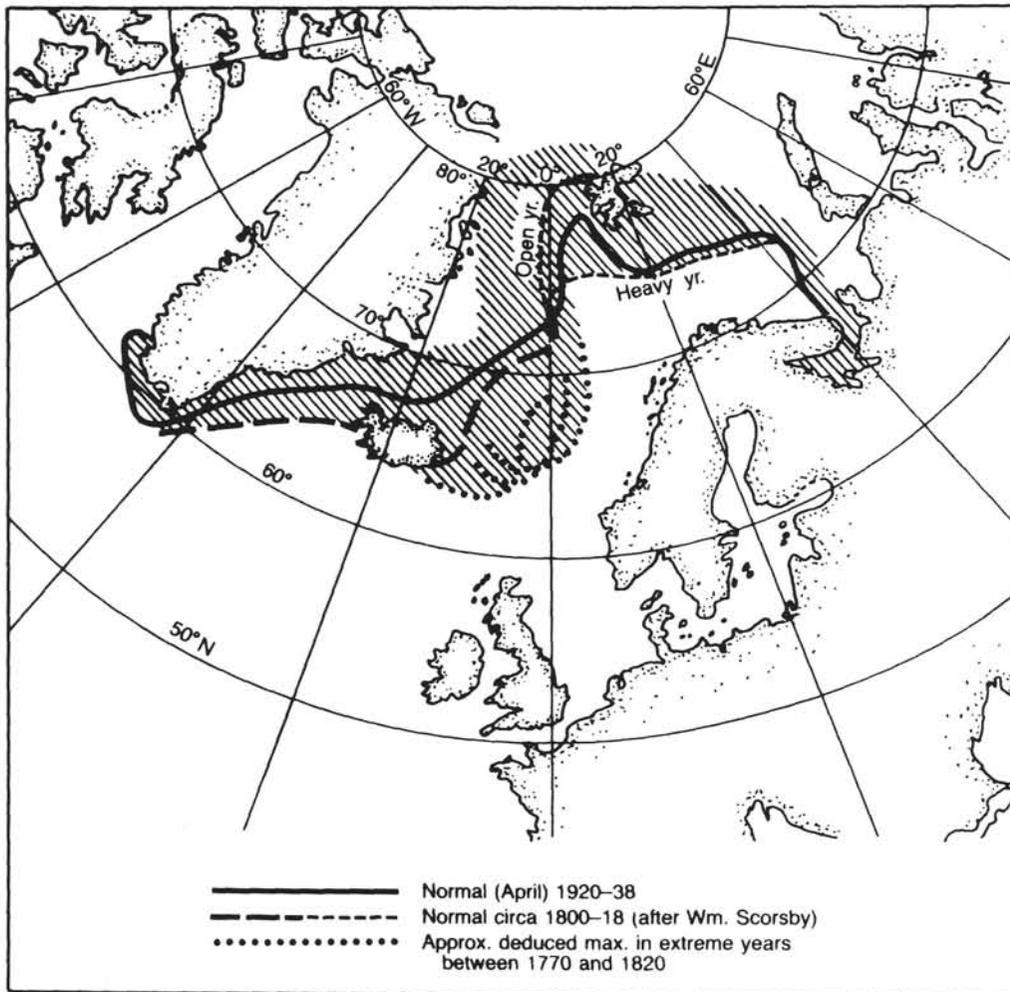


Figure 2. Variability of the modern Norwegian-Greenland Sea sea ice cover (Lamb, 1972).

(1984, 1987), Mutter et al. (1984) and Skogseid and Eldholm (1987) for discussions of geophysical data, models and summary of earlier studies. In the seismic record the top of the outer basement high is defined by a strong reflector, EE (Fig. 4), documented by DSDP drilling to represent lower Eocene volcanics (Talwani, Udintsev et al., 1976). EE is underlain by seaward-dipping reflector sequences (Figs. 4 and 5) and the inner part of the main wedge rests on a band of low-frequency reflectors of which the uppermost is named K. A relatively thin section of Cenozoic sediments covers the high. It has been common to subdivide the outer margin into zones according to the character of the acoustic basement and/or sub-basement features in the seismic record (Figs. 4 and 5). The most seaward region, Zone IV, is characterized by oceanic basement. Zone III represents wedges of seaward-dipping reflector sequences below reflector EE. Between the apex of the inner wedge and the Vøring Plateau Escarpment there is a sequence of short, irregular, and often gently landward-dipping reflectors between EE and K. The reflector band associated with K has only been recognized from below the innermost part of Zone III to the Vøring Plateau Escarpment. Another typical horizon extends some tens of kilometers into the Vøring Basin landward of the escarpment. This reflector, denoted inner flows and interpreted as the continuation of EE at the marginal high, designates Zone I.

The marginal highs off Norway were emplaced during the early Tertiary breakup between Norway and Greenland when separation took place within a system of older sedimentary basins. The history of those basins has gradually become better known, largely due to commercial exploration activities on the shelf (Bøen et al., 1984; Bukovics and Ziegler, 1985). The region has been a depositional area since the Carboniferous, and its structural evolution is dominated by several rifting events which failed to culminate in sea-floor spreading. Subsequent to the cessation of the Caledonian Orogeny, sedimentation started on an epeirogenic subsiding surface. Late Paleozoic tectonism resulted in a series of rotated fault blocks filled in with sediments. From late Paleozoic to early Mesozoic time the relief became gradually smoother forming a large regional basin in the Early Jurassic. Extensional tectonism dominated in the middle and Late Jurassic, culminating in the Late Jurassic-Early Cretaceous tectonic phase. These events created most of the present system of basins and highs at the margin (Figs. 3, 5) which were covered by marine sediments in a regionally subsiding epicontinental basin during the Cretaceous and early Paleocene.

At the onset of the Tertiary, the crust between Norway and Greenland was again being thinned. This rifting phase continued, evolving into generation of oceanic crust during the negative polarity interval between magnetic anomalies 25 and 24B, close to the Paleocene-Eocene transition (Talwani and Eldholm,

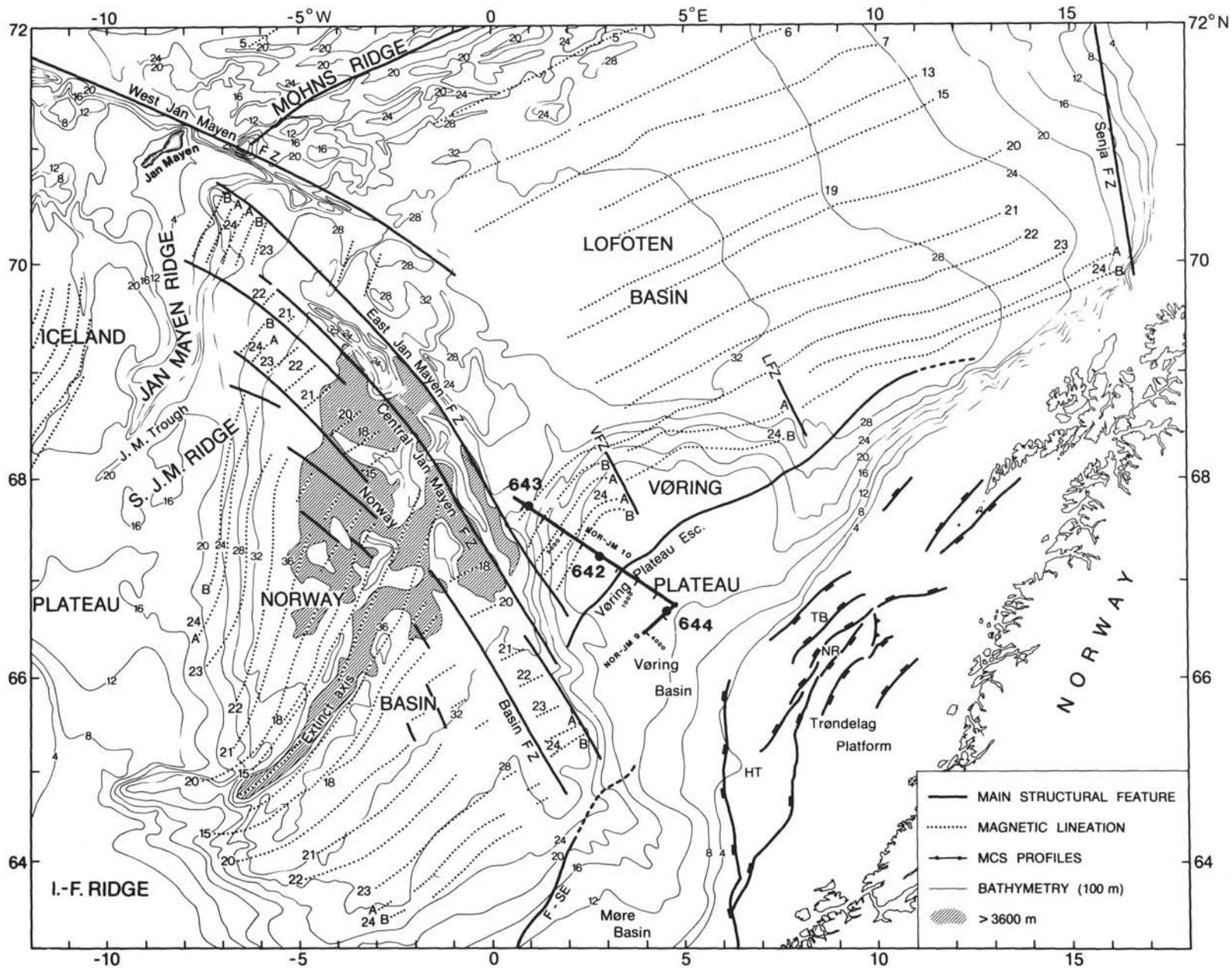


Figure 3. Bathymetry of the Vøring Plateau continental margin and adjacent regions of the Norwegian-Greenland Sea (Perry et al., 1980). Marginal escarpments, main structural elements, sea-floor spreading type magnetic lineations, ODP drill sites (642, 643, 644), and location of multichannel seismic reflection profiles NOR-JM 9 and 10 (Fig. 4) shown. Based on Skogseid and Eldholm (1987). NR: Nordland Ridge, TB: Traen Basin; HT: Halten Terrace; VFZ: Vøring Fracture Zone; LFZ: Lofoten Fracture Zone, F-SE: Faeroe-Shetland Escarpment.

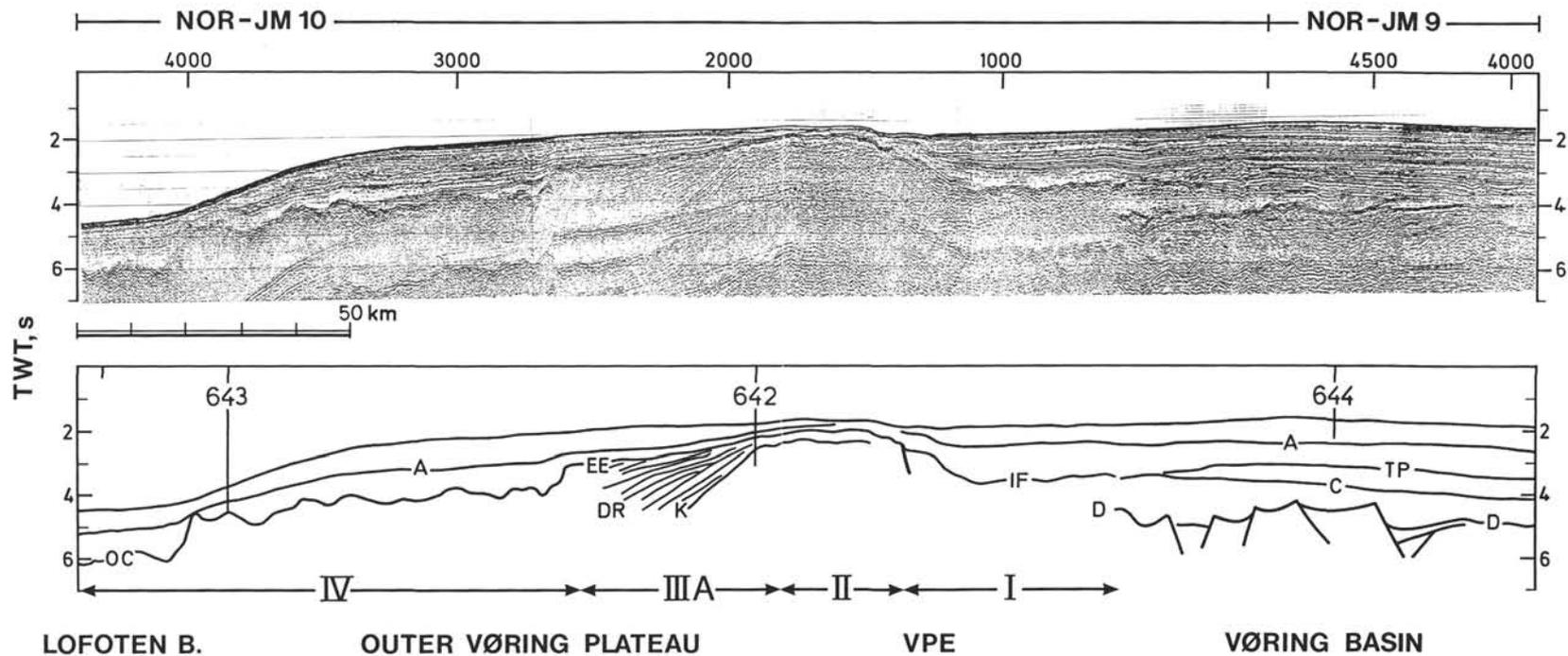


Figure 4. Multichannel seismic reflection profiles NOR-JM 9 and 10. The profiles were recorded by the University of Oslo onboard F/F *Håkon Mosby* in 1986 and run through all three Leg 104 drill sites. Shotpoint numbers on the top of the profile refer to Figure 3. The profiles reveal the main geologic features of the Outer Vøring Plateau as indicated on the simplified interpreted section below. OC: Oceanic crust, DR: Seaward-dipping reflector sequence, K: Reflector K, EE: The top of the lower Eocene flow series, IF: Inner flows, A: lower Miocene unconformity. Numbers I-IV refer to the zonation in Figure 5 discussed in the text. A detailed interpretation of the seismic profiles is presented by Skogseid and Eldholm (this volume).

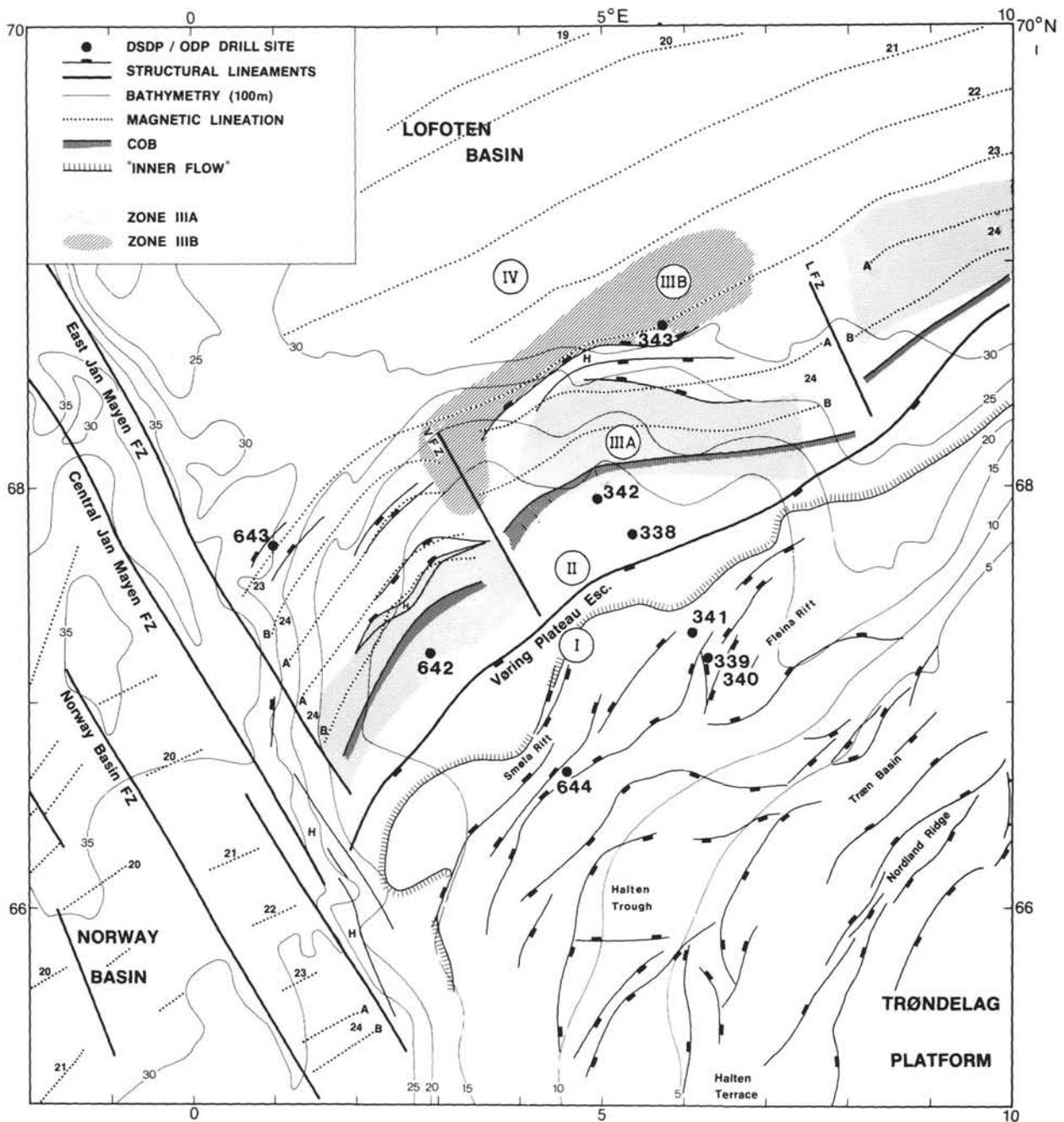


Figure 5. Simplified Vøring Plateau Margin structural map (Skogseid and Eldholm, 1987; this volume) including ODP (642, 643, 644) and DSDP (338-343) drill sites. Zones I-IV refer to a division of volcanic units at the level of reflector EE and below. VFZ: Vøring Fracture Zone; LFZ: Lofoten Fracture Zone.

1977). Since that time, the Norwegian-Greenland Sea gradually widened and deepened during a complex plate tectonic evolution that is characterized by two main phases having different relative plate motions and local migration of the plate boundary (Talwani and Eldholm, 1977; Nunns, 1983). These events have greatly influenced the present structural framework of the margins (Eldholm et al., 1984, 1987).

In terms of the Vøring Plateau margin we particularly point to the following events:

1. A small shift of the plate boundary took place at the Vøring Plateau just subsequent to anomaly 24A time, causing a duplication of the

24A-B anomaly sequence seaward of the Vøring Plateau Escarpment (Hagevang et al., 1983).

2. A very complex spreading history occurred south of the Jan Mayen Fracture Zone including fan-shaped spreading, westward axial migration and development of the Jan Mayen Ridge microcontinent.

3. Local tectonism took place, possibly influenced by stress patterns induced by the two previous events.

The margin landward of the escarpments is dominated by a number of Mesozoic structural elements along which the movements appear to have ceased at mid-Cretaceous time. Little structural activity has been reported in conjunction with the early Tertiary opening, therefore the Møre and Vøring Plateau

margins are often thought to be a nonextensional type of the passive continental margin. Mapping by Skogseid and Eldholm (this volume), however, shows that a moderate amount of extension was associated with the breakup at the outer Vøring Plateau margin. Furthermore, a later phase of deformation containing elements of compression caused local inversion and thrusting in the Møre and Vøring basins.

The Møre Basin, which is the direct southern continuation of the Vøring Basin, is largely unstructured except for the steep eastern flank. It has been a prominent depocenter since Late Jurassic time, probably containing 9–10 km of Cretaceous and Cenozoic sediments. The deposition is related to a phase of rapid basin subsidence that started during the mid-Cretaceous time. On the other hand, the pre-Cretaceous sequence is thin, reflecting early Mesozoic uplift and erosion of a late Paleozoic basin.

The Vøring Plateau margin consists of two regional geologic provinces separated by a structurally complex transition zone (Figs. 3, 5). Regionally, the eastern province is a platform-like area comprising several ridges and sub-basins such as the Nordland Ridge and Helgeland Basin. The province was structured by the Late Jurassic–Early Cretaceous movements after being developed as a depocenter in Late Triassic–Early Jurassic time. In general, the cover of younger sediments in the eastern province is thin compared with the Vøring Basin to the west of the transition zone. This basin was formed by extension which caused block faulting and rapid subsidence in Late Jurassic and Early Cretaceous time.

Since the opening of the Norwegian–Greenland Sea, the margin has received an increasingly thicker sediment cover largely prograding from the east. The total Cenozoic sediment thickness in the Møre Basin reaches a maximum of about 3.5 km, compared with an average thickness of 2–2.5 km in the Vøring Basin (Bøen et al., 1984; Eldholm and Mutter, 1986). We note in particular that the Faeroe–Shetland and Vøring Plateau marginal highs may not have been entirely buried before late Oligocene/early Miocene time. It is also significant that most of the Cenozoic sediments are of Neogene and Quaternary age, reflecting a higher rate of deposition and subsidence the last 10 m.y.

### Oceanographic Framework

Plate tectonic movements during the Cenozoic have resulted in an Atlantic Ocean whose oceanographic characteristics differ greatly from those of the Pacific and Indian oceans. The opening of the Norwegian–Greenland Sea was the final step in establishing pathways for the exchange of surface and bottom waters across all climatic zones. The opening also formed a contiguous Atlantic Ocean connecting the polar deep-sea basins of both the Northern and Southern Hemispheres. The tectonic and volcanic processes generating the deep-sea basin between Greenland and Europe have also resulted in the construction of major sills separating the Norwegian–Greenland Sea from the main North Atlantic Ocean to the south and the Arctic Ocean to the north. However, the geological evolution of the Greenland–Scotland Ridge system (Bott et al., 1983) and the Fram Strait is poorly known. Furthermore, morphologically well-expressed fracture zones and the active mid-ocean ridge system have compartmentalized the Norwegian–Greenland Sea proper into a number of smaller sub-basins (Fig. 1).

As a consequence of the plate tectonic evolution and the geographic position, the Norwegian–Greenland Sea is characterized by a peculiar hydrography having an important impact on the Northern Hemisphere climate (especially Greenland and Northwest Europe), as well as on the deep-water renewal of almost the entire world ocean. Properties of Norwegian–Greenland Sea surface and bottom waters have responded rapidly and drastically to the Northern Hemisphere late Cenozoic paleoclimatic changes, resulting in very fast and virtually complete rearrangements of

major water mass boundaries and currents. These changes are expected to be documented in the pelagic and hemipelagic sediment cover, providing a wider perspective to the studies of the Norwegian–Greenland Sea depositional environments.

Two major current regimes dominate the modern surface circulation of the Norwegian–Greenland Sea (Fig. 6). The Norwegian Current transports temperate water masses from the area south of the Greenland–Scotland Ridge along the Norwegian continental margin north into the Arctic Ocean, as initially described by Scoresby (1820). The temperate water masses, however, are balanced by the cold and ice-covered East-Greenland Current, which trails the east Greenland continental margin transporting Arctic water masses through the Denmark Strait into the North Atlantic Ocean. This oceanographic asymmetry has profound climatic consequences and is responsible for the dramatically different climates on either side of the North Atlantic Ocean at the present time.

In the Vøring Plateau region two nearly subparallel current systems define the surface circulation along the Norwegian continental margin. The Norwegian Coastal Current is centered on the shelf, and the dominating Norwegian Current flows farther west over the continental slope and the Vøring Plateau (Fig. 6). Both currents carry temperate water from the North Atlantic Ocean into the Norwegian–Greenland Sea, but are clearly distinguished by the reduced salinities of the Norwegian Current. The Norwegian Current is well-developed and narrow over the Vøring Plateau and steep hydrographic gradients separate it from the cold polar water masses of the main Norwegian–Greenland Sea. However, the water-mass boundaries show rapid seasonal fluctuations and complex systems of gyres are often formed (Mork, 1981).

The bottom waters of the Norwegian–Greenland Sea and the Arctic Ocean are renewed rapidly (Koltermann, 1987), although the oceanographic processes causing this rapid vertical circulation are not well understood. It has earlier been assumed that dense and cold water masses were sinking to the ocean floor in the Greenland Sea (Mosby, 1961; Aagaard et al., 1985) filling the entire deep-water area and flowing over the Greenland–Scotland Ridge into the North Atlantic (Meincke, 1983) (Fig. 7). However, recent investigations suggest that an important proportion of the renewed deep-water originates from brine formation on the continental shelves (Swift et al., 1983; Midtun, 1985). The Arctic Bottom Water that overflows the Greenland–Scotland Ridge entering the North Atlantic, has been traced into the Pacific and Indian oceans as well, demonstrating the hydrographic impact of the modern Norwegian–Greenland Sea on the world ocean.

The situation described above has a short geologic history that developed in direct response to changes in the basin geometry and the evolution of the Cenozoic paleoclimate. Although plate tectonic considerations give reasonable estimates about the Cenozoic basin configuration, precise timing and history of the vertical motion for the northern and southern parts of the ocean are still lacking. The subsidence of the Iceland–Faeroe Ridge is poorly known, although it appears to have been a barrier for water circulation during most of the Tertiary and complete submergence may not have occurred before the late Miocene (Thiede and Eldholm, 1983). The region between northeast Greenland and northern Svalbard started opening after anomaly 13 time, however final continental separation and initiation of the deep-water exchange may have been achieved much later (Myhre and Eldholm, 1988).

### Framework for Reconstruction of the Depositional Paleoenvironment

As most paleoenvironmental inferences are derived from sea-floor samples and DSDP drilling (Talwani, Udintsev et al.,

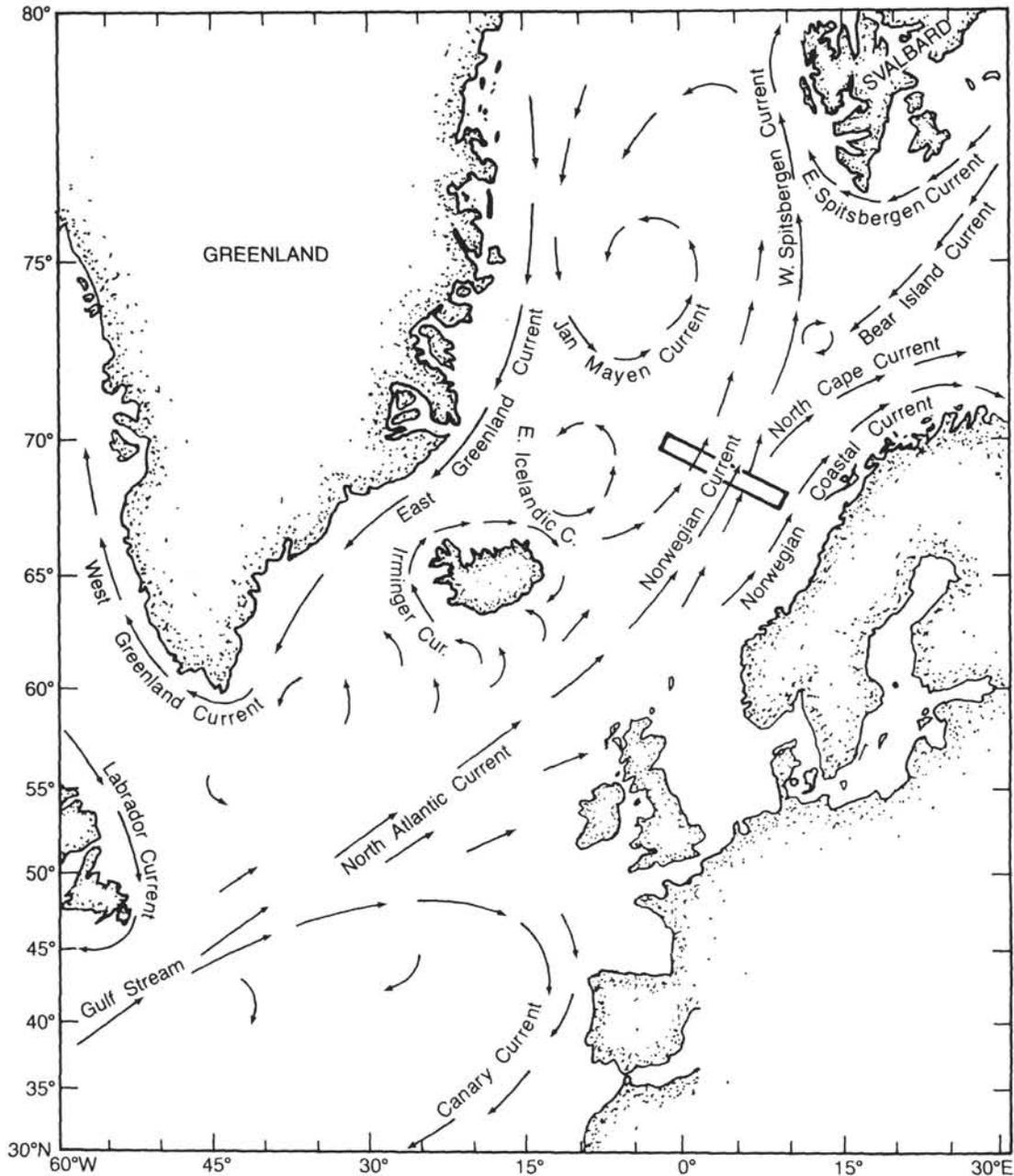


Figure 6. Present-day surface-current patterns in the Norwegian-Greenland Sea compiled from a number of sources (Kellogg, 1975; 1976). The box indicates the ODP Leg 104 paleoenvironmental transect.

1976), one should keep in mind the geographical bias in available data from the Norwegian-Greenland Sea. First, there is almost no information from the western, ice-covered parts of the ocean. Second, there is an order of magnitude more information from east of the present plate boundary than from the western region. Thus, much of the analyzed material originates from areas which have been, at least at times, under influence of the northerly moving temperate surface currents during the last few million years.

The oldest sediments sampled during DSDP Leg 38 are of early Eocene age and suggest that fully pelagic and relatively warm water conditions existed there then. The similarity of marine pelagic fossil assemblages on either side of the Greenland-Scotland Ridge (Berggren and Schnitker, 1983) suggests that the sill was discontinuous then. Thiede et al. (1986) showed that the

main part of the Paleogene, and possibly the lowermost Neogene, sediments originate from a limited number of source regions on the continental shelf.

The mid-Tertiary depositional environment is less known because a lower Neogene hiatus spans the transition between preglacial and glacial deposits (Schrader et al., 1976). South of the Greenland-Scotland Ridge, glacially influenced material was deposited 2.3-2.4 Ma (Shackleton, Backman, et al., 1984). On the other hand, DSDP Site 344 (Schrader et al., 1976) and Arctic cores (Clark et al., 1980; Thiede et al., in press) yield evidence of glacial conditions as early as late Miocene-early Pliocene time.

The initiation of a glacial-type regime in the Norwegian-Greenland Sea changed the depositional conditions. Depositional patterns in glacial and interglacial times were controlled by the

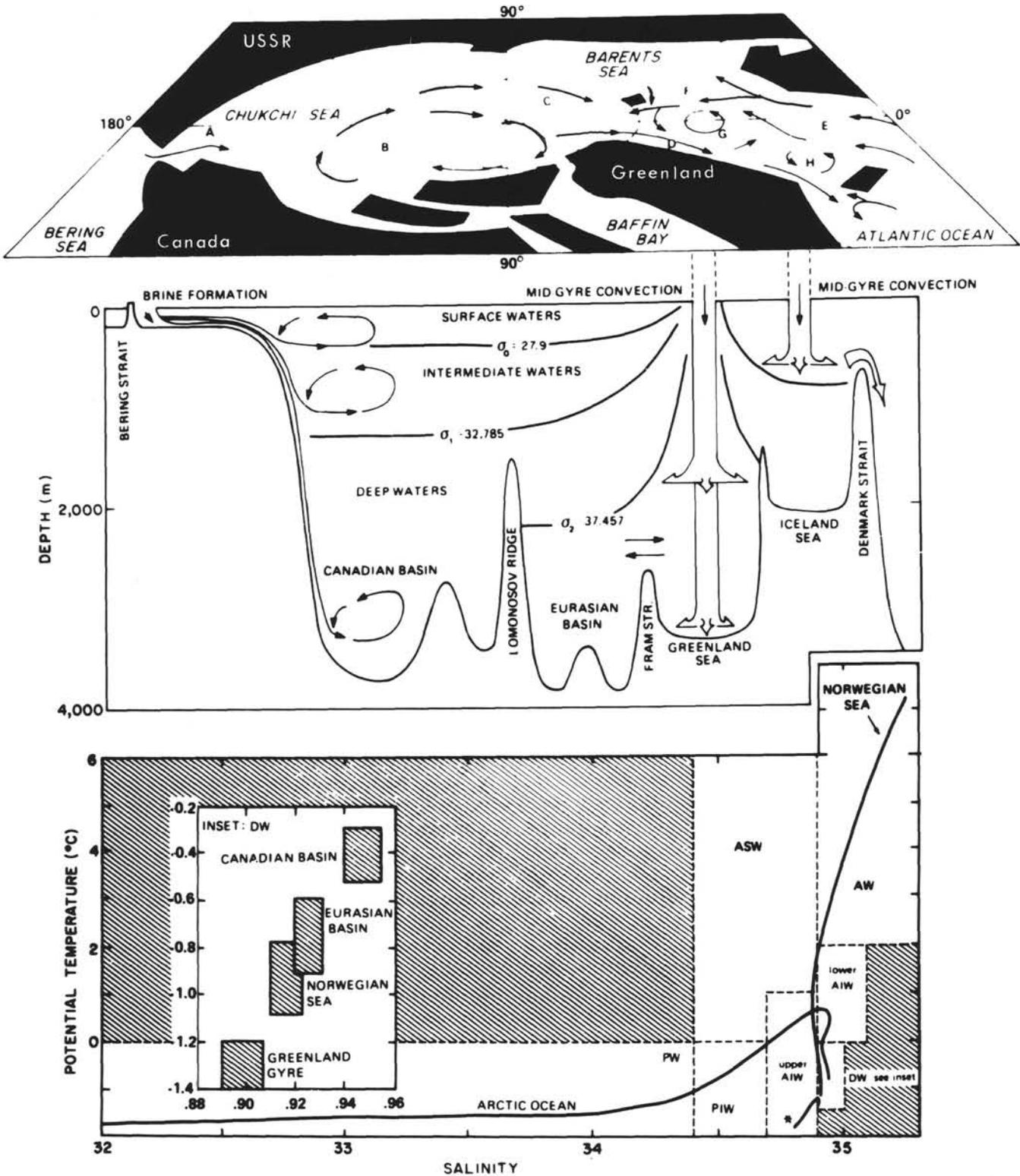
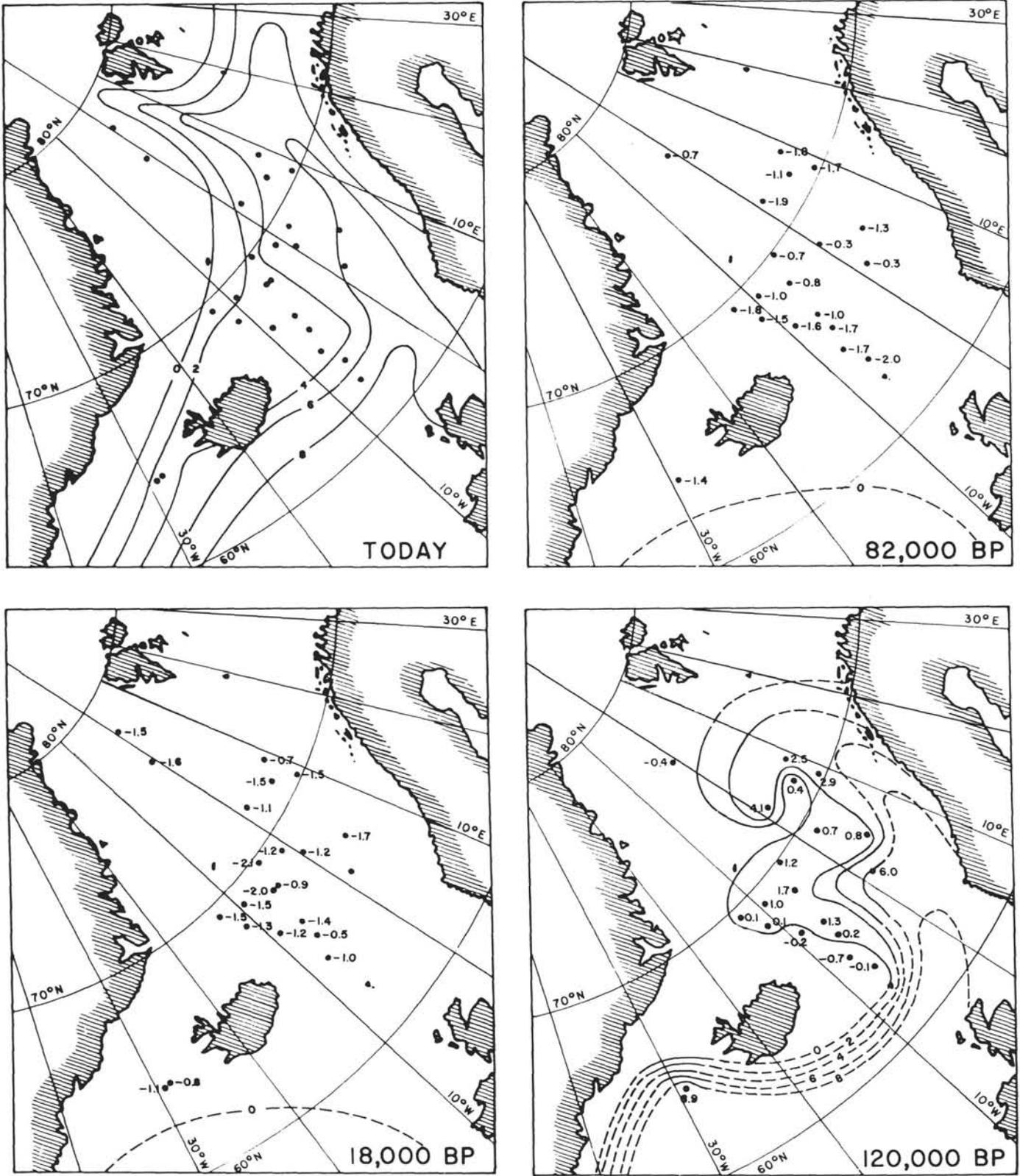


Figure 7. Schematic circulation and water mass structure in the Norwegian-Greenland Sea and the Arctic Ocean (Aagaard et al., 1985).

surface-water circulation. In addition, there is also a strong response to the glacial-interglacial climatic changes during the late Neogene and Quaternary. In fact, this ocean underwent the fastest and most dramatic oceanographic changes caused by the variable climate (Fig. 8) (CLIMAP, 1976). Stratigraphic work (Kellogg, 1975, 1976; Bjørklund and Goll, 1979) revealed that

the Norwegian Current existed only during selected peak interglacials, whereas the surface waters remained polar or ice covered for most of the latest Neogene and the Quaternary. The properties and mode of formation of the bottom water during this period is not settled (Jansen and Erlenkeuser, 1985), although a two-phase step-wise transition from the last glacial



**A** Figure 8. A: Reconstruction of the late Quaternary paleoceanography of the Norwegian-Greenland Sea (Kellogg, 1980). B: Modern and last glacial maximum in the Northern Hemisphere environment (CLIMAP, 1976).

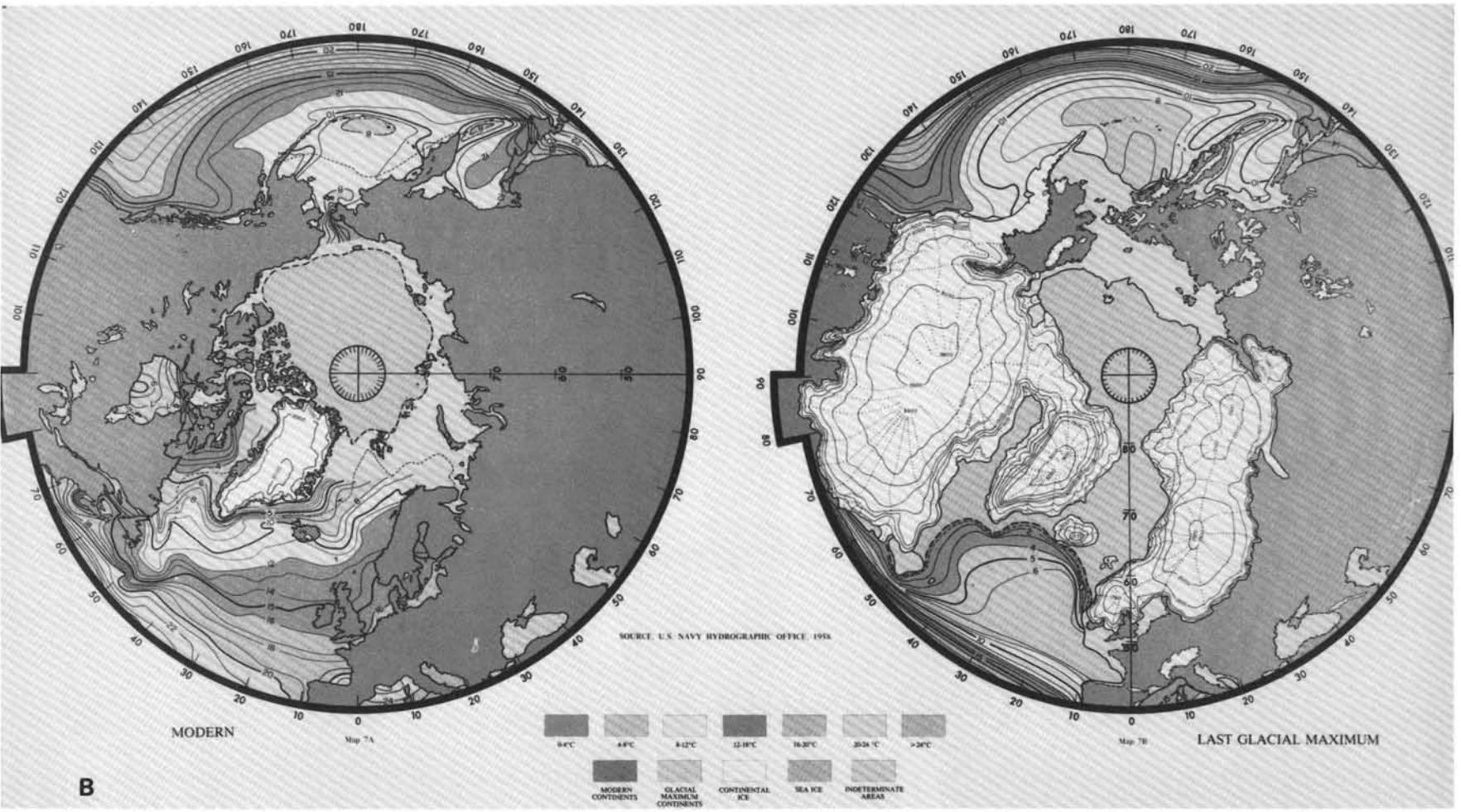


Figure 8 (continued).

maximum to the Holocene might be inferred (Jansen et al., 1983). Finally, the sediments suggest relatively stable depositional environments in the Holocene.

The Tertiary and Quaternary sediment cores of the Norwegian–Greenland Sea document mainly the evolution of the marine depositional environment, which appears to have been dominated by a glacial mode of circulation for most of the time since 2.5–2.6 Ma. Recent observations (Funder et al., 1985) suggest, however, that northeastern Greenland was covered by boreal forests during the late Pliocene and early Pleistocene, which contradicts the oceanic data. Hence, more work must be carried out before a detailed correlation of the paleoclimate over the adjacent continents and the Norwegian–Greenland Sea paleoceanography is possible.

## DRILLING OBJECTIVES AND SITE SELECTION

The two main scientific objectives of Leg 104 were to drill deep into the marginal high to investigate the initial margin development, and to obtain information relating to the Cenozoic, particularly the Neogene and Quaternary, paleoenvironment.

Although seaward-dipping reflector sequences had been documented from a number of passive margins (Hinz, 1981), the actual composition of these formations remained to be proven, although many investigators had suggested a volcanic nature for the sequence. This inference was supported by DSDP Leg 38 drilling that showed that the top of the unit, reflector EE (Fig. 4), was basalt. Furthermore, DSDP Leg 81 drilled into the uppermost part of a series of seaward-dipping reflectors at the Hatton Bank margin, recovering mainly subaerial tholeiitic flow basalts and minor interbedded sediments (Roberts, Schnitker, et al., 1984).

Specifically, the margin evolution goals were:

1. The composition and structure of the seaward-dipping reflector sequence;
2. The time, elevation, and crustal environment during the emplacement of the sequence;
3. The origin of the seismic reflector pattern characterizing the sequence;
4. The nature of reflector K at the base of the dipping wedge;
5. The composition and structure of the rocks beneath reflector K and their emplacement history;
6. The crustal nature of Vøring Plateau marginal high.

These data were expected to provide crucial constraints on possible models for the evolution of the Vøring Plateau marginal high and the seaward-dipping series. Furthermore, the results would yield a greater insight to the early evolution of the continental margin and the nature and location of the continent/ocean boundary.

The paleoenvironmental objectives included:

1. The history of vertical motion of the outer margin. This target is also of key importance for understanding the early history of opening;
2. The depositional history of a passive continental margin in the polar-subpolar realm and its response to the evolution of a marginal plateau;
3. The paleoceanographic history of the Norwegian–Greenland Sea; particularly, the development of the Norwegian Current as the continuation of the Atlantic Gulf Stream system into the northern polar deep-sea basins;
4. The Cenozoic paleoclimatic history;
5. The initiation and variability of the Northern Hemisphere glaciations;
6. The Cenozoic evolution of pelagic faunas and floras in response to the paleoclimatic and paleoceanographic processes in the Norwegian–Greenland Sea; and
7. Obtaining a data base for comparison with the Southern Hemisphere pelagic fossil records.

To meet these goals within the time frame of a single drilling leg, a transect of three sites was selected (Figs. 3–6). All sites were located on the basis of good-quality multichannel seismic profiles. Table 1 relates site locations and adjacent multichannel seismic profiles. The detailed site approaches and underway geophysics work were described by Eldholm, Thiede, Taylor, et al. (1987). Due to problems with locating Site 643 on the steep outer flank of the plateau, the actual site location is located off profile NH-1 on which it was targeted. However, in 1986 the University of Oslo recorded new continuous multichannel seismic profiles through all three sites (Fig. 4).

The deep penetration site (642) was placed over the innermost, thinnest part of the seaward-dipping wedge. The actual site location had to satisfy two requirements: (a) We wanted to sample the dipping sequence in a representative location, and (b) the site should allow us to drill to reflector K and into the underlying rock if the drilling progressed satisfactorily.

Site 642 forms the center of the paleoenvironmental transect that includes Site 643 at the lower outer flank of the Vøring Plateau and Site 644 in the Vøring Basin near the base of the inner continental slope. Because of safety considerations, the scientific research license granted by the Norwegian Petroleum Directorate specified a maximum drilling depth of 250 m within the Vøring Basin.

The premise for the transect is that the location of the Vøring Plateau is well suited to study the depositional environments of surface-water current systems as well as of bottom water. The marginal plateau is elevated above the adjacent turbidite-covered abyssal plains and was therefore expected to accumulate pelagic and hemipelagic sediments not interrupted by turbidites. On the other hand, it is known that downslope mass movements have occurred even on gentle slopes elsewhere along the Norwegian margin. Thus, we attempted to avoid the most disrupted seismic stratigraphic sections when selecting Site 643. Finally, the concept of a drill-site transect (Fig. 6) would provide enough lateral spacing to establish the horizontal gradients between different surface-water masses and the vertical gradients between different layers of the water column which once filled the Norwegian–Greenland Sea.

**Table 1. Leg 104 drill site locations relative to the nearest single and multichannel seismic lines. An asterisk indicates that the line passes through the site.**

Site	MCS-profile	Shotpoint	SCS-profile	Date/time
<b>ODP</b>				
642	BGR-1	1635*	V2705	17-9/0130
	NOR-JM-10	1932*	V2803	18-8/0610
	NH-1-79	7485		
	BGR-76-38	7380		
643	C162	5215		
	NOR-JM-10	3870*		
	NH-1-79	9430		
644	NOR-JM-9	4652*		
	B-10-81	4115		
	NH-1-79	5600		
<b>DSDP</b>				
338	C165	5050	V2705	17-9/0940
	C165	3620		
339	BGR-79-8	170		
	C165	3610		
340	BGR-79-8	150		
	C165	4000		
341	C174	7030		
	C165	5490	V2705	17-9/0720
342	BGR-76-38	5030	V3011	22-9/1145
	C167	1110	V3011	26-9/0710
343			V3011	26-9/0800

**DEEP SEA DRILLING PROJECT LEG 38 RESULTS**

During DSDP Leg 38, six sites were drilled at the northern part of the Vøring Plateau (Talwani, Udintsev et al., 1976). Of these, three sites (339, 340, 341) were in the Vøring Basin 40–60 km landward of the Vøring Plateau Escarpment; two sites (338, 342) over the marginal high at the outer plateau; and one site (343) at the foot of the outer slope, at the transition to the Lofoten Basin (Fig. 5). The Leg 38 drilling data complement those of Leg 104, thus we summarize the results here.

Table 2 shows key drilling information and Figures 9 and 10 illustrate the cored lithological units and their biostratigraphically determined ages.

In the Vøring Basin, two sites were in a prominent diapir province discovered by Talwani and Eldholm (1972). Piston cores from the diapirs revealed middle Eocene diatomaceous clay (Bjørklund and Kellogg, 1972). The drilling confirmed that the diapiric material consists of diatomaceous oozes. Site 341, on the other hand, was drilled west of the diapirs in undisturbed flat-lying sediments, a setting not unlike that of ODP Site 644. After penetrating a glacial sequence (Fig. 9), the hole terminated in middle Miocene diatomaceous oozes and diatomites. Coring was suspended because the sediments near the bottom of the hole had a strong petroliferous odor (Morris, 1976). Moreover, relatively biogenic gas concentrations were prevalent at all the sites.

At the Outer Vøring Plateau, Site 338 yielded the most complete sedimentary section. The sediments are comprised of ter-

igenous Eocene material, predominantly pelagic Oligocene and Miocene sediments, and an upper section of terrigenous Pliocene-Pleistocene sediments. Site 342 recovered only Neogene and Quaternary material. Both sites terminated in strongly altered alkalic basalt. K/Ar dating indicated middle Eocene ages of 46.6 and 44.0 Ma at sites 338 and 342, respectively (Kharin et al., 1976). This age is at odds with the biostratigraphically dated lower Eocene sediments sampled just above the basalt in Site 338 (Fig. 10).

The most seaward site, 343, sampled a glacial terrigenous section over middle Miocene hemipelagic sediments. A distinct hiatus separates the latter from terrigenous lower Eocene material above a basaltic basement dated as 28.5 Ma by Kharin et al. (1976). Again there is a pronounced discrepancy between the radiometric ages and that of the overlying sediments. Talwani and Udintsev (1976) noted that this difference might be explained by later extrusive volcanic activity or a large amount of alteration in the dated rocks. We note they characterize the basalts at Site 338 as normal oceanic floor tholeiites. In view of the Leg 104 results, the strong alteration in the very uppermost part of the volcanic section has probably contributed to these age discrepancies.

**PRINCIPAL DRILLING RESULTS, LEG 104**

A total of eight holes were drilled at three sites during 43 drilling days. In the sediment section, the general approach was to drill with the advanced piston coring (APC) technique until the operational limit of 100,000 lb. overpull during pullout was

**Table 2. DSDP Leg 38 coring summary (Talwani, Udintsev, et al., 1976).**

Hole	Latitude	Longitude	Water depth (m)	Penetration (m)	No. of cores	Meters cored	Recovered (m)	Recovery (%)
338	67°47.11'N	05°23.26'E	1297	437.0	45	427.5	208.7	48.8
339	67°12.65'N	06°17.05'E	1262	108.0	12	108.0	50.5	46.7
340	67°12.47'N	06°18.38'E	1217	104.5	11	104.5	67.2	64.3
341	67°20.10'N	06°06.64'E	1439	456.0	34	313.5	213.0	67.9
342	67°57.04'N	04°56.02'E	1303	170.5	8	75.5	48.0	63.6
343	68°42.91'N	05°45.73'E	3131	284.0	16	132.0	59.3	44.9

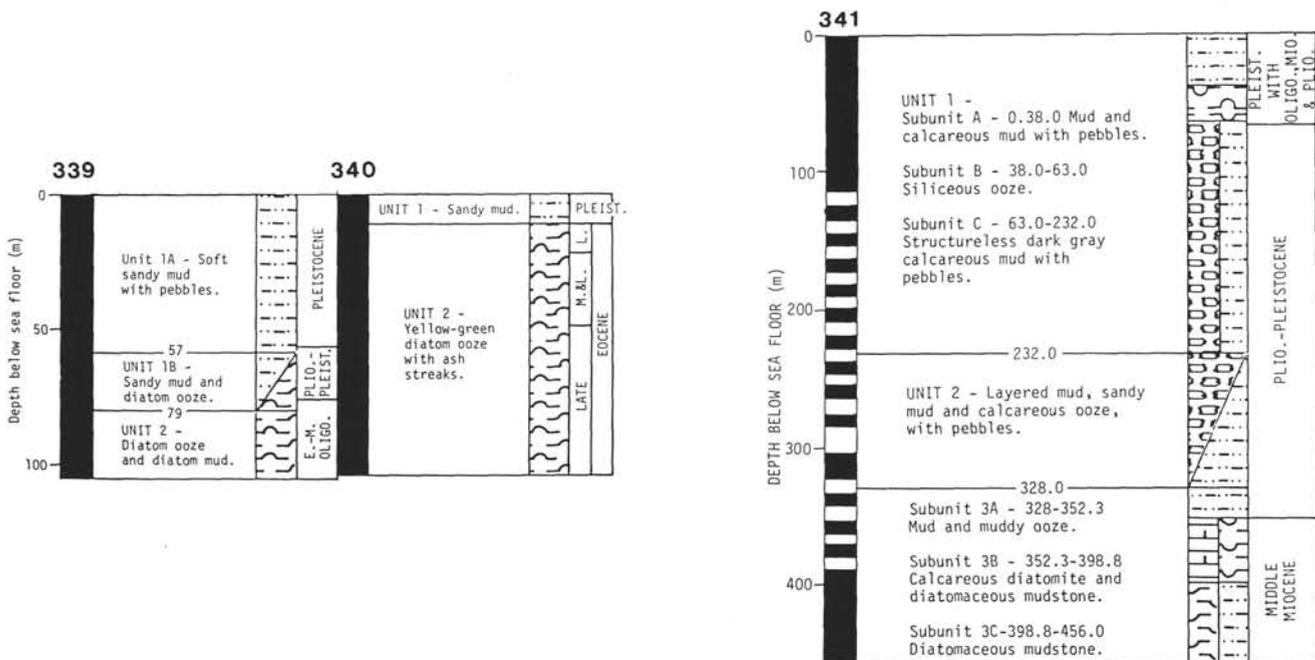


Figure 9. Summary diagrams for DSDP Sites 339, 340, and 341 in the Vøring Basin (Talwani, Udintsev, et al., 1976).

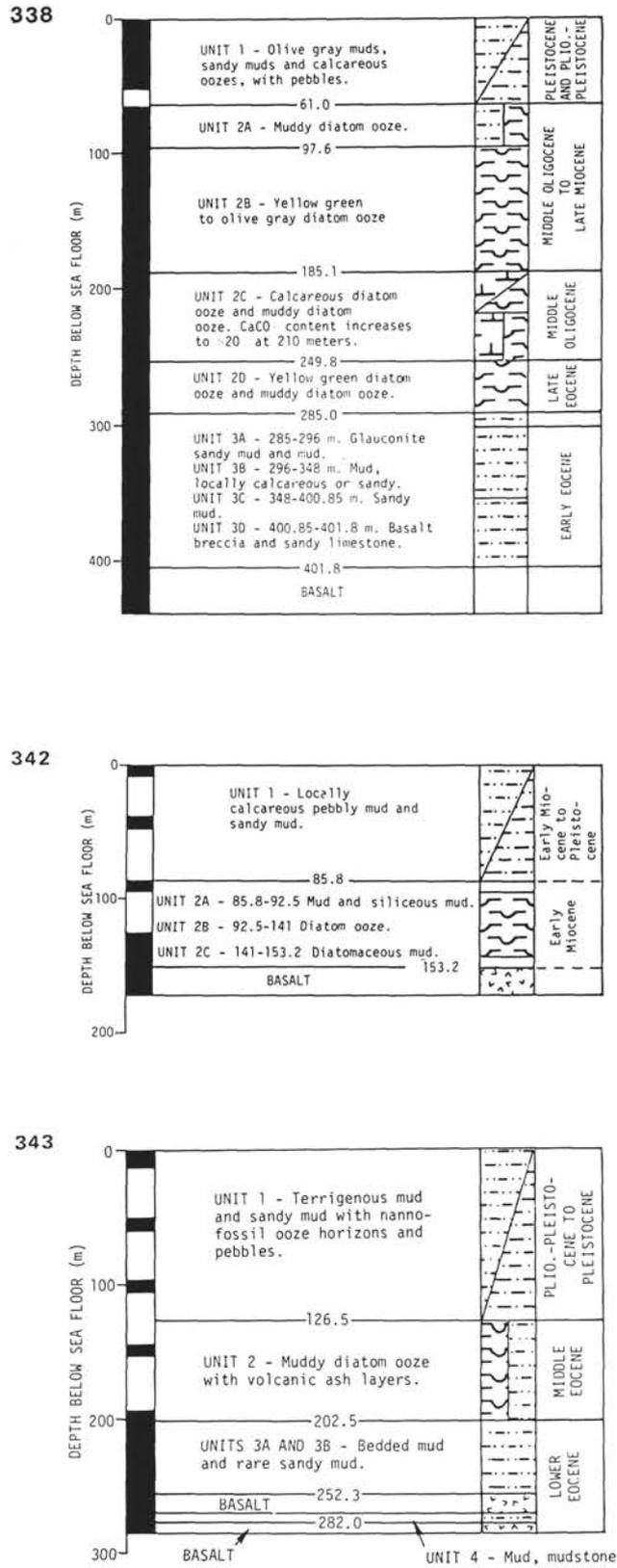


Figure 10. Summary diagrams for DSDP Sites 338 and 342 at the Outer Vøring Plateau and Site 343 at the foot of the outer flank of the plateau (Talwani, Udintsev, et al., 1976).

approached. Then, drilling was continued by using the extended core barrel (XCB) system. When the volcanic section was reached in Hole 642E, drilling was continued using the rotary core barrel system (RCB). To obtain optimal coverage of the Neogene sediments, Sites 642 and 644 were double-cored in a staggered sampling mode using the APC technique. A summary of the coring data is presented in Table 3.

#### Site 642 (Fig. 11)

The sampled section consists of a sedimentary sequence divided into four lithological units above a volcanic sequence comprising an upper and a lower volcanic series. The entire section had been deposited in a terrestrial environment.

Lithologic Unit I is a glacial sequence composed of upper Pliocene to Holocene interbedded dark, carbonate-poor muds and light, carbonate-rich sandy muds representing glacial and interglacial periods, respectively. Lithologic Unit II, divided into four subunits, consists of interbedded, partly mixed, upper Miocene to upper Pliocene siliceous and nannofossil muds and oozes. Lower and middle Miocene siliceous muds and oozes form the bulk of lithological Unit III. At the base of this unit there is a major hiatus and the underlying sediments are lower Eocene volcanoclastic and altered volcanoclastic muds, sandy muds, and sands possibly originating from erosion of the volcanic material below lithological Unit IV. As many as 50 discrete ash layers within the three upper units document late Cenozoic volcanism.

The recovered cores and the logging data have allowed us to establish a detailed stratigraphy of the volcanic section. The upper series consists of 120 lower Eocene flows which are aphyric to moderately plagioclase and olivine-phyric, having N-type MORB composition. These tholeiitic lavas are of two varieties, fine and medium grained. The two flow types, which differ in granularity, crystallinity, flow fabric, physical properties, and average thickness, do not exhibit significant geochemical differences. Fifty-three separate interlayered volcanoclastic sediment beds, composed primarily of basaltic vitric tuffs, constitute approximately 4% of the upper series. This series corresponds to the seaward-dipping wedge of reflectors in the seismic record.

A 13.2 m-thick sediment layer separates the two series at the level of reflector K in the seismic record. The sediment layer consists of laminated mudstones containing compacted pumice fragments cut by an erosional surface above which there are volcanic mass flows with interbedded zones rich in quartz and mica. The lower series is composed of 16 glassy, variolitic, and microcrystalline flows, 6 sediment layers, and 4 dikes. The series was probably emplaced during the earliest Eocene. Chemically, the flows form three groups, (a) a dacitic type that might represent shallow partial melting of continental material; (b) a mix-

ture of this melt and the tholeiites of the upper series; and (c) an intermediate type. The sediments make up 29% of the series, containing significant amounts of continentally-derived clastic mineral grains. Two of the dikes are chemically similar to their bounding flows, whereas the others might be feeders of the upper series.

#### Site 643 (Fig. 12)

The recovered sediments were divided into five lithologic units of which the upper, Unit I, represents a glacial sequence of Pleistocene to Holocene muds and sandy muds. Lithologic Unit II is separated into three subunits and contains upper Miocene and Pliocene siliceous, nannofossil, and partly diatomaceous muds and oozes. Middle and lower Miocene diatomaceous ooze characterizes Unit III. Unit IV is composed of lowermost Miocene monotonous compaction-laminated mudstones, some chalk, and siliceous mudstone. This unit exhibits a high degree of consolidation, and complex diagenetic alteration is observed below 300 mbsf. The lowermost Unit V contains Oligocene and Eocene zeolitic mudstone and altered pyroclastic material including a basaltic conglomerate sampled near the bottom.

Downslope mass movements may have occurred in the two upper units, disturbing the lithologic and biostratigraphic patterns. Fifty-six fresh tephra horizons were detected within Units I, II, and III, whereas no ash was found within the lower units.

#### Site 644 (Fig. 13)

The recovered Quaternary and Neogene sections consist of two lithologic units. The upper, Unit I, which comprises three subunits, is a Holocene to upper Pliocene glacial sequence of muds and oozes. Lithologic Unit II is composed of Pliocene interbedded siliceous oozes and mixed siliceous nannofossil oozes. High concentrations of biogenic gas are characteristic of large parts of the section. These sediments are particularly suited for high-resolution studies of late Cenozoic climatic events.

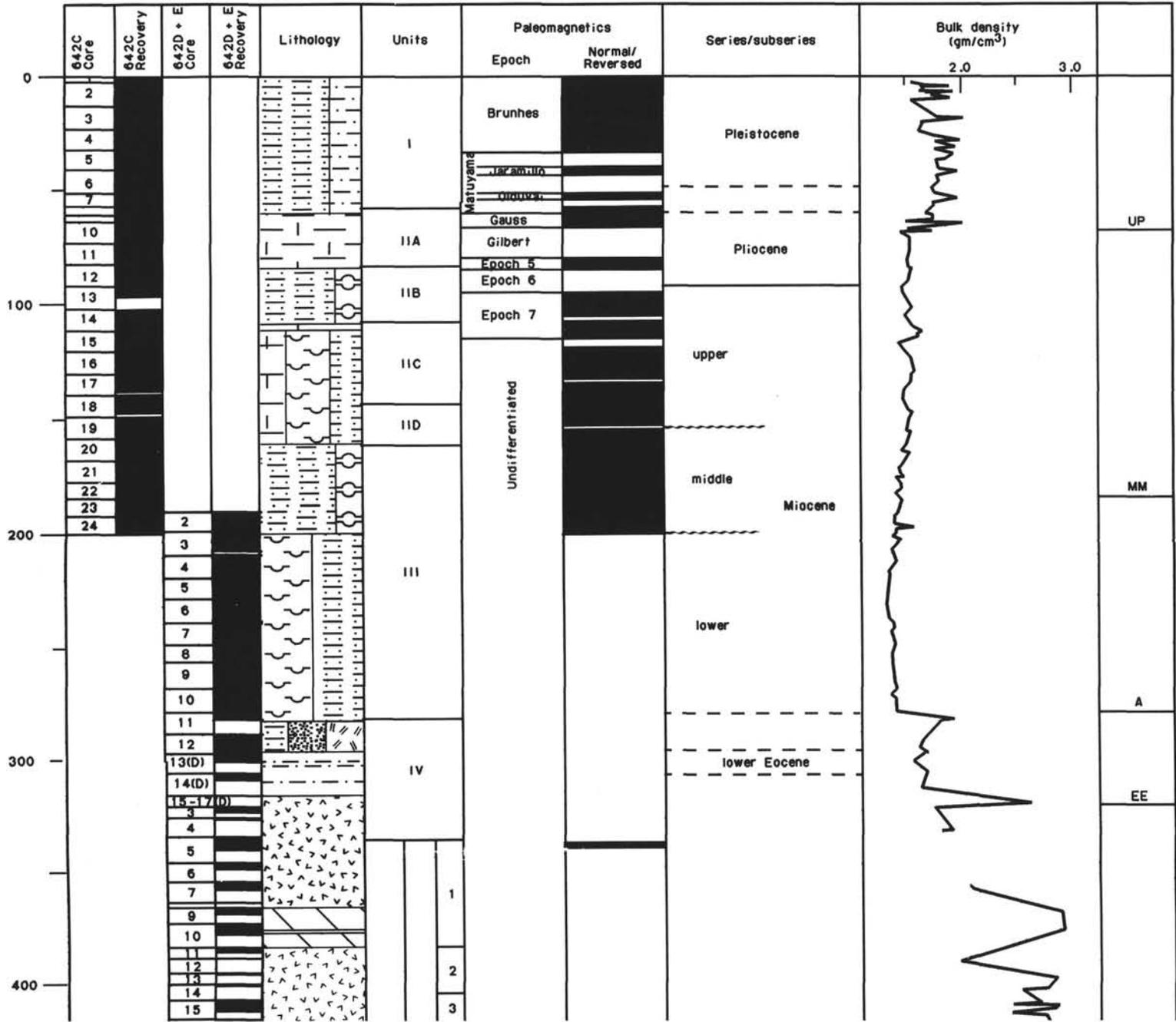
### SUMMARY OF MAJOR ACHIEVEMENTS

Leg 104 was in many ways a shake-down leg for *JOIDES Resolution* and the Ocean Drilling Program. In addition, the leg was the first operation of ODP in a high-latitude environment. The scientific objectives were quite ambitious, requiring a high recovery of undisturbed cores as well as deep reentry penetration and satisfactory recovery in crustal rocks. Nevertheless, the vessel and entire onboard staff performed well and most problems were quickly solved. Both in terms of operations and science we believe the leg was successful.

Operationally, both the APC and XCB coring systems proved to be excellent tools, and the RCB basement penetration was faster and yielded better recovery than anticipated. The 11 reen-

Table 3. ODP Leg 104 coring summary (Eldholm, Thiede, Taylor, et al., 1987).

Hole	Latitude	Longitude	Water depth (m)	No. of cores	Meters cored	Meters recovered	Percent recovered	Total penet. (m)
642A	67°13.5'N	2°55.7'E	1292.7	1	9.5	9.9	104	10.8
642B	67°13.5'N	2°55.7'E	1292.7	25	221.1	215.6	98	221.1
642C	67°13.2'N	2°55.8'E	1292.1	24	199.6	192.8	97	199.6
642D	67°13.2'N	2°55.8'E	1292.1	20	139.0	117.0	84	328.9
642E	67°13.2'N	2°55.8'E	1289.0	107	906.9	372.6	41	1229.4
Totals for Site 642				177	1476.1	907.9	62	1989.8
643A	67°42.9'N	1°02.0'E	2779.8	61	565.2	449.2	79	565.2
644A	66°40.7'N	4°34.6'E	1226.3	34	252.8	238.4	94	252.8
644B	66°40.7'N	4°34.6'E	1225.9	15	127.7	103.6	81	127.7
Total for Site 644				49	380.5	342.0	89	380.5
All Sites				287	2421.8	1699.1	70	2935.5



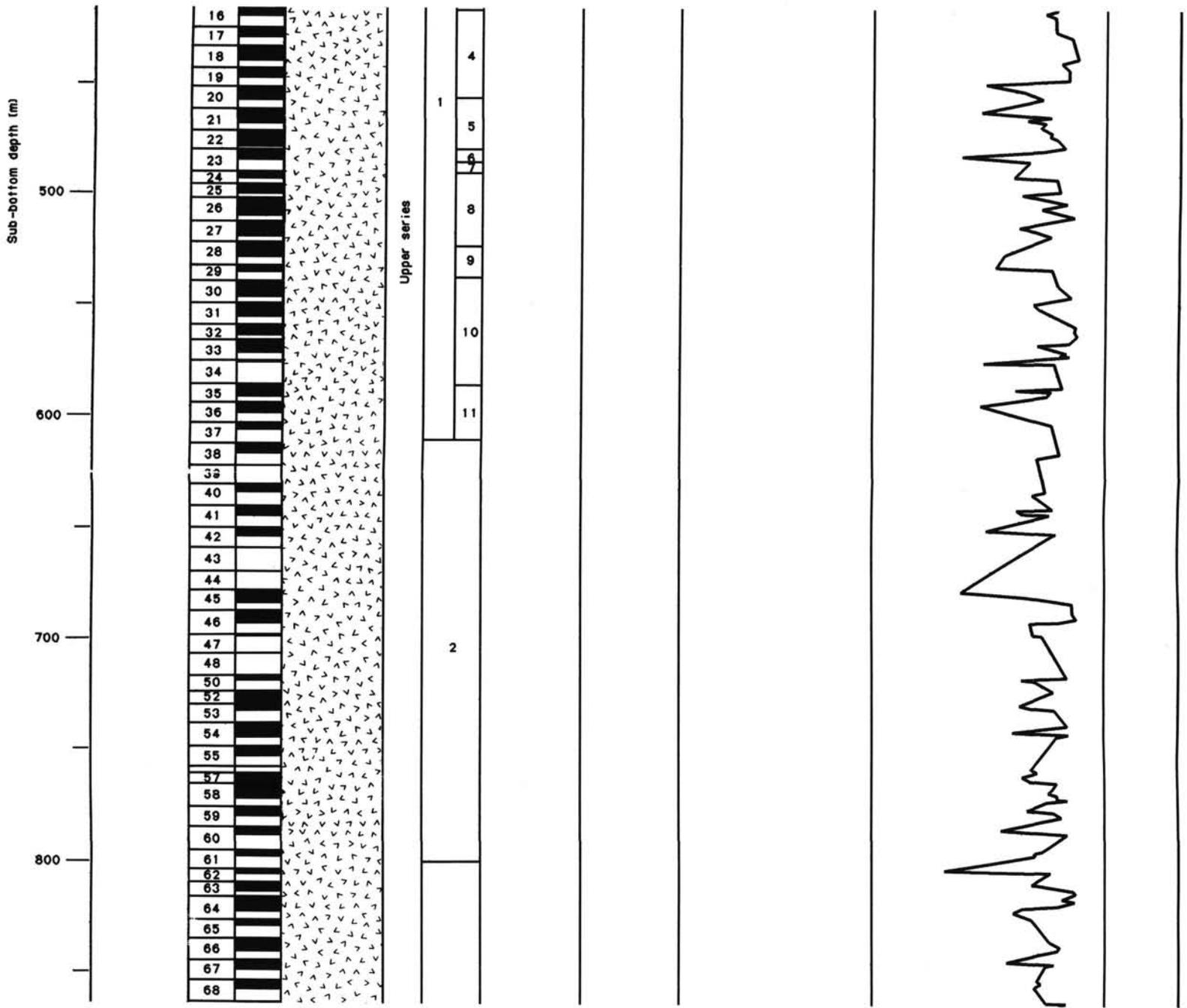


Figure 11. Summary diagram for ODP Site 642.

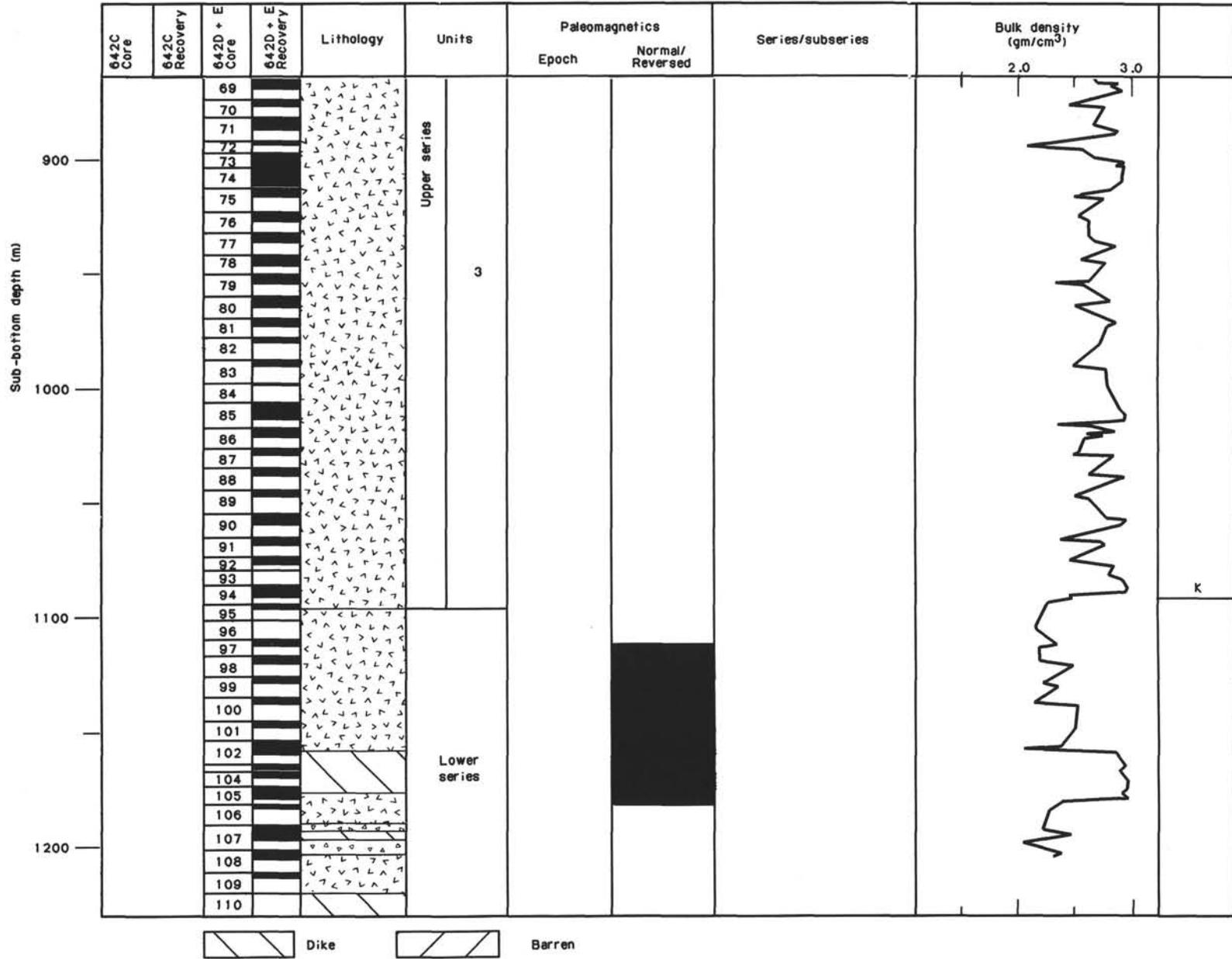


Figure 11 (continued).

tries at Hole 642E must also be noted. The leg featured the first dual-casing reentry cone installation and first VSP experiment of the ODP. It achieved the deepest basement penetration ever during one leg of deep sea drilling, and as of December 1988 Hole 642E was still the deepest ODP site drilled. Finally, despite the high latitude of the operational area, which at times caused severe weather conditions, no weather downtime accrued.

Scientifically, all major objectives were achieved. We drilled through the entire seaward-dipping reflector sequence, the disputed reflector K, and into the underlying rocks. Despite the existence of numerous hiatuses causing correlation and interpretation challenges, the recovered sediment cores have provided a new and unique opportunity for detailed high-resolution studies, particularly of the Neogene paleoenvironment. Both the initial data presentation (Eldholm, Thiede, Taylor et al., 1987) and the present volume are only considered first attempts using the data collection as a basis for geological models and understanding.

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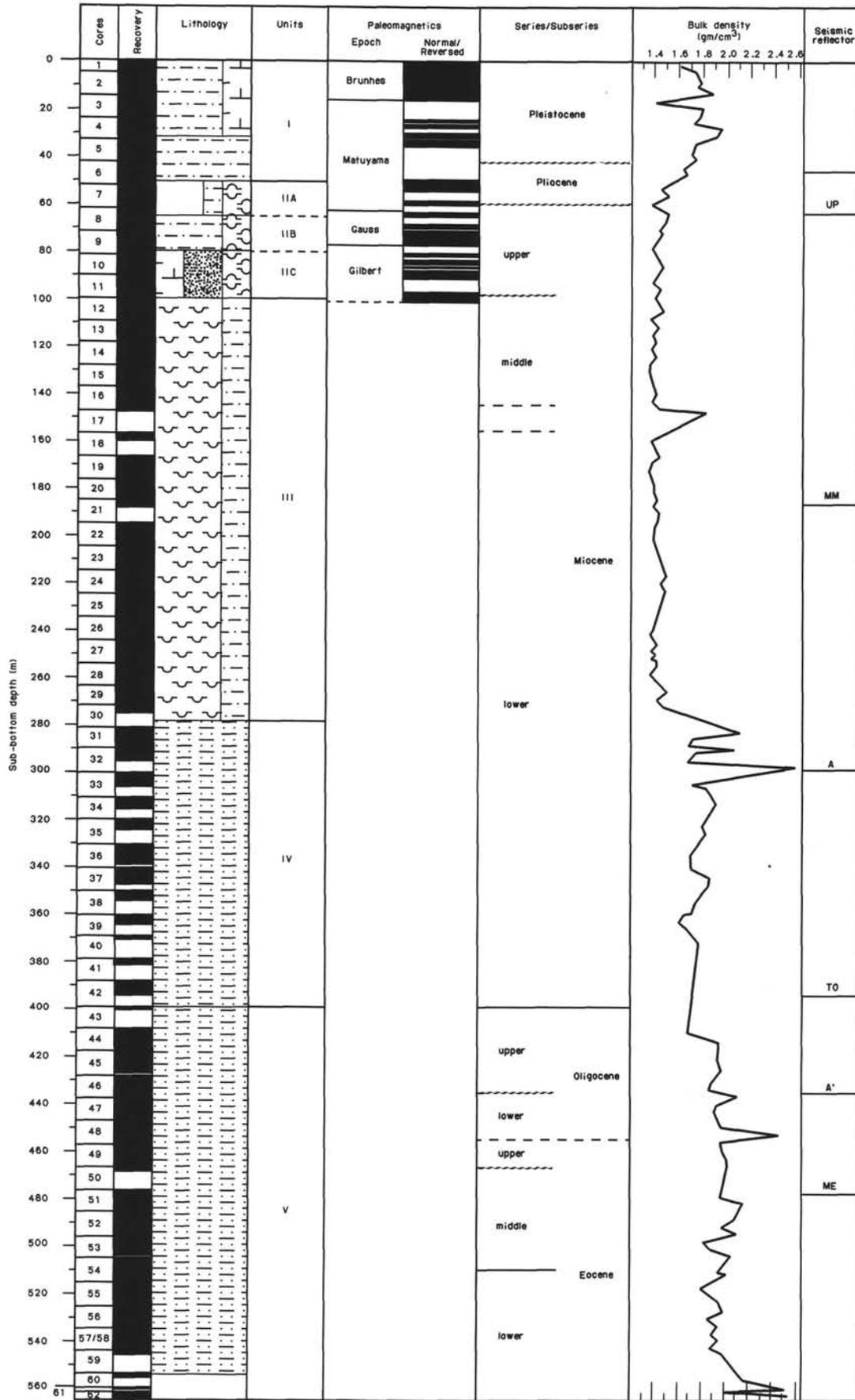
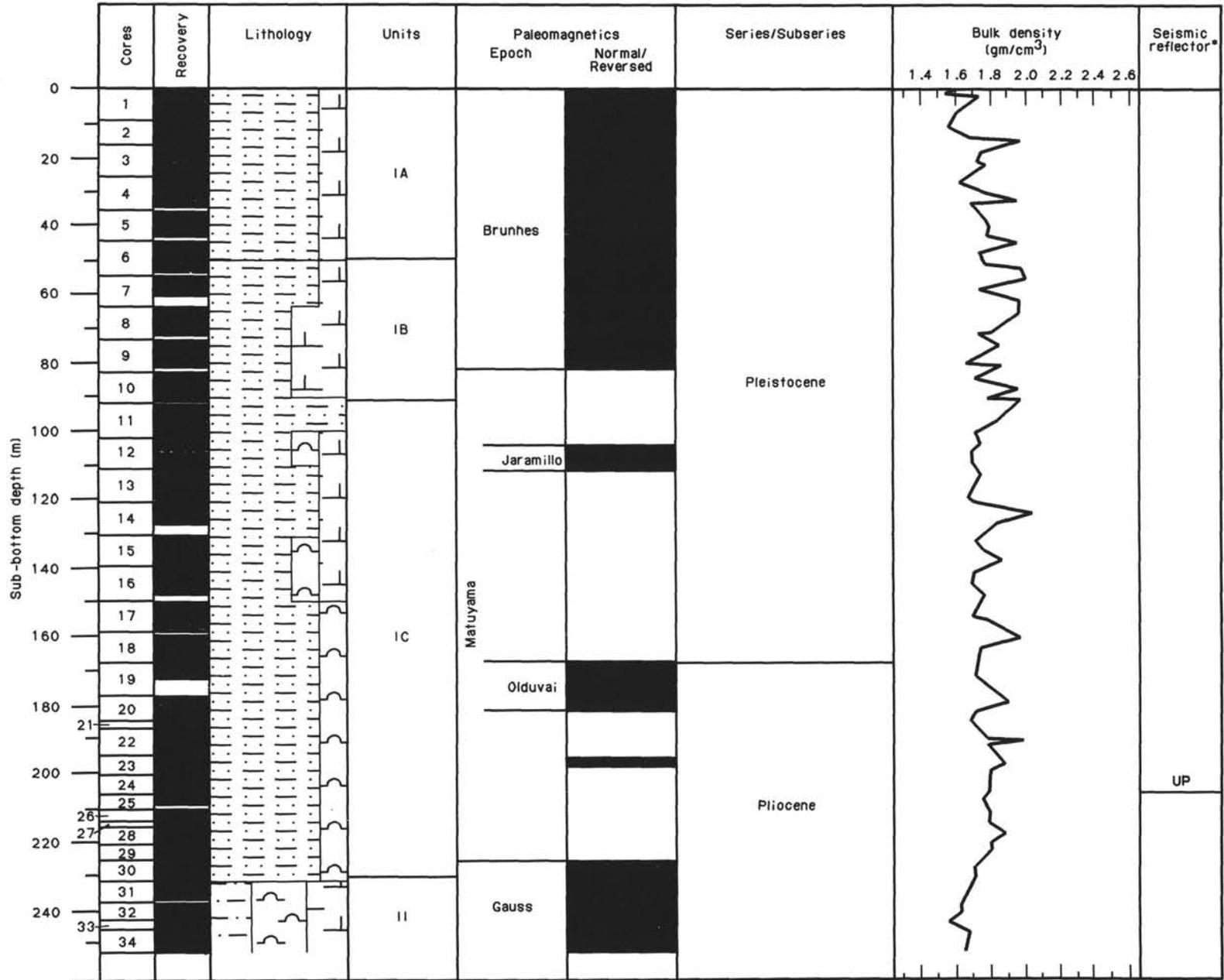


Figure 12. Summary diagram for ODP Site 643.



\* Reflectors are not marked.

Figure 13. Summary diagram for ODP Site 644.