Duncan, R.A., Larsen, H.C., Allan, J.F., et al., 1996
Proceedings of the Ocean Drilling Program, Initial Reports, Vol. 163

3. SITE 988[1]

Shipboard Scientific Party[2]

HOLE 988A

Date occupied: 8 September 1995

Date departed: 10 September 1995

Time on hole: 1 day, 22 hr, 30 min

Position: 65°42.255′N, 34°52.262′W

Bottom felt (drill-pipe measurement from the rig floor, m): 272.7

Distance between rig floor and sea level (m): 10.1

Water depth (drill-pipe measurement from sea level, m): 262.6

Total depth (from rig floor, m): 304.7

Penetration (m): 32.0

Number of cores (including cores having no recovery): 5

Total length of cored section (m): 32.0

Total core recovered (m): 9.6

Core recovery (%): 30

Oldest sediment cored:
Depth (mbsf): 10
Nature: rounded cobbles of continentally derived igneous and metamorphic rocks, probably ice rafted
Earliest age: unknown, probably Quaternary

Top of basement:
Depth (mbsf): 10
Nature: massive and vesicular olivine-pyroxene-plagioclase phyric basalt
Measured velocity (km/s): 5.5–6.0 (5.7 average)

Principal results: Site 988 is located 56 km east of the East Greenland coast, within the northern drilling transect EG66 (Fig. 3, "Introduction" chapter, this volume). The site was selected to penetrate deeply into the featheredge of the seaward-dipping reflector sequence that overlies the transition zone between continent and ocean crust. The primary drilling objectives at this site were to determine the composition, age, and eruption environment of the SDRS in a position close to the Faeroe-Iceland-Greenland Ridge, for comparison with the distal SDRS cored during Leg 152.

Lithologic Unit I is a thin layer (0–10 m below seafloor [mbsf], estimated from seismic profiles and the driller's log; 0.4 m recovered in Core 163-988A-1R) of Quaternary(?) glaciomarine sediments, including rounded cobbles of gabbro, white and pink fine-grained granite, dark gray to black aphyric basalt, and gneiss. The glaciomarine rocks unconformably overlie basaltic basement (igneous Units 1 and 2) at about 10 mbsf.

Two igneous flow units were recognized in the core recovered from the interval at 10–32 mbsf. Igneous Unit 1 is a dark, greenish gray, plagioclase-pyroxene-olivine-phyric basalt. The upper contact was not recovered, and the base of the unit is placed below Section 163-988A-5R-1 (Piece 10); the thickness of the unit is between 19 and 21 m. The unit has a massive aspect and is sparsely vesicular; the vesicles are filled with smectite/saponite and some contain the zeolite chabazite. The glassy groundmass and the majority of the sparse olivine phenocrysts have been replaced by brown smectitic clay. Other phases are unaltered. Igneous Unit 2, of which only 90 cm was recovered from the interval from 29 to 32 mbsf is, by contrast, highly to completely altered, with relict clinopyroxenes in a clay matrix. Texturally, this unit appears to represent the top of a fragmental, perhaps scoriaceous, basalt flow top.

Shipboard X-ray-fluorescence (XRF) data show that both units have high Nb/Zr (0.12), identical to Tertiary basalts from Iceland. The low Ni content and low Mg# of Unit 1 (approximately 74 ppm and 50, respectively) are consistent with the evolved three-phase phenocryst assemblage of this basalt. Both units most likely were emplaced as lava flows, but the absence of an upper contact in Unit 1 means that we cannot eliminate the remote possibility that it is a sill. The highly oxidized aspect of Unit 2 is consistent with emplacement as a flow in a subaerial environment.

The basalts at Site 988 are subhorizontal to gently dipping and show only modest amounts of brittle deformation. Subhorizontal magmatic flow banding is noted locally. Subhorizontal calcite-filled veins occur at a spacing of 0.5–1.0 m. Joints and veins filled by calcite and clay were also found in a subhorizontal and subvertical bimodal distribution. An alteration halo was noted around one subvertical fracture.

Paleomagnetic data for the Site 988 basalts were obtained from the archive-half sections of Cores 163-988A-1R through 5R using the shipboard cryogenic magnetometer. The initial NRM intensity of the core was between 5 and 10 A/m. Demagnetization of each section up to 30 mT removed a steep downward-dipping remanence, possibly acquired by drilling, and reduced intensities to 5%–10% of initial values. The core has a consistent reversed polarity with two exceptions. One interval (163-988A-1R-2, 5–55 cm) of apparent normal polarity occurs within what appears to be a single thick flow. As this is an unlikely occurrence, we conclude that two pieces of core were inverted during labeling and splitting. Another interval of normal polarity is located in the highly altered clay-rich flow top material of Unit 2 present near the bottom of the last section (163-988A-5R-2, 0–10 cm). The magnetic orientation of this material was probably affected by the high degrees of secondary alteration observed or possibly by the drilling process.

Measurements of index properties from minicores yielded an average bulk density of 2.91 g/cm^3, an average grain density of 2.97 g/cm^3, porosities of 10% or less, and *P*-wave velocities from 4.94 to 5.73 km/s for igneous Unit 1. *P*-wave velocities measured directly on the working half of the split core increase downcore through Unit 1, from values of 5.5–5.7 km/s at the top of Unit 1 to 6.0 km/s near its base. An intermediate interval (26.14–26.18 mbsf) with unusually high velocities appears to correlate with flow banding observed at that level (Section 163-988A-4R-1 [Piece 5, 32–38 cm]). The highly vesicular, fragmented, and altered basalts from Unit 2 were not measured.

BACKGROUND AND OBJECTIVES

Site 988 is located 56 km offshore of the East Greenland coast, within the northern drilling transect EG66 (Figs. 1, 2), and is one of the three drill sites that were planned for this transect (Fig. 3, "Introduction" chapter, this volume). Landward (west) of the EG66

[1]Duncan, R.A., Larsen, H.C., Allan, J.F., et al., 1996. *Proc. ODP, Init. Repts.,* 163: College Station, TX (Ocean Drilling Program).
[2]Shipboard Scientific Party is given in the list preceding the Table of Contents.

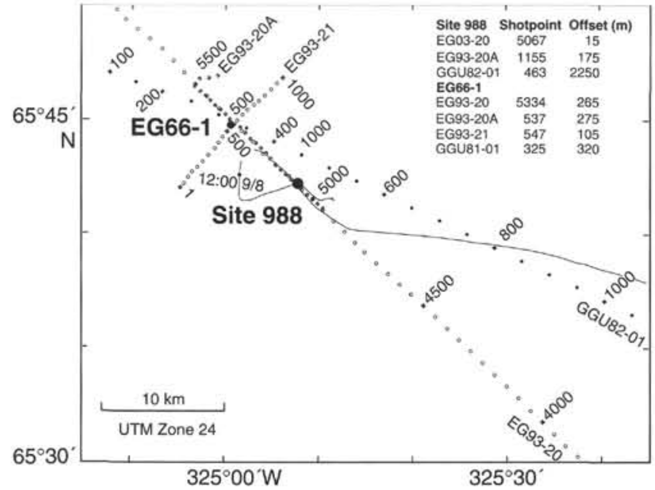

Figure 1. Location of Site 988 drill site and site-survey data.

transect, Precambrian basement is exposed within the high coastal mountains. Along the outermost coast the Precambrian crust is intruded by coast-parallel dikes and plutonic complexes of early Tertiary age (Wager and Deer, 1938; Larsen, 1978; Myers, 1980; Brooks and Nielsen, 1982). Remnants of a more extensive lava cover are locally preserved close to gabbroic intrusions. The lavas have been tectonically rotated seaward and dip as much as 40°–50° (Myers, 1980; Myers et al., 1993).

Geophysical data imply that this geological structure continues seaward for approximately 35 km. At this offset from the coast, a continuous lava cover onlaps basement from the east-southeast (Fig. 5, "Introduction" chapter, this volume). The onlap zone is a monoclinal seaward-facing flexure zone with the lavas dipping up to about 30°. The offshore lava sequence abruptly thickens seaward and is part of the featheredge of the Southeast Greenland SDRS. Within the flexure zone, the lava flows crop out at the seabed or subcrop below thin (5–10 m) glaciomarine sediments in a zone approximately 3 km wide that comprises a lava sequence with a stratigraphic thickness of 1.5–2 km (Fig. 5, "Introduction" chapter, this volume). Seaward, the lavas become covered with progressively thicker postrift sediments of presumed Eocene and younger age. A seafloor-spreading anomaly interpreted as Anomaly 24N is located seaward of the site ("Introduction" chapter, this volume).

Site 988 is located in 262.6 m of water, within the upper part of the lava sequence that crops out at the seabed (Fig. 2). At the drill site, only thin (10–15 m) glaciomarine sediments cover the volcanic series. The top of the volcanic series is marked by a particularly strong reflector package defining a lithologic unit about 20–30 m thick. This top unit shows a gentle seaward dip of approximately 10° and seems to form an integrated part of the overall lava pile.

The main objective of drilling at Site 988 was to retrieve a stratigraphic record of the early part of the Paleogene SDRS at a position close to the Iceland hotspot track (Faeroe-Iceland-Greenland Ridge). At this offset from the Faeroe-Iceland-Greenland Ridge, incompatible-element-enriched, Icelandic plume-type lavas are known from oceanic crust of Neogene age (DSDP Sites 407–409; Luyendyk, Cann, et al., 1979) and from the Reykjanes Ridge itself (summarized in Schilling, 1986). The drill site was located to test whether or not such enriched, plume-related material can be traced back to the time of breakup. The implications of whether such material is clearly present, not present, or only vaguely present from the time of breakup are far reaching with regards to plume emplacement and plume structure (see also Larsen et al., 1994).

Stratigraphically, the drill site was located nearly 2 km above the base of the lava succession. It was hoped that this position would be similar in terms of the overall volcanic development to that of Site 915 and the uppermost part of Site 917 (i.e., above the transition from a lower continental flood basalt sequence into an upper and more oceanic sequence) (Larsen et al., 1994). This would permit sampling a section of early (pre-Chron 24n age) oceanic volcanism with limited or no contamination by continental lithosphere and allow us to determine the influence of the Iceland plume on the source composition during breakup (see also "Introduction" chapter, this volume).

Deep basement penetration at Site 988 was required to provide a long representative lava section. This possibly could include a lower continental succession similar to the lower part of Site 917 and the continental flood basalts exposed onshore north of Site 988. Another important objective of the site was to sample material suitable for precise age determination by $^{40}Ar/^{39}Ar$ methods to further establish the timing and duration of the East Greenland volcanism.

OPERATIONS

Transit to Site 988

At 0800 UTC on 7 September, we began the short transit from Reykjavik to Site 988. Because possible interference by ice at several of the Leg 163 drill sites was expected, *Gadus Atlantica* was hired for the entire leg as an ice support vessel to scout for sea ice and to move small "growlers" (floating pieces of glacial ice <1 m above sea level and <20 m^2 in size) from the vicinity of the *JOIDES Resolution.* At 0915 UTC on 8 September, *Gadus Atlantica* reported the presence of many icebergs, bergy bits (larger pieces of floating glacial ice, 1–5 m above sea level and <300 m^2 in size), and growlers in the drilling area.

At 1115 UTC on 8 September, we approached the survey area. After a 19-km seismic run with the 3.5-kHz depth sounder, as we prepared to drop the beacon on coordinates, we encountered a large iceberg bearing down on the beacon drop point. Because the iceberg was passing close to Site 988, we slowly moved on site approximately 2.6 km "behind" the iceberg as it moved southwest at about 1 kt. We avoided the iceberg by making a sharp turn to starboard after dropping the beacon at 1230 UTC. By 1300 UTC, *JOIDES Resolution* was on site (65°42.255′N, 34°52.262′W).

Hole 988A

Hole 988A was spudded about 56 km offshore of the Southeast Greenland coast in 262.6 m of water. The original plan for Site 988 was to core a single deep (700 mbsf) hole into basaltic basement using a free-fall funnel or, if necessary, a reentry cone with casing. If a single deep hole proved impossible to achieve, we planned to drill a series of shallower offset holes.

We began coring at 2115 UTC on 8 September with a nine-collar RCB bottom-hole assembly (BHA), including a new RBI C-4 bit (SN BD472). Before coring commenced, we viewed the seafloor with a video camera and determined that there was sufficient sediment cover for an RCB spud-in by conducting a drill-string penetration test. Initial coring advanced slowly to 21.4 mbsf with 2.4 m recovered (11%; Table 1). After little advance of the drill bit was made during the latter part of coring of Core 163-988A-2R, the bit was tripped to the surface and found to be jammed with a large amount of basalt in the bit throat and the bit body. Mechanical impressions on two recovered basaltic fragments suggest that the 163-988A-2R core barrel landed on basalt dropped out from the 163-988A-1R core barrel, preventing it from properly seating.

Hole Reentry

Coring resumed with a new harder formation bit (Security H87F). Drill-string reentry of the open hole was accomplished in 15 min without requiring a free-fall funnel. RCB coring advanced in Hole

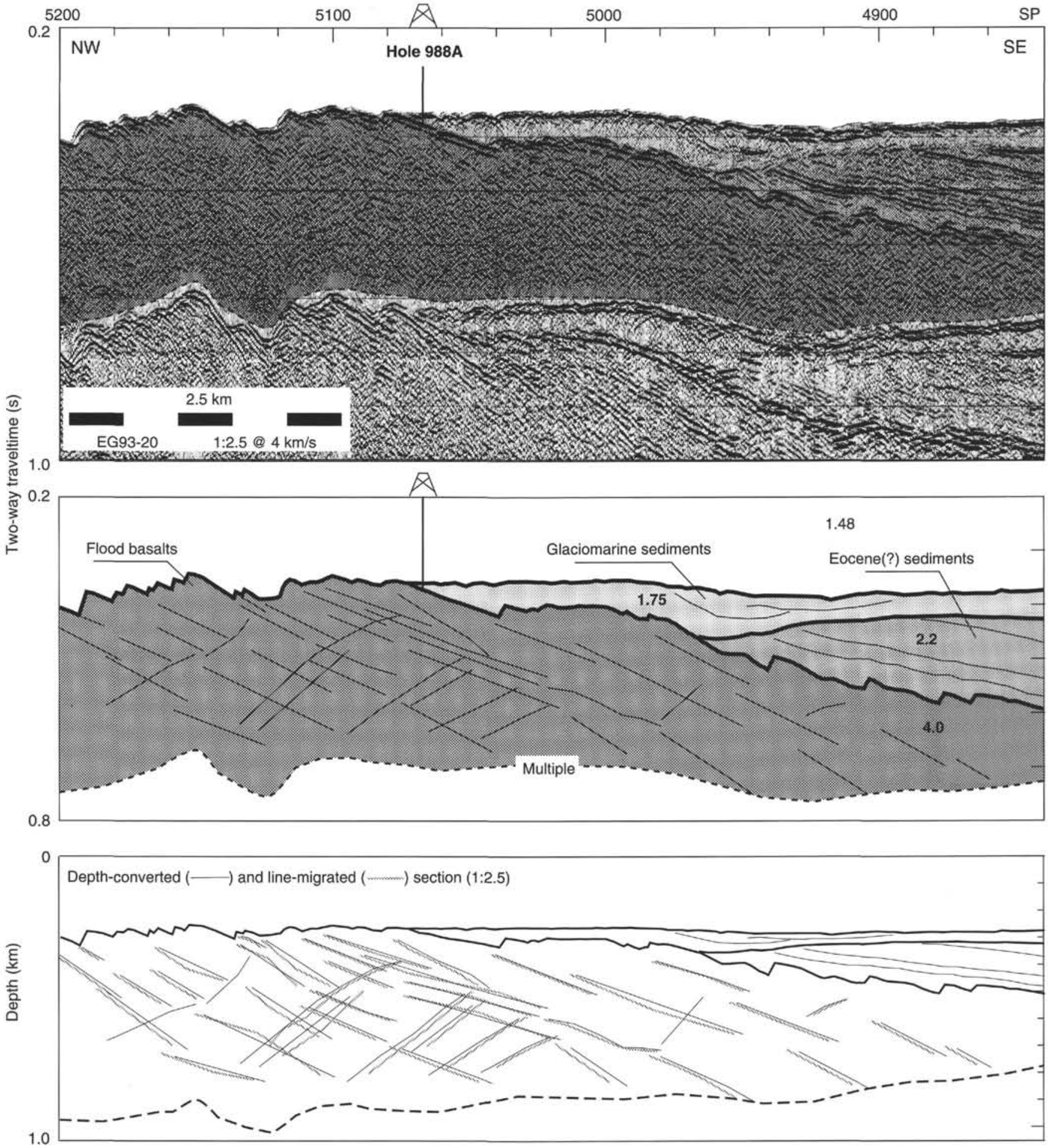

Figure 2. Seismic cross section through Site 988 (top). Interpretations are shown in the line drawing (middle) and migrated section (bottom). The Eocene age of the postrift sediments is inferred through correlation with the EG63 transect (Larsen, Saunders, Clift, et al., 1994). Seismic velocities used in the depth conversion and migration are given in km/s.

988A to 32 mbsf with an average rate of penetration of 1.7 m/hr. After retrieving Core 163-988A-5R, the driller was unable to establish circulation and the hole began to pack off. The drill string could not be rotated and the bit became firmly stuck at 27 mbsf.

While working the stuck drill pipe in an attempt to free the drill string, a joint of 5-in. pipe, approximately 30 m above the BHA and 135 m below the rig floor, parted at 0515 UTC on 10 September. The recoil resulting from the pipe failing under tension caused both tilt-link pin anchors in the top drive motor frame/guide dolly assembly to be torn apart. These anchors secure the swivel to the dolly assembly and are made of 1–1.5-in.-thick steel plate. The top drive and swivel also sustained damage as a result of this recoil. In addition, the imme-

Table 1. Site 988 coring summary.

Core	Date (Sept. 1995)	Time (UTC)	Depth (mbsf)	Length cored (m)	Length recovered (m)	Recovery (%)
163-988A-						
1R	9	0230	0.0–12.4	12.4	1.50	12.1
2R	9	0850	12.4–21.4	9.0	0.85	9.4
3R	9	2245	21.4–27.0	5.6	4.40	78.6
4R	10	0115	27.0–28.0	1.0	1.25	125.0
5R	10	0345	28.0–32.0	4.0	1.59	39.7
Coring totals:				32.0	9.59	30.0

diate release of tension on the drilling line as a result of the rebound caused the drilling line to jump out of the dead line sheave. Because of the extent of hardware damage, it was not possible to effect repairs on location. We steamed to Reykjavik, Iceland, arriving at 1830 UTC on 10 September.

LITHOSTRATIGRAPHY

The sedimentary sequence at Site 988 was not recovered in any coherent way by coring, but several other lines of evidence suggest that the thin sediment cover at Site 988 should be considered a single lithologic unit (lithologic Unit I). Seismic profiles across Site 988 and the driller's log from the site indicate a sediment thickness of approximately 10 m, and sediment characteristics appear homogeneous throughout this interval. The only material recovered from lithologic Unit I consists of discrete rock fragments between 2 and 7 cm long, which were labeled Section 163-988A-1R-1 (Pieces 1–5). These pieces include medium-grained gabbro, white and pink fine-grained granite, dark gray to black aphyric basalt, and gneiss. The lithologies of these clasts are consistent with the lithologies of ice-rafted material recovered during Leg 152; as a result, the clasts recovered at Site 988 are also interpreted as ice-rafted erratics, even though they were not recovered within a finer grained matrix. In comparison with the glacial tills and the glaciomarine sediments drilled at the shelf sites during Leg 152, drilling conditions within the sediments at Site 988 suggest that these are glaciomarine deposits, rather than overcompacted glacial tills.

PALEOMAGNETISM

Paleomagnetic data obtained from Site 988 were measured by the whole-core cryogenic magnetometer on archive-half Sections 163-988A-1R-1 through 163-988A-5R-2. The initial NRM of the core was between 5 and 10 A/m. Demagnetization of each section up to 30 mT removed a steep downward-dipping remanence and reduced intensity to 5%–10% of the initial values, implying that 90% of the original intensities was due to a low-coercivity magnetization, possibly induced by drilling (Fig. 3).

Penetration rates indicate the thickness of the unconsolidated sediments is approximately 10 m, placing the top of the igneous rocks in Hole 988A at 10 mbsf. As the core from Hole 988A was not oriented, only the inclination and intensity of magnetization are meaningful. The core has a consistent reversed polarity from 10.5 to 29.7 mbsf (Table 2 on the CD-ROM in the back pocket of this volume, Fig. 4). The drilling rubble recovered in the intervals from 10.0 to 10.5 mbsf and 13.7 to 21.6 mbsf precluded measurements on these parts of the core. One interval (163-988A-1R-2, 5–55 cm) of apparent normal polarity was recorded within what appears to be a single thick basalt flow. As a reversal in the middle of a flow is unlikely, it is probable that two pieces of the core were inverted during the labeling and splitting process. No marks indicating the bottom of these pieces were found.

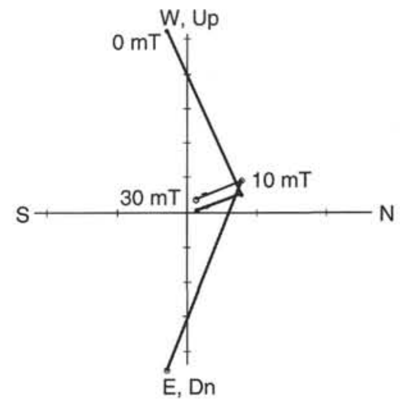

Figure 3. An example of the typical demagnetization curves of the core at Site 988 plotted on a vector component diagram (Zijderveld, 1967). Solid symbols represent projections on the horizontal plane, and open symbols represent projections on the vertical plane. Demagnetization values are shown next to the vector end-points. The diagram illustrates the presence of the subvertical, low-coercivity, high-intensity component typical for much of the Site 988 core.

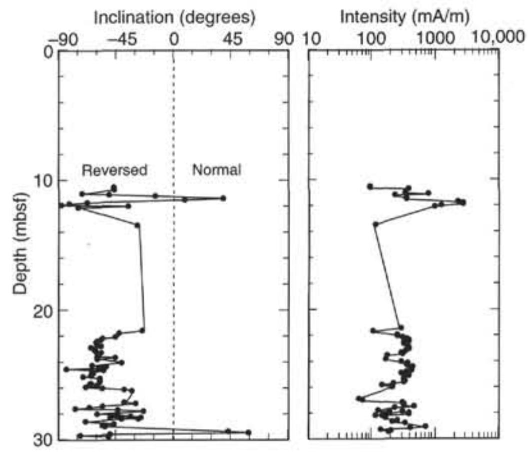

Figure 4. The magnetostratigraphy of Site 988 showing the variation of inclination and intensity after demagnetization at 30 mT. The coring data indicate unconsolidated sediments from 0 to 10 mbsf.

Another interval of normal magnetic polarity is located in the highly altered clay-rich flow-top material near the bottom of the core in igneous Unit 2 (Section 163-988A-5R-2) (see "Igneous Petrology" section, this chapter). We assume that the magnetic orientation of this flow top was probably affected either by high degrees of secondary alteration or by the drilling process, rendering the entire section unreliable for paleomagnetic determinations.

STRUCTURAL GEOLOGY

The recovered sections from Hole 988A show only modest amounts of deformation. The structural measurements made are recorded in Table 3 on the CD-ROM in the back pocket of this volume. Bedding of the lavas appears subhorizontal in the core. Note, however, that although no strong evidence exists in the recovered material

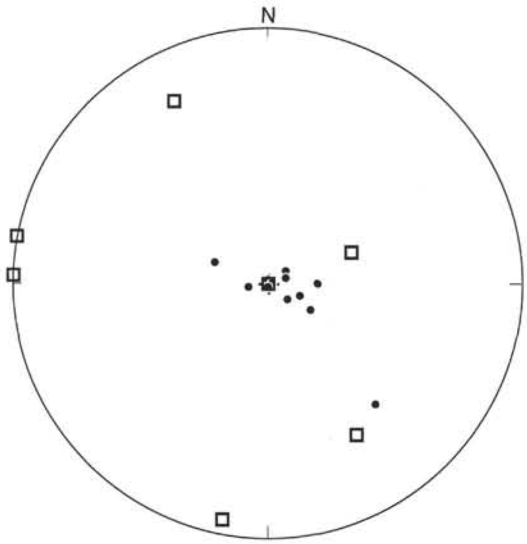

Figure 5. Equal-area stereographic projection showing the measured orientation of features relative to core coordinates. Squares are poles to veins, and dots are magmatic layering and flow banding. A square and three dots are plotted in the center. Magmatic features are strongly clustered at an approximately horizontal orientation, whereas veins show no consistent dip.

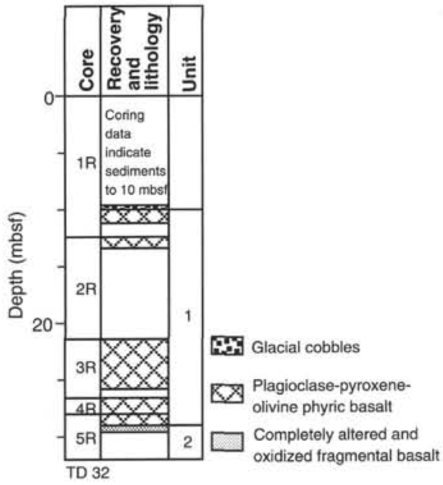

Figure 6. Coring and lithologic summary for Hole 988A.

for significant dips, seismic surveys show a seaward dip of the cored units of about 8°–10° (see "Background and Objectives" section, this chapter). This discrepancy is thought to arise from the lack of precise dip indicators within the recovered core. Brittle jointing and veining of the massive lavas were observed, but were seen to be well spaced with only one joint every 0.5–1.0 m. Joints and veins are oriented in two preferred directions: subhorizontal and subvertical. Figure 5 shows the measured orientations of veins and magmatic features relative to core coordinates. No reorientation of the core to geographic coordinates was made for this site, as no reorientation data were available. Many thin, short veins filled with calcite could not be measured precisely because they do not extend through the core; however, where present they have a consistent subhorizontal orientation. Some of the subvertical fractures are filled by a dark gray clay and calcite, forming veins up to 2–3 mm thick, but typically <1 mm thick. Such veins are present in all sections except Sections 163-988A-2R-1 and 3R-3. Alteration is also apparent as a whitish alteration halo about 1 cm thick around one subvertical fracture in Section 163-988A-3R-1. No displacement was noted along any of the fractures. Given the small penetration achieved and the number of joints and veins, it is not possible to draw any significant conclusions regarding the structural development of the lavas, except to say that they are still relatively flat lying and only weakly deformed.

IGNEOUS PETROLOGY

Lithology

Coring data (penetration rates) indicate that the sediments in Hole 988A are approximately 10 m thick. Therefore, the top of the igneous succession in Hole 988A is placed at 10 mbsf (Fig. 6). Igneous rocks were cored from 10 mbsf to the bottom of the hole, at 32 mbsf. The recovered core consists of two igneous units.

Unit 1 is at least 19 m thick. It is a dark greenish gray to dark gray, slightly to moderately altered plagioclase-pyroxene-olivine glomeroporphyritic basalt. The upper contact is not preserved. We place the lower contact below the sharp and undulating 6-cm chill zone in Section 163-988A-5R-1 (Piece 10). The unit has a massive aspect. It is sparsely vesicular, containing 1%–2% nearly spherical vesicles that are rounded and, in most instances, filled with dark green clay. The upper 1.5 m of this unit has ≤10% vesicles that are commonly flattened and horizontally aligned. The lower 0.4 m of Unit 1 has a patchy distribution of vesicles with vesicularity locally as high as 50% (Section 163-988A-5R-1 [Piece 9, 90–92 cm]). Thin platy olivine phenocrysts also show a nearly horizontal alignment, and faint flow banding is evident in some sections of the flow interior (notably Section 163-988A-4R-1 [Piece 5, 38 cm; Piece 7, 62 cm; and Piece 13, 117–125 cm]).

Unit 2 is a fragmental, highly vesicular, plagioclase-pyroxene-olivine glomeroporphyritic basalt. It is highly to completely altered and in places appears scoriaceous. Only 90 cm of this unit was recovered from the cored interval 29.0 to 32.0 mbsf.

Primary Mineralogy

Phenocrysts of plagioclase, augite, and olivine occur throughout Unit 1. Plagioclase and augite commonly occur together as glomerocrysts (either granular aggregates or ophitic intergrowths) that constitute up to 12% of the rock (Fig. 7; see color version on the CD-ROM). The proportions of the phenocryst phases vary slightly throughout the unit (4% to 8% plagioclase and augite; trace to 2% olivine). The augite phenocrysts show faint pink-green pleochroism, and several crystals exhibit hourglass sector zoning (Fig. 8; see color version on the CD-ROM). The plagioclase shows normal and fine-scale oscillatory zoning (approximately An_{75} to An_{55}) and varying amounts of resorption. The olivine phenocrysts occur as single crystals of either equant or thin, platy habit.

The groundmass of all thin sections contains a mesostasis (~10%–12%) that is now almost entirely replaced by clay. Within the mesostasis are lathlike and commonly skeletal plagioclase, granular anhedral clinopyroxene, and subhedral to anhedral opaque oxides showing magnetite-ilmenite exsolution textures.

In the upper part of the unit all olivine is altered to brown clay, whereas in the lower part of the unit (Section 163-988A-4R-2) some fresh olivine is preserved in the cores of clay pseudomorphs. The other mineral phases are unaltered.

In contrast to Unit 1, Unit 2 is almost completely altered and oxidized to dark yellowish brown clay-rich material with red streaks. Relict clinopyroxene crystals, some of which may be fragments of originally euhedral or subhedral phenocrysts, are scattered through

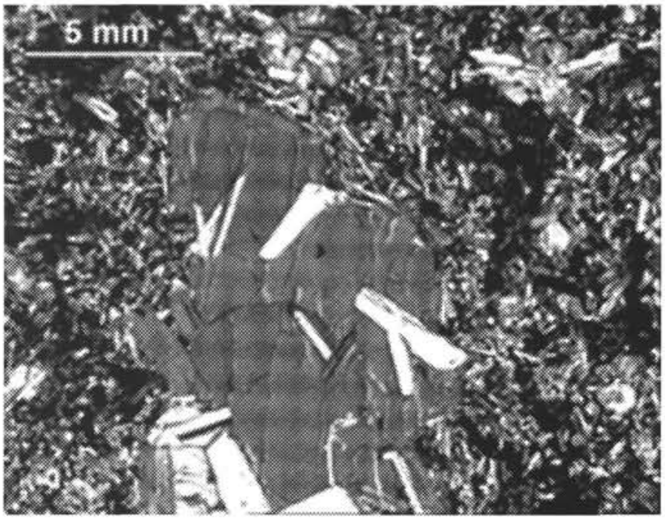

Figure 7. Ophitic enclosure of plagioclase by augite in a glomerocryst in Sample 163-988A-1R-2 (Piece 3C, 28–29 cm). Note the semicontinuous 50-µm-wide outer rim on the augite crystal. A color version of this figure can be found on the CD-ROM (back pocket).

Figure 8. Hourglass sector zoning in a small augite phenocryst in Sample 163-988A-2R-1 (Piece 5, 36–38 cm). A color version of this figure can be found on the CD-ROM (back pocket).

the rock. Ghost outlines of plagioclase crystals, now completely replaced, are also visible embedded in the altered matrix.

Major Oxide and Trace-element Composition

Four samples of volcanic rock (three from Unit 1 and one from Unit 2) were selected for XRF analysis, and the data are presented in Table 4. The three samples from Unit 1 have very similar compositions, suggesting that they represent parts of the same igneous unit. Mg# (~50) and Ni (70–78 ppm) are both much lower than expected for melts in equilibrium with mantle olivine, indicating that the magmas have undergone considerable fractionation. This is consistent with the three-phase (cotectic) phenocryst assemblage. The basalts from Unit 1 are compositionally similar to basalts from the Tertiary lava pile of East Iceland, the Scoresby Sund area of East Greenland, and Site 407 in the Irminger Basin, especially in their ratios of incompatible elements (Table 4).

The composition of Unit 2 has been strongly modified by alteration. MgO, CaO, Sr, Ba, and Ce appear to have been removed from the basalt and K_2O and Rb added. The less mobile elements (Fe, Al, Zr, Nb, Cr, Ni, and V) have been concentrated during the weathering (laterization) process.

Alteration

In the basalts of Unit 1, alteration is most commonly manifested as the partial to total replacement of olivine phenocrysts and the partial to complete filling of vesicles (up to 5 mm) by green clay minerals (trioctahedral smectite/saponite; Table 5). Localized zones of larger vesicles are developed in Section 163-988A-1R-2 (Pieces 7 through 10). These vesicles have clay linings and are only partially filled by a euhedral colorless zeolite (chabazite; Table 5). In thin section the basalts appear slightly to moderately altered with the complete replacement of the mesostasis by clay minerals and iron-oxyhydroxides and extensive iron-staining of grain boundaries and fractures within phenocrysts. Vesicles commonly display narrow concentric rims of brown clay with a more massive filling of lighter brown clay.

Three vein types are present in Unit 1. Thin veins of green smectite display subhorizontal to subvertical orientations and rarely occur with an associated (10 mm) red-brown "oxidation" halo (e.g., Section 163-988A-3R-1 [Pieces 10B, 10C, and 10D]). Thin, wispy, discontinuous veinlets of an unidentified white, silicate mineral (zeolite?) are common in Sections 163-988A-3R-4 through 5R-1. A number of subvertical thin (≈0.1 mm) calcite veins with green smectite wall linings (Table 5) are in Section 163-988A-1R (Pieces 6, 7, 8, and 12). These veins clearly cut through the smectite-filled vesicles.

Unit 2 is a very highly to completely altered vesicular basalt. The recovered material is extensively replaced by red, ocher, and brown clay minerals and iron oxyhydroxides, although relict igneous textures exist within less altered fragments. All traces of the original igneous texture are obliterated in localized patches 1 to 3 cm across, where the primary minerals are replaced by ocher clay minerals. Sample 163-988A-5R-2 (Piece 2) is crosscut by a 2-mm-thick horizontal gypsum vein with an associated rim comprising complex swirls and bands of red to ocher clay minerals. X-ray-diffraction analysis indicates that this rim material is made up of illite-smectite mixed-layer clays and goethite.

Conclusions

The absence of a recovered contact at the top of Unit 1 precludes a precise assessment of the emplacement environment of this unit. The moderately vesicular flow top and base and faint flow banding suggest that it was emplaced as a lava flow, with the flow top either removed by erosion or simply not recovered. The massive aspect and generally low vesicularity of the unit leave the remote possibility that it may be a sill. The highly vesicular, oxidized, and weathered nature of Unit 2 suggests that it is the top of a basalt flow that was erupted in a subaerial environment. The similarity between Units 1 and 2, at least in terms of highly immobile element ratios (e.g., Nb/Zr), suggests that the two units originated from a similar parental magma.

The trace-element abundances, particularly of immobile elements such as Zr and Nb, are similar to those in Tertiary basalts from Iceland; Scoresby Sund, East Greenland; and Site 407 in the Irminger Basin (Table 4).

PHYSICAL PROPERTIES

One sedimentary unit and two igneous units were drilled at Site 988, but physical properties measurements at Site 988 were limited to the short interval cored within the igneous units. The multisensor track was being upgraded during the drilling of Site 988 and was un-

Table 4. Major oxide (wt%) and trace-element (ppm) composition of basaltic rocks from Hole 988A and from East Iceland, Scoresby Sund in East Greenland, and DSDP Site 407 in the Irminger Basin.

Hole:	988A	988A	988A	988A			407
Core, section:	1R-2	3R-3	4R-1	5R-2	East	Scoresby	39-1
Interval (cm):	25–28	108–113	71–74	28–31	Iceland	Sund	55–59
Unit:	1	1	1	2			
Major oxides							
SiO_2	48.69	48.43	48.69	39.84	48.51	48.24	48.19
TiO_2	2.42	2.47	2.46	4.74	2.71	2.59	2.88
Al_2O_3	14.31	14.22	13.92	24.87	14.57	14.16	13.26
Fe_2O_3(t)	13.57	14.04	13.89	23.13	14.28	14.01	14.43
MnO	0.19	0.24	0.21	0.25	0.21	0.18	0.22
MgO	6.12	6.51	5.99	1.38	6.02	6.69	6.02
CaO	11.52	11.14	11.34	1.74	10.58	11.31	10.92
Na_2O	2.40	2.30	2.31	1.45	2.42	2.37	2.48
K_2O	0.42	0.46	0.46	0.94	0.39	0.28	0.38
P_2O_5	0.25	0.26	0.26	0.10	0.31	0.23	0.33
Total	99.87	100.05	99.51	98.41	100.00	100.06	99.11
LOI	0.49	0.98	0.44	8.80	0.90	0.91	0.79
Mg#	50.85	51.57	49.73	12.01	49.18	52.29	48.92
Trace elements							
Nb	18.1	18.6	18.2	30.6	19.2	11.8	22.8
Zr	156	158	158	255	171	147	195
Y	31	31	31	53	37	31	42
Sr	232	216	230	72	293	247	235
Rb	3.0	3.7	4.8	16.8	5.6	4.4	4.4
Zn	102	110	102	168	117	102	ND
Cu	275	204	228	198	125	234	ND
Ni	78	73	70	122	63	139	ND
Cr	117	118	108	441	118	262	106
V	372	366	337	662	365	ND	403
Ce	35	33	39	BDL	38	ND	ND
Ba	100	113	115	BDL	114	71	74
Nb/Zr	0.12	0.12	0.12	0.12	0.11	0.08	0.12
Ce/Y	1.13	1.06	1.26	—	1.03	—	—

Notes: East Iceland basalt: average of 588 analyses (J.G. Fitton and B.S. Hardarson, pers. comm., 1995). Scoresby Sund basalt: Sample 215495 (Larsen et al., 1989). Basalt from DSDP Site 407 (Luyendyk, Cann, et al., 1978). Fe_2O_3(t) = total iron as Fe_2O_3. LOI = loss on ignition. Mg# = 100[MgO/(MgO + FeO)] (molecular oxide amounts) with Fe_2O_3/FeO = 0.15. BDL = below detection limit. ND = not determined. All determinations by X-ray-fluorescence spectrometry (analysts Don Sims and Joel Sparks).

Table 5. Selected minerals from Site 988 identified by X-ray diffraction.

Core, section, piece, interval (cm)	Description	XRD identification
163-988A-		
1R-1 (Piece 8, 60–68)	White vein mineral	Calcite ± saponite
1R-1 (Piece 12A, 104–105)	Green vesicle filling	Trioctahedral smectite
1R-2 (Piece 8, 89–91)	White to colorless euhedal vug filling	Chabazite (zeolite)
5R-2 (Piece 2, 25)	White crystalline vein (2 mm) filling	Gypsum
5R-2 (Piece 2, 25)	Ocher clay/vein margin	Illite/smectite mixed-layer clay + goethite

available for use; as a result, index properties and *P*-wave velocities were measured on three minicores and *P*-wave velocities were measured on seawater-saturated split cores.

Acoustic Velocity

Measurements were made on samples of Site 988 core material with three objectives: (1) to determine the *P*-wave velocities of the samples, (2) to establish the reproducibility of the *P*-wave velocities measured, and (3) to compare velocities measured on minicores to velocities measured directly on the working half of the split core. The *P*-wave velocities measured on the three minicores from igneous Unit 1 are listed in Table 6. These values range from 4.94 to 5.73 km/s and decrease as the porosity of the sample increases. Velocities were measured repeatedly on two seawater-saturated split-core samples (20 measurements each), yielding a standard deviation in the velocity measurements of 0.03 km/s (less than 1% error).

To answer objective (3), velocities were measured directly on the working half of the split core at a 2-cm interval along competent pieces of basalt within igneous Unit 1, using the Hamilton Frame velocimeter. These velocity measurements are listed in Table 7 and plotted in Figure 9. The velocities measured on the minicores are approximately 3% faster than the velocities measured directly on the corresponding portions of the split core. This difference may be due to the retarding effects of drilling-induced fracturing along the outer walls of the core sections.

In general, both the velocities measured on the minicores and the velocities measured directly on the working half of the split core are high (near and above 5.5 km/s), and the split-core velocities increase to greater than 6 km/s near the base of igneous Unit 1. Section 163-988A-3R-4 (Piece 6) (26.18–26.24 mbsf) yielded velocities that are consistently higher than those of the immediately overlying and underlying material. In a general sense, the high velocities presented for igneous Unit 1 may be somewhat misleading because drilling is expected to preferentially recover fresh and compact basalts. Highly vesicular, fragmented, or altered basalts, such as those in igneous Unit 2, either are not well represented in the recovered core or, where present, did not yield reliable measurements of seismic velocities. As a result, the average *P*-wave velocity of approximately 5.7 km/s in the recovered material may be considered an upper limit for the average velocity of the entire interval drilled.

Index Properties

Index properties were measured on three minicores that subsampled the thick igneous Unit 1 at Site 988. These data are presented in

Table 6. *P*-wave velocity and index properties measured on minicores from igneous Unit 1, Site 988.

Core, section, interval (cm)	Depth (mbsf)	Saturated *P*-wave velocity (km/s)	Saturated Mass (g)	Saturated Volume (cm^3)	Dry Mass (g)	Dry Volume (cm^3)	Bulk density (g/cm^3)	Water content (%)	Porosity (%)	Grain density (g/cm^3)	Comments
163-988A-											
1R-2, 76–78	1.9	5.47	33.474	11.53	32.720	11.01	2.91	2.30	6.4	2.97	Filled vesicles
1R-2, 82–84	1.96	4.94	29.181	10.11	28.307	9.39	2.89	3.20	8.6	3.02	Vesicular
3R-3, 71–73	24.81	5.73	38.140	13.02	37.812	12.97	2.93	0.80	2.4	2.92	Fine grained

Notes: Salinity = 0.035; pore-fluid density = 1.024 g/cm^3.

Table 7. *P*-wave velocity measurements performed directly on seawater-saturated split core sections from Hole 988A.

Core, section, piece, interval (cm)	Depth (mbsf)	*P*-wave velocity (km/s)	Comments
163-988A-			
1R-2 (Piece 5A, 50)	1.63	5.26	
1R-2 (Piece 5A, 54)	1.67	5.33	
2R-1 (Piece 2, 14)	12.54	5.99	Irregularly shaped piece
3R-1 (Piece 10A, 58)	21.98	5.70	
3R-1 (Piece 10A, 60)	22.00	5.71	
3R-1 (Piece 10A, 62)	22.02	5.70	
3R-1 (Piece 10A, 64)	22.04	5.72	
3R-1 (Piece 10A, 66)	22.06	5.65	Crack
3R-1 (Piece 10A, 68)	22.08	5.67	
3R-1 (Piece 10A, 70)	22.10	5.74	

Note: Where possible, the sampling interval was 2 cm within a competent basalt piece.

Only part of this table is reproduced here. The entire table appears on the CD-ROM in the back pocket of this volume.

Table 6. The average bulk density of these 15 samples is 2.91 g/cm^3, with a standard deviation of 0.03 g/cm^3. The average grain density is 2.97 g/cm^3, with a standard deviation of 0.03 g/cm^3. Porosities are 10% or less, and the calculated porosities and densities vary as expected from the visual descriptions of sample vesicularity (see "Comments," Table 6).

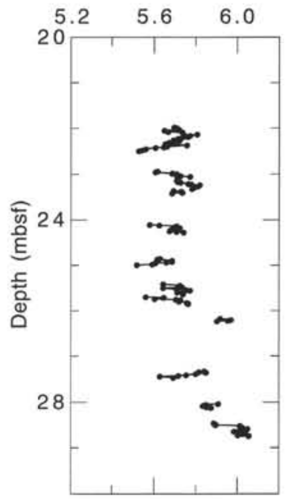

Figure 9. Downcore profile of *P*-wave velocity in igneous Unit 1, Site 988, measured on the working half of the split core. Where possible, the sampling interval was 2 cm within a competent basalt piece.

REFERENCES

Brooks, C.K., and Nielsen, T.F.D., 1982. The East Greenland continental margin: a transition between oceanic and continental magmatism. *J. Geol. Soc. London,* 139:265–275.

Larsen, H.C., 1978. Offshore continuation of East Greenland dyke swarm and North Atlantic Ocean formation. *Nature,* 274:220–223.

Larsen, H.C., Saunders, A.D., Clift, P.D., and the Shipboard Scientific Party, 1994. Introduction: breakup of the Southeast Greenland Margin and the formation of the Irminger Basin: background and scientific objectives. *In* Larsen, H.C., Saunders, A.D., Clift, P.D., et al., *Proc. ODP, Init. Repts.,* 152: College Station, TX (Ocean Drilling Program), 5–16.

Larsen, L.M., Watt, W.S., and Watt, M., 1989. Geology and petrology of the Lower Tertiary plateau basalts of the Scoresby Sund region, East Greenland. *Bull.—Groenl. Geol. Unders.,* 157:1–164.

Luyendyk, B.P., Cann, J.R., et al., 1979. *Init. Repts. DSDP,* 49: Washington (U.S. Govt. Printing Office).

Myers, J.S., 1980. Structure of the coastal dyke swarm and associated plutonic intrusions of East Greenland. *Earth Planet. Sci. Lett.,* 46:407–418.

Myers, J.S., Gill, R.C.O., Rex, D.C., and Charnley, N.R., 1993. The Kap Gustav Holm Tertiary Plutonic Centre, East Greenland. *J. Geol. Soc. London,* 150:259–276.

Schilling, J.-G., 1986. Geochemical and isotopic variation along the Mid-Atlantic Ridge axis from 79°N to 0°N. *In* Vogt, P.R., and Tucholke, B.E. (Eds.), *The Western North Atlantic Region:* Boulder, CO (Geol. Soc. Am.), Geol. of North Am. Ser., M:137–156.

Wager, L.R., and Deer, W.A., 1938. A dyke swarm and coastal flexure in East Greenland. *Geol. Mag.,* 75:39–46.

Zijderveld, J.D.A., 1967. AC demagnetization of rocks: analysis of results. *In* Collinson, D.W., Creer, K.M., and Runcorn, S.K. (Eds.), *Methods in Palaeomagnetism:* New York (Elsevier), 254–286.

Ms 163IR-103

NOTE: For all sites drilled, core-description forms ("barrel sheets") and core photographs can be found in Section 3, beginning on page 71. Thin-section data can be found in Section 4, beginning on page 253. See Table of Contents for material contained on CD-ROM.