OCEAN DRILLING PROGRAM

LEG 163 PRELIMINARY REPORT

SOUTHEAST GREENLAND MARGIN

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ABSTRACT

ODP Leg 163 was the second of two drilling legs to the Southeast Greenland margin to core an enormous pile of subaerially, erupted basalts associated with continental breakup that occured in the early Tertiary. Together with Leg 152 this program addressed the nature of rifting and breakup at this rifted continental margin and, in particular, assessed the impact of the Iceland mantle plume on breakup and early spreading. These investigations build on earlier DSDP and ODP drilling of seaward-dipping reflector sequences (SDRSs) on the Rockall and Vøring Plateaus (Legs 81 and 104), with the these SDRS occurrences and associated extensive subaerial exposures of Tertiary basalts on Greenland, the Faeroe Islands, and western British Isles collectively forming the North Atlantic Volcanic Province. Principle results are as follows:

1. completion of the record of volcanic evolution of the East Greenland margin at latitude 63°N, from continental breakup to oceanic crustal production;

2. fundamental constraints on the age of SDRS volcanism, from preliminary identification of the first two magnetic polarity reversals yet discovered in the East Greenland SDRS; and

3. the identification that the Iceland plume mantle component is more strongly expressed in the composition of the basalts at latitude 66°N compared with 63°N.

The third result, together with previous evidence from DSDP Leg 81 and ODP Leg 104, provides sufficient information to map the basic compositional structure of the mantle melting regime that existed during the initiation of the Iceland plume and breakup of the North Atlantic.

INTRODUCTION

Strategy

The Southeast Greenland margin is a type example of a volcanic-rifted margin. The margin is characterized by a broad seaward-dipping reflector sequence (SDRS) composed of basalt that onlaps continental (mainly Precambrian) crust to the west and terminates eastward in oceanic crust of early Tertiary age (Figs. 1, 2). In the Northeast Atlantic, seafloor-spreading Anomalies 24n–24r are the oldest identified pair of anomalies (Talwani and Eldholm, 1977; Srivastava and Tapscott, 1986; Larsen, 1988). Anomaly 24n is developed off Southeast Greenland as a double-peaked anomaly, reflecting the three short positive events C24n.1 through C24n.3 and relatively high spreading rates during this interval (approximately 3 cm/yr half-rate; Larsen, 1980).

The minimum age of the Southeast Greenland SDRS is constrained by the seaward occurrence of well-developed seafloor-spreading anomalies (Fig. 1; Larsen and Jakobsdottir, 1988). In the north, close to the Iceland-Greenland Ridge, the SDRS extends seaward to Chrons C22n-C21n (49-47 Ma). However, most of the Southeast Greenland SDRS is found landward of and is older than C24n.1 (53 Ma; Cande and Kent, 1992). Weak and semilinear magnetic anomalies are present over the main SDRS and may represent either low-amplitude anomalies older than C24n (e.g., C25n–C27n, 56–61 Ma) or short magnetic events within C24r (the chryptochrons of Cande and Kent, 1992; see also discussion in “Summary” chapter, Larsen, Saunders, Clift, et al., 1994).

Evidence for significant magmatism and tectonism during continental breakup is not restricted to the offshore areas. A coast-parallel dike swarm and associated seaward flexuring of the crust one present from 63°N along the east Greenland coast and northward. Within this zone, gabbroic and syenitic intrusions are present (Fig. 1; Myers, 1980; Myers et al., 1993) and locally associated with basaltic lavas overlying thin sediments (for review see Larsen, 1980; Nielsen et al., 1981; Brooks and Nielsen, 1982). Farther north, a much more extensive and thick flood basalt province is preserved (Fig. 1; Larsen et al., 1989). Comprehensive studies of the onshore region are being conducted in parallel with Ocean Drilling Program (ODP) drilling and will be augmented in 1996 with a program of deep crustal seismic imaging that includes the region (Larsen et al, in press). In particular, ODP drilling and field geological studies will aim at correlating the on- and offshore parts of the crustal flexure zone and the volcanic stratigraphy within the two areas.

Drilling was positioned along two margin transects, located distal (Legs 152 and 163) and proximal (Leg 163) to the Iceland plume center. The two transects were named EG63 and EG66, respectively, in reference to their approximate latitudes. At each transect, drilling was targeted at the prerift crust, the breakup unconformity and earliest volcanism, the transition from initial continental volcanism to ocean crust volcanism, and, most seaward, a reference hole in steady-state spreading crust. This drilling strategy was designed (Larsen et al., 1991) with two primary objectives: (1) the investigation of the development with time along each transect would tell us about the progressive weakening of the continental crust and the associated magmatic development and (2) the study of magmatic development and the magma source at different offsets from the Iceland plume would enable us to evaluate possible radial zonation in the original plume structure. Additional reference points for the second objective are provided by the earlier Deep Sea Drilling Project (DSDP) Leg 81 drilling at the Hatton Bank margin (most distal southern offset; Joron et al., 1984) and ODP Leg 104 drilling at the Vøring margin (intermediate northern offset; Viereck et al., 1988; see also Larsen, Saunders, Clift et al., 1994).

Geophysical Database

Legs 152 and 163 were based on a large set of seismic data over the Southeast Greenland margin (Fig. 3). The database comprises three different sets of seismic data: (1) regional to detailed grids of shallow, high-resolution multichannel seismic (MCS) data (Larsen et al., 1994); (2) a regional grid of deep 7-s (two way traveltime, TWT) MCS data; and (3) deep 14-s (TWT) MCS data (Larsen, in press). In addition, aeromagnetic and regional marine gravity data exist (for a more extensive review and references see Larsen, 1990; Larsen, Saunders, Clift, et al., 1994).

Leg 152 Results and Implications for Leg 163

A number of important observations made during Leg 152 drilling into the Southeast Greenland SDRS significantly affected the detailed planning of Leg 163. These include the following: (1) highly tilted to subvertical prerift sediments occur below the inner part of the SDRS; (2) an early, continentally hosted and contaminated basaltic to andesitic volcanism of 61–62 Ma age (Sinton et al; 1994) overlies these sediments; (3) the upper limit of these lower lavas is a sharp transition — possibly a hiatus — into picritic to tholeiitic lavas followed by basalts of a rather uniform composition that resemble depleted tholeiites from Iceland and appear to make up the main part of the SDRS; and (4) all recovered igneous units were erupted subaerially. Thus, Leg 152 confirmed that the SDRS is a wedge of predominantly basaltic material extruded subaerially in accord with the model for crustal accretion in Iceland (Pàlmason, 1986) and with the interpretation of seismic data (Mutter et al., 1982; Larsen and Jakobsdottir, 1988).

The Leg 152 findings imply the presence of a rapid transition from continental to oceanic crust below the inner part of the SDRS. During formation of this continent to ocean transition, pre-rift sediments were deposited in a basin of unknown width and, later, in a zone close to the final line of breakup, subjected to faulting and crustal extension, uplift and erosion prior to volcanism (see also Larsen, Saunders, Clift et al., 1994).

The Leg 152 data are deficient in a number of aspects. These include a lack of suitable material for age determination of the oceanic succession (i.e., the main part of the SDRS), noncontinuous sampling of the transition from initial picritic to depleted tholeiitic volcanism within the oceanic succession, and nonrecovery of the oldest part of the continental volcanic succession. In addition, the prerift sediments were poorly sampled because of their subvertical orientation, and they have been too strongly metamorphosed to yield any age-diagnostic fossils or palynomorphs.

Leg 163 was planned to overcome these deficiencies within the southern EG63 transect, as well as to sample the breakup and early seafloor spreading volcanism in a more proximal position to the proposed Iceland “hot spot” track along the northern EG66 transect. The faint signature of the Iceland plume in the Leg 152 rocks suggests that a stronger plume imprint could be present at this location closer to the former plume axis, which, if true, would indicate a radial zonation within the original plume structure.

Integration of observations from drilling, field geology, and geophysics on crustal structure and deformation, timing of volcanism and the involvement of Iceland plume material in the breakup process eventually will enable a critical review of current models of plume structure and the impact of mantle plumes on the process of continental breakup (e.g., Mutter et al. 1988; White and McKenzie, 1989; Richards et al., 1989; Campbell and Griffiths, 1990; Coffin and Eldholm, 1992; Kent et al., 1992; Holbrook and Keleman, 1993).

Drilling Plan

In order to meet the main objectives, a total of six first-priority sites was planned for the two transects. Three sites were planned for the innermost part of the EG63 transect. Two sites were targeted to increase the sampling of the prerift crust and oldest volcanic cover, and one site was to deepen Site 915 in order to provide stratigraphic overlap with Site 917 (Figs. 2, 3). Three sites were also planned for the northern EG66 transect. The two sites within the innermost part had objectives roughly similar to the inner sites of the EG63 transect, though less ambitious in terms of stratigraphic coverage. The additional seaward site was planned in SDRS-type oceanic crust of Anomaly 22 age (i.e., in steady-state accreting Icelandic-type oceanic crust).

Changes in the Drilling Plan Imposed by Drilling Problems and Weather

A drilling accident and damage to the ship sustained during extreme storm conditions reduced the scientific drilling operations at Leg 163 to less than one-half of the planned program. Recoil from a break in the drill pipe on 10 September 1995 damaged the top-drive assembly after only one day of drilling at the first, shallow-water site. A port call to Reykjavik, Iceland, was made in order to make the necessary repairs. Permission to drill in water depths shallower than 300 m was temporarily withdrawn by ODP/TAMU, pending review of safety procedures and the delivery of supplementary drilling hardware. Operations therefore resumed at the deeper water sites along the southern EG63 transect on 16 September. Drilling progressed, though with interruptions, because of heavy seas and icebergs drifting across the drill sites, until 29 September.

Extreme hurricane conditions built rapidly through the night of 29 September. At many times the north-northeast wind exceeded 100 kt, and it remained at hurricane force for at least 26 hr. By the morning of 30 September, the ship was being battered by short-period, 60–70-ft-high waves, and she was unable to maintain position without risking severe damage. The ship’s bridge took water through a broken window, which caused both radars to fail and threatened the computers for the dynamic-positioning system. Numerous thrusters were mechanically damaged or became inoperable because of flooding. In spite of reduced maneuverability, the ship was able to maintain heading in the wind and sea while it was being forced south at a speed of up to 4 kt. While drifting in this manner, there was an increased potential of colliding with icebergs. When the storm abated to gale force on 1 October , the ship was turned to the south and the transit to Halifax, Nova Scotia, for repair was started.

At this point, major repairs and a thorough examination of the ship's structure and systems were needed. This ruled out the possibility of further drilling operations during Leg 163. As a result of these untimely events, only three of the planned six sites were drilled.

RESULTS

Site 988

Site 988 is located 56 km east of the East Greenland coast, within the northern drilling transect EG66 (Figs. 2, 4). The site was selected to penetrate deeply into the featheredge of the SDRS 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 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 drillers' 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 compacted diamicton recovered at Leg 152 Sites 914 through 916 (Figs. 2, 4) to the south is absent at this site. The glaciomarine rocks unconformably overlie basaltic basement (igneous Units 1 and 2) at about 10 mbsf.

Two flow units were recognized in the core recovered from the interval 10–32 mbsf. Igneous Unit 1 is a dark, greenish gray, plagioclase-pyroxene-olivine-phyric basalt. The upper contact was not recovered, but the lower contact is preserved in 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 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) and Ce/Y (1.2), identical to Tertiary basalts from Iceland (Fig. 5). The low Ni content and low Mg# of Unit 1 (about 74 ppm and 0.50, respectively) are consistent with the evolved three-phase phenocryst assemblage of this basalt. Both units were most likely 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 around one subvertical fracture was noted.

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 natural remanent magnetization (NRM) intensity of the core was between 5 and 10 A/m. Demagnetization of each section by 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 (section 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 (section 163-988A-5R-2, 0–10 cm). The magnetic orientation of this material was probably affected by the high degree of secondary alteration observed or possibly by the drilling process.

Measurements of index properties from minicores yielded an average bulk density of 2.907 g/cm^3, an average grain density of 2.969 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 in 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 level (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.

Site 989

Site 989 is located 23 nmi east of the East Greenland coast. It is one of the three drill sites planned for the southern drilling transect EG63 (Figs. 2, 4). Drilling at Leg 152 Sites 915 and 917 had penetrated a thick lava sequence that recorded development from an early continental crust-contaminated volcanism, through transitional picritic and tholeiitic volcanism contemporaneous with breakup, into steady-state oceanic volcanism. Site 989 was selected to penetrate and sample the very oldest lavas of the SDRSs that overlie the breakup unconformity and underlying, layered prerift crust. The primary drilling objectives at this site were to (1) determine the stratigraphy, composition, age, and eruption environment of the volcanic rocks above the breakup unconformity; (2) determine the nature and age of the breakup unconformity; and (3) determine the nature and deformation of the continental basement and/or prerift sediments beneath the volcanic sequence.

Lithologic Unit I is a thin layer (0–4 mbsf) of Quaternary(?) glaciomarine sediments unconformably overlying basaltic basement (igneous Units 1 and 2). The only material recovered consists of discrete rock fragments, including gneiss, aphyric basalts/metabasalts, quartzite, and dolerite. The lithologies of these clasts are consistent with an ice-rafted origin, even though no finer-grained matrix was recovered. The relatively weak nature of the sediments recovered at Site 989 suggests that these are glaciomarine deposits, rather than overcompacted glacial tills.

Two igneous flow units were recognized in the core recovered from the interval 4–84 mbsf (Hole 989B). From seismic data, these are interpreted to lie stratigraphically below the lavas drilled at Site 917 and represent the oldest part of the SDRS. Igneous Unit 1 is at least 69 m thick, the thickest lava flow yet reported from an SDRS. It is notable for its constant grain size, constant vesicularity, high mesostasis content, and repeated bands showing quench textures. These features indicate rapid cooling during solidification throughout the lava flow. We interpret Unit 1 as a compound lava flow consisting of numerous individual flow units 0.1–10 m thick. The large number of thin flow units, together with the absence of sharp flow contacts, may indicate both (1) proximity to the eruptive vent and (2) rapid eruption of the entire lava flow. The observed decrease in maximum flow unit thickness upward in the lava may reflect an exponentially diminishing eruption rate with time.

Unit 1 is essentially aphyric. The groundmass consists of plagioclase, augite, magnetite, trace olivine, and mesostasis. Clay alteration is total for both mesostasis and olivines whereas plagioclases and augites are generally fresh. The textures vary between two extremes: (1) a very fine grained rock with quench textures of spherulitic, acicular, and skeletal plagioclases (and sporadic augites) within a vesicular and mesostasis-rich matrix and (2) a “normal” fine-grained intersertal, intergranular to variolitic and sub-ophitic rock with large disseminated vesicles (up to 20% and up to 4 mm across). The transition between quenched and normal textures may be sharp (internal flow boundaries) or gradational.

Igneous Unit 2 is porphyritic with phenocrysts of plagioclase, augite, and trace olivine in a very fine grained matrix. Olivine phenocrysts occur as individual disseminated grains that are now totally altered to clay. Plagioclase and augite phenocrysts are fresh, commonly strongly zoned and resorbed (plagioclase), and in glomerocrystic clusters. The groundmass has a seriate texture defined by microphenocrysts of very elongate plagioclases (4%–5% of groundmass). Stubby olivines (trace to 2%) and anhedral augites (<1%) also form microphenocrysts. The groundmass (up to 0.2-mm grains) consists of plagioclase laths, equant augites, euhedral to skeletal magnetite, and mesostasis in an intersertal/intergranular to variolitic texture.

The two units recovered at Site 989 are both strongly depleted in a number of incompatible elements such as Zr, Nb, Ti, and P and presumably melted from a depleted mantle source (Fig. 5). Both lava flows are composed of evolved basalt, which implies storage in a magma chamber underlying this part of the volcanic succession. Similar crustal magma chambers were invoked for the lavas in the Lower Series at Site 917, which have assimilated a Sr- and Ba-rich crustal component. The low Sr and Ba contents in the Site 989 lavas preclude a direct correlation with the Lower Series in Site 917. In contrast, the lavas at Site 989 have either escaped crustal contamination or have assimilated a crustal component very different from that which contaminated the lavas in Site 917.

Physical property measurements (*P*-wave velocity, bulk and grain densities, porosity) of Unit 1 are quite constant with depth and correlate well between the holes. The transition from Unit 1 to Unit 2 is clearly recognized, with average *P*-wave velocity increasing from 5.2 to 6.0 km/s, density increasing from 2.8 to 3.0 g/cm^3, and porosity decreasing from 12% to 2%. The 3% average reduction between *P*-wave velocity measurements performed on minicores vs. half-rounds may be due to drilling-induced fracturing of the outer edges of the cores.

Deformation of the cored sequence at Site 989 is principally in the form of brittle fracturing, manifest as veining and jointing. Veining is commonly present as two conjugate sets, one postdating the other, but both infilled with a combination of green clays and zeolites. Measured dips within Unit 1 for flow banding and other forms of textural variation, such as vesicular layers, are scattered but are concentrated between 15˚ and 45˚. These features are interpreted to be chilled surfaces of flow units within a compound flow.

Unit 1 recovered in both holes appears to carry a normal magnetic polarity with a mean inclination of 68.4°. If confirmed, this will be the first flow of normal polarity reported from the East Greenland margin, and current stratigraphic evidence correlates this normal event with Chron C27n. Unit 2 appears to contain both normal (top) and reversed polarity. The top part of the flow was possibly remagnetized during the emplacement of the normally magnetized Unit 1. All discrete samples from Holes 989A and 989B sections, demagnetized to 80 mT and measured on the cryogenic magnetometer, carry normal polarity. Discrete samples from the lower part of Unit 2 contain reversed polarity. Confirmation of the magnetic polarity must await further alternating field and thermal demagnetization studies on shore.

Site 990

Site 990 is located 28 nmi east of the East Greenland coast, within the southern drilling transect EG63. It was one of three drill sites planned to complete the stratigraphic sampling of the earliest volcanism along this margin (Figs. 2, 4). The site was located at the position of previous ODP Site

915 in order to more deeply penetrate the lava succession to test the hypothesis that Iceland-type oceanic crustal accretion and steady-state production of Iceland-type tholeiites were initiated within this stratigraphic interval. Another important objective at the site was to sample material suitable for precise radiometric and magnetostratigraphic age determinations in order to assess the magnitude of a suspected hiatus in volcanic activity, located between the Middle and Upper series lavas at Site 917.

Because the sedimentary section had been cored at Site 915 during Leg 152, Site 990 was washed to a depth of 182.0 mbsf and rotary cored below that level. Sediments were recovered in the interval 182.0–202.3 mbsf and subdivided into two lithologic units. According to ODP convention, these two units are termed lithologic Unit I and lithologic Unit II, even though data from Site 915 indicate that the material above 182 mbsf probably forms two additional lithologic units. As a result, we correlate lithologic Units I and II at Site 990 with lithologic Unit III at Site 915. The ages of both Site 990 units are unknown, but the ages of the overlying sediment and underlying basalt at Site 915 suggest an early Eocene age.

Lithologic Unit I is a calcite-cemented mixed-cobble conglomerate, dominated by clasts of altered basalt, gabbro, and dolerite; quartzite and siliciclastic siltstone form the remainder of the cobbles. The cobbles are generally rounded to well rounded and range in size from 4 to >12 cm in diameter. The matrix is a poorly sorted silty sand, with angular grains, sand-sized mudstone intraclasts, and calcite cement.

Lithologic Unit II directly overlies basalt and is a clayey volcaniclastic breccia, dominated by basaltic debris. Clasts in the breccia are predominantly angular and composed of dark yellowish brown, altered basaltic material. The matrix of the breccia is dominated by clay and iron oxides, probably derived from the alteration of basaltic material, and minor well-rounded silt to fine sand-sized quartz grains. The presence of poorly developed flow indicators, the repeated vertical changes between clast-supported and matrix-supported fabric, and the absence of macroscopic pedogenic features indicate that Unit II was deposited by a moving fluid, such as a matrix-rich debris flow, after a limited distance/energy of transport. The large size and the rounding of the clasts in lithologic Unit I suggest that this unit was deposited in a high-energy environment, possibly a high-gradient stream; a shallow, wave-influenced marine setting; or a fan delta. Additional sedimentary material, apparently untransported, was recognized as red, brecciated to clayey material on the tops of flow units within the basalt basement. This material has been described as part of the igneous sequence, but reflects in situ alteration and soil development.

Thirteen flow units were recognized in the core recovered from the interval 212–325 mbsf on the basis of changes in phenocryst assemblage or the presence of weathered and/or vesicular flow tops. Lava flows fall into one of three types: aa, pahoehoe, and transitional. Pahoehoe flows dominate in the lower part of the drilled sequence, whereas aa flows are ubiquitous in the upper portion. The top of the volcanic section at this site (and the previously drilled Site 915) is deeply weathered and oxidized, indicating that eruption occurred subaerially with some time gap between successive flow units.

Flow units cored at Site 990 range from aphyric to highly olivine or plagioclase-olivine-clinopyroxene phyric basalt. The olivine content decreases upward in the section, whereas both grain size and flow thickness increase upward. There is a subtle but systematic compositional variation in trace-element contents from the base to the top of the sequence (i.e., decreasing Cr and Ni and increasing V, Nb, Zr, and Y). In general, the lavas are moderately evolved, with low trace-element abundances, and geochemically similar to the one unit recovered from Site 915 and all units at Site 918 (72 km to the east; Fig. 5). No lavas similar to the Upper Series units cored at Site 917 (3 km to the west) were found, indicating that the transition from the breakup-related series to the Iceland-type tholeiitic series that dominates the oceanic SDRS is abrupt and occurs over a stratigraphic interval of <100 m.

The basaltic rocks recovered at Site 990 exhibit numerous planar, primary magmatic features that consist of vesicular layers, elongated patches of filled vesicles, and widely developed diffuse, thin flow bands. Many of these magmatic features occur in an almost horizontal attitude. The only evidence of deformation consists of a relatively dense network of veins and, to a lesser extent, of fractures, some of which show the development of slickensides. The veins, usually 1–2 mm thick, are commonly lined and filled with green clay. Other minerals less commonly seen in veins include zeolite minerals, carbonates, native copper, and gypsum.

Paleomagnetic data for the Site 990 basalts reveal a magnetic reversal between the upper two normally magnetized flows and the lower 11 reversely magnetized flows. Integration with Leg 152 results suggests that the normal polarity interval may be correlated with either magnetochron C25n or C26n and the underlying reverse polarity interval with C25r or C26r. The discovery of normal polarity intervals, together with results from future radiometric dating, offers the promise of a precise chronology for East Greenland margin volcanism.

Measurements of index properties from half-round cores and discrete minicores correlate with the flow structure. Specifically, *P*-wave velocities and bulk densities vary from 2 km/s and 2.3 g/cm^3 in altered, vesicular flow tops to 6 km/s and 3.0 g/cm^3 within the central, more compact portions. From the high rates of recovery and detailed sampling, it is apparent that the often reported differences between velocity and density measurements on discrete core samples and estimates derived from seismic reflection or downhole logging result from preferential recovery of the compact, central flow material. Magnetic susceptibilities range from $100 * 10^{-5}$ to $5000 * 10^{-5}$ SI. Thermal conductivity values are similar to those measured at Hole 989B, namely ~2 W/m/K.

CONCLUSIONS

Despite the significant loss of operational time because of environmental conditions, extraordinary recovery of core at three critical sites provided the material to address most of the high-priority objectives of the leg. However, the main tectonic objective of drilling through the breakup unconformity and sampling the prerift crust (presumably sediments) was not fulfilled.

The following are the initial, major results of the cruise:

1. There now exists a virtually complete record of the volcanic evolution of the East Greenland margin at latitude 63°N, from earliest, depleted and continentally contaminated, relatively deeply segregated magmas, through breakup-related picritic and tholeiitic magmas derived by shallower and larger degrees of melting, to a steady-state oceanic magma series.

2. Preliminary identification of two magnetic polarity reversals, the first ever recorded from the early Tertiary age volcanic materials of East Greenland, and the recovery of fresh, feldspar-phyric flow units suitable for radiometric dating offer the promise of a detailed and precise time scale for the volcanic activity. This basic chronology will reveal the timing and rates of volcanic and tectonic processes.

3. The Iceland plume mantle component is more strongly expressed in the compositions of basalts at latitude 66°N compared with 63°N. Together with evidence from DSDP Leg 81 (Hatton Bank, Rockall Plateau) and ODP Leg 104 (Vøring Plateau), we now have sufficient information to map the basic compositional structure of the mantle melting regime that existed during the initiation of the Iceland plume and breakup of the North Atlantic.

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FIGURES

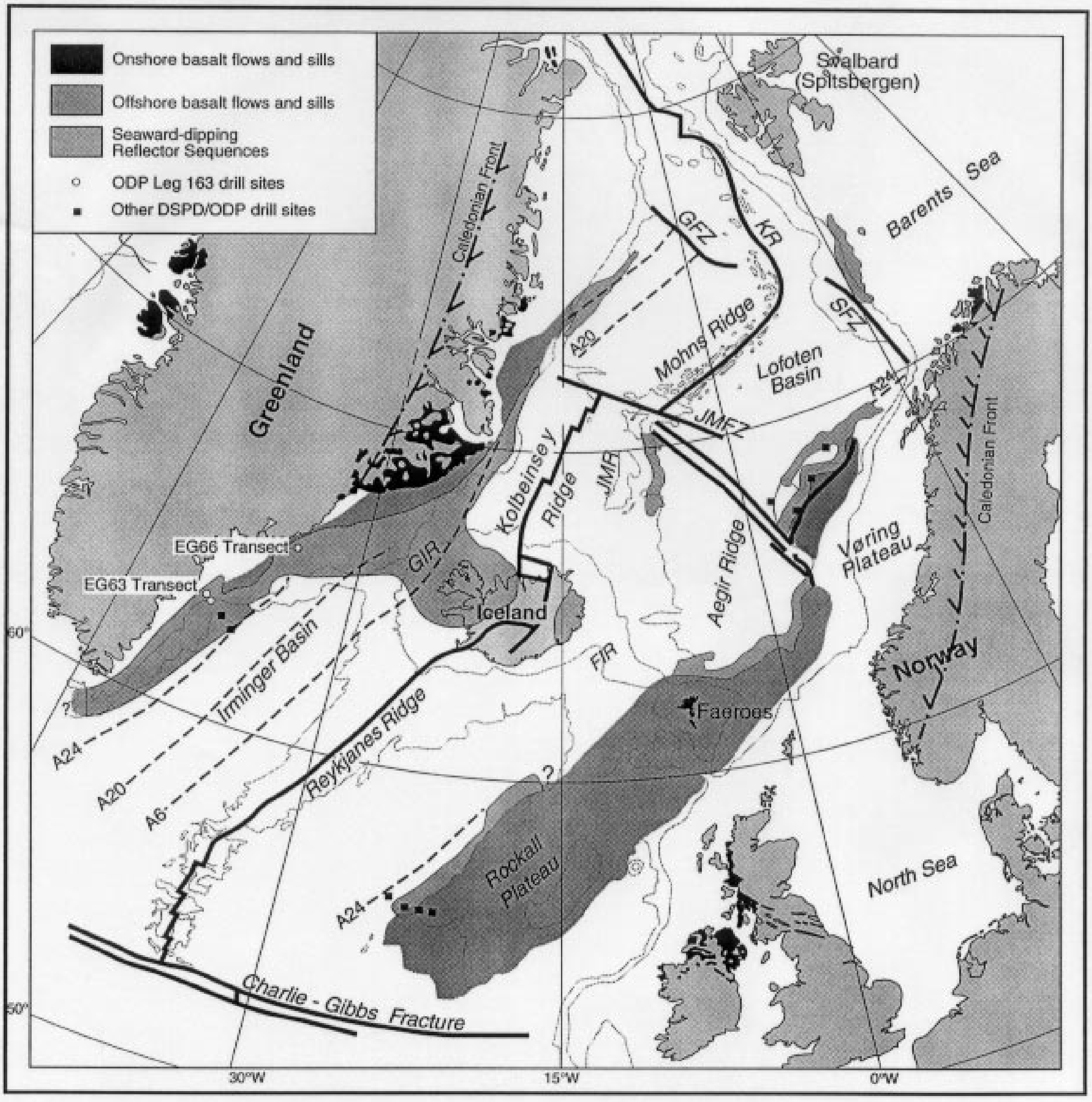
Figure 1. Geological map (modified from Larsen, 1990) showing distribution of seaward-dipping reflector sequences and continental flood basalts of the North Atlantic Volcanic Province. ODP and DSDP drill sites along the volcanic rifted margins of the North Atlantic are shown. Subaerially erupted basalts show flood basalt structure landward of the inferred continent/ocean boundary and have a SDRS structure seaward of the boundary. The part of Northwestern Iceland that shows SDRS-like structure is included. Note that the spreading history of the Iceland Plateau north of the GIR is different from that south of the GIR. In the young crust north of the GIR, the typical SDRS structure is not continuously present and extends to a depth of only about 2 km. However, below the GIR itself, the SDRS may attain a thickness of 10 km (Larsen and Jakobsdóttir, 1988).

Figure 2. Seismic track map and regional bathymetry. Previously drilled holes and Leg 163 drilled sites and planned sites are shown. Ice-free, subaerial bedrock outcrop is stippled.

Figure 3. Seismic cross section through Site 988 (top). Interpretations shown in 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 in km/s.

Figure 4. Seismic cross section through Site 989 (top). Interpretations shown in line drawing (middle) and migrated interpretation (bottom). Steeply dipping to subvertical prerift sediments were encountered within the rotated fault block located below the lava sequence at Site 917. ODP Sites 914–917 are described in Larsen, Saunders, Clift, et al. (1994). Seismic velocities used in the depth conversion and migration are given in km/s.

Figure 5. N-MORB normalized (Sun and McDonough, 1989) minor-element and trace-element spidergrams of cored basalts from the SDRS along the EG66 transects (Site 988) and EG63 (Sites 915, 917, 918, 989, and 990). The Site 917 data include only samples with 6%–9% MgO; samples with high Nb/Zr were also excluded. The fields for basalts from Sites 917 and 918 are based on data in Fitton et al. (in press). The Site 990 lavas are virtually identical in composition to lavas recovered from Site 918, 72 km farther offshore and in the center of the seaward-dipping reflector sequence (Larsen, Saunders, Clift, et al., 1994; Fitton et al., in press). This observation implies that seafloor-spreading-type magamtism was established soon after breakup of the continental margin (represented by the Site 917 Upper Series). The Site 988 lavas are considerably enriched in the incompatible elements as compared to those from the EG63 transect. The Site 988 lavas are about 300 km closer to the Greenland-Iceland Ridge than lavas from the EG63 transect and are similar to Tertiary basalts from Iceland and Scoresby Sund, East Greenland (Larsen et al., 1989; Fitton et al., in press). The offset from the Iceland plume and its palaeoposition (Iceland-Greenland Ridge), at which we observe this marked enrichment are similar to that mapped by DSDP Sites 406-408 (Fig. 2) and along the Reykjanes Ridge (Schilling, 1986). This observation suggests that the generation of enriched, Iceland-type tholeiites has been limited to about the same (~200–300 km) offset from the center of the Iceland hot-spot since the inception of rifting and ocean floor formation.



Onshore basalt flows and sills
Offshore basalt flows and sills
Seaward-dipping Reflector Sequences
ODP Leg 163 drill sites
Other DSPD/ODP drill sites
Svalbard (Spitsbergen)
Barents Sea
Greenland
Caledonian Front
GFZ
KR
SFZ
A20
Mohns Ridge
Lofoten Basin
A24
JMFZ
Kolbeinsey Ridge
JMR
Aegir Ridge
Vøring Plateau
Caledonian Front
EG66 Transect
EG63 Transect
GIR
Iceland
Irminger Basin
FIR
Norway
Faeroes
A24
A20
A6
Reykjanes Ridge
Rockall Plateau
A24
North Sea
Charlie - Gibbs Fracture
60°
50°
30°W
15°W
0°W

Figure 1

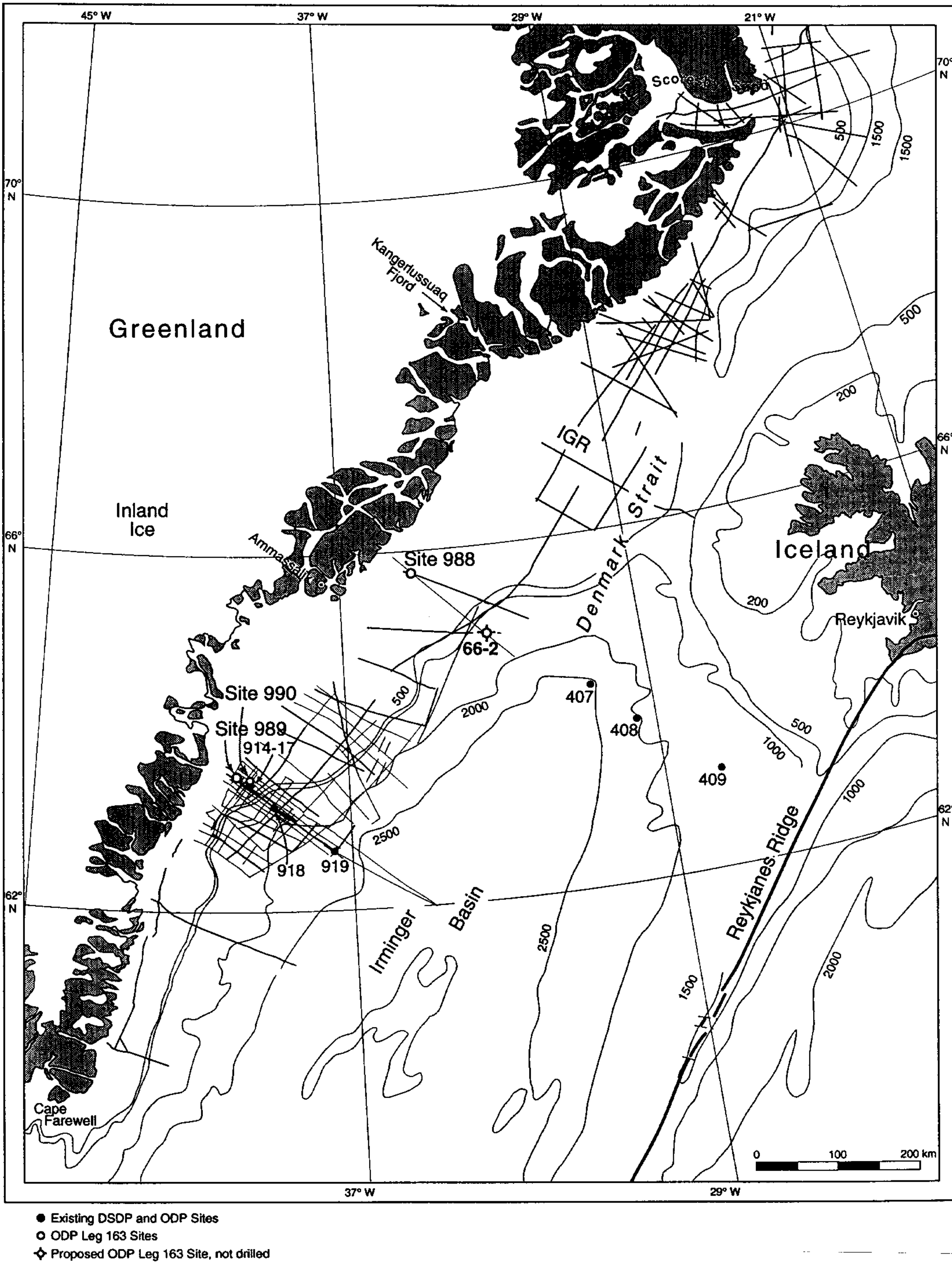

45° W
37° W
29° W
21° W
70° N
66° N
62° N
Greenland
Inland Ice
Kangerlussuaq Fjord
Ammassalik
IGR
Denmark Strait
Iceland
Reykjavik
Site 988
66-2
Site 990
Site 989
914-17
918
919
407
408
409
Irminger Basin
Reykjanes Ridge
Cape Farewell
500
200
1000
1500
2000
2500
0
100
200 km
● Existing DSDP and ODP Sites
○ ODP Leg 163 Sites
Proposed ODP Leg 163 Site, not drilled

Figure 2

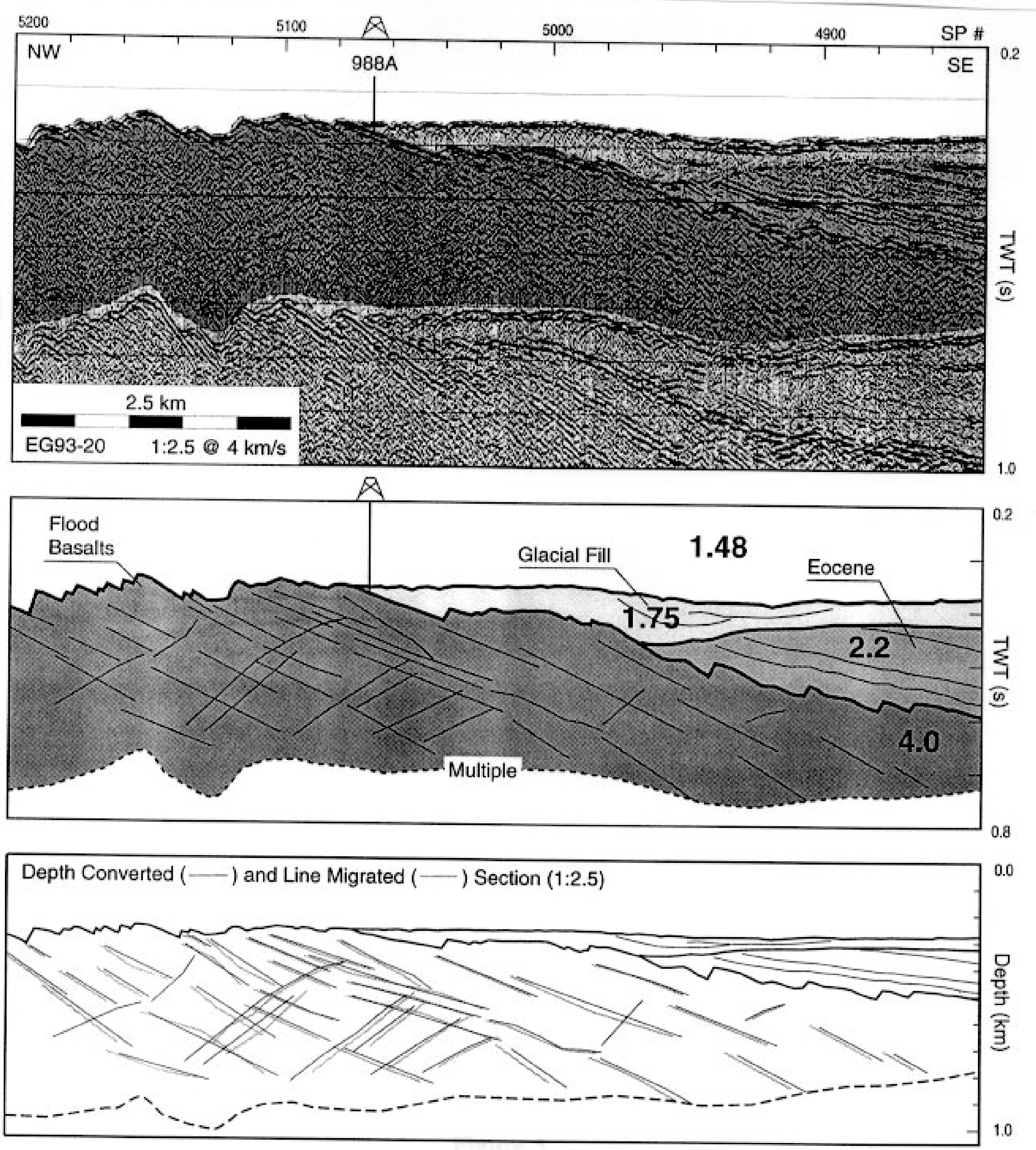

5200
5100
5000
4900
SP #
NW
988A
SE
0.2
TWT (s)
2.5 km
EG93-20
1:2.5 @ 4 km/s
1.0
Flood
Basalts
Glacial Fill
1.48
Eocene
1.75
2.2
4.0
Multiple
0.2
TWT (s)
0.8
Depth Converted (——) and Line Migrated (——) Section (1:2.5)
0.0
Depth (km)
1.0

Figure 3

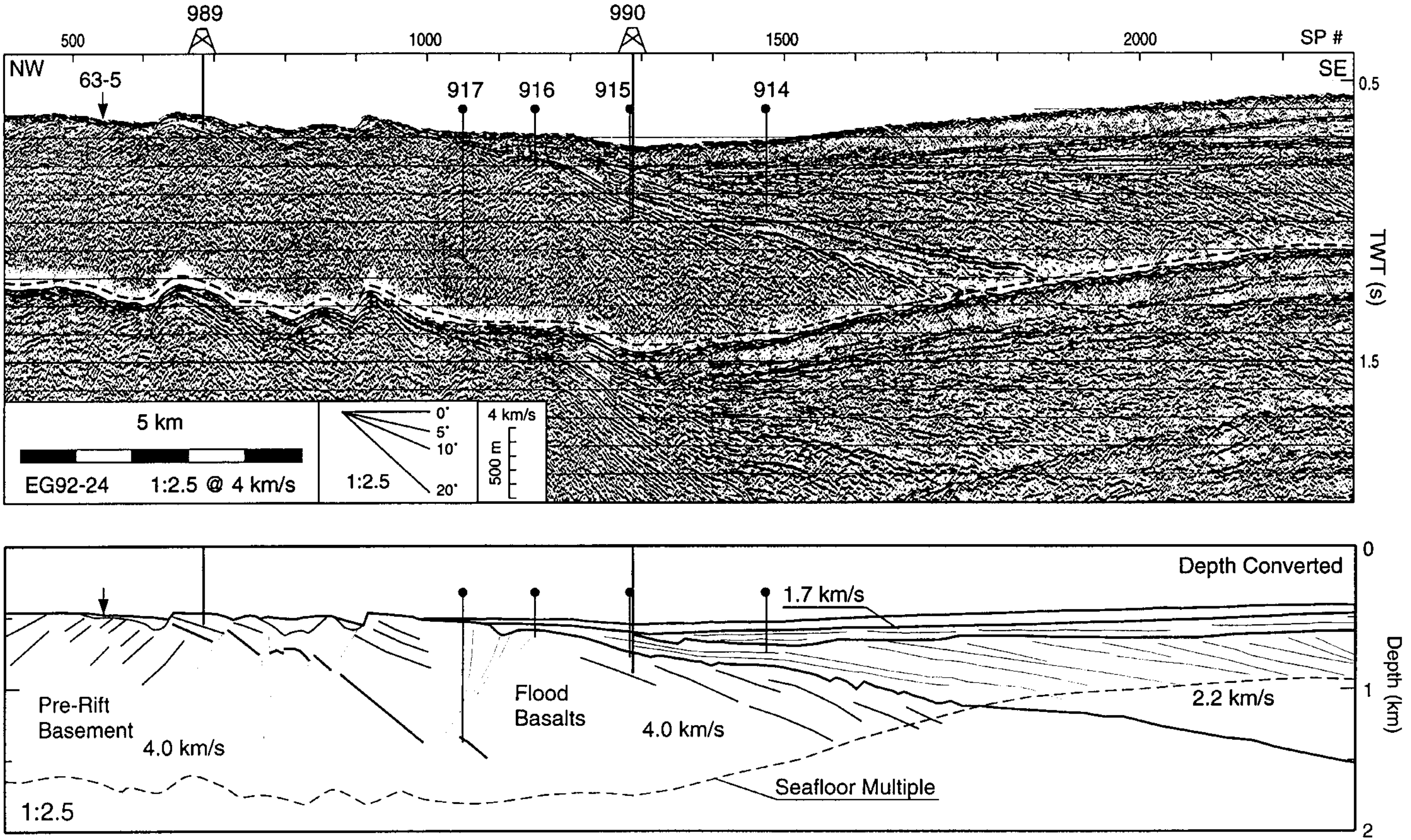

989
990
500
1000
1500
2000
SP #
NW
SE
63-5
917
916
915
914
0.5
TWT (s)
1.5
5 km
EG92-24
1:2.5 @ 4 km/s
0°
5°
10°
20°
1:2.5
4 km/s
500 m
Depth Converted
1.7 km/s
Pre-Rift Basement
4.0 km/s
Flood Basalts
4.0 km/s
2.2 km/s
Seafloor Multiple
1:2.5
0
1
2
Depth (km)

Figure 4

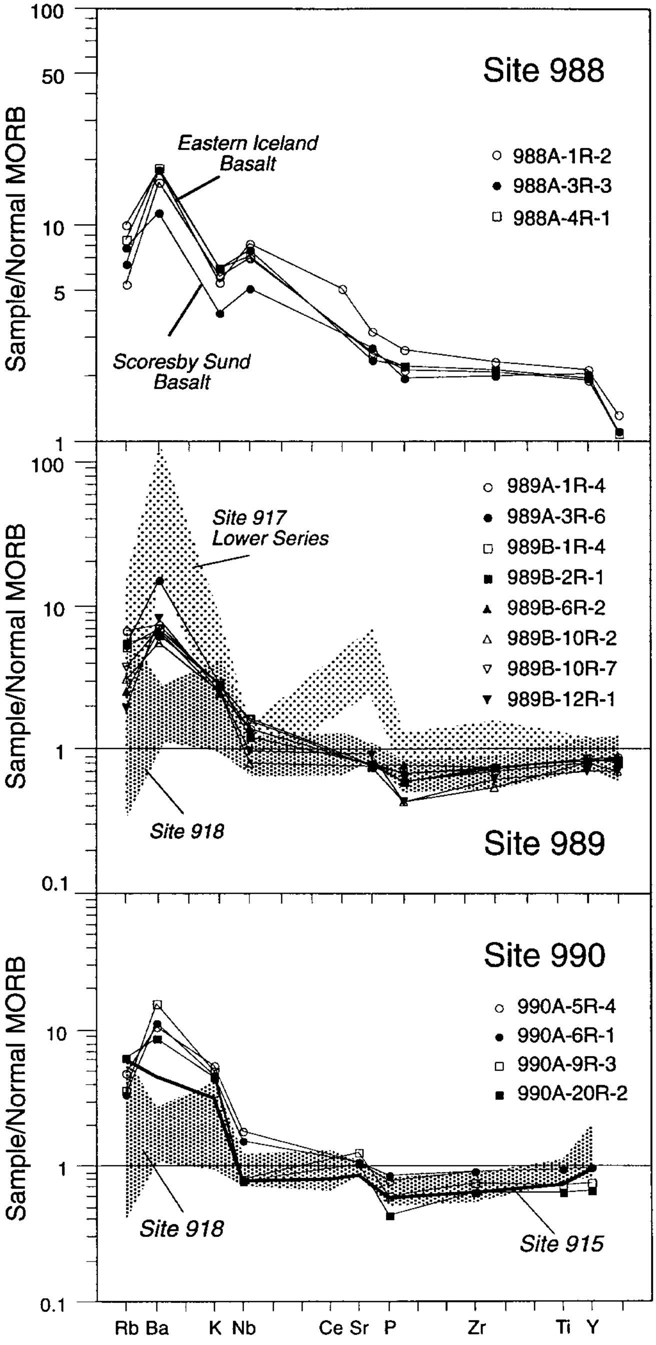

Site 988
Eastern Iceland Basalt
Scoresby Sund Basalt
988A-1R-2
988A-3R-3
988A-4R-1
Sample/Normal MORB
100
50
10
5
1
Site 989
Site 917 Lower Series
Site 918
989A-1R-4
989A-3R-6
989B-1R-4
989B-2R-1
989B-6R-2
989B-10R-2
989B-10R-7
989B-12R-1
0.1
Site 990
990A-5R-4
990A-6R-1
990A-9R-3
990A-20R-2
Site 915
Rb Ba K Nb Ce Sr P Zr Ti Y

Figure 5

OPERATIONS

The ODP Operations and Engineering personnel aboard *JOIDES Resolution* for Leg 163 were:

Operations Manager:	Ron Grout
Development Engineer:	Scott McGrath
Schlumberger Engineer:	Raymond Faust

TRANSIT FROM REYKJAVIK TO SITE 988

At 0800 GMT on 7 September, we began the short transit to the Site 988. Because of expectations of possible interference by ice at several of the Leg 163 drill sites, the *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 GMT on 8 September, the *Gadus Atlantica* reported that there were 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.

SITE 988

At 1115 GMT on 8 September, we approached the survey area. After a 10-nmi seismic run with the 3.5-kHz depth sounder, we were preparing to drop the beacon on coordinates when 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 1.4 nmi “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 GMT. By 1300 GMT, the *JOIDES Resolution* was on site (65°42.255´N, 34°52.262´W).

Hole 988A

Hole 988A was spudded about 30 nmi 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 m below seafloor, or 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 would drill a series of shallower offset holes.

We began coring at 2115 GMT on 8 September with a nine-collar, rotary core barrel bottomhole assembly (RCB BHA), including a new RBI C-4 bit (SN BD472). Before coring commenced, we viewed the seafloor with a TV 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%). 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 seating properly.

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 988A to 32 mbsf with an average rate of penetration (ROP) 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 GMT 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 swivel also sustained damage as a result of this recoil. The immediate 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. In order to repair the top drive motor frame/dolly, we returned to Reykjavik, Iceland, arriving at 1830 GMT on 10 September.

SITE 989

After a series of repairs to our top drive and related rig hardware in Reykjavik, we transited back to the more southerly EG63 transect. A brief 3.5-kHz survey completed over the site along the track of seismic line GGU/EG92-24/1 covered proposed Sites EG63-6 and EG63-5. The seismic record suggested that 5–10 m of sediment lay on top of the lava flow sequence and that this was sufficient to allow spudding in the RCB.

Hole 989A

The beacon marking the site was dropped by Global Positioning Sysytem (GPS) coordinates at 1445 GMT on September 16. The beacon prereleased, requiring deployment of a second beacon. The strong southerly current in the area caused this second beacon to drift 150 m aft of the deployment point. Because of the shallow water in the region (459.5 m), it was necessary to offset north of the location and drop a third beacon at 1455 GMT. This deployment was successful.

Because of the near-hard-rock spudding, a shorter and more flexible BHA (6-collar) utilizing a mechanical bit release (MBR) was used. Initial sediment penetration was made without the benefit of a video camera. Hole 989A was spudded at 2000 GMT at 63°31.355´N and 39°54.113´W. After quickly drilling 3 m, the rate of penetration dropped signifiantly. Recovery of the first core revealed that a large, gneissic glacial erratic boulder had been cored, followed by massive basalt.

Another two cores were drilled to 21.4 mbsf before an iceberg forced the ship to abandon operations. At 1100 GMT on 17 September, an iceberg estimated to be 100 m wide and 15 m high approached within 3.5 nmi of the vessel. The *Gadus Atlantica* was directed to attempt to tow the iceberg away from the *JOIDES Resolution.* Shortly after the first attempt at towing the iceberg had failed, instructions were given to the drill crew to deploy a free-fall funnel. After four attempts, the *Gadus Atlantica* was still unable to snare the iceberg with a towing line.

With the iceberg at distance of 1.5 nmi and closing at 1–2 kt, coring was suspended and the bit raised to 14 mbsf. Attempts to lasso the iceberg possibly influenced its course, which suddenly appeared to change, directing it toward the *JOIDES Resolution.* The change in the path of the iceberg surprised the drilling crew, who were unable to pull the drill pipe from the hole because the elevators and rotary bushing had been set back in preparation to deploy a free-fall funnel. With the iceberg at 0.5 nmi, the Captain gave instructions to offset the vessel 800 m astern, dragging the BHA and bit out of the hole. The iceberg passed within 100 m of the *JOIDES Resolution* and cleared the vessel to port.

The core barrel was retrieved with no difficulty or drag, which implied that the drill string was not bent. The bit was tripped to the surface, and the drill string and BHA were inspected and found to be in good condition. A new, harder formation C-7 bit was then substituted for the C-4 bit, and three additional drill collars were added to the BHA to add weight.

Hole 989B

An attempt was then made to reenter Hole 989A. Although the iceberg prevented us from deploying a free-fall funnel, the Hole 989A crater was easily detected on the TV camera, as was a noticeable furrow leading away from the hole that resulted from dragging the BHA out of the hole. After several unsuccessful attempts to reenter Hole 989A, Hole 989B was spudded at 2400 GMT on 17 September, at 63°31.355´N and 39°54.110´W. The hole was then washed down to 4 mbsf, where contact was made with basalt.

Because of the light weight on bit (2–4 thousand pounds), the first core took 420 minutes to advance 5.2 m. When the barrel was retrieved, it contained 4.6 m of basalt. Continuous rotary coring then advanced slowly but with spectacular recovery to 74 mbsf (97% of the cored interval), where the basalt noticeably hardened and recovery lowered.

A free-fall funnel was deployed when the depth of the hole reached 21 mbsf. After 52 rotating hours were accumulated, the drill string was tripped to the surface from 84 mbsf to change the bit. The video camera was deployed to observe the retraction of the drill bit out of the hole and ensure that the free-fall funnel was not moved during the process.

Instead of replacing the bit and reentering Hole 989B, we decided to temporarily cease operations at this site and move to the next site. This was done because northwest winds were driving ice to within 4 nmi of the site. The forecast from the Danish Meteorological Society (DMI) indicated that strong winds were expected to continue from this sector for the next couple of days, which implied that the ice threat would only increase at this location. At 1930 GMT on 20 September, the vessel was dynamically offset 5 nmi to the southeast to begin operations at Site 990.

SITE 990

The site beacon was dropped by GPS coordinates at 2145 GMT on 20 September, after dynamically moving the vessel from Site 989. A standard RCB nine-collar BHA was made up with a C-4 bit and an MBR. Because the sediment section of this site had been cored on Leg 152, the plan was to drill through most (180 m) of the sediments and core from this depth into basement.

Hole 990A

The hole was drilled to 41 mbsf before excessive heave generated by a sudden gale forced us to come out of the hole for 3hr. We reentered the hole at 0645 GMT, 21 September, and advanced to 27 mbsf before drilling was stopped again to allow a large iceberg to clear the drilling area.

A free-fall funnel was then deployed to ensure that any progress would not be lost if a sudden exit were required because of ice or weather. Drilling resumed and deepened the hole to 45 mbsf when another iceberg approached, forcing the driller to lift the bit to 10 mbsf. The 70-m-high iceberg passed within 1.2 nmi of the vessel, moving south at 1.1 kt. Two more hours of washing and reaming were required before advancing the bit back down to 45 mbsf.

By 0515 GMT on 22 September, the hole had been deepened to 63 mbsf. At this time, the mates on the bridge suddenly detected a large bergy bit very close to the vessel. The drill floor was advised to pull out of the hole and the vessel was immediately offset to starboard. A second growler was then observed within 10 m of the vessel. The ship changed heading to meet this piece of ice head-on, which bounced off the port bow and then passed the vessel on the port side, without causing damage. The predominantly low profile of the ice, combined with the rough sea state, made it difficult to detect growlers and bergy bits by radar or with searchlights.

After waiting on ice for 15 min, the bit was pulled to the surface and a mill-tooth tricone drilling bit was made up with an MBR. It was expected that the mill-tooth bit would penetrate the 180 m of sediment much faster than a coring bit.

The second reentry of the hole was accomplished at 1530 GMT on 22 September. The hole was washed and reamed from 10 to 134 mbsf, after which the hole was drilled ahead to 182 mbsf. After flushing the hole with mud, the bit was tripped to the surface to change to a coring bit.

A new C-4 bit was made up with a nine-collar BHA and run back to the bottom of the hole, and at 0322 GMT on September 24, the third reentry of the hole was made. The hole was washed and reamed from 19 to 181 mbsf, after which the wash barrel was retrieved and a core barrel dropped. Finally, at 0900 GMT, coring was initiated in Hole 990A. After a first core containing conglomerate and drilling rubble was retrieved, coring had to be terminated because of a developing storm. The drill string was pulled out of the hole, with the bit clearing the seafloor at1600 GMT that day. A Force 10 storm from the north prevailed during the afternoon and late into the evening, with wind gusts as high as 60 kt and 20–30-ft seas. By 1100 GMT the next day, the winds had died down and the large swell was abating. Reentry of the hole was delayed for nearly 5 hr to repair a defective TV camera on the vibration-isolated television (VIT) system.

Medical Evacuation

During this storm, a lost-time accident occurred involving crane operator Andy Fitzmorris. One half of a free-fall funnel was secured to the starboard main deck under the drill floor with a new 3/8 in. cargo chain. A large wave came over the side, hit the free-fall funnel, broke the chain, and washed the free-fall funnel into the aft moonpool tugger. Andy and two other men were trying to resecure the free-fall funnel when another wave came over the side. Andy was hit by the wave and lost his footing while holding on to the chain to avoid being swept into the moonpool, which resulted in the dislocation of his shoulder and torn ligaments.

A medivac helicopter arrived the next day 25 September at 1505 GMT and transported Andy to Ammassalik, Greenland, from where he was flown to Iceland for medical treatment. This incident broke a string of 1368 days without a lost-time accident.

At 1700 GMT on 25 September, the hole was reentered, and after extensive reaming of the bottom section (181-191 mbsf), coring was resumed in Hole 990A. Rotary coring advanced routinely to 260 mbsf, where the drill pipe got stuck. After the string was picked up to 249.6 mbsf to retrieve Core 163-990A-12R, the hole began to pack off around the drill string and circulation and rotation were lost. After restoring rotation and working the pipe up the hole for 2.5 hr (incurring overpulls as large as 200,000 lb, with a 420,000-lb total string weight), the drill string finally became free. Because of the presence of a large iceberg approaching the location, the bit was then tripped to the surface for inspection. Although the bit was in very good condition, drilling resumed with a new C-4 bit and a new MBR.

At 2100 GMT on 27 September, iceberg number 107 of the leg passed within 0.5 nmi of the vessel, moving south at 1.2 kt. The first mate calculated the height of the iceberg using radar distance and sextant angle to be 135 m. The Captain then gave approval to reenter the hole, with the bit reentering the free-fall funnel cone at 2115 GMT. The bit was run into the hole to 166 mbsf without reaming, indicating that the top portion of the hole had now stabilized. The hole was washed and reamed from 166 to 231 mbsf, and then flushed with a high-viscosity mud. The bit was subsequently run back into the hole to 260 mbsf where coring was resumed. Rotary coring advanced in basalt from 260.0 to 302.7 mbsf, with increasing rates of penetration and excellent recovery. Within this interval, the average rate of penetration was 3.1 m/hr (with rates as high as 4.8 m/hr) with an average recovery of 85.9%. As coring advanced from 302.7 to 343.1 mbsf, the rate of penetration increased significantly and recovery dropped (44%–56%), with an extraordinarily high rate of penetration (7.2 m/hr) from 317.9 to 327.5 mbsf.

By 1200 GMT on 29 September, the winds had increased to 40 kt, with gusts to 50 kt from the north and 18-ft seas. The sea state was complex, with swells coming from the north and east. The vessel heave increased to 16–18 ft, with very short-period excursions. As a result, very rapid and confused ship motion developed, which caused the heave compensator to bottom out. Coring operations were stopped and the pipe pulled out of the hole to 144 m below sea level (mbsl) to wait for the storm to blow over.

The Storm

From the DMI weather forecast of 28 September, we expected gale force winds from the northeast, starting on the morning of 29 September and extending into the morning of 1 October. The maximum sustained winds were forecast to be 23 m/s (approximately 47 kt).

During the morning of 29 September, the winds increased gradually from the north to a sustained 42 kt, gusting to 50 kt by noon. The wind then began to slowly shift to the north-northeast and decreased to 20 kt by 1800 GMT. The winds then started to increase, with the direction holding steady from the north-northeast. When the new evening DMI forecast arrived (2130 GMT), the winds were revised upward in strength to 50–60 kt from the north-northeast to north for the next 48 hr, indicating rapid development into a full storm (Fig.1). By midnight (0200 GMT on 30 September),wind speed was back up to 40 kt and the seas had grown to 20 ft.

By 0600 GMT on 30 September, the wind speed was a constant 63–66 kt with gusts to 76 kt. It was now no longer possible to maintain the ship’s position. The wind direction started to drive the vessel slowly westward toward the Greenland coast (approximately 30 nmi distant) and higher concentrations of icebergs. The Captain was awakened, called to the bridge, and apprised of the situation. Winds were now gusting to over 80 kt, and green water routinely came over the bow, threatening the functionality of the forward thruster motors, which are necessary to maintain the ship’s heading into the wind.

Because of the very short wave periods (8 to10 s), the ship’s stern was coming out of the water with every wave, causing the propellers to clear the water and overspeed to 200 rpm. The chief engineer set back the power limit to the main shafts, reducing the overspeeding of the propellers and the risk of overheating and bearing failure. The result of reducing power, was a loss of position, with the vessel moving slowly to the south. Even though the ship was buffeted by high winds, we could still maintain a northerly heading. East bias in dynamic positioning (DP) commands was necessary to prevent the vessel from being blown into ice flows west of site.

With the decision made to give ground to the storm, the vessel's motion then became less violent, but she moved aft at speeds of up to 4 kt. This attitude was made possible only by having the capability of applying lateral force to the forward end of the vessel via the bow thrusters. Lookouts were posted aft to ensure that no icebergs were overtaken.

By midmorning on 30 September, the winds had increased to a sustained 75–78 kt with gusts to 100 kt or greater (100 kt is the maximum indication possible with the shipboard system). This high wind speed (gusts of >70 kt) was sustained for over 26 hr. As waves broke over the bow, high-velocity sheets of spray raked the vessel. The weather stations were long blown away by this time, but it was estimated that the air temperature was about 3 °C (sea temperature). The seas continued to build to 60–70 ft, with recorded pitch angles of up to 14° and rolls to 18°, extraordinary values in DP mode. The BHA remained hanging off on the 500-ton elevators.

At 1245 GMT on 30 September, the port outboard bridge window was blown in by a wave, knocking out both radar displays, denting in the bridge wall, and flooding the entire bridge. A group of Sedco and ODP drilling and technical personnel quickly transformed themselves into a crisis team and built a cover to the open window with plywood, 2″ * 4″ lumber, and tarp, and secured this improvised patch with screws and carriage bolts. During this emergency, many individuals risked their lives by exposing themselves to extremely high winds, very rough seas, and low temperatures as they stood outside the bridge to affect repairs. The efficiency with which the repairs were performed ensured that more water did not enter the bridge.

The large volume of seawater that entered the bridge migrated below decks via electric cable ways. Some forecastle deck compartments were flooded as seawater dripped from around overhead light fixtures. The water came within 1 vertical inch of flooding the DP computer electronics. If the DP computer had been shorted out, the only manner by which heading could have been maintained would have been to steam ahead into the seas with the main propellers. At a minimum, that would have increased the chances of more green water hitting the bridge windows and possibly taking out more glass. The lowest barometer reading of 979.0 mb was made at 1100 GMT on 30 September. After this, the barometer began to rise slowly and the winds slowly, almost imperceptibly, started to decrease.

During the storm, radio contact was lost with the *Gadus Atlantica*. A Danish Navy warship in the area and Greenland Command were apprised of the lost communication with the picket boat. At 2100 GMT that day, the vessel reestablished contact with the *Gadus Atlantica*, which had been steaming into the storm and was now well north of our location in good condition.

By 0400 GMT on 1 October, the winds had dropped to 57 kt with gusts to 65 kt, but waves remained over 60 ft in height. At this time, another wave hit the bridge deck and damaged the patched window, spraying the bridge with more seawater and shorting out the sole repaired radar display. The broken patch was quickly repaired.

At 0720 GMT, the forward thruster pod was lost as a result of water entering the motor housing. Several other thrusters were not operational because of overheating or flooding. Directional control of the vessel was then taken over by the mates on the bridge, supplemented by the remaining thrusters. Luckily, the reduced seas (40–50 ft high) and lowered wind speed made directional control considerably easier, and this method of maintaining heading worked well.

By 1500 GMT, the storm had abated to 37 kt, with seas down to 25 ft. The drillstring was then retrieved, and at 1815 GMT the vessel came about with the assistance of the remaining thrusters. After the hydrophones and thrusters were retracted, the vessel began the voyage to Halifax, Nova Scotia, for repairs, signaling an end to drilling operations on Leg 163. The *Gadus Atlantica* accompanied the vessel and provided surveillance of the transit path until one of the radar units was repaired.

Figure 1. Satellite image of the storm at 1201 GMT on 29 September 1995, showing the relative positions of the East Greenland coast and the *JOIDES Resolution.* This exceptional storm developed rapidly out of two easterly moving low-pressure systems that merged into system that was more intense and more northerly-moving than initially forecast.

Ship position

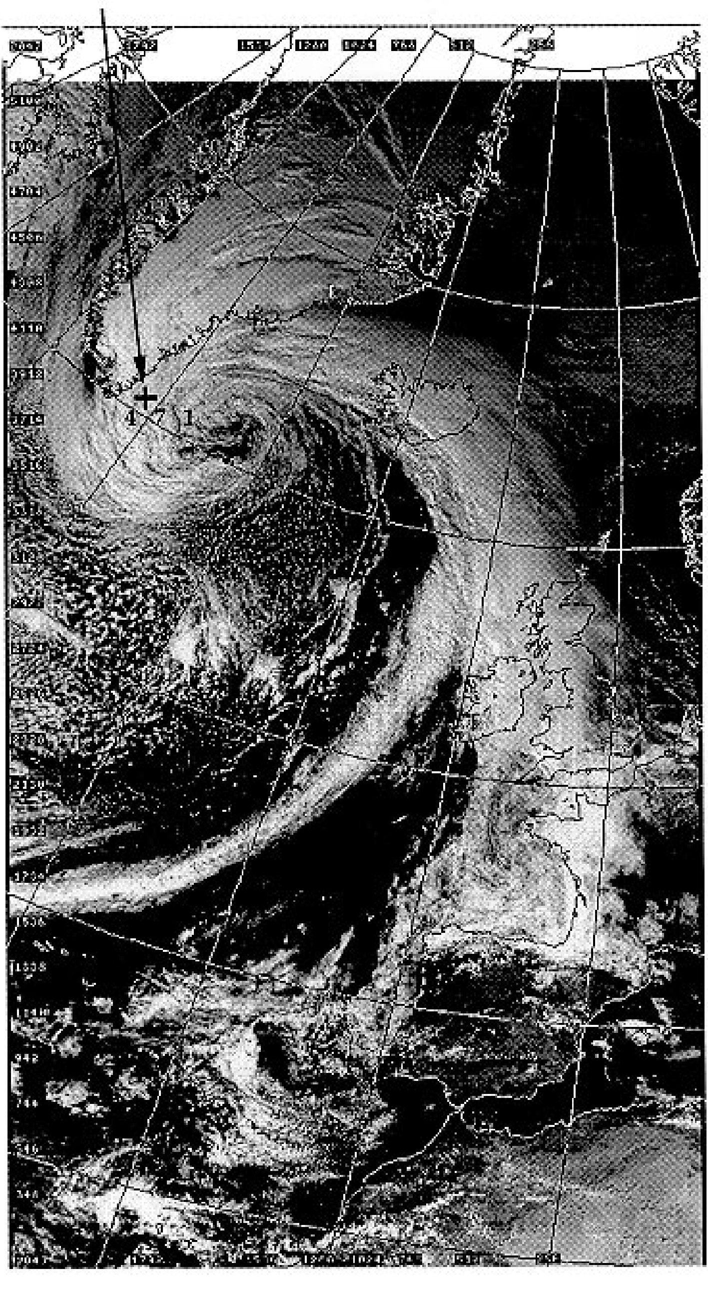


Figure 1

ODP LEG 163

OPERATIONS SUMMARY

Toatal days (3 September 1995 – 7 October 1995)		33.91
Total days in port		7.10
Total days underway		10.13
Total days on site		16.68
Tripping time	3.04	
Coring	7.19	
Reentry	0.78	
Waiting on weather	3.25	
Stuck pipe/downhole trouble	0.10	
Drilling	2.11	
Repair time (contractor)	0.21	
Logging/downhole science	0.00	
Other	0.00	
Total distance traveled (nmi)		2787.0
Average transit speed (kt)		9.9
Number of sites		3.0
Number of holes		4.0
Number of cores attempted		46.0
Total interval cored (m)		294.3
Total core recovery (m)		204.6
% core recovery		69.5
Total interval drilled (m)		186.0
Total penetration (m)		480.3
Maximum penetration (m)		342.7
Minimum penetration (m)		32.0
Maximum water depth (m from drilling datum)		552.4
Minimun water depth (m from drilling datum)		272.7

OCEAN DRILLING PROGRAM
SITE SUMMARY
LEG 163

HOLE	LATITUDE	LONGITUDE	WATER DEPTH (mbsl)	NUMBER OF CORES	INTERVAL CORED (meters)	CORE RECOVERED (meters)	PERCENT RECOVERED (percent)	DRILLED (meters)	TOTAL PENETRATION (meters)	TIME ON HOLE (hours)	TIME ON SITE (days)
988A	65 42.255 N	34 52.262 W	262.6	5	32.0	9.59	30.0%	0.0	32.0	47.00	2.0
		988 SITE TOTALS:		**5**	**32.0**	**9.59**	**30.0%**	**0.0**	**32.0**	**47.00**	**2.0**
989A	63 31.355 N	39 54.113 W	459.5	3	21.4	16.02	74.9%	0.0	21.4	20.58	0.9
989B	63 31.355 N	39 54.110 W	459.5	14	80.2	73.96	92.2%	4.0	84.2	75.50	3.1
		989 SITE TOTALS:		**17**	**101.6**	**89.98**	**88.6%**	**4.0**	**105.6**	**96.08**	**4.0**
990A	63 28.372 N	39 46.808 W	541.5	24	160.7	105.00	65.3%	182.0	342.7	257.25	10.7
		990 SITE TOTALS:		**24**	**160.7**	**105.00**	**65.3%**	**182.0**	**342.7**	**257.25**	**10.7**
		LEG 163 TOTALS:		**46**	**294.3**	**204.6**	**69.5%**	**186.0**	**480.3**	**400.33**	**16.7**

TECHNICAL REPORT

The ODP Technical and Logistics personnel aboard *JOIDES Resolution* for Leg 163 were

Laboratory Officer:	Bill Mills
Marine Laboratory Specialist:	Matthias Börner
Marine Laboratory Specialist (Photography):	Roy Davis
Marine Laboratory Specialist (Storekeeper):	John Dyke
Marine Computer Specialist:	Cesar Flores
Marine Laboratory Specialist (Paleomagnetics):	Edwin Garrett
Marine Laboratory Specialist (Chemistry/Underway Geophysics):	Dennis Graham
Marine Laboratory Specialist (Thin Section/Downhole):	Gus Gustafson
Marine Laboratory Specialist (Yeoperson):	Michiko Hitchcox
Marine Laboratory Specialist (Physical Properties):	Kevin MacKillop
Marine Electronics Specialist:	Eric Meissner
Marine Electronics Specialist:	Dwight Mossman
Marine Laboratory Specialist (Chemistry):	Chieh Peng
Marine Laboratory Specialist (Assistant Laboratory Officer/X-ray):	Don Sims
Marine Laboratory Specialist (Curatorial Representative):	Lorraine Southey
Marine Laboratory Specialist (X-ray):	Joel Sparks
Marine Computer Specialist:	Barry Weber

PORT CALL: REYKJAVIK, ICELAND

The JOIDES *Resolution* docked in Reykjavik, Iceland, on 3 September 1995, ending Leg 162. On the same morning, the Leg 163 crew arrived and began crossover activities. Besides our usual logistical work, we also off-loaded Leg 162 cores , cleaned our foul-weather gear, and conducted tours for a small group of Icelandic geologists and drilling engineers.

At high tide on 7 September, we cast off lines and were underway for the east coast of Greenland with a crew of 111 (including 48 scientists and technicians). On 9 September we returned to Reykjavik to affect repairs to the top drive dolly, damaged when the drill string parted. After3 days in port the repairs were completed and we again departed for the Greenland sites. Prior to departing port, ODP's public relations officer and the *Dallas News* reporter left the ship.

UNDERWAY

Technicians routinely collected bathymetric, magnetic, and navigational data on all transits.
The seismic equipment was not used this leg. The sites were surveyed using the 3.5-kHz depth recorder to correlate with preexisting seismic lines and to determine the drilling locations.

Some problems were encountered with the WINFROG “calculation” display, but overall, the data were acceptable, and definitely better than the old system. The recent upgrade of the WINFROG PC hardware allowed automated backups of the data files to be performed daily.
A “Remote Station WINFROG User Manual” was written.

During the storm all systems were powered off, except the GPS, to avoid potential fires. Dynamic positioning (DP) requested that WINFROG be brought back up so they could see a visual image of the ship’s heading and track. Of course, this was done, but it points out a weakness in our system. In an emergency situation (such as we were in) the bridge or DP should have the master machine.

OPERATIONS

Our second severe gale developed on 28 September, and by the morning of 29 September, it had grown into a full hurricane. Winds over 100 kt with seas running at 60 ft or more forced the ship to give ground. At first, the northeasterly winds drove the ship toward the shore (15 nmi to the west) until they shifted to the north. This allowed the ship to give way to the storm in a southerly direction that was parallel to the coastline.

During the height of the storm, the ship’s thrusters were our only means of holding the heading. At the same time, we used the thrusters to move the ship eastward to clear the coast and icebergs hidden by the heavy seas. Understanding that our situation depended on the thrusters is why we responded so quickly when the bridge port-side window was smashed by a wave, flooded the bridge. The seawater not only knocked out the ship's radar but also threatened the DP computer that controlled the thrusters.

When the window broke, a damage-control team of Sedco and ODP employees was quickly organized. Using materials from our wood shop, the damaged window was covered in minutes and fully secured within 30 min. To effect repairs, members of the damage-control team had to work outside, in front of the bridge, exposed to the adverse weather. Fortunately, none was injured in the efforts to save the ship.

Throughout the day, the technical staff stood by to lend assistance as needed. The laboratories were secured, power was turned off to all equipment to reduce the threat of fire, and around-the-clock watches were maintained in the laboratories. Because of these measures, no personnel were injured or equipment damaged.

By the afternoon of the following day, the storm had abated enough to allow us to turn safely and head for Halifax. Because of the damage sustained and the deteriorating weather and ice conditions off East Greenland, the remainder of Leg 163 drilling operations was canceled. It was estimated that it would take 3 weeks to repair the damage to the ship.

CURATION

Only basaltic lavas and breccias were recovered this leg. Even though the breccias were “sediments” all pieces were labeled as hard rock because description and sampling would require handling them in a similar manner.

Shipboard sampling was managed by the Curator. As no sediment was recovered, no sampling shifts were established.

As suggested and approved in the Pre-Cruise Sampling Plan, a few oversized basalt samples (100 cm^3) were collected from a thick unit of good recovery for interlaboratory standards (Hole 989A). Each investigator who expressed an interest will receive a split of the homogenized powder (to be ground on shore).

CORE LABORATORY

The core laboratory ran smoothly and in a normal manner for a hard-rock leg. The sonic welder was reinstalled in the core-splitting room and housed in a splash-proof metal enclosure.

PALEOMAGNETICS LABORATORY

The hard-rock cores had very intense magnetization. This made it difficult to measure the sections on the cryomagnetometer, as the high signal overflowed the counters, even after demagnetization. But the instrument worked better on minicores, as the sample volume was low enough that the instrument could handle the high intensity.

The spinner magnetometer had numerous problems and was not functional for most of the leg. Some of the problems were mechanical and could be fixed, but others were due to software and electronics failures and could not be adequately repaired on board.

The SC IM-10 impulse magnetizer and the Kappabridge KLY-2 magnetic susceptibility meter were used extensively this leg. The Kappabridge was used in range 9, so the ship’s movement did not affect the instrument. Scientists were checking for anisotropy and comparing their data with the multisensor track (MST) magnetic susceptibility data. The Schonstedt demagnetizer was used frequently. However, the scientists recommended purchasing a tumbling demagnetizer, which would eliminate much of the repetitive manual labor involved in demagnetizing samples.

PHYSICAL PROPERTIES LABORATORY

Methods B and C were used to calculate the index properties for Sites 988 and 989. Wet volume and wet weight were the only measurements made on the minicores from Site 990; therefore, only bulk density was calculated for samples from this site. The physical properties specialist determined that oven drying the samples altered their structure to the degree that post-cruise velocity measurements on oven-dried minicore samples would differ significantly from shipboard velocity measurements made prior to oven drying. Measurement of dry volumes proved difficult with the pycnometer.

Half-space thermal conductivity measurements were made on seven samples representative of the lithology at Sites 989 and 990. It was determined that the results differed little between polished and unpolished samples.

Measurements were made at discrete intervals on split cores with the Hamilton Frame (DSV 3). These were based on calibrations derived from a new polycarbon and ionized aluminum standard. Also, a load cell was installed so that consistent pressure could be applied to the sample during analysis. This removed variance in the data produced by the application of different pressures, and should extend the operational life of the *P*-wave transducers.

STOREKEEPING

The Reykjavik port call went smoothly, even with the incredible amount of core to off-load. Four containers were loaded within 2 days of arrival. A TV winch reel and a pallet of K-boxes were included in the surface shipment. Shipment # 0521 (hand-carry items) needed to be processed after the Halifax port call.

During the second port call (when the ship returned to Reykjavik for repairs) two DHL shipments were sent from the ship.

Modifications were made to the MATMAN sysyem to reflect new items and changes in usage. Also, a physical count and reorganization of the Hold Store was completed.

CHEMISTRY LABORATORY

No chemistry samples were collected during this cruise. Four XRF samples were run on the CNS for sulfur determination. Routine maintenance was performed on equipment and instruments in the laboratory while time allowed.

THIN-SECTION LABORATORY

A total of 59 thin sections was produced this leg. Twelve of the sections were East Greenland basalts collected prior to the leg by Co-Chief Scientist Bob Duncan during recent field work. The slides and billets will remain with the ODP collection for this leg. The 47 sections produced from Leg 163 drill sites are basalts, altered basalts, gabbros, conglomerates, and breccias.

X-RAY LABORATORY

The XRF and XRD both ran well despite two power cuts and being shaken by the adverse weather.

Six fused discs were made of interlaboratory standard BAS-140 using the NT-2100 (and the new flux #6). These disks were run 6 times on the XRF over a period of about three days. The results were that five of the six disks were all within analytical error, and the sixth was just slightly outside normal error. The small error was probably due to weighing. This exercise showed that for major element runs we should increase the number of digits reported for Mn, K, and P from two to three. Given the level of precision on the ship, the extra digit would be significant.

Refinements to the XRF procedures documentation continues. The sample preparation documentation is nearly complete, and the “XRF Operational Guide” is half finished.

The NT-2100 Bead Sampler was tested. It was found that disks could be easily and reliably made if a releasing agent (LiBr) is added to the flux/sample mixture.

A Fisons service call was scheduled for 28 October. Discussions centered around the possibility of using AX-06 and InSb analyzing crystals to improve intensities for Na, Mg, and Si.

MICROSCOPES AND PHOTOGRAPHY LABORATORY

All the new axioplan and axioscope microscopes were set up in the Paleontology Laboratory, for use on this predominantly hard-rock leg. Two objectives on one of the axioplans were from the older SV-8 stereoscope. A new light base was received for the SV-11 stereoscopes to provide more light when viewing thin sections.

Operations and support in the Photography Laboratory were routine.

COMPUTER SERVICES

Six more DEC Celebris XL590 PCs were received for this leg to finish the year's upgrade. In addition, 10 new 17 in. SONY monitors and 2 HP scanners were installed. There are now 15 Pentium PCs and 19 PowerMACs on board the ship. Bill Mills did extensive work this leg transferring the functionality of our old MST setup to one Macintosh. The new software was well received by the scientists.

Solaris 2.4 was installed on two of the shipboard Sun work stations this leg, a SPARC20 (Peary) and a SPARC5 (Ewing). The goal was to use Peary as the Sun shipboard server. Peary was configured to be the DNS/home directory server for most of the shipboard Suns.

Scientists in the Paleontology Laboratory used the digitizers this leg, which prompted the installation of a large external SCSI drive on one of the microscope MACs to store the image files.

The new version of the AppleShare server was installed in conjunction with the latest client software on all the MACs and PCs throughout the ship. The new system performed well and was much faster than the old Novell server.

YEOPERSON SUPPORT

Computer hardware and software was upgraded in the Yeoperson's office. The library received several new publications and reprints, and a comprehensive inventory was taken.

ELECTRONICS SUPPORT

Assistance and support were required in several of the laboratories. The spinner magnetometers in the Paleomagnetics Laboratory required significant effort to keep them running, while the cryomagnetometer, also required some attention. In the Physical Properties Laboratory, work was required on the MST, sonic velocity, and thermal condutivity instruments.

Water was found in the weather systems antenna. The antenna was dried out and then sealed. What was thought to be interference caused by atmospherics, was in fact due to the new high-intensity light installed less than 1 ft from the antenna. With the light off, we were able to receive data from both the weather system and the Marisat. The computer for the weather system was destroyed during the storm. A new computer is on order. In the interim, a 386 computer was installed and the system brought back on line.

The new magnetometer was tested and seemed to work well. However, it was very difficult to tell for certain, because WINFROG was the only display device. Efforts were made to obtain the complete software package to enable troubleshooting in the event of magnetometer failure.

Routine service and regular attention to the Xerox machines resulted in serviceable copies from both machines. The gym and entertainment system were also kept in good working order.

SPECIAL PROJECTS

- New MST software and hardware were installed.
- A pressure transducer was installed under DSV 3 (Hamilton Frame) to improve the precision of measurements.
- The sonic welder was reinstalled in the core-splitting room and housed in a splash-proof metal enclosure.
- A signal cable running from the Schlumberger logging cab to the Underway Laboratory was installed
- The operating systems on the Sun work stations were upgraded to Solaris 2.4.
- AppleShare network software was upgraded to version 4.0.2.
- Six new DEC Celebris KXL590 PSs were installed.
- Two new HP scanners were installed.

PROBLEMS REPORTED

- The thermal conductivity equipment is still plagued with problems, but was repaired once again.
- The Stairmaster control panel failed. A replacement is on order.
- WINFROG still fails to display the magnetometer trace.
- Both copiers were barely operational during the leg. New copiers are scheduled for installation during the Halifax port call.
- The Laws weather station computer and color printer took a direct hit from the seawater when the bridge window broke. A spare computer is currently in use and a replacement is on order.

- The 2.1-GB network hard drive failed during the leg. A replacement is on order.
- Some of the core-receiving platform tarps were damaged by the storm. They were repaired in Halifax and returned to the ship.
- The 55-gal drum storage container was destroyed during the storm, and a drum of seismic streamer oil was lost overboard. A 35-gal drum of oil has been ordered.
- The fantail work bench and tool cabinet were flooded with sea water during the storm. Tools and parts were cleaned, but we expect more corrosion damage in the future.
- The deck under the aft port core laboratory door has rusted through into the X-ray Laboratory. A temporary patch was installed. New thresholds will be fabricated and installed on a future leg.

HALIFAX PROJECTS

- Completed Leg 163 science support.
- Sandblasted and “hot dip” galvanized two gun carts and three tow fish.
- Painted metal trim work throughout the laboratories.
- Painted bridge and fo’c’sle decks and the stairwell landings from the main to the bridge deck.
- Remodeled Physical Properties Laboratory. Including rack-mounting the VSR electronics.
- Onloaded Leg 164 freight.
- Prepared posters about the new MST and VSR software for the 5th International Conference on Paleoceanography.
- Prepared ship for 4 days of Canadian public relations tours.
- Repaired damaged tarps.
- Started installation of Leg 164 H_2S detection equipment.
- Cleaned foul-weather gear.
- Refilled liquid N_2 dewars.
- Thoroughly cleaned and reorganized both the Paleontology Laboratory and Science Library. Identification tags were added to the bindings to indicate “Property of ODP” and to which library they belong.

LEG 163 LABORATORY STATISTICS

GENERAL	
Sites:	3
Holes:	4
Meters drilled:	186
Meters cored:	294
Meters recovered:	205
Time on site (days):	16.7
Number of cores:	46
Number of samples:	750
Number of core boxes:	38
ANALYSIS	
Physical Properties Laboratory	
Index properties:	102
Velocity:	2191
Thermal conductivity:	38
MST:	171
Chemistry Laboratory	
CNS:	4
X-Ray Laboratory	
XRD:	78
XRF:	39
Thin-sections	59
UNDERWAY GEOPHYSICS	
Bathymetry (nmi):	2718