

13. SUMMARY AND PRINCIPAL RESULTS¹

Shipboard Scientific Party²

INTRODUCTION

Leg 152 on the Southeast Greenland Margin was designed to address fundamental aspects of the magmatic and tectonic development of a volcanic rifted margin that developed in the vicinity of a mantle plume (Fig. 1). Secondary objectives included the development of the Irminger Basin adjacent to the margin, correlation of Paleogene biostratigraphic and magnetostratigraphic events, and the history of late Cenozoic glaciation of Southeast Greenland. The fundamental problems and the more detailed objectives are reviewed in Section 1 (this volume). In this chapter, we summarize the basic geological framework of the drilling and the main results of Leg 152.

Primary Objectives

Our main drilling objective was deep sampling of the volcanic basement at two sites, approximately 75 km apart, on the seaward dipping reflector sequences (SDRS) that characterize this margin (Fig. 2). One proposed site was on the continental shelf, within the oldest and relatively thin part of the SDRS. In this area, the SDRS onlaps onto the continental crust, and it is at this site that it is likely to show a transition from initial through more developed breakup volcanism. The second proposed site was in the adjacent deep Irminger Basin, within the central part of the SDRS. In this location, the SDRS are thick and, supposedly, accreted in a steady-state mode without influence of the continental lithosphere.

The shelf was drilled at four closely spaced sites (Sites 914–917) to provide a composite stratigraphic section, with deep (779 m) basement penetration at Site 917. The deep basin drilling (Site 918) penetrated an 1199.5-m-thick sedimentary cover and 120 m of basement (see "Principal Drilling Results" section, this chapter).

The drilling transect is located within an area where early Tertiary continental breakup of the North Atlantic Ocean took place within cratonic lithosphere, which apparently had stayed geologically undisturbed since early Proterozoic time. This removes a number of geological complexities present on many other rifted margins. Also, the line of breakup is unusually close to the present-day coastline, which provides further optimum control on the setting of the continent/ocean transition (Fig. 2). High-resolution stratigraphic control within the volcanic basement can be established by correlation of the well-developed seafloor-spreading anomalies to the magnetic cryptochrons of Cande and Kent (1992), if a paleomagnetic calibration of the observed signal can be made to the volcanic basement.

One of the primary objectives of Leg 152 was to characterize the mantle source of the huge volumes of magma represented by the Northeast Atlantic SDRS. Clearly, a thermal anomaly was present to generate the anomalous amount of volcanism, but was this associated with a mantle plume, such as that present below Iceland? Other important questions we hoped to address included, do the SDRS initially form on land only over stretched continental crust, or do they continue to form subaerially at more seaward locations? What was the rate of igneous crustal accretion during the formation of the SDRS?

Can the emplacement mode and nature of the lavas help us to deduce the origin of the thick, underlying igneous crust? What is the subsidence history of SDRS across a margin? The significance of these questions was described in Section 1 (this volume).

Secondary Objectives

A secondary objective of Leg 152 was to provide insight into the Cenozoic development of outer continental shelf and the adjacent deep Irminger Basin, which subsequently formed between the continental margin and the modern Reykjanes Ridge (Figs. 1 and 3). This basin is composed of up to 1.5-km-thick Eocene to Holocene sediments deposited on igneous crust. The shelf and the basin mainly receive detritus from the Southeast Greenland Margin and, therefore, are likely to record the erosional and paleoclimatic history of this margin. In addition, the close proximity of the drill sites to the important oceanographic gateway between Greenland and Iceland (part of the Faeroe-Iceland-Greenland Ridge [FIGR]) also makes it an important paleoceanographic observation point. Questions to be answered by drilling the shelf-and-basin stratigraphic record concerned the onset of uplift and erosion of the margin, the subsidence of the FIGR and overflow of the cold, Norwegian Sea water into the North Atlantic Deep Water, and the onset and history of glaciation of Southeast Greenland. All these questions were discussed in more detail in Section 1 (this volume).

In the following, we first summarize the principal observations made at the six different sites (Sites 914–919). We then present some preliminary conclusions with regard to the volcanic and tectonic development of the margin.

PRINCIPAL DRILLING RESULTS

Introduction

Six sites (914 through 919) were drilled along multichannel seismic-reflection profiles (Fig. 2) GGU 81-08 and EG92-24 (Larsen, 1983, 1990, 1993) and yielded Holocene to Eocene sediments overlying the basaltic acoustic basement. Volcanic basement was recovered at Sites 915, 917, and 918. At Site 917, the volcanic basement was fully penetrated, and still older volcanic sediments were recovered. Principal drilling results are reviewed below according to scientific objectives.

Igneous Rocks

Summary logs of Holes 915A, 917A, and 918D, which penetrated SDRS, are shown in Figure 4. Drilling at Hole 917A penetrated a 779.2-m-thick sequence of volcanic rocks forming the SDRS and continued into underlying sediments (see "Tectonic History and Subsidence of the Margin" section, this chapter). Internal structures in the lavas indicate a tilt of about 20° to 30°. Fault zones were encountered at several levels below 538 mbsf. Drilling terminated close to a major normal fault, which probably throws the basalts into contact with the pre-basaltic sediments (Fig. 5). As a result, 300 to 400 m of the oldest volcanic rocks have not been drilled.

The igneous rocks drilled in Hole 917A comprise 92 lithological units, of which 89 are lava flows, 2 are tuffs, and 1 is a dike. Some of the lavas have red, oxidized flow tops, indicating that they were

¹ Larsen, H.C., Saunders, A.D., Clift, P.D., et al., 1994. *Proc. ODP, Init. Repts.*, 152: College Station, TX (Ocean Drilling Program).

² Shipboard Scientific Party is as given in the list of participants preceding the contents.

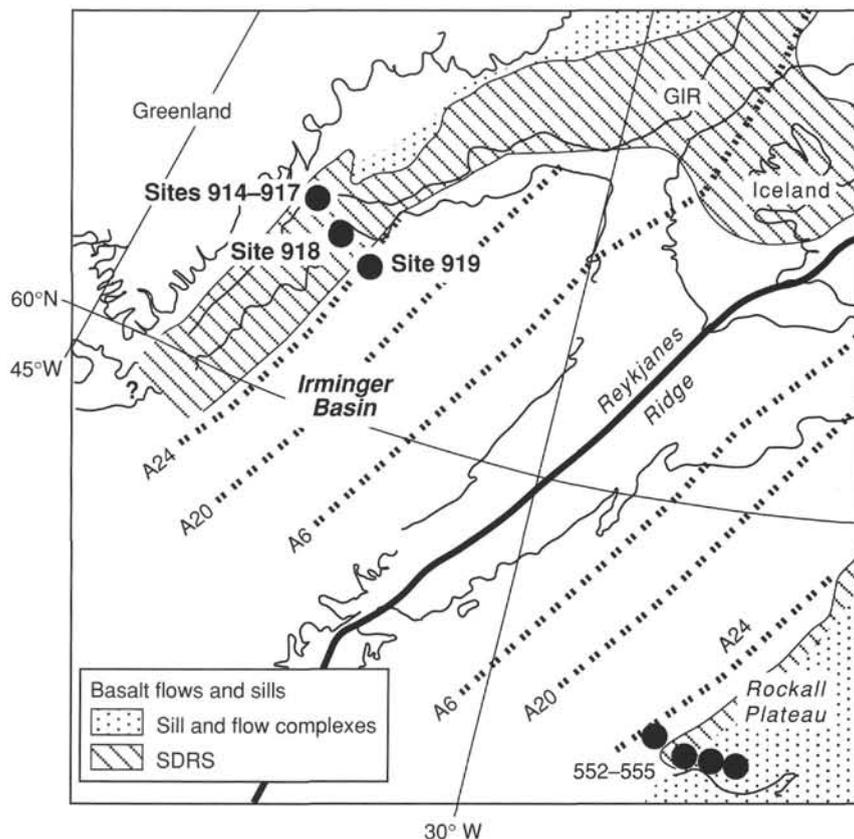


Figure 1. Location of the margin transect (Sites 914 through 919) with regard to the main structure of the North Atlantic Ocean. Sites 552 through 555 were drilled during Leg 81 of the Deep Sea Drilling Project (Roberts, Schnitker, et al., 1984).

erupted subaerially. The volcanic sequence was divided into three series. The Upper Series (igneous Units 1–33, 41.9–183.4 mbsf) consists of dominantly pahoehoe lavas of olivine basalt and subordinate picrite. This series is separated from the Middle Series by a short interval of fluvial sandstone, indicating a break in the volcanic activity. The Middle Series (Units 34–57, 184.1–376.7 mbsf) consists of aa lavas and two tuff horizons of evolved rocks that range from aphyric basalt to plagioclase-pyroxene-phyric dacite. The Lower Series (Units 58–92, 376.7–820.8 mbsf) consists of intercalated aphyric-olivine basalts and more evolved, often porphyritic basalts. Compositional variation among the three series is clearly demonstrated in the plot of Ni vs. depth (Fig. 14, “Igneous Petrology,” section, “Site 917” chapter, this volume). The Lower Series shows regular and smooth compositional variations with stratigraphic height, whereas the Middle Series has uniformly low Ni contents. In contrast, the Upper Series displays large and rapid compositional variations with height. This has been interpreted in terms of differences in magma storage and plumbing systems. Variations in incompatible trace elements (Ba/Zr and Zr/Nb values) suggest variable degrees of interaction between the continental lithosphere and magmas derived from a depleted mantle source. This is detailed in the “Igneous Petrology” section (“Site 917” chapter, this volume) and discussed further in the “Nature and Development of the Breakup Volcanism” section (this chapter).

In Hole 915A, basalt was encountered from 187.8 mbsf to the base of the hole at 209.4 mbsf. The 21.6 m of rock includes a slightly altered plagioclase-olivine-pyroxene-phyric basalt lava flow having a chemical composition broadly similar to the lavas encountered 71 km farther offshore in Hole 918D. Overlying this flow is a highly altered basalt flow (saprolite) and a heterolithic conglomerate.

In Hole 918D, basalt was encountered between 1168.2 and 1178.0 mbsf, within shallow-marine sediments. This unit (Unit 1) has been interpreted as a sill or a lava flow related to a nearby, post-SDRS volcano seen in the seismic profiles (see “Background and Scientific Objectives” section, “Site 918” chapter, this volume). Lavas of the

SDRS were penetrated from 1188.5 mbsf to the base of the hole at 1310.1 mbsf. In this 121.6-m sequence, 18 flow units were recorded, all of which have red, oxidized flow tops, indicating that they were in general erupted subaerially. One occurrence of a hyaloclastite may indicate local or temporary presence of shallow water. The degree of oxidation and alteration between the flows increases with stratigraphic height, suggesting successively longer time intervals between eruptions. The top of the lava pile had been thoroughly altered to a depth of at least 17.6 m before it was covered by shallow marine sediment. All the lavas are aphyric basalts that show little compositional diversity. This is further detailed in the “Igneous Petrology” section (“Site 918” chapter, this volume), and the implications are discussed later in the “Nature and Development of the Breakup Volcanism” section (this chapter).

Figure 5 is a northwest-southeast profile through the innermost part of the SDRS, drawn from the seismic profile (Fig. 2, “Shelf Stratigraphic Synthesis” chapter, this volume). The position of the three lava series found in Hole 917A has been constructed by assuming constant velocity within the basalts and constant dips of the series parallel to the dipping seismic reflectors. The displacement along the lowest, and largest, of the faults in the zone of faulting was assumed to be equal to the displacement shown by the breakup unconformity. In this reconstruction, the occurrence of faults below 538 mbsf in the recovered cores from Hole 917A (see the “Igneous Petrology” section, “Site 917” chapter, this volume) fits well with the faulted zone seen in the seismic profile. A notable feature that emerges from Figure 5 is that the constructed position of the boundary between the Middle and Upper Series coincides with a major seismic reflector northwest of Site 917 and that it seems possible to trace this reflector toward the southeast across the fault.

According to the reconstruction in Figure 5, the basalt drilled in Hole 915A is situated at a stratigraphic level between 100 and 200 m above the drilled part of the Upper Series. This rock is more evolved than any of the drilled Upper Series rocks, and it shows much closer

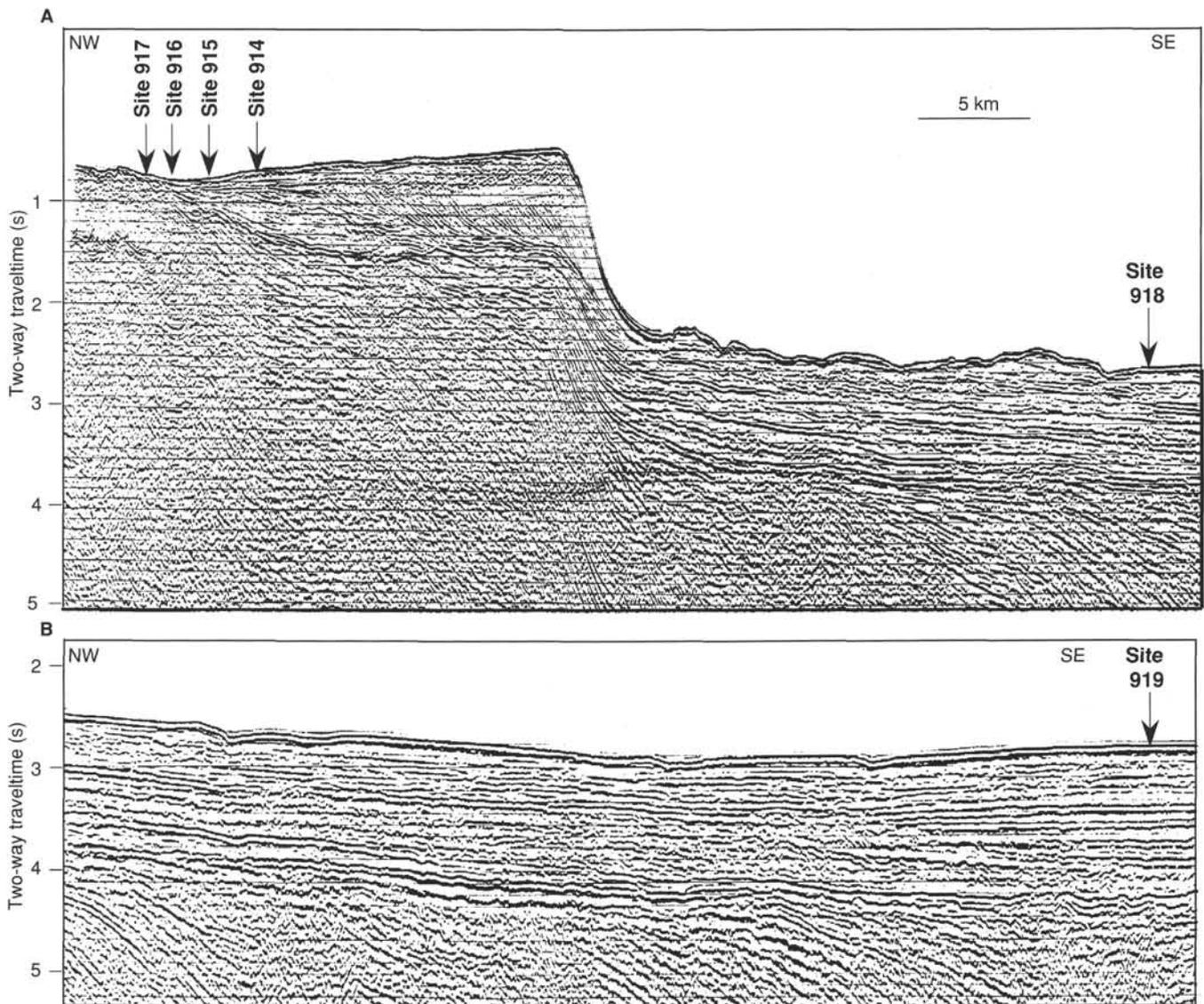


Figure 2. Seismic Line GGU81-01 along the Leg 152 drilling transect. The two sections (A and B) join together to form a continuous profile.

similarity to the basalts farther offshore in Hole 918D. It appears that the eruption of the primitive magmas seen in the Upper Series of Hole 917A took place during a very short time interval after continental rapture.

Eocene and Oligocene Sedimentation

A detailed discussion and correlation of the four sites drilled on the East Greenland Shelf is given in the "Shelf Stratigraphy Synthesis" chapter (this volume), so that only a brief synopsis of the stratigraphy of the shelf sites is given here. Two (Sites 915 and 917) of the four sites drilled on the shelf reached basaltic basement. The deepest rock recovered at Site 916 is basaltic conglomerate, thought to be immediately overlying the basement. The top of the basement is marked by either a weathered basalt horizon (Site 915) or fluvial sediment derived from a weathered basaltic terrain (Site 917, Figs. 6 and 7). The presence of kaolinite in the weathered, possibly pedogenic, zone at Site 915 and in sediment intercalated with the basalt at Site 917 indicates a fairly wet and warm-to-temperate, perhaps even subtropical, climate for this area during the early Eocene, substantiating a similar finding from DSDP Site 336 on the Iceland-Faeroe

Ridge (Nilsen and Kerr, 1978). In addition, studies of clay minerals recovered during Leg 104 also substantiate a moist, damp, Eocene climate and consequent dense vegetation on the Vøring Plateau (Froget et al., 1989; Thiede et al., 1989).

Following a period of post-emplacment weathering of the basalt, the oldest post-volcanic sedimentary record we have from Leg 152 comes from marginal marine-to-freshwater silt and sand deposited in a small half-graben at Site 916 (Fig. 6), and shallow marine silt and greensand deposited at Site 918 (Figs. 6 and 7). As discussed in the "Shelf Stratigraphic Synthesis" chapter (this volume), features of the deposit at Site 916 suggest deposition in an interdistributary bay of a prograding, fluvially dominated delta. The absence of marine siliceous or calcareous microfossils precluded shipboard dating. Possible coeval sediment at Site 918 is a coarse green sand deposit that grades upward into volcanoclastic silt. The glauconitic sediment at Site 918 suggests a starved basin with low sedimentation rates. This seems incompatible with a deltaic system only 75 km away, unless it was of limited extent. It may be that these two deposits are not time correlative or that tectonic relief on the shelf effectively barred deltaic sediment from spilling over onto the outer shelf, or directed the spillover elsewhere. Paleogene sediment of similar general deltaic

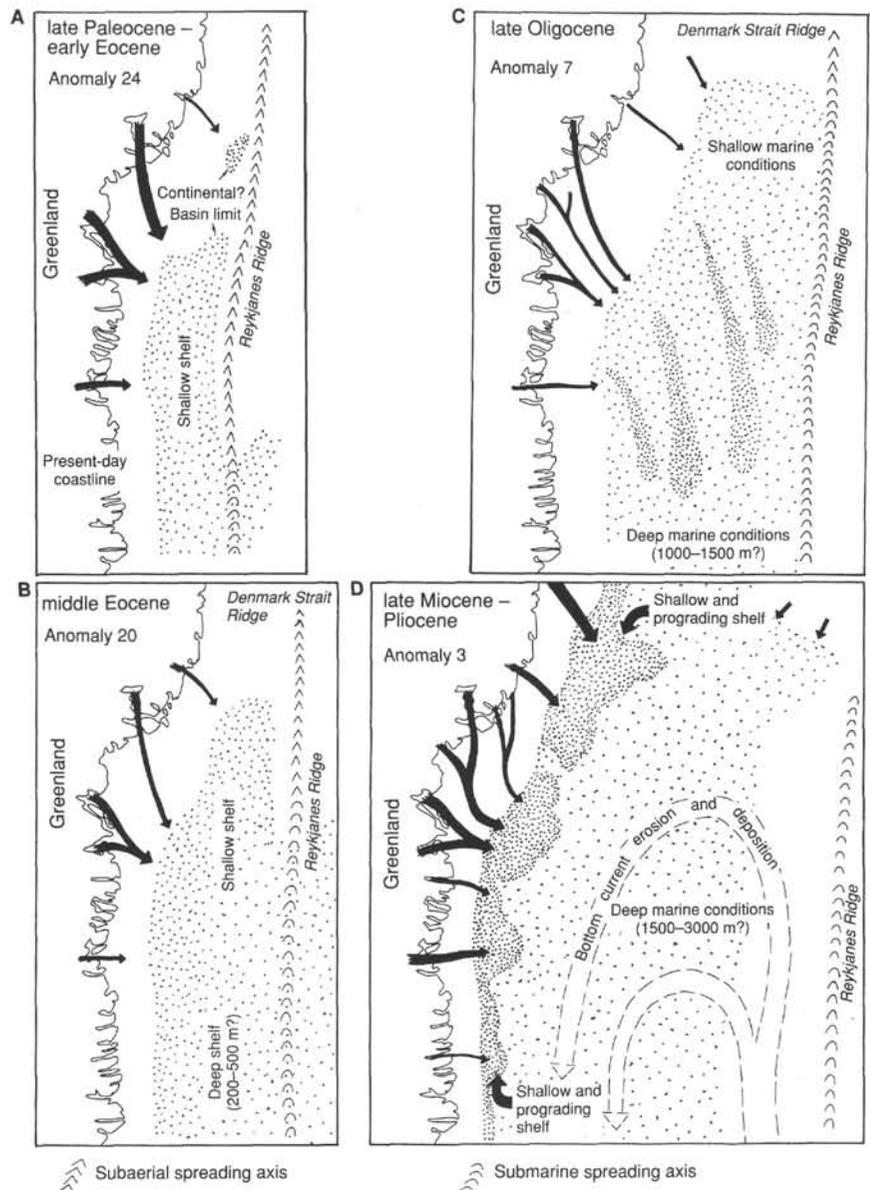


Figure 3. General development of the Irminger Basin. Four stages (A, B, C, and D) of the formation of this Cenozoic basin are shown. Considerable deepening of the basin took place during the early Tertiary, when sediment supply also was limited (from Larsen, 1990).

facies are known from East, North, and West Greenland and are often associated with early Tertiary volcanic rocks (Dawes, 1976; Henderson, 1976; Pedersen, 1976; Nielsen et al., 1981).

Subsidence of the Margin and Formation of the Irminger Basin

During the middle Eocene, the Irminger Basin at Site 918 subsided from water depths of 75 to 200 m to 200 to 600 m (see "Biostratigraphy" section, "Site 918" chapter, this volume). This development within the basin may have been coeval with deposition on the shelf of coarse, rounded basalt cobbles in an aqueous (probably marine) environment at Sites 915, 916, and 917 (Figs. 6 and 7). This calcite-cemented basalt cobble conglomerate thus may represent a basal, transgressive event for the inner East Greenland Shelf. Deposition at Site 918 changed from shallow-water silt and thin sand beds enriched in glauconite to nannofossil chalk interbedded with volcanoclastic silt during the early to middle Eocene. Chalk deposition proceeded through nannofossil Zone CP14a (late middle Eocene).

On the shelf, a hiatus of unknown duration persisted from the deposition of the lower Eocene basalt cobble conglomerate until the middle Eocene marine silt and thin sand interbeds were deposited at Sites 915 and 917 (Fig. 7). The absence of sedimentary structures and the modest thickness of these deposits suggest a quiet middle- to outer-shelf environment with a flourishing benthic fauna where sediment accumulated at low rates below the wave base. This low-energy regime was punctuated episodically by enhanced bottom current activity during which the sand beds were deposited (during large storms?) and later heavily bioturbated by a diverse bottom infauna. This style of sedimentation persisted on the shelf through the early Oligocene at Site 914. It was interrupted for some time between the middle and late Eocene at Site 915 by the deposition of laminated, reddish-brown silt, which has been interpreted as prodelta mud, possibly deposited during a lowstand of sea level (see "Shelf Stratigraphic Synthesis" chapter, this volume).

During the early Oligocene, silt sedimentation with thin sand interbeds persisted at Site 914, representing the youngest Tertiary sediment that we recovered on the shelf. Seismic data suggest that younger Tertiary deposits may be present seaward of Site 914, but

these were not drilled (Fig. 3, "Shelf Stratigraphic Synthesis" chapter, this volume). Unlike the shelf, no lower Oligocene sediment was recovered from the Irminger Basin. However, during the late Oligocene, a submarine canyon system developed on the shelf-slope that fed into the Irminger Basin. A channel from this submarine fan system, which was filled with gravel and massive sand (lithologic Subunit IIIB, Fig. 4, "Shelf Stratigraphic Synthesis" section, this volume), was penetrated at Site 918. Turbidity currents flowed infrequently through the channel system, as indicated by extensive bioturbation and calcite cementation of many of the sand beds. Fan development coincided with a presumed uplift on the East Greenland Margin and a marked eustatic sea-level lowstand (Haq et al., 1987; Fig. 7). A moist climate also may have contributed to fan development, as indicated by abundant wood fragments in the turbiditic sands. The wood and the large quantity of sand suggest that the fan was fed by a deltaic system somewhere on the shelf.

As fan activity at Site 918 declined during the late Oligocene, thinner sand beds were deposited. These punctuate background sediments comprising nanofossil chalk and terrigenous silt (lithologic Unit IIIA, Site 918). Turbidity currents persisted through the early Miocene. Once sand deposition stopped at Site 918, silt and nanofossil deposition proceeded at slow rates, as indicated by the presence of glauconitized hardgrounds in the lower 20 m of lithologic Unit II, all of which are early Miocene age.

Development of Modern North Atlantic Bottom Water

More than 30 cycles of silt-nanofossil chalk in lithologic Unit II culminate in a series of glauconitized hardgrounds, showing erosional features at their tops (Fig. 18, "Lithostratigraphy" section, "Site 918" chapter, this volume). Above each of these contacts is a poorly sorted sand enriched in quartz, illite, rip-up clasts from the hardgrounds, and ripples rich in glauconitic pellets (Fig. 19, "Lithostratigraphy" section, "Site 918" chapter, this volume). Poor sorting of the overlying sand and the erosive contact with the hardgrounds indicate likely transport and deposition of the sand by a highly concentrated flow, possibly related to the initiation of bottom water overflow from the north (i.e., North Atlantic Bottom Water [NABW]) into the Irminger Basin. Above the last glaucony hardground in Section 152-918D-37R-1, only one thin, nanofossil chalk bed and two micritic horizons occur before the onset of noncalcareous or only sparsely calcareous silt deposition (lithologic Unit I, Site 918), suggesting that either cold, corrosive bottom waters precluded carbonate preservation, or that the surface waters cooled and inhibited coccolith blooms. The appearance of NABW-affiliated benthic foraminifers within and above these hiatuses, but not before, substantiates the hypothesis that this influx represents nascent, modern NABW. (See "Biostratigraphy" section, "Site 918" chapter, this volume). Coccoliths and foraminifers deposited before this event are indicative of warmer waters than those that occur in the basin today. In addition, benthic fauna change over this same interval from a rich *Zoophycos-Planolites-Chondrites* assemblage to a sparse *Chondrites* assemblage.

At present, bottom waters of the Irminger Basin are produced mostly by overflow of cold and dense water from the Norwegian-Greenland Sea across three sills on the ridge connecting Greenland and the British Isles (Faeroe Bank Channel at 800 m; Iceland-Faeroe sill at 400 m; and the Denmark Strait sill at 600 m). Combined, these overflows add water to the Irminger Basin at a rate of about $10 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ (Warren, 1981). The initiation of these overflows is not well constrained. On the basis of studies of sediments from the Vøring Plateau, which show a rapid change from calcareous to siliceous plankton within the middle Miocene, Heinrich et al. (1989) concluded that this may have occurred as early as 13.6 Ma.

Onset of Glaciation in Greenland

Terrigenous silt with fining-upward sand intercalations constitutes the uppermost lithologic unit (I) at Sites 918 and 919. The lower

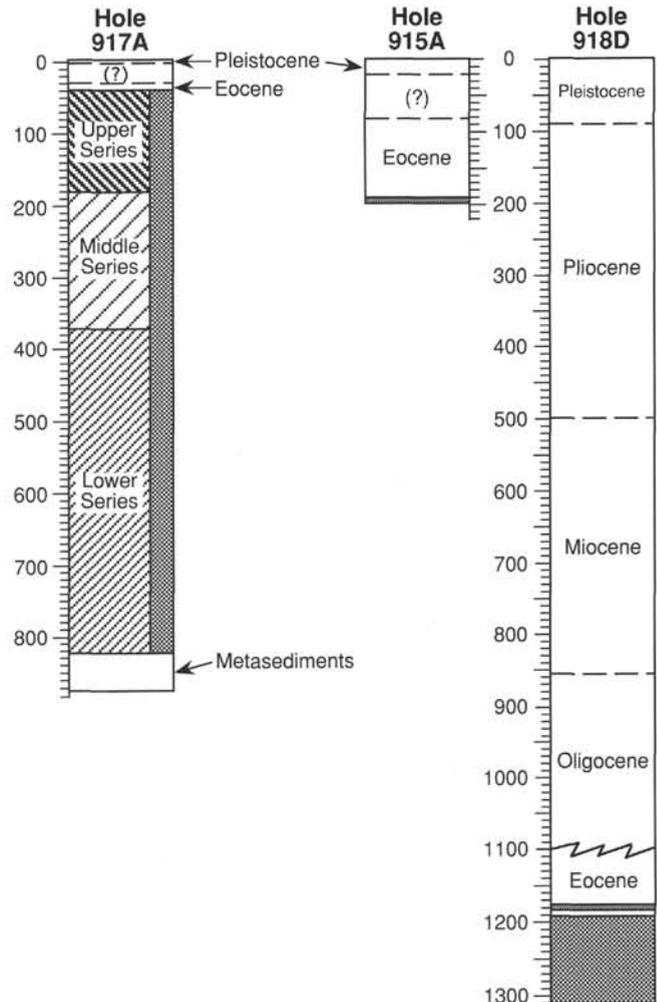


Figure 4. Summary logs of the igneous rocks (shown by heavy stippling) drilled in Holes 917A, 915A, and 918D. The holes are shown in a northwest-southeast sequence, but note that the distances between them are very different: Site 917 is situated 36 km from the coast of Greenland, Site 915 is just 3 km farther offshore, and Site 918 is 71 km farther offshore (Fig. 1).

55 m of this unit at Site 918 (Subunit IE) contains volcanoclastic and continental material, the latter including some kaolinite and illite in the clay fraction. Glacial sedimentation begins with the first occurrence of dropstones in this unit at 543.6 mbsf in upper Miocene silt, where a 30-cm-thick zone of ice-rafted debris (IRD) contains gravel-sized clasts of Greenland gneiss and basalt in a silty matrix (Larsen, Saunders, Clift, et al., 1994) and "Lithostratigraphy" section, "Site 918" chapter, this volume). Dropstones, IRD, microscopic quartz, and other minerals increase in concentration up the section, while kaolinite and illite disappear and nanofossils and foraminifers decrease in abundance (lithologic Subunit ID). Glacial sedimentation is also reflected in a large increase in the sedimentation rate. The percentage of CaCO_3 , controlled in the North Atlantic mainly by the diluting influx of ice-rafted, noncarbonate debris (Shackleton et al., 1984), decreases from 40% to less than 10%, also reflecting the beginning of glacial sedimentation. We dated the sediment containing the first dropstones as 7 Ma. (See "Sedimentation Rates" section, "Site 918" chapter, this volume). We arbitrarily defined a diamictite when the concentration of dropstones reached 10 per section (see "Lithostratigraphy" section, "Site 918" chapter, this volume). This level was reached within lithologic Subunits IA through ID. The greatest abundance of diamicton was over a Pliocene, 89-m-thick section (lithologic Subunit IC).

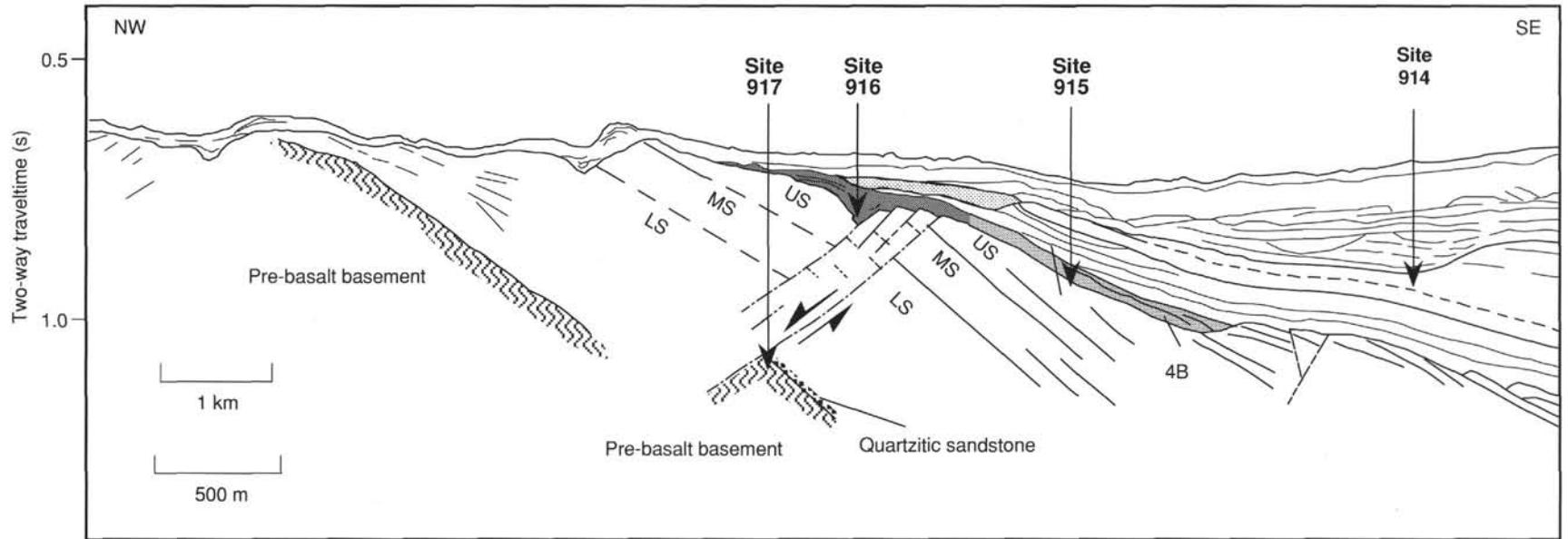


Figure 5. A reconstruction of the position of the three lava series established in Hole 917A within the innermost part of the SDRS. LS = Lower Series; MS = Middle Series; US = Upper Series. The figure is based on the seismic profile (Figs. 1 and 2, "Shelf Stratigraphic Synthesis" chapter, this volume) and assumptions stated in the text. The constructed position of the boundary between the Middle and Upper Series coincides with seismic reflectors on both sides of Hole 917A (thick lines). The boundary may represent the time of the final rupture of the continent. Drilling at Site 917 probably penetrated the southeastern fault block at the crest of the pre-basaltic basement, implying that only part of the sediments at the breakup unconformity was recovered. About 300 to 400 m of the oldest lavas has not been drilled. Note that the dips are exaggerated; the true dip of the lavas and main normal fault is about 20° to 30° .

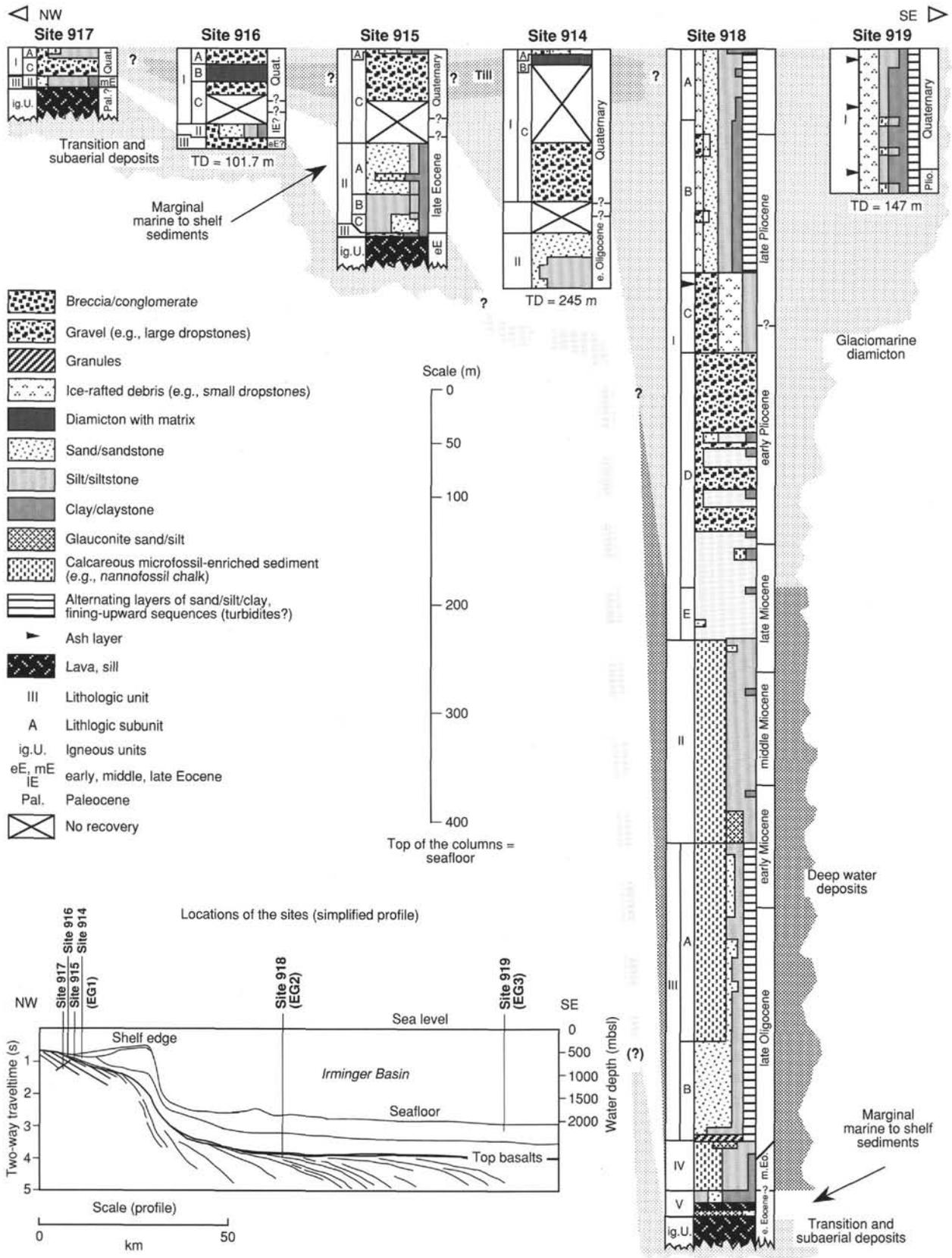


Figure 6. Lithostratigraphic summary of all sites drilled during Leg 152. Sites 914 through 917 were drilled on the East Greenland Shelf. Sites 918 and 919 were drilled in the Iringer Basin.

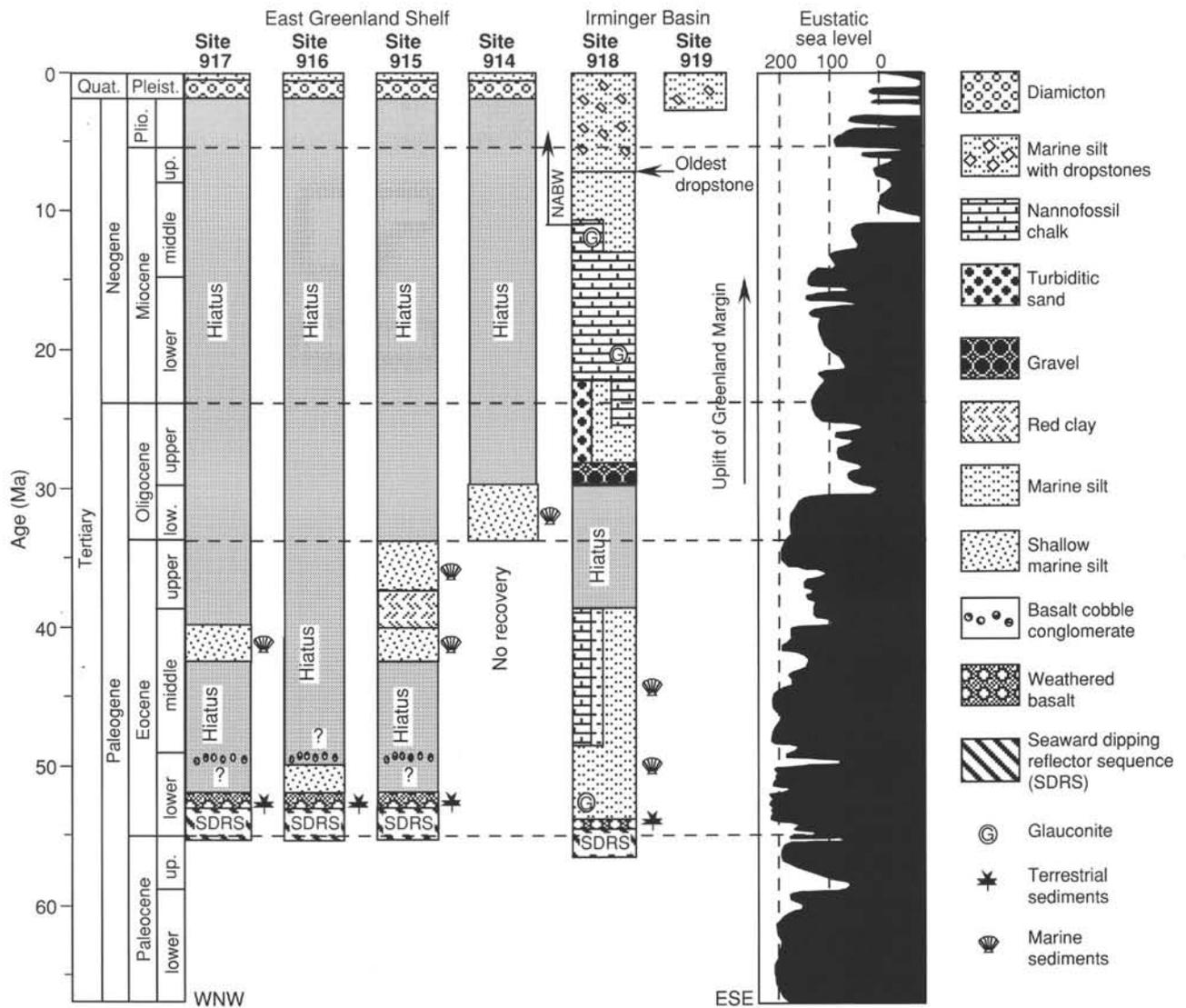


Figure 7. Summary of principal sedimentation events, Leg 152.

The lithologies of the IRD reflect the proximity and distribution of geological units along the southeast and east central coasts of Greenland. At least 50% of the gravel clasts in each diamictite consist of gneiss and granite from the Precambrian basement terrain of south-eastern Greenland. Abundant basaltic clasts were likely derived from thick Tertiary sequences exposed on the inner shelf and along the coast to the north. Other, less frequently encountered lithologies include limestone and sandstone, which were probably transported in icebergs from similar rocks exposed in the fjord zone of northeastern Greenland. The matrix of these IRD-rich intervals consists of highly permeable, quartz-rich rock flour that ranges in size from clay to fine sand and evidently was derived from glacial comminution of the felsic Precambrian rocks. Modern IRD from East Greenland has similar characteristics (Molnia, 1983).

A Pliocene–Holocene series of turbidites, with possible admixtures of contourites, occurs over a 226-m interval (lithologic Subunits IA and IB, “Site 918” chapter; lithologic Unit I, “Site 919” chapter, this volume). Two distinct types of turbidite are interbedded, with one “package” having brown-to-gray, thicker, more massive, and finer-grained sediment enriched in calcareous and/or siliceous microfossils. The other package has thinner beds, no fossils, abundant quartz, and a distinct green color. Both packages are influenced by continued glaciation as dropstones and IRD occur randomly in background

sediment of all grain sizes. IRD was also found at Site 919, 75 km farther out into the Irminger Basin, though in much smaller amounts (<10%) than at Site 918, and at the shelf Sites 914 through 917.

Detailed seismic stratigraphy indicates correlation of Pliocene–Holocene sediments at Sites 918 and 919 in the deep basin with glacial deposits on the Southeast Greenland Shelf (Figs. 4 and 5, “Shelf Stratigraphic Synthesis” chapter, this volume). The outer continental shelf is constructed of a sedimentary unit showing a lateral stack of shingled, seaward-dipping beds. Landward, this unit can be traced into a horizontally bedded, coeval to slightly younger sediment package comprising the glaciomarine sediment and till recovered at Sites 914 through 917 (Fig. 3, “Shelf Stratigraphic Synthesis” chapter, this volume). During past advances of the Greenland Ice Sheet (GIS) onto the shelf, sediments from the continent together with material reworked from below the glacier were apparently transported seaward and deposited as part of a large-scale, progradational, glacial fan at the shelf edge (Boulton, 1990). Glaciomarine sediments (lithologic Unit IA, “Site 914” through “Site 917” chapters, this volume) recovered from the shelf sites are intercalated with a strongly compacted glacial till, characterized in its upper part by high shear-strength (150 kPa; lithologic Unit IB, “Site 914” and “Site 916” chapters, this volume). This till is locally more than 20 m thick and was evidently deposited during a past advance of the GIS, which

extended at least 75 km onto the continental shelf. The clast assemblage of the till resembles that of the glaciomarine deposits, although the glaciomarine sediments contain more basaltic clasts, reflecting southward, coast-parallel, transport of debris in icebergs carried by the East Greenland Current from basaltic areas to the north. The proximal marine sediment from Southeast Greenland sheds new light on some long-standing problems in the Pliocene paleoclimatology of the North Atlantic area. Scattered dropstones and IRD are seen in North Atlantic marine sediments older than 2.4 Ma (Jansen et al., 1989), but the source and significance of such sediments have been uncertain. Similarly, the late Pliocene was characterized by several positive anomalies in the benthic $\delta^{18}\text{O}$ record, dated to 3.1, 2.7, 2.6, and 2.4 Ma (Keigwin, 1987), but no evidence has been seen for corresponding glacial fluctuations.

The sequence of glaciomarine sediments at Site 918 suggests that at least three glaciations occurred in Southeast Greenland between approximately 2.0 and 5.3 Ma. The glacially influenced zones are separated by marine sediments completely free of dropstones or diamictites, which apparently correspond to times when glaciers on Greenland retreated from coastal areas or perhaps disappeared entirely. One or more of the apparent ice-free intervals may correlate with an interval during the late Pliocene, when warm conditions and boreal forests are thought to have prevailed in Greenland (Funder, 1989b).

NATURE AND DEVELOPMENT OF THE BREAKUP VOLCANISM

The volcanic rocks recovered from the Southeast Greenland SDRS have preserved a remarkable record of spatial and temporal changes in mantle source and style of magmatism over the period leading to breakup along the continental margin. Details of these changes have been given in the individual site summary chapters. The most important conclusions are discussed further and summarized here.

All the basaltic lava flows sampled at Sites 917 (Upper and Lower Series), 915, and 918 are relatively basic (MgO contents mostly greater than 7 wt%). Incompatible-element ratios, therefore, will not have undergone any modification through fractional crystallization. The rocks are moderately altered, with little fresh olivine, so that their compositions must be treated with caution. However, the concentrations of elements generally regarded as mobile during alteration (Rb, Ba, and Sr) show a close coherence with the less mobile elements (Zr and Nb). It is likely, therefore, that the relative abundances of the incompatible elements will reflect those of their parental magmas.

Contributions from depleted asthenosphere, and a lithospheric source rich in Ba and Sr, can be recognized in the basalts at Site 917 (see "Igneous Petrology" section, "Site 917" chapter, this volume). This can be seen in Figure 8, in which Zr/Nb and Ba/Zr values in all the Leg 152 basalts are compared with data from Greenland, Iceland, and MORB. Icelandic basalt and MORB represent, respectively, plume and depleted mantle end members. The Greenland basalts are interpreted as the products of variable degrees of interaction between the two. Despite the scatter in the Leg 152 data, it is clear that the basalts from Sites 917 (Upper Series), 915, and 918 are transitional between West Greenland basalts and MORB. Their source was more depleted than that of the Scoresby Sund (East Greenland) basalts, which were erupted close to the inferred position of the Iceland plume axis at 55 Ma. The source of the basalts from Sites 917 (Upper Series), 915, and 918 was probably ambient asthenosphere, with at the most only a small contribution from the Iceland plume. This is consistent with their having been erupted at a site distal from the center of the plume. The only exception is the "sill" from Site 918, which post-dates the SDRS basalts and may be related to an off-axis volcano. The sill appears to have had a source even less depleted than Icelandic basalt, though it might also be the product of a much smaller degree of melting of the same depleted mantle source.

The Lower Series basalts from Site 917 plot above the array defined by Icelandic basalt and MORB and must have had a contri-

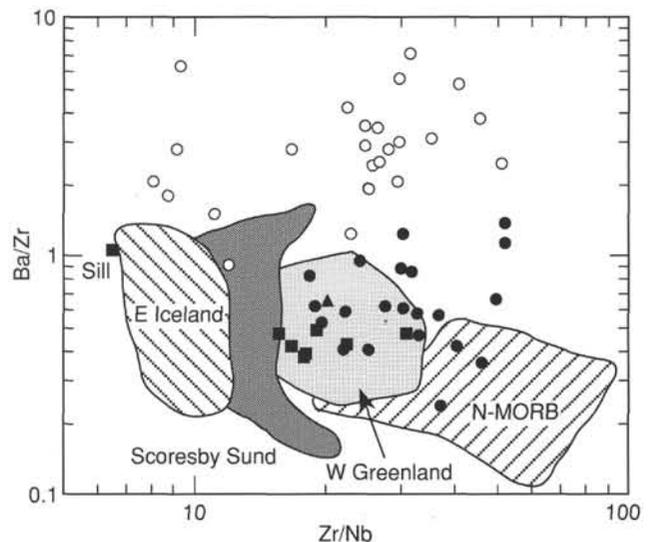


Figure 8. Variation in Ba/Zr and Zr/Nb values in the Leg 152 basaltic rocks compared with the Tertiary basalts of East Iceland (B.S. Hardarson and J.G. Fitton, unpubl. data), Scoresby Sund in East Greenland (L.M. Larsen et al., 1989), West Greenland (Holm et al., 1993), and with normal MORB (A.D. Saunders, unpubl. data; Nb estimated from Ta abundances using Nb/Ta = 16). The Middle Series lavas from Site 917 have been omitted because these are evolved. Open circle = Site 917, Lower Series; closed circle = Site 917, Upper Series; closed triangle = Site 915; closed square = Site 918.

but ion from a source rich in Ba. Because even the most magnesian Lower Series basalts have high Ba/Zr values, contamination with the continental crust may not have been completely responsible. Interaction with continental lithospheric mantle, with variable degrees of crustal contamination, is also a possible explanation. Isotopic and more detailed chemical studies should resolve this uncertainty.

Whatever the contributions from crust and lithospheric mantle, it is clear from Figure 34, "Igneous Petrology" section, "Site 917" chapter (this volume) that the contamination declined rapidly within the time interval between the Middle and Upper Series at Site 917. Similarly rapid transitions from lithosphere-contaminated to uncontaminated magmas are seen in the East Greenland successions (Holm, 1988) and in the late Cenozoic basaltic lavas of the Basin and Range Province in the western United States (Fitton et al., 1991). In both these regions, it has been proposed that magmas were generated in response to lithospheric extension over a mantle plume.

Other SDRS have been drilled at Hatton Bank, on the outer margin of Rockall Plateau (Joron et al., 1984; Merriman et al., 1988), and on the Vøring Plateau (Viereck et al., 1988, 1989). Virtually no Ba data have been published from either area, so these cannot be represented in Figure 8. Basaltic lavas from the Vøring Plateau have Zr/Nb values of 10 to 30 (Viereck et al., 1988, 1989), and those from Hatton Bank, of 13 to 60 (Joron et al., 1984; Merriman et al., 1988). Basalts from Sites 915 and 918, and from the Upper Series at Site 917, thus are closely comparable with those recovered from Hatton Bank, but are more depleted than any other SDRS yet sampled.

In the "Site 917" chapter ("Igneous Petrology" section, this volume), we concluded that magmas of the Lower and Middle Series evolved in large, long-lived reservoirs. These were periodically replenished, as shown by peaks in the Ni content (Fig. 14, "Igneous Petrology" section, "Site 917" chapter, this volume), but the overall trend was toward more evolved compositions with time. This trend culminated in the eruption of the evolved magmas of the Middle Series. The Upper Series at Site 917, by contrast, consists of thoroughly magnesian basalt in which rapid oscillations in Ni content with stratigraphic height (Fig. 14, "Igneous Petrology" section, "Site 917" chapter, this volume) imply short-term storage in smaller reser-

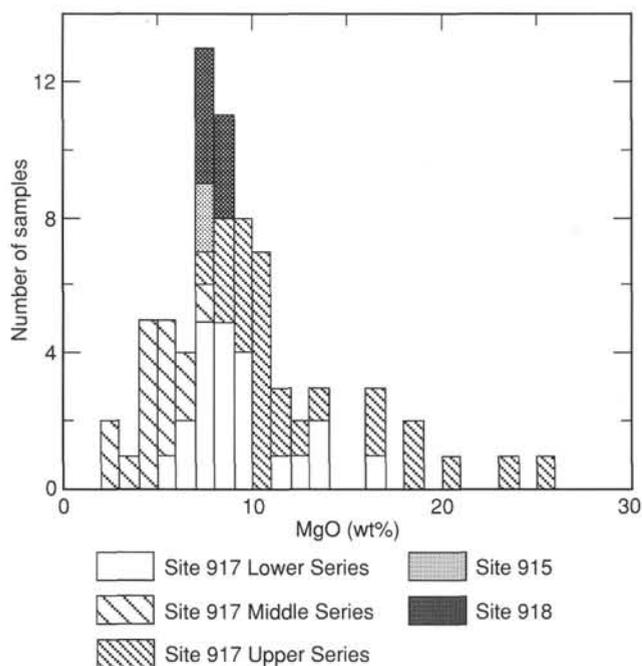


Figure 9. Histogram showing the distribution of MgO content in the Leg 152 volcanic rocks. Note the restricted range of the basalts from Sites 915 and 918 compared with those from Site 917.

voirs, accompanied by crystallization and accumulation of olivine phenocrysts. Evolved magmas are absent from the Upper Series. The simplest explanation for these temporal changes is a transition from a system based on large magma chambers to one dominated by dikes, and we propose that this transition might be the magmatic response to the final breakup of the Southeast Greenland Margin. A close connection between continental rapture and the eruption of picrite has been advocated for other parts of the North Atlantic Tertiary igneous province by L.M. Larsen et al. (1992).

The basalts from Sites 915 and 918 extend our view of this evolving system forward to the time at which fully oceanic conditions had been established (Larsen and Jakobsdóttir, 1988). Despite the limited data set available to us, it is clear that these basalts have a much more restricted composition than those from Site 917. The basalts from Sites 915 and 918 have MgO contents in a very narrow range of 7 to 9 wt% (Fig. 9), similar to the range observed in North Atlantic MORB (Schilling et al., 1983). By this time, the system seems to have evolved toward the re-establishment of permanent reservoirs, this time in denser basaltic crust. The existence of permanent reservoirs is consistent with fast spreading rates (Kuznir, 1980), as inferred for the portion of the SDRS drilled during Leg 152 (approximately 5 cm/yr; see "Tectonic History and Subsidence of the Margin" section, this chapter). As with mid-ocean ridges, the SDRS magma reservoirs appear to have imposed a density filter to restrict the range of erupted magma compositions.

The Southeast Greenland SDRS transect drilled during Leg 152 records the transition from continental to oceanic magmatic systems. The Lower and Middle Series magmas from Site 917 were ponded deep within the continental crust, where they differentiated by fractional crystallization and were susceptible to crustal contamination (cf. Cox, 1980). Rupture of the continental crust during the final breakup phase permitted primary picritic magmas to reach the surface to form the Upper Series lavas at Site 917. This was only a transient phase, however. The establishment of permanent magma reservoirs in the proto-oceanic rift zone once again prevented the eruption of primary magmas and led to the restricted range of basaltic compositions sampled at Sites 915 and 918.

TECTONIC HISTORY AND SUBSIDENCE OF THE MARGIN

Timing and Nature of Breakup

Timing

Drilling during Leg 152 has confirmed that continental breakup and extrusion of the SDRS on the Southeast Greenland Margin took place during latest Paleocene to early Eocene time. The age of break-up was obtained from several types of evidence, primarily aeromagnetic data, in combination with biostratigraphic and paleomagnetic data from Sites 915, 917, and 918. More circumstantial evidence is available from comparisons of the pre-breakup sediments from Site 917 with sediments exposed onshore. Shore-based studies of the Leg 152 cores, including determination of the radiometric age of the volcanic rocks and studies of palynofossils from sediment intervals having no shipboard age determination, are likely to improve the stratigraphic framework greatly.

The general chronostratigraphic setting of the Southeast Greenland SDRS is constrained by the seafloor-spreading magnetic anomaly pattern along the margin (Fig. 10). This shows that at the EG63 transect, the entire SDRS pre-dates magnetic Chron C24n.1n. The very youngest part of the SDRS along the EG63 transect (see Fig. 6, "Introduction" chapter, this volume) correlates with Chron C24n.3n (early Eocene, 52.791–53.250 Ma, according to Cande and Kent, 1992). Landward of seafloor-spreading anomaly C24n.3n, two essentially different scenarios are possible: (1) the entire broad magnetic low and its associated, semilinear, positive anomalies (Fig. 10) represent Chron C24r; or (2) the positive, low-amplitude anomalies within the broad magnetic low represent true normals, Chrons C25n, C26n, and possibly C27n (see also "Introduction" chapter, this volume). Shipboard data strongly suggest that Scenario 1 is the more correct and, hence, that the low-amplitude anomalies within C24r most likely are the result of short field excursions and/or intensity variations, such as the cryptochrons of Cande and Kent (1992).

All the volcanic basement drilled at Sites 915, 917, and 918 indicated reversed magnetic polarity, except for four adjacent flows at Site 917, which exhibited a shallow positive inclination (? normal polarity). At Site 918, a succession of normal (top part) to reverse polarity sediments (lower part) of early Eocene age (51–53 Ma; see "Biostratigraphy" and "Paleomagnetism" sections, "Site 918" chapter, this volume) directly overlies reversely magnetized volcanic basement (18 basaltic flows recovered). According to shipboard data, a very short normal polarity magnetic event may be present within the lower, reversely magnetized sediments. The basal sediments and the lavas possibly form a continuous section with mainly subaerially erupted basaltic flows of the main SDRS (presence of hyaloclastite indicated in only one flow). The lavas are directly overlain, first, by shallow-water sediments and, higher up the section, by more deep-water sediments. Thus, the total body of data strongly suggests an age of Chron C24r for the basement at Site 918. A younger age is not possible (anomaly constraints), and an older age (C25r or older) seems inconsistent with the biomagnetostratigraphic data.

No biostratigraphic ages could be obtained on board the ship for the sediments directly overlying basement at Sites 915, 916, and 917. The oldest datum at these sites was of middle Eocene age (nannofossil Zone CP14a, 39.5–42 Ma).

No evidence was seen within the SDRS of normal polarity chrons that pre-date Chron C24r, which suggests that the Southeast Greenland SDRS formed entirely within magnetic Chron C24r. The possible identification of one, perhaps two, small, normal polarity events at Sites 917 and 918 suggests that magnetic cryptochrons are present in the SDRS (Cande and Kent, 1992). Tentative correlation of the aeromagnetic data with these supposed cryptochrons within Chron C24r indicates that a number of the 11 cryptochrons reported by Cande and Kent (1992) might be present (Fig. 10). This implies that the entire SDRS accumulated during a period of no more than about

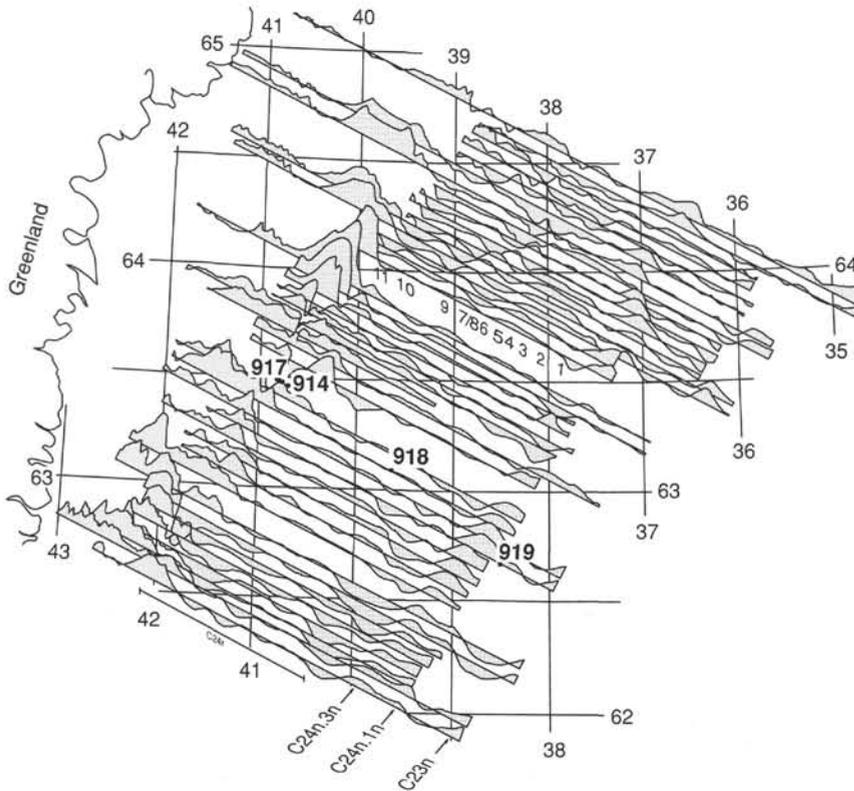


Figure 10. Aeromagnetic profiles over the Southeast Greenland Margin. Position of Leg 152 drill sites is shown. Seafloor-spreading anomalies corresponding to Chrons C23n, C24n.1n (C24n.2n indistinguishable), and C24n.3n are easily identifiable and form well-defined lineations that link with the regional North Atlantic seafloor-spreading anomaly pattern (Larsen, 1980). A deep, broad magnetic low is present landward of C24n and can be correlated with C24r. Low-amplitude, positive anomalies occur within this low and form a fairly linear array not dissimilar to seafloor-spreading anomalies. These have been tentatively correlated with the Chron C24r cryptochrons of Cande and Kent (1992). The preliminary identification made here is consistent with Leg 152 drilling data and implies initial spreading rates of about 7 cm/yr, abating to about 3 cm/yr at Chron C24n to C23n time.

2.9 m.y., between approximately 55.9 Ma and 53.0 Ma. More refined, shore-based paleomagnetic, biostratigraphic, and radiometric work may further narrow the time interval in which the Southeast Greenland SDRS formed.

The pre-SDRS metasediments recovered from below the breakup unconformity (lithologic Unit VI, Site 917) provide an important, albeit circumstantial, age control on the timing of the breakup. Unit VI was probably laid down in a marine, moderately deep-water (mid-deep shelf), low-energy environment. A considerable volcanogenic (basaltic) component within the sediment is suggested by major- and trace-element analyses of these sediments, although the weak magnetization of the sediments does not support this interpretation. The setting and nature of these sediments make correlation with the onshore Late Cretaceous to early Tertiary, pre-basaltic sediments likely (see Larsen, 1980, and Nielsen et al., 1981, for review). A tentative correlation with either the pre-volcanic, Late Cretaceous to Paleocene Ryberg Formation, or with the very earliest Eocene (\approx Sparnacian, 55–55.5 Ma, according to Cande and Kent, 1992; Ali and Jolly, in press) lower, tuffaceous part of the Vandfaldsdalen Formation. The Vandfaldsdalen Formation marks the onset of the onshore flood basalt volcanism and unconformably overlies the Ryberg Formation (Nielsen et al., 1981). Correlation of the pre-SDRS lithologic Unit VI with the Vandfaldsdalen Formation could imply that the rifting, crustal thinning, and subsequent eruption of the entire SDRS all took place between 55 and 53 Ma (i.e., in only about 2 m.y.). Although such a rapid development seems unlikely, it is noteworthy that the sediments of Unit VI show indications of deformation before they were completely lithified (i.e., that they were deformed shortly after their deposition).

Rift Tectonism

The structural development of volcanic rifted margins is not well known because of the strong volcanism within the initial rift zone, which tends to cover the early rift structures. Thus, apart from the characteristic crustal flexuring associated with the steady-state formation of the SDRS, the amount of faulting and deformation during breakup at volcanic-rifted margins is virtually unknown. However,

core data from Leg 152 demonstrate that possibly as many as three generations of normal faulting and a minimum of one episode of uplift and erosion took place during breakup. We cored through only the last generation of faults and through the erosional unconformity below the basaltic lavas (see “Principal Drilling Results” section, this chapter). The general development we envisage on the basis of seismic and coring data comprises pre-breakup sedimentation into a fault-bounded basin, followed by strong, tectonic extension; uplift; and erosion; and, finally, normal faulting and seaward-flexuring of the crust (Fig. 11). It is possible that the younger faults in part may be the result of reactivation of older faults.

The pre-breakup sediments and the early breakup volcanic rocks were deposited onto a Precambrian craton with no record of earlier sedimentation during the Phanerozoic (see also “Introduction” chapter, this volume). Thus, a tectonic mechanism (i.e., extension and normal faulting) seems required to explain the subsidence of the craton to the water depths inferred for the sediments of Unit VI drilled at Site 917 (Fig. 11). This basin fill clearly was strongly tilted prior to eruption of the unconformably overlying basalts. This most likely took place through a second episode of major extension, including fault block rotation. The tilted sediments of Unit VI have suffered more nonpenetrative strain and low-grade metamorphism at higher temperatures (approximately 300°C, indicated by coexisting metamorphic chlorite and biotite) than the overlying lavas seem to have experienced (120°C, indicated by the zeolite assemblage). This may indicate high heat flow following crustal thinning, but this cannot be distinguished from possible later heating by dikes, sills, or shallow magma chambers.

The pre-basaltic sediments (Unit VI) were uplifted and eroded, and unconformably overlain by a thin quartzose sandstone (Unit V). The likely fluvial facies of the sandstone agrees with the general subaerial nature of the SDRS and shows that a dominantly continental, nonvolcanic sediment source was available. This uplift together with the possible metamorphism suggest the development of a strong thermal anomaly within the embryonic rift zone.

Following deposition of the SDRS, the area was again faulted by a third generation of landward-dipping (20°–25°) normal faults (Fig. 11). In contrast to the earlier phases of faulting, for which we have only

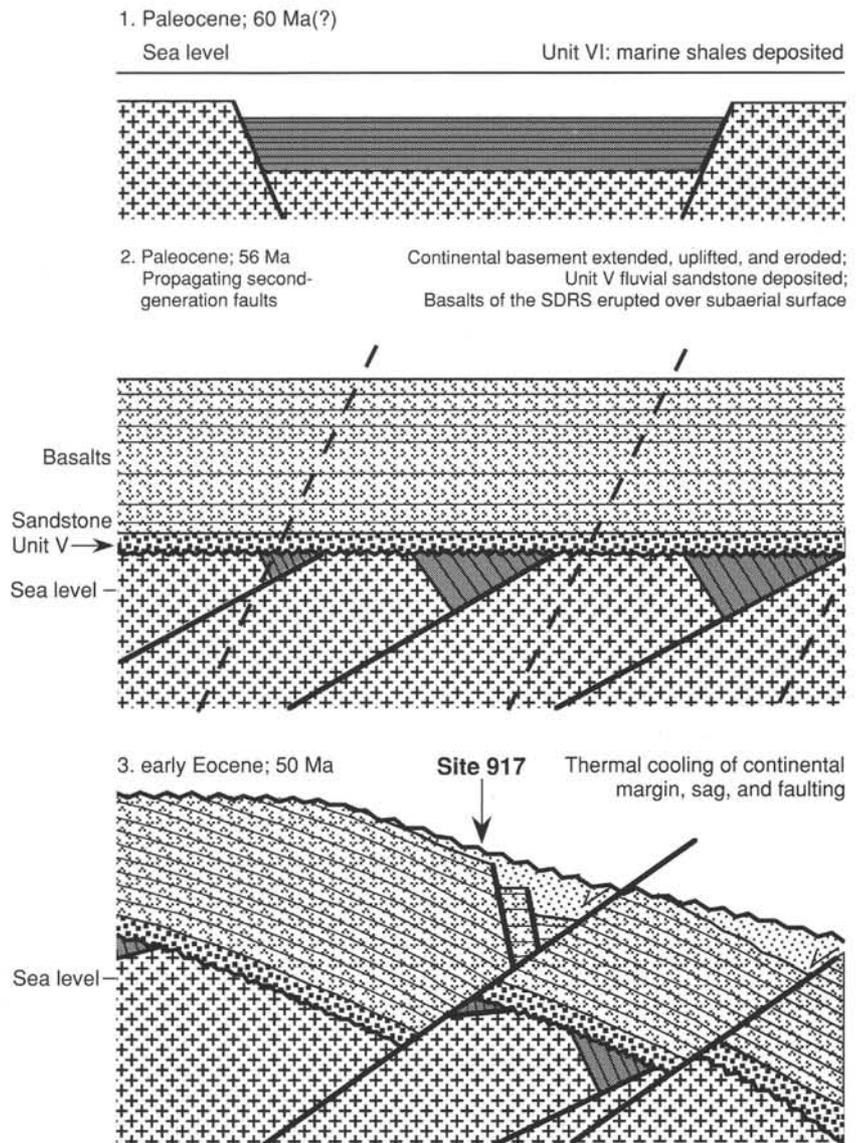


Figure 11. Three stages of tectonic deformation, inferred by Site 917 drilling. The structure in stage 3 is constrained by seismics and drilling, except for the lower boundary of the tilted Unit VI and occurrences of Unit VI outside Site 917. Stages 1 and 2 are interpretations based on the drilling data and other available information; see text for discussion.

circumstantial evidence, this latest phase was seismically imaged and cored at Sites 916 and 917 (see "Principal Drilling Results" section, this chapter). The low dip of the faults results from a late seaward-flexuring of about 20° of the whole lava pile, which also partly affected the overlying sediments. The original dip of the faults, therefore, was probably at least 45° . The fault zone drilled at Sites 916 and 917 displaces the breakup unconformity by approximately 300 m (Fig. 6, "Shelf Stratigraphic Synthesis" chapter, this volume, and Fig. 11).

The scenario presented at Site 917 has complicated tectonic implications. First, the time interval available for these deformations and the early SDRS volcanism seems very short. Second, the uplift and formation of a steep angular unconformity prior to eruption of the SDRS suggest that after initial crustal extension and basin formation (stage 1 in Fig. 11), the rift zone experienced further faulting and extension, after which it was inverted, uplifted, and eroded. Uplift possibly was caused by a thermal anomaly that developed during this second, and apparently main, tectonic rifting episode (stage 2 in Fig. 11).

It is remarkable that we see no tectonic unconformity between the Middle and the Upper Series of lavas. This boundary, associated with a thin sediment layer, seems to mark the final breakup in a magmatic sense, that is, a change from magmatic products having a perceptible residence time in, and reaction with, the continental lithosphere, to a type of magmatism that is characterized by the almost free access of

very primitive magma to the surface (see "Nature and Development of the Breakup Volcanism" section, this chapter). This observation implies that the further thinning of the lithosphere after initial tectonic extension essentially must have been thermal.

In conclusion, we can distinguish between a phase of tectonic rifting, followed by a phase of massive volcanism and thermal thinning of the lithosphere. The latter eventually leads to final breakup and accretion of igneous crust in a manner similar to mid-ocean ridge crustal accretion.

Emplacement of Lavas and Construction of the SDRS

Lava Emplacement

In the "Introduction" chapter (this volume), we adapted the model proposed by Pálmason (1980, 1986) for formation of the SDRS. This model seems to explain all the characteristic seismic stratigraphic features of this unit. One important and testable part of the model is the mainly subaerial deposition of the lavas within the SDRS.

Sites 915 and 917, on the continental shelf at the feather edge of the SDRS, and Site 918, 70 km to the southeast of Site 917 in the main SDRS, provide information about the emplacement environment (see "Principal Drilling Results" section, this chapter).

At Site 917, the 779-m-thick volcanic pile clearly was emplaced in a subaerial environment, as demonstrated by the reddened and oxidized flow tops of the flows, the absence of pillow structures, and the occasional development of red soil horizons. However, the brecciated and quenched bases of a few flows indicate that these were emplaced in shallow water or onto wet surfaces.

At Site 918, the upper part of the volcanic sequence was deeply weathered. A thin clay layer (soil?) was preserved below the overlying early Eocene shallow-marine sediments, indicating transition from subaerial to shallow-marine conditions shortly after volcanism ceased. Scoriaceous tops and bases of some flows, possible presence of quenched margins, and alteration to clay of glassy tops may indicate brecciation in shallow water for some units. Nevertheless, the absence of pillow structures or true hyaloclastite units and the persistent and intensely reddened and oxidized flow tops strongly indicate eruption of the lavas in a subaerial environment with only temporary presence of very shallow water.

Hole 917A illustrates a progressive change in the dynamics of the lava flows in the volcanic pile, from relatively viscous and thick aa flows (>20 m on average) toward the base, to thinner (<5 m), high-temperature pahoehoe flows upward. While these rheological differences directly reflect the trend in the chemical composition of the lavas at Site 917 (see "Igneous Petrology" section, "Site 917" chapter, this volume), the decrease with time in the volume deposited at a given point within the SDRS and the consistent subaerial nature of the lavas are also completely consistent with the kinematic model proposed for their formation (Pálmason, 1980, 1986).

At Site 917, the original top of the lava sequence has been eroded away. In contrast, the entire volcanic sequence seems to have been preserved at Site 918. This difference in preservation of the lava pile may introduce slight differences in their morphological appearance. This is because volcanism at any given point within the SDRS is abating with time, hence, the very late, low-rate volcanism is likely to lag behind the ongoing subsidence and to take place at a lower elevation than the main phase of the volcanism.

At Site 918, the thickness of the SDRS is at least 6 km. If the lavas now at a depth of 6 km below Site 918 also were subaerially erupted, similar to the drilled upper part, then these lowermost lavas of the SDRS would have subsided approximately 6 km. The time interval available for this subsidence is only a fraction of the entire interval of SDRS formation and, hence, is considerably less than 1 m.y.

Crustal Accretion Rates

Estimates of crustal accretion rates in terms of both extrusive magmatic activity and of horizontal crustal accretion (i.e., spreading rate) are an important part of our study because they are complementary to the geochemical and igneous petrology data in the characterization process of volcanic margin breakup. The following preliminary estimates will be expanded later with more precise biostratigraphic and paleomagnetic data.

It has been argued above that the entire SDRS accumulated during a maximum of 2.9 m.y., and possibly during an even shorter period. Assuming an average thickness of 6 km of the SDRS, the crustal accretion rate over this period implies an average extrusive rate of 0.28 km³/k.y. per kilometer of rift axis (half-rate) or a total of 0.56 km³/k.y. per kilometer of rift length (Southeast Greenland only represents the western half of the original rift system; the conjugate Rockall/Hatton Margin is the other half). The spreading rate on average was approximately 5 cm/yr (half-rate), but initially, probably was faster, and slowed down to approximately 3 cm/yr during the Chron C24n to C23n interval (Larsen, 1980). In terms of eruption frequency, the accretion rate corresponds to the eruption of one flow, 8 m thick, 70 km wide (35 km on each side of the rift axis), every 1000 yr.

Compared to data obtained from the continental flood basalts onshore East Greenland and from Iceland, the rate of volcanic pro-

ductivity within the SDRS at the EG63 transect is high. For Iceland, Pálmason (1980) estimated on average 0.13 km³/k.y. per kilometer of rift length. For the East Greenland flood basalts, Larsen et al. (1989) estimated a volcanic productivity between 0.115 and 0.15 km³/k.y. per kilometer of rift length. Thus, as suggested by Larsen and Jakobsdóttir (1988), the accretion rate for Southeast Greenland SDRS seems to be more than four times greater than the average accretion rates found in Iceland and within the East Greenland flood basalts.

Post-Breakup Subsidence, Uplift, and Erosion of the Margin

Subsidence of the Igneous Crust

Following the cessation of basalt eruption and relative seaward migration of the zone of crustal accretion, the basalts of the SDRS began to subside toward their present depths because of thermal contraction of the lithosphere. Interestingly, the basalts at Site 918, despite being younger than those at Sites 914 through 917, were the first to be covered by marine sediments during the early Eocene (51–53 Ma), after only a short period of subaerial exposure. Lavas at Sites 915 through 917 apparently were not covered by marine sediments until the middle Eocene (39.5–42 Ma). This difference may be the result of several factors. The most obvious explanation is that basalts at Sites 915 through 917 were higher above sea level immediately after eruption ceased than those at Site 918. A difference in relative elevations could be the result of a decrease in the thermal anomaly of the plume through time since an initial maximum. However, in contrast to Site 918, Sites 915 through 917 are located on the feather edge of the SDRS, where the basalts were erupted onto thinned continental crust. Thus, while the basalts at Site 918 are likely to have subsided exponentially like oceanic crust (cf. Parsons and Sclater, 1977), the basalts at Sites 915 through 917 could have been isostatically supported by the less dense continental crust. Although flexural support by thinned continental crust probably is modest (Barton and Wood, 1984), concentration of extension close to the sharp continent/ocean transition might have caused this factor to have had more effect.

An additional factor is the effect of underplated magma onto the base of the crust. Magmatic underplating of gabbroic material under the Rockall/Hatton Bank was considered by White (1988) to provide a buoyant root to the thinned crust. Thermal subsidence of the Rockall/Hatton Bank, therefore, is less than expected for the amount of stretching calculated for this area. The same might be true of the Greenland Margin. Magmatic underplating of the area of Sites 915 through 917 may explain why subsidence of the thinned continental crust was relatively modest.

Regardless of the detailed nature of the differences in crustal rheology between the inner, feather edge, and the central, main part of the SDRS, these differences led to the flexuring and faulting between the two areas (Fig. 6, "Shelf Stratigraphic Synthesis" chapter, this volume).

Uplift and Erosion of the Inner Margin

The feather edge of the SDRS is thought to have been only lightly eroded prior to transgression by Eocene marine sediments. Analyses of the thickness of the basalt flows within the SDRS show a marked tendency to thinning up the section at Site 917 (see "Igneous Petrology" section, "Site 917" chapter, this volume). An extrapolation of this trend would suggest that only limited material had been removed prior to transgression.

No evidence exists for any rapid uplift of the SDRS immediately after eruption. In fact, marine lower Eocene sediments at Site 918, only about 70 km seaward of the SDRS feather edge, indicate low sedimentation rates with limited terrigenous influx before a middle Eocene to upper Oligocene hiatus. The sudden and strong influx of coarse clastic turbidites at Site 918 during the late Oligocene may

have been triggered in part by the uplift of the inner margin. However, according to Haq et al. (1987), the late Oligocene timing of the uplift of the margin is almost synchronous with a major fall in sea level (see "Principal Drilling Results" section, this chapter). This makes it less unequivocal that the uplift actually occurred at this time. The late Oligocene timing, however, is in good agreement with data from the coastal region; these data indicate the presence of a kilometer-scale, late Oligocene to Neogene margin uplift (Larsen, 1990; Christiansen et al., 1992). Such late uplift is difficult to explain in terms of breakup events, including current ideas of underplating. Recently, it was pro-

posed that the uplift is in part related to the ridge-push effect of the developing Reykjanes Ridge (Larsen and Marcussen, 1992). Borehole caliper measurements (FMS) taken at Site 917 (see "Downhole Measurements" section, "Site 917" chapter, this volume) show that the present-day principal compressive stress direction is compatible with a ridge push from the modern Reykjanes Ridge.

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