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1. Leg 210 Summary[1]

Shipboard Scientific Party[2]

ABSTRACT

Ocean Drilling Program Leg 210 was devoted to studying the history of rifting and postrift sedimentation in the Newfoundland–Iberia rift. Drilling was conducted in the Newfoundland Basin along a transect conjugate to previous drilling on the Iberia margin (Legs 149 and 173). This was the first time that deep-sea drilling has been conducted on both sides of a nonvolcanic rift in order to understand the structural and sedimentary evolution of the complete rift system. The prime site during Leg 210 (Site 1276) was drilled in transitional crust between known continental crust and oceanic crust identified by magnetic Anomalies M3 to M0 (Barremian–Aptian). On the conjugate Iberia margin, extensive geophysical work and deep-sea drilling have shown that the transitional crust is exhumed mantle that is extensively serpentinized in its upper part. Transitional crust on the Newfoundland side, however, is typically a kilometer or more shallower and has much smoother topography, and seismic refraction data suggest that the crust may be thin (~4 km) oceanic crust. These features indicate that the rift may have developed asymmetrically. A major goal at Site 1276 was to investigate these differences by sampling basement and the facies responsible for a strong overlying basinwide reflection (U) that is poorly developed on the conjugate Iberia margin, together with the intervening lithologic section.

Site 1276 was cored from 800 to 1739 m below seafloor with excellent recovery (average = 85%). Before drilling was terminated because of unstable conditions in the uncased lower part of the hole, we cored sills >10 m thick that are estimated to be 100–200 m above basement. The sills are diabases of probable alkaline composition. They have sedimentary contacts that show extensive hydrothermal alteration. Associated sedimentary and structural features suggest that the sills were intruded at shallow levels below the seafloor. The top of the upper sill is approxi-

[1] Examples of how to reference the whole or part of this volume.
[2] Shipboard Scientific Party addresses.

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mately coincident with the U reflection, within uppermost Aptian(?) to lower Albian fine- to coarse-grained sedimentary gravity flows. The nature of basement at this site remains uncertain, but the presence of the deep sills indicates that there was a significant postrift magmatic event that may have affected much of the basin. This feature of the basin could help to explain the asymmetry in basement depth and basement roughness on the Newfoundland and Iberia conjugate margins.

The overlying Albian to lower Oligocene sediments record paleoceanographic conditions similar to those documented in the main North Atlantic Basin and on the Iberia margin, including deposition of Cretaceous black shales, but they show an extensive component of gravity-flow deposits throughout. Major paleoceanographic events including a number of Oceanic Anoxic Events, the Cretaceous/Tertiary boundary, and the biotic recovery from the Paleocene/Eocene Thermal Maximum are well represented in the cored section. A prominent seismic marker (equivalent to Horizon A^u) that is correlated with the initiation of deep circulation in the North Atlantic was cored, and preliminary biostratigraphic data indicate that it is a hiatus dating to the middle Eocene, perhaps several million years older than proposed in previous interpretations.

Site 1277 was drilled 80 m into a shallow basement high ~40 km southeast of Site 1276. This crust, presumed to be oceanic, is on the young side of a magnetic anomaly interpreted as M1. Cores from the upper part of basement at this site recovered a remarkable assemblage of basalt flows interleaved with gravity flows containing fragments of gabbro and serpentinized peridotite and also sediments (e.g., fine- to coarse-grained volcaniclastic sandstones and breccias). Below these largely allochthonous rocks, basement is serpentinized peridotite with veins of gabbro; this rock is interpreted as being in situ. The basement rocks were emplaced in a magma-limited, highly extensional environment that we interpret to represent very slow seafloor spreading.

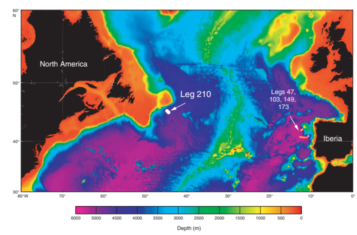
INTRODUCTION

Rifting of a continent and birth of a new oceanic spreading center are fundamental yet poorly understood parts of the plate tectonic cycle. Rifted margins are commonly classified as two types, volcanic and nonvolcanic (White et al., 1987; Mutter et al., 1988; White and McKenzie, 1989), although a relatively continuous range of margin types that vary in character according to tectonic stress, lithospheric strength, and mantle conditions is likely (Mutter, 1993). Two principal models of lithospheric extension have been proposed for nonvolcanic margins. In the pure shear model (McKenzie, 1978), crustal thinning is relatively uniform across a rift; brittle deformation causes thinning and faulting of the upper crust and ductile deformation thins the lower crust. This model predicts that conjugate margins will have generally similar crustal thickness, structure, composition, and subsidence history. Progress in modeling of continental rift structure and extensional tectonics together with observations of significant asymmetries in conjugate margins, however, suggests that many rifts may develop by a simple shear mechanism (e.g., Lister et al., 1986, 1991; Rosendahl, 1987; Wernicke, 1985). Simple shear predicts an upper plate margin consisting of weakly structured upper continental crust with a rift-stage history of uplift and a lower plate margin dominated by highly structured lower continental crust and a history of subsidence. Melt generation and attendant volcanism, compared to a pure shear environment, is probably minimal (Latin and White, 1990; Buck, 1991).

As continental plates separate, crustal thinning, volcanism, faulting, uplift, subsidence, and sedimentation profoundly modify the structure of the rifted margins. To understand these processes, we need detailed information on the resulting geological record, particularly the basement architecture and the overlying sedimentary framework. Furthermore, in order to evaluate the role of pure shear, simple shear, or other mechanisms of rift extension, it is essential to examine the geological record of *conjugate* rifted margins. This is best done by acquiring and analyzing wide-angle reflection/refraction and vertical-incidence reflection data along carefully chosen conjugate margin transects and then by sampling critical sections by drilling.

In the early 1990s, the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) North Atlantic Rifted Margins Detailed Planning Group recommended the Newfoundland and Iberia conjugate margins as high-priority drilling targets to understand the evolution of nonvolcanic rifts (Fig. **F1**). These margins presented several advantages for such a study:

F1. Bathymetric map of the conjugate Newfoundland and Iberia margins, p. 39.



1. They are considered to be representative of nonvolcanic rifting.
2. Rifting is complete, so the entire rift history can be studied.
3. The along-rift spatial relations of crustal conjugates are well constrained in plate reconstructions.
4. Sediments are comparatively thin, so important basement targets can be imaged by seismic reflection/refraction and they are accessible by drilling.
5. The locations are logistically convenient, thus facilitating access.

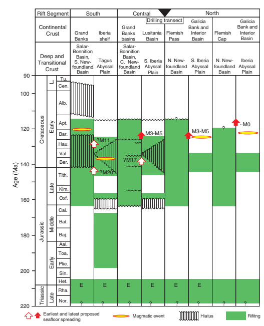
By design of the JOIDES advisory and planning structure, extensive drilling (Ocean Drilling Program [ODP] Legs 149 and 173) was conducted on the Iberia half of the rift (Fig. **F1**). This complemented earlier drilling (ODP Leg 103) on the western margin of Galicia Bank, and it was supported by extensive geophysical work (e.g., Whitmarsh et al., 1990, 1996; Pinheiro et al., 1992; Reston et al., 1995; Whitmarsh and Miles, 1995; Reston, 1996; Pickup et al., 1996; Discovery 215 Working Group, 1998). An early drill site from Deep Sea Drilling Project (DSDP) Leg 47B (Site 398) also provided valuable information near the Leg 149/173 transect. These studies, summarized below, provided surprising results about the composition and origin of crust in the transitional zone between known continental and known oceanic crust on the Iberia margin. They also raised major questions about how the Newfoundland–Iberia rift developed and whether rifting was symmetrical or asymmetrical. To answer these questions, it is necessary to investigate the structure and evolution of the conjugate Newfoundland margin, which was the major objective of Leg 210. The following section outlines the geological setting of the Newfoundland–Iberia rift and summarizes the results of a site survey that was conducted in preparation for drilling on the Newfoundland margin.

GEOLOGICAL SETTING

Rift Development and Basement Structure

The Newfoundland and Iberia margins first experienced significant extension in Late Triassic time when rift basins initially formed within the Grand Banks and on the Iberia margin (Lusitania Basin) (Figs. F2, F3). The Grand Banks basins accumulated siliciclastic "redbed" sediments, and these were succeeded by deposition of evaporite deposits, which extended into the earliest Jurassic in both the Grand Banks and Lusitania basins (Jansa and Wade, 1975; Wilson, 1988; Rasmussen et al., 1998). A second prolonged rift phase in the Late Jurassic through Early Cretaceous extended the crust in several subbasins, but it ultimately focused extension between the Grand Banks and Iberia (Enachescu, 1987; Tankard and Welsink, 1987; Wilson et al., 1989). This culminated in continental breakup and formation of the first oceanic crust no later than Barremian to Aptian time. Excepting the Southeast Newfoundland Ridge at the southernmost edge of the rift, no significant thickness of volcanic rocks or magmatic underplating is known to be present in the rift. Thus, the system is considered to be nonvolcanic.

F2. Rift events in the Newfoundland–Iberia rift, p. 40.



F3. Anomaly M0 reconstruction, p. 41.

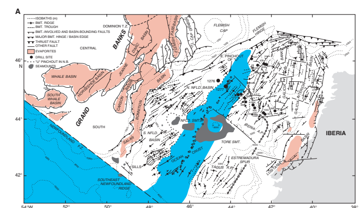


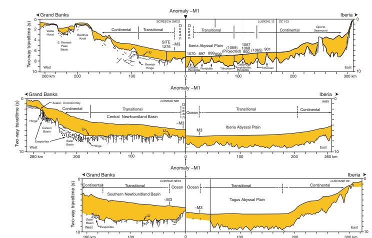
Plate reconstruction of the Newfoundland–Iberia conjugate margins at the time of Anomaly M0 (Barremian/Aptian boundary; ~121 Ma) (Fig. F3) provides a regional overview of the rift and the conjugate margins. At this time, thick continental crust of Flemish Cap was close to extended continental crust of Galicia Bank at the northern end of the rift. To the south, geophysical studies and magnetic anomaly identifications suggest that ocean crust was present, extending landward from a seafloor-spreading axis to at least Anomaly M3 (early Barremian; see blue-shaded area in Fig. F3). Along axis, the Newfoundland–Iberia rift can be roughly divided into three segments: (1) a northern segment containing Flemish Cap and Galicia Bank, (2) a central segment bounded on the south by the Newfoundland and Tore seamounts, and (3) a southern segment extending south to the Southeast Newfoundland Ridge and the present-day Gorringe Bank off southwestern Iberia. Each of these is reviewed below.

In the northern segment, Flemish Cap has full continental crust thickness of ~30 km (Funck et al., 2003) and it is separated from the shallow Grand Banks by thinned continental crust under the Flemish Pass Basin and Flemish Cap Graben (Enachescu, 1987). Galicia Bank is extended continental crust that has a maximum thickness of ~20 km in its central part and thins to zero thickness at its western margin; it is separated from Iberia by the Galicia Interior Basin, which contains rifted continental crust that is thinned to ~10 km (González et al., 1999; Pérez-Gussinyé et al., 2003). Anomaly M0 appears to occur just seaward of the edges of continental crust in these conjugate segments (Srivastava et al., 2000), but there are no older M-series magnetic anomalies present. At the seaward margin of Galicia Bank (ODP Site 637), the westward transition from continental to ocean crust is marked by a prominent ridge composed of serpentinized peridotite (Boillot, Winterer, Meyer, et al., 1987; Boillot et al., 1995).

On the Iberia margin, the southern limit of this rift segment lies roughly at the southern edge of Galicia Bank. In this location, the shallow crust of Galicia Bank is expressed in a series of rift-parallel ridges that plunge to the south and lose a large portion of their amplitude beneath the southern Iberia Abyssal Plain. It is along this transition that the Leg 149/173 transect was drilled. The seaward edge of known continental crust passes southeastward through this transect near ODP Site 1069, then probably to the south toward Estremadura Spur (Fig. F3). On the conjugate Newfoundland margin, continental crust reaches seaward at least to the Flemish Hinge near Flemish Cap and to a hinge line at the eastern edge of the Salar-Bonnition Basin to the south. Seaward of the Flemish Hinge, no along-strike change has been identified in the basement structure that would correlate with the structural change at the southern margin of the conjugate Galicia Bank.

The central segment on both margins has an abrupt transition from shallow continental shelf to deep basin, although there are rift basins beneath the continental shelves that are completely filled with sediments (Fig. F3). On the Newfoundland margin these are the Jeanne d'Arc, Carson, and Salar-Bonnition basins, and the Lusitania Basin is present on the Iberia margin. These basins are in extended continental crust that reaches seaward an uncertain distance beneath the continental slope and rise, and they contain evaporites of Triassic age (Jansa et al., 1980; Austin et al., 1989). Farther seaward, the basement is deep and is considered to be "transitional" crust out to a point where magnetic Anomalies M3 to M0 are identified (Fig. F4).

F4. Interpretation of conjugate seismic reflection sections, p. 43.



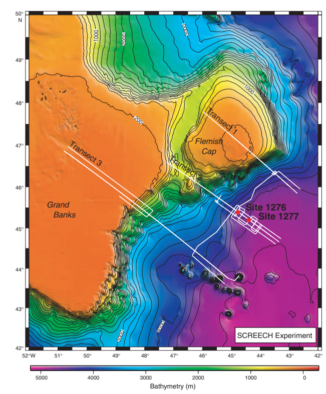
The origin of the transitional crust has been a matter of intense debate. Structural trends in the basement are oriented north-northeast to northeast, subparallel to the Anomaly M0 spreading axis. Srivastava et al. (2000) suggested that magnetic anomalies as old as M17 (early Berriasian; ~140 Ma) are present in this segment, but it is unclear whether the low-amplitude anomalies represent polarity reversals or are related to the basement relief. In the transition zone at the northern margin of the segment, Leg 149 and 173 drilling recovered serpentinized peridotite from basement (Fig. F4). To the south (line IAM9; Fig. F4), seismic data reveal a thin (1.0–2.5 km) unreflective basement layer overlying a more reflective layer (Pickup et al., 1996). This upper layer also has been interpreted to be serpentinized upper mantle peridotite, grading downward into less altered and unaltered peridotite. Seismic refraction experiments there seem to agree, defining a low-velocity "crust" that is only 2–4 km thick and that overlies a layer with velocities of ~7.1–7.7 km/s; these layers are thought to be partially serpentinized peridotite (Whitmarsh et al., 1990; Discovery 215 Working Group, 1998; Dean et al., 2000). In the conjugate central Newfoundland Basin, similar "crustal" thicknesses and velocity structure have been detected in the transition zone (Srivastava et al., 2000). The transition zone width in the central segment is ~150 km on both margins.

The southern segment is like the central segment in that it has deep and thin crust in the transition zone and the zone is ~130–150 km wide. On the Newfoundland side, refraction data of Reid (1994) indicate the presence of very thin crust (~2 km) over apparently serpentinized mantle (7.2–7.5 km/s) that extends at least ~50 km east of the seaward hinge of the Salar-Bonnition Basin. Very similar results have been reported for the conjugate Iberia transitional crust beneath Tagus Abyssal Plain (Pinheiro et al., 1992). Srivastava et al. (2000) suggested that the transitional crust in the southern segment is oceanic and that it is Tithonian (Anomaly M20; ~145 Ma) in its oldest part. The landward portions of the southern segment differ from the central and northern segments in that there are no major rift basins in the proximal continental crust, excepting the southern Salar-Bonnition Basin on the Newfoundland side. On the Newfoundland margin, the southeasternmost Grand Banks is intact continental crust that has been in a subaerial or shallow-shelf environment throughout the Mesozoic and Cenozoic (Jansa and Wade, 1975).

Just as the three rift segments differ from one another from north to south, the conjugate sides of each segment also show dissimilarities. In the northern segment, the major distinction is in the amount of crustal extension (i.e., the thick, intact crust of Flemish Cap vs. the extended and structured crust of Galicia Bank). In the central and southern segments, the major differences are in crustal depth and crustal roughness. The Newfoundland transitional basement averages a kilometer or more shallower than the Iberia basement (Fig. F4), even when corrected for sediment loading. In addition, Newfoundland basement is relatively smooth compared to that off Iberia, where >1 km of basement relief is common.

Structural trends in the transitional basement (Fig. F3) tend to show some convergence toward the north. This, together with the northward-narrowing zone of ocean crust in the M0 reconstruction, suggests that the rift may have opened from south to north, which is consistent with a stage pole of opening a short distance north of the rift (Whitmarsh et al., 1990; Srivastava et al., 2000). Considering the segment-to-segment differences in the extent of rifting in the shallower continental crust, the southern part of the rift may have switched from continental rifting to seafloor spreading relatively early and abruptly, while the northern part experienced prolonged continental extension and a delayed change to normal seafloor spreading.

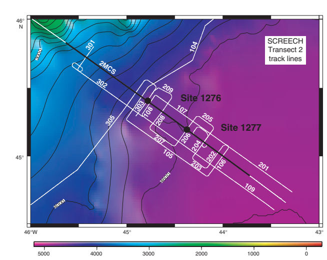
F5. Three transects of the SCREECH survey, p. 45.



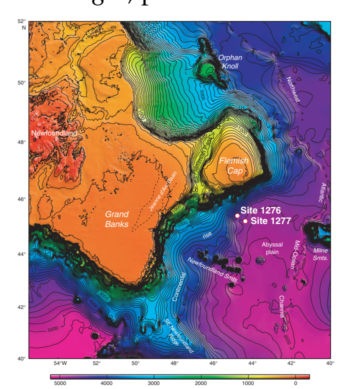
Insights from the Newfoundland Basin Geophysical Survey

Additional constraints on basement structure and sedimentary stratigraphy of the Newfoundland transition zone were obtained in 2000 during the Study of Continental Rifting and Extension on the Eastern Canadian Shelf (SCREECH) program (*Ewing* Cruise 00-07). In this program, multichannel seismic (MCS) and ocean bottom hydrophone/seismometer surveys were made in three major transects across the Newfoundland margin (Figs. F3B, F5, F6). Each transect extended from full-thickness continental crust on the landward end seaward to known oceanic crust beyond magnetic Anomaly M0. Transect 2 was located so that it is conjugate to the Leg 149/173 drilling on the Iberia margin (Fig. F3B), and it is along this transect that Leg 210 drilling was conducted (Fig. F7). To provide regional perspective, the principal results for all three transects are summarized below.

F6. SCREECH survey along transect 2, p. 46.



F7. Bathymetry of the Newfoundland margin, p. 47.



Transect 1

Transect 1 across Flemish Cap is in a position conjugate to Leg 103 drilling conducted on the seaward margin of Galicia Bank (Fig. F3B). It shows that continental crust thins rapidly from ~30 km beneath Flemish Cap to ~2 km beneath the lower continental slope at the Flemish Hinge (Funck et al., 2003; Hopper et al., 2004). Farther seaward, probable ocean crust appears first with oceanic Layer 2/3 velocity structure and it is 3–4 km thick. It then changes eastward to Layer 2 velocity structure and is only 1 km thick. This crust reaches to slightly beyond Anomaly M0, where ocean crust of a more normal thickness (5–7 km) is present. Both the thin continental and thin ocean crust overlie a layer of probably serpentinized mantle (V_P = 7.6–7.9 km/s) that is 3–5 km thick.

Transect 2

Transect 2, as noted above, is conjugate to Leg 149 and 173 drilling on the Iberia margin and was the focus of drilling during Leg 210 (Figs. F3B, F4, F7). On this transect continental crust thins rapidly seaward beneath the continental slope from 30 km to ~7–8 km over a distance of 60 km, and then over the next 50 km it thins more slowly to ~5 km at the Flemish Hinge (Fig. F3). Beyond this, transition-zone crust out to Anomaly ~M3 is only 3–5 km thick. Like part of transect 1, this crust has velocities characteristic of oceanic Layers 2/3, but there appears to be no significant underlying zone of possibly serpentinized mantle (Nunes, 2002). This contrasts with transect 1 and with the velocity structure on the conjugate Iberia margin, where a thick zone of serpentinized mantle appears to be present at and south of the Leg 149/173 drilling transect. Also unlike the Iberia conjugate, transect 2 seismic reflection data do not image an unreflective upper basement layer that might be highly serpentinized peridotite.

Transect 3

Transect 3 exhibits still another set of basement structures. Although continental crust thins rapidly from 35 to <10 km under the continental slope near the seaward edge of the Salar-Bonnition Basin (Fig. F3B), thin (<5 km) continental crust above serpentinized mantle appears to reach seaward 50 km into the transition zone. The remainder of the transition zone to the east has extremely thin (~2 km thick) "crust" that may be either a serpentinized layer of exhumed mantle or thin ocean crust (Lau et al., 2003).

A common feature of all three transects is that there is thin crust and apparently very limited magmatism in the transition zone. The transects differ, however, in how magmatism was expressed, in distribution and character of tectonic extension, and in development of serpentinized "lower crust." Thus, it appears that the balance between tectonic extension and limited magmatism was heterogeneous both along and across the Newfoundland–Iberia rift.

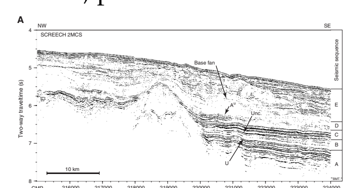
Seismic Sequences

Basal Sequence (Seismic Sequence A)

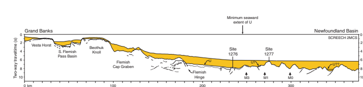
In the transition zone off Newfoundland there is a very flat, high-amplitude reflection (U) that closely overlies or intersects basement (Figs. F4, F8, F9). The U reflection is observed some 600 km south to north in the basin and up to ~150 km across the transition zone. Where traced landward, it merges with the Lower to mid-Cretaceous Avalon unconformity on the Grand Banks (Tucholke et al., 1989). At its seaward edge it normally pinches out on crust of about Anomaly M3 age (Hauterivian–Barremian) (Figs. F8, F9). These features suggest that the horizon has an Early Cretaceous age.

The lithologic sequence between basement and U is defined here as seismic Sequence A. It is seismically laminated, exhibits strong and laterally coherent reflections, and is as much as ~0.5 s (two-way traveltime) thick along the proximal part of the margin (Figs. F8, F9, F10). At many locations, basement below U is not identified as a distinct reflection but as a downward disappearance of reflections (Fig. F8A, F8B). This suggests that the impedance of Sequence A is high and is probably

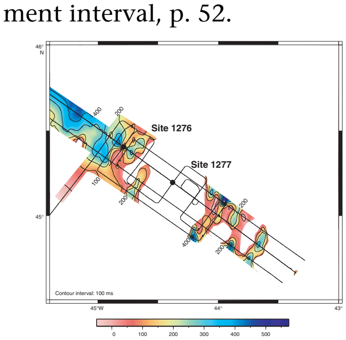
F8. SCREECH line 2MCS in three sections, p. 48.



F9. Simplified interpretation of SCREECH line 2MCS, p. 51.



F10. Isopach map of the U–basement interval, p. 52.



close to that of the underlying basement. The sequence is often faulted near its seaward margin, but there appears to be less faulting at other locations in the transition zone (Tucholke et al., 1989). The apparent age of U and underlying sediments is similar to that of the Blake-Bahama Formation (Hauterivian–Barremian limestones, capped by Horizon β) in the western North Atlantic Basin (Jansa et al., 1979; Tucholke and Mountain, 1979). The reflection character is also similar, although the U horizon generates a much stronger reflection than Horizon β. These features predict that Sequence A could be equivalent to the Blake-Bahama Formation in the western North Atlantic Basin.

Locally, U appears to truncate the underlying basement (Tucholke et al., 1989). The possible truncations, areal extent, and flatness of the horizon led Tucholke et al. (1989) to suggest that it could be an unconformity eroded at or above sea level on extended continental crust. This interpretation has been evaluated with thermal-mechanical modeling (B. Tucholke and N. Driscoll, unpubl. data). The results indicate that if erosion occurred at sea level, it would have to be on continental crust at least ~18 km thick, given reasonable upper mantle temperatures of 1300°–1400°C. Thus, if the horizon originated in this way, it must be a synrift unconformity and not a "breakup unconformity."

U and Sequence A can also be compared to a similar deep reflection sequence across probable continental crust of southern Galicia Bank on the Iberia margin (see Figs. F11, F12). The sequence there is capped by the "orange" reflection that was drilled at Site 398 (Shipboard Scientific Party, 1979). It is represented by Site 398 lithologic Subunit 4C, of Aptian age, which is composed of bioturbated mudstones, turbiditic mudstones, thin laminated and cross-laminated fine-grained sandstones and siltstones, and debris flows or mud flows. The unit was interpreted as an upward-fining submarine fan sequence with initial fan deposition in Barremian time and waning deposition in the late Aptian. Seismic profiles and the mapped distribution of this sequence (seismic Unit 4 of Réhault and Mauffret [1979]) show that it fills basement depressions (Fig. F13). A deeper lithologic unit just above basement (lithologic Unit 5), consists of nannofossil limestones interbedded with laminated mudstones. Velocity in lithologic Units 4 and 5 at Site 398 probably increases with depth, but a mean assumed velocity of 3.59 km/s results in good fit between seismic reflections and a synthetic seismogram based on borehole physical property data (Bouguigny and Wilm, 1979). Thus, velocities and impedance in the deep part of the section are high and may be close to those of the underlying basement, much as it is interpreted on the Newfoundland margin. However, on a regional scale, the reflectivity of the orange reflection and the upper part of the sequence appear to be lower than the reflectivity of Sequence A on the Newfoundland margin.

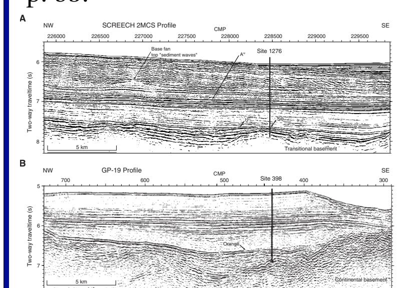
Shallower Sedimentary Sequences

Reflection profiles in the Newfoundland Basin show five principal seismic sequences in the section above U. These are differentiated from one another by broad changes in reflection character, which in turn suggest general changes in depositional conditions and/or deformation. The sequences are summarized below, from base to top.

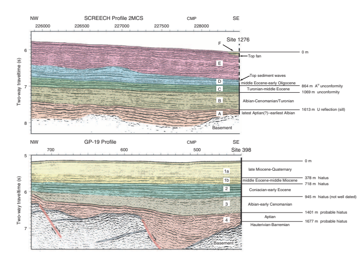
Seismic Sequence B

This sequence is conformable to the underlying U reflection and extends upward to the base of a strongly laminated zone near middepth

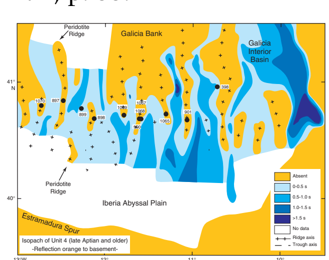
F11. Time-migrated profiles, p. 53.



F12. Seismic sequences and lithologic breaks and age, p. 54.



F13. Isopach map of acoustic Unit 4, p. 55.



in the sedimentary column (Fig. F8). In the landward part of the transition zone it has a thickness of ~0.5 s two-way traveltime. Reflections in Sequence B have low amplitude compared to reflections in the underlying and overlying sequences, but they are still relatively well defined and are mostly laterally continuous over distances of tens to hundreds of kilometers. Reflections tend to be more coherent and readily traced in the lower part of the sequence than in the upper part, where they are sometimes disrupted or even chaotic. At some locations in the upper part of Sequence B, reflections show seaward downlap and landward onlap that suggest local control of depositional patterns (e.g., in a fan-channel system). The top of the sequence is marked by an apparent unconformity that truncates progressively deeper beds in a landward direction. The predicted age of this sequence is mid-Cretaceous, which would include black shales equivalent to the Hatteras Formation farther south in the central North Atlantic Basin.

Seismic Sequence C

Sequence C exhibits a series of very strong, flat, coherent reflections that are easily traced laterally for distances of 100 km or more. The interval represents ~0.3 s of reflection time and occurs midway in the sedimentary section. Reflection character of this sequence suggests that it consists of interbedded high- and low-velocity layers (e.g., sandstone, turbidites, and shale). In its landward portions, the upper part of Sequence C remains strongly layered in its lower section but its upper section expands and contains chaotic reflections; these reflections appear to be caused by debris flows and other downslope mass movements.

The reflection that marks the top of Sequence C, as discussed below, appears to be equivalent to Horizon A^u in the western North Atlantic, suggesting that Sequence C is Eocene at its top; it probably extends into the Paleocene or possibly the Upper Cretaceous at its base. The equivalents to the following central North Atlantic formations would be included in this sequence, from base to top: black shales of the Hatteras Formation, reddish and multicolored pelagic shales of the Plantagenet Formation (± Maastrichtian limestones of the Crescent Peaks Member), and siliceous shales and cherts of the Bermuda Rise Formation (Jansa et al., 1979).

Seismic Sequence D

This sequence is characterized by reflections with distinctive pinch-and-swell morphology that suggests current-controlled deposition and formation of sediment waves, much like Oligocene–Miocene seismic sequences along the eastern margin of North America to the south (Mountain and Tucholke, 1985). The sequence is thickest close to the margin (~0.4 s reflection time), and inferred sediment waves are best developed there. Seaward, it thins to ~0.1 s. A number of strong reflections are well developed and continuous through the sequence, but weaker intervening reflections are often broken up, particularly in the lower part of the sequence and in its thinner section away from the margin. The semichaotic character of these reflections suggests that debris flows and mass wasting deposits may form part of the sequence.

The base of this sequence is interpreted to be equivalent to Horizon A^u along the western margin of the North Atlantic south of the Newfoundland Basin. There, the horizon is a widespread unconformity that was eroded when strong abyssal circulation (Deep Western Boundary Current [DWBC]) developed in the basin (Tucholke and Mountain, 1979). On the Newfoundland margin the reflection shows truncation of the underlying irregular beds of upper Sequence C beneath the inner continental rise, but farther seaward it is mostly conformable to deeper bedding. The source of bottom water for the DWBC is thought to be in the sub-Arctic/Arctic seas, so the Newfoundland Basin has been the "gateway" region through which this current flowed southward and may contain an important record of how abyssal circulation developed in the North Atlantic Ocean. The DWBC is interpreted to have developed in the latest Eocene to early Oligocene (e.g., Miller and Tucholke, 1983; Davies et al., 2001). The predicted age of Sequence D is early Oligocene at the base, extending up into the Miocene at the top.

Seismic Sequence E

This sequence is well developed all along the Newfoundland margin. It is consistently thicker close to the margin (~0.8 s two-way traveltime) and thins seaward to as little as ~0.2 s beneath the outermost continental rise and abyssal plain. Sequence E has a very distinctive seismic signature. It is marked by undulating and contorted reflections that usually can be traced for only limited distances. Some reflections have the form of poorly developed sediment waves. In its upper part the sequence contains channels that are filled with chaotic debris, and other portions also show chaotic signature that probably represents rapid deposition of mass-wasting deposits. The sequence is also permeated by small-throw normal faults, almost none of which extend into the underlying or overlying sequences. These features are commonly developed in abyssal fans; they suggest that the sediments were deposited rapidly while trapping pore fluids and that they later failed as the sediments dewatered. Similar seismic sequences appear along the U.S. East Coast margin (Mountain and Tucholke, 1985) and on other margins across the globe in the middle Miocene to Pliocene–Pleistocene. They appear to document a global period of margin progradation (Bartek et al., 1991).

Seismic Sequence F

This is the topmost seismic sequence in the Newfoundland Basin and it consists of reflective, flat-lying turbidites that form an abyssal plain seaward of the lower continental rise. The turbidites interfinger with and lap landward onto underlying fan Sequence E. Thus the base of the sequence is time-transgressive, becoming younger landward. Within the turbidites, it is common to observe chaotic beds as thick as ~0.1 s that extend for many tens of kilometers (Fig. **8B, 8C**). These appear to be debris flows that originated from the continental rise. The predicted age of the turbidities is late Pliocene to Quaternary.

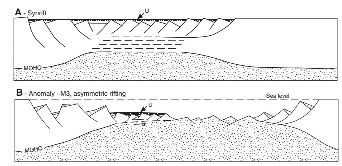
LEG 210 OBJECTIVES

Drilling objectives for Leg 210 were twofold. The primary objective was to sample the deep sedimentary structure and basement in order to investigate early rift development. A related objective was to study the shallower stratigraphy and to elucidate the postrift sedimentation processes and paleoceanographic history of this gateway between the North Atlantic and the sub-Arctic seas. The background for each of these objectives is summarized below.

Origin of Transitional Crust

Drilling results from the Iberia margin and geophysical data from both sides of the Newfoundland–Iberia rift show clearly that the rift was characterized by very limited volcanism, that there are marked asymmetries between margin conjugates, and that there is significant structural variability along strike between rift segments. These features are particularly manifested in the transition zones between known continental and known oceanic crust on the opposing margins. We posed three hypotheses to explain the crustal structure and basal stratigraphy in the Newfoundland and Iberia transition zones and the cross-rift asymmetries between these zones (e.g., Tucholke et al., 1999) (Fig. F14). Leg 210 provided the first direct test of these hypotheses by drilling in the transition zone along transect 2 on the Newfoundland margin (Figs. F3, F4, F8B).

F14. Schematic models of rift development, p. 56.



Hypothesis 1: Newfoundland Transition Zone Is Strongly Thinned Continental Crust

Newfoundland transitional crust is shallower and has less roughness than Iberia crust, and it could be the upper plate in an asymmetric detachment system (Fig. F14B). According to this hypothesis, the lower Iberia plate east of Anomaly ~M3 would be exhumed lower continental crust and mantle (e.g., Whitmarsh et al., 2001). Strong thinning of the Newfoundland crust without significant brittle extension might be possible if the lower crust was thinned by ductile flow (e.g., Driscoll and Karner, 1998) (Fig. F14A). This should be reflected in rapid synrift subsidence of the Newfoundland basement. If U corresponds to a subaerially eroded unconformity, the rapid subsidence would be recorded in the sedimentary section above the reflection.

There are two other possible explanations for U. One is that it corresponds to the top of basalt flows emplaced either subaerially (i.e., it is synrift on continental crust) or on the seafloor (Enachescu, 1988). If melt was extracted from the rising lower plate and emplaced in the Newfoundland upper plate (e.g., Fig. F14C), the exhumed Iberia mantle could be virtually melt-free, as has been suggested by existing Iberia drilling (Whitmarsh and Sawyer, 1996). Although it seems unlikely that smooth basalt flows could be as widespread as is indicated by the distribution of U, there are documented instances where such flows are known to be extensive (e.g., Larson and Schlanger, 1981; Driscoll and Diebold, 1999).

Another explanation is that U corresponds to the top of high-velocity sedimentary deposits that were shed from the Grand Banks, probably in Early Cretaceous time. As already noted, this sequence could be similar to the Aptian fan deposits recorded on the conjugate Iberia margin (see also **"Comparison with Iberia Margin Stratigraphy,"** p. 24), although the stronger seismic signature on the Newfoundland margin suggests much higher–velocity beds that possibly are very coarse grained or carbonate rich.

Hypothesis 2: Transition Zones Reflect Extreme Extension in an Amagmatic Rift

According to this hypothesis, continental extension proceeded under nearly amagmatic conditions to a state where only mantle was exposed and at some point an asymmetric shear developed within the exposed mantle (Fig. F14C). This hypothesis differs from the one above in that Newfoundland transitional crust would be exhumed, probably serpentinized mantle. U could not correspond to a subaerial unconformity because it would be impossible to uplift extending mantle to sea level. The U–basement interval could correlate with basalt flows, with melt generated from the rising lower plate in an asymmetric extensional system, or it could be high-velocity sedimentary beds, as noted above.

Hypothesis 3: Newfoundland Transitional Crust Was Formed by Ultra-Slow Seafloor Spreading

Slow seafloor spreading (Fig. F14D) is known to expose lower crust and mantle (e.g., in the Labrador Sea [Chian and Louden, 1995; Osler and Louden, 1995]), and it could explain the transitional crust in the Newfoundland Basin. However, symmetrical ultra-slow seafloor spreading in the rift seems unlikely because it does not explain the extensive mantle exposures off Iberia, nor does it explain the asymmetries in crustal structure and depth between the conjugate transition zones. It is possible that extension first exposed mantle in the rift, that ultra-slow seafloor spreading then initiated on the Newfoundland side of the rift, and that this ocean crust was subsequently isolated on the Newfoundland margin by an eastward jump of the spreading axis (Fig. F14D). This hypothesis precludes U from corresponding to a subaerial unconformity because it would overlie thin ocean crust. As in the above hypotheses, U might correlate with either basalt flows or the top of high-velocity sedimentary beds.

Sedimentary History and Paleoceanography

Rifting between Labrador and Greenland, and between Greenland and Eurasia (Rockall Trough), began in the Early Cretaceous, leading to Late Cretaceous seafloor spreading in the Labrador Sea and Paleocene spreading east of Greenland (e.g., Eldholm et al., 1990; Srivastava and Roest, 1999). The Newfoundland–Iberia rift was a gateway between the main North Atlantic and these developing ocean basins, so it is in a key position to investigate sedimentary history and paleoceanographic links through the northward-expanding ocean basins.

Two features of the predicted sedimentary record above U were of particular interest during Leg 210. The main basin of the adjacent North Atlantic was accumulating black shales of the Hatteras Formation in Barremian–Cenomanian time, followed by deposition of the Plantagenet Formation under oxygenated seafloor conditions in the Late Cretaceous (Jansa et al., 1979). The Newfoundland Basin Cretaceous sedimentary record provides an opportunity to examine whether this record of reduced and then increased ventilation of the deep basin extended northward into the developing ocean basins, as well as information on the timing of that record. It also allows investigation of paleobiogeography in a zone where Tethyan and boreal flora and fauna were expected to have mixed.

The second feature of interest was the upper Eocene–lower Oligocene sedimentary record, which could contain important information on the first development of strong abyssal circulation in the North Atlantic. As already noted, the source of the bottom water for this developing circulation has been interpreted to be the sub-Arctic seas and the timing has been estimated as latest Eocene to early Oligocene (Miller and Tucholke, 1983; Davies et al., 2001). However, these predictions are based largely on the occurrences of hiatuses in boreholes farther south in the North Atlantic; the lack of sedimentary records in the critical intervals there makes it difficult to verify the predictions. New data from the gateway region could help to constrain the source and timing of the circulation event.

DRILLING STRATEGY

The most direct and productive method to test our hypotheses about basement structure and the deep reflection sequence in the Newfoundland transition zone was to drill a deep hole (up to ~2200 m) into that zone. Such a hole would also recover an expanded Cretaceous and Tertiary sedimentary record with which to investigate the paleoceanographic history in this gateway region. The prime site that was selected to accomplish these objectives was Site 1276 (proposed Site NNB01A), located in the westernmost edge of the abyssal plain at the foot of the Newfoundland continental rise. In the event that our basement and deep sedimentary objectives could not be achieved at this site and sufficient drilling time remained during Leg 210, we also developed a series of alternate sites that extend seaward onto known oceanic crust and could be drilled in order to partially satisfy our objectives.

Depths of major seismic horizons, including basement, were predicted from semblance velocity analysis of MCS reflection data obtained along the drilling transect during the SCREECH site survey program in 2000. This analysis indicated that the major drilling objectives at proposed Site NNB01A (i.e., U and basement) were at depths of ~1860 and ~2080 meters below seafloor (mbsf), respectively (Table **T1**). Sampling to these great depths in one drilling leg was considered to be an ambitious goal, but the objectives were deemed to be achievable by following a plan of drilling, casing, and logging the hole as shown in Figure **F15**. To improve our chances of meeting the objectives within the time available for drilling, it was agreed that the upper 800 m of the hole would be drilled without coring. Thus, we expected that the first sediments recovered from the hole would be of Oligocene age, above Horizon A^u.

Actual hole conditions and time constraints necessitated modification of this plan in real time during Leg 210. Nonetheless, we were able to follow part of the drilling and casing plan at Site 1276 (Fig. **F16**) and we achieved a significant part of our objectives. In addition, we drilled a short hole ~95 m into basement at Site 1277 (proposed Site NNB04A). Table **T2** summarizes drilling and coring at Sites 1276 and 1277, and a time breakdown of operations while on site is shown in Figure **F17**. Drilling results of both sites are summarized below.

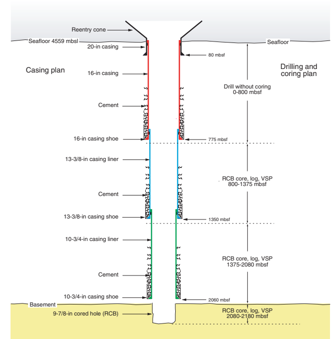
SITE 1276 SYNTHESIS

Lithostratigraphy

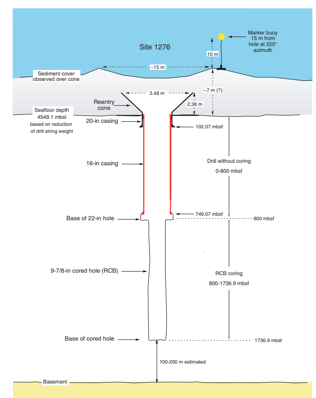
Coring at Site 1276 started at ~800 mbsf. Recovery was excellent throughout the entire cored interval, averaging 85% and approaching or exceeding 100% for many cores. Five lithologic units are recognized (Fig. **F18**), ranging in age from latest Aptian(?)–early Albian to latest Eocene–earliest Oligocene. The units are defined primarily by the proportions of sediment types, sedimentary facies, and mineralogy of detri-

T1. Predicted depths of reflection boundaries, Site 1276, p. 77.

F15. Proposed drilling and casing plan, Site 1276, p. 58.

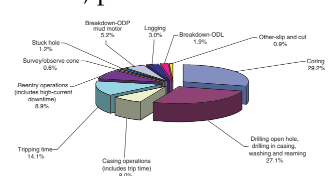


F16. Site 1276 installation and cored intervals, p. 59.

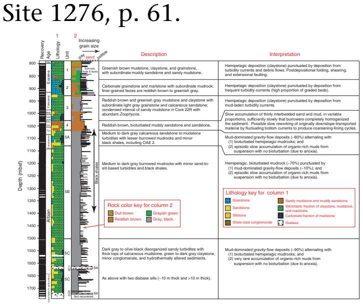


T2. Coring summary, Leg 210, p. 78.

F17. Breakdown of operational activities, p. 60.



F18. Lithostratigraphic units at Site 1276, p. 61.



tal and biogenic components. The sedimentary succession consists mainly of background hemipelagic mudrocks (bioturbated claystone and mudstone) with interbedded gravity-flow deposits that vary from minor in some intervals to dominant in others. For example, Unit 2 and Subunits 5A and 5C are largely gravity-flow deposits, whereas Subunit 5B is primarily hemipelagic mudstones and claystones. An exception to this generalization is Unit 4, in which reddish brown, intensely burrowed muddy sandstones (Fig. F19) are inferred to have been reworked by bottom currents on a well-oxygenated seafloor.

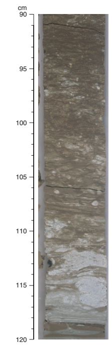
Gravity-flow deposits show remarkable variability. They include deposits of debris flows (Figs. F20, F21), low-density turbidity currents (Figs. F22, F23), and mud-laden, viscous gravity flows that formed spectacular contorted structures in many beds (Fig. F24). Texturally, the gravity-flow deposits range from siliciclastic mudrocks, siltstones, and sandstones to carbonate grainstones and marlstones. The sand fraction in these sediments is mainly (a) quartz, feldspar, mica, and rock fragments derived from metamorphic and plutonic source rocks; (b) recycled carbonate components derived from unlithified to loosely consolidated outer-shelf to slope sediments; (c) contemporaneous biogenic components; and (d) minor ash (e.g., in the mid-Paleocene). Bioclasts include benthic and planktonic foraminifers, red algae, bryozoans, mollusk fragments, and echinoderms. Other locally common particles include carbonate intraclasts and glauconite pellets. With rare exceptions, only the gravity-flow deposits contain significant biogenic carbonate. This consists of bioclasts in grainstones and nannofossils in mudstones and marlstones. Most of the interbedded hemipelagic sediments are noncalcareous, reflecting deposition mainly below the calcite compensation depth (CCD).

Diagenesis is moderate throughout the succession, with minor mobilization and precipitation of silica in Units 1 through 3 as quartz and opal-CT, together with common carbonate cementation of grainstones, sandstones, and siltstones in Units 2 through 5. Authigenic siderite and dolomite form many concretionary bands and nodules in the hemipelagic mudrocks of Subunit 5B. Downhole changes in clay mineral assemblages, from mostly illite-smectite in Unit 1 through Subunit 5A to kaolinite-chlorite below Subunit 5A, are attributed to paleoenvironmental changes rather than to burial diagenesis.

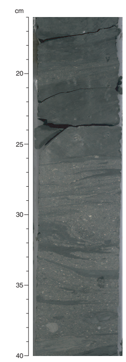
Subunit 5C is intruded by two major diabase sills that locally altered and contact-metamorphosed their host sediments (Fig. F25). The remainder of the uppermost Aptian(?)–lower Albian to basal Turonian Unit 5 is very thick (>700 m). In addition to gravity-flow deposits, it is characterized by ~5% finely laminated, organic-rich, calcareous claystones to marlstones ("black shales") (Fig. F26) with total organic carbon (TOC) reaching ~10 wt% in some beds. The carbonate is mainly in the form of nannofossils. These laminated sediments record times of enhanced input of mostly terrestrial organic matter under low-oxygen conditions, with the notable exception of Oceanic Anoxic Event (OAE) 2 (Cenomanian/Turonian) and OAE 1b (lower Albian), which contain significant amounts of marine organic matter.

Sedimentation rate was rapid during the latest Aptian(?)–early Albian to Turonian (maximum = ~100 m/m.y.), but it dropped sharply to <15 m/m.y. thereafter (Fig. F27). The Albian sediment influx is attributed to enhanced continental weathering in a warm humid climate, possibly accentuated by clastic input from active rifts farther north. After initial accumulation in a restricted ocean basin (i.e., black shale deposition), Site 1276 experienced a pulse of seafloor erosion and reworking by bot-

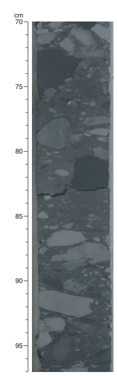
F19. Poorly sorted muddy sandstone, p. 62.



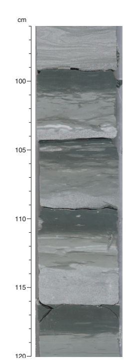
F20. Massive, poorly sorted grainstone with carbonate granules, p. 63.



F21. Chaotic mud-clast conglomerate, p. 64.



F22. Repeated graded beds, p. 65.



tom currents during the Turonian–Santonian; this is inferred to have been caused by the establishment of a deep-ocean connection between the North and South Atlantic.

A hiatus in the middle Eocene at the boundary between Units 1 and 2 correlates with a discontinuity in the seismic reflection record that separates parallel reflections below from large sedimentary waveforms above. This may mark the initiation of strong abyssal circulation along the foot of the Newfoundland margin, correlative with Horizon A^u in the western North Atlantic.

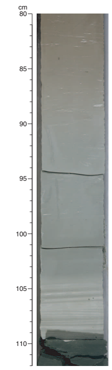
The uppermost Aptian(?)–lower Albian to uppermost Eocene–lowermost Oligocene succession at Site 1276 has stratigraphic and facies similarities to DSDP and ODP sites in the western North Atlantic (Fig. F28) and on the conjugate Iberia margin. For example, dark-colored mudrocks that are locally carbon rich in the Albian to lower Turonian interval at Site 1276 are like those of the Barremian–Cenomanian Hatteras Formation. Also, the younger parts of the Site 1276 succession are comparable to the Plantagenet, Bermuda Rise, and Blake Ridge formations. Site 398 on the conjugate continental margin off Iberia is similar but contains significant nannofossil-rich sediment, indicating that it was above the CCD from the Campanian to early Oligocene.

Igneous and Metamorphic Petrology

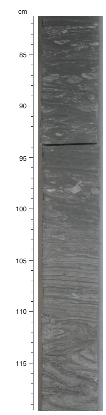
One of the major discoveries at Site 1276 was two diabase sills emplaced within uppermost Aptian(?)–lower Albian sediments, ~100–200 m above basement as estimated from seismic reflection data. The upper sill is ~10 m thick, and the lower sill, which was not fully penetrated, is thicker than 10 m. Indirect constraints suggest that the sills were emplaced at a very shallow level beneath the seafloor. These constraints are (1) the occurrence of vesicles in the sill, (2) the growth of porphyroblastic calcite within adjacent contact-metamorphosed sediments and predating final compaction of these sediments, and (3) strong compaction folding of a calcite vein that was emplaced vertically in the sediments probably at the time of intrusion (Fig. F25). The sills preserve chilled margins, and toward their centers they show an increase in average crystal size and a change of magmatic textures from predominantly intersertal to subophitic or ophitic (Fig. F29). Sill/sediment contacts preserve a thermal overprint marked by color changes, recrystallization processes, and very high reflectance of organic matter.

The sills are predominantly aphyric diabase composed of primary plagioclase (40%–60%), pyroxene (10%–30%), magnetite (<5%), olivine (<5%), and glass (<20%). More differentiated rocks occur in segregation bands (e.g., sample 4i in Fig. F29) that form <5% of the rocks in the sills. Hydrothermal alteration in the sills ranges from high to complete at the margins to moderate toward the centers (see the alteration column in Fig. F29). The diabases are silica-poor basanites, with SiO_2 values that range from 40 to 46 wt% and follow an alkaline differentiation trend. Samples taken from less altered parts of the sill show surprisingly coherent patterns for elements like K_2O, NaO_2, and CaO, assuming that the sills preserve their initial magmatic signature. Future petrological, geochemical, and geochronological studies of these rocks are expected to provide information on the nature and evolution of the mantle source underlying the Newfoundland margin, as well as the age of emplacement.

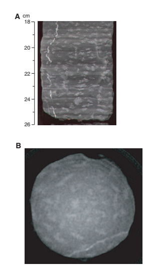
F23. Planar-laminated carbonate grainstone grading into marlstone, p. 66.



F24. Highly disorganized gravity-flow deposit, p. 67.



F25. Core photograph and CT scan of a porphyroblastic mudrock, p. 68.



Biostratigraphy

Paleogene and Cretaceous sediments cored at Site 1276 were deposited in abyssal depths (>2000 m) below the CCD. Hence, calcareous microfossil assemblages, particularly the planktonic foraminifers, were severely affected by dissolution in most intervals of Site 1276. High-resolution biostratigraphic analysis will ultimately depend on full integration of organic-walled microfossils (palynomorphs: dinocysts, spores, and pollen), calcareous plankton (calcareous nannofossils and planktonic foraminifers), and siliceous microfossils (radiolarians). In situ agglutinated and redeposited calcareous benthic foraminifers also provide both a biostratigraphic and paleoenvironmental assessment of the deep western North Atlantic Ocean and the adjacent Newfoundland continental margin. Shipboard analysis of these varied microfossil groups provided a robust model of age vs. depth in the hole, as well as important insights into the changing paleoceanographic and depositional conditions during latest Aptian(?)–early Albian to early Oligocene time.

Calcareous nannofossils provided excellent biostratigraphic control for most of the section, and planktonic foraminifers preserved in sandstone turbidites proved helpful in refining that biostratigraphy. Palynomorphs provided a critical component for biostratigraphic age control in carbonate-free intervals. Calcareous benthic foraminifers indicate changes in the source areas for the turbidites cored at Site 1276; distinctive shelf vs. slope fauna are found in different turbidites. Reworking had a constant effect on assemblages of all fossil groups, rendering the use of last occurrence datums problematic, particularly in the Paleogene section, where reworking of older material is pervasive. On the other hand, a uniform age progression of the samples and minimal reworking of older material in the Cretaceous section indicates that redepositional processes appear to have been largely penecontemporaneous.

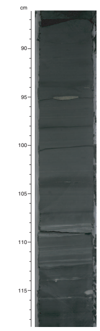
Age-Depth Model for Site 1276 and Comparison to the Iberia Margin (DSDP Site 398)

The age-depth model (Fig. F27) reveals marked changes in sedimentation rate, including at least three unconformities or condensed intervals. The changes in slope correspond closely to lithologic unit boundaries. An unconformity marks the boundary between lithologic Units 1 and 2 at ~864 mbsf based on palynomorph and nannoplankton data. Over the full stratigraphic section, comparison of the sedimentation rate at Site 1276 with that at Site 398 shows striking similarity not only in the positions of hiatuses or condensed intervals, but also in overall sedimentation rate.

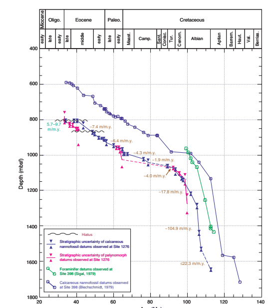
Abyssal Paleoceanography and History of the CCD

The paleoceanographic history of the opening of the North Atlantic is documented in the faunal composition of benthic foraminifers recovered at Site 1276. Exceptionally well preserved autochthonous deep-water agglutinated foraminifers (e.g., Kuhnt and Urquhart, 2001) throughout most of the sedimentary sequence imply that Site 1276 has remained at abyssal depths (>2000 m) since at least latest Aptian(?) to early Albian time.

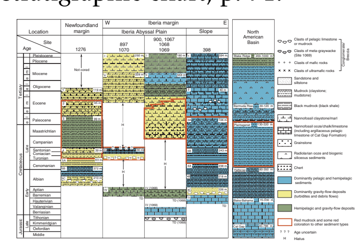
F26. Laminated black shale with siltstone laminae and lens, p. 69.



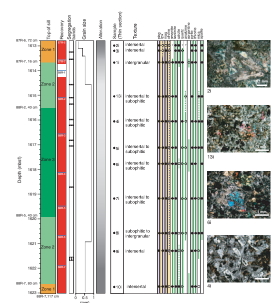
F27. Age-depth plots, Sites 1276 and 398, p. 70.



F28. Simplified time-stratigraphic chart, p. 71.



F29. Summary of upper diabase sill properties, Site 1276, p. 72.



Paleoceanography and Paleoenvironment

All microfossil groups examined indicate that Site 1276 was influenced by transitional surface water masses during much of the Cretaceous and early Paleogene. This is suggested by the presence of select Boreal taxa and the absence or paucity of key Tethyan taxa. Hence, these taxa will be invaluable in determining oceanographic communication routes between the northwestern Atlantic, Tethys, and eastern Atlantic.

Although many of the sediments recovered are barren of calcareous fossils, debris flows and turbidites brought in well-preserved assemblages. Specifically, in the Paleocene and Eocene sections many debris flows contain robust assemblages of shallow-water origin, including calcareous benthic foraminifers that indicate a neritic facies and abundant holococcoliths not generally preserved in deepwater sections. These taxa can provide insights into the paleoceanographic history of the nearby shallow-water areas. These allochthonous faunas indicate original depositional environments, together with the provenance of turbiditic packages and the timing of climatic change and/or tectonic disturbance.

For the expanded Albian–Turonian section of Site 1276, palynological data indicate a strong terrestrial influence, which is documented by very high amounts of terrigenous organic matter. There is an overall downhole trend toward an increase of terrestrial influence. Samples from Albian black mudstones seem to be characterized by especially high amounts of terrestrial palynoclasts and sporomorphs. This is tentatively interpreted to indicate accelerated runoff from adjacent land masses during the time of black mudstone deposition.

Critical Events

A series of "critical events" in Earth's history were cored at Site 1276. The recovered records are affected by abyssal seafloor depths below the CCD and by frequent turbidites, which make lithologic and microfossil information discontinuous. Nevertheless, the integrated results from the different microfossil groups, together with chemical and sedimentologic data, provide a preliminary documentation of the stratigraphy and environmental conditions during these intervals.

Paleocene/Eocene Boundary

Worldwide, uppermost Paleocene marine sections are characterized by a sudden shift from carbonate-marl deposition to clayey, calcite-free deposition. The Paleocene/Eocene boundary interval is also characterized by an abrupt worldwide warming event referred to as the Paleocene/Eocene Thermal Maximum (PETM). In addition to the dissolution interval, the Paleocene–Eocene transition in the oceanic sedimentary record is distinguished by a sharp negative $\delta^{13}C$ excursion and a benthic foraminiferal extinction event (Zachos et al., 1993; Thomas and Shackleton, 1996). The abrupt negative carbon isotope excursion and widespread pattern of decreased carbonate content are consistent with the hypothesis of a massive methane flux in the ocean-atmosphere inorganic carbon reservoir, which caused a short-term "super greenhouse" event (Dickens et al., 1997).

A nearly complete uppermost Paleocene to lower Eocene section is present at Site 1276. Even though the specific clay boundary layer is missing, probably because of incomplete core recovery, a complete succession of the calcareous nannofossil events occurring immediately above the boundary clay layer is recognized in Cores 210-1276A-13R and 14R. In the Paleocene–Eocene transition, the calcareous nannoplankton community shows a great turnover characterized by peculiar biotic changes (Bralower et al., 1995; Angori and Monechi, 1996), which are recognized at Site 1276. This material is sufficiently well preserved to document a detailed biostratigraphic and evolutionary history of this fossil group, which can then be compared with other sections of the Atlantic domain in the framework of biochronological and paleoenvironmental changes associated with the PETM.

Cretaceous/Tertiary Boundary

The Cretaceous/Tertiary (K/T) boundary records one of the most catastrophic perturbations to the Earth's biosphere and coupled ocean-climate system. A wealth of ODP research has provided data on the link between the K/T boundary mass extinction and a large-body impact on the Yucatan Peninsula. The Caribbean and North Atlantic sections are crucial to understand not only the marine biotic response to this event but also to document disruption of the stratigraphic record as a consequence of the impact.

One of the few nearly complete upper Maastrichtian to lower Danian abyssal sections was recovered at Site 1276. Extensive reworking and common carbonate-free sediments prevent this section from being suitable for analyzing extinction processes, but the succession of biotic changes is obvious. The sequence includes a sharp increase of calcareous dinoflagellates ("*Thoracosphaera* bloom?") and an increase in Cretaceous survivor species, followed by blooms of dwarf earliest Danian species ("dwarf *Biscutum* bloom;" Gardin and Monechi, 1998). Penecontemporaneously reworked planktonic foraminifers preserved in sandstone turbidites provide an additional record of biotic extinction and recovery; this includes an interval characterized by Cretaceous survivors (*Guembelitria*), together with earliest Danian species (*Parvulorugoglobigerina eugubina* and *Woodringina* sp.) and *Thoracosphaera*. The high sedimentation rates in the lower Paleocene section provide good resolution for study of biotic recovery following the impact.

Oceanic Anoxic Events

Oceanic Anoxic Events were short-lived episodes of widespread organic carbon burial, typically coupled with rapid changes in the ocean-climate system and marine biosphere. These perturbations in the global carbon cycle occurred during times of elevated tectonic activity, high global sea level, and generally warm climates of the mid- to Late Cretaceous (Leckie et al., 2002). A thick interval of gray to olive-black mudrocks was cored at Site 1276 (lithologic Unit 5). Much of the organic matter preserved in these hemipelagic and turbiditic sediments seems to be of terrigenous origin, based on preliminary geochemical analyses and the preponderance of terrestrial organic matter observed in foraminiferal and palynomorph preparations. However, within Subunits 5A and 5C, there are several thin intervals characterized by laminated black shale, high TOC contents (3–7 wt%), and hydrogen index (HI) values (231–452 mg HC/g TOC) that are characteristic of marine algal organic matter. The black shales in Core 210-1276A-31R correlate with uppermost Cenomanian–lowest Turonian OAE 2 ("Bonarelli" event). OAE 2 is one of the most widespread black-shale events recognized in the marine record. It represents a time of enhanced productivity, perhaps triggered by tectonic activity or changes in ocean circulation. Black shale in Core 210-1276A-94R is potentially correlated with OAE 1b ("Paquier" event). Four other possible OAEs are summarized in **"Geochemistry,"** p. 20, and Figure **F156,** p. 281, in the "Site 1276" chapter. A black shale in Core 210-1276A-98R, bounded by bioturbated sediments and located 8 cm above the lower sill cored at Site 1276, is strongly thermally altered; currently, it is not identified as a named OAE.

Paleomagnetism

Paleomagnetic studies consisted of routine measurements of natural remanent magnetization (NRM) and magnetic susceptibility of the archive half of split cores of recovered sediments and rocks. Paleomagnetic data obtained from Site 1276 samples exhibit considerable variations in demagnetization behavior among various lithologies, and only one magnetic reversal was detected in the entire hole (Chron C21r, Section 210-1276A-9R-5, early/middle Eocene).

In the middle Eocene to lower Oligocene cores in lithologic Unit 1, varicolored mudstone and claystone have low NRM intensity and low magnetic susceptibility. A few discrete peaks of higher NRM and susceptibility values could in some cases be tied directly to visible presence of pyrite. Although the NRM intensity of the upper Paleocene to middle Eocene sediments in lithologic Unit 2 was also low, we were able to define the characteristic remanent magnetization (ChRM) direction from a few intact cores. Both magnetic susceptibility and NRM intensity records show an anomalous peak at approximately the lower/upper Paleocene boundary. Upper Campanian to lower Paleocene lithologic Unit 3 has relatively high NRM intensity and magnetic susceptibility; this is caused by the presence of numerous dark burrowed beds that have relatively high concentrations of magnetic minerals. NRM intensity and magnetic susceptibility for lithologic Unit 4 (Turonian–Santonian) are relatively high, perhaps because of the presence of fine-grained iron oxides. A strong drilling-induced overprint is present throughout this unit, which severely limits paleomagnetic work. Sedimentary cores from lithologic Unit 5 are uppermost Aptian(?) to basal Turonian claystones and mudstones that have low NRM intensity and low magnetic susceptibility. There are more significant variations in susceptibility in lithologic Unit 5 than in lithologic Unit 4. Characteristic susceptibility peaks reflect carbonate and sandstone layers, and troughs correspond to green and gray claystones and mudstones. The susceptibility peaks that correlate with the diagenetic carbonates may reflect an iron component in these rocks, most likely siderite.

Drilling in Subunit 5C recovered two diabase sills. The inclinations of the ChRM direction for these sills are all positive. The simplest explanation of the positive inclinations is that they represent normal-polarity magnetization, probably acquired within the Cretaceous Normal Superchron. Significant changes in inclination and intensity values within the upper sill suggest that it may contain two intrusive units.

In order to test the archive-half data and to identify magnetic carriers in sediments of this hole, selected discrete samples from the five different lithologic units were demagnetized with stepwise alternating fields or were thermally demagnetized. Most samples show unblocking temperatures between 350° and 550°C, indicating that titanomagnetites are the likely magnetic carriers in these samples.

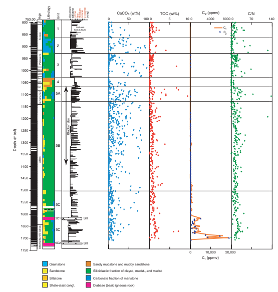
Time-series analysis was conducted on magnetic susceptibility and natural gamma ray data for several pelagic marlstone cores in lithologic

Unit 5, with the goal of identifying paleoclimatic cycles driven by changes in the Earth's orbit (Milankovitch cycles). Preliminary results are encouraging, and they demonstrate that certain Leg 210 cores seem to be suitable for magnetic detection and extraction of climatic cycles and sedimentary changes in the Cretaceous.

Geochemistry

At Site 1276, an extensive Albian to basal Turonian black shale/mudstone sequence was cored. This lithologic unit (Unit 5) is thicker than 700 m (1067.24–1719.40 mbsf). It is characterized by moderately enriched TOC contents (mostly <2 wt%) (Fig. F30). This turbidite-dominated sequence shows low HI values (HI < 100 mg HC/g TOC) and C/N ratios averaging ~20, suggesting a strong influence of terrestrially derived organic matter. A positive correlation between C/N ratios and TOC contents supports the importance of a terrigenous contribution to the sedimentary organic matter. T_{max} values ranging between 435° and 470°C indicate that kerogen present in the sediments may be derived mainly from reworked, preheated terrestrial components (Wagner and Pletsch, 2001). Ni/Al ratios are higher in Unit 5 than in overlying units, confirming the importance of anoxia, and therefore preservation, in the accumulation of organic matter throughout the sequence.

F30. Downhole plots of $CaCO_3$, TOC, C_1 and C_2, and C/N, Site 1276, p. 73.



Headspace methane (C_1) concentrations start to increase downhole above background levels only at a depth of 1140 mbsf in lithologic Subunit 5B (Fig. F30), with more significant increases beginning at ~1480 mbsf. In Unit 5, a possible weak correlation exists between higher TOC and higher methane concentrations, suggesting that the concentration of organic matter may play a role in the generation of methane. C_1 concentrations increase dramatically at 1623 mbsf immediately below the upper diabase sill (Subunit 5C1) and particularly in Cores 210-1276A-96R and 97R (1692.33–1703.5 mbsf), which are above the lower sill. The latter increases correspond to layers of anomalously underconsolidated, high-porosity clays, so the methane concentrations are directly linked to the character of the formation. The sills probably formed seals and prevented gas and interstitial water from escaping. Low C_1/C_2 ratios and the presence of longer-chain volatile hydrocarbons (at low concentrations) in the deeper part of the hole indicate that some thermogenically derived gas is present; it could either have migrated to this location or been generated in situ.

Oceanic Anoxic Events

Within lithologic Unit 5, six sedimentary intervals have high TOC contents, in several instances coupled with high HI (characteristic of marine-derived organic matter) and high S_2, and they may record OAEs:

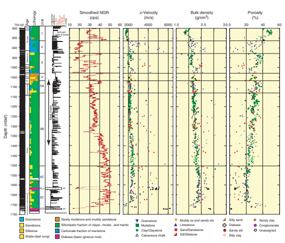
1. The top of lithologic Subunit 5A (Cores 210-1276A-30R and 31R) is upper Cenomanian–lowermost Turonian, and it likely corresponds to the "Bonarelli" event, OAE 2.
2. Core 210-1276A-33R (middle of Subunit 5A) probably represents the "mid-Cenomanian event" (Leckie et al., 2002).
3. The top of Subunit 5B (Cores 210-1276A-42R to 44R) is uppermost Albian and may correspond to OAE 1d, dominated by terrigenous organic matter.
4. In lithologic Subunit 5B, Core 210-1276A-55R (characterized by terrestrially derived kerogen) may correspond to OAE 1c.

5. The bottom of Subunit 5B (Core 210-1276A-73R) does not correspond to any known OAEs; however, it has the potential to represent an OAE-type layer.
6. Core 210-1276A-94R (middle of lithologic Subunit 5C) is lower Albian, and it might represent the "Paquier" event, OAE 1b (Leckie et al., 2002).

Physical Properties

Leg 210 physical property data for rocks and sediments include measurements of seismic velocity, density, porosity, natural gamma radiation (NGR), magnetic susceptibility, and thermal conductivity. Such data are critical for seismic stratigraphic studies and for understanding the complex physical and chemical processes responsible for the development of rift systems and passive-margin sedimentation. At Site 1276, obtaining an excellent physical property data set was facilitated by very high core recovery through ~930 m of section. NGR, vertical velocity, bulk density, and porosity profiles for Site 1276 are shown in Figure F31. The data are color-coded to indicate lithology as defined from the visual core descriptions, allowing assessment of the control of sedimentary facies on physical properties behavior. We hope that this type of display becomes standard procedure on future Integrated Ocean Drilling Program legs.

F31. Composite physical property plots, Site 1276, p. 74.



Bulk density and porosity mirror one another downhole, with bulk density increasing from ~1.9 to 2.3 g/cm^3 and porosity decreasing from ~50% to 20%. These trends result from the progressive mechanical reduction of void space with increasing burial depth. Abrupt variations in the general density and porosity trends correlate well with lithologic unit boundaries. High-density and low-porosity outliers tend to be associated with siderite-enriched carbonate concretions and cementation of grainstones and sandstones. In marked contrast, a relatively thick zone of low density and high porosity at ~1690 mbsf defines a zone of undercompacted, very soft mudstones.

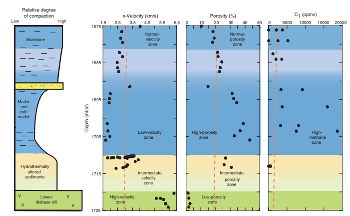
Vertical (z-direction) velocity generally increases downhole from 1900 to 2600 m/s, and it appears to be insensitive to gross lithologic variations (Fig. F31). Rather, the velocity trend is primarily related to changes in bulk density and porosity. Numerous high-velocity outliers exist, however, and they invariably relate to zones of increased cementation (both siliceous and carbonate cements) and zones of siderite precipitation. Low-velocity outliers (1650–1800 m/s) correlate with the zone of undercompacted, low-density mudstones between 1690 and 1710 mbsf.

The NGR profile shows a general decrease uphole, with several large spikes that tie closely to lithologic unit boundaries. In general, NGR reflects changes in the relative amounts of sand (low NGR) and terrigenous clays (high NGR). The observed uphole decrease of NGR may reflect the progressive increase of paleowater depth following rifting and breakup of the region and, thus, a slow transition from terrigenous to pelagic sedimentation. This trend should be punctuated by eustatically enhanced events when coarser sediment was delivered to the deep basins.

Undercompacted Systems: High-Porosity, Low-Velocity Mudstones

From 1690 to 1710 mbsf, a zone of mudstones and calcareous mudstones has unusually high porosities (27%–43%) and low velocities (1690–1960 m/s) for its depth of burial (Fig. F32). Furthermore, these sediments are very soft, with consistencies comparable to modeling clay. The porosity, velocity, density, and apparent plasticity of these mudstones are comparable to those of normally compacted sediments recovered much higher in the section (840–1020 mbsf) (Fig. F31), and they clearly demonstrate that the sediments are significantly undercompacted with respect to their depth.

We surmise that the mechanical compaction of these mudstones was halted at a relatively shallow burial depth, perhaps because of emplacement of two diabase sills, one above and one below the mudstones (Figs. F31, F32). It is possible, but not necessary, that this interval was overpressured. Evidence of past fluid flow exists in the hydrothermally altered sediment that lies immediately above the lower sill and beneath the undercompacted mudstones (Fig. F32). Furthermore, the highest measured concentration of hydrocarbons exists in this 20-m-thick interval. Geochemical analysis measured C_1 levels of nearly 19,000 ppm (Fig. F32), implying that fluids in this interval were trapped. Emplacement of the bounding igneous intrusions is the most likely reason that this interval did not compact normally or expel pore fluids.



F32. Physical properties and C_1 concentration in an underconsolidated zone, p. 75.

SITE 1277 SYNTHESIS

Lithostratigraphy

Site 1277 is located on a basement ridge (Mauzy Ridge) beneath thin sediment cover (Figs. F8B, F9, and Fig. F20, p. 34, in the "Site 1277" chapter). The main objective was to recover samples of basement, so the site was drilled without coring from 0 to 103.90 mbsf. It was predicted that the bit would be some tens of meters above the sediment/basement contact at that depth. During drilling, a "wash" core barrel was in place. When retrieved, this core barrel contained 2.29 m of fractured igneous rock and associated volcaniclastic sediments (Core 210-1277A-1W) that are indistinguishable from rock in the top of the next core, Core 2R. During drilling, hard zones were encountered at 85–89 and 97.5–100 mbsf. Thus, it is believed that the recovery in Core 210-1277A-1W comes from depths between 85 and 103.90 mbsf. We set the top of basement (Unit 1) at a nominal depth of 85 mbsf.

Two lithologic units are recognized (see Fig. F2, p. 15, in the "Site 1277" chapter). Unit 1 is a succession of alternating basalt flows (~50%), coarse breccia units containing a wide variety of clasts of gabbro and serpentinite (~20%), and minor volcaniclastic and ferruginous sediments (~10%). There are also variably deformed gabbroic rocks (~20%) that may be very large clasts. All these rocks are fractured and have veins filled with mineral precipitates and detritus. The interpreted depth of this unit is 85–142.10 mbsf. The principal characteristic of Unit 1 is that it is a sedimentary and volcanic succession. The sedimentary units are derived entirely from rock types characteristic of the underlying basement at this site.

Lithologic Unit 2 (142.10 mbsf to the bottom of the hole at 180.30 mbsf) consists almost entirely of tectonized, altered ultramafic rocks including harzburgite, dunite, and serpentinite mylonite (see Fig. F2, p. 15, in the "Site 1277 chapter"). There is a gabbro cataclasite at the top of the unit. Unit 2 is cut pervasively by magmatic and hydrothermal veins that record several stages of fracturing and fluid precipitation. Many of the smaller veins cutting the serpentinized peridotite are composed of talc, magnetite, and calcite. There are no sediments or lavas in Unit 2 that would indicate formation in proximity to the seafloor. The rocks are interpreted as mantle that was exposed by tectonic extension and that was associated with pervasive deformation and hydrothermal alteration. During or after their exhumation, these serpentinites were buried by the lavas, allochthonous debris, and coarse sediments of Unit 1. The allochthonous debris was probably shed from local seafloor topography along the crest of the basement ridge.

Biostratigraphy

No shipboard biostratigraphic analysis was conducted on the few sedimentary rocks recovered at Site 1277 because no suitable materials were recovered.

Agglutinated benthic foraminifers occur in a single piece of indurated ferruginous sediment (Sample 210-1277A-1W-1, 5–9 cm) overlying igneous rocks at Site 1277. The few poorly preserved specimens include planispirally coiled forms with numerous chambers and alveolar internal walls similar to those in the family Cyclamminidae. There are also encrusting(?) tubelike forms possibly belonging to the family Ammodiscidae. In addition, several tiny planktonic foraminifers were observed in a dark-colored sedimentary clast. No age-diagnostic taxa were observed.

Paleomagnetism

We made pass-through magnetometer measurements and magnetic susceptibility measurements on the archive halves of all cores at 2-cm intervals. To isolate the ChRM, cores were subjected to alternating-field demagnetization up to 60 mT. We analyzed the results in Zijderveld diagrams (Zijderveld, 1967) and calculated ChRM direction using principal component analysis (Kirschvink, 1980). We also determined magnetic susceptibility on all whole cores at 2.5-cm intervals as part of the multisensor track analysis, and we measured split-core sections at 2-cm intervals with the point-susceptibility meter run on the archive multisensor track. No shipboard discrete samples were taken because of time constraints at the end of the leg.

Paleomagnetic data exhibit significant variations in demagnetization behavior among recovered lithologies. As at Site 1276, there was drilling-induced remagnetization, but at Site 1277 it was reduced in comparison. Greenish gabbro cataclasite in Core 210-1277A-2R has the lowest NRM intensity (~0.02–0.3 A/m), contrasting with stronger intensities in relatively fresh aphyric basalt in Cores 1R, 3R, and 5R (~1–4 A/m), gabbro at the base of Core 4R and in the lower part of Core 5R (0.2–0.5 A/m), and serpentinite in Core 9R (1–9 A/m). The basalts appear to record a stable component of magnetization with normal inclinations (~45°). The green gabbro cataclasite, on the other hand, displayed variable inclinations (from positive shallow to negative shallow). Gabbros and adjacent sediments have the same stable inclination values (~40°), similar to those of the basalt.

The serpentinized peridotites in different parts of long, coherent core pieces in Core 210-1277A-9R showed ChRM inclinations that cluster around a mean of 40°, generally in agreement with inclinations in the basalts and gabbros. Because NRM intensities of the serpentinized peridotites are on the order of 1–9 A/m, they could contribute significantly to the regional magnetic anomaly. There is a distinct difference between gabbro, with relatively low magnetic susceptibility and high median destructive field (MDF), and serpentinite, with high susceptibility and low MDF. This difference may be explained by either the finer grain size of the gabbros or their higher degree of low-temperature alteration, or both.

Geochemistry

Because of time constraints at the end of the leg, no shipboard geochemical analyses were conducted on rocks from Site 1277.

Physical Properties

Evaluation of physical properties at Site 1277 included nondestructive measurements of density, porosity, velocity, and thermal conductivity. Porosity varied between 2% and 25%, bulk density varied between 2.3 and 2.8 g/cm^3, and grain density varied between 2.60 and 3.00 g/cm^3. Compressional wave velocity ranged from 3300 to 6300 m/s. Velocity is lowest (~3270 m/s) in highly altered and veined breccias (Section 210-1277A-4R-2), and it is highest (6325 m/s) in a coarse-grained gabbro (Section 5R-3). Velocity in the serpentinized peridotites ranged from ~3300 to 4700 m/s. Thermal conductivity ranged from 1.6 to 2.25 W/(m·K), with no obvious trend in the values.

COMPARISON OF SITE 1276 WITH IBERIA MARGIN STRATIGRAPHY

It is instructive to compare seismic reflection profiles, lithologic units, and sediment accumulation patterns on the conjugate margins of the Newfoundland–Iberia rift. This is true particularly for the deepest parts of the sedimentary section, which were deposited at a time when the two margins were close to one another. For this purpose we compare Site 1276 with Site 398, which was drilled on continental crust of southern Galicia Bank on the Iberia margin (Fig. **F11**). Site 398 has the most complete and expanded stratigraphic range of sediments among the Iberia margin drill holes. Other holes drilled during Legs 149 and 173 were on basement highs and did not penetrate significant sections of pre-Tertiary sediments. At the time of Anomaly M0 (earliest Aptian; ~121 Ma), Sites 1276 and 398 were separated by only ~250 km (Fig. **F3A**). The paleoceanographic environment in this young ocean basin should have been similar on both margins. Indeed, we observe comparable occurrences of mid-Cretaceous black shales and Upper Cretaceous red-brown and multicolored shales, although there are some significant differences in details of sedimentary processes and paleowater depths between the two sites. Below, we summarize and compare principal features of the sedimentary sequences on the two margins. A more detailed comparison of facies between the margins, and with facies developed in the central North Atlantic Basin, is given in **"Comparisons**

with the Conjugate Iberia Margin and the Western Central North Atlantic," p. 57, in the "Site 1276" chapter.

Seismic and Sedimentary Succession at Site 1276

Seismic sequences in the Newfoundland Basin around Site 1276, outlined more fully in "Geological Setting," p. 4, are summarized in Figure F12. Water depth at Site 1276 is 4549 m. The deepest seismic sequence, A, is seismically laminated, flat-lying, and has impedance high enough that there is little reflection from the underlying basement. Its top is the flat, strong, basinwide U reflection. The sequence covers and smooths the underlying basement topography, and its greatest thicknesses are between underlying basement blocks (Fig. F10). Correlation of the exact top of the seismic sequence to Site 1276 borehole results is not certain, although it seems likely that the upper of two diabase sills (at 1613 mbsf) correlates with U (see "Seismic-Borehole Correlation," p. 107, in the "Site 1276" chapter). Both sills intruded into dark mudstones, siltstones, and sandstones of latest Aptian(?) to early Albian age (see "Biostratigraphy," p. 73, in the "Site 1276" chapter).

Seismic Sequence B is not strongly laminated compared to the underlying interval. It correlates with dominantly green-gray to black claystones and mudstones with variable amounts of siltstones and sandstones. The sediments were deposited in the early Albian to late Turonian.

The overlying seismic Sequence C is flat-lying and strongly reflective. It correlates with brown sandy mudstones, overlain by multicolored (e.g., brown, red, and gray green to black) hemipelagic claystones interrupted by frequent calcareous turbidites. The sediments are latest Turonian–Coniacian to middle Eocene in age.

Seismic Sequence D was sampled at Site 1276 only in its lower part, where it consists of middle Eocene to lower Oligocene(?) gray-green hemipelagic claystones and mudstones. Although the sequence shows distinct sediment waves in the landward seismic section (Figs. F8, F11), there is little indication of current-controlled deposition at Site 1276 and the section is dominated by turbidites and debris flow deposits.

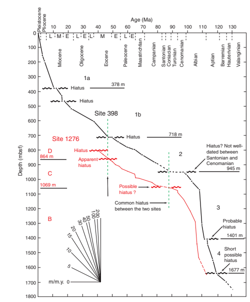
Seismic Sequences E and F were not sampled during Leg 210, although they can reasonably be interpreted from their seismic signature. Sequence E is an abyssal fan marked by irregular reflections, poorly developed sediment waves, and local debris-filled channels. Sequence F is an abyssal plain with widespread planar reflections that are very characteristic of turbidite deposits. Both sequences record extensive downslope sedimentation during Oligocene to recent time. The Sequence F turbidites most likely are latest Pliocene and Quaternary.

Seismic and Sedimentary Succession at Site 398

Site 398 was drilled at a water depth of 3900 m, ~20 km south of Vigo Seamount on the southern margin of Galicia Bank (Fig. F3A). The site is on thinned continental crust on the seaward side of the Galicia Interior Basin and ~40 km north of the Leg 149/173 drilling transect. A representative MCS reflection profile extending northwest–southeast through the site (GP-19; Figs. F11, F12) displays a sedimentary sequence that shows little apparent interruption by unconformities or condensed sections.

Basement on profile GP-19 exhibits some coherent internal reflections and apparent fault blocks that appear to record tectonic extension of the continental crust (Figs. F11, F12). The overlying moderately smooth and seismically laminated seismic sequence is termed acoustic Unit 4 (Groupe Galice, 1979), and it is capped by a moderately strong reflection termed the orange reflection. In the lowest part of the sequence, reflections are moderately conformable to basement and locally may diverge, but reflections in the upper part are unconformable and lap against the flanks of the fault blocks. This sequence was interpreted as being deposited during tilting of the fault blocks (Groupe Galice, 1979; Shipboard Scientific Party, 1979), but the onlap relations indicate that at least the upper part of the sequence is postrift. Site 398 drilling results show that the sequence consists of thin sand-silt-clay graded layers that are interbedded with thick slumps or debris flows (Shipboard Scientific Party, 1979). The sequence is interpreted as an upward-fining set of abyssal fan deposits. Its top (orange reflection) appears to match a small stratigraphic gap at the Aptian/Albian boundary (Fig. F33) (Sigal, 1979). At its base is an interval of white indurated limestone and marlstone/siltstone of Hauterivian–Barremian age (Shipboard Scientific Party, 1979). This has been interpreted as part of the basement complex at Site 398.

F33. Sedimentation rates at Sites 398 and 1276, p. 76.



A large set of MCS profiles in this area allows us to correlate acoustic Unit 4 from the thinned continental crust of Galicia Bank southward onto the transitional crust beneath the Iberia Abyssal Plain (Fig. F13). Mapped thickness patterns show that on Galicia Bank the sequence is deposited between north-south–oriented basement blocks that plunge to the south under the abyssal plain. Just south of the Leg 149/173 drilling transect, the surface of the sequence reaches across the tops of all these blocks. The sequence also thins toward the west, indicating a source of the clastic sediments along the shallow Iberia margin. The sequence pinches out on crust of late Barremian age ~30 km west of ODP Site 1070.

The overlying acoustic Unit 3 is a weakly reflective interval in which faint, semicontinuous reflections are observed. It correlates with a series of dark gray to black laminated to homogeneous claystones and interbedded mudstones that include black shales; calcareous mudstones appear in the upper part of the interval. The sediments are lower Albian–lower Cenomanian, and the top of the sequence may be marked by a hiatus (Fig. F33).

Acoustic Unit 2 is flat-lying and highly stratified, and it consists of siliceous mudstone, red marly chalk, and brown, dark reddish, and reddish gray mudstone and claystone, predominantly massive and unburrowed. Ages of the sequence at Site 398 are Coniacian to early Eocene.

Acoustic Unit 1 is stratified in its lower part (Subunit 1b), but it has only weak reflections in its upper part (Subunit 1a). The lower part is marly nannofossil chalk, nannofossil chalk, and siliceous marly chalk, and the upper part is rhythmically bedded marly nannofossil ooze. Although the sequence is locally eroded away, apparently by bottom currents (right side of Fig. F11), its internal reflections are flat-lying and show few if any signs of current-controlled erosion or deposition. Ages of the sequence range from middle Eocene to Quaternary.

Comparison of Seismic Sequences at Site 1276 and Site 398

It is clear that there are significant similarities in the deeper parts of the seismic sections and the correlative lithofacies of the Newfoundland and Iberia conjugate margins (Figs. F11, F12). These similarities persist up through seismic Sequence C on the Newfoundland margin and the correlative acoustic Unit 2 on the Iberia margin. They indicate that the two margins shared common depositional environments when the ocean basin was young and relatively narrow. At shallower levels in the sedimentary record the seismic signatures become significantly different, reflecting divergence in sedimentation patterns as the margins became more widely separated. We summarize this development below.

Basal seismic Sequence A off Newfoundland and acoustic Unit 4 on Galicia Bank show comparable seismic signatures. The age at the base of the sedimentary sequence at Site 1276 is unknown, but it may be very similar to the Hauterivian age of basement limestones cored at Site 398. Magnetic Anomalies M3 and M0 lie to the east of Site 1276. If the crust at the drill site is oceanic and we extrapolate a crustal age from these anomalies to the drill site (assuming constant spreading rate), the basement dates to ~126 Ma (the Hauterivian/Barremian boundary). Although the top of seismic Sequence A appears to be slightly younger than that of acoustic Unit 4 (lower Albian vs. Aptian/Albian boundary), depositional conditions were comparable on both margins. Dark-colored, low-carbonate hemipelagic sediments indicate that the basin experienced low-oxygen conditions below the CCD, where sedimentation was dominated by turbidity currents and debris flows. Widespread dispersal of these flows across the basin floor accounts for the seismically laminated signature of the interval.

Newfoundland seismic Sequence B matches the seismic signature of Iberia acoustic Unit 3. The correlative sedimentary section on both margins is Albian to Cenomanian (or lower Turonian) gray-green and black shales, similar to the Hatteras Formation in the main North Atlantic Basin (Jansa et al., 1979). At Site 1276 these shales are hemipelagic through most of the section, with important gravity-flow deposits at the top and base of the section. At Site 398 gravity-flow deposits are important at the top, but sediments are mostly hemipelagic in the deeper section. During the Albian–Turonian, the basin width increased from 600 to 1000 km. Nonetheless, the two margins show remarkable correspondence in sediment facies and they also have very similar sediment accumulation patterns. Notably, these sedimentation rates are high (up to 100 m/m.y.) in the lower part of the section and somewhat reduced (to ~18 m/m.y.) in sections at intermediate depths on both margins (Fig. F33). These correlations indicate that both margins provided similar source areas for sediment input to the deep basin. The deep seafloor was at least intermittently anoxic and was below the CCD.

In the Late Cretaceous (approximately Coniacian–Campanian), both margins either developed hiatuses or had severely reduced sedimentation rates (Figs. F27, F33). This condensed or missing record corresponds to the top of seismic Sequence B off Newfoundland, where truncations of reflections indicate that an unconformity is present. Similar truncation in the Iberia GP-19 seismic profile is not apparent, although a slight unconformity was identified on other profiles (Groupe Galice, 1979). This correlation between margins indicates a riftwide event; it may indicate the development or invigoration of deep circulation that marked the end of significant black shale deposition, possibly coupled with rising sea level, higher CCD, and sediment starvation. This scenario is consistent with the presence of red and brown sediments deposited on a more oxygenated seafloor in the overlying section on both margins.

Seismic signatures that are similar on both margins persist upward into seismic Sequence C off Newfoundland and acoustic Unit 2 off Iberia. The basin width increased from 1000 to 2000 km during this period (Coniacian–middle Eocene). The sequences are red-brown mudstones on the Newfoundland margin and marly chalks on the Iberia margin, deposited under mostly oxygenated seafloor conditions. Turbidity currents delivered carbonate sediments to the deep seafloor in large quantities on the western side, but they mostly bypassed Site 398, where pelagic carbonates are abundant (50–60 wt%). Even so, sedimentation rates were similar (5–8 m/m.y.) on both margins. The difference in sedimentation processes at the two drill sites is not apparent in the seismic signature.

Beginning with the middle–upper Eocene record, there is significant divergence in the seismic signature of sediments on the two margins. Newfoundland seismic Sequence D shows clear evidence of sediment waves developed by strong abyssal circulation (Fig. **F8A, F8B**), but there is no similar seismic signature on the Iberia side (Fig. **F12**). The reflection at the base of Newfoundland seismic Sequence D appears to correlate with an unconformity between lithologic Units 1 and 2 at Site 1276, and biostratigraphic data indicate a middle Eocene hiatus at this level (Figs. **F27, F33;** see **"Biostratigraphy,"** p. 73, in the "Site 1276" chapter). All these features indicate that the reflection may be equivalent to Horizon A^u in the western North Atlantic, which marks the influx of cool bottom waters from the Norwegian-Greenland Sea and corresponds to initiation of strong abyssal circulation in the basin (e.g., Miller and Tucholke, 1983). Because of the Coriolis effect, the deep currents were primarily concentrated along the western boundaries of the ocean basins. Although the currents seem not to have affected the seismic architecture of the Iberia margin at Site 398, there could be a short middle Eocene hiatus there (Fig. **F33**), so there might be some subtle erosion or attenuation of the sedimentary record.

The uppermost sedimentary sections on the opposing margins are markedly different in seismic character (Figs. **F11, F12**), and they clearly show a divergence in sedimentary processes during the late Cenozoic. As already noted, seismic Sequences E and F on the Newfoundland margin are dominated by downslope sedimentation. In contrast, acoustic Unit 1 around Site 398 is a less reflective sequence of largely pelagic sediments. It is clear that this southern part of Galicia Bank became progressively isolated from downslope sedimentation throughout the Cenozoic.

SUMMARY AND CONCLUSIONS

Overview

The prime drilling objectives of Leg 210 were to sample basement and the facies corresponding to the overlying U reflection in the Newfoundland Basin, both of which were deep targets. Additional objectives included investigation of the Cretaceous paleoceanography of the Newfoundland–Iberia rift and the record of how abyssal circulation developed in Paleogene time through this gateway to the sub-Arctic and Arctic seas.

At our prime site, 1276, basement was estimated to be at 2080 mbsf and depth of U was estimated at 1866 mbsf. Drilling and coring to these depths presented considerable engineering and operational challenges, both expected and unexpected. We were able to follow our operational plan to case the hole at Site 1276 with both 20- and 16-in casing as planned (Figs. **F15, F16**), but very tight hole conditions prevented us from installing liners to greater depths. Ultimately, these hole conditions also prevented us from logging the hole.

Despite these difficulties, drilling at Site 1276 was an outstanding success. We cored from 800 to 1736.9 mbsf with a remarkable average core recovery of 85%, and we obtained a detailed record of sedimentation from the time that the Newfoundland–Iberia rift was a very narrow ocean basin (latest Aptian[?] to earliest Albian) up to the early Oligocene. This record captures an extensive series of major oceanographic events that affected the expanding North Atlantic Ocean, and it allowed us to accomplish virtually all of our major paleoceanographic objectives.

Site 1276 bottomed in diabase sills that appear to have been intruded into uppermost Aptian(?) to lower Albian sediments at very shallow subbottom depths. These sills are estimated to lie only 100–200 m above basement, and it appears completely feasible that future drilling at this site can core to, and into, basement. The sills were intruded at the level of U, and this basinwide horizon is interpreted to represent a combination of extensive gravity-flow deposits and intrusive sills. The occurrence of the sills raises intriguing new questions about the magmatic history of the Newfoundland side of the rift and about its relation to the nonmagmatic exhumation of mantle on the conjugate Iberia margin.

With a few days remaining during Leg 210, we were able to drill at Site 1277, a shallow-penetration basement site ~40 km southeast of Site 1276 on presumed ocean crust. Here we recovered a unique assemblage of ~35 m of basalt flows interleaved with allochthonous slivers of gabbro, serpentinized peridotite, and fine- to coarse-grained breccias and sediments at the top of basement. These overlie at least ~45 m of serpentinized peridotite that appears to represent intact basement. The Site 1277 basement rocks record complex processes of limited magmatism, deep-crust and mantle exhumation, and mass wasting at the eastern margin of the Newfoundland transition zone in ocean crust that probably accreted at very slow spreading rates.

Engineering and Drilling Challenges

The hole at Site 1276 was cased to 750 mbsf, and the engineering plan was to extend casing liners to a depth as great as 2060 mbsf, just above projected basement depth (Fig. **F15**). Hole conditions below the casing, however, prevented liners from being installed. Tight spots at numerous intervals (see **"Operations,"** p. 4, in the "Site 1276" chapter) indicated that the hole was persistently closing on the drill string, and it was clear that liner could not be forced into this section, even with a predrilled, oversize hole. The engineering assessment is that if drill-in casing had been available for this section, it most likely could have been successfully emplaced and latched into the reentry cone.

Tight spots in the (ultimately) 987 m of open hole below the casing slowed operations throughout the drilling, requiring frequent wiper trips to condition the hole as well as significant redrilling each time we tripped the pipe and reentered the hole. The persistent hole closure also prevented lowering of logging tools, and we were ultimately unable to obtain any logs. Fortunately, the excellent core recovery allowed us to obtain an extensive set of laboratory physical property data that will be used for borehole-seismic correlation and synthetic-seismogram modeling.

Reentry was another significant operational challenge. Beginning with the first reentry, the reentry cone was found to be completely covered by sediment and its location could only be determined from an overlying craterlike depression in the seafloor. On a number of reentries, muddy water streaming from the crater largely obscured it, and reentry was accomplished only by careful tracking of the crater in both sonar images and in very limited visual images. Currents presented an additional problem. Bottom currents at times appeared to approach 50 cm/s (estimated from the streaming sediment noted above), and this displaced the drill bit up to 75 m laterally from the location of the moonpool. The conventional assumption on reentry is that the drill bit is within a few meters to tens of meters directly below the ship, so this unexpected offset at one point caused a long search for the reentry cone. We ultimately found the cone by working "upstream" along the trail of muddy water noted above. Subsequently, a transponder was placed on the vibration-isolated television frame; this allowed us to track the location of the drill bit with respect to the cone, and it greatly facilitated further reentries.

Highlights of Scientific Results

Site 1276

Sills

We drilled two sills, one at 1613–1623 mbsf and a second from 1719 mbsf to the bottom of the hole at 1737 mbsf (the base of the lower sill was not reached or recovered). These are diabase of inferred alkaline composition based mainly on the relative abundances of stable ("immobile") major and trace elements. The sills were intruded at very shallow levels beneath the seafloor, in uppermost Aptian(?) to lowermost Albian sediments at or near the level of the U reflection. They exhibit chilled margins, and they developed striking hydrothermal alteration effects in the enclosing sediments. It appears that the upper sill may have formed a seal over the underlying sediments, preventing them from becoming normally compacted and also isolating fluids (including methane) in the section. Seismic signal reflection from the strong impedance contrasts created by these interbedded igneous and sedimentary rocks may explain the poor seismic signal penetration through U and thus the typically poor seismic definition of underlying basement.

The source of magmatism that created the sills is presently unknown, and such magmatism is certainly unexpected considering the nonvolcanic nature of the conjugate transition zone crust off Iberia. A source (mantle plume?) associated with development of the Newfoundland Seamounts ~180 km to the south seems to be unlikely, considering the basinwide distribution of the U reflection. However, some kind of regional postrift magmatic effect could help to explain the marked asymmetry of basement depth and roughness between the Newfoundland and Iberia conjugate margins (Fig. F4). Shore-based analysis of the Newfoundland Basin reflection data, together with synthetic-seismogram modeling based on the Site 1276 physical property data, age dating, and geochemical analyses, are expected to provide significant insights into this issue.

U Reflection

Preliminary shipboard synthetic-seismogram modeling and velocity-depth analysis indicate that the U reflection is at or near the top of the upper sill noted above. In the lithologic column this level is near the top of extensive lower Albian sedimentary gravity flows. This is much like the Iberia margin where the orange reflection, coincident with uppermost Aptian "fan deposits," lies at the top of a similar, although regionally weaker, reflection sequence. Off Newfoundland, it is somewhat puzzling that there is not a stronger lithologic or physical property contrast at the top of these gravity-flow deposits, in light of the fact that U is consistently a very strong reflection. New insights provided by future analysis of physical property results and synthetic-seismogram modeling may help to resolve this issue.

Black Shales and Oceanic Anoxic Events

A greatly expanded sedimentary sequence of Cretaceous black shales, equivalent to the Hatteras Formation in the western North Atlantic, was cored at Site 1276. The sequence extends from the lowermost Albian, or possibly the uppermost Aptian, upward through the Cenomanian/Turonian boundary. It reflects deposition under relatively low oxygen conditions in the deep basin, probably punctuated by intervals of total anoxia. Discrete black, organic carbon–rich layers contain either terrestrial or marine carbon, or both, indicating that both sources intermittently contributed to reducing conditions at and below the seafloor. Terrigenous organic carbon is present throughout the succession.

Sediments that may include five OAEs were recovered at Site 1276. These are uppermost Cenomanian–lowest Turonian OAE 2 (Bonarelli event); the mid-Cenomanian event; and OAE 1b (Paquier event), OAE 1c, and OAE 1d in the Albian. In addition, one other, possibly new, Albian event is recognized from its characteristic black color coupled with high TOC and related geochemical indicators (see Fig. **F156,** p. 281, in the "Site 1276" chapter). OAE 2 (Cenomanian/Turonian boundary) and OAE 1b (basal Albian) are associated with marine organic matter, whereas other OAEs are dominated by terrestrial organic matter. Analysis of these sediments will provide a rich data set to examine the paleoceanography of the Cretaceous North Atlantic Ocean as it expanded northward through the Newfoundland–Iberia rift.

Interestingly, similar dark sediments with locally black layers were recovered in parts of the uppermost Cretaceous and Paleocene section. This kind of occurrence has also been observed on the southern Bermuda Rise at Site 387 (Tucholke, Vogt, et al., 1979), suggesting that low-oxygen conditions intermittently affected the North Atlantic at times well after the main episodes of anoxia that are documented in OAEs.

Upper Cretaceous Multicolored Mudstones

Most upper Turonian and younger sediments are facies characterized by reddish, brown, green-gray, and other light colors that indicate a well-oxygenated basin, in marked contrast to the underlying section with its black shales. This change is well documented farther south in the main North Atlantic Basin, where the multicolored sediments form the Plantagenet Formation (Jansa et al., 1979). The paleoceanographic change is thought to be associated with development of longitudinal deep circulation between the North and South Atlantic Oceans when these two oceans first became fully connected at abyssal depths near the end of Cenomanian time (Tucholke, Vogt, et al., 1979). Documentation of this oceanographic change off Newfoundland indicates that the widening rift was connected to the rest of the North Atlantic Ocean over full ocean depth.

Cretaceous/Tertiary Boundary

We recovered one of the few nearly complete upper Maastrichtian to lower Danian abyssal sedimentary sections across the K/T boundary at Site 1276. Extensive reworking and frequent carbonate-free sediments prevent this section from being suitable for analyzing processes of biotic extinction, but the succession of biotic changes is obvious. High sedimentation rates in the lower Paleocene section will facilitate high-resolution study of biotic recovery following the Chicxulub (Yucatan) impact event at the K/T boundary.

Paleocene/Eocene Thermal Maximum

The Paleocene/Eocene boundary interval is characterized worldwide by an abrupt warming event referred to as the PETM, which is recorded by clay-rich precursor beds, followed by a sharp negative $\delta^{13}C$ excursion and a benthic foraminiferal extinction event. We cored this sequence at Site 1276. Although the specific boundary clay layer appears to be missing in our cores, a complete succession of the calcareous nannofossil events was recognized immediately above this level and will provide important information on biotic recovery after this event.

Initiation of Abyssal Circulation

Sedimentation patterns in the North and South Atlantic Oceans have been profoundly affected by bottom currents ever since the initiation of strong abyssal circulation in Paleogene time. Determining when this initiation occurred, however, has been problematic because the currents created major unconformities (e.g., Horizon A^u in the central North Atlantic Basin) and thus left little lithologic or biostratigraphic record to establish the timing of the event. Current interpretations are that the abyssal circulation developed near the Eocene/Oligocene boundary (Miller and Tucholke, 1983; Davies et al., 2001).

At Site 1276, we cored through a seismic marker that appears to coincide with this Paleogene circulation event. It matches an unconformity between lithologic Units 1 and 2 and a middle Eocene hiatus identified from preliminary biostratigraphy. The hiatus seems to represent a limited length of geologic time compared to other places where the unconformity has been cored, probably because gravity flows were flooding the Newfoundland deepwater margin with abundant sediment at the time. If our preliminary shipboard conclusions about the age of the hiatus are correct, then the age of this major paleoceanographic event may be 4–7 m.y. older than previously supposed. Shore-based analyses are planned to investigate this phenomenon in detail.

Site 1277

Site 1277 was drilled into the crest of a prominent basement ridge just on the young side of a magnetic anomaly identified as M1, and the crust therefore is presumed to be oceanic. Coring recovered a spectacular section of mixed pillow basalts, fine to very coarse grained gabbros, serpentinized peridotites, and calcite-cemented breccias. From initial interpretations, rocks in the upper section have been displaced to their present location in local slumps, slides, and debris flows. The distance of transport cannot have been large because they were cored from the crest of the ridge, and they must have been displaced only from local basement irregularities. The deepest four cores, consisting of minor gabbros in a cataclastic damage zone, and underlying serpentinites appear to represent intact basement.

The occurrence of coarse-grained gabbros and serpentinites at the crest of this ridge suggests that the ridge must have been formed by large-scale fault displacement that unroofed lower crust and upper mantle or that magmatic crust at this site is extremely thin, or both. Both of these features are expected in very slow spreading ocean crust that is characterized by limited magma supply and extreme tectonic extension.

Concluding Remarks

We undertook Leg 210 with a full understanding that drilling, casing, coring, and logging a 2+ km hole during only one drilling leg would be a major challenge. Although we were unable to fully meet this objective at Site 1276, in the final analysis we judge that the leg was a clear success. We cored to 1737 mbsf and recovered an exceptionally complete sedimentary record. Engineering analysis indicates that Site 1276 can reasonably be deepened to reach and core basement if casing is drilled into the lower part of the existing hole. In addition, Site 1277 returned a remarkable record of lower oceanic crust and upper mantle from a hole with very short penetration. As is true of the best scientific problems, results from these two sites raise exciting new questions. Among the most important of these is: How do we reconcile a record of extreme tectonic extension in an apparently slow spreading and magma-starved environment (Site 1277) with a record of significant postrift magmatism in nearby crust at Site 1276? We look forward to future drilling in the Newfoundland Basin to answer such questions and to determine the nature of the crust in the Newfoundland transition zone.

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Figure F1. Bathymetric map of the North Atlantic Ocean showing locations of Sites 1276 and 1277 in the Newfoundland Basin and DSDP and ODP drill sites on the western and southern margins of Galicia Bank on the conjugate Iberia margin (Legs 47B, 103, 149, and 173).

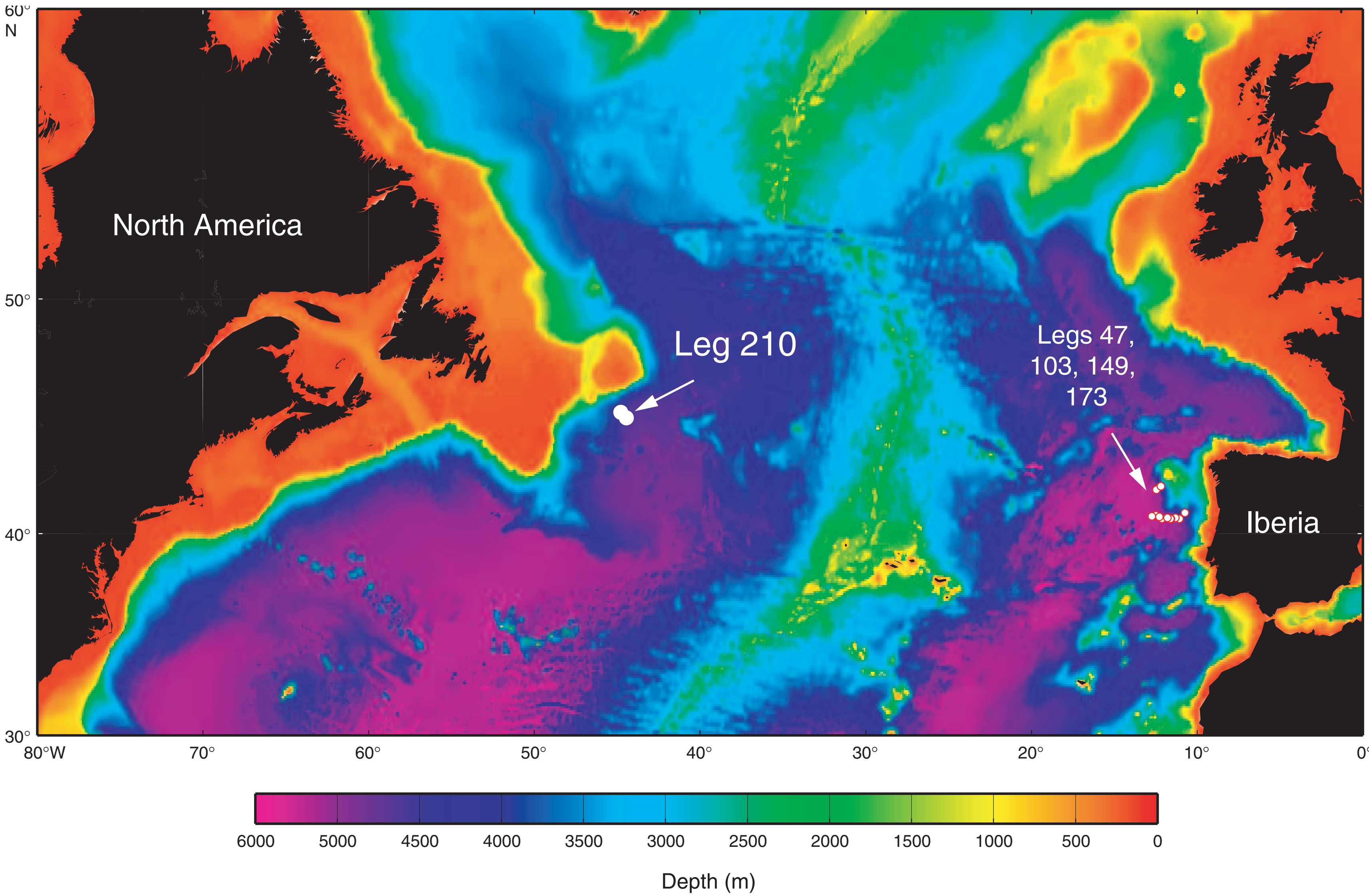

Figure F2. Summary diagram of rift events in the Newfoundland–Iberia rift. Leg 210 drilling was at the boundary between the central and northern rift segments (black triangle at top of the figure). Hiatuses probably developed because of tectonic uplift associated with rifting. "E" at the bottom indicates evaporites deposited in shallow rift basins during the Late Triassic to Early Jurassic. Minor magmatism in the rift is documented south of Tagus Abyssal Plain in Gorringe Bank (Schärer et al., 2000) and on Galicia Bank (Schärer et al., 1995; Beard et al., 2002). The Southeast Newfoundland Ridge at the southern margin of the Newfoundland Basin was a major locus of volcanism in the Barremian–Aptian (Tucholke and Ludwig, 1982). Open arrows = earliest proposed seafloor spreading, solid arrows = estimates for latest initiation of spreading. (Southern segment earliest = 145–131 Ma [Anomaly M20–M11] [Srivastava et al., 2000; Mauffret et al., 1989]; central segment earliest = 140 Ma [Anomaly M17] [Srivastava et al., 2000], latest = 127–125 Ma [Anomaly M5–M3] [Whitmarsh and Miles, 1995; Russell and Whitmarsh, 2003]; northern segment = ~122 Ma [Anomaly M0] [Srivastava et al., 2000; Boillot, Winterer, Meyer, et al., 1987]). Other data are compiled from Enachescu (1987), Tankard and Welsink (1987), Wilson (1988), Balkwill and Legall (1989), Murillas et al. (1990), Driscoll et al. (1995), Rasmussen et al. (1998), and Wilson et al. (2001).

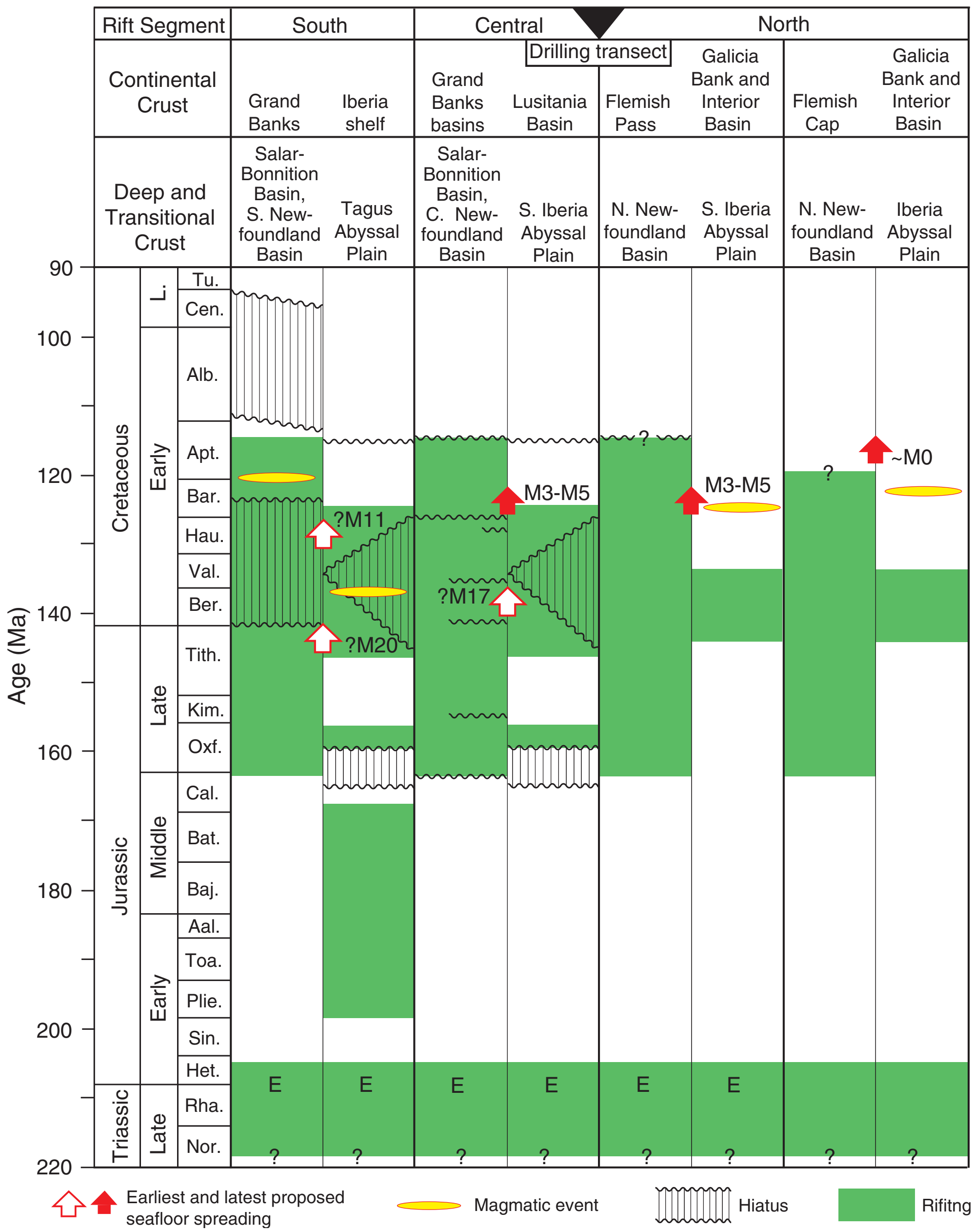

Figure F3. A. Reconstruction of the Newfoundland–Iberia rift to Anomaly M0 time (121 Ma), based on the reconstruction pole of Srivastava et al., 2000. Newfoundland plate is fixed in present geographic coordinates. Solid circles = locations of Sites 1276 and 1277 in the Newfoundland Basin plus DSDP and ODP drill sites on the conjugate Iberia margin. Tectonic and other data are compiled from numerous sources (structural data from the SCREECH survey [Fig. F5, p. 45] are not included). The diamond pattern on the Iberia side shows the seaward limit of continental crust (poorly controlled south of the Iberia abyssal plain). Light red = evaporites in continental rift basins. Ocean crust (center, blue) is presumed to have formed beginning near Anomaly M3. A south-to-north zipperlike opening would account for the observed splayed tectonic trends between the two margins and the northward-narrowing zone of ocean crust. On the Newfoundland side, the U reflection extends throughout the Newfoundland Basin and pinches out seaward near Anomaly M3. BMT. = basement, SMT(S). = seamount(s). NFLD. = Newfoundland, A.P. = abyssal plain, FL. = Flemish, N.B. = Newfoundland Basin. F.Z. = fracture zone, T.Z. = transition zone. (Continued on next page.)

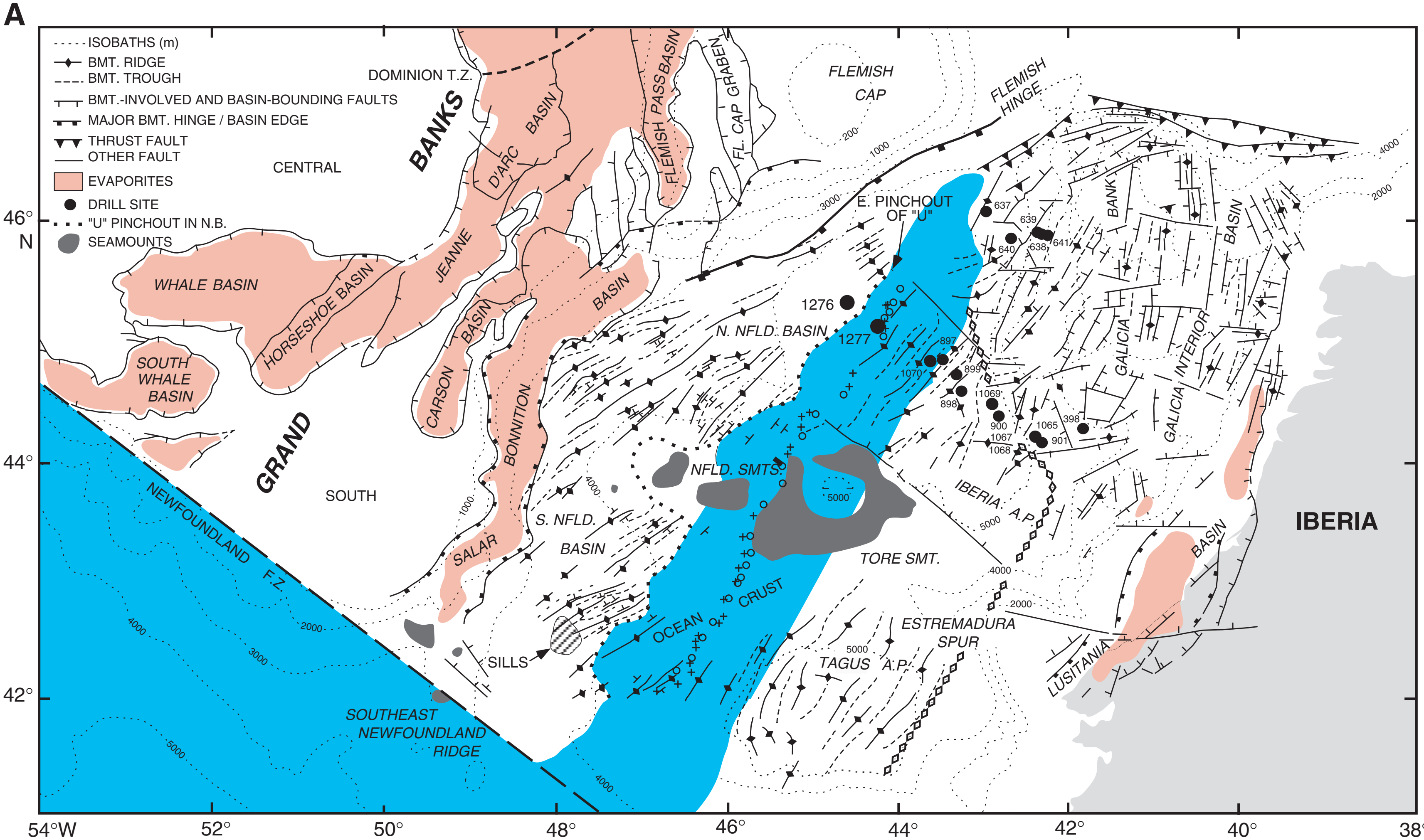

Figure F3 (continued). B. Anomaly M0 reconstruction as in A, with locations of reflection profiles. Solid lines show locations of profiles in Figure F4, p. 43, and dotted lines show positions of other SCREECH transects not illustrated here (see Fig. F5, p. 45).

B

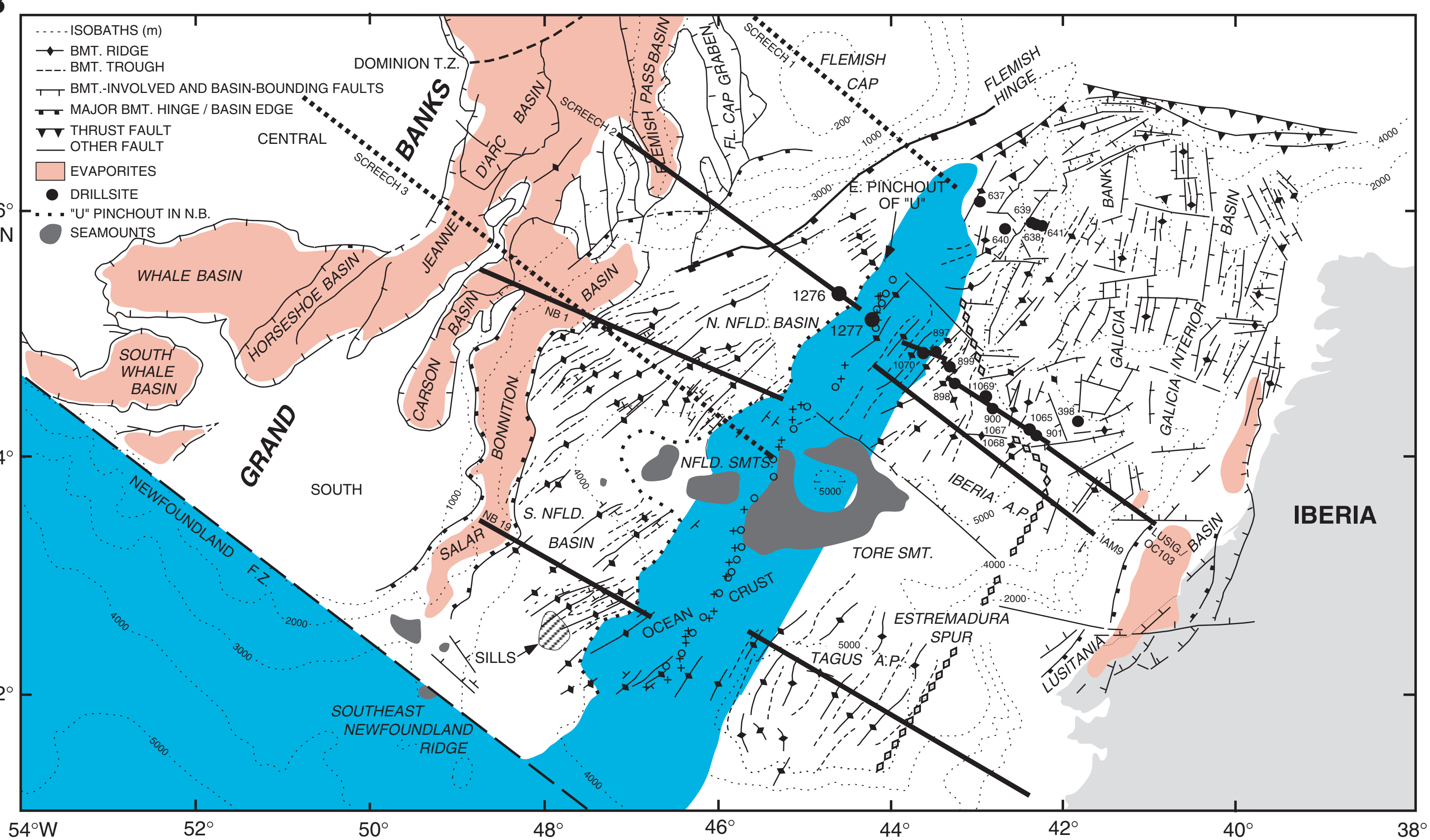

Figure F4. Simplified interpretations of conjugate seismic reflection sections from the Newfoundland and Iberia margins, juxtaposed at Anomaly ~M1. Profiles are displayed north to south (top to bottom), and locations are shown in Figure F3B, p. 42. Vertical exaggeration = ~12.5. On the Newfoundland side, sediments are shaded brown above basement and/or the intersecting U reflection; on the Iberia side, sediments are similarly shaded above basement. Top left: Simplified interpretation of SCREECH line 2MCS with location of Site 1276. Top right: Composite seismic section (*Sonne* 16, *JOIDES Resolution, Lusigal* 12, *OC* 103) along the conjugate Iberia drilling transect, adapted from ODP Leg 173 Scientific Party (Shipboard Scientific Party, 1998). Drill sites are numbered, and lithology at the bottom of the Iberia holes is indicated. Center left: *Conrad* multichannel seismic (MCS) line NB1 about 150 km south of SCREECH line 2MCS, showing another view of Newfoundland basement structure and the overlying U reflection. Center right: MCS line IAM9 about 50 km south of *Lusigal* 12 off Iberia. Bottom left: *Conrad* MCS line NB19 in the southern Newfoundland Basin. Bottom right: Conjugate MCS profile *Lusitanie* 86 over Tagus Abyssal Plain. Note the marked asymmetries in basement depth and roughness between the Newfoundland and Iberia sides of the rift. (**Figure shown on next page.**)

Figure F4 (continued). (Caption shown on previous page.)

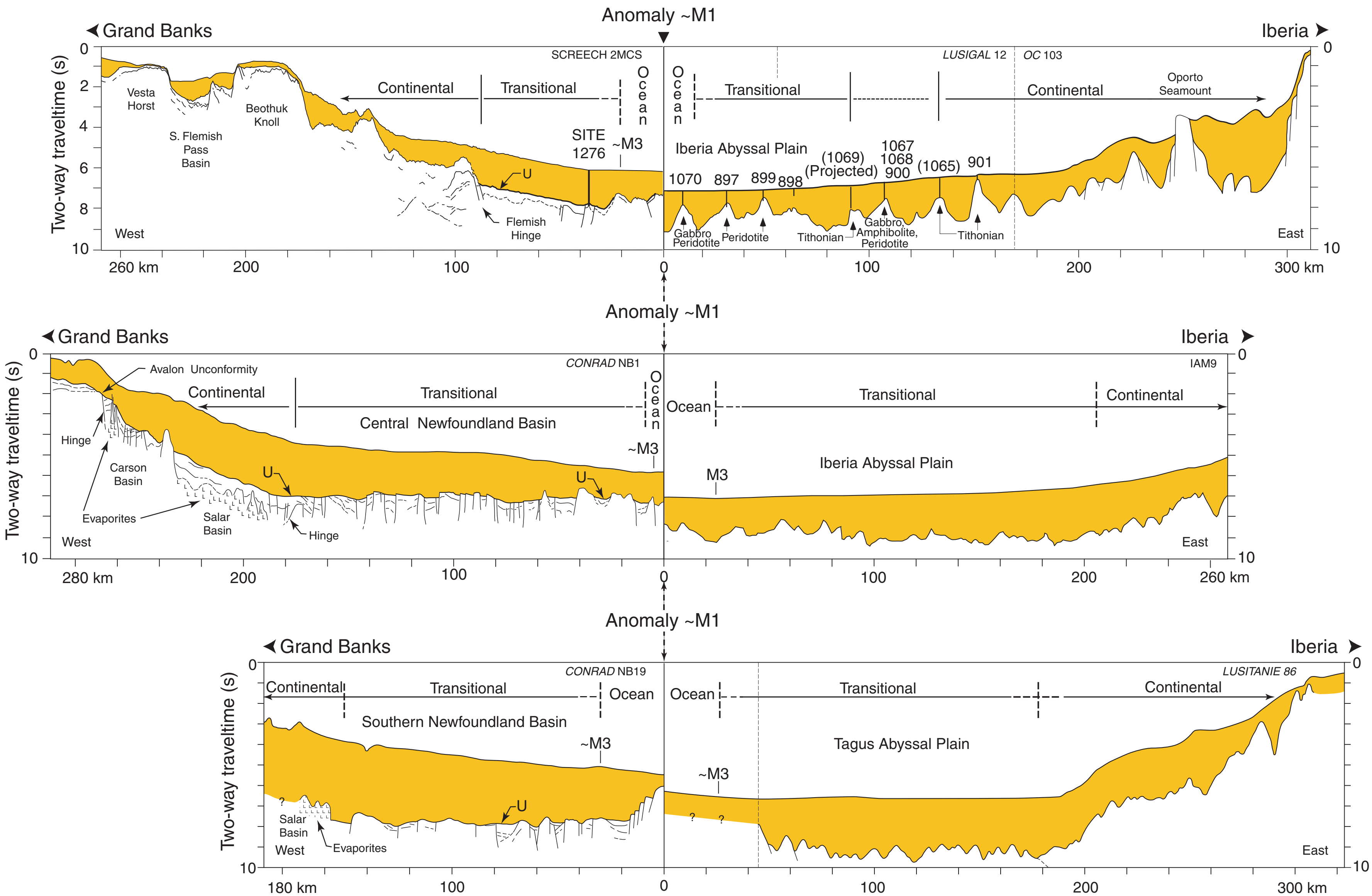

Figure F5. Track-line map showing three transects of the SCREECH survey (*Ewing* cruise 00-07) across the Newfoundland continental margin. Leg 210 drilling was on transect 2 (see Fig. F6, p. 46). Bathymetric contour interval = 200 m.

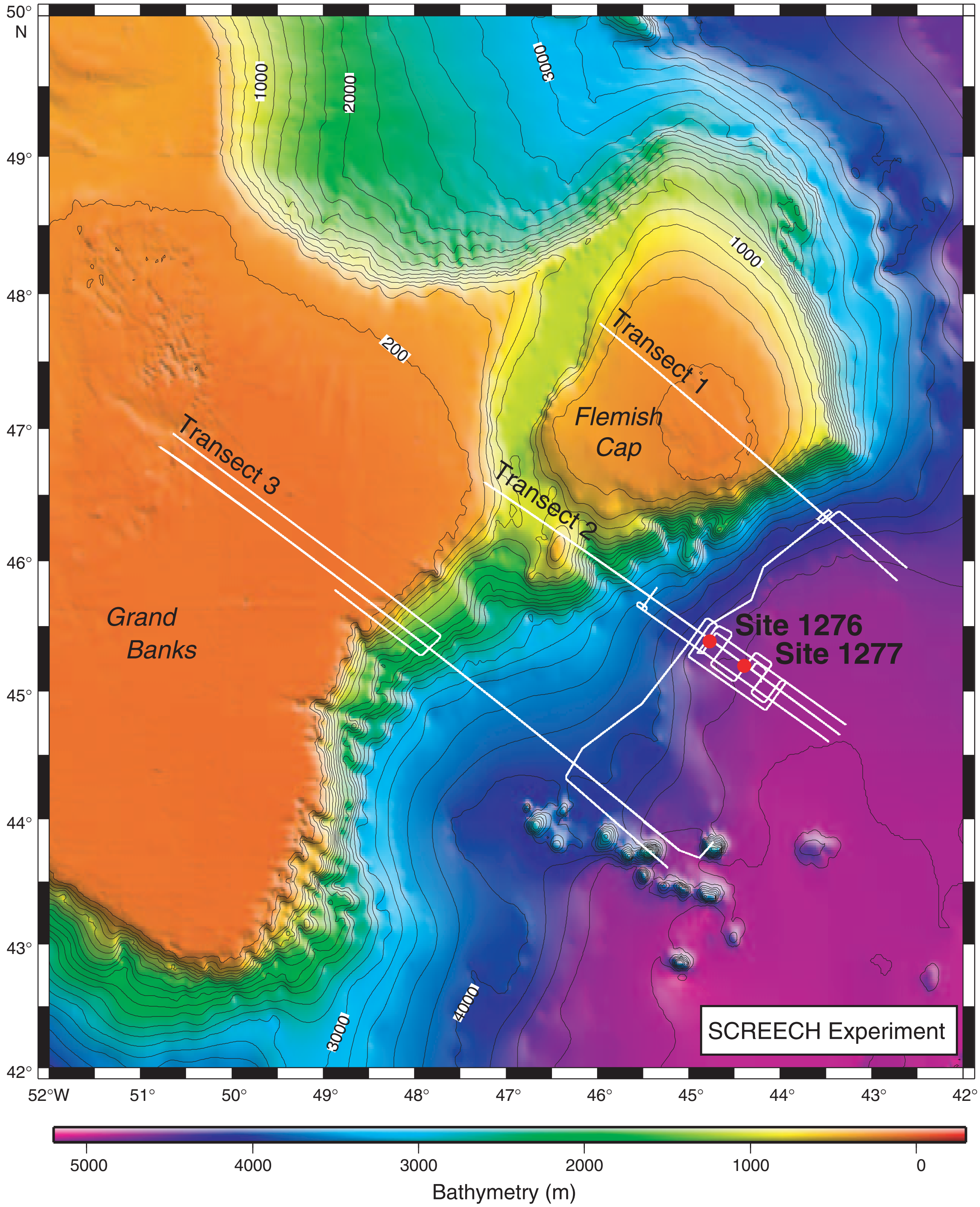

Figure F6. Track-line map of the SCREECH survey (*Ewing* cruise 00-07) along transect 2, conjugate to the ODP Leg 149/173 drilling transect on the Iberia margin (see also Fig. F3B, p. 42). Locations of Leg 210 Sites 1276 and 1277 are indicated. The black section of the track line shows the section of reflection profile 2MCS illustrated in Figure F8, p. 48. The complete set of multichannel seismic data is presented in Shillington et al., this volume. Bathymetric contour interval = 200 m.

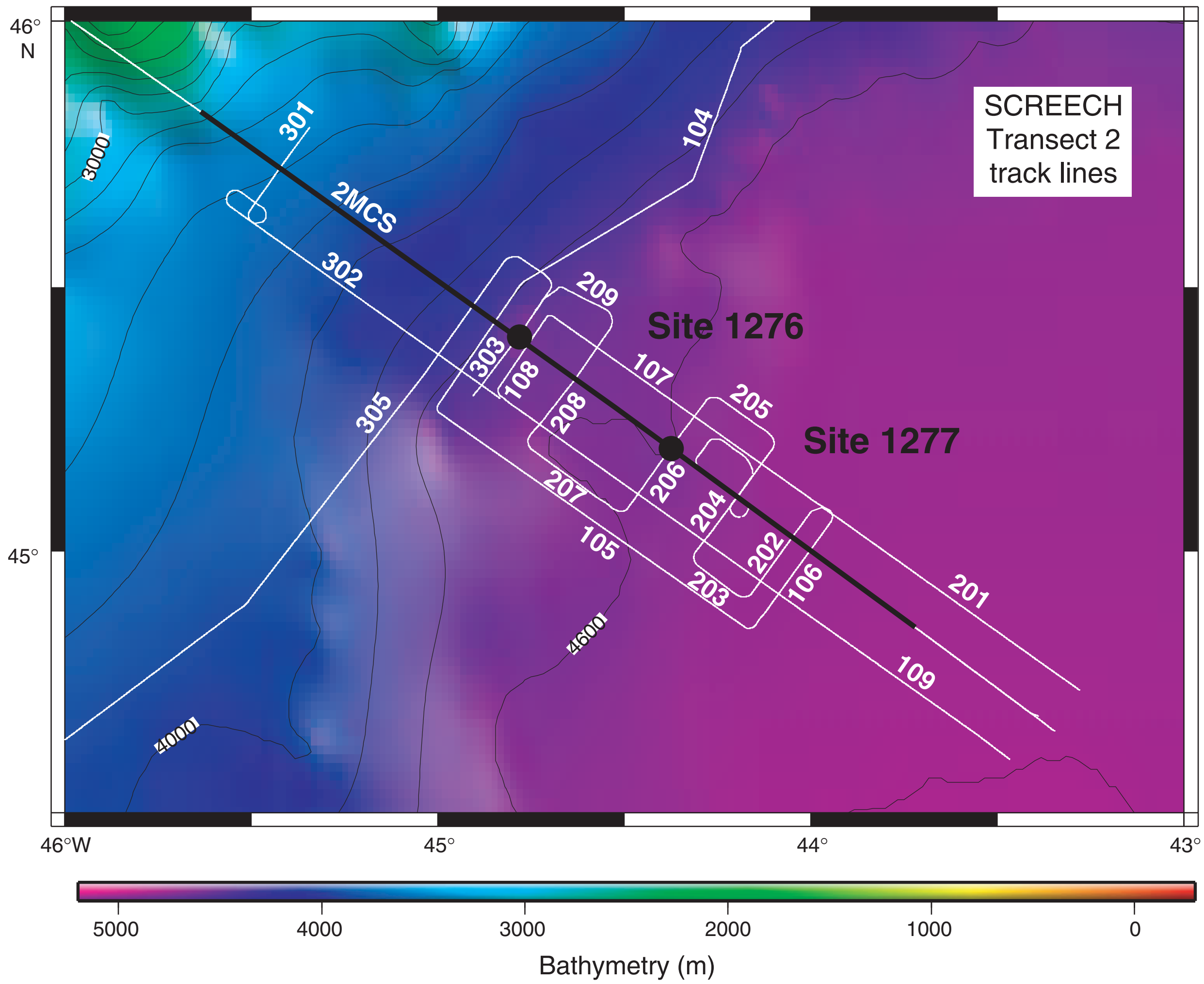

Figure F7. Bathymetry of the Newfoundland margin showing the locations of Sites 1276 and 1277. Bathymetric contour interval = 100 m. Smts. = seamounts.

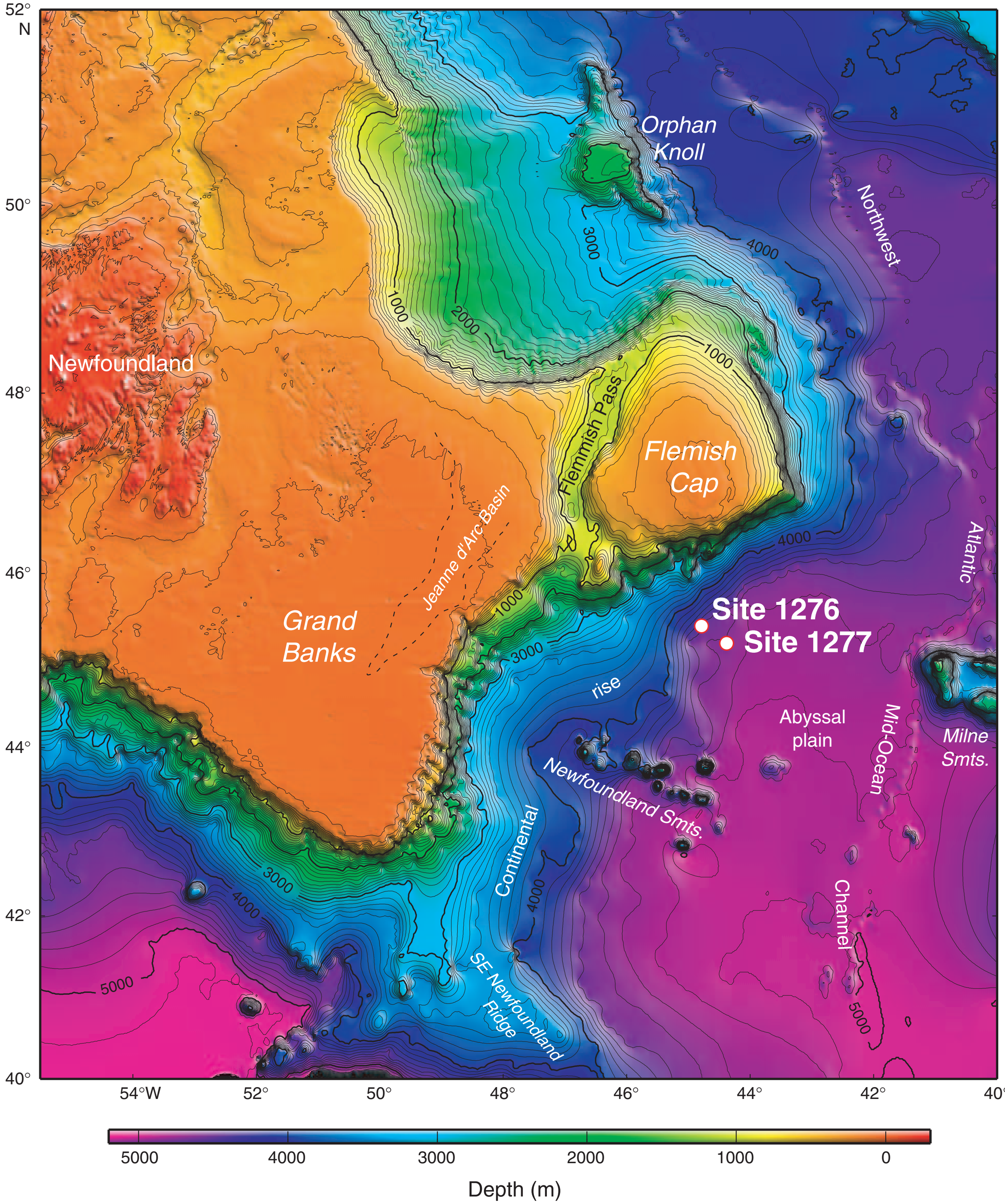

Figure F8. SCREECH line 2MCS from the central Newfoundland continental rise seaward to oceanic crust east of Anomaly M0, illustrated in three sections. Location is shown in Figure F6, p. 46. Seismic sequences discussed in the text are shown. **A.** Lower continental rise. The basement block at center is the landward side of the Flemish Hinge and is capped by probably lower Mesozoic, prerift sediments. Major deep-basin reflections and seismic sequences to the east are identified. CMP = common midpoint, Unc. = unconformity, BMT. = basement, Seis. seq. = seismic sequence. (Continued on the next two pages.)

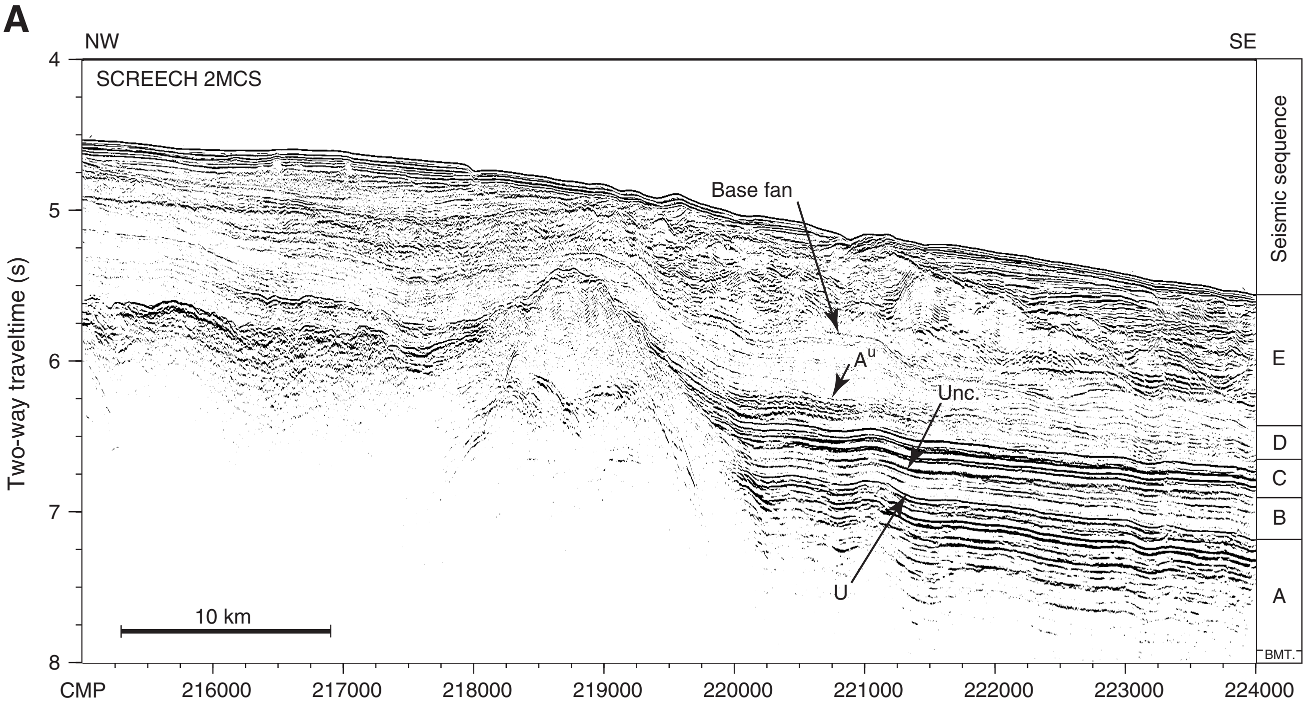

Figure F8 (continued). B. SCREECH line 2MCS over the lowermost continental rise and western margin of the abyssal plain. Sites 1276 and 1277, major reflections, seismic sequences, and magnetic anomaly locations are identified.

B

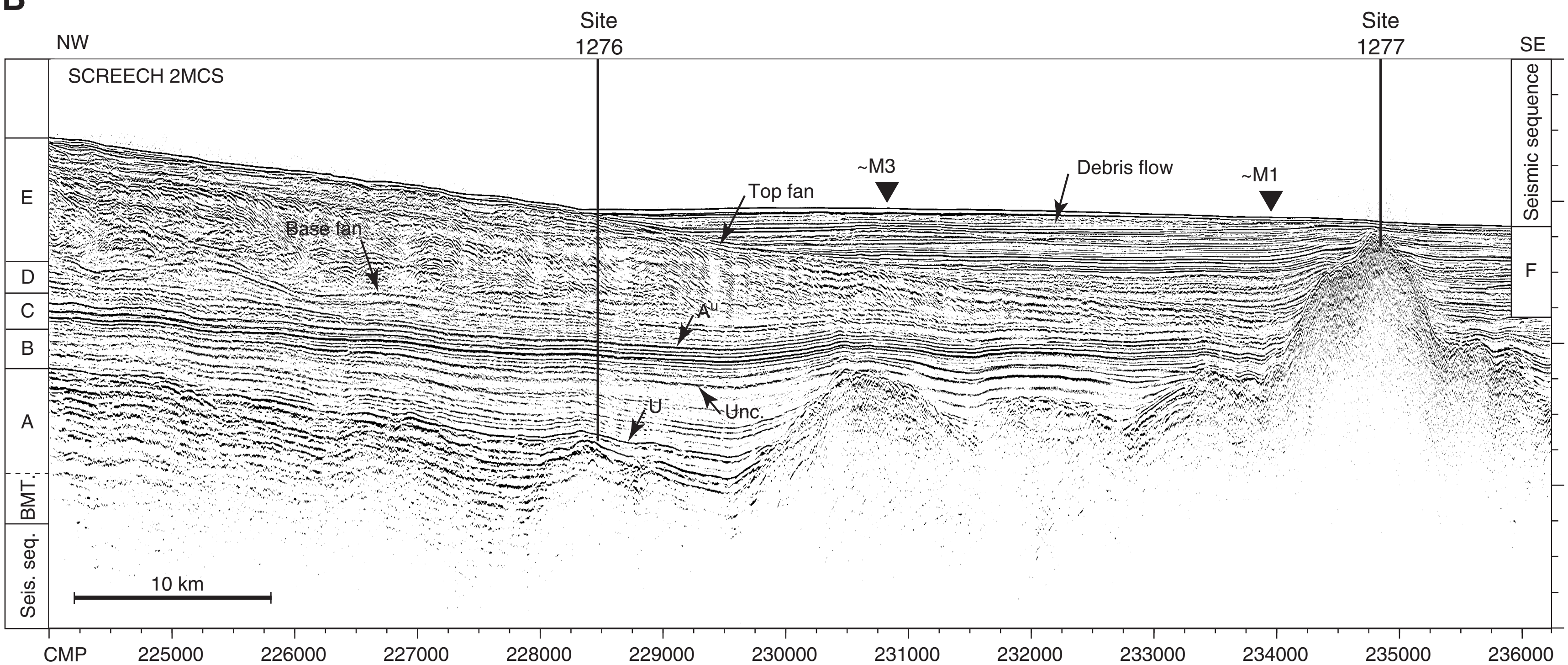

Figure F8 (continued). C. Seaward portion of SCREECH line 2MCS over the abyssal plain, with Horizon A^u and location of Anomaly M0 indicated.

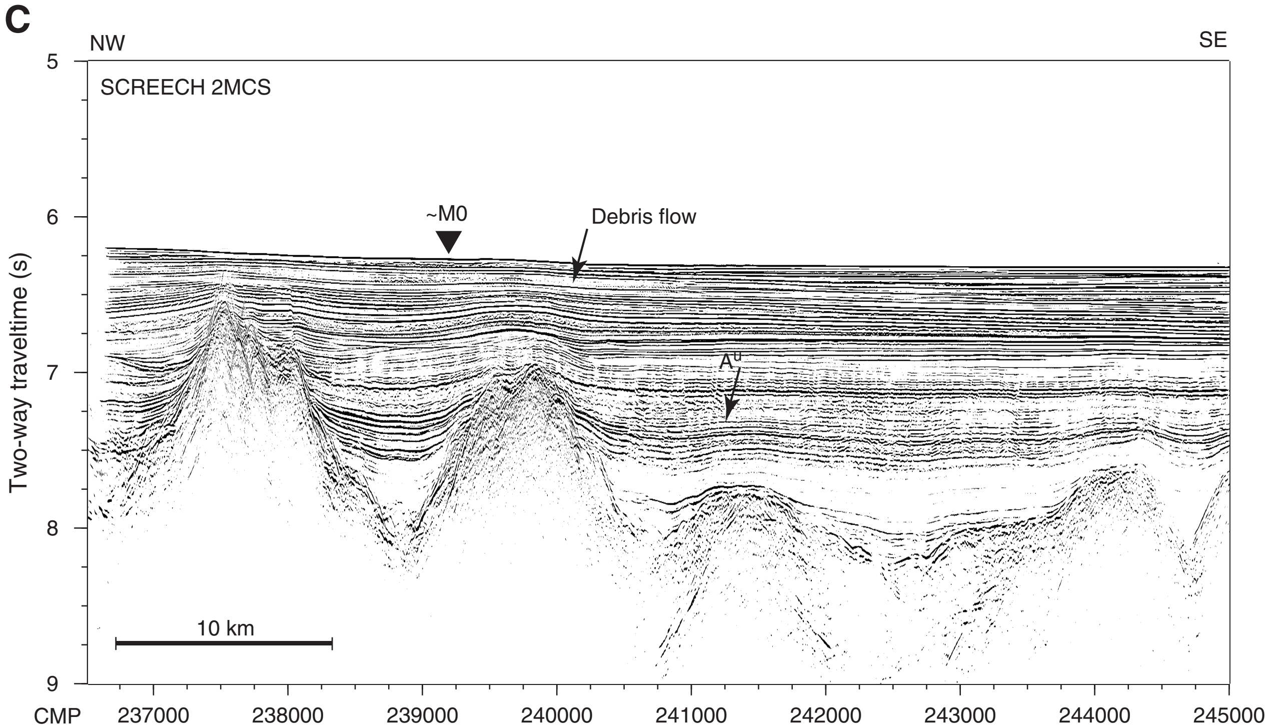

Figure F9. Simplified interpretation of SCREECH line 2MCS across the Newfoundland continental margin, with magnetic anomaly locations of Srivastava et al. (2000) indicated. Line location (transect 2) is shown in Figure F5, p. 45.

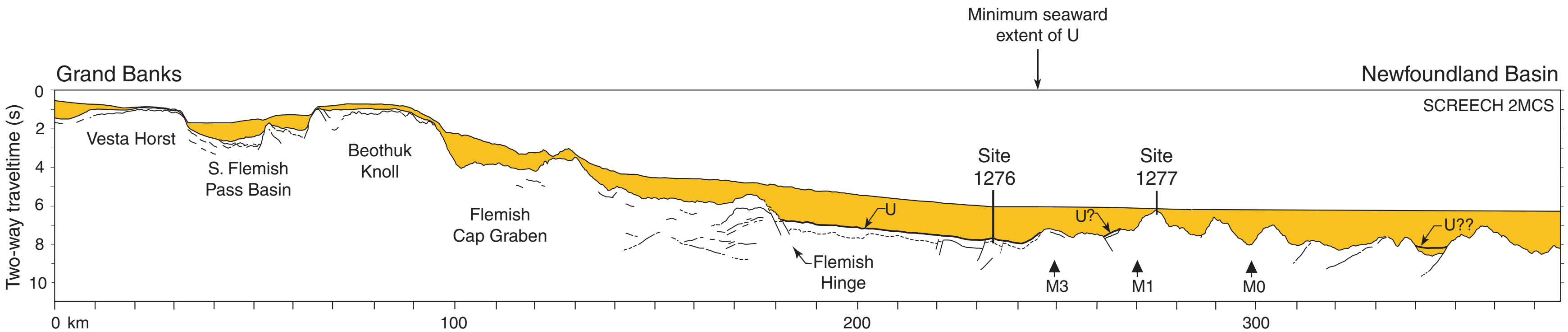

Figure F10. Isopach map of the U–basement interval showing two-way traveltime between the U reflection and basement, based on MCS profiles of the SCREECH survey (*Ewing* cruise 00-07) along transect 2. Locations of Sites 1276 and 1277 are indicated. Note that the deposits below the U reflection fill depressions between basement ridges. Interpretation of the U–basement interval southeast of Site 1277 is tentative; the U reflection cannot be traced continuously to this location from farther west in existing seismic data, and the possible U reflection there is inferred only on the basis of reflection character and depth (see, e.g., Fig. F9, p. 51, for one example of possible occurrence of U in this zone).

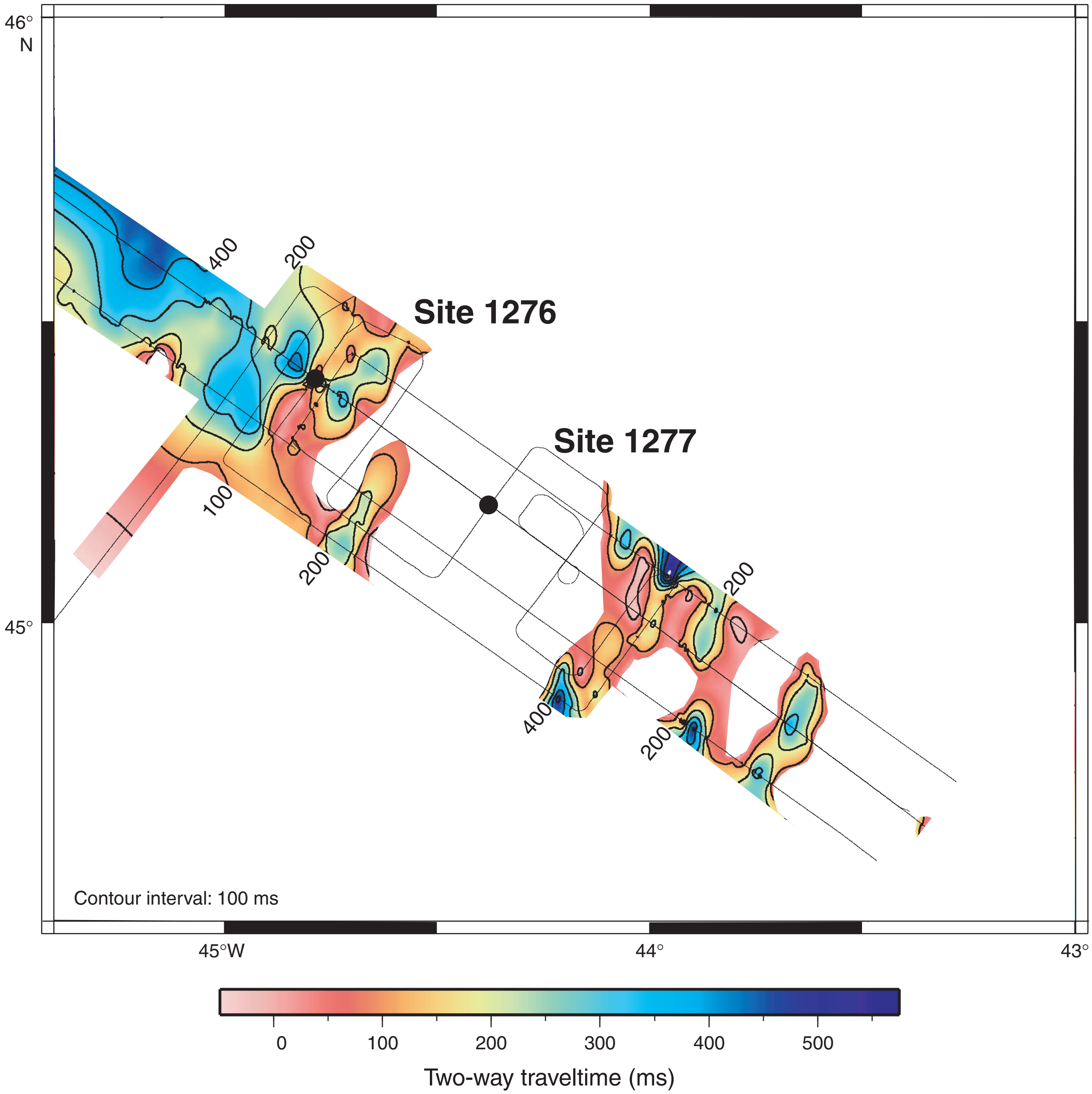

Figure F11. A. Time-migrated SCREECH line 2MCS seismic profile with location of main seismic reflections and location of Site 1276. **B.** Time-migrated IFP-CNEXO seismic profile GP-19 (Bouguigny and Wilm, 1979) with location of main seismic reflections and location of Site 398. CMP = common midpoint.

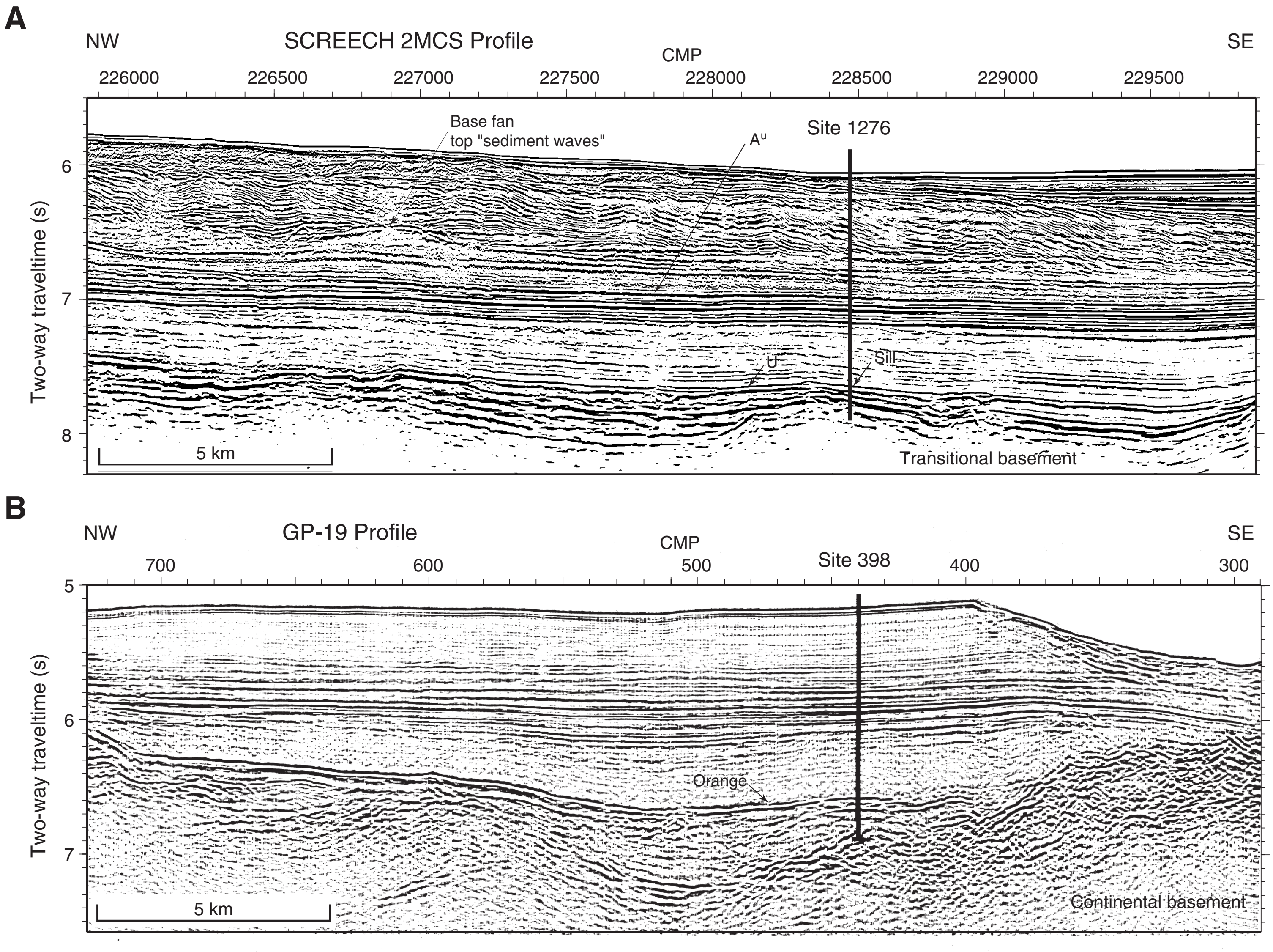

Figure F12. Comparison of seismic sequences and lithologic breaks and age at Site 1276 with those at Site 398 (Shipboard Scientific Party, 1979) (see **"Lithology,"** p. 20, in the "Site 1276" chapter). CMP = common midpoint.

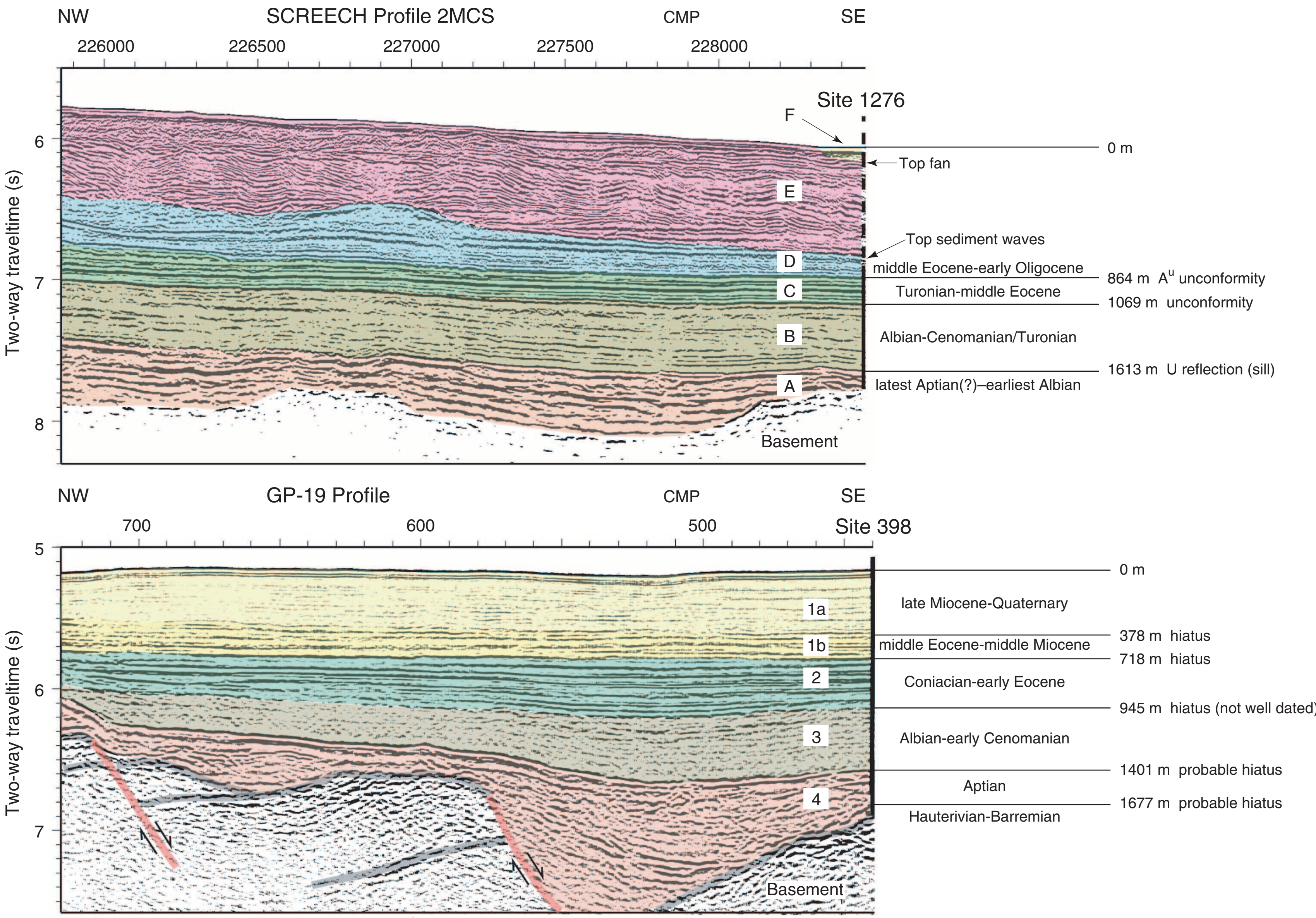

Figure F13. Isopach map of acoustic Unit 4 beneath the orange reflection on the Iberia margin. Sources are (1) the isopach map of acoustic Unit 4 by Réhault and Mauffret (1979) based on seismic data available in 1975; (2) MCS lines acquired in 1997 by the *Maurice Ewing* during the Iberian Seismic Experiment (ISE, Dale Sawyer, Principal Investigator), MCS line IAM 9 (Pickup et al., 1996), and MCS line *Lusigal* 12 (Beslier, 1996); (3) the Iberia Abyssal Plain (IAP) basement map (Shipboard Scientific Party, 1998) compiled from all available seismic data in the IAP; and (4) a detailed bathymetric map of the northeast Atlantic Ocean (Loubrieu et al., 2002). Locations of DSDP and ODP drill sites are shown by solid circles.

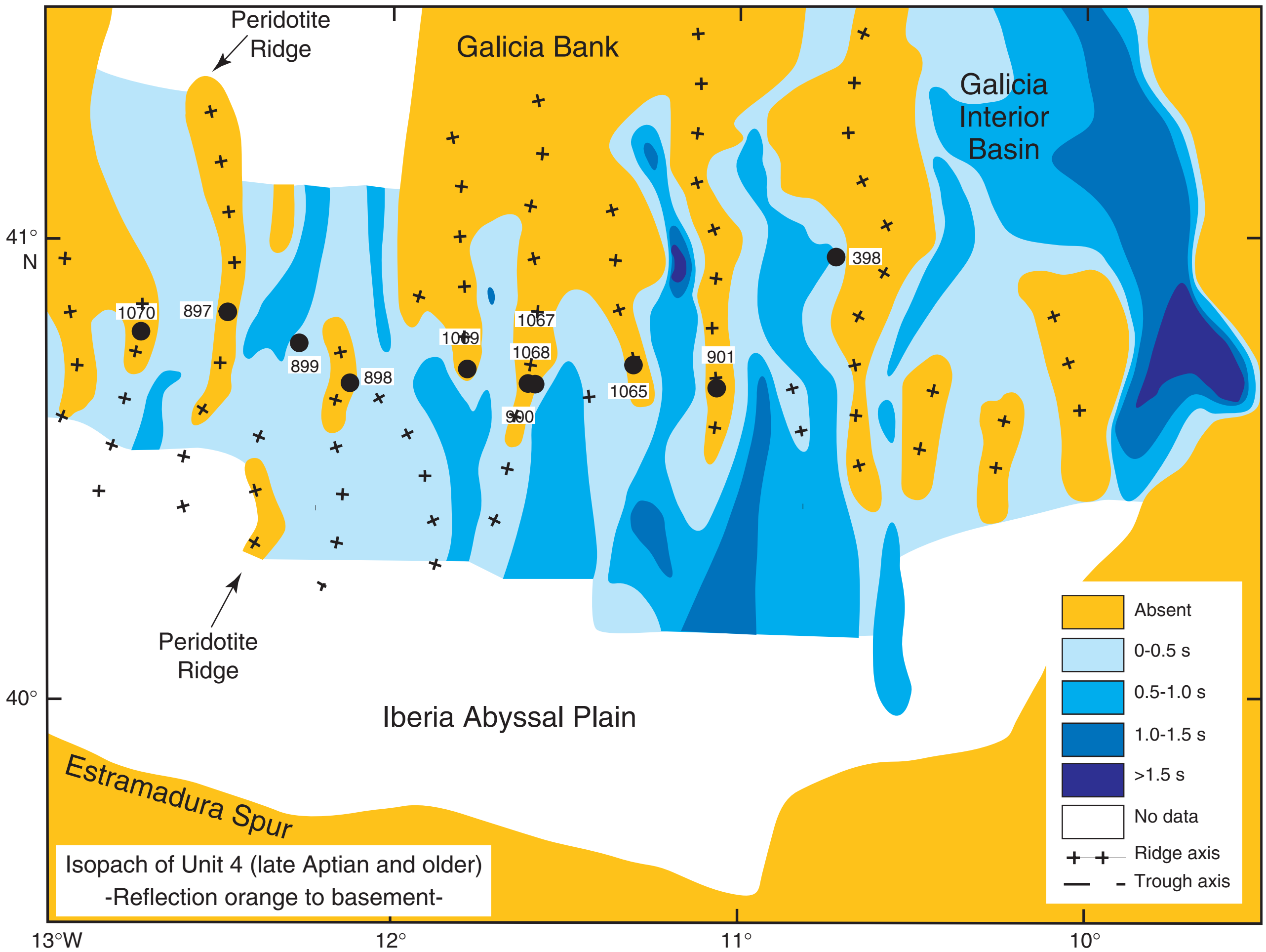

Figure F14. Schematic models to explain observed deep structural asymmetries between the Newfoundland (left) and Iberia (right) transition zones. **A.** Synrift extension of continental crust. In the central part of the rift, lower crust is thinned ductilely (dashes) but brittle upper crust has limited tectonic extension (e.g., Driscoll and Karner, 1998). **B.** Anomaly ~M3; the rift evolves asymmetrically, with a thin remnant of continental crust forming an upper Newfoundland plate, and serpentinized peridotite and remnants of ductilely thinned lower crust forming a lower Iberia plate. Bending stresses could account for faulting in the cold, brittle mantle footwall as it is exhumed on the Iberia side. Differences of basement depth on the two margins reflect buoyancy of thin continental crust (shallow) vs. serpentinized mantle (deep). The U reflection could be a synrift unconformity developed near sea level, basalt flows, or high-velocity sediments (see C and D). MOHO = Mohorovicic discontinuity. (Continued on next page.)

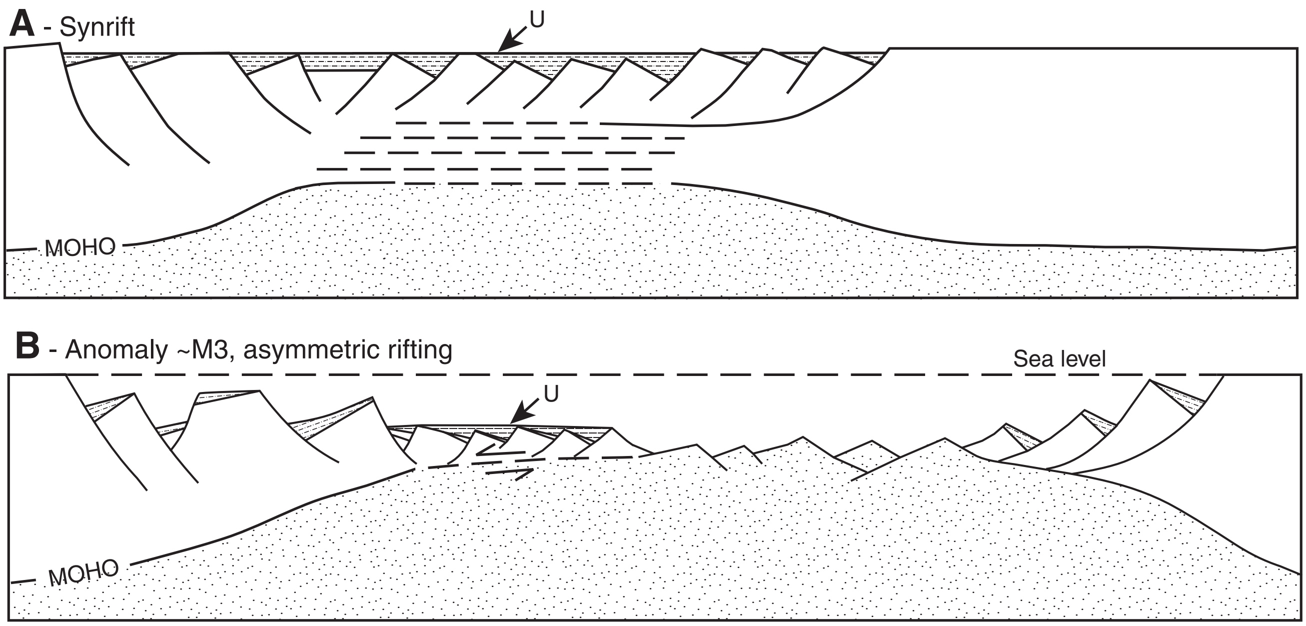

Figure F14 (continued). **C.** Alternate model at Anomaly ~M3; mantle is exposed on both sides of the rift at an early stage, followed by development of an asymmetric shear. Melt extracted from the lower plate may permeate the Newfoundland upper plate and flood its surface to form the U–basement sequence in a submarine setting. Basement depth differences between the two margins reflect buoyancy differences caused by melt intrusion/extrusion on the Newfoundland side. **D.** Second alternate model at Anomaly ~M3, representing ultra-slow seafloor spreading. Symmetrical spreading is unlikely because it would not account for extensive exposure of serpentinized mantle on the Iberia side or asymmetry in basement structure of the transition zones on the two margins. Rather, ocean crust may have formed in the western part of the rift by seafloor spreading after initial exposure of mantle, with the ocean crust subsequently being isolated on the Newfoundland side by a jump of the spreading axis (from a failed rift [FR] eastward to a more central location). The U–basement sequence might be explained by basalt flows capping the ocean crust or as a high-velocity sedimentary sequence. More buoyant Newfoundland ocean crust would be shallower than the serpentinized mantle on the Iberia side, and differences in basement roughness would reflect dissimilar tectonic extension in the two kinds of lithosphere.

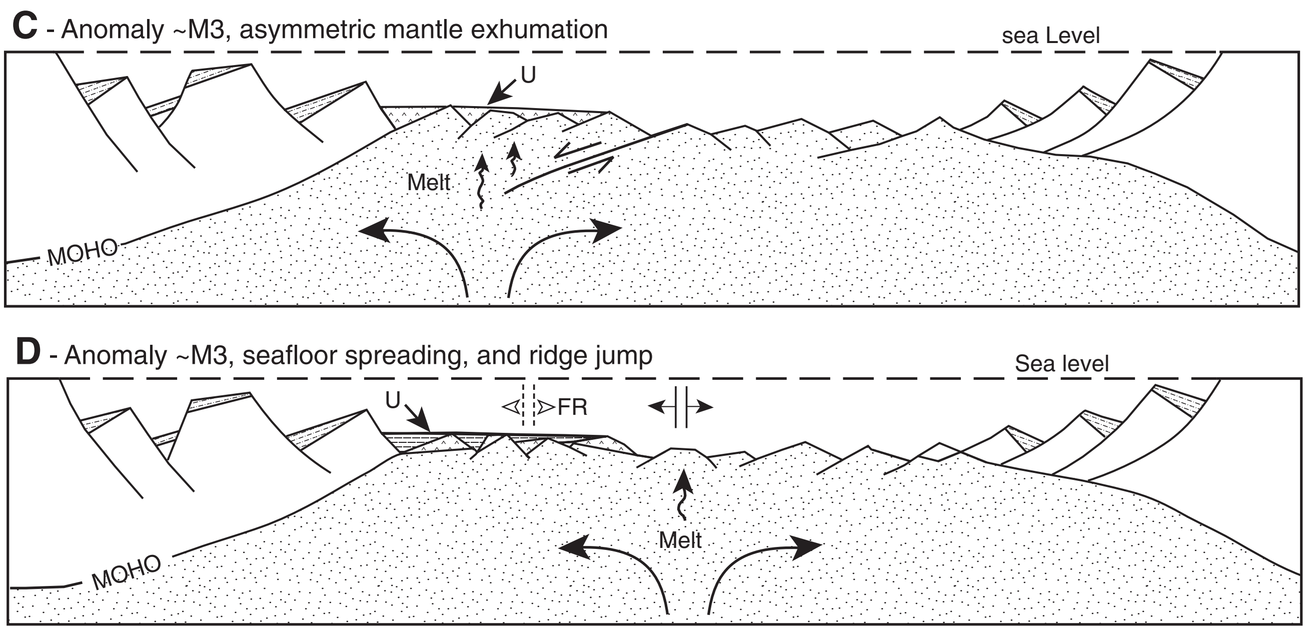

Figure F15. Proposed drilling and casing plan for the deep hole drilled at Site 1276. RCB = rotary core barrel, VSP = vertical seismic profile.

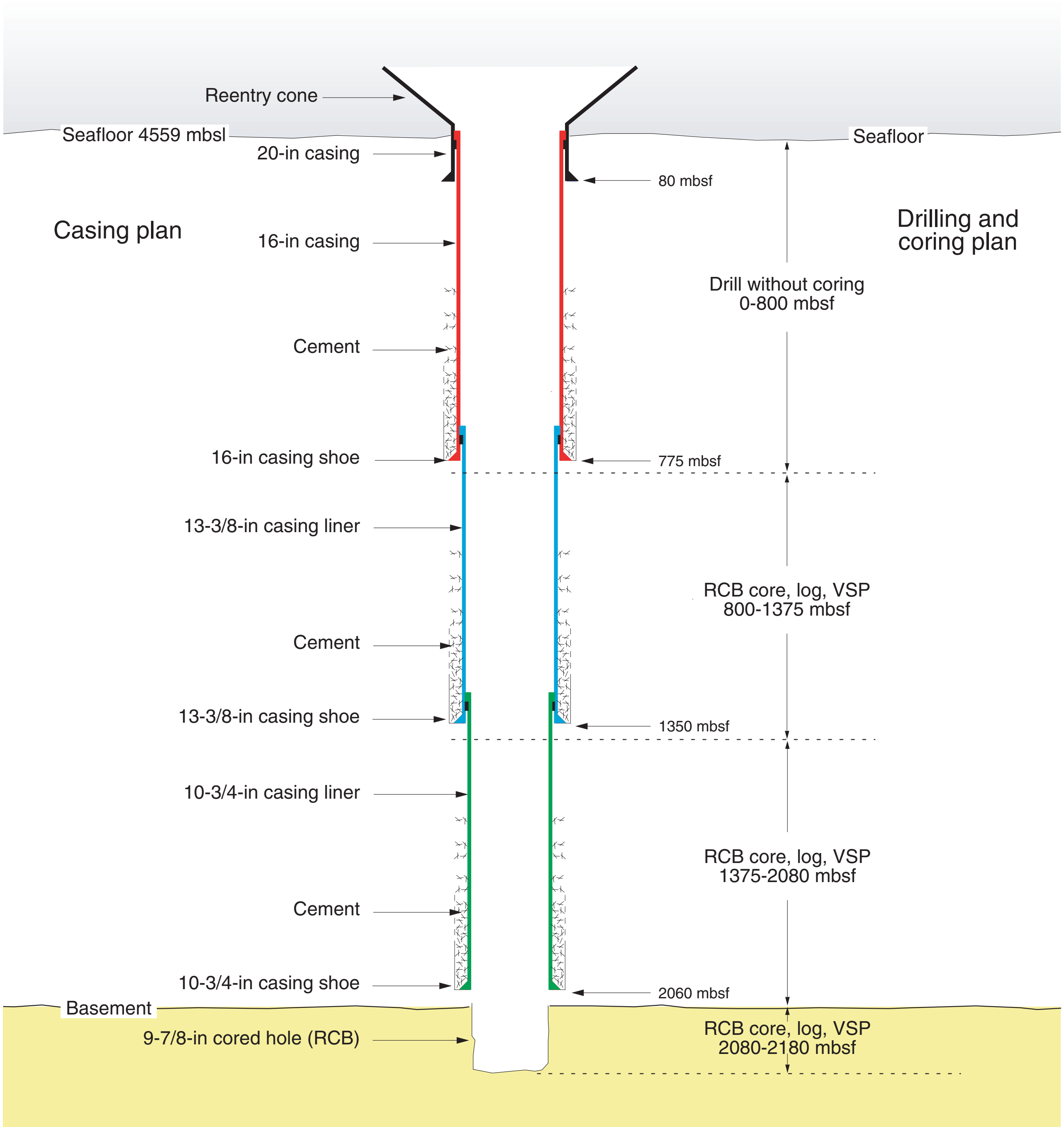

Figure F16. Schematic illustration of actual Site 1276 installation and cored intervals. The depth of the seafloor was determined by observing a reduction in drill string weight, so the seafloor depth of 4549.1 m below sea level is likely deeper than the true sediment/water interface. The exact sediment thickness over the reentry cone is unknown. RCB = rotary core barrel.

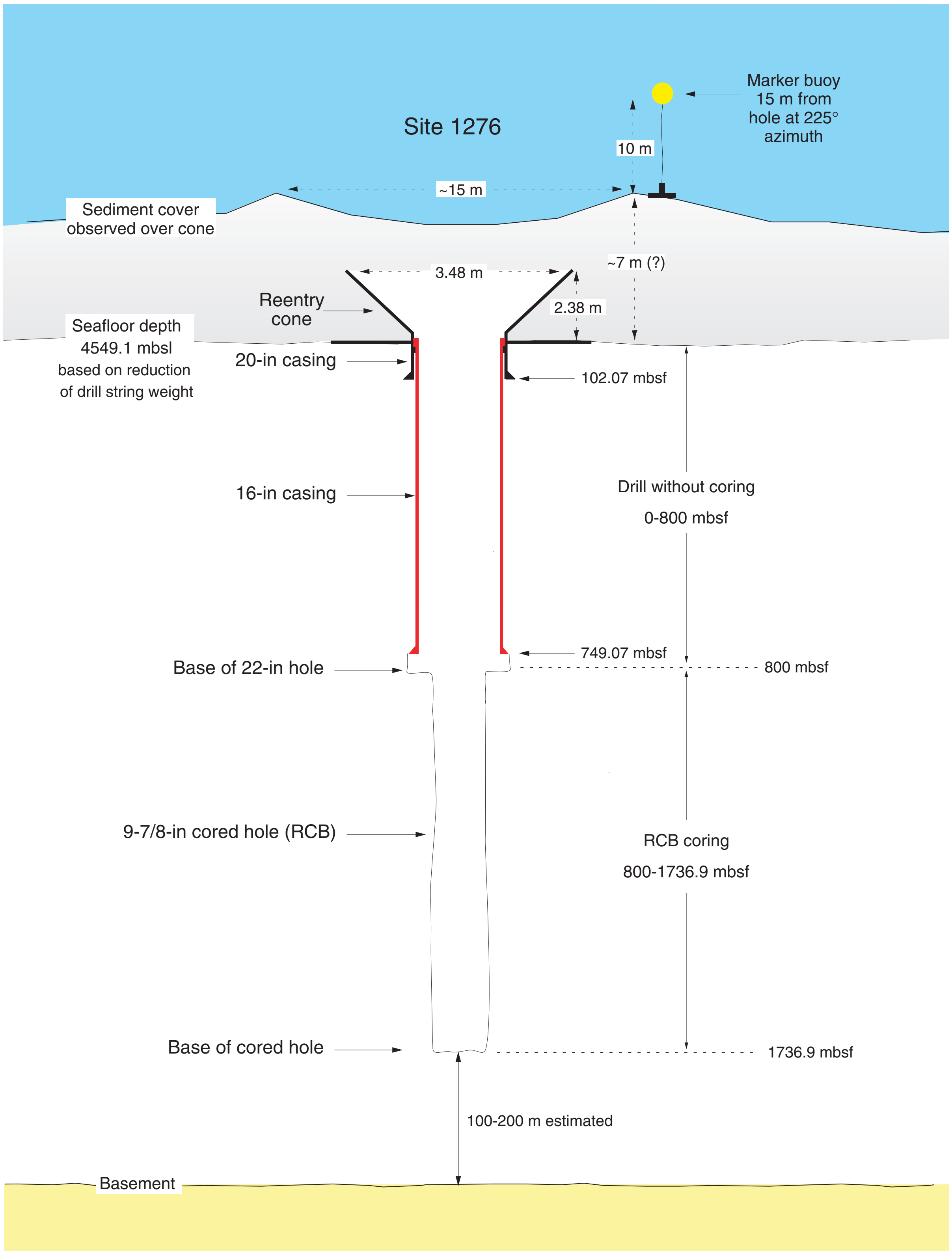

Figure F17. Breakdown of operational activities during Leg 210. ODL = Overseas Drilling Ltd.

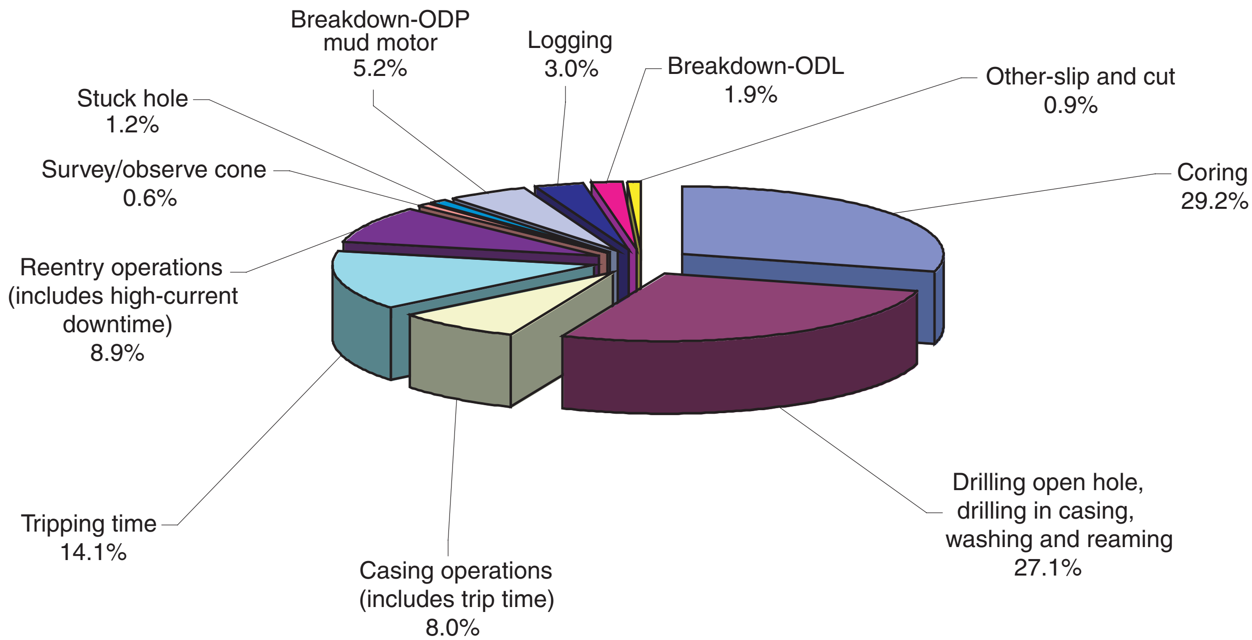

Figure F18. Summary of lithostratigraphic units recognized at Site 1276. Columns show core recovery (solid black boxes), age, and lithology on a core-by-core basis (see separate key), grain size and color variation (pseudoweathering profile and separate color key), and primary characteristics. OAE = Oceanic Anoxic Event.

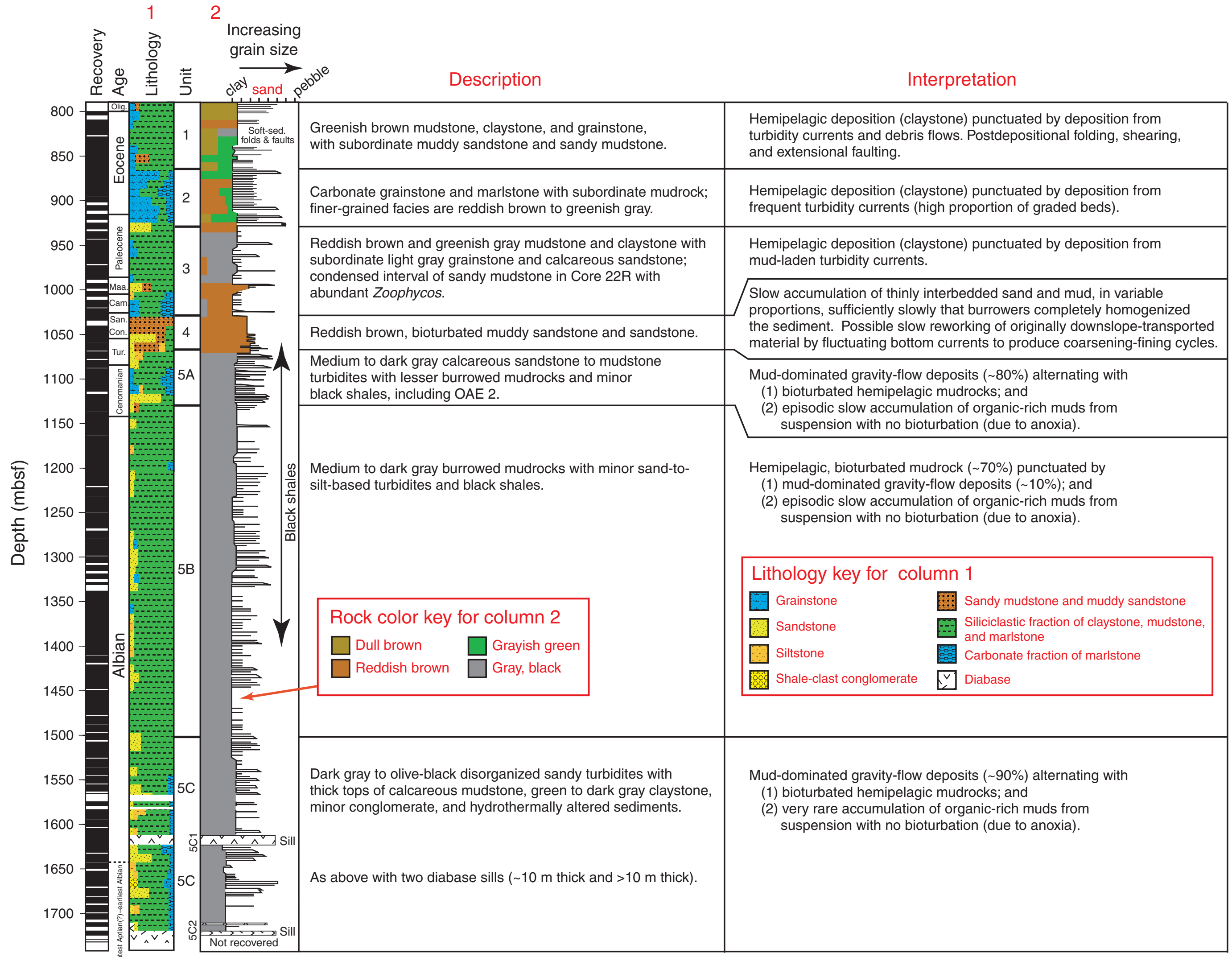

Figure F19. Close-up photograph of typical poorly sorted muddy sandstone of lithologic Unit 4 (interval 210-1276-29R-1, 90–120 cm). Note the intense burrowing and reddish color attributed to well-oxygenated bottom waters.

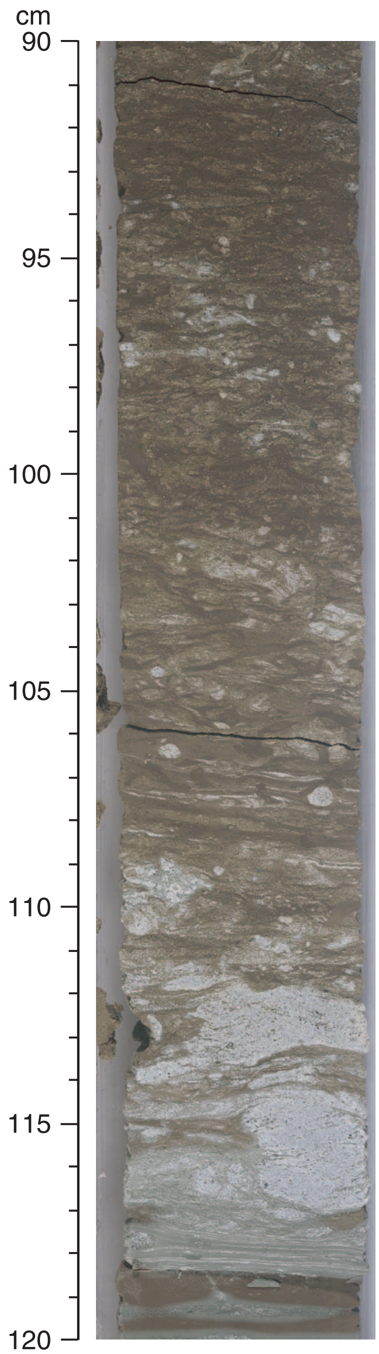

Figure F20. Close-up photograph of massive, poorly sorted grainstone with carbonate granules (mainly bioclasts) and abundant large mud clasts in lithologic Unit 1 (interval 210-1276A-7R-2, 16–40 cm). The sediment has a swirled appearance because of soft-sediment deformation and differential compaction.

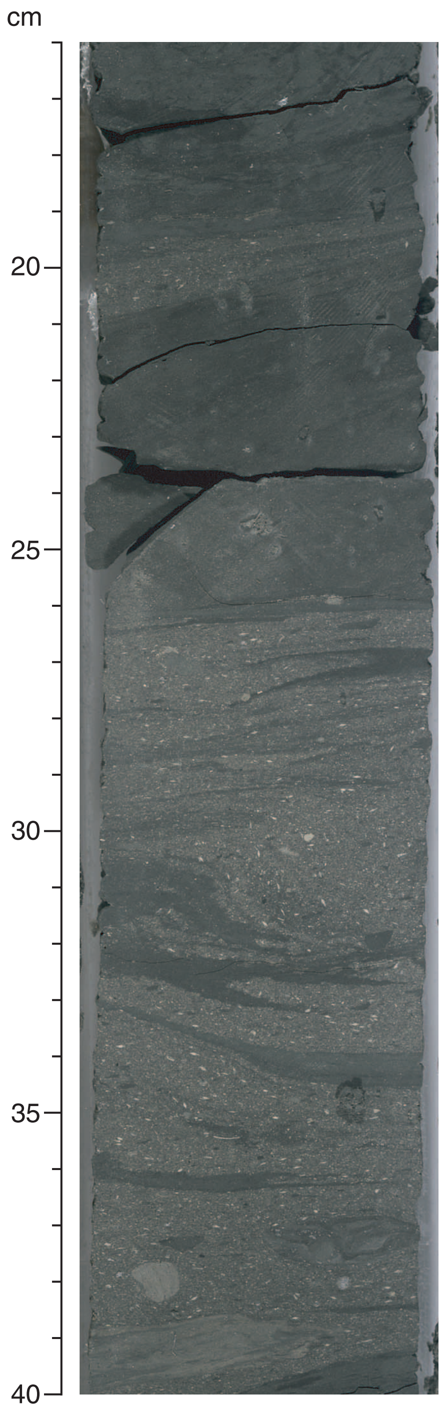

Figure F21. Close-up photograph of central part of a chaotic mud-clast conglomerate in lithologic Subunit 5C (interval 210-1276A-93R-3, 70–97 cm). Note the range in colors of the mudstone clasts and the variety of clast shapes.

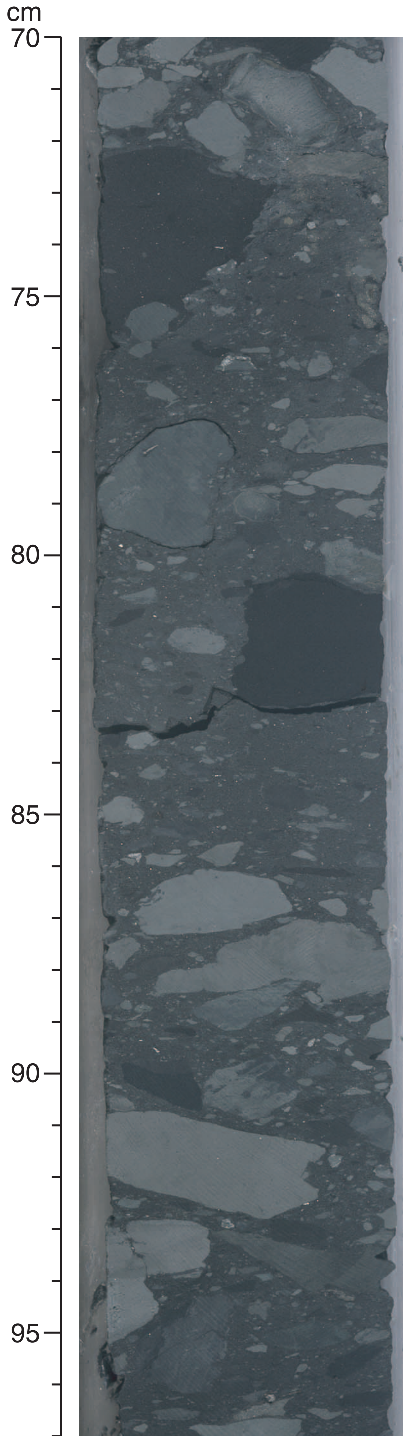

Figure F22. Close-up photograph of an excellent example of repeated graded beds in lithologic Unit 2 (interval 210-1276A-9R-2, 96–120 cm). Note the sharp bases of these turbidites and upward fining into burrowed and laminated intervals.

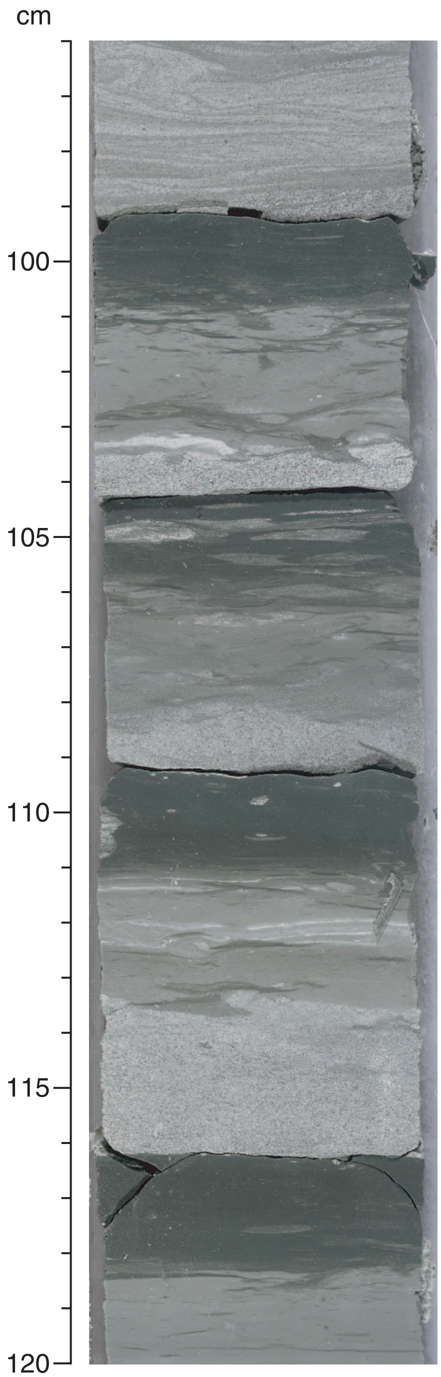

Figure F23. Close-up photograph of planar-laminated carbonate grainstone grading upward into marlstone in lithologic Unit 3 (interval 210-1276A-19R-5, 80–112 cm). Above 99 cm, there are contorted and flattened laminae and pockets of silt that formed when the sediment was in a plastic state.

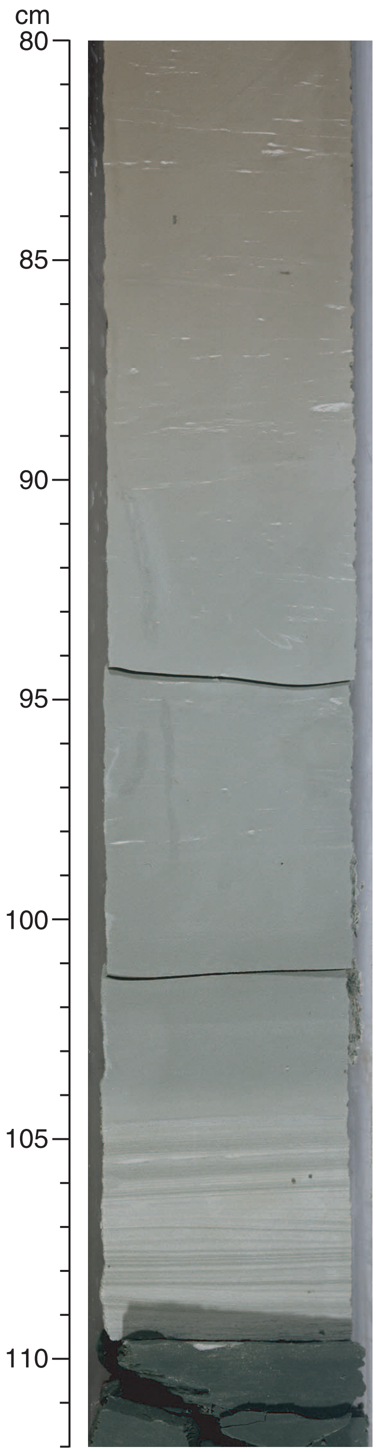

Figure F24. Close-up photograph of middle part of a highly disorganized gravity-flow deposit in lithologic Subunit 5C (interval 210-1276A-89R-6, 81–120 cm). Note the planar lamination (at 104–120 cm) passing upward into a convoluted and swirled interval above 100 cm. Such flow features characterize this lithologic subunit.

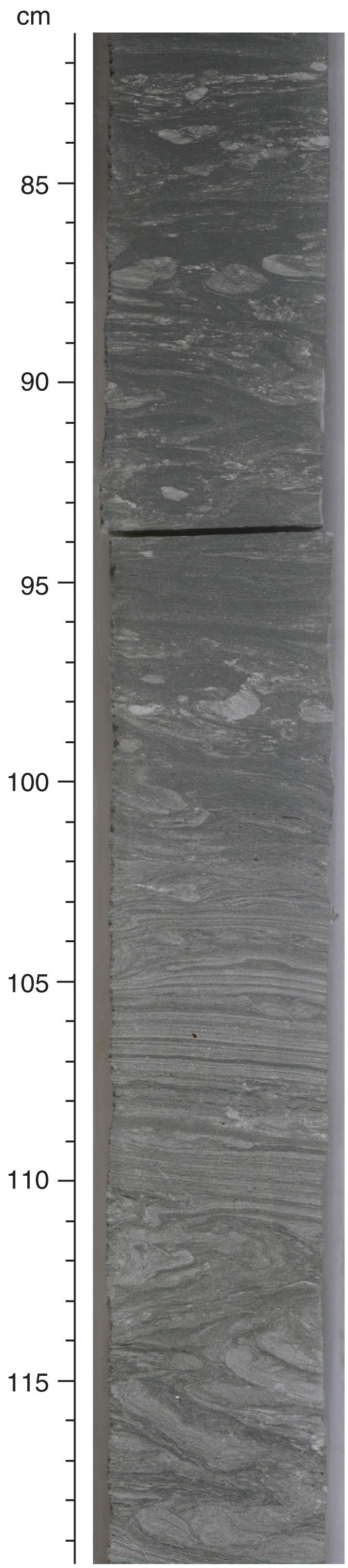

Figure F25. Comparison of (**A**) core photograph and (**B**) computed tomography (CT) scan of a porphyroblastic mudrock formed by thermal and hydrothermal effects of the intrusion of the upper diabase sill in lithologic Subunit 5C (interval 210-1276A-87R-6, 18–26 cm). In A, note the once-straight but now vertically compressed vein. In B, the CT scan is a horizontal slice through a three-dimensional reconstructed image, viewed with IMAGEJ software; note the apparent near-random orientation of the porphyroblasts.

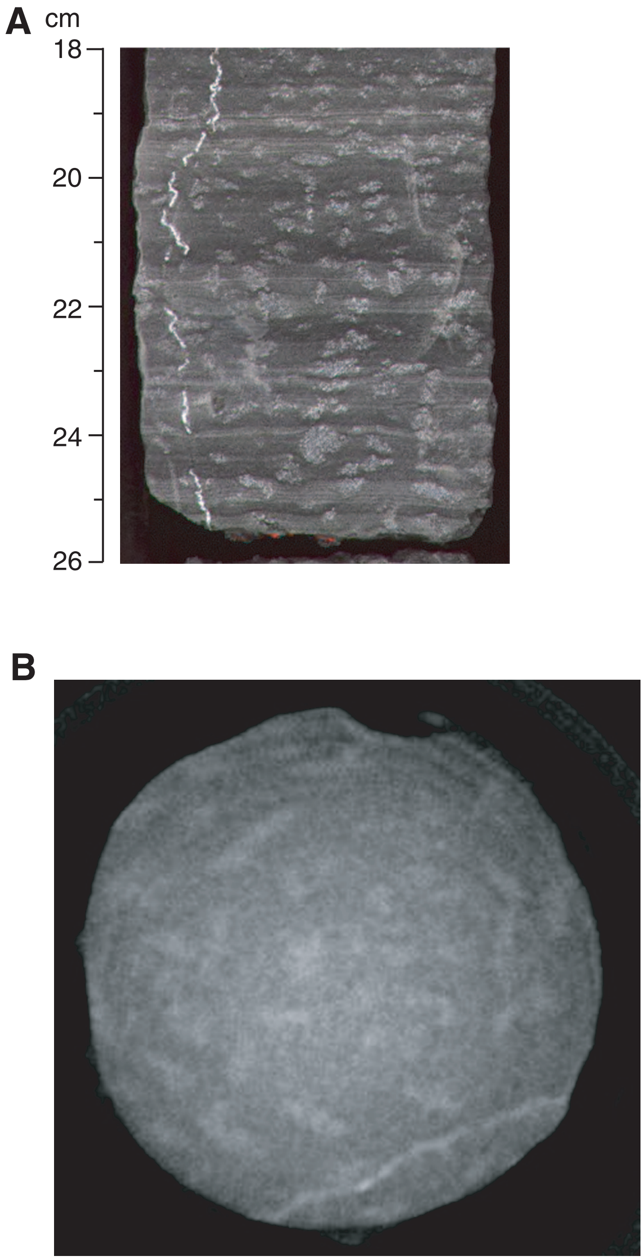

Figure F26. Close-up photograph of very finely laminated black shale with planar siltstone laminae and a small siltstone lens (at 95.5 cm) in lithologic Subunit 5B (interval 210-1276A-43R-2, 86–119 cm).

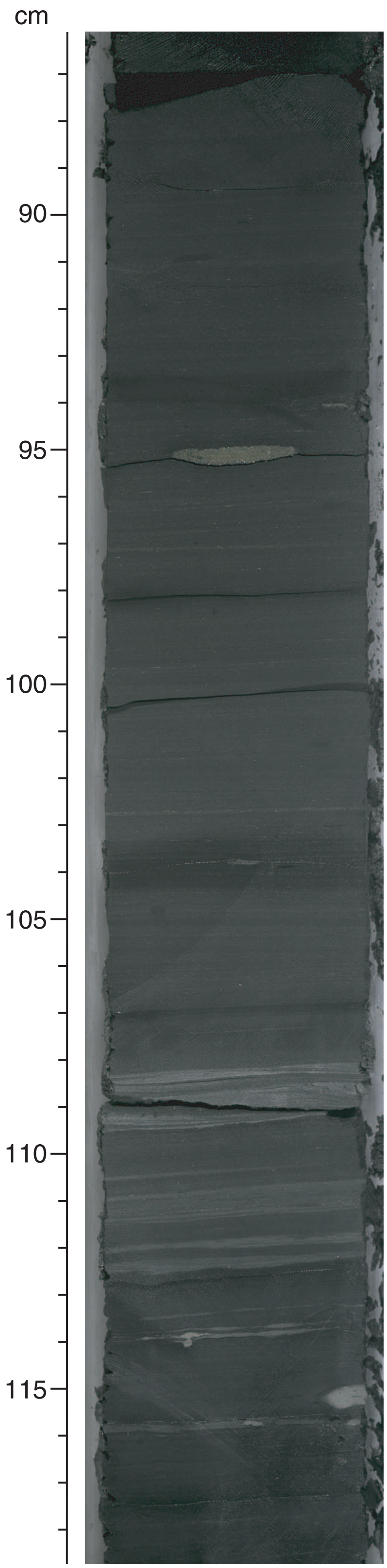

Figure F27. Age-depth plots based on first and last occurrence datums of microfossils at Site 1276 and DSDP Site 398. Dashed lines represent intervals in which no samples were analyzed, age-diagnostic datums are uncertain, or in which samples were found to be barren. Approximate sedimentation rates at Site 1276, based on calcareous nannofossils, are shown in blue, whereas those based on palynomorphs are depicted in red. Datums used to construct age-depth plots at Site 1276 are listed in Table T12, p. 338, in the "Site 1276" chapter; datums used to construct age-depth plots at Site 398 are listed in Table T13, p. 339, in the "Site 1276" chapter.

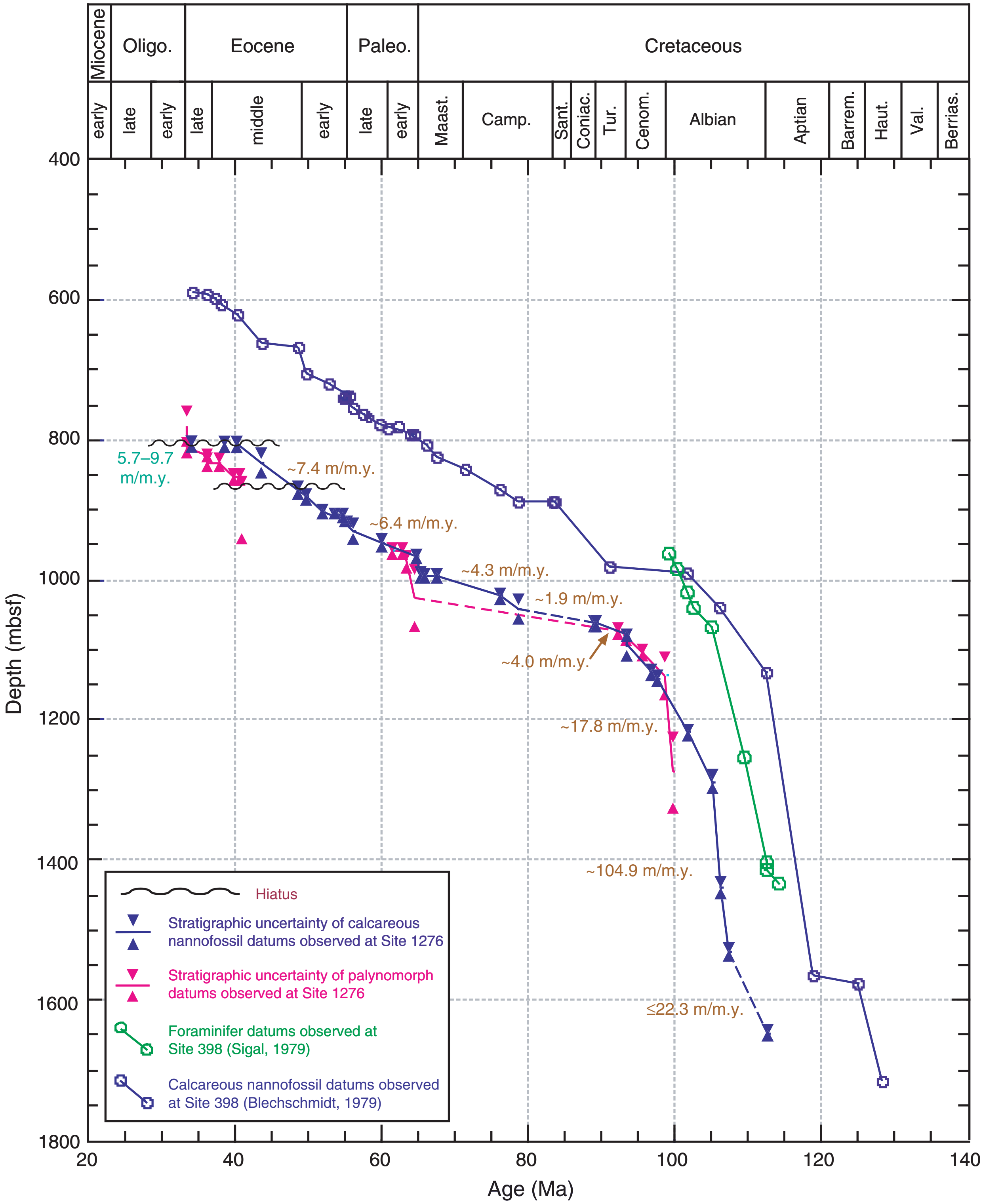

Figure F28. Simplified time-stratigraphic chart comparing the lithostratigraphic successions encountered on the Newfoundland and Iberia conjugate margins. The Iberia margin data are from previous DSDP and ODP volumes, with corresponding lithologic units shown on the left sides of the columns. For comparison, a similar summary of formally defined sedimentary formations is provided (at right) for the geographically separate North American Basin in the western central North Atlantic. Thicknesses of the units are shown on the right sides of the columns. TD = total depth.

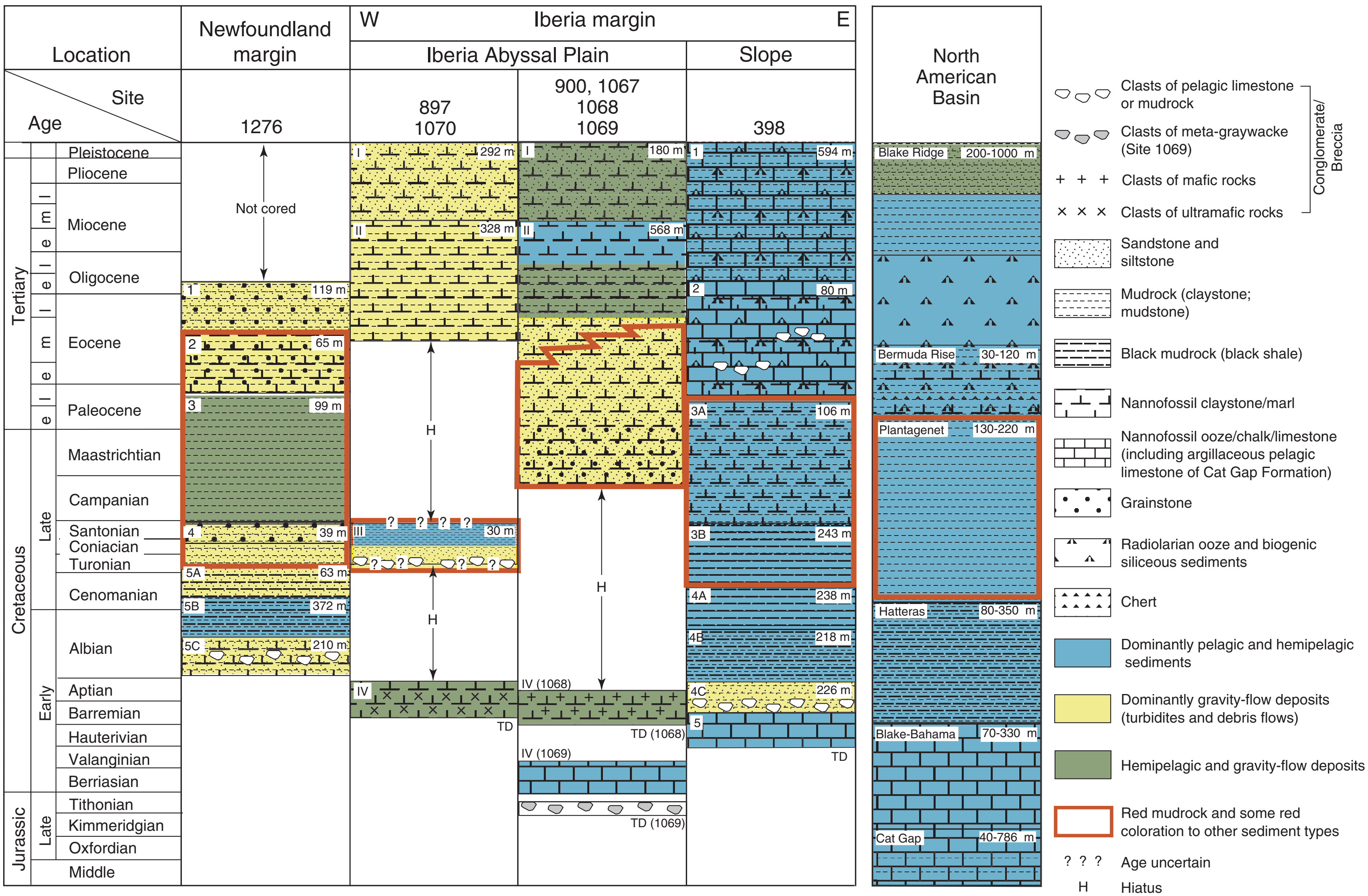

Figure F29. Summary of core recovery and observations of segregation bands, grain size, relative degree of alteration, thin section sample locations, texture, and minerals from X-ray diffraction data for the upper diabase sill at Site 1276. Photomicrographs 2i (Sample 210-1276A-87R-6, 86–89 cm), 13i (Sample 210-1276A-88R-1, 93–95 cm), and 6i (Sample 210-1276A-88R-3, 121–125 cm) show the texture denoted in the texture column. Photomicrograph 4i (Sample 210-1276A-88R-2, 93–96 cm) shows the mineralogical composition and texture of a segregation band. The alteration is shown with gray shades, where dark gray is complete alteration and lighter shades are moderate alteration. The core recovery is shown in red. plag = plagioclase, cpx = clinopyroxene, mag = magnetite.

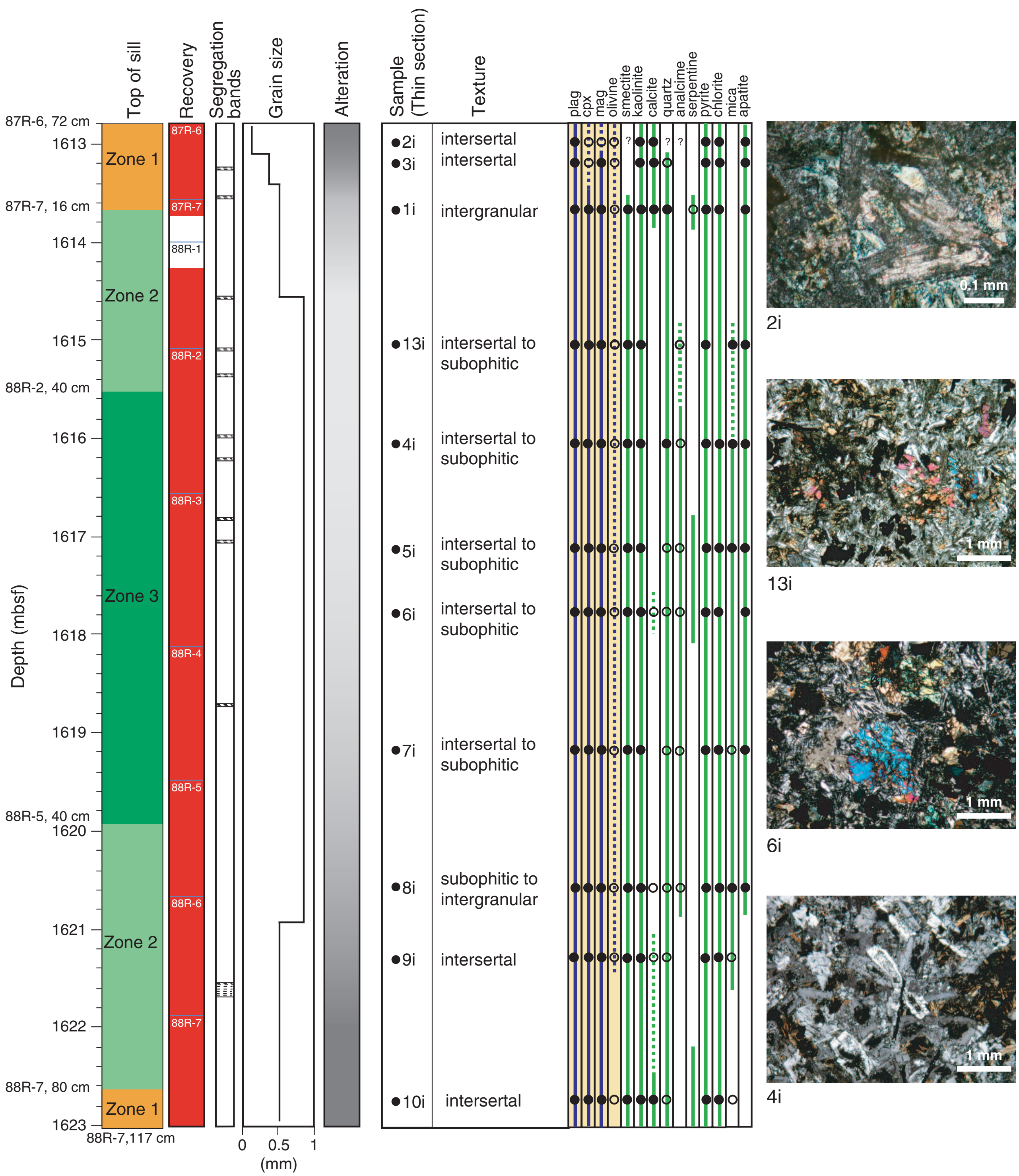

Figure F30. Downhole plots of $CaCO_3$, TOC, C_1 and C_2 concentrations, and C/N ratios, Site 1276. Core lithology and recovery are shown on the left. v. = very, congl. = conglomerate, clayst. = claystone, mudst. = mudstone, marlst. = marlstone.

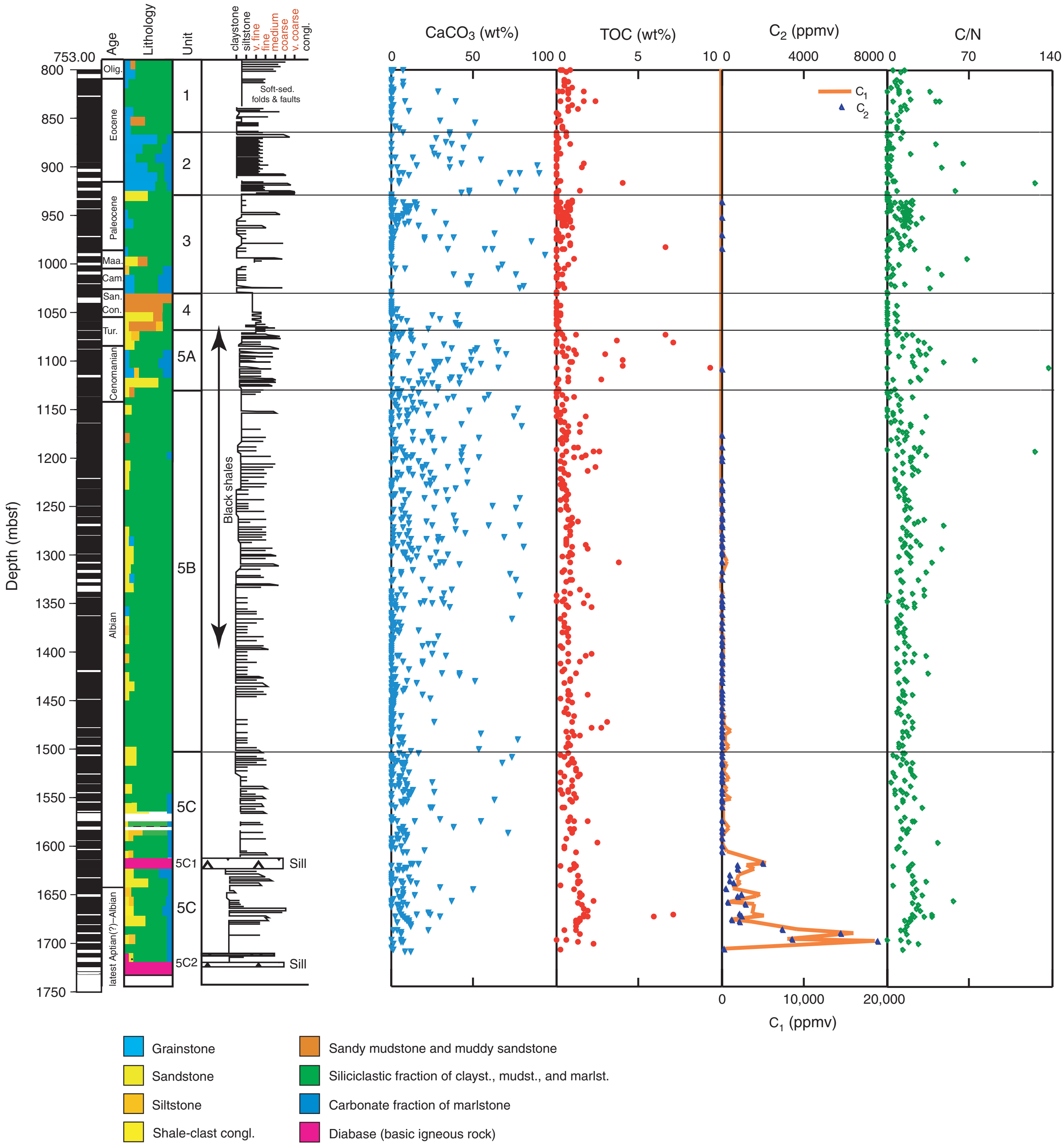

Figure F31. Composite physical property plots of smoothed natural gamma radiation (NGR), vertical (z-direction) compressional wave velocity, bulk density, and porosity plotted against depth for Site 1276. Age, lithology, and grain size are also indicated. Lithology and sedimentary facies keys are shown at bottom. v. = very, congl. = conglomerate, clayst. = claystone, mudst. = mudstone, marlst. = marlstone, ss = sandstone, sts = siltstone.

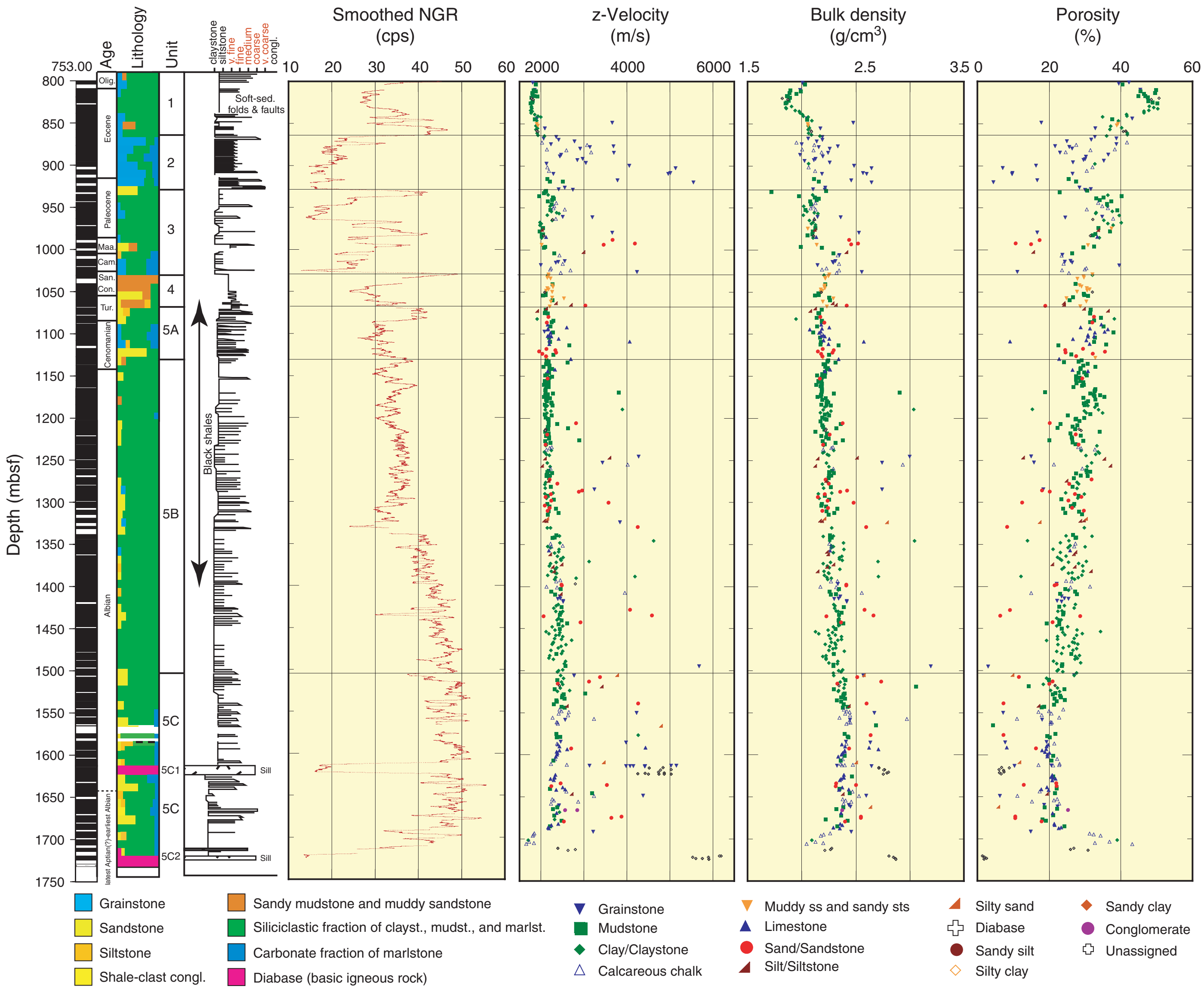

Figure F32. Schematic lithologic column in a "weathering profile" and x-velocity, porosity, and methane (C_1) plots vs. depth for the lowermost 50 m of Site 1276 (1675–1725 mbsf). Right-hand border on the lithologic column indicates relative degree of compaction. Black circles indicate shipboard measurements. Dashed red lines are trend lines for each data set for sediments in lithologic Subunit 5C above the anomalously low velocity, high-porosity sediments. Mudst. = mudstone, calc. = calcareous.

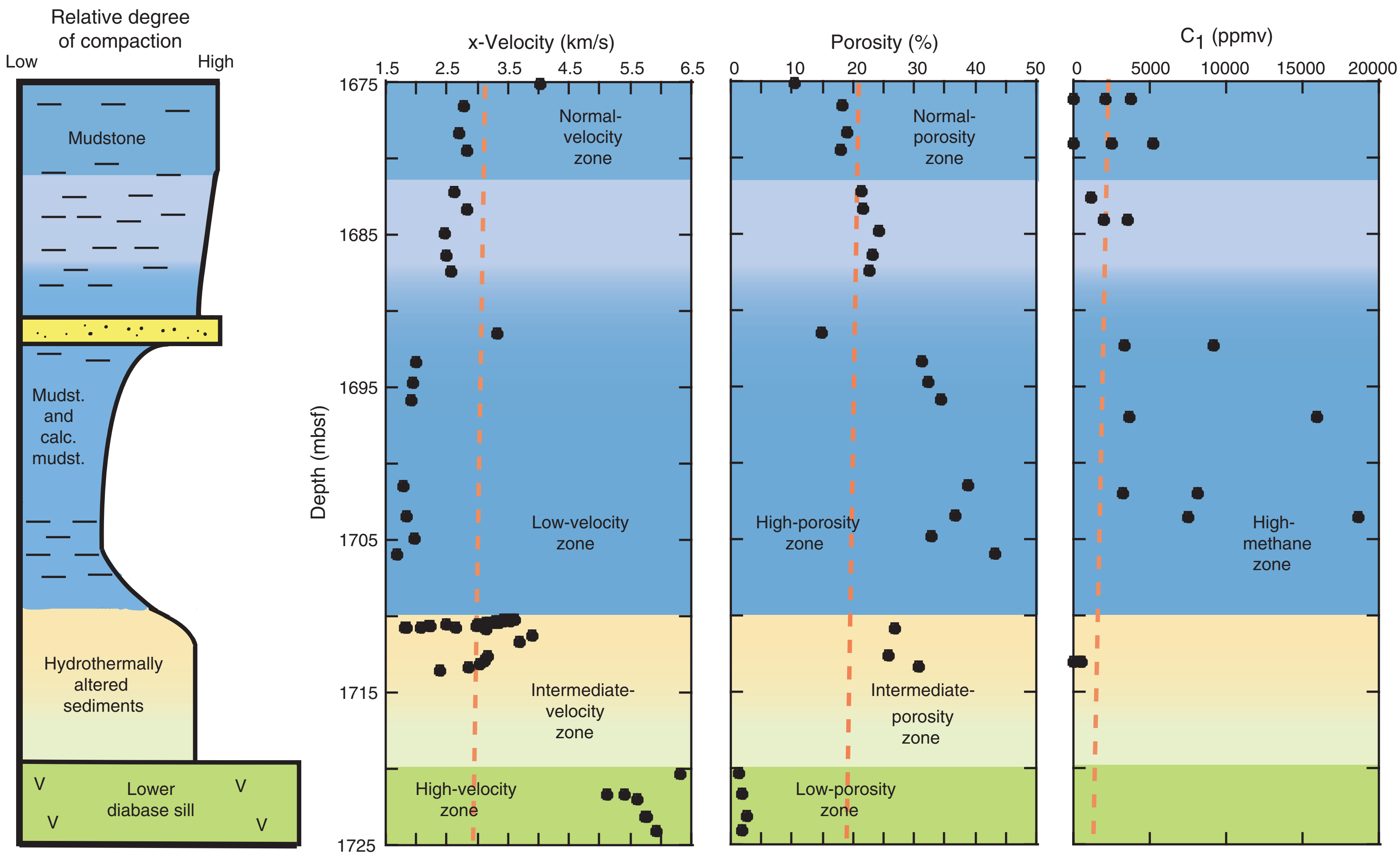

Figure F33. Age-depth plots for Site 398 taken from Shipboard Scientific Party (1979) and simplified for Site 1276 (see Fig. F27, p. 70, for comparison; see also "Biostratigraphy," p. 73, in the "Site 1276" chapter); timescale from Berggren et al. (1995) and Gradstein et al. (1995). Site 398 seismic sequences (numbers) (Shipboard Scientific Party, 1979) and Site 1276 seismic sequences (letters) (see "Seismic Sequences," p. 7, in "Geological Setting") are indicated.

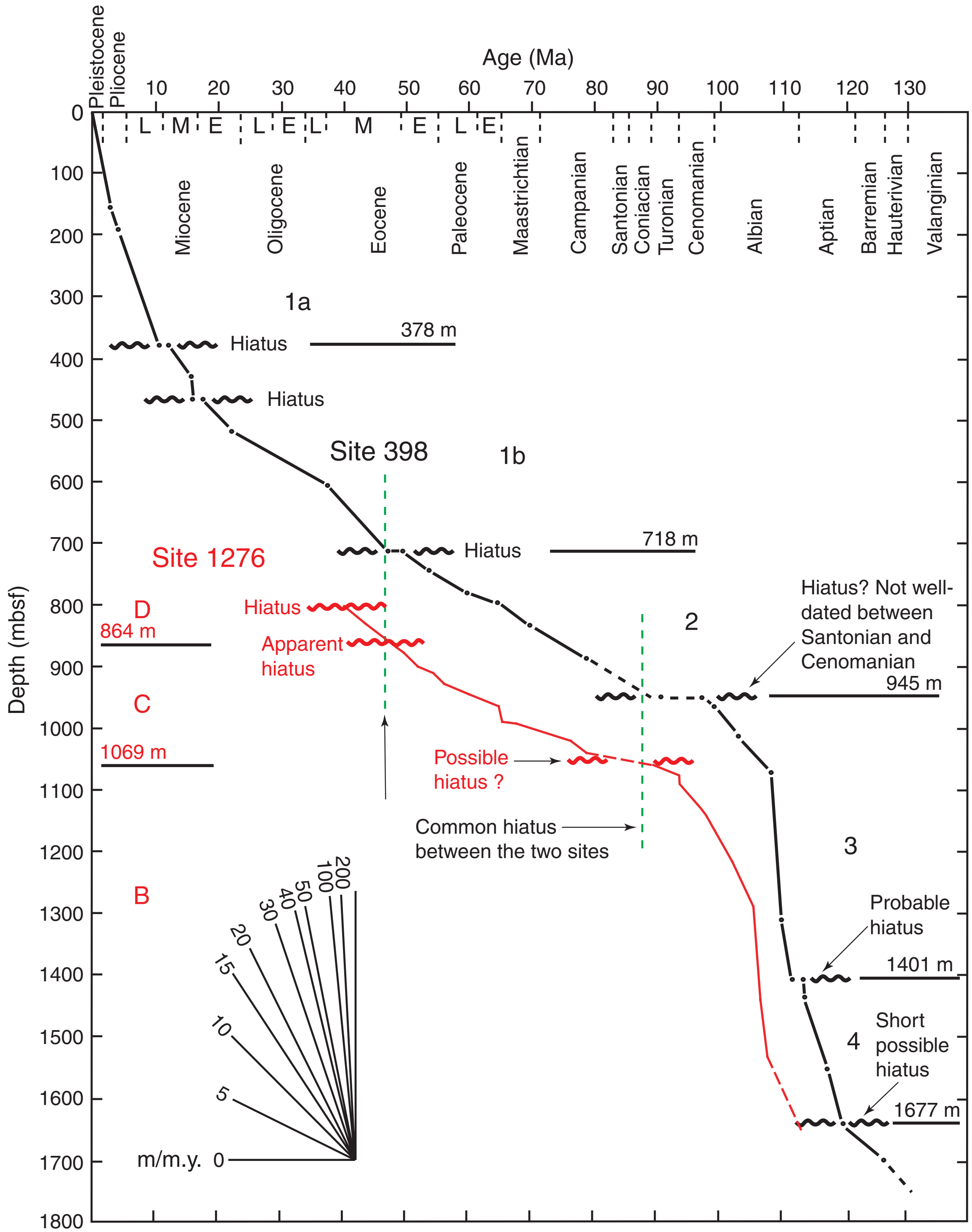

Table T1. Predicted depths of major reflection boundaries at Site 1276 from MCS stacking velocities.

Reflection boundary	Predicted depth (mbsf)	Average interval velocity to overlying boundary (km/s)
Base of turbidites	50	~1.87
Base of fan	711	~1.87
Horizon A^u	966	2.22
Reflection U	1866	2.73
Basement	2080	3.50

Note: MCS = multichannel seismic.

Table T2. Leg 210 drilling and coring summary.

Hole	Latitude	Longitude	Seafloor depth (mbrf)	Number of cores	Interval cored (m)	Core recovered (m)	Recovery (%)	Interval drilled (m)	Total penetration (m)	Time on site (days)
1276A	45°24.3198′N	44°47.1496′W	4560.0	103	936.9	796.72*	85	800.0	1736.9	48.28
1277A	45°11.8002′N	44°25.5999′W	4639.4	8	76.4	29.24†	38	103.9	180.3	2.29
			Leg 210 totals:	111	1013.3	825.96	–	903.9	1917.20	50.57

Note: * = not including 6.37 m from wash Core 210-1276A-1W, † = not including 2.29 m from wash Core 210-1277A-1W.