Basalt sills of the U reflector, Newfoundland Basin: A serendipitous dating technique

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ABSTRACT

High core recovery at Ocean Drilling Program (ODP) Leg 210, Site 1276, provided a high-resolution porosity-depth relationship and an equally impressive age-depth model based on first and last occurrences of microfossils. Site 1276 was drilled over transitional crust in the Newfoundland nonvolcanic margin, offshore Canada, between known continental crust on the west and apparent oceanic crust on the east as identified by seafloor-spreading magnetic anomalies M3 to M0 (Barremian–Aptian, 129.8–124.8 Ma). At Site 1276, two diabase sills were drilled at depths equivalent to the U reflection, a bright reflection that overlies transitional crust interpreted from seismic reflection profiles throughout the Newfoundland Basin. The sills were emplaced within uppermost Aptian fine- to coarse-grained sediments, 100–200 m above basement as estimated from seismic reflection data. Magma emplacement occurred at shallow levels within the sediment column, as evidenced by: (1) the occurrence of vesicles in the sill, and (2) compaction-induced folding of calcite veins that were emplaced near vertically in the sediments and are assumed to be coeval with the intrusion. By calculating the degree of shortening of the calcite veins and determining the reconstructed porosity of the sediments during vein emplacement, the age of magma emplacement can be deduced. From the porosity-age curve, the age of sill emplacement is estimated to be 82.5–109.1 Ma, consistent with recent $^{40}Ar/^{39}Ar$ radiometric dating of the upper sill that gave ages of 105.95 ± 1.78 Ma and 104.7 ± 1.7 Ma. The source of magmatism responsible for the diabase sills is necessarily postrift, and the sills are temporally equivalent to alkali basalts dredged from the Newfoundland Seamounts. The simplest explanation for the Site 1276 diabases and the widespread distribution of the U reflection relates to the migration of the Azores, Madeira, and Canary plumes across the Newfoundland Basin between 80 and 120 Ma.

Keywords: Newfoundland Basin extension, early postrift magmatism, Ocean Drilling Program, compaction.

INTRODUCTION

During 6 July to 6 September 2003, Ocean Drilling Program (ODP) Leg 210, the final leg of the program, was devoted to studying the rift and postrift sedimentation histories in the Newfoundland-Iberia rift (Fig. 1). Drilling was conducted in the Newfoundland Basin along a transect conjugate to previous drilling on the Iberia margin (Legs 149 and 173). The prime site of Leg 210, Site 1276, was drilled above transitional crust between known continental crust on the west and apparent oceanic crust on the east as identified by magnetic anomalies M3 to M0 (Barremian–Aptian, 129.8–124.8 Ma). One of the primary scientific objectives of Leg 210 was to determine the origin of the U reflection, a strong, laterally uniform reflection mapped throughout the deep Newfoundland Basin in multichannel seismic reflection profiles (red arrows; Fig. 1B). The U reflection is observed ~600 km south to north in the basin and as much as ~150 km across the zone of transitional crust. 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, the U reflection normally pinches out on crust of about magnetic anomaly M3 age (early Barremian, 129.8–127.8 Ma).

Previous seismic stratigraphic correlations suggested that the U reflection might correspond to the Albian-Aptian boundary, and some researchers identified U as a candidate for the breakup unconformity (e.g., Tucholke et al., 1989). However, at Site 1276, drilling reached depths equivalent to the U reflection where two diabase sills separated by sediments with normal densities (2400 kg/m^3) and sediments with exceptionally low densities (2100 kg/m^3) were recovered (Tucholke et al., 2004). Knowing the age of the sills is crucial for understanding the tectonic significance of U for both the synrift and postrift evolution of the margin, particularly because the Newfoundland-Iberia margin system is traditionally classified as nonvolcanic. Nonvolcanic rifted margins are produced by rifting and are not accompanied by significant magmatism, which is in contrast to the voluminous magmatism that commonly masks extensional structures on volcanic margins (e.g., Louden and Chian, 1999).

The Site 1276 diabase sills were emplaced within uppermost Aptian fine- to coarse-grained sediments, 100–200 m above basement as estimated from seismic reflection data (Fig. 2; Tucholke et al., 2004). The upper sill (1612.72 m below seafloor [mbsf]; Unit 5C1) is ~10 m thick, while the lower sill (1703.5 mbsf; Unit 5C2) was not fully penetrated—the minimum thickness of the lower sill is ~28.6 m. Magma emplacement occurred soon after sediment deposition and at a very shallow level beneath the seafloor, as evidenced by: (1) the occurrence of vesicles in the upper sill, and (2) compaction-induced folding of calcite veins that were emplaced near vertically in the sediments, probably at the time of intrusion (Tucholke et al., 2004).

An excellent physical property data set measured at Site 1276 facilitated by high core recovery provided a well-defined porosity-depth relationship (Tucholke et al., 2004). Similarly, calcareous nannofossil and dinoflagellate cyst data provided excellent biostratigraphic control to define an age-depth curve for Site 1276 (Tucholke et al., 2004). An age-porosity relationship can be constructed by cross correlation. The purpose of this paper is to take advantage of a serendipitous situation in which we measure the present-day porosity of a porphyroblastic mudstone containing shortened calcite veins, estimate the amount of shortening by integrating the length of the calcite folds, and thus estimate the porosity of the sediment during vein emplacement. Assuming that the veining is synchronous with the magmatic activity responsible for emplacing the upper diabase, the age-porosity relationship can be used to infer the age of magma emplacement. This method could provide ages elsewhere where radiometric ages are not possible due to alteration.

Site 1276 Porosity Measurements and Age Determinations

Coring at Site 1276 started at ~800 mbsf. Recovery was excellent throughout the cored interval, from 800 to 1739 m, averaging 85% and approaching 100% for many cores, resulting in an excellent physical property data set (Fig. 2). Five lithologic units were recog-

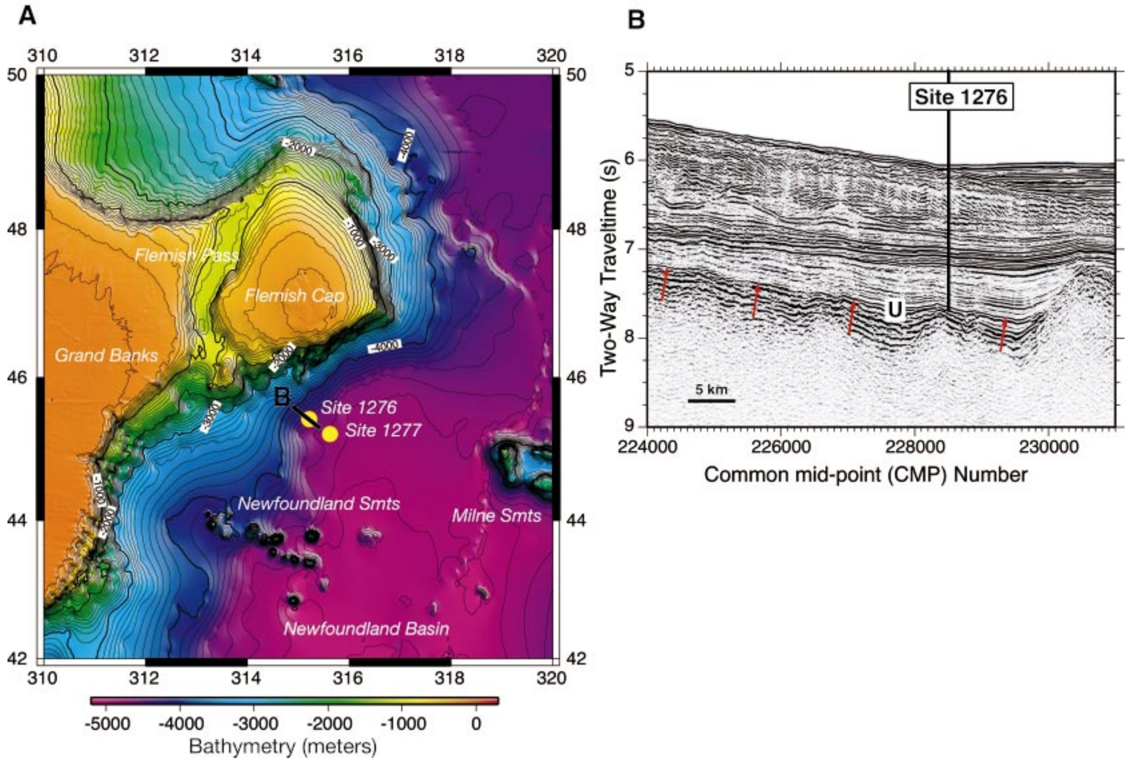

Figure 1. A: Bathymetric map of North Atlantic Ocean (Intergovernmental Oceanographic Commission, International Hydrographic Organization, and British Oceanographic Data Centre, 2003) showing locations of Ocean Drilling Program (ODP) Leg 210, Sites 1276 and 1277, in Newfoundland Basin. B: Time-migrated multichannel seismic profile (Line 2; Shillington et al., 2004) showing character and regional distribution of U reflection (red arrows) and location of ODP Site 1276. Mapping Software of Wessel and Smith (1995) used.

nized, ranging in age from uppermost Aptian to Eocene. The general porosity in lithologic Units 1 and 2 decreases steeply from ~47% ± 10% at the top of Unit 1 to 30% ± 10% at the base of Unit 2. The general trend of porosity in lithologic Units 3 and 4 and Subunits 5A and 5B decreases less steeply, from ~35% ± 10% at the top to 23% ± 10% at the base. The porosity in lithologic Subunit 5C is roughly uniform at 20% ± 10%. In lithologic Unit 2 through Subunit 5C, ~10% of the samples, which are randomly distributed through the interval, have porosities as much as 20% lower than the general trend. These low porosities are associated with thin zones of carbonate/siderite concretions or from well-lithified carbonate cemented sandstones (Tucholke et al., 2004) and are not included in the porosity-depth plot shown in Figure 2A.

From 1690 to 1710 mbsf, mudstones and calcareous mudstones have unusually high porosities (27%–43%) and low velocities (1690–1960 m/s) for their depth of burial (Tucholke et al., 2004). The porosity, velocity, density, and apparent plasticity of these mudstones are comparable to those of normally compacted sediments recovered higher in the section from 840 to 1020 mbsf, demonstrating that these sediments are significantly undercompacted (but normally pressured) with respect to their depth. It would seem that the bounding sills prevented the intervening sediment from compacting normally and expelling pore fluids.

The downhole porosity trend results from the progressive mechanical reduction of void space with increasing burial depth. Porosity behavior as a function of depth is often described in terms of Athy's law (Athy, 1930). This empirical law presumes a negative exponential relationship between depth and porosity:

$$\Phi(z) = \Phi_o \exp(-kz), \quad (1)$$

where $\Phi(z)$ is the porosity as a function of depth z, Φ_o is the surface porosity, and k controls the rate of decay of porosity with depth. A linear regression of $\ln[\Phi(z)]$ vs. z can be used to estimate the natural logarithm of Φ_o and k. Using only the measured porosity-depth data for claystones, mudstones, and siltstones, which form the majority of the recovered core from Site 1276, gave an initial porosity Φ_o and k of 79% and 1.177 km^{-1}, respectively (Fig. 2A). Porosities from the undercompacted section between the diabase sills are not included in this analysis because these sediments have very different compaction histories. The functional relationship between porosity and depth is represented by the least-squares fit to the data (Fig. 2A), the differences between the observations and the least-squares fit having a standard deviation of ±4.1%.

While Athy's law was used to describe statistically how porosity changes with depth, any of the more sophisticated quantitative compaction relationships could have been applied, such as the Giles, Schneider, or Yang/Applin algorithms. However, the actual equation used is not the issue. The use of Athy's law, an empirical relationship that by default includes mechanical and cementation effects, is simply to obtain a depth-porosity function in much the same way as the polynomial interpolation approach to describe the age-depth relationship. Such an analysis does not imply anything fundamental between polynomials and age variations. Particularly important is the fact that the measured porosities of samples from the porphyroblastic zone conform to the general porosity-depth relationship (blue circles; Fig. 2A). This is despite the expectation that the intrusion of sills and hydrothermal precipitation of calcite veins should have disrupted the normal compaction processes of mechanical pore space reduction, intergrain dissolution, and diagenetic growth of pore minerals. While this does not prove that cementation or porphyroblastesis is not interfering with compaction per se, it nevertheless shows a consistent behavior of Aptian-Eocene mudstone compaction as a function of depth.

Calcareous nannofossils provided excellent biostratigraphic control for most of the Site 1276 section, and planktonic foraminifers preserved in turbiditic sandstones proved helpful in refining that biostratigraphy (Tucholke et al., 2004). Palynomorphs provided a critical component for biostratigraphic age control in carbonate-free intervals. The resulting age-depth model for Site 1276 (Fig. 2B), based on first and last occurrence datums of microfossils, is shown in Figure 2B. Changes in slope

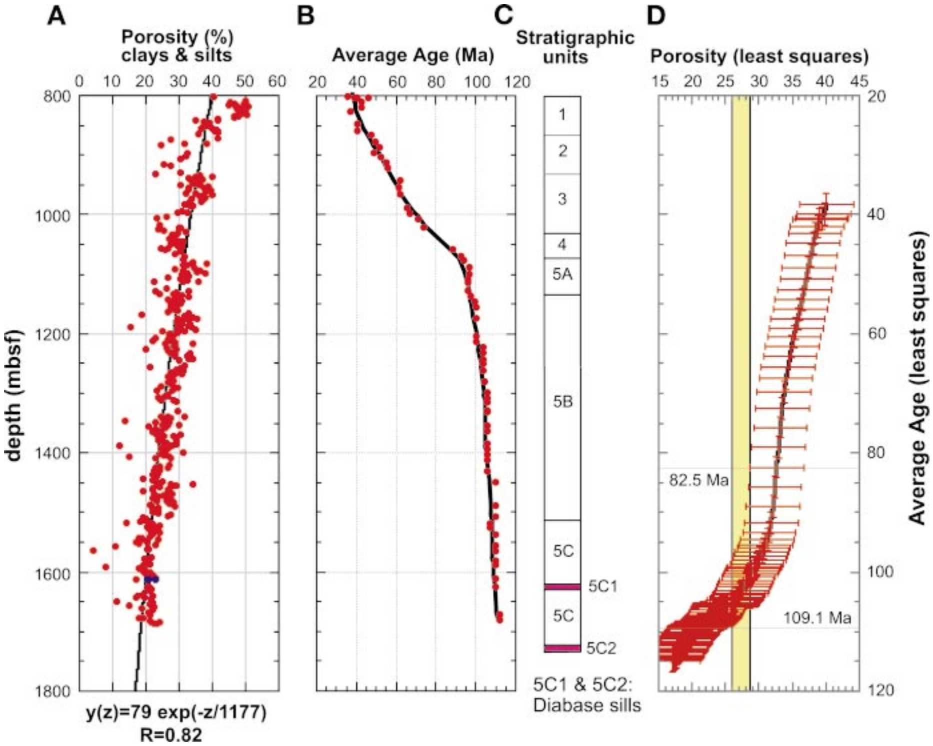

Figure 2. A: Measured porosity as a function of depth in meters below seafloor (mbsf) for Ocean Drilling Program (ODP) Leg 210, Site 1276 claystones, mudstones, and siltstones (red circles) with superimposed negative exponential function least-squares approximation (bold black line). Least-squares regression gives surface porosity of 79% and rate of change in porosity with depth of 1177 m. Blue circles: measured porosities from porphyroblastic zone. B: Average age as function of depth estimated from first and last occurrence datums of microfossils (red circles). Bold black line represents polynomial curve fit to data. C: Stratigraphic units mapped in Site 1276. Units 5C1 and 5C2 (magenta) represent diabase sills. Five lithologic units are recognized, ranging in age from uppermost Aptian to Eocene. D: Porosity as function of average age (bold black line) with superimposed error bars (one standard deviation; ±4.1% and ±1.8 Ma from porosity-depth and age-depth regressions, respectively). Superimposed porosity zone between 26.0% and 28.8% (yellow zone) represents range in porosity at time of sill intrusion.

correspond closely to lithologic unit boundaries. The functional relationship between age and depth is obtained using a polynomial curve fit to the data (Fig. 2B), the differences between the observations and the polynomial curve fit having a standard deviation of ±1.8 m.y.

Contact Metamorphism and Calcite Vein Emplacement

Sediments in close proximity to the diabase sills (Units 5C1 and 5C2; Fig. 2) were affected by a range of thermal and hydrothermal alteration conditions. Calcareous mudstones overlying the upper sill are characterized by elongate, light-colored porphyroblasts and recrystallized grainstones (i.e., marbles) that preserve a primary sedimentary lamination (Fig. 3A; Tucholke et al., 2004). A subvertical, crenulated calcite vein is in the calcareous siltstones overlying the upper sill (Fig. 3A; ~1612 mbsf). We presume that the folding of the vein is related to porosity reduction shortening, implying that the vein formed before significant sediment compaction.

Deeper in the section within the metamorphosed claystones above diabase Unit 5C2 (1710.1–1711.2 mbsf), similar calcite veins remain subvertical and have not undergone shortening (Fig. 3B). The sediments into which these subvertical veins were emplaced show unusually high porosities (27%–39%) and low velocities (1689–1958 m/s) considering their depth, and are part of the undercompacted section discussed earlier. As such, this section has not been allowed to undergo compaction and thus the calcite veins are not folded.

TABLE 1. MEASURED AND RECONSTRUCTED POROSITIES

Core	Depth (mbsf)*	Porosity (%)	Original porosity (%)	Age (Ma)
1276A-87R6	1612.17	22.8	28.8	99.9
1276A-87R6	1612.34	21.0	26.5	104.3
1276A-87R6	1612.54	20.6	26.0	105.2

*mbsf—meters below seafloor.

Estimating the Age of Diabase Emplacement

Site 1276 bottomed in diabase sills that appear to have been intruded into uppermost Aptian sediments at relatively shallow subbottom depths. The length of the folded vein (Fig. 3), where it can be clearly identified and does not fold back on itself, is calculated to be 31.12 ± 1.82 cm, and the vertical extent of the vein is 24.62 ± 1.25 cm, giving a vein length reduction of 20.8% ± 2.4%. The means and standard deviations were based on five sets of vein measurements using a range of techniques. A 4° variation in vein trend from the vertical translates to a length error of <1%; a value of 20.8% was used for calculating the values summarized in Table 1. Measured present-day porosities of the porphyroblastic mudstones range between 20.6% and 22.8% (blue circles; Fig. 2A), and correcting for the reduction in vein length gives original porosities of 26.0% to 28.8% (Table 1). Cross-correlating depth-porosity with age-depth results in a porosity-age curve (Fig. 2). From the reconstituted original porosities, the age of sill intrusion is estimated to be 82.5–109.1 Ma at sediment depths of 0–556 mbsf. Robust $^{40}Ar/^{39}Ar$ radiometric dating of the upper sill gave ages of 105.95 ± 1.78 Ma and 104.7 ± 1.7 Ma (S. Hart, 2005, personal commun.).

DISCUSSION AND CONCLUSIONS

The source of magmatism that created the sills is not clear, especially given that such magmatism is unexpected considering the nonvolcanic nature of the conjugate Iberian margin. Volcanic rocks of Early Cretaceous age have been drilled on the Scotian Shelf (Jansa and Pe-Piper, 1985) and the South Whale and Jeanne d'Arc basins on the southern Grand Banks (Jansa and Pe-Piper, 1988). Most of the volcanic rock analyses from the southern Grand Banks are whole-rock K/Ar age estimates ranging in value from 62 ± 23 Ma to 135 ± 6 Ma (Pe-Piper et al., 1994). Alkaline volcanics of the southern Grand Banks are contained within fault-bounded basins and have a trace element and isotopic composition distinct from those of plume-related Cretaceous rocks elsewhere in eastern North America (Pe-Piper et al., 1994). As most of the Early Cretaceous volcanic activity on the southern Grand Banks and Scotian Shelf is located along the major Newfoundland fracture zone, Pe-Piper et al. (1994) ad-

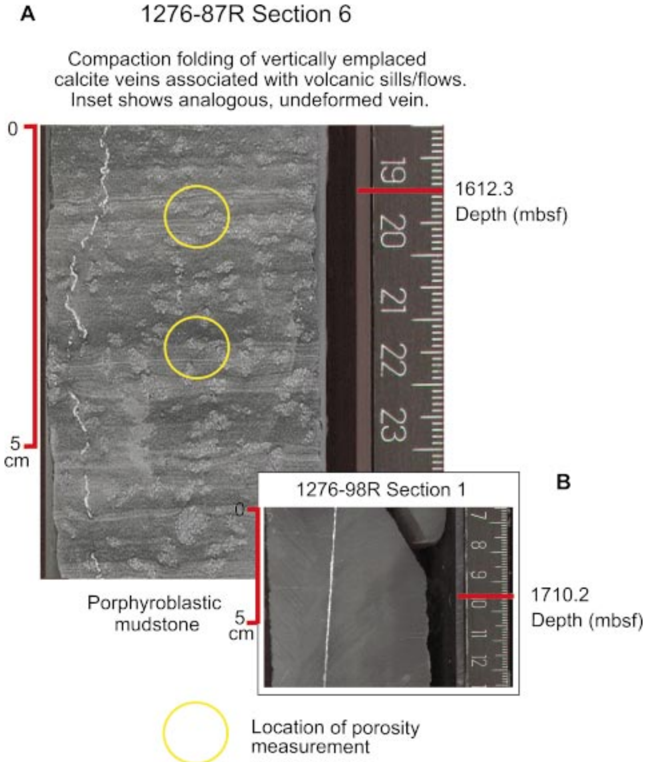

Figure 3. A: Photographs of Site 1276 core at 1276–87R section 6, 18–26 cm (~1612.3 m below seafloor [mbsf]). B: Site 1276 core at 1276–98R section 1, 6.5–13 cm (~1710.2 mbsf). Shallower porphyroblastic calcareous mudstone contains subvertical calcite vein that was folded after emplacement. Deeper down section (~1710.2 mbsf), calcite veins are undeformed. By calculating degree of shortening of vein, it is possible to reconstruct porosity of mudstone during vein precipitation, which we assume is coeval with sill emplacement. Age of sill emplacement is estimated from porosity-age curve.

vanced the idea that volcanic activity was a consequence of mantle decompression due to reactivation of this fracture zone. Such a model does little to explain the presence of volcanics in the Jeanne d'Arc Basin, the Labrador Shelf, and at Site 1276. In contrast, Duncan (1984) suggested that the source of the volcanism was related to the migration of the Azores, Madeira, and Canary plumes across the Labrador Shelf and Jeanne d'Arc Basin and the formation of the Newfoundland Ridge and Newfoundland Seamounts. The predicted hotspot tracks suggest that the Newfoundland Basin should have been subjected to plume-related volcanism between 80 and 120 Ma (Duncan, 1984; redrawn in Fig. 2.24 of Pe-Piper et al., 1990). Even though the Newfoundland Seamounts are ~180 km to the south of Site 1276, this distance is well within the range of plume head radii (200–1000 km; e.g., Burov and Guillou-Frottier, 2005; White and McKenzie, 1989), and thus plume activity seems to be a viable process to explain the diabase at Site 1276. The $^{40}Ar/^{39}Ar$ radiometric ages of dredged alkali basalts and trachytes from the Newfoundland Seamounts range between 97.7 $\pm$ 1.5 Ma (Sullivan and Keen, 1977, as reported in Pe-Piper et al., 1990). It would seem that our estimated age of the upper sill at Site 1276 is coeval with the emplacement of the Newfoundland Seamounts and thus represents a postrift magmatic event. Therefore, while the presence of postrift sills within the Newfoundland Basin adds an important piece of information concerning the thermal history of this region, it does not necessarily imply a magmatic Newfoundland-Iberia rift system.

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