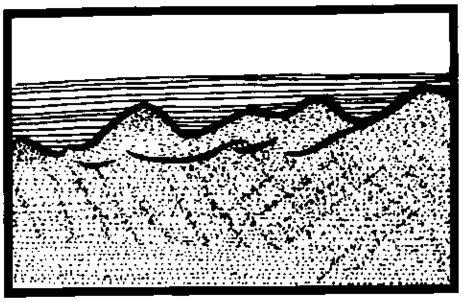

Insights from Scientific Drilling on Rifted Continental Margins

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SUMMARY

Sampling of sedimentary and crustal formations across rifted continental margins has long been a priority of DSDP, ODP, and other scientific ocean drilling. Recent results of drilling and related geophysical surveys across several margin segments in the North Atlantic have revealed that continents break apart in two fundamentally different ways. Volcanic margins form when rapid mantle upwelling produces a large amount of melt just prior to and during rifting. On non-volcanic margins, slow rates of rifting the continental crust expose regions of serpentinized mantle with little evidence of melting. Sampling, however, has thus far been restricted to regions of thin sediment cover, which has limited our ability to study the full range of rifted margin evolution. The next phase of scientific drilling will have enhanced capabilities that will allow drilling of both shallow- and deep-water basins, including those with thick sediments with hydrocarbon potential, such as the outer Grand Banks and Scotian margins. To make this a reality, it will be essential to combine both industry and academic interests and work to ensure continued Canadian participation.

RÉSUMÉ

L'échantillonnage des formations sédimentaires et crustales à travers les marges continentales divergentes, a longtemps été une priorité pour le DSDP, l'ODP et d'autres projets scientifiques de forages océaniques. De récents résultats de forages et de levés géophysiques concomitants à travers plusieurs segments de marges en Amérique du Nord ont montré que les continents se fragmentent de deux façons fondamentalement différentes. Des marges volcaniques se forment lorsque des remontées mantelliques entraînent l'accumulation de forts volumes de roches fondues juste avant et durant la distension crustale. Sur les marges non-volcaniques, de faibles taux de distension crustale dévoilent des régions de nature mantellique serpentinisées montrant peu d'indices de fusion. Mais, jusqu'à présent, l'échantillonnage a été limité aux régions au couvert sédimentaire mince, ce qui ne nous a pas permis d'étudier la gamme complète de l'évolution des marges de divergence. La prochaine phase de forage scientifique sera pourvue d'un équipement amélioré permettant de forer aussi bien les bassins d'eaux peu profondes que profondes, dont ceux à fortes épaisseurs sédimentaires et comportant un potentiel d'hydrocarbures comme ceux des marges des Grands bancs et de la marge écossaise. Pour y arriver, il faudra que l'industrie et le secteur académique travaillent de concert pour assurer la continuation d'une participation canadienne.

INTRODUCTION

The boundary between thicker continental crust and thinner ocean crust is one of the most fundamental of the Earth's transitions. These continent-ocean boundary zones are formed by the rifting of the continental lithosphere, which is a principal component of the plate tectonic cycle. These boundary zones are also important because major hydrocarbon reservoirs are located within the thick sedimentary basins produced by the extension, and because these same sediments hold vital stratigraphic clues for unravelling sea level fluctuations created by previous changes in climate.

Sampling both sedimentary and igneous crustal formations across continental margins has long been a priority of scientific ocean drilling. In recent years, results of drilling and related geophysical surveys taken during the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) have revealed that continents break apart in two fundamentally different ways. Volcanic margins form when a large amount of mantle melting is produced prior to and during rifting (White *et al.*, 1987). This melt creates both extrusive layers that form at or near sea level and underplated layers that form at the base of the crust, with combined thicknesses several times greater than normal oceanic crust. This thick igneous crust is continuous with adjacent continental flood basalts along many margins, and together they form a significant component of the earth's large igneous provinces (Coffin and Eldholm, 1994). In sharp contrast, non-volcanic margins form with little or no associated melting of the mantle. Instead, the basement that floors these basins may consist of mantle rocks that have been exposed during the final stages of rifting and breakup of the continental crust (Louden and Chian, 1999). This exposed peridotite is serpentinized by reaction with seawater, reducing its density and rheological strength and thus allowing it to deform into salt-like diapirs.

The North Atlantic Ocean contains both types of rifted margins that have formed during separate periods of rifting (Fig. 1). An initial episode of volcanic rifting beginning in the Middle Jurassic (~180 Ma) characterized most of the initial separation between North America and Africa. At the northern end of this region, the Nova Scotian margin appears to be a transitional segment between volcanic and non-volcanic types. During most of the Cretaceous period (~130 Ma to 60 Ma), continental rifting between North America and Europe-Greenland was not associated with major amounts of volcanism. Three episodes of rifting, progressing from south to north, resulted in separations of: 1) the southern Grand Banks and Iberia; 2) Flemish Cap and Goban Spur; and 3) Labrador and Southwest Greenland. A subsequent period of volcanic rifting, probably associated with the Iceland plume, began again at ~60 Ma when rifting started between Greenland and Europe to the northeast.

A number of legs of the Deep-Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP), along with related geophysical surveys, have been dedicated to studying these various margin segments:

- Crustal extension of the volcanic Voring Margin (VM), Hatton Bank (HB) and East Greenland (EG) margins during DSDP Leg 81 and ODP Legs 104, 152 and 163;
- Crustal extension of the non-volcanic Goban Spur (GS), Galicia Bank (GAL) and Iberia abyssal plain (IAP) continental margins during DSDP Leg 80 and ODP Legs 103, 149 and 173; and
- Stratigraphic sequences to document sea-level histories on the New Jersey shelf and slope (NJ) during ODP Legs 150, 150X, 174A, 174AX.

In this paper, we will briefly summarize some important results of drilling on the volcanic Southeast Greenland and the non-volcanic Iberia margins. Finally, we will discuss recent initiatives for future drilling of the eastern Canadian rifted margins.

SOUTHEAST GREENLAND VOLCANIC MARGIN

The southeast Greenland margin (EG; Fig. 1) is characterized by a well-developed seaward-dipping reflector sequence (SDRS) in a wide zone across the shelf and in the adjacent offshore region (Fig. 2). A similar SDRS sequence was first sampled on the Edoras Bank (EB) and Voring Margin (VM) during DSDP Leg 81 and ODP Leg 104. These results showed that the SDRS were formed by subaerial or shallow marine lavas produced from a fairly narrow, Iceland-type spreading center. The purpose of the Leg 152 and 163 drilling transect (Fig. 1) was to better define the complete tectonic and magmatic sequences from pre-rift to syn-rift and breakup to post-rift. Of particular importance was characterizing the progression from the landward flood basalts exposed on East Greenland to the seaward SDRS.

Along the inner part of the primary transect at 63°N, a smooth, basement reflector steps down to the northwest between sites 989 and 917 (Planke and Alvestad, 1999; Fig. 3). The position of this reflector beneath and landward of the SDRS indicates that it

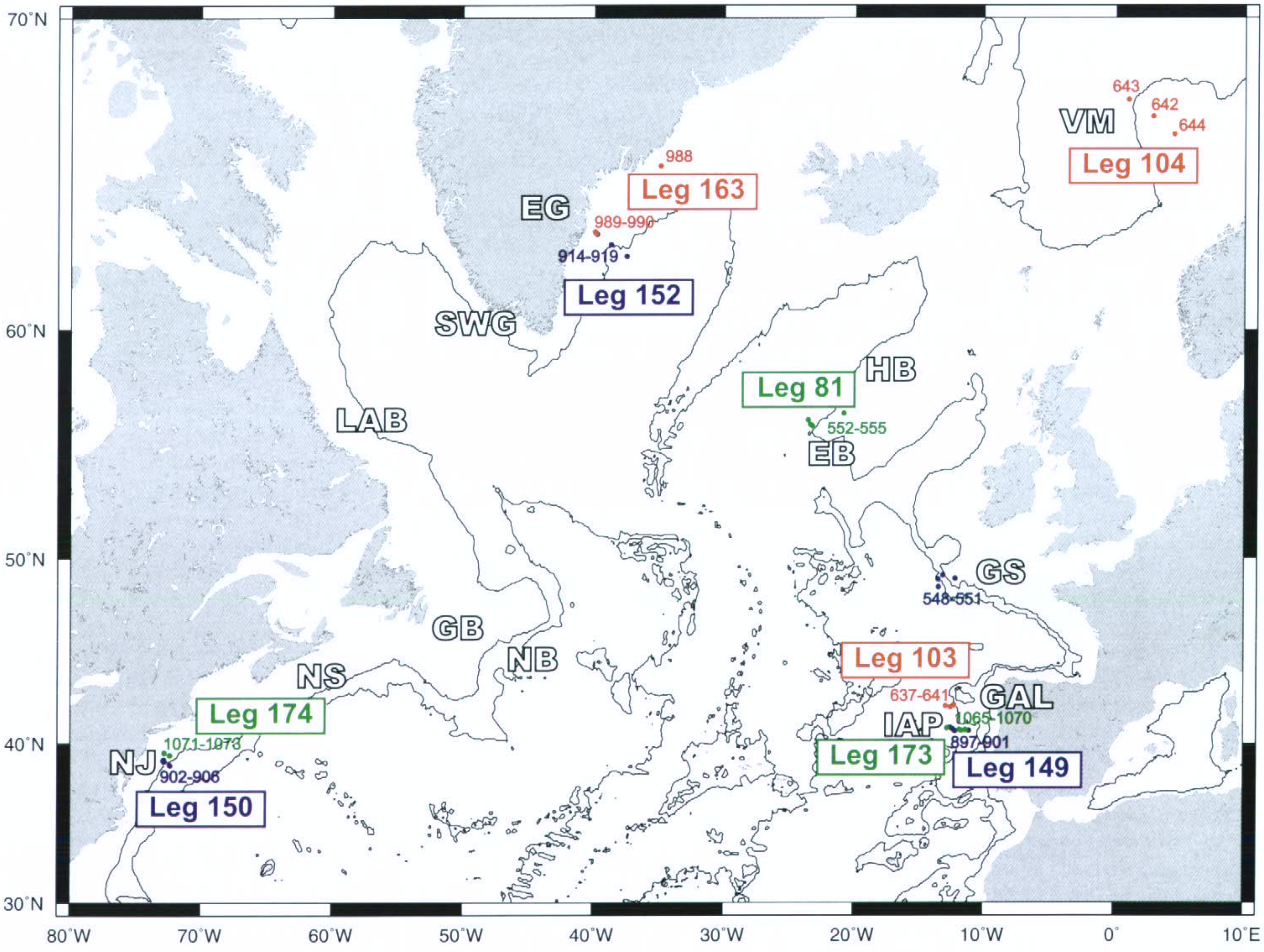

Figure 1 ODP and selected DSDP legs and borehole sites located on rifted margins of the North Atlantic Ocean. Margins identified are: Edoras Bank (EB), Southeast Greenland (EG), Galicia Bank (GAL), Grand Banks (GB), Hatton Bank (HB), Iberia Abyssal Plain (IAP), Labrador (LAB), Newfoundland basin (NB), New Jersey (NJ), Nova Scotia (NS), Southwest Greenland (SWG), and Voring Margin (VM).

relates to the lower continental succession (Landward Flows unit). A weak basal reflector drilled at Site 917 was found to be the base of this volcanic complex. Reflection profiles and gravity models indicate significant thinning of the continental crust within a narrow 25-km-wide ocean-continent transition (OCT) zone seaward from Site 917 (Larsen *et al.,* 1998). Seaward of the continent-ocean boundary (COB), two well-defined SDR units are observed, separated by a 20-km-wide zone with more disrupted reflectivity (Fig. 3).

Drilling during Legs 152 and 163 sampled the feather edge and the central part of the SDRS, recovering mainly basaltic lavas that were exclusively subaerially erupted (Larsen *et al.,* 1994; Duncan *et al.,* 1996). Site 918 drilled 121 m into the volcanic basement, recovering 21 basaltic lava flows, and Site 917 penetrated 779 m of basalts and dacites of late Paleocene age (61 Ma). The four shallow basement sites along the inner part of the transect (Sites 915, 916, 989, 990) all terminated within the landward volcanic complex and numerous subaerially emplaced basaltic lava flows were recovered. Drilling results indicate that the SDRS comprises a lowermost (innermost) continentally contaminated lava sequence (LS and MS) followed by an upper series (US) of picrites and tholeiites with much reduced or no continental contamination.

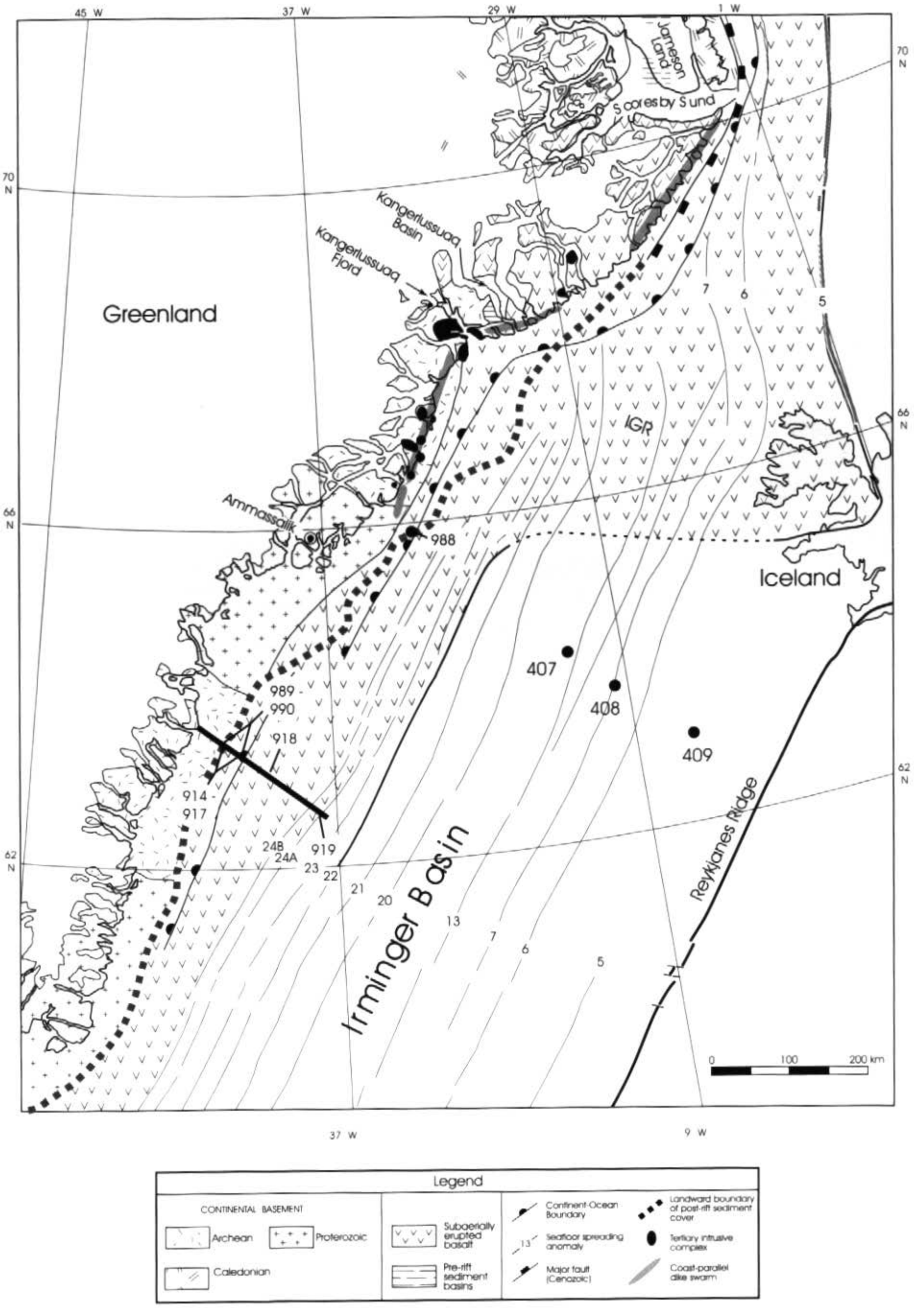

Figure 2 Leg 152 and 163 borehole sites across the East Greenland 63°N transect (EG63). The subaerially erupted basaltic lavas (typically 5-6 km thick) show SDRS structure seaward of the continent/ocean boundary (COB; thick dashed line). The East Greenland flood basalts show similar thickness toward the coast east and northeast of the Kangerlussuaq Basin (from Larsen and Saunders, 1998).

These drilling results allow a complete time series for the evolution of the rifted margin to be constructed (Larsen and Saunders, 1998; Tegner and Duncan, 1999). This time series includes continental-type volcanism at ~61-60 Ma, syn-breakup volcanism beginning at ~57 Ma, and post-breakup volcanism at ~49.6 Ma. There is an apparent time gap of ~3-4 m.y. between the Middle Series of Landward Flows (MS, Fig. 3) and the main seaward SDRS series. These discrete time windows coincide with distinct periods of tholeiitic magmatism from the onshore East Greenland Tertiary Igneous Province. They are consistent with discrete mantle melting events triggered by plume arrival under central Greenland (61-60 Ma) [Continental Succession], continental breakup (57-54 Ma) [Oceanic Succession], and passage of the plume axis beneath the East Greenland rifted margin after breakup (50-49 Ma).

A regional picture emerges of widespread, Paleocene pre-breakup magmatism, stretching from West Greenland through East Greenland to the British Isles, which covers a distance of more than 2000 km. The nearly simultaneous timing and duration of widely separated locations of flood basalt magmatism suggest that the plume ascended and spread out at velocities 10-100 times faster than the observed crustal spreading rates of several centimetres per year. Convection models within a temperature and depth-dependent mantle rheology are consistent with this picture, especially if viscous heating of the fast rising plume is included (Larsen *et al.,* 1999). Geochemical evidence indicates declining mantle temperatures and decreases in depth of melting during eruption of the onshore flood basalt succession in East Greenland (Saunders *et al.,* 1998). This suggests that, during onshore flood basalt erruption, an initially large reservoir of melt within the plume is quickly exhausted, and normal temperature asthenosphere mantle starts to rise and melt below the rift.

Unfortunately, there are some difficulties in accepting this simple picture as a paradigm for other volcanic margins. A recent seismic velocity profile across the East Greenland margin at 66°N (Korenaga *et al.,* 2000) indicates an approximately constant mean velocity of 6.9-7.0 km/s within the transitional crust generated by the plume, while its thickness reduces from 25 km to 10 km. Melt models (Kelemen and Holbrook, 1995) require a constant mantle potential temperature of ~1300°C in order to fit the constant mean crustal velocity, coupled with a drastic 8-fold decrease in the ratio of vertical upwelling rate to spreading rate in order to fit the variation in thickness. There are also significant differences in the width and duration of rifting for East Greenland and for the Voring Margin (Skogseid *et al.,* 2000). In addition, for the volcanic United States East Coast margins, a plume source for the volcanics is not at all clear (Kelemen and Holbrook, 1995). Thus, detailed results for East Greenland may not be generally applicable to other volcanic margins.

IBERIA NON-VOLCANIC MARGIN

The West Iberia non-volcanic margin comprises three segments, which have experienced progressive breakup from south to north during the Early Cretaceous, with very little associated magmatism (Pinheiro *et al.,* 1996). These segments form conjugate margin pairs to the Grand Banks and Flemish Cap, as indicated by plate reconstructions (Fig. 4). ODP Legs 149 and 173 were designed to study the sedimentation history and tectonic evolution of the Iberia-rifted

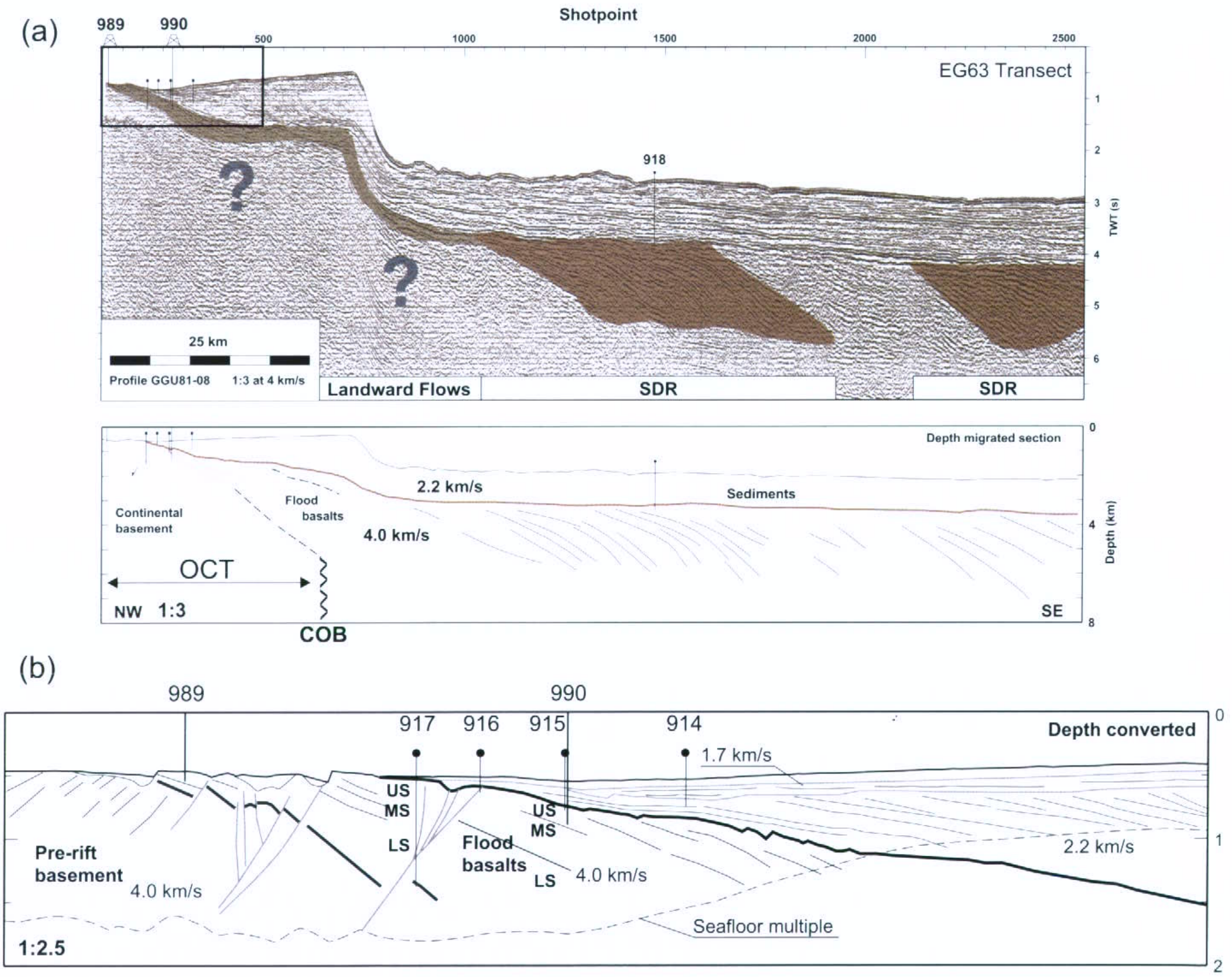

Figure 3 Interpreted time and depth-converted MCS reflection profiles along the EG63 transect. (**a**) Full transect showing entire time sequence from Landward Flows to outer SDR; (**b**) Depth converted high-resolution profile along the inner part (after Planke and Alvestad, 1999).

margin south of Galicia Bank, including the mechanisms of thinning and breakup of the continental lithosphere and the early stages of oceanic crust formation. Seismic reflection and refraction profiles and magnetic and gravity models (Discovery 215 Working Group, 1998) suggest that seafloor exposures of mantle peridotite on the western margin of Galicia Bank extend southward beneath the sediments of the Iberia Abyssal Plain (Fig. 5).

During Leg 149, drilling was conducted at five sites (897 to 901, Fig. 4) located over basement highs (Sawyer *et al.,* 1994). The discovery of multiple outcrops of serpentinized peridotite at Sites 897 and 899 and the almost total absence of basalt was a surprise. Apparently, the peridotites were brought up to the seabed by the final stretching and break-up of continental crust as Newfoundland separated from Iberia about 130 Ma. The basement high at Site 899 is capped by a set of unusual breccia flow units composed almost entirely of serpentinized peridotite and underlain by a mass-flow deposit. From the region predicted to be extended continental crust at Site 900 (Fig. 6), basement consists of metagabbro, which recent dating indicates is part of the continental crust that was rifted to form the margin. At the most landward site 901, sediments of Tithonian (Late Jurassic) age were recovered. These sediments, deposited about 20 m.y. before the onset of seafloor spreading on this segment of the margin, are syn- or pre-rift in origin and suggest that this site overlies thinned continental crust.

During Leg 173, five sites (Sites 1065 to 1070, Fig. 6) were drilled at the tops of structural highs to complete the east-west transect (Whitmarsh *et al.,* 1998). Sites 1065 and 1067-1069 lie within the ocean-continent transition zone (OCT), and the westernmost, Site 1070, is located over presumed early oceanic crust. Continental crust appears to underlie sites 1065 and 1069; the latter site is probably an isolated continental fault block flanked to east and west by synrift melt products and/or exhumed mantle (Fig. 6). The basement at Site 1067 consists of a 92-m-thick sequence of mafic rocks, with enriched to normal mid-ocean ridge affinities. Site 1068, located on the western flank of the same structural high, encountered breccias with clasts similar to the basement lithologies at Site 1067, and then, after drilling through a fault zone, serpentinized peridotite. The superposition of mafic rocks over ultramafics indicates that the strong seismic reflector that cross cuts the top of the basement on this structure is likely to be the crust/mantle boundary rather than a major synrift tectonic contact (Fig. 6; Whitmarsh *et al.,* 2000).

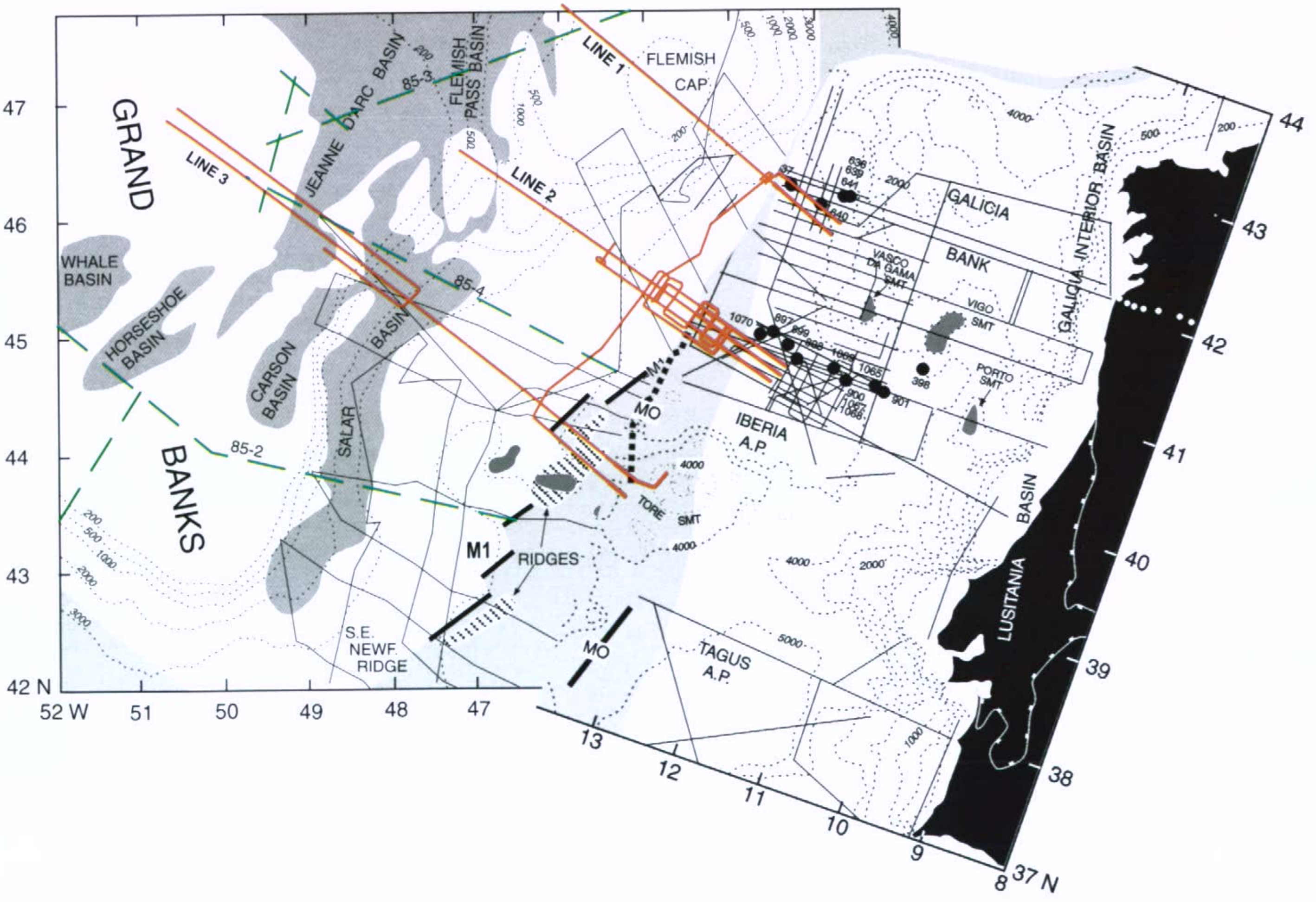

Figure 4 Reconstructed positions at Magnetic Chron M0 for Newfoundland and Iberian margins (Srivastava *et al.,* 2000) showing locations of selected seismic profiles. Red lines show most recent MCS profiles collected during summer 2000.

Site 1070 was located in a region characterized by an oceanic crustal structure and by seafloor-spreading magnetic anomalies. Basement at this site consists of serpentinized peridotite intruded by gabbroic veins. This may represent the early stages of mantle melting to form seafloor spreading, but no evidence of upper oceanic crust (lavas or sheeted dikes) was found.

The results of crustal drilling mentioned above have given us critical information for interpreting the complex pattern of basement structures (Figs. 5, 6) across the ocean-continent transition. The combined interpretation for the West Iberia Margin is that the OCT consists of a region of exposed mantle that has undergone variable amounts of serpentinization (Chian *et al.,* 1999). The width of this zone varies significantly along strike of the margin. It is widest along profile IAM9 in the south (Fig. 5), narrows to the north along LG12 and CAM144 (Fig. 5), and is probably limited to a single narrow ridge at Site 637 west of Galicia Bank. The near absence of melt products within this region is most readily explained by conductive cooling of the mantle during slow rates of extension (Bown and White, 1995). However, an alternate explanation also has been proposed for the formation of the OCT as oceanic crust (Srivastava *et al.,* 2000). The lack of boreholes within the deep syn-rift sediment between the basement highs (Fig. 6), and the absence of boreholes across the conjugate Newfoundland margin, means that the duration and style of rifting is still only poorly constrained.

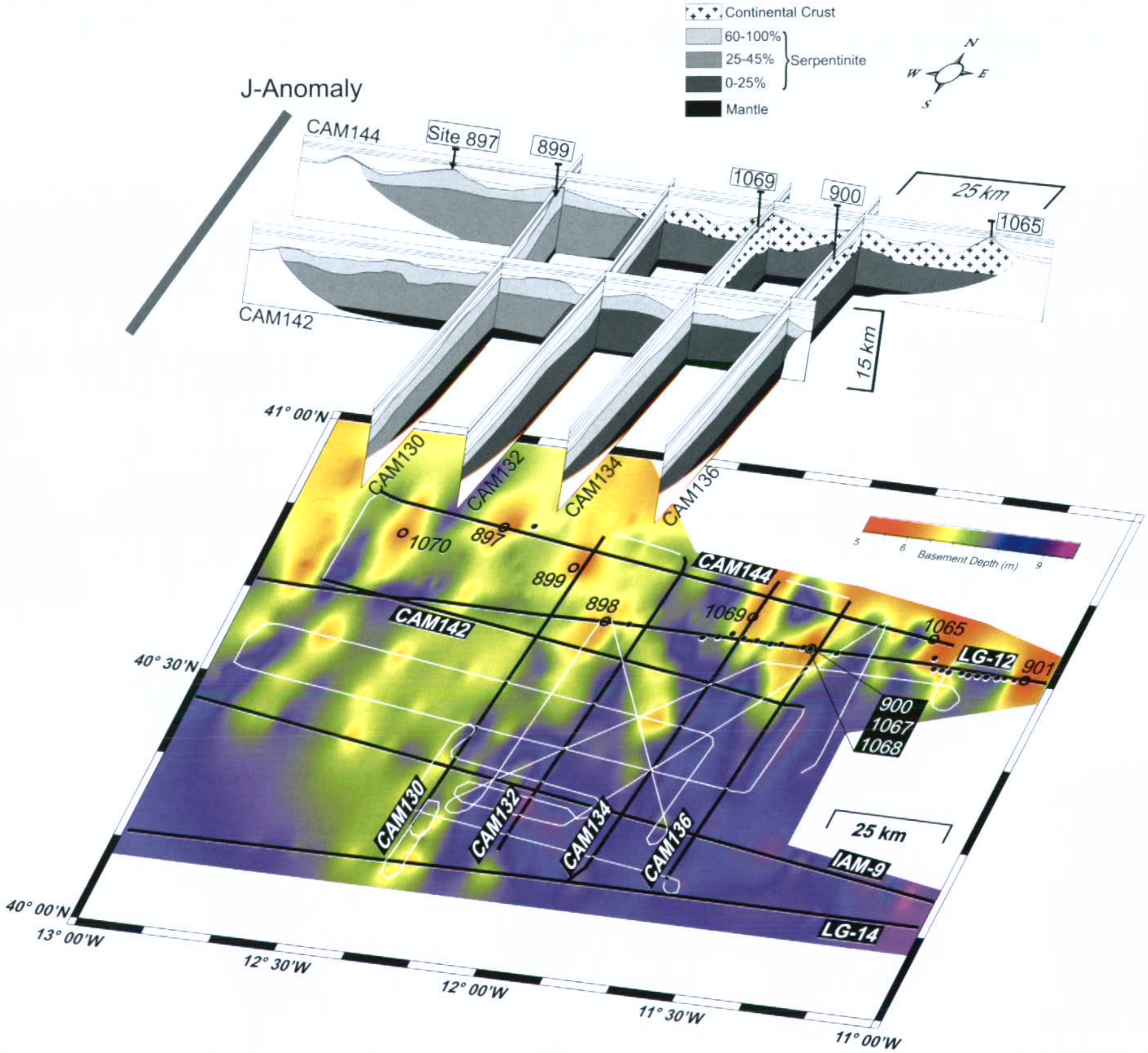

Figure 5 Summary of basement depth and velocity structure across the Iberia Abyssal Plain (from Discovery 215 Working Group (1998) and Chian *et al.*, 1999).

EASTERN CANADIAN MARGINS AND FUTURE SCIENTIFIC DRILLING

The lack of a riser and/or blowout prevention (BOP) systems on the present ODP drill ship (JOIDES *Resolution*) has greatly inhibited our ability to drill deeply into thick marginal sedimentary basins with hydrocarbon potential. This significant limitation has meant that scientific drilling to understand variations in deep syn-rift structures across complete margin transects generally has not been possible. This is particularly true for drilling thick sedimentary deposits where detailed subsidence histories are best recorded. Thus, drilling to define a complete syn- to post-rift history from the Early Cretaceous or Triassic to the present, including possible inter-relationships between basement structures and subsequent sedimentary deposition, has not been possible. For instance, in Figure 7 we show a recent multichannel seismic profile across the continental slope off the Eastern Grand Banks margin. It is clear that the many fascinating but complex reflectors are difficult to trace from shallow to deep water, particularly the deeper ones that intersect the prominent basement high. Although there are many industry wells in shallow water on the Grand Banks, the concentration on hydrocarbon targets and general absence of coring by commercial drilling has meant that we still know little about the nature, geometry, and origin of most of these stratigraphic sequences.

The next phase of post-2003 scientific drilling, the International Ocean Drilling Program (IODP), is presently being planned (see http://www.iodp.org/pdf/IODP_Init_Sci_Plan.final.pdf). The IODP will include both a deep riser vessel, currently being designed with an initial capacity to drill in water depths of up to 2500 m and eventually to 4000 m (see http://www.jamstec.go.jp/jamstec-e/odinfo/index.html), and an enhanced non-riser vessel (see http://www.joi-odp.org/USSSP/cdc/cdcreportfinal.pdf). These new drilling tools will have a great impact on our ability to fulfill remaining objectives for future scientific studies of rifted margins (see reports from the CONCORD [http://www.jamstec.go.jp/jamstec-j/reports/ CONCORD.pdf] and COMPLEX [http://www.oceandrilling.org/COMPLEX/complex_full.pdf] meetings. Given the economic potential of deeper offshore basins for future oil and gas exploration, including regions of eastern Canada with present exploration activity, it also is clear that these studies will be of both scientific and commercial interest.

Proposals for joint IODP-Industry objectives are currently being developed, including possible drilling targets in basins of the outer Grand Banks and the

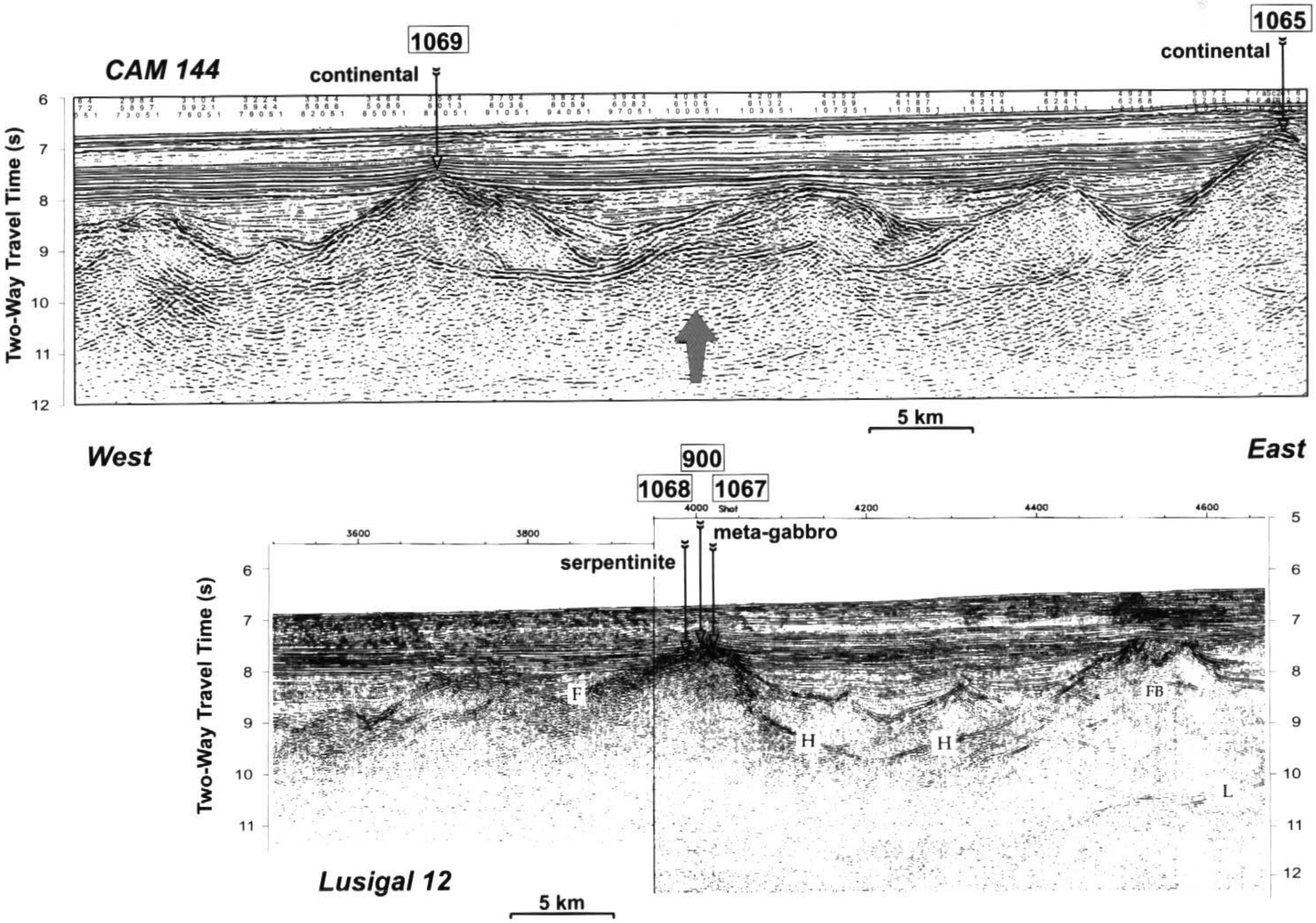

Figure 6 MCS reflection profiles CAM 144 and Lusigal 12 with locations of ODP drill sites and primary basement rock types in the Iberia Abyssal Plain.

Scotian margins. Some possible drilling targets of joint interest to academics and industry were recently discussed at a meeting in Calgary (October 2000) sponsored by CanadaODP. The possibility of combining previous scientific drilling results from the Iberia margin with new drill sites across the outer Grand Banks and Newfoundland basins would produce a complete transect of both margin conjugates that would elucidate fundamental questions of how such non-volcanic margins are formed and evolve. In addition, drilling on the outer Scotia margin would allow us to study the transition from volcanic to non-volcanic margin type within a single margin setting (Keen and Potter, 1995). Combining both industry and academic interests and a continuation of Canadian participation in the IODP is one way to make these possibilities a reality.

CONCLUSIONS

Drilling of passive continental margins in the North Atlantic has detailed huge differences in volcanic activity during rifting. The margins of East Greenland, Norway and western Rockall all exhibit massive volcanic activity associated with rifting and continental breakup. This activity was of relatively short duration and followed soon after a nearly synchronous period of continental flood basalt magmatism extending over a radius of ~2000 km. For East Greenland, the OCT is narrow and spreading rates were initially rather rapid. In contrast, the margins of Galicia Bank and the Iberia Abyssal Plain show little volcanism and very slow rates of opening. Their OCTs have an extremely variable width and a complex structure that is associated with exposure and uplift of serpentinized mantle. For each type of margin structure, however, there are significant asymmetries between and along margin conjugates. At present, we lack consistent controls from both drilling and seismic imaging across and along even a single margin conjugate. In addition, the limited capabilities of drilling through deep sediment basins on margins have left many important targets for future drilling during IODP. At the same time, it is hoped that the increased commercial activity in deep water drilling for oil and gas will lead to fruitful collaboration between scientific and commercial interests.

ACKNOWLEDGMENTS

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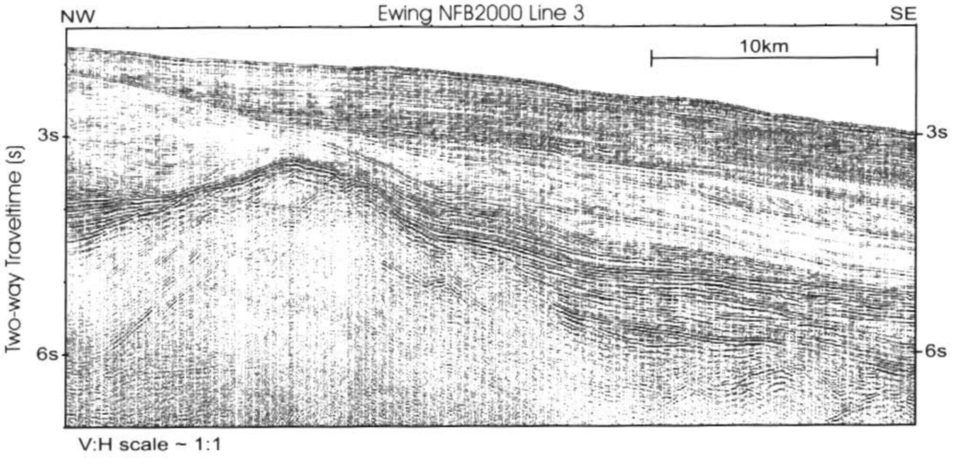

Figure 7 Time migrated section of MCS profile NFB2000 Line 3 across the continental slope of the Grand Banks margin (see Fig. 4 for location). Note the many complex sediment reflectors which are difficult to trace from shallow to deep water, particularly for those that intersect the basement high. This profile was processed at the Department of Earth Science, Memorial University of Newfoundland with help from Sharon Deemer.

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