MARIPROBE: Introduction and General Objectives

Ocean margins are a primary, global-scale feature of the Earth's surface that generally mark the transition between thick continental and thin oceanic crust, and are formed by combinations of horizontal and vertical motions of the Earth's lithospheric plates. Convergent margins are associated with the subduction or collision of oceanic and continental crust; rifted margins are created by the extension and breakup of continental crust to form intervening ocean basins; and transform margins exist where ocean and continental blocks slip laterally past each other. They include sites of some of the world's largest accumulations of sediments that form repositories for significant hydrocarbon reserves. Some margins are seismically active and their large relief and potential for accumulation of shallow gas and gas hydrates means that most are prone to slope failure. Thus, a clearer knowledge of the structure, composition and evolution of ocean margins will not only improve scientific understanding of lithospheric processes but will be crucial to the future wealth and well-being of coastal nations including Canada. Previous investigations have still left many unanswered questions, primarily because of the large spatial scale of structures and the significant resources required for their study. A number of coordinated international initiatives recently have been taken in order to improve our understanding of the structure and evolution of both rifted and collisional continental margins. These include a US Margins Program (NSF funding of approximately 5 M USD/yr) [1], a UK Ocean Margins Program (NERC/DTI funding of 4.5 M GBP over 4-5 years with matching in-kind contributions from UK-based industry) [2] and a European Ocean Margins Network Proposal (currently being considered for funding by ESF) [3].

Canada should play a role in these initiatives now, in order to take advantage of these collaborative opportunities. The Canadian landmass contains one of the longest margin systems in the world that includes most important types. These regions are not only of continuing scientific interest but they also hold commercially important oil and gas resources (e.g. Hibernia, Terra Nova and White Rose oil fields, Sable Island and environs gas fields, Beaufort Sea discoveries), which probably extend into deeper water regions farther offshore. Recent oil company bidding for exploration licences over deep water basins offshore Newfoundland and Nova Scotia was very strong, indicating their long-term interest in these areas. This offshore region is quite wide and complex, with structures that vary significantly both along margin segments and between margin conjugates (i.e. margins which once formed the same continental landmass but have been separated by seafloor spreading). The next major improvement in our understanding of continental rifting will require comprehensive studies of pairs of conjugate margins including continuous seismic images across the entire region of continental extension and breakup. This endeavor will require a large-scale effort with extensive international collaboration, including the drilling of deep boreholes. Scientific understanding of large-scale structures will aid in subsequent location of detailed studies of offshore regions with commercial potential. Regional studies of the offshore can build on existing profiles such as those collected during the Lithoprobe program.

To begin discussions on a Canadian Margins initiative, a one-day meeting with participants from university, government and industry was held on 8 May 1999 at the University of Calgary [4]. There was general enthusiasm to proceed with this initiative (referred to as MARIPROBE) by coordination of efforts. MARIPROBE will be an umbrella for a variety of research initiatives that will be built on the notion of the development and application of seismological techniques to fundamental problems relevant to resources and hazards associated with Canadian continental margins. ***This particular proposal is one specific result which concerns regional investigations of two high priority areas of E. Canadian rifted margins (Grand Banks and Scotian Shelf) that will build on existing datasets and take advantage of extensive international collaboration on the conjugate margin pairs. It will also serve to: (i) develop further coordinated MARIPROBE initiatives including specific targets identified in consultation with industry, (ii) establish an easily accessible database of seismic data, (iii) improve relevant marine capabilities for future seismic investigations within the academic and governmental community, and (iv) facilitate Canadian representation on future international MARGINS initiatives.***

On the Formation of Non-Volcanic Rifted Margins: Previous insights from the Labrador Sea

Rifted margins are commonly classified as either volcanic or non-volcanic based on the amount of extrusive and intrusive igneous activity that occurred during rifting. Both margin archetypes exist in the North Atlantic (Fig. 1). However, the behavior of the lithosphere under extension is best studied on non-volcanic margins where the extensional fabric has not been modified by large volumes of syn- or post-rift volcanism. We also need to locate regions where deep-imaging crustal transects exist on both sides of respective conjugate margin pairs. The North Atlantic offers one of the few regions where such conditions are met. Plate reconstructions [5] indicate a period of rifting between North America and Europe-Greenland from approximately 130 to 60 Ma, which is not associated with major amounts of volcanism. During this period, there were three episodes of continental rifting, progressing from south to north that resulted in separations of the Southern Grand Banks and Iberia, Flemish Cap and Goban Spur and Labrador and SW Greenland (Fig. 1).

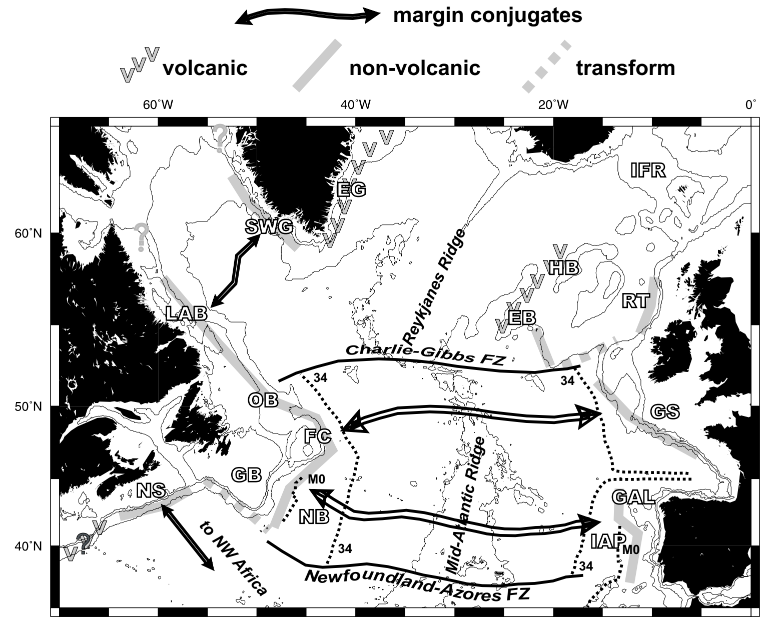

Fig. 1. Continental Margins of the North Atlantic

Numerous studies of individual margins have been made over the past years. However, the GSC-Dalhousie study of the Labrador-SW Greenland margins [6-9] remains the only consistent set of deep multi-channel seismic reflection profiles (MCS) and wide-angle seismic refraction profiles using ocean bottom seismometers (OBS) across both margin conjugates. Combination of these data have allowed a direct comparison of their structures (Fig. 2). The seismic profile for Labrador shows an abrupt termination of upper crustal faulting but a very broad zone of primarily lower crustal thinning across the thickly sedimented continental shelf [8]. In contrast, the SW Greenland profile shows an abrupt thinning of the lower crust and a wider, thinly sedimented zone of upper crustal faulting above a possible detachment [6]. In both cases, a wide zone of enigmatic high velocity lower crust (HVLC) is observed in a transitional region between thinned continental crust and oceanic crust. Our interpretation is that these HVLC zones formed primarily by serpentinization of the upper mantle with little or no production of melt. A fundamental asymmetry of the conjugate margins appears after removal of the oceanic and HVLC zones (Fig. 2). Thinning of the lower crust is particularly asymmetric, with location of breakup offset towards the Greenland margin and a broad zone of extended lower crust beneath the outer Labrador margin. Simple conceptual models indicate, that initial thinning of the Labrador-Greenland continent may have occurred symmetrically until a factor ß~2 (i.e. 50% thinning), at which point the locus of thinning migrated toward the Greenland margin where final breakup occurred once the crust had been thinned by a ß-factor of 7-8 (Fig. 2). The two primary implications from this model for the ocean-continent transition (OCT) are that: (a) late stages of continental rifting often appear asymmetric between margin conjugates, with one side having a broader region of highly faulted upper crust, typically underlain by a horizontal detachment between crust and serpentinized upper mantle; and (b) very little melt is produced over a zone 100-200 km wide where the continental crust has been thinned by very large (possibly infinite) stretching factors, exposing the upper mantle and leading to extensive serpentinization [10].

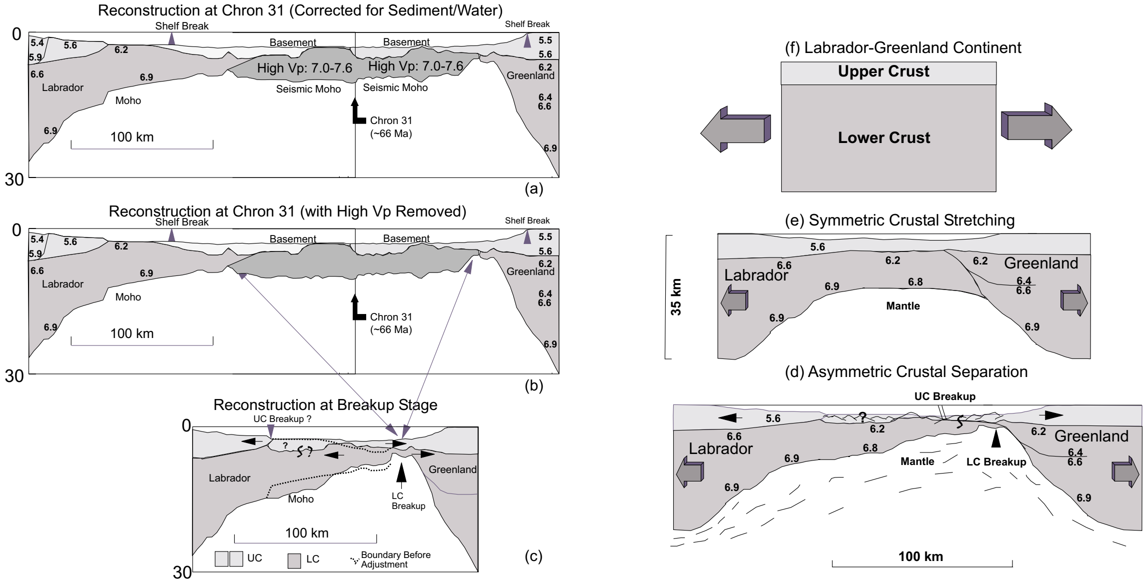

Fig. 2 Reconstruction of conjugate crustal sections and rifting model of Labrador-Greenland margin

If this interpretation is correct, the apparent lack of melt production during rifting remains a paradox for these margins. Models of decompressional melting [11] indicate that vertical conductive cooling during a finite period of rifting can decrease melt production at large stretching factors particularly if mantle temperatures are lower than normal. However, heat flow measurements indicate that mantle temperatures were probably much higher than normal [12], possibly due to influence from the Iceland hot-spot. An alternate possibility is that very slow rates of extension reduced melt production [13]. Slow extension might also have created the asymmetric pattern of continental faulting through the temperature dependence of rheological strength. This effect may be influenced by the initial conditions of continental crustal thickness and thermal conditions within the lithosphere [14,15], in which diffusive cooling of the mantle will modify the geometry of the rift primarily when the upper mantle is initially weak and viscous. In this case, the locus of maximum strain-rate moves laterally once the initial rifted region starts to cool until concentrating at the transition between deformed and undeformed lithosphere. Therefore, the Labrador-Greenland transect may be unique because of its extremely slow rates of extension [16] and/or lithospheric thermal structure that may have been warmed and weakened by the beginning of the Iceland plume. It is important to find out if different structures exist on other margins where rates of extension are higher and the initial thermal structure of the lithosphere is cooler than it was during initial opening of the Labrador Sea. It is also important to consider how rapidly structural styles may vary along as well as across margin conjugates and to obtain ground truth of basement type and rates of extension from deep drilling into syn-rift sediment and basement that is lacking for the Labrador-Greenland margins.

MARIPROBE Phase 1: Opportunity for Major Step Forward in Understanding Rifted Margins

This proposal seeks to address the need to obtain significant new seismic data across the other rifted margins of Atlantic Canada as a major step forward in understanding rifted margins. This proposal is made now so that the investment of Canadian efforts can be leveraged several times by integration with new programs on these margins and their conjugates being led by groups in the U.S., Denmark, U.K and

Germany. In this case, the scientific returns will be greater than those gained just by the leverage of international collaboration, because of recent and planned new advances in experimental design. The Labrador study just cited, and the recent work by international groups (including the P.I. on this proposal) on the Iberian margin that is conjugate to the Newfoundland basin, have demonstrated that the next major breakthroughs in understanding the process of passive margin formation will come from studies of conjugate margins which combine all the following***:***

- ***continuous seismic reflection profiling, from demonstrably unextended continental shelf across the rift zone, transitional crust, to demonstrably ocean crust;***
- ***continuous wide-angle seismic profiling collinear with the reflection profiles;***
- ***application of high resolution acquisition to the seismological experiments, with much closer spacing of detectors and sources, and the use of tuned source arrays;***
- ***interpretation by integration with well-resolved potential field data, conventional industry basin seismic, and direct sampling (existing, and future, some via ODP);***
- ***application of newly-established criteria for distinguishing the nature of crustal blocks, based on multi-parameter geophysical characterization.***

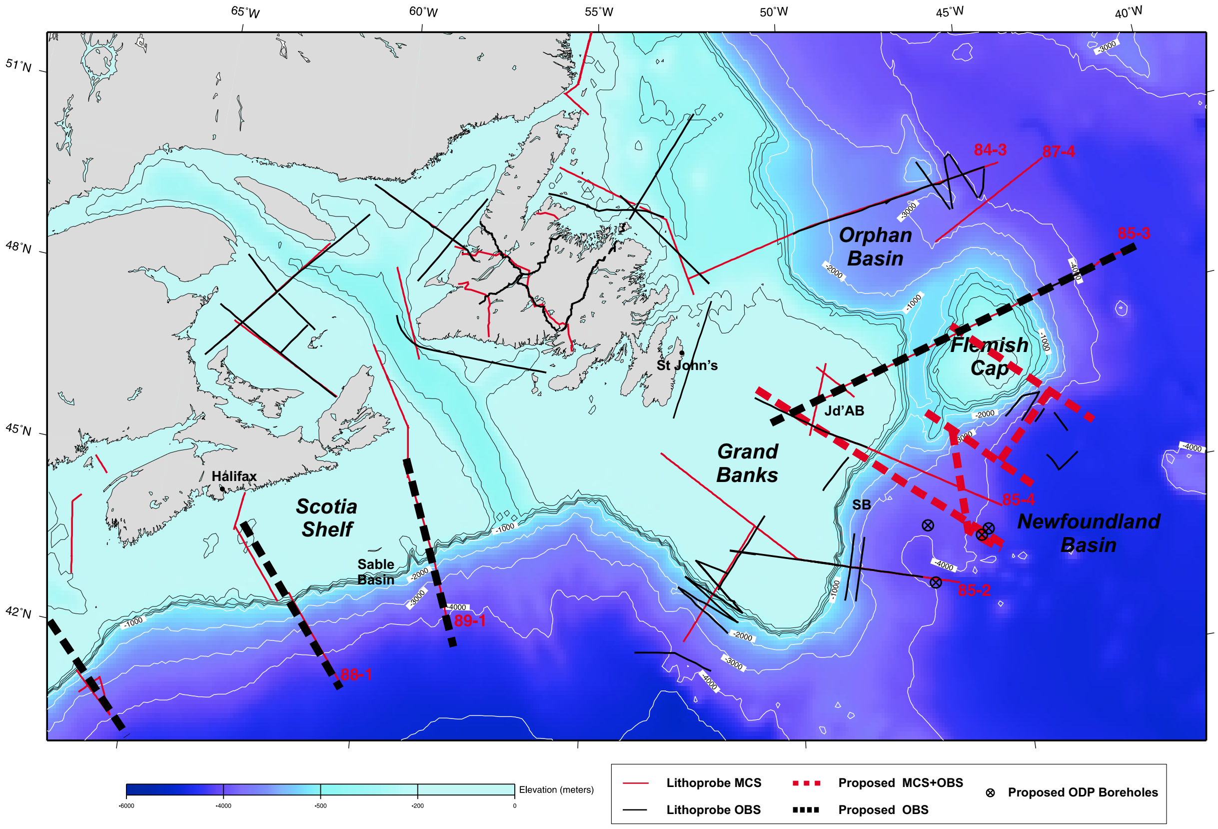

Fig. 3 Proposed and exiting seismic profiles and ODP borehole sites off E. Canada

The detailed plans described below show how these new multi-parameter experiments can be expected to discriminate among existing models for the formation of the Atlantic Canadian rifted margins. We will accomplish this in three parts, with the proposed profiles shown in Fig. 3, through a major collaborative effort with several international partners. This will allow us to pool the substantial resources of ship time and equipment necessary to undertake such profiles and to analyze these new data in the context of conjugate margin structures off W Europe and NW Africa. At the same time, we will build on existing deep MCS profiles and on the possibility of new deep drilling by the Ocean Drilling Program.

- ***We will collect and jointly analyze both deep seismic reflection (MCS) and wide-angle (OBS) profiles to constrain the complete structural transition from continent to ocean on several margins***
- ***We also will investigate the application of detailed wide-angle data for improved imaging of deep sedimentary basins on the continental slope where traditional MCS images are often poor.***
- ***We will take additional measurements of heat flow where lacking to constrain the lithospheric thermal structure.***
- ***With our international partners, we will produce combined depth sections of both margin conjugates. These final models will be analyzed in terms of new geodynamic models of continental rifting.***

Part 1: Newfoundland-Iberia Transects

The Newfoundland basin (NB) extends from the eastern Grand Banks to 4500m water depth (Fig. 4). It is bounded to the north by Flemish Cap and to the south by the SE Newfoundland Ridge (SENR). The NB can be divided into two zones on the basis of existing MCS profiles (e.g. Fig.5): (1) A landward zone, Salar basin, lies beneath the continental slope and is thought to be continuous with the Flemish Pass rift basin to the north [17]. The basin contains hummocky, diapiric evaporites deposited during a Triassic-Early Jurassic phase of rifting [18]. Underlying basement is masked by these evaporites in most existing MCS profiles. (2) A transitional zone extends ~150 km from Salar basin to the J anomaly ridge, and it exhibits unique deep structure in seismic profiles. Most striking is the flat, strongly reflecting basin-wide unconformity (U) that closely overlies, intersects, or locally truncates the underlying basement. The character of U strongly suggests that it was eroded at sea level [19]. It appears to be mid-Cretaceous in age and can be seismically correlated to the "Avalon Unconformity" on the Grand Banks [20]. It pinches out seaward on the western side of the J-anomaly ridge. It extends north to the area near proposed Line 3 but its extent toward Flemish Cap is uncertain. Below U, the basement is poorly resolved in most existing MCS profiles, but appears to be broken into asymmetrical fault blocks with slightly rotated to unconformable inter-block fill. Only weak magnetic anomalies exist landward of ~M1. A variety of hypotheses for crustal origin have previously been proposed for this enigmatic region (Fig. 5): thinned continental crust [19]; exhumed and serpentinized mantle [21]; ultra-slow spreading oceanic crust [22]; and normal ocean crust [23]. The lack of coincident MCS and OBS profiles throughout the basin that extend from unstretched continental crust beneath the Grand Banks to unequivocal oceanic crust at M1, leaves the nature and width of the OCT unresolved [24].

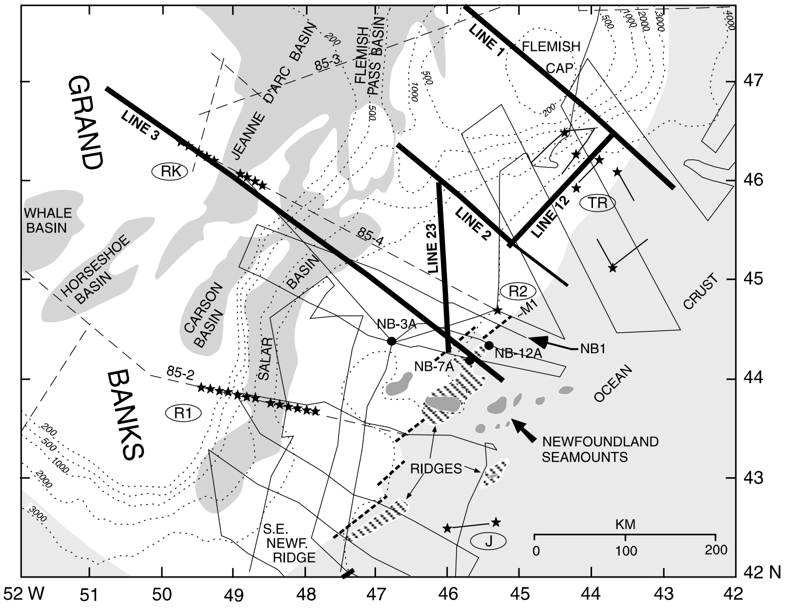

Fig. 4 Newfoundland Basin structures and seismic profiles

Two of the main reasons for obtaining improved images of the NB are that: (i) sites with basement objectives have been proposed to the ODP for drilling before the end of the current program in 2003; and (ii) it lies in a conjugate position to the Iberia margin (Figs. 1 and 5). No other non-volcanic margin has been as well characterized as the West Iberian margin on the basis of both MCS and OBS profiles. These include a dense suite of profiles taken in 1995 across the Iberia Abyssal Plain (IAP) in collaboration between Southampton Oceanography Centre (SOC), Cambridge University and Dalhousie [25], and profiles taken just to the north across Galicia Bank in 1997 [26]. In the IAP, seismic profiles indicate a very broad zone of transitional crust with a reflection character and velocity structure distinct from either thinned continental or oceanic crust (Fig. 5). Basement sampling of this zone on ODP Legs 149 and 173 [27,28] recovered thick sections of highly serpentinized peridotite and few syn-rift melt products that indicate low degrees of melting [29]. In contrast, the structure of Galicia Bank contains a broad region of thinned continental crust characterized by suites of dipping and/or horizontal (S-type) reflectors that truncate to the west at a narrow serpentinized ridge [30,31]. The broad, deep region of flat basement and transitional crust in the IAP may be similar to the deep transitional region of the NB, but no region of highly stretched continental crust comparable to Galicia Bank has been observed on the western margin of the Grand Banks and Flemish Cap. This suggests the presence of asymmetric rifting (Models A in Fig. 5) as in our model for Labrador-Greenland; but alternate models that include jumps in ocean spreading (e.g. Model B) are also possible [32]. Definitive models of rifting between Iberia and Newfoundland still await new seismic profiles across the NB with combined MCS and OBS analysis that are comparable to those across Iberia. The purpose of our proposed seismic profiles in the NB (Fig. 4) is thus to:

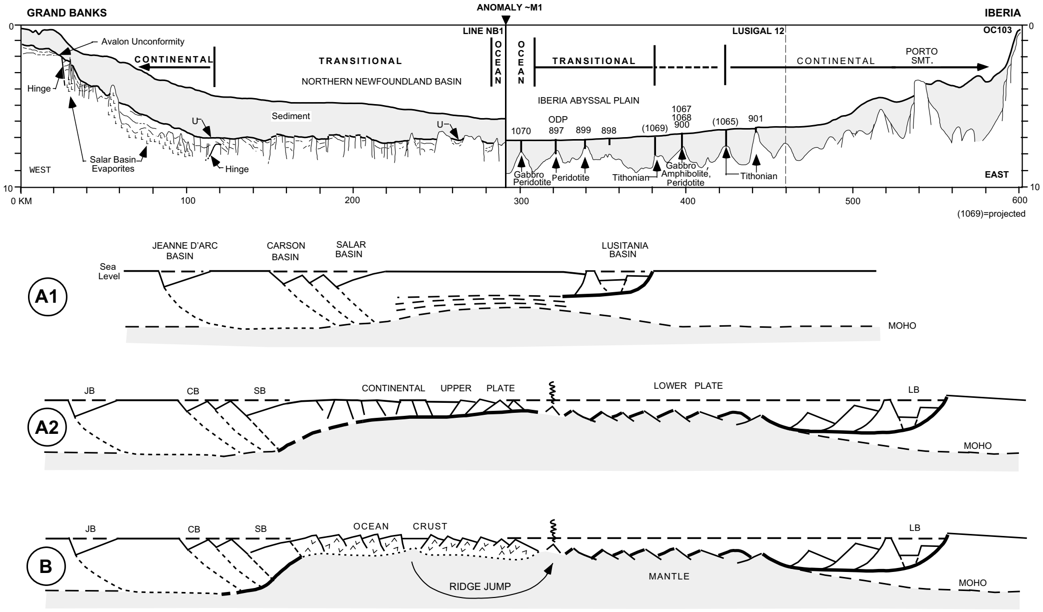

Fig. 5 Near conjugate MCS profile traces and possible models for formation of NB-IAP margins

- ***Characterize the regional crustal structure of the Newfoundland margin including complete transects from unextended continental crust beneath the Grand Banks/Flemish Cap, rifted and thinned continental crust beneath the slope and rise, transitional crust of disputed origin in the deep NB and ocean crust seaward of the transitional crust.***
- ***Define the nature of boundaries between each crustal type and determine how these vary along strike of the Newfoundland margin in positions where they can be compared to existing data on the conjugate margin beneath Galicia Bank and the Iberia Abyssal Plain.***
- ***Constraining the gross amount of melt produced during the rifting process by determining if regions of crustal underplating occur and whether basement exists of thin oceanic crust or exhumed mantle.***
- ***Compare crustal structure of the Newfoundland margin with conjugate structures on the Iberian margin in terms of likely extensional mechanisms.***
- ***Satisfy site survey requirements at proposed ocean drilling sites.***

The 5 new seismic profiles shown in Fig. 4 will be taken in collaboration with B. Tucholke (Woods Hole), S. Holbrook (U Wyoming) and H.C. Larsen (Danish Lithosphere Centre). Primary funding for this experiment of ~2 M$US is provided by the US National Science Foundation (NSF) and includes a total of 65 days of ship time on two research vessels (scheduled for July/Aug 2000). The MCS profiles (~2000 km total length) will be conducted from the R/V EWING using the Lamont 20 gun, 8473 in^3 airgun array and new 6-km hydrophone streamer. A total of 92 deployments of 34 instruments (14 DAL-GSC OBS and 20 WHOI OBH with hydrophone only) will be made separately from the R/V OCEANUS. These will be some of the most densely-sampled OBS profiles ever recorded across a rifted margin, with instrument spacings as little as 5 km in critical regions. The Canadian contribution to this program will support use of the DAL-GSC OBS instruments (52 deployments) and processing and analysis of roughly 1/4 of the MCS and OBS data (500 km). In addition, heat flow measurements using a new 32-sensor Dalhousie heat flow probe will be made during shooting of the profiles, in order to compare with previous heat flow measurements taken across the IAP [33] and Galicia Bank [34]. These data will constrain thermal parameters for geodynamic modeling and will determine whether depth differences between the NB and IAP transects (Fig. 5) are caused by differences in lithospheric thermal structures. They will also be used for ODP site survey requirements of hydrocarbon maturation potential at proposed drill sites.

Part 2: Flemish Cap - WAM Transect

The Goban Spur - Flemish Cap conjugate margins lie north of a triple junction that was active until chron 33 (80 Ma) during rotation of Iberia to form the Bay of Biscay [35]. The absence of magnetic chron M0 in the oceanic crust [36] and the dating of synrift sedimentary sequences from drill holes on the Goban Spur and Biscay margins [37] indicate that rifting began somewhat later than on the Newfoundland-Iberia conjugates to the south. In contrast to Labrador-Greenland and Iberia, these margin conjugates have previously been interpreted to have an abrupt OCT. MCS data along the WAM profile across Goban Spur [38] has been interpreted as consistent with pure shear stretching, although heat flow data suggest that the upper crust may be thinned more rapidly than the lower crust [34]. A problem with the seismic interpretation is that the crust interpreted as oceanic has a deep, relatively smooth basement without clearly defined Moho reflections [10]. This characteristic is quite similar to what is observed in the transitional regions of the IAP and NB. Coincident wide-angle data was taken along the WAM profile, but with very limited sea-ward coverage that in fact shows an amplitude pattern quite different from the typical oceanic structure originally proposed [39].

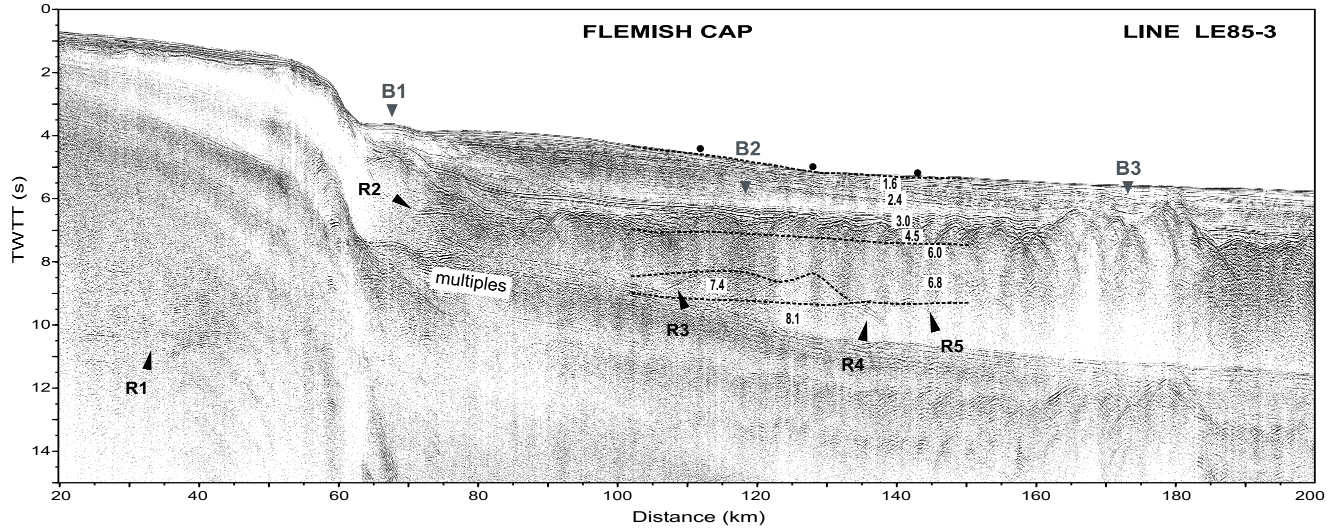

Fig. 6 MCS Profile LE85-3 and OBS Profile 87-10 across the Flemish Cap margin

MCS profile 85-3 [23] which crosses Flemish Cap in a conjugate position to Goban Spur is shown in Fig. 6 along with results from wide-angle profile 87-10 over a very short offshore section [40]. Features of this profile also indicate unusual structures within a wide transitional region. Seaward of the continental Moho (R1), there is no clear connection between tilted fault blocks and crustal thinning. A prominent fault block is observed at 65-70 km distance (B1) and is underlain by a horizontal reflection (R2) that may terminate at the top of basement (75 km distance). Within the area of the refraction profile, a number of both landward (R3) and seaward (R4) dipping events appear to border a layer of high velocity (7.4 km/s) lower crust (HVLC). The reflection from the top of basement (B2) is flat and deepest over this transitional region. Moho reflections are absent until ~140 km distance (R5), seaward of which lies a rougher elevated basement (B3).

Thus, a transitional region 70 to 100 km wide occurs between the last continental fault block and the first appearance of a reflection from oceanic Moho, with a pattern of basement morphology and crustal reflectivity similar to the WAM profile. However, the manner of continental faulting and crustal thinning appears quite dissimilar between these two margin conjugates, with a much broader region across Goban Spur compared to Flemish Cap. This was noted by Keen *et al.* [41] in their initial reconstructions of the two profiles. They suggested that this asymmetry might have occurred if final breakup was offset towards Flemish Cap. The revised interpretation of Louden & Chian [10] suggests that the continental crust of Flemish Cap may have thinned over a much shorter horizontal distance than Goban Spur. Another asymmetry between the margins is indicated by the presence of the sub-horizontal mid-crustal reflection (R2) beneath the tilted fault block off Flemish Cap, which is not evident off Goban Spur. These asymmetries in addition to the asymmetry between upper and lower crustal thinning previously noted indicate that evidence for pure shear extension during final breakup is not as clear as previously suggested.

In order to characterize the crust within the OCT of the Flemish Cap and Goban Spur margin conjugates and produce well-constrained depth sections from the existing MCS profiles, new wide-angle OBS profiles are needed along the full length of the conjugate transects. T. Minshull (SOC) has recently received funding from the NERC (UK) including 16 days ship time (summer 2000) to take new OBS data along the WAM profile, using 22 ocean bottom hydrophones (OBH) from GEOMAR and a 6346 in^3 12-airgun array. We propose to collect a similar data set for the Flemish Cap conjugate along the existing MCS 87-3 profile. However, ***in order that our data will be of comparable quality to those for Goban Spur (and of similar quality to the EWING NB profiles), we will require upgrades to the HUDSON airgun array and a larger number of OBS***. These needs are more fully justified in a following section. We propose a two-week cruise on HUDSON (summer 2002-3) with the equipment upgrades to be built during the previous year. This will allow us to obtain dense wide-angle data in two separate deployments of 375-km each, along the entire 750-km long MCS profile 87-3. Some additional heat flow measurements will be taken between OBS recovery and redeployment in order to contrast the thermal structure of the lithosphere south of the Charlie-Gibbs FZ (Fig. 1) to compare with the normal oceanic values previously measured off Goban Spur [34] and the higher values previously collected in the Labrador Sea to the north [12]. Velocity models produced from seismic modelling will be used to convert the MCS data to depth section. Construction and interpretation of conjugate sections will be made in collaboration with T. Minshull (SOC). We also plan to take some additional OBS measurements in a detailed grid on the slope region in order to investigate the use of these methods to improve images of sedimentary structures where they are not well-defined in traditional MCS profiles. Final selection of this study area will be made in collaboration with current industry data.

Part 3: Nova Scotia-NW Africa Transects

The Nova Scotia margin (Fig. 7) represents the northern most section of the 2000 km-long North American-NW African rifted margin. A prominent feature on the margin is the Sable Basin, which is one of the deepest sedimentary basins of the entire North American margin and contains significant hydrocarbon deposits. It is filled with syn-rift sediments of Triassic and E. Jurassic age, which are overlain by thick sequences of post-rift sediments [42]. Seaward of the basin, an extensive region of salt diapirs (Sedimentary Ridge Province) underlies much of the continental slope and rise. The diapirs are cored by salt of E. Jurassic age which obscures deeper seismic horizons and complicates the correlation of slope and rise stratigraphy with deep wells drilled on the shelf [42]. South of the Sable Basin, the LaHavre Platform is a region of much thinner sediment fill.

The region has a long history of geological and geophysical exploration [43]. The Basin Atlas Series volume [44] (Fig. 7) has compiled potential field data, 125 wells and more than 300,000 km of industry reflection profiles. Cross-sections of the margin resulting from this synthesis are based primarily on industry MCS profiles, controlled near the surface by well information and at depth by the sparse and poorly-controlled seismic refraction profiles of the early 1960's. These sections show significant variations along the margin which suggest linkages between overlying sedimentary accumulation and basement structure [45]. For instance, the depth-to-basement contours parallel the modern margin on the SW Scotian margin where the East Coast Magnetic Anomaly (ECMA) is observed; whereas, the depth-to-basement contours are displaced up to 75 km landward of the shelf break in the Banquereau Bank area.

Two deep MCS reflection profiles from the 1980's cross the margin and define the general geometry, reflective fabric and the shape of the major sedimentary basins [46]. This information has revealed major variations in the structural fabric both along and across the margin. These variations include transitions from a volcanic margin style in the southwest [47] (more typical of the US Atlantic margins to the south) to a non-volcanic margin in the middle; and a wide transition zone of uncertain composition across the margin between thinned continental and ocean crust [46]. However, these profiles leave many unanswered questions. Where do the velocities indicate the OCT exists and how do they correlate with the MCS profiles? How do the lower continental crustal velocities vary along the margin? Does a high velocity lower continental crust exist in the SW part of the margin? Further understanding of these transitions requires modern wide-angle OBS profiles that are able to constrain the velocity structure on profiles that are coincident with the existing deep MCS reflection data. The lack of

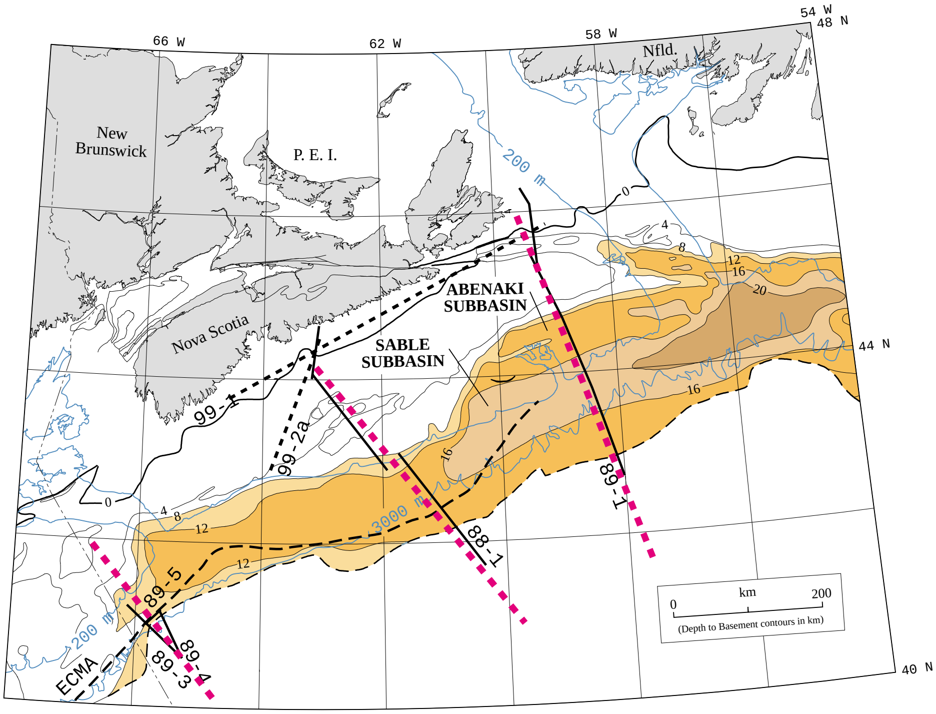

Fig. 7 Nova Scotian margin structures and location of deep seismic profiles

wide-angle OBS profiles (Fig.7) means that the thickness and velocities of the deep sedimentary section, crust and mantle are unconstrained. Furthermore, a recent 1999 OBS refraction profile parallel to the coast [48] indicates significant discrepancies with the older data that were previously used for migration of seismic reflection profiles and for characteristic densities of gravity models. For instance, basement beneath the Abenaki and Sable basins previously has been interpreted as Meguma, the outer most tectonostratigraphic terrane of the Appalachians; but the new velocities and densities associated with the Meguma based on the 1999 refraction profiles raise questions about the validity of this interpretation.

A number of the questions to be addressed by our proposed new seismic data are how and why the Scotian margin varies along strike and how and why it varies across the rift zone. In particular, we want to better define:

- ***The nature of the pre-existing Appalachian continental structure;***
- ***The possible connection between variations in underlying crustal properties and overlying sedimentary thicknesses;***
- ***The nature of the crust in the continent-ocean transition;***
- ***The nature of the transition between the volcanic margins of the US to the south and nonvolcanic margins of Newfoundland/Labrador to the north;***
- ***The nature of rifting symmetry (or asymmetry) with the conjugate African margin;***
- ***Depth to basement and thickness of the underlying salt within the Sedimentary Ridge Province.***

The two deep MCS profiles 89-1 and 88-1 cross the margin in regions with distinct differences in the depth to basement (Fig. 7); but interpretations based on these profiles lack velocity control in the deep sediment and crust. We plan to collect coincident wide-angle OBS data along these lines to fill this gap. Further extension into oceanic crust will be aided by additional seismic profiles collected by German Bundesanstalt für Geowissenschaften und Rohstoffe (BGR). The wide-angle OBS survey will be run from the HUDSON in a two-week period (summer 2001-2). We will also collect OBS data in the vicinity of profiles 89-3/4/5 to determine the velocity structure of the region of seaward-dipping reflectors on the SW margin. Finally we will examine with industry, the possibility of using a denser array of OBS profiles to help define basement in regions where it is obscured by salt. New depth migrations of existing MCS profiles will be made using more accurate velocities. Existing magnetic and gravity data sets will be analyzed with the seismic profiles to produce two crustal cross-sections of the margin from unstretched continental crust to oceanic crust. In addition, gravity models with densities based on the better determined velocities will be constructed to refine interpretation of the crustal models, particularly the large positive anomaly seaward of Sable Island [45]. Finally we will collaborate with BGR in joint interpretation of these cross-sections with conjugate sections across the NW African margin.

Part 4: Geodynamic Modelling and Synthesis of Results

The seismic profiles described above will be used to produce depth sections on six complete conjugate margin transects (1, Flemish Cap-Goban Spur; 3, NB-Iberia; 2, Nova Scotia-NW Africa). Reconstructions of these margins at the time of continental breakup can then be compared to our previous result from Labrador-SW Greenland. ***These transects will mark an important culmination of many years of effort to define the crustal-scale architecture of these non-volcanic margins***. These seismic observations of crustal geometry provide the primary constraints for geodynamic models of lithospheric extension in which to investigate the controlling mechanisms that produce the observed variability in margin style. In particular, comparison with observations and model predictions will allow the degree of asymmetry, and hence mode of extension, to be evaluated. The models in turn may provide predictions and limits useful in discriminating between ambiguous interpretations and observations, such as the feasibility of producing wide zones of highly extended continental crust or zones of serpentinized mantle with little or no melt adjacent to a rift margin.

Much work has already been accomplished in understanding how various lithospheric parameters affect modeling results. We know from these studies that temperature, composition, and strain rate all have a strong influence on the modelled pattern of lithospheric deformation during rifting [49]. ***Previously, however, we lacked a coherent suite of observations with which to fit the model results***. Clear identification of the ocean-continent boundary at a margin is particularly important for determining the width of the zone of thinned continental crust and the rheology and thermal conditions at the time of rifting. In addition, comparison of crustal observations for both sides of a conjugate margin pair has important implications for predicting the mode of lithospheric extension and the degree of asymmetry across a rift system. The relative amounts of synrift and postrift subsidence and the shape of sedimentary basins at rift margins are also strongly dependent on the style of extension and the compensation of rift-related loads by the variable-strength lithosphere [50].

Theoretical models also will help us to link features of both the bulk crustal geometry in the velocity models and images of faulting on reflection profiles. For instance, deep seismic reflection data from both the northern Grand Banks and Nova Scotia margins have indicated the presence of crustal-scale faults that extend into the lower crust. Models combining lithospheric extension and regional isostasy [51] have suggested that extension was focused at greater depths on these margin segments than for nearby areas where deep faulting is not exhibited. A possible explanation for these results is the episodic, slow rifting between North America and Africa/Iberia, which would have minimized lithospheric heating during extension and allowed the lithosphere to maintain strength to greater depth. The new seismic data will provide an opportunity to constrain these existing models with complete crustal profiles for several complete conjugate margins.

Field Equipment for Seismic Profiling: Existing Systems and New Requirements

The main purpose of our field seismic programs is to collect new MCS and OBS datasets to complete conjugate crustal depth sections across the three margin transects previously described. The first field program (July-Aug 2000) will be done on two US research vessels using the new Lamont MCS system and an existing combination of 34 instruments (20 Woods Hole OBH and 14 DAL-GSC OBS). Subsequent OBS profiles across the Flemish Cap and Scotian margins will be conducted using the GSC airgun array and joint DAL-GSC OBS pool. However, the existing capability of our Canadian equipment is not sufficient to obtain data of comparable quality to either the Newfoundland basin profiles or to the new profiles planned for Goban Spur. When analyzing margin transects it is very important to use data of comparable quality in order to properly interpret similar or dissimilar features. Thus it is important to upgrade our capabilities in order to collect data of comparable quality. This does not mean starting from scratch but building on existing systems to increase their capabilities. There are two fundamental requirements which are described in the following sections:

- ***Increase the total number of the DAL-GSC pool of digital OBS from 14 to 24. The GSC will contribute their existing hardware for 10 new instruments. This grant will provide funds to build the new electronics compatible with the 14 existing instruments.***
- ***Improve the existing GSC airgun source. We request NSERC funds to purchase new airguns for a tuned 12-gun array based on the British NERC airgun array. The GSC will commit their support for the implementation of this system on HUDSON.***

These upgrades will be useful not just for this current project but also for future studies requiring seismic profiling. This includes full MCS reflection profiling capability when combined with the UVIC multichannel array recently refurbished from the former DREP array using CFI funds and successfully used on the Vancouver margin in July-Aug 1999.

(a) Ocean Bottom Seismometers

The current pool of DAL-GSC digital OBS consists of 6 instruments previously built by Dalhousie and 8 recent additions by the GSC. These 14 instruments use the same packaging, recovery aids and release mechanism of the earlier GSC analog instruments, which had been the backbone of most previous Canadian OBS profiles (e.g. Fig. 3) since the early 1980's. The newer digital electronics was originally designed in 1993 by Dalhousie using an NSERC Strategic equipment grant and some additional funding and ship time for instrument testing from DREA. Since 1995, they have been used on 7 experiments with a total of 77 deployments, no losses, and an overall data recovery rate of 95%. Data quality has proven comparable or better than other instruments when used on joint experiments, such as the 1995 study in the Iberia Abyssal Plain and 1998 SHIPS program in Georgia Straits.

However, 14 instruments is not sufficient for efficient use on the very long profiles required for complete continent-ocean transects of the Flemish Cap and Scotian margins. A general rule of wide-angle modelling is that the minimum horizontal resolution of the velocity field is generally constrained by the average spacing of receivers. To improve the resolution of critical boundary regions along continent-ocean transects requires decreasing the spacing between receivers of 25-50 km that are typical of our previous results from Labrador-Greenland. With use of 24 instruments on the Flemish Cap and Scotian margin profiles, instrument spacing can be reduced to ~10 km in critical regions. This will significantly improve our ability to match variations in the velocity structure on the wide-angle OBS data to variations in reflectivity indicated on the MCS profiles. It will provide similar instrument spacing to the Newfoundland Basin and Goban Spur profiles. This will allow us to process the wide-angle OBS data using reflection imaging methods such as depth migration. It will allow us to test the use of OBS bottom hydrophone/geophone data on shorter 2-D or 3-D profiles for improved definition of deeper structural boundaries, in regions where standard MCS profiles have problems in imaging structures (e.g. slope basins and salt).

(b) Airgun Source Array

We request funds to improve the existing GSC airgun array from its current configuration of six, 1000 in^3 airguns to a tuned system similar to the NERC 6346 in^3 array. Using the present array with the same volume for all airguns results in a “ringy” character to the signal, because secondary pulses resulting from ghosts and oscillations of the rising air bubbles constructively interfere. In contrast, using a variety of different airguns in a tuned array can suppress these secondary pulses by destructive interference. This effect is illustrated in Fig. 8, where the unfiltered source signature of the present GSC array shows three distinctive pulses following the initial peak. For comparison, the signatures of the NERC 6346 in^3 airgun array (12 airguns with volumes from 120 to 1000 in^3) and the Lamont 8473 in^3 array used on EWING (20 airguns with volumes from 145 to 850 in^3) lack these later pulses. This characteristic is particularly important for a seismic source used in MCS profiles, where these second pulses can interfere with later reflections.

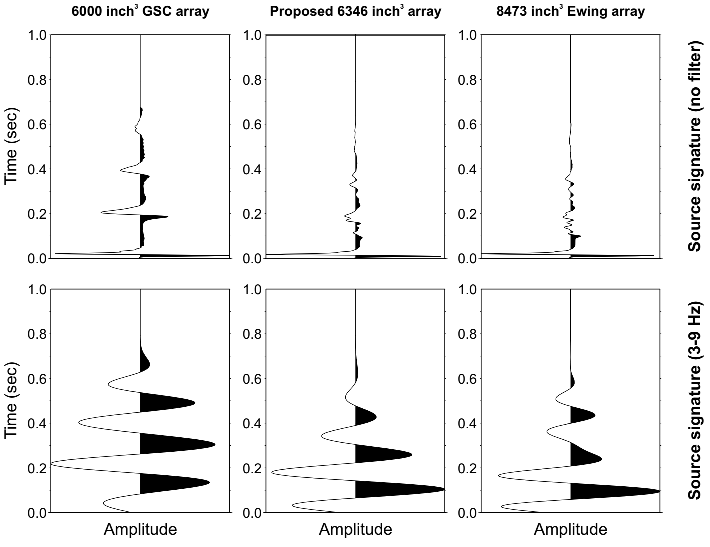

Fig. 8 Comparison of Airgun source wavelets

In deep seismic and refraction seismic experiments with long shot-receiver offsets, the higher frequency components of the signal are attenuated by the earth. To simulate this effect, the original signals were filtered (3-9 Hz) as shown in the lower part of Fig.8. The GSC array has a sweep length of 600 ms, while the major energy in the NERC and Lamont arrays falls in a 200-300 ms window. Second arrivals in wide-angle seismic experiments from mid-crustal reflections/refractions contribute significantly in defining crustal structures. These arrivals often follow the first arrivals by a few hundreds of msecs and the present GSC array is often not capable of detecting them. A reduction of the sweep length is therefore essential to improve the seismic image.

Research Team, Methodology and Project Management

This project brings together research groups at three universities (Dalhousie, Memorial, and Calgary) and at the Geological Survey of Canada - Atlantic in combination with our international partners from the United States, Denmark, Britain and Germany. These groups all have had long-standing research interests and experience in previous studies of rifted margins. This experience includes the development and use of equipment for making seismic and heat flow measurements at sea and in the application of modern processing, analysis and modeling techniques. Various research teams will concentrate on specific aspects of this combined effort as described below.

Keith Louden (Dalhousie University) will be the overall project coordinator. A research associate will be hired to assist in running the program and synthesizing all data to be collected by the project in coordination with our international partners. This will also include central collection of all existing data sets (primarily seismic) relevant to the Scotia and Newfoundland margins and their conjugates. This task will be coordinated with the GSC-Atlantic, where much of the data already has been collected. Together with the Memorial and Calgary groups, we will produce enhanced images along transects from existing seismic data. We will also investigate the location and possible availability of more recent industry data. For the new field work, Dalhousie and Memorial groups will take lead roles in the Newfoundland Basin and Flemish Cap studies, and the GSC-Atlantic group will lead the Scotian margin study. The CREWES group (Calgary) will help with processing techniques and coordinate the higher resolution detailed studies of the shelf/slope regions using 4-C OBS receivers.

Field support of sea-going instruments for the three cruises will be shared by Dalhousie and GSC. Dalhousie will operate the joint DAL-GSC OBS instruments for wide-angle profiles to be taken on the three field projects and for production of the digital data in standard (segy) format. Dalhousie will operate their new 32 sensor heat flow probe in the Newfoundland basin and Flemish Cap cruises. (Borehole and off-shore heat flow data already exist on the Scotian margin). The DAL heat flow probe is being built with contract funds from commercial surveys in 1998 off the W African margin and in the Gulf of Mexico. We are requesting minimal Canadian ship time to test this new system before its first use in summer 2000. GSC will take the lead role in constructing the new joint seismic equipment. In consulation with Dalhousie the GSC will construct the 10 new OBS to augment the existing GSC-DAL OBS facility. The GSC will construct the new 12-gun tuned seismic source array and operate it at sea.

Analysis of the OBS and heat flow data along the major transects will be done by Dalhousie (Keith Louden, the new research associate, and PhD student Helen Lau) for the NB and Flemish Cap transects and at GSC-Atlantic (Ruth Jackson) for the Scotian margin transects. Techniques for wide-angle modeling include standard use of 2-D modeling routines RAYINV and RAYAMP. In addition, we have recent experience with tomographic methods in 2-D and 3-D, which we have used during analysis of wide-angle data in Labrador (Lithoprobe ECSOOT program) [52]. We also have previous experience in combining velocity models from the OBS profiles with coincident MCS reflection profiles from our work in the Iberia margin [53]. Processing and analysis of heat flow data have been conducted for many years at Dalhousie. We have recently improved our processing procedures for use with our new 32-sensors probe.

J. Hall and C. Hurich (Memorial) will have responsibility of processing MCS data for the NB study. Both have extensive experience in processing deep marine MCS data. The MUN seismic data processing facility includes several SUN workstations, stand-alone PCs running Linux and Windows-based software, and a networked PC farm using Parallel Virtual Machine software (proven capable of very fast pre-stack migrations). Seismic data processing software includes batch processing packages for marine data (STARPAK), interactive packages (IT&AInsight), Seismic Unix, VISTA, various other proprietary packages, and various code written in-house for pre-stack migration and wavefield-extrapolation multiple removal. The costs of a standard marine processing sequence is modest (estimated at 3 hours per km @ $8 per cpu hour), but includes f-k filtering, decon, bandpass filtering, velocity analysis by semblance, stack, repeated migrations, and coherency-filtered plots. Significant extra cost attaches to dip move out and pre- stack migrations. We allow for partial use of these processes to critical parts of the data set, where dips and lateral velocity gradients are high, and structure complex.

For L. Lines and R. Stewart (CREWES), there are several interesting areas of application for use of 4-C ocean bottom data. (1) The use of prestack depth migration techniques to ocean bottom seismic recordings of P-P and P-S converted wave images. Reflected elastic wave images should tie at depth [54] and the imaging of P-S wavefields can produce vastly improved depth images compared to P-P reflections, especially in the presence of gas clouds in the subsurface [55]. (2) The use of multi-component ocean bottom recording to suppress water bottom multiples through techniques such as the dual sensor recording [56] and through deconvolution of dual wavefields. These multiple suppression applications are part of a joint project between CREWES, MUN, and industry sponsors [57]. (3) Wavefield separation on OBS data. Three-component geophone receivers record both P and S waves on vertical and horizontal sensors. Algorithms are being developed to output a pure P wavefield and pure S wavefield from the 3-C recorded data [58]. In addition, the inclusion of statics in the separation process can help in recovering pure wavefields. (4) OBS coupling and 3-C geophone response. A significant problem for bottom receivers is coupling of the sensor to the sea-bottom. Problems such as cross-coupling of horizontal to vertical motion can occur. OBS data will be used to analyze correction algorithms that have been developed to ameliorate this problem [59]. These results have potential application to similar coupling problems with use of ocean bottom cables (OBC). (5) Vertical cable acquisition and processing. Vertical cable acquisition and imaging may be beneficial in regions with highly dipping features that are problematic for conventional horizontal array techniques [60]. The Dalhousie OBS have the capability to be used with vertical hydrophone cables of up to 12-channels each. We will investigate their potential use in this configuration.

Sonya Dehler and Ross Boutilier (GSC-Atlantic) will have primary responsibility for development of geodynamic models relevant to these conjugate sections. Synthesis of the margin transects with their conjugates will be coordinated with our international partners. At the end of the project, Dalhousie will coordinate the production of a complete synthesis of results (e.g. maps, seismic data, interpretation of margin cross-sections, etc) in addition to the normal research publications.

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