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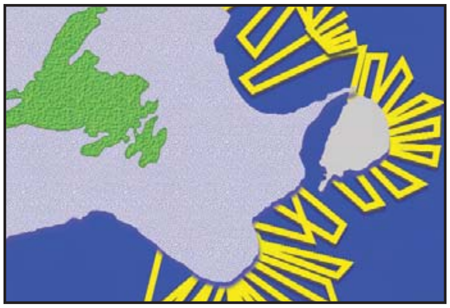

Defining Canada's Extended Continental Shelves

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SUMMARY
Article 76 of the United Nations Convention on the Law of the Sea provides a process to delineate Canada's continental shelf where it extends beyond 200 nautical miles. After ratification of the Convention in 2003, Canada started a program to acquire and analyze the scientific data required for a submission to the Commission on the limits of the continental shelf. This submission will assist Canada in defining the outer limits of its continental shelf, thereby determining, with precision, the area where Canada may exercise its sovereign rights over natural resources. This paper outlines the scope of that program and summarizes the scientific activities to date. Data collection along the Atlantic margin was completed according to plan and the data are presently being analyzed. Data collection in the Arctic has been challenging because of ice and weather conditions, and several innovative solutions were implemented to collect seismic and bathymetry data using icebreakers and large ice camps. The narrow Pacific margin provides no clear prospects for an extended continental shelf. Overall, the program is on schedule to meet the December 2013 deadline for submission to the Commission.

SOMMAIRE
L'article 76 de la Convention des Nations Unies sur le droit de la mer comporte une procédure permettant de définir l'étendue du plateau continental canadien au-delà des 200 miles nautiques. Après ratification de la Convention en 2003, le Canada a lancé un programme d'acquisition et d'analyse des données scientifiques exigées par la Commission pour définir les limites du plateau continental. Le dépôt de ces données aidera le Canada à définir les limites extérieures de son plateau continental, et donc, de déterminer précisément le territoire où il pourra exercer des droits souverains sur les ressources naturelles. Le présent article décrit ce programme et résume les activités scientifiques réalisées à ce jour. Le long du plateau continental de l'Atlantique la collecte des données s'est terminée comme prévu et leur analyse est en cours. Dans l'Arctique, la collecte des données n'a pas été facile en raison de la glace et les conditions météorologiques, et plusieurs solutions innovantes ont dues être mises en œuvre afin de recueillir des données sismiques et bathymétriques, comme l'utilisation de brise-glaces et le recours à de grands camps de glace. Sur la côte du Pacifique, l'étroitesse du plateau continental exclu toutes possibilités d'extension évidemment. En gros, le programme se déroule comme prévu, et la date limite du décembre 2013 pour soumission du dossier à la Commission devrait être respectée.

INTRODUCTION
In scientific terms, the continental margin is generally defined as the zone separating the thin ocean crust from the thick continental crust. The margin, comprising the continental shelf and slope, can be viewed as the submerged extension of the continent. The geology and geomorphology of continental margins is diverse and reflects the tectonic processes that formed them, including rifting, collision and subsidence.

Because of its complexity and variety, the continental margin is often defined, in geological terms, as a zone with unclear boundaries, thereby making it unsuitable to be used in a legal definition of marine jurisdiction. It is in this context that the United Nations Convention on the Law of the Sea (UNCLOS), among its many provisions, provides a legal definition of the continental shelf.

This paper summarizes those parts of UNCLOS that are pertinent to the continental shelf and outlines the links between some of the legal and scientific concepts. Some of these concepts were described earlier (Macnab and Haworth 2001), but the present paper describes the next step, a major program to collect the scientific data required to define the outer limits of Canada's continental shelves in the

Atlantic and Arctic oceans. This contribution provides a status report on this ongoing program, but does not speculate on its final outcomes.

UNCLOS and ARTICLE 76

UNCLOS has sometimes been called the constitution of the oceans. It provides a comprehensive framework for the governance of a large part of the world's oceans. The Convention was adopted in 1982, after nine years of negotiations, and came into force in 1994, after ratification by 60 states. Canada ratified the Convention in 2003. With 161 parties, the Convention has become one of the most broadly accepted treaties in the world.

The provisions of UNCLOS range from resource development to protection and preservation of the marine environment; marine scientific research to navigation; and conservation and management of living marine resources to settlement of disputes (United Nations 1982). The Convention identifies several maritime zones (Fig. 1A), such as the territorial sea, the contiguous zone, the (juridical) continental shelf and the Area. All coastal states are entitled to a continental shelf of 200 nautical miles (nm) and states that meet certain criteria may have a shelf that extends beyond 200 nm.

A state has sovereign rights over the natural resources on, and under, the seabed of its continental shelf (inside 200 nm this includes rights over the living resources in the water column). These rights are exclusive and do not depend on occupation or proclamation (United Nations 1982, Article 77). The seabed beyond the continental shelves is called the Area; its natural resources are considered the common heritage of mankind and are administered by the International Seabed Authority. In the case of an extended continental shelf, i.e. beyond 200 nm, states are required to determine, with precision, the area in which they may exercise their sovereign rights. In Article 76, the Convention sets out a process by which a state can do this.

Article 76

Article 76 provides a definition of the juridical continental shelf by incorporating both legal and scientific terms

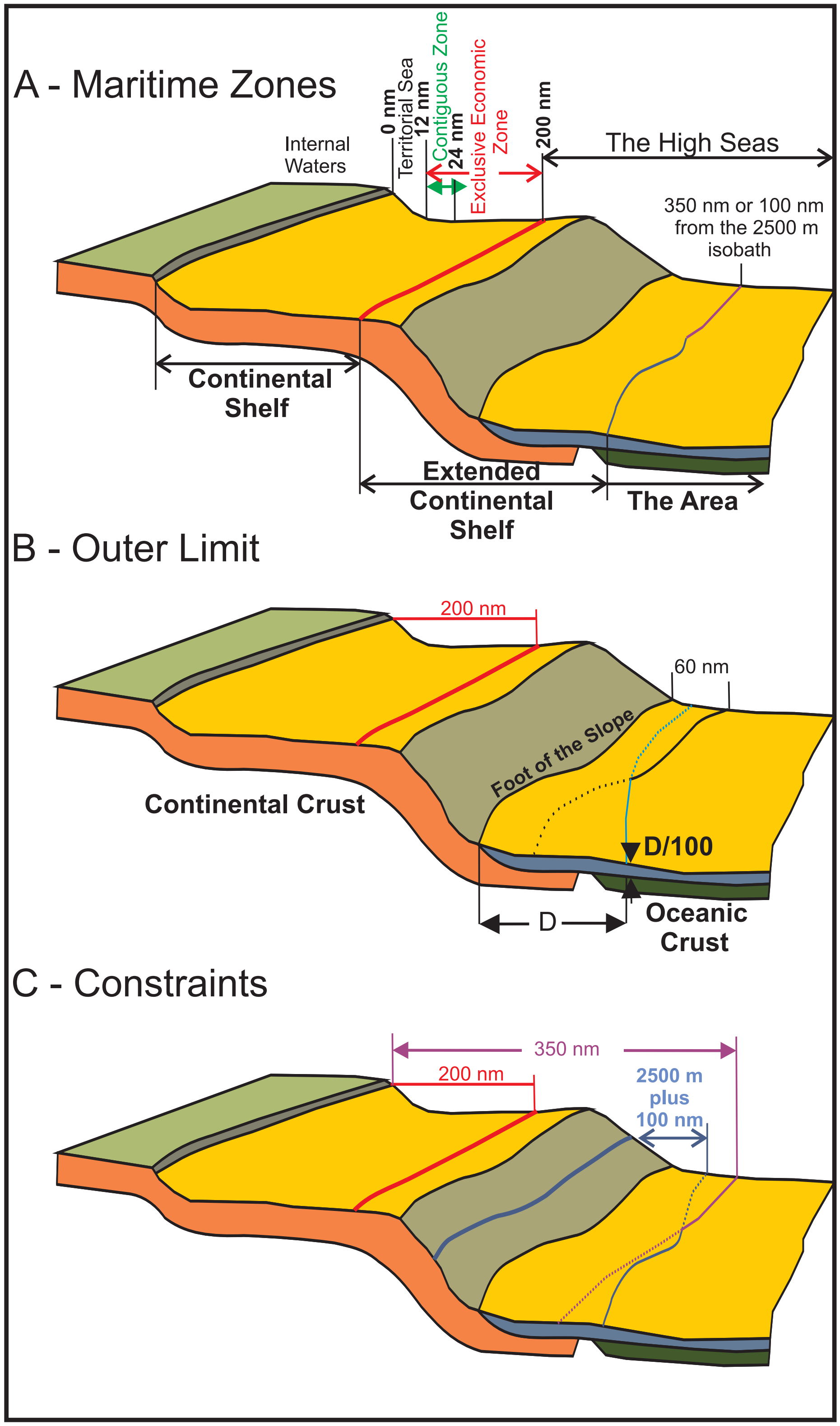

Figure 1. A. The maritime zones as outlined by UNCLOS. **B.** Sketch of an idealized seafloor showing how the foot of the slope (FOS) plus 60 nm (nautical mile) line and the sediment line are combined to form the outer limit. The green line is the Gardiner line, defined by D = the distance to a point where the thickness of the sedimentary layer is at least 1% of the shortest distance from that point to the FOS. **C.** Sketch of an idealized seafloor showing how the 350 nm line and the 2500 m isobath plus 100 nm line are combined to define constraints on the maximum extent of the continental shelf.

(Fig. 1). The Article also describes the entitlement of coastal states to delineate the extended continental shelf. The continental shelf is defined as: … *the natural prolongation of its land territory to the outer edge of the continental margin, or to a distance of 200 nautical mile* …(paragraph 1). This definition uses the continental margin as a 'yardstick', which is defined as: …*the submerged prolongation of the land mass of the coastal State, and consists of the seabed and subsoil of the shelf, the slope and the rise. It does not include the deep ocean floor with its oceanic ridges or the subsoil thereof* (paragraph 3).

It is important to realize the differences between the scientific definition of the continental shelf (gently sloping submerged marginal zone of the continents extending from shore to an abrupt increase in bottom inclination) and the above legal definition, which includes the continental margin and can include parts of the deep ocean floor (Fig. 1). To avoid confusion, we will use in this paper the term 'shelf' when we indicate the scientific continental shelf. The term 'continental shelf' will be used for the legal continental shelf, as defined above.

If the outer edge of the continental margin extends beyond 200 nm, a coastal state must demonstrate that it meets the criteria of Article 76 and collect the geological and geomorphological data to define its extended continental shelf. Article 76 provides formulae for measuring the continental shelf seaward (Fig. 1B). The first step is to identify the 'foot of the continental slope' (FOS), defined as the point of maximum change in gradient at its base. Measuring from this point, the outer limit is established either at a distance of 60 nm from the FOS, or the distance to a point where the thickness of the sedimentary layer is at least 1% of the shortest distance from such point to the FOS. A line connecting these points is known as the Gardiner line. It is often overlooked that establishing a Gardiner line requires a sediment thickness that is 1% of the distance to the FOS. Therefore, the seismic records need to be depth converted, using sediment velocities. Establishing those velocities is not always easy, especially in the Arctic (see below).

Figure 2. Canada's potential extended continental shelf based on a preliminary study in the mid 1990s. Black line denotes Canada's Exclusive Economic Zone and the red line shows the preliminary outer limit of the extended shelf. The graphic is for illustrative purposes only.

Article 76 also imposes constraints on the maximum extent of the continental shelf (Fig. 1C). Again, it provides two options: the outer limit shall not exceed 350 nm from the baselines of the coastal state, or extend beyond 100 nm from the 2500 m isobath. A coastal state can use a combination of the above criteria to determine the area of its continental shelf. The outer limit of the continental shelf beyond 200 nm is delineated by straight lines not exceeding 60 nm in length connecting the derived points.

The coastal state must gather and analyze scientific data and then prepare and file a submission to the Commission on the Limits of the Continental Shelf (CLCS). The role of the CLCS is to review a state's submission in light of Article 76 criteria and make recommendations to the state. The members of the CLCS are elected by state parties to the Convention and are to be experts in the fields of geology, geophysics, or hydrography. They serve a five-year term and are eligible for reelection. To assist coastal states, the CLCS produced a set of technical guidelines outlining the information to be submitted (United Nations 1999). Only the coastal state can establish the outer limits of its shelf and if it does so based on recommendations of the CLCS, they are final and binding (Article 76, paragraph 8). It is important to note that the CLCS has no mandate to resolve disputes between states and that the actions of the CLCS are without prejudice to the delimitation of boundaries between coastal states. Disputes must be resolved by the states involved through negotiation or a dispute settlement process.

States have ten years from the date they became party to the Convention to make their submission to the CLCS, although by virtue of decisions taken at meetings of state parties to UNCLOS, this deadline can now be satisfied through the filing of preliminary information about an intended submission. Since states became party to the Convention at different times, they have different deadlines. Canada became a party to the Convention in December 2003 so its deadline is December 2013.

THE CANADIAN SITUATION

Canada is surrounded by three oceans (Fig. 2) and the shelves and margins of each ocean reflect a variety of origins and forms. The Canadian Atlantic margin is a passive margin whose most recent geological history reflects the opening of the Atlantic Ocean. Rifting and subsequent seafloor spreading progressed from south (Scotian margin) to north (Labrador margin). The Scotian Shelf is more than 700 km long and at some places over 200 km wide. The Grand Banks shelf has a width that extends to 450 km and the Labrador Shelf represents the western margin of the Labrador Sea and is as wide as 300 km in some places (Keen and Piper 1990).

The Canadian Arctic margin is poorly understood. The western segment was formed during the opening of the Canada Basin. However, there is some debate over the mechanism of formation of this basin; according to some models of tectonic evolution, the basin resulted from rifting, while in others the opening created a transform or shear margin or a combination of both (e.g. Cochran et al. 2006). Farther to the north, the presence of the Alpha and Lomonosov ridges dominate the margin (Fig. 2). The Arctic shelf varies in width from 65 to 180 km (Johnson et al. 1990).

The Canadian Pacific continental margin is an active subduction margin that occurs at the intersection of the North American, Pacific, Juan de Fuca and Explorer tectonic plates (Hyndman and Rogers 2010). The margin comprises a narrow (in places almost absent) shelf having a steep slope that features terracing, fault scarps, and a poorly developed rise, all merging onto an irregular deep ocean floor.

Using existing datasets and following the parameters and conditions set out in Article 76, the Geological Survey of Canada (GSC) and Canadian Hydrographic Service (CHS) conducted a desktop study in the mid 1990s to get a preliminary indication of Canada's extended continental shelves (Fig. 2). This analysis demonstrated that Canada potentially has an extended continental shelf in both the Atlantic and Arctic oceans that could be as large as the three prairie provinces (GSC 1994). The study also indicated that the narrow margin in the Pacific Ocean provided no clear prospects for an extended continental shelf. Although no full assessment of the resources in the extended continental shelf was included in the desktop study, it stated that some sedimentary basins in the Atlantic Ocean extend beyond 200 nm offshore, e.g. the Grand Banks, and are prospective for hydrocarbons. Information about the Arctic regions beyond 200 nm is inadequate, but the outlook for gas hydrates in that area is promising.

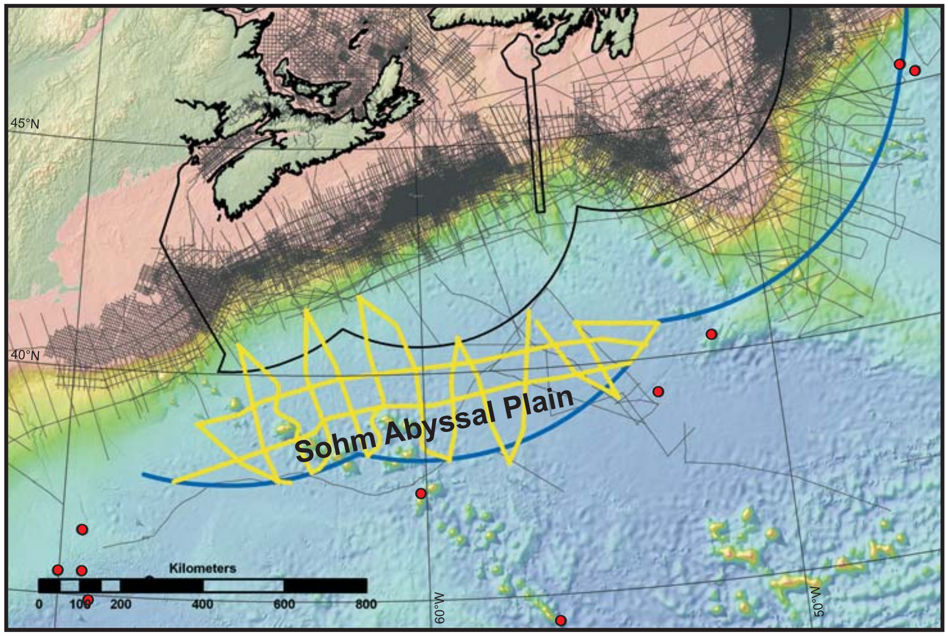

Figure 3. Existing industry seismic data on the Scotian margin (black lines) are mainly located on the shelf. In 2007, 6900 km of multi-channel seismic data were acquired over the Sohm Abyssal Plain (yellow lines). Also shown are the 200 nm (black) and 350 nm (blue) limits, as well as the location of Ocean Drilling Program drill holes (red circles).

THE CANADIAN PROGRAM

After Canada's ratification of UNCLOS in late 2003, work began on acquiring the necessary data to produce a scientifically sound and defensible submission to the CLCS. Securing international recognition for the full extent of Canada's continental shelf is a priority for the Government of Canada and as a result, the 2004 federal budget announced $69 million over 10 years for the collection of bathymetric and seismic data. The 2008 federal budget announced an additional $40 million to cover increased data collection and logistics costs as well as legal costs for submission preparation. Canada's Extended Continental Shelf (ECS) Program is the joint responsibility of Foreign Affairs and International Trade Canada (DFAIT), the GSC (part of Natural Resources Canada), and the CHS (part of Fisheries and Oceans Canada). DFAIT provides the legal expertise and advice and is responsible for the overall preparation and presentation of the submission to the CLCS. The GSC and the CHS are responsible for the scientific and technical work necessary for the submission. Based on the analysis of existing data and recommendations of the aforementioned desktop study, survey programs were designed to focus on the Atlantic and Arctic Oceans.

THE ATLANTIC PROGRAM

Geologic and hydrographic data acquisition in offshore Eastern Canada started in the mid 1960s using multiparameter surveys, collecting bathymetric, seismic, gravity and magnetic data. In addition, industry collected a large amount of seismic data for exploration purposes. After amalgamation of these existing data, it is clear that the focus of previous data collection had been on the shelf and that there existed large information gaps in farther offshore areas. As an example, Figure 3 shows a compilation of seismic data on the Scotian margin, demonstrating that few data existed prior to the program in the area beyond 200 nm, where the thickness of sediment is one of the key parameters required to define the outer limits of the continental shelf.

Scotian Margin

The Scotian margin developed after Pangea rifted and North America began to separate from the African continent by the Early to Middle Jurassic. The margin includes a steep narrow slope that extends from 200 to 4000 m water depth onto the Sohm Abyssal Plain (Fig. 4). Underlying the slope region is the Scotian Basin, a prominent sedimentary basin of Early Jurassic age. Basin fill thicknesses exceed 16 km in parts of the basin, and sedimentary units thin gradually seaward to the continental rise and adjacent Sohm Abyssal Plain. Jurassic salt deposition results in salt diapirism (Fig. 4), which impacts the morphology of the lower slope and rise even today (Shimeld 2004).

The Sohm Abyssal Plain generally has a thick sediment cover; compilations of sediment thickness estimate that the thickness is over 2 km in the area beyond 200 nm (GSC 1994). Because a sediment thickness of more than 1 km will result in an outer limit of the continental shelf that is farther seaward than the FOS + 60 nm, it was decided that in this area the Gardiner formula would be appropriate to apply, and additional seismic data were collected for this purpose.

In 2007, a total of 6900 km of seismic data were collected over the Sohm Abyssal Plain (see Fig. 3 for the survey lines). The survey was designed to cover the area beyond 200 nm offshore, and the lines extended to 350 nm (the maximum possible outer limit). The processed seismic data show layers of sediment covering the plain (Fig. 4). The analysis is ongoing and we are using stacking or processing velocities for depth conversion to locate the 1% sediment thickness points (using existing bathymetry profiles to define the FOS). However, locating the FOS along this margin is complicated by the presence of slope failures and other downslope processes.

Slope Processes

Downslope processes, slope failures and erosion along a continental margin can produce a complex lower slope. These depositional features are characteristic of slopes and not of rises. For that reason, the CLCS has considered slope processes as an integral part of the definition of the outer edge of the continental margin. This case is an example of the evolving interpretation of Article 76, which benefits states that are still in the process of analyzing their data.

As an example, in some parts of the Scotian margin, downslope processes clearly played a significant role in establishing its morphology, and these processes are therefore important for establishing FOS locations. The present seafloor on the Scotian Slope has major submarine canyons (Fig. 5) that provide routes for sediment transport from the shelf down the slope (Jenner et al. 2006). Outboard of the troughs and channels are sedimentary fans, the mid-Pleistocene to Holocene Laurentian Fan being the largest (Piper et al. 2007). Figure 5 shows the offshore extent of the Laurentian Fan and how it extends the morphology of the slope outboard relative to the rest of the margin. The Scotian Slope was further modified by processes that cut into and transported unconsolidated sediments to the lower slope and abyssal plain. For example, Mosher et al. (2010) studied a Plio-Pleistocene mass transport deposit from the central Scotian Slope that extends hundreds of kilometres from the shelf break of the margin to beneath the Sohm Abyssal Plain.

Although a final outer limit on the Scotian margin has not yet been established, initial analyses show that the outer limit is located farther seaward than 200 nm, and that Canada will be able to define an extended continental shelf in this area.

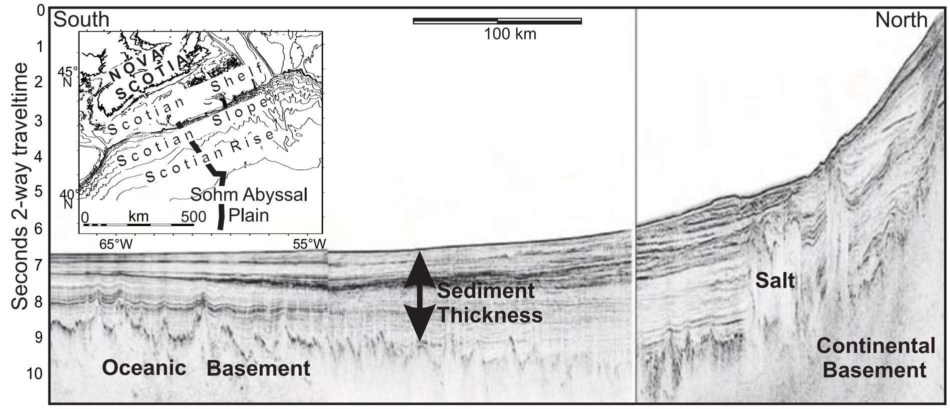

Figure 4. Example of a composite of seismic lines across the Scotian margin into the Sohm Abyssal Plain (see inset for location). This record clearly shows the large thickness of sediments extending into the abyssal plain.

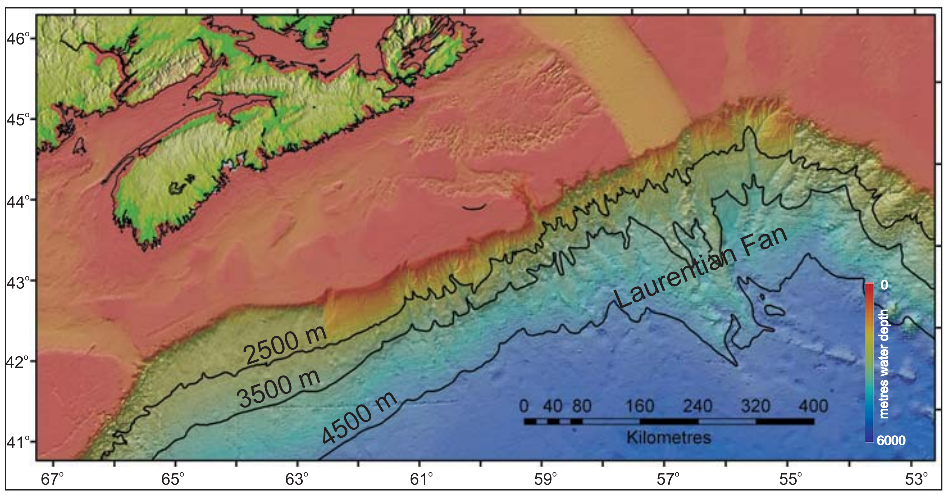

Figure 5. Bathymetry across the Scotian margin; contours clearly demonstrate submarine canyons as well as the Laurentian Fan.

Grand Banks

The Grand Banks is a broad platform, generally shallower than 100 m, underlain by Appalachian continental crust and extending in some places beyond Canada's 200 nm limit. The southwestern Grand Banks is a transform margin associated with the rifting event that separated Nova Scotia from Africa. The eastern Grand Banks margin formed as a result of the rifting and subsequent seafloor spreading that separated it from the Iberian margin. The northern segment of the Grand Banks was formed as a result of the separation from Goban Spur (Keen et al. 1990).

Much of the slope around the Grand Banks is similar to the Scotian Slope, with canyons and gullies providing conduits for downslope transport of sediment. The southwestern Grand Banks slope shows evidence of mass transport processes moving sediment to the lower slope, rise and abyssal plain (Giles et al. 2010). Orphan Basin, on the north flank of the margin, largely consists of stacked mass transport deposits and interbedded turbidites (Tripsanas et al. 2008), providing the sedimentary infill between the Grand Banks margin and Orphan Knoll (Fig. 6).

For a significant part of the Grand Banks margin, the most seaward outer constraint under Article 76 is formed by the 2500 m (isobath) +100 nm limit. Moreover, for a large part of the margin, the FOS + 60 nm points are located either near or beyond that constraint. Therefore, it is important that around the Grand Banks we have a good definition of the FOS and also of the location of the 2500 m isobath. For this reason, in 2006 we acquired 18 500 line-km of multi-beam bathymetry profiles (Fig. 6).

Around the Grand Banks, there are several features that might complicate the determination of the outer limit, or offer an opportunity to further extend the limit (Fig. 6). For example, Flemish Cap is a submarine knoll consisting of a central core of Neoproterozoic rocks associated with the Appalachian Avalon Zone (King et al. 1985). Orphan Knoll is located farther north and its continental origin was confirmed by drilling (Laughton et al. 1972). Orphan Basin links Orphan Knoll to the Grand Banks and this basin is underlain by thinned continental crust (Chian et al. 2001). To consider these features part of the Grand Banks, it must be demonstrated that they all fall inside the envelope of the FOS around the Grand Banks. A bathymetric profile across the Orphan Basin and Orphan Knoll (Fig. 6, see profile bottom of figure) indicates that this is the case: the deep ocean floor and the FOS, as defined under Article 76, are located on the seaward side of Orphan Knoll.

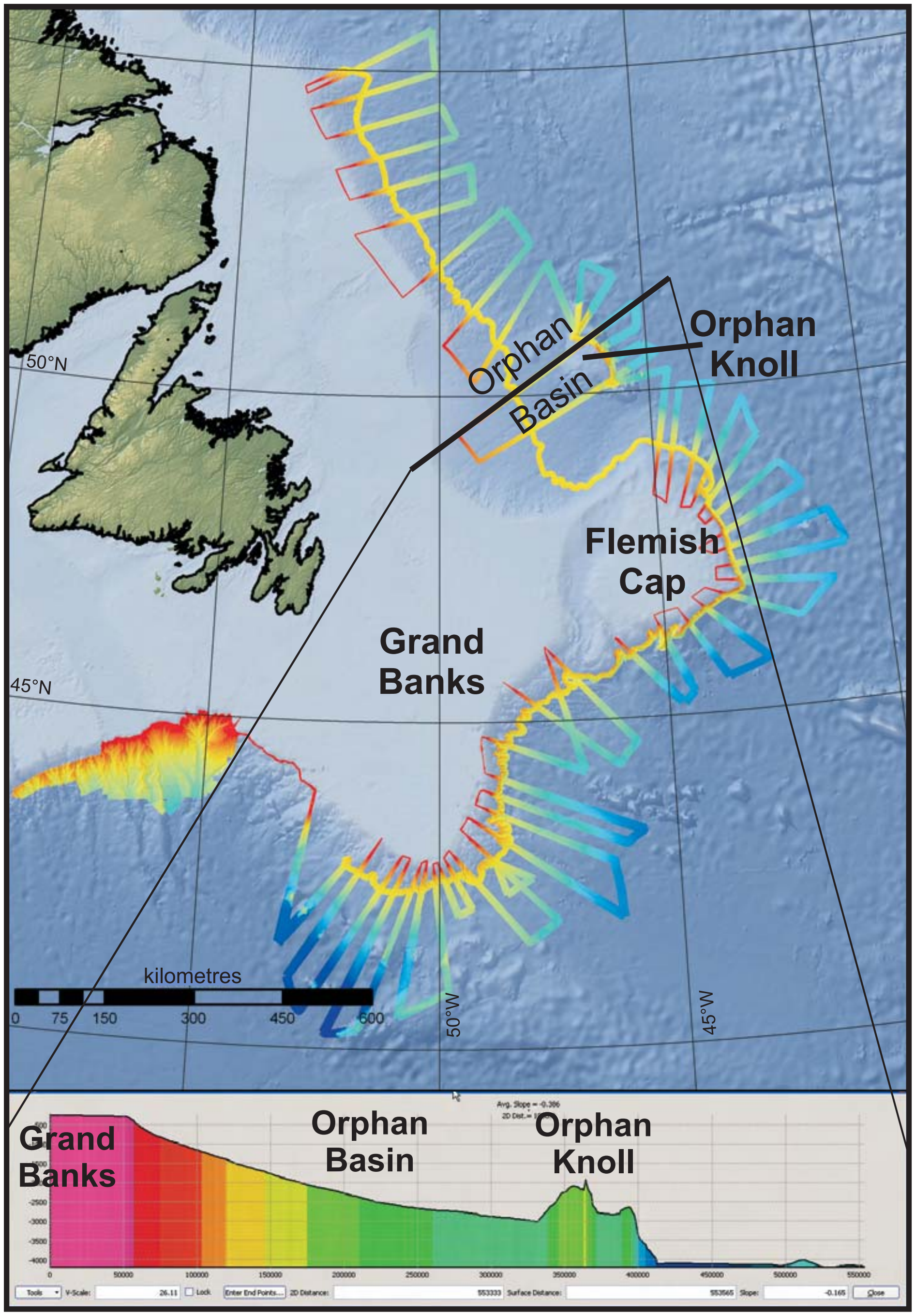

Figure 6. Location of the 2006 multi-beam bathymetry profiles around the Grand Banks. Together with existing bathymetry data in the area, these data will provide locations for the FOS. The inset shows a bathymetric profile across Orphan Basin and Orphan Knoll.

Labrador Margin

The Labrador margin was formed by rifting of the North Atlantic Precambrian craton (Keen et al. 1994). This rifting started in the Early Cretaceous and the subsequent seafloor spreading formed the Labrador Sea. The exact timing of the onset of seafloor spreading is debated, highlighting the complication of the location and nature of the ocean–continent boundary. It is generally agreed that seafloor spreading began during chron 27 (Paleocene) and stopped in the Early Oligocene (just before chron 13). The Labrador Sea remains a small ocean basin that is significantly shallower than the standard deep ocean (Roest et al. 1992).

The upper slope of the Labrador margin appears almost entirely eroded, though some buttes and ridges exist as remnants. Mid-slope gullies coalesce and form channels that transect the rise and abyssal plane to eventually merge with the Northwest Atlantic Mid-Ocean Channel (NAMOC) in the central Labrador Sea. Large mass transport deposits were also imaged on the slope and rise (Deptuck et al. 2007). Another dominant process on the Labrador margin is contour-parallel currents entraining, transporting and depositing sediment. The strong Labrador and North Atlantic deep-water currents form abundant sediment waves along the slope and rise, and have constructed several large drift deposits such as Hamilton Spur (Goss 2006).

The initial analysis of the Labrador margin and possible locations of the foot of the slope concluded that using the FOS+60 nm option would define an outer limit of the continental shelf that is likely to be mostly inside 200 nm (GSC 1994). Therefore, we reviewed existing seismic data to define sediment thickness. Figure 7 shows the location of existing seismic profiles and illustrates that several tracks cross the entire Labrador Sea, covering both the Labrador and Greenland margins (Hinz et al. 1979; Keen et al. 1994). Based on that review, it was decided to collect additional multi-channel seismic data (Fig. 7). Several Ocean Drilling Program well sites provide groundtruth to these seismic data.

Denmark is also in the process of defining the outer limit of the Greenland continental shelf. For that purpose, they have acquired new multichannel seismic data off the Greenland margin (Fig. 7). During the last few years, Canada collaborated with Denmark (acting for Greenland, in this and subsequent contexts) in sharing and jointly analyzing the seismic data in the Labrador Sea. This approach is beneficial to both countries: since the interpretation of the data from each side of the Labrador Sea is consistent and in agreement, each country's submission is strengthened.

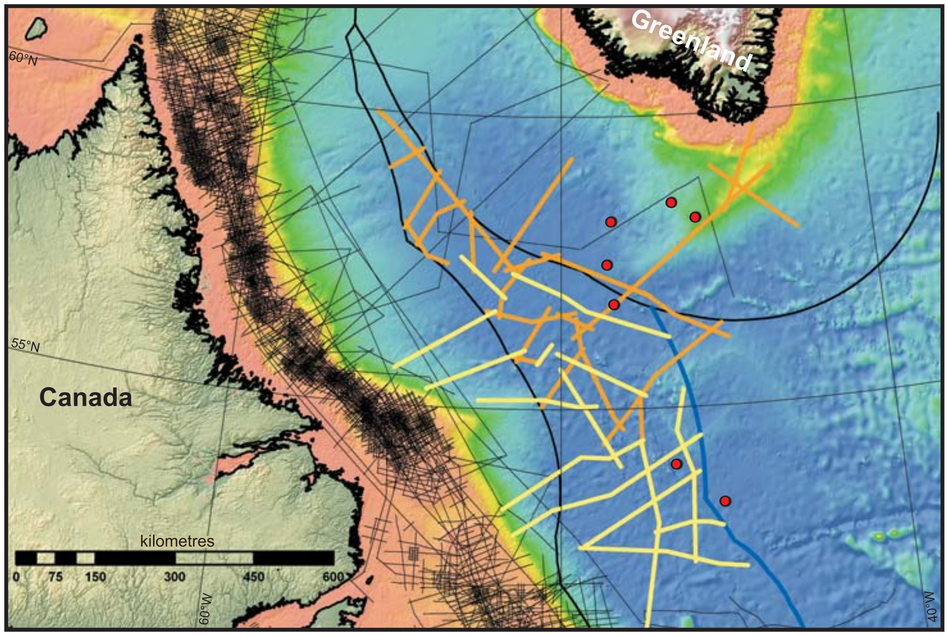

Figure 7. Existing seismic data across the Labrador margin (thin black lines) and the newly acquired multi-channel seismic data (yellow lines). Also shown are the seismic data acquired by the Danish Geological Survey (orange lines) and the 200 nm lines from Canada and Greenland (heavy black lines) and Canada's 350 nm limit (blue line). The red circles denote the location of the ODP drilling sites.

THE ARCTIC PROGRAM

The Arctic Ocean is one of the most understudied oceans in the world. The acquisition of scientific data is logistically and technologically challenging because of its remoteness, the harsh environment, the unpredictable weather and ice conditions, and short field seasons. It is unique because over 50% of its area is underlain by shelf that is generally shallower than 200 m (Jakobsson et al. 2003). The deeper seafloor is divided into two major basins: the Eurasian Basin and the Amerasia Basin (Fig. 8). The Eurasian Basin is relatively well understood to result from seafloor spreading about the Gakkel Ridge. The evolution of the Amerasia Basin and its sub-basin, the Canada Basin, is ambiguous, mainly as a result of complicated geology and insufficient data. Two large submarine mountain ranges (the Lomonosov and Alpha–Mendeleev ridges; Fig. 8) are generally seen as dividing the two major basins. These submarine features were unknown until the middle of the last century (Weber and Roots 1990). The Lomonosov Ridge is generally viewed as a continental sliver that stretches across the Arctic Ocean (e.g. Cochran et al. 2006). In contrast, the origin and structure of the Alpha–Mendeleev Ridge is debated (e.g. Dove et al. 2010). For the purposes of defining the outer limits of Canada's continental shelf, it was necessary to demonstrate that these two features are natural prolongations of its land territory, as defined in Article 76.

Article 76 also considers submarine elevations, including ridges, and their relationship to the continental shelf. It specifically excludes in the definition of a continental margin …*the deep ocean floor with its oceanic ridges*…(paragraph 3). However, it includes ….*submarine elevations that are natural components of the continental margins, such as its plateaux, rises, caps, banks and spurs* (paragraph 6). Submarine ridges that are not natural components of the continental margin are subject to a 350 nm cut-off; if they are a natu-

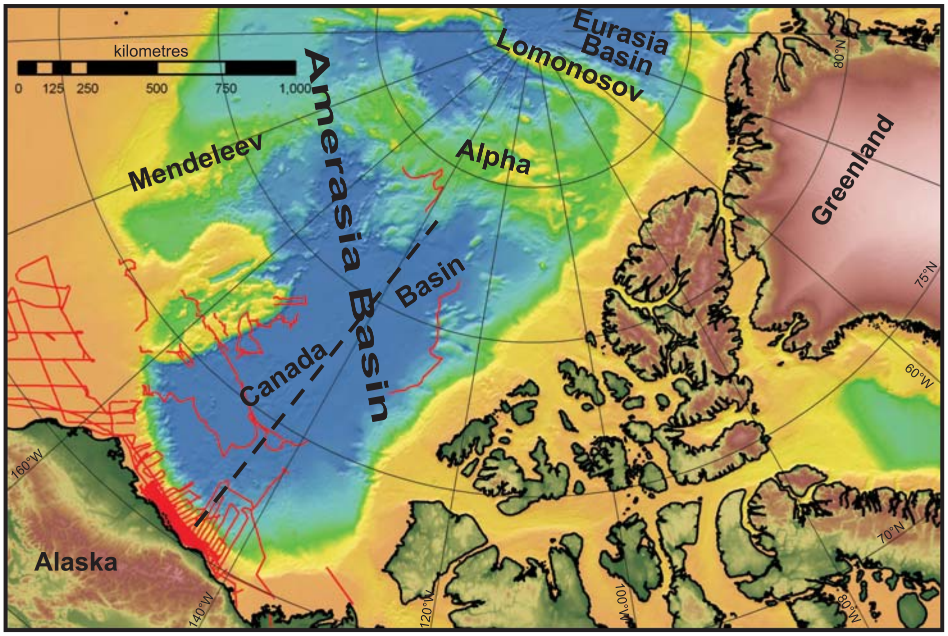

Figure 8. General bathymetry of the Arctic Ocean (based on the International Bathymetric Chart of the Arctic Ocean; Jakobsson et al. 2003). Also shown are the main structural features as well as seismic data (red lines) in and around the Canada Basin that were collected prior to Canada's ECS surveys. The dashed black line is the approximate location of the seismic profile shown in Figure 12.

ral component, the continental shelf can extend beyond 350 nm, but shall not exceed 100 nm from the 2500 m isobath. These 'ridge provisions' have become one of the most contentious and difficult aspects of applying Article 76. Their interpretation has evolved and the CLCS has recently summarized its views: *in cases where seafloor highs are enclosed by the FOS envelope, such highs are automatically regarded as an integral part of that continental margin* (CLCS 2011).

The survey program in the Arctic was designed with two main components. In the western Arctic, in the Canada Basin, sediment thickness is the key factor and to determine this, seismic surveys are required. Ice conditions in the western Arctic generally allow the use of heavy icebreakers to collect scientific data (Hutchinson et al. 2009), hence a data collection program was designed to use icebreakers to collect seismic and bathymetric data. In the eastern Arctic, heavy ice conditions generally occur, especially in the region north of Ellesmere Island, and icebreaker use is often difficult if not impossible (MacDougal et al. 2008). Therefore, offshore ice camps were constructed to use as base camps from which data were collected using helicopter and fixed wing aircraft.

International Collaboration

The Arctic Ocean coastal states (Canada, Russia, Norway, Denmark and the US) are all in the process of defining their extended continental shelves, although they are at different stages. Since data acquisition in the Arctic is a challenging and expensive undertaking, Canada has explored and implemented international partnerships to collect data of mutual benefit. This cooperation mitigates the risks, and reduces costs and environmental impacts; at the same time, a common data interpretation by neighbouring countries enhances the probability of a successful submission.

Over the past five years, Canada has conducted seven joint surveys with Denmark, and is moving forward on joint interpretation and publication of results. With the United States, Canada has conducted three joint surveys in the western Arctic (2008–2010) using the Canadian icebreaker *CCGS Louis S. St-Laurent* and the US icebreaker *USCGC Healy;* a fourth survey is planned for 2011. Since 2007, annual meetings have taken place between Canadian, Danish and Russian officials to discuss the ongoing programs and results; these meetings recently also included officials from the US (from 2009) and Norway (2010).

Canada's Eastern Arctic Program

From the Canadian perspective, the eastern Arctic continental margin is dominated by the Lomonosov and Alpha ridges (Fig. 8). It is important to demonstrate that these features are natural prolongations of the continent; for the Lomonosov Ridge, this is of interest to both Canada and Denmark, whereas Alpha Ridge is important only to Canada. The bathymetry in that region shows a trough north of Ellesmere Island that seemingly separates the ridges from the mainland (Fig. 9). It was therefore necessary to image the crustal structure below the seafloor by measuring the crustal seismic velocities of the ridges, to compare them with those on the adjacent continent.

The 2006 LORITA project (LOmonosov RIdge Test of Appurtenance) was a joint project between Canada and Denmark that conducted seismic and bathymetric surveys on the Lomonosov Ridge. For this expedition, Canadian Forces Station Alert was used as a main base and we established a small ice camp about 100 km offshore. Despite losing 65–70% of the days to bad weather, the primary objective of collecting seismic refraction data was achieved along a 440 km-long north–south profile and a 110 km-long profile along the bathymetric trough (Fig. 9). The data were interpreted jointly with Denmark and the conclusion is that there is continuity of the continental crust from the coast across the trough and onto the Lomonosov Ridge. The velocity structure in the trough suggests that no oceanic crust occurs there (Jackson et al. 2010).

In the spring of 2008, a similar project (ARTA) was undertaken on Alpha Ridge, north of Ellesmere Island (Fig. 9). For this project, a large ice camp was constructed near the mouth of Nansen Sound as well as a small camp about 100 km farther offshore. The seismic refraction experiment consisted of a 350 km-long line perpendicular to the margin and a 175-km-long cross line on the bathymetric trough (Fig. 9). Initial results of this

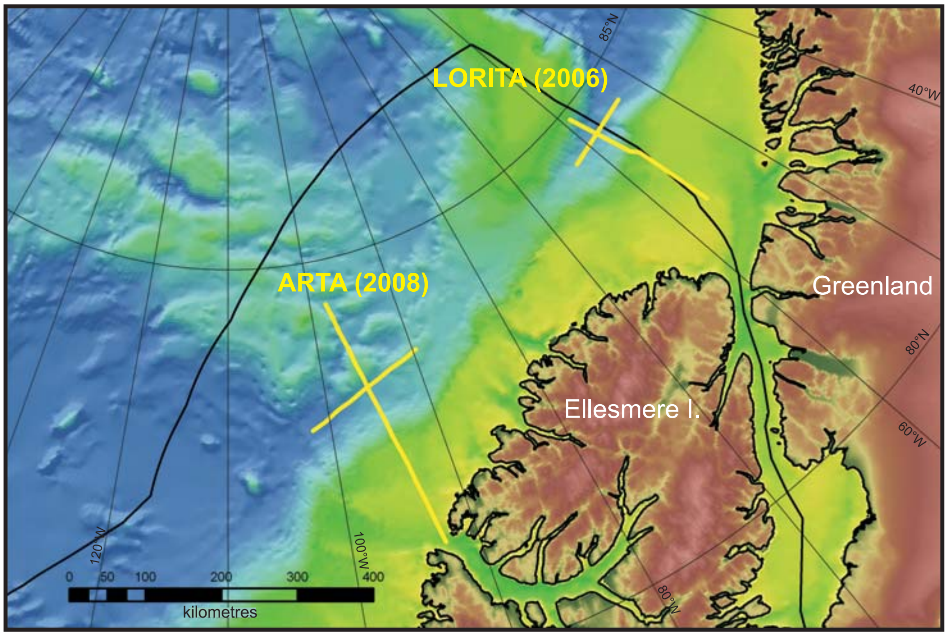

Figure 9. Location of the two seismic refraction experiments (LORITA and ARTA) to investigate the deeper structures of the Lomonosov and Alpha ridges, respectively.

experiment were reported by Funck et al. (2010). Together with previously acquired seismic refraction data and recently acquired Russian data on the Mendeleev and Lomonosov ridges, a more complete model of the deeper crustal structure will be developed to assess that these features are natural components of the Canadian continental margin.

A 2009 joint project with Denmark collected bathymetric data to measure the shape of the seafloor in the area between the Alpha and Lomonosov Ridges. These three surveys were successful and collected a significant amount of new data. However, the construction of large ice camps in remote areas (10–15 large tents, with a population of 30–40 people; see Fig. 10), including flattening the area for runways for supply aircraft, was time consuming and expensive. Moreover, unpredictable weather and ice conditions became a main concern. Open leads generated ice fog, preventing helicopters from flying, and ice floes were breaking up, leading to dangerous situations (requiring an emergency evacuation of a small offshore camp in 2009). Moving farther offshore, as was planned for the last phase of the program, was deemed very risky, and alternatives were investigated. In 2008, a joint project was initiated with DRDC (Defence Research and Development Canada) to use autonomous underwater vehicles (AUV) to go under rather than on or through the ice to collect the requisite data.

Autonomous Underwater Vehicles (AUVs)

The AUVs were constructed by Vancouver-based ISE Ltd. The vehicles are about seven metres long, battery powered, can cover distances of up to 400 km on a single charge and go to water depths of up to 5000 m. In addition, they have a high resolution multi-beam bathymetry system on board.

The AUVs were deployed in April 2010 from a main camp near Borden Island (Fig. 10A); the survey started at the main camp, near shore (Fig. 10B), and then moved to the remote offshore camp (Fig. 10A). A typical mission requires about 3 days, during which time there is no communication with the AUV. During that period, however, the offshore camp, which is on an ice floe, has often drifted away from its original position, sometimes by 10–20 km. This movement necessitated the development of a homing system so that the AUV could find its way to the camp's new location. The first deployments of the AUV (Fig. 10C) were successful; it travelled over 1000 km during a continuous operating period of 10 days, at water depths of over 3300 m under the ice. It also successfully homed in to a moving ice camp from a distance of 50 km. During the missions, it completed about 500 km of bathymetric measurements in key areas. Collectively these achievements represent a world record for under-ice operations in the Arctic.

Canada's Western Arctic Program

To define the outer limits of Canada's extended continental shelf in the Canada Basin, the thickness of the sediment cover is needed to be able to define the points where this thickness is at least 1% of the distance to the foot of the slope. Therefore, the program in the western Arctic consists mainly of seismic surveys. Prior to 2006, there were only a few seismic lines crossing the basin (Fig. 8), constituting a serious knowledge gap in producing a sediment thickness map of the Arctic (Jackson et al, 1990).

The collection of seismic data in the Arctic given prevailing ice conditions is extremely difficult. The potentially heavy ice conditions require that surveying be done with an icebreaker and the noise of its powerful engines can interfere with the seismic sound source. Moreover, the standard equipment for seismic data collection needs to be strengthened because of fragments of ice behind the icebreaker, which may interfere with the towing of the seismic sound sources and receivers. A modified seismic system was developed (e.g. Mosher et al. 2009), consisting of an 1150 cubic inch (18.8 litre) G-gun array and a 16 channel digital hydrophone streamer. To prevent interference of the source array with ice, it is towed at 11.5 m depth, below the keel of most sea ice. The hydrophone streamer is towed from the rear of the source array, also to keep it deep beneath the ice. The length of the streamer (100 m) is short for operating in deep water, providing little move-out for velocity analysis. Instead, velocity information is derived from wide angle reflection and refraction data received on expendable sonobuoys, deployed at regular intervals.

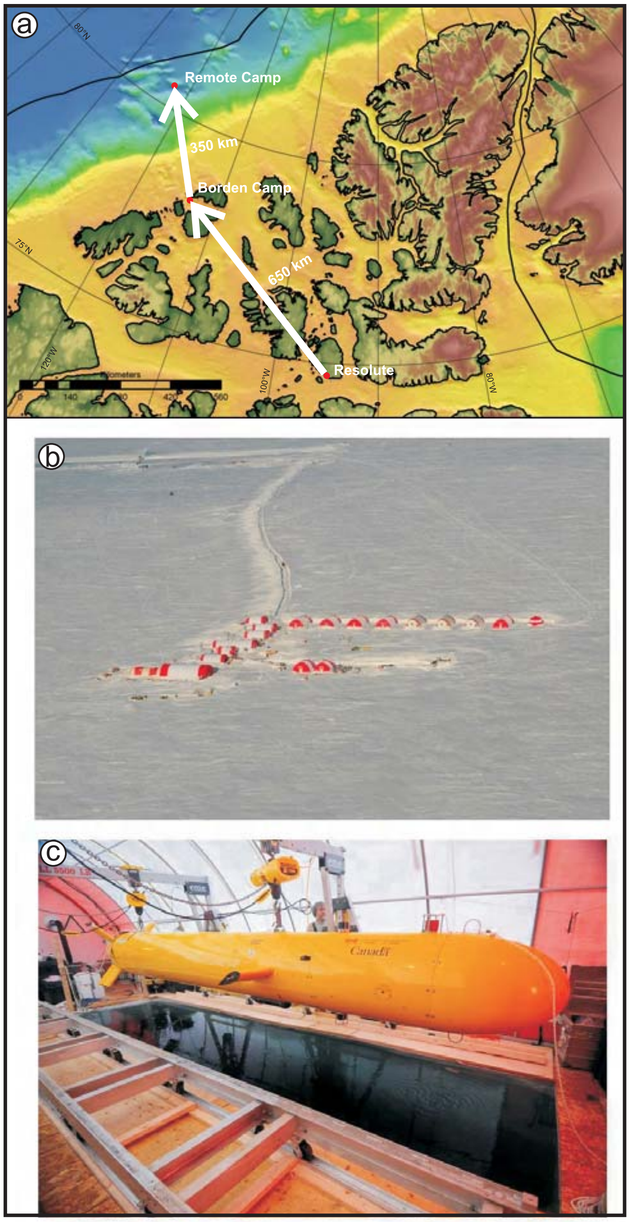

Figure 10. A. Location diagram of the Borden main ice camp and the remote offshore ice camp for the AUV survey. All equipment was brought to Resolute and then flown to the two camps. **B.** Image of the Borden main ice camp. The camp has 17 tents and a population of over 40 people. Also shown at the upper left side of the image is the runway (image courtesy of Janice Lang, DRDC). **C.** Image of the AUV at the Borden main ice camp, prior to being sent out on a mission. Also shown is the large hole that was created by removing over 30 000 kg of ice (image courtesy of Janice Lang, DRDC).

After testing in 2006, on board the *CCGS Louis S. St-Laurent*, a six-week seismic and bathymetric survey was conducted in September 2007 in the southern part of Canada Basin. Ice conditions varied; to the north and east, near the Canadian Archipelago, heavier ice was generally encountered, and it was concluded that to collect seismic data in these regions, two icebreakers would be required. In 2008, a joint survey with the US was organized using both the *CCGS Louis S. St-Laurent* and the US icebreaker the *USCGC Healy*. In areas where seismic data are important, the *USCGC Healy* breaks ice and the *CCGS Louis S. St-Laurent* follows with its seismic system; in areas where the shape of the seafloor is important, the Canadian vessel breaks ice and the US vessel follows with its high resolution multi-beam bathymetry system. The advantage of this configuration is that since the following icebreaker does not have to break heavy ice, the quality of the data collected is significantly improved.

Four major surveys have now been completed in the western Arctic (3 joint with the US) and over 13 500 km of high quality seismic data were collected (Fig. 11). During these same surveys, in excess of 18 000 km of bathymetry data were also collected. In addition, velocity information was collected with 146 sonobuoy deployments across the entire Canada Basin. After processing, these data will provide a model for the velocity structure of the sediments to be used in seismic depth conversion.

These recent icebreaker surveys covered most of the area in which data were needed for ECS purposes (Fig. 11). The data coverage has more than tripled as a result of these surveys and these new data will significantly improve our knowledge of the region. Figure 12 shows flat lying sediments with thicknesses generally decreasing northward, and pinching out against the topographic highs associated with the Alpha Ridge (Mosher et al. 2011).

Initial interpretations of the data were presented at scientific conferences (Shimeld et al. 2010; Mosher et al. 2011) and publications are in preparation. In the context of defining the outer limits of Canada's continental shelf, the main finding is that the Canada Basin is generally covered by sediment more than 4 km thick, thinning to the north and to the west. These data will support Canada's definition of a significant extended continental shelf in this region.

NEXT STEPS

The main data collection phase in the Atlantic is complete and the data are presently being analysed to determine locations of the foot of the slope and preliminary outer limits of the continental shelf. The data collection in the Arctic is not yet complete. In 2011, we plan to collect seismic and bathymetry data in an area between the Alpha and Lomonosov ridges (Fig. 11). This expedition will be another joint survey with the USA, and includes plans to deploy the AUVs from the icebreaker to collect bathymetry in heavy ice-covered regions. If the 2011 survey is successful, we will have all required data to allow completion of the Arctic analysis.

The program is on schedule for preparation of Canada's submission to CLCS by the deadline of December 2013. Once the submission is received by the CLCS, it will be placed in the queue for review by the Commission, although at the present pace of consideration it may be many years before it is reviewed and recommendations provided.

CONCLUSIONS

The Atlantic component of Canada's Extended Continental Shelf Program has acquired all of the necessary scientific data as planned. Analysis of data is progressing well and initial analyses are encouraging. The Arctic component has proven challenging to date and continues to face the risk of delays

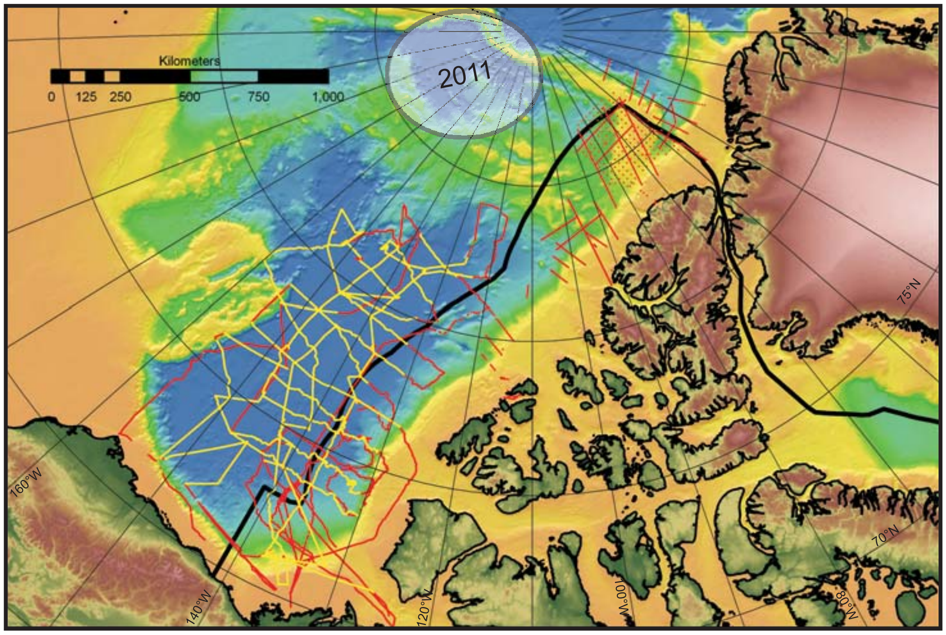

Figure 11. Overview of seismic (yellow) and key bathymetry (red) data collected over the period 2007–2010 in the Arctic Ocean. A total of over 13 500 km of seismic and over 18 000 km of bathymetry data tripled data holdings in the Arctic. Also shown is the outline of the area for the 2011 survey.

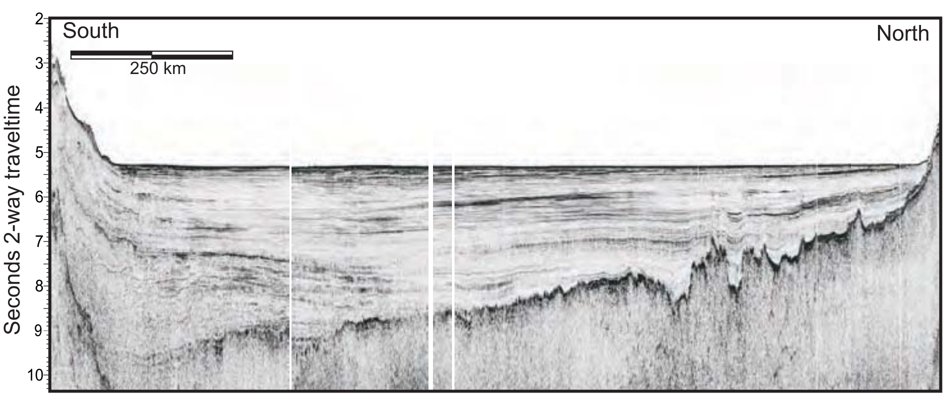

Figure 12. Example of a composite seismic record across the Canada Basin. The record covers about 1200 km from the Alaskan margin in the south to Alpha Ridge in the north (see Fig. 8 for location).

due to weather and ice conditions. As of the end of the 2010 field season, the program has collected most of the required data in the western Arctic but needs additional data in the eastern Arctic. It is hoped that these data will be collected during the fourth Canada – USA joint survey planned for 2011.

The amount of data collected in the Arctic and also the high quality of the data has surpassed the initial hopes of the program. Acquiring these data necessitated several innovations, such as the development of a seismic system that worked in heavy ice conditions and the use of automated underwater vehicles. Effective and continuing cooperation between Arctic Ocean coastal states is a key contributor to this achievement. In addition to providing strong support for Canada's submission to the Commission, the wealth of new data will no doubt lead to a better understanding of the origin and tectonic evolution of the Arctic Ocean.

Presently, Canada is on schedule to prepare and submit its outer limits of the extended continental shelf and substantiating information to the Commission by its deadline of December 2013.

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This program has involved many organizations and dedicated staff to collect and analyse the scientific data. We thank all those who did the logistics for the ice camps (Polar Continental Shelf Program, Environment Canada, Canadian Ice Service, all the pilots and technical staff); those who were involved in the shipborne operations (Canadian Coast Guard, the Commanding Officers and crews of the *CCGS Louis S. St-Laurent*, the *CCGS Hudson*, and the *USCGC Healy*) and our staff and contractors who went out to ice camps and on board ships under rather difficult and sometimes dangerous situations to collect the data. We would also like to acknowledge our partners in the scientific work in Canada, in the USA and in Denmark. We thank Sonya Dehler and Allison Saunders for their thorough reviews. Kevin DesRoches helped prepare illustrations.

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