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Cover image: The Canadian Coast Guard Ship Louis S. St-Laurent operating solo in the perennial icepack of the Arctic Ocean during the 2007 expedition. Photograph by D. Reimer. NRCan photo 2021-493.

Introduction

Upon ratifying the United Nations Convention on the Law of the Sea in 2003, the Government of Canada needed bathymetric and geologic information to define the outer limits of its Extended Continental Shelf (ECS) in the Arctic Ocean basin across an area of about 1.2 million km^2 (Figure 1; Government of Canada, 2019). Multi-year pack-ice, thicker than 1 m and with extensive pressure ridging, still covers much of the area despite increased melting due to global warming. The remoteness and perennial ice-cover make this amongst the most challenging and expensive ocean regions in which to map the seafloor and underlying geology. Multi-national efforts collected reconnaissance-scale geophysical and geological information, beginning in the 1960s with drifting ice camps and in the 1980s with icebreakers. Nonetheless, the vast majority of the area remained un-surveyed when Canada mounted an ambitious program of eight icebreaker expeditions in 2007–2011 and 2014–2016 to acquire geophysical data and seafloor samples. Efforts were coordinated amongst three federal government departments (Natural Resources, Fisheries and Oceans, and Global Affairs) and involved multiple operational collaborations with the United States, Denmark and Sweden to share information and resources (Ridell-Dixon, 2017; Government of Canada, 2019).

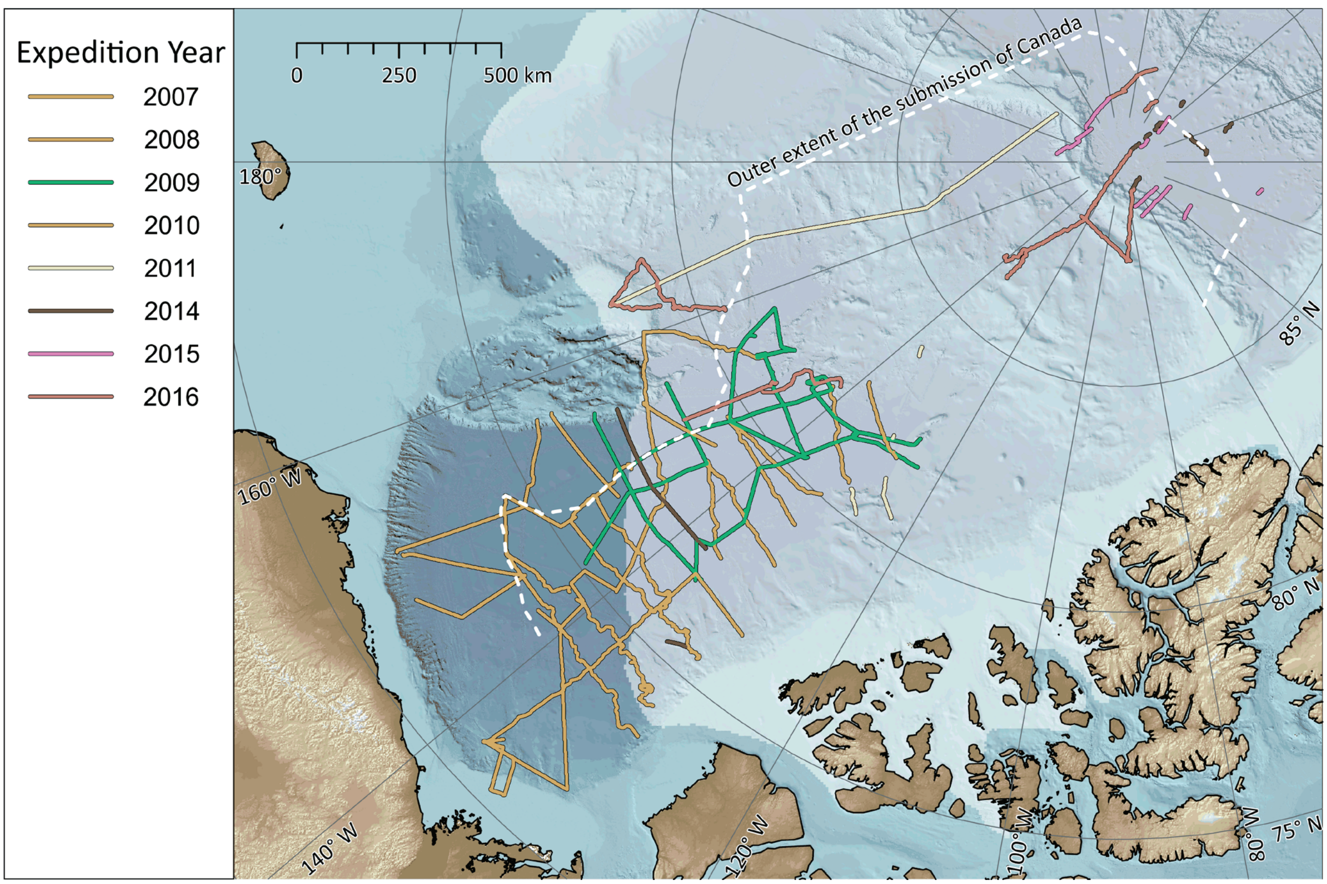

Figure 1: Map of 157 seismic reflection track-lines, with a combined total distance of 18622 km, collected during eight icebreaker expeditions during 2007–2011 and 2014–2016. The dashed white line indicates the outer extent of the submission of Canada in accordance with the United Nations Convention on the Law of the Sea (Government of Canada, 2019). The semi-transparent white polygon indicates the region where the 6-year median ice thickness exceeds 0.5 m at the start of the field season, calculated for August 15 between 2015 and 2020 using data from the Pan-Arctic Ice Ocean Modeling and Assimilation System (Zhang & Rothrock, 2003).

The Geological Survey of Canada (GSC), in the department of Natural Resources, provides scientific knowledge about the ECS region on topics such as the nature and evolution of the Earth's crust and its overlying sedimentary succession. Towards this mandate, GSC scientific and technical staff designed and operated a seismic reflection system for deployment during the icebreaker program (Figure 2). The receiver array consisted of a 16-channel hydrophone streamer with a maximum offset of 250 m. It was towed safely below the pack-ice, at nominal depth of 11.2 m, from a 2300 kg-mass sled immediately astern of the icebreaker. Three G-guns suspended beneath the sled comprised the seismic source, which in most instances had a total volume of 18.8 L. Signals digitized in the streamer were transmitted by ethernet connection to a conventional recording system onboard the icebreaker.

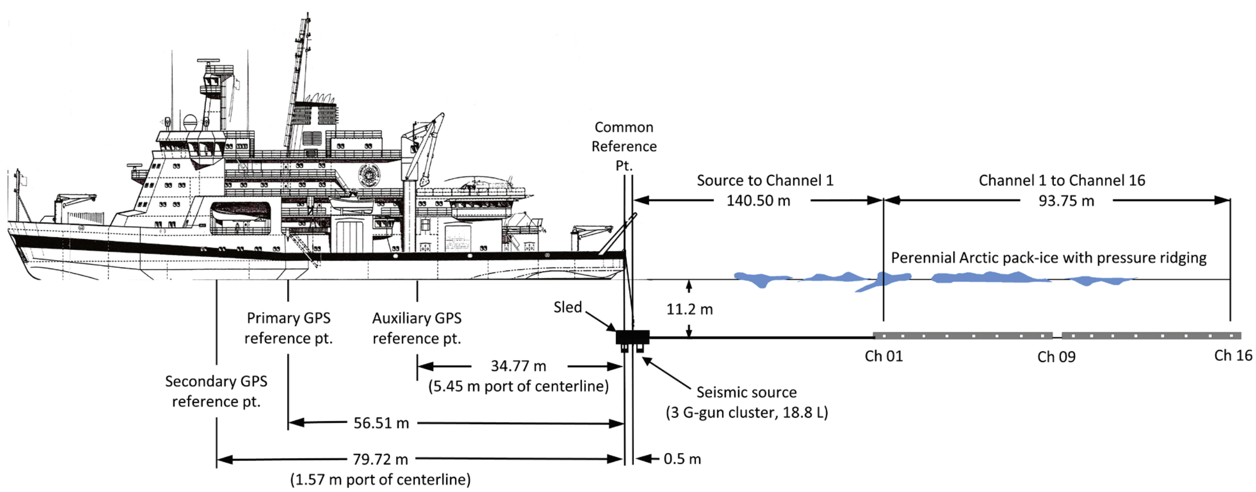

Figure 2: Typical geometry of the seismic source and receiver array towed beneath the pack-ice from a 2300 kg-mass sled immediately astern of the CCGS Louis S. St-Laurent. Navigational data for the shot records are from a differential geographical positional system (GPS) relative to surveyed reference points (pt) onboard the icebreaker.

The first expedition in 2007, with the Canadian Coast Guard Ship *Louis S. St-Laurent,* yielded good-quality data but demonstrated the need for a second icebreaker to clear track-lines ahead of the *Louis* (Hutchinson *et al.*, 2009; Mosher *et al.*, 2012). Between 2008 and 2011, the US Coast Guard Cutter *Healy* fulfilled this purpose, followed in 2014 and 2015 by the Canadian Coast Guard Ship *Terry Fox* and, in 2016, by the icebreaker *Oden* operated by the Swedish Polar Research Secretariat. These eight expeditions produced 157 seismic reflection lines with a combined track-length of 18622 km (Table 1), including four 2016 lines collected in collaboration with the Geological Survey of Denmark and Greenland onboard the *Oden*. Mosher *et al.* (2016) provided a digital release of the 2007–2011 seismic reflection lines with the signal processing that had been applied shipboard during each icebreaker expedition. Signal-to-noise ratio and signal penetration are markedly better in these seismic data compared to those from the 1980s and 1990s, revealing abundant new information about the crust and overlying sedimentary succession (Figure 3).

Table 1: Listing of icebreaker expeditions conducted for the Canadian ECS program between 2007–2011 and 2014–2016.

Survey name	**Icebreaker for seismic operations**	**Icebreaker for clearing track-lines**	**Total seismic track-length (km)**	**Field report**
LSSL2007	*Louis S. St-Laurent*	none	2957	Jackson, 2008
LSSL2008	*Louis S. St-Laurent*	*Healy*	2816	Jackson & Desroches, 2010
LSSL2009	*Louis S. St-Laurent*	*Healy*	4016	Mosher *et al.*, 2009
LSSL2010	*Louis S. St-Laurent*	*Healy*	3763	Mosher *et al.*, 2011
LSSL2011	*Louis S. St-Laurent*	*Healy*	1445	Mosher, 2012
LSSL2014	*Louis S. St-Laurent*	*Terry Fox*	746	Mosher *et al.*, 2018
LSSL2015	*Louis S. St-Laurent*	*Terry Fox*	527	Director, UNCLOS Program, NRCan, *pers. comm.*
LSSL2016	*Louis S. St-Laurent*	Phase 1: *Oden* Phase 2: none	2155	Shimeld & Boggild, 2017
ODEN2016	*Oden*	none	197	Funck *et al.*, 2016; Shimeld & Boggild, 2017
			Total: 18622	

Shimeld & Boggild (2017) further refined and improved the signal processing workflow during the 2016 expedition to address the seismic source signature, noise-types, and navigational complexities associated with the *Louis* operations. We have applied their improved workflow consistently to all the 2007–2011 and 2014–2016 seismic reflection lines collected with the *Louis*, and we share the reprocessed results in this open file both as raster images and as SEG-Y formatted files. The four 2016 *Oden* seismic lines were collected with significantly different acquisition parameters, requiring different processing methods and parameters, so they are provided with their original shipboard processing.

We also offer a tool, called the Seismic Explorer, for browsing the raster images in geographical and geological context with a map-based interface. It runs on standard JavaScript-enabled web-browsers, enabling users to quickly obtain a regional understanding of the data set, make first-order observations, and generate publication-quality figures without requiring access to a specialized seismic interpretation workstation. The raster images are supplied in both greyscale and colour versions with consistent spatial and amplitude scaling at nearly the full resolution of the data.

The following sections describe the signal processing workflow, Seismic Explorer and digital file formats.

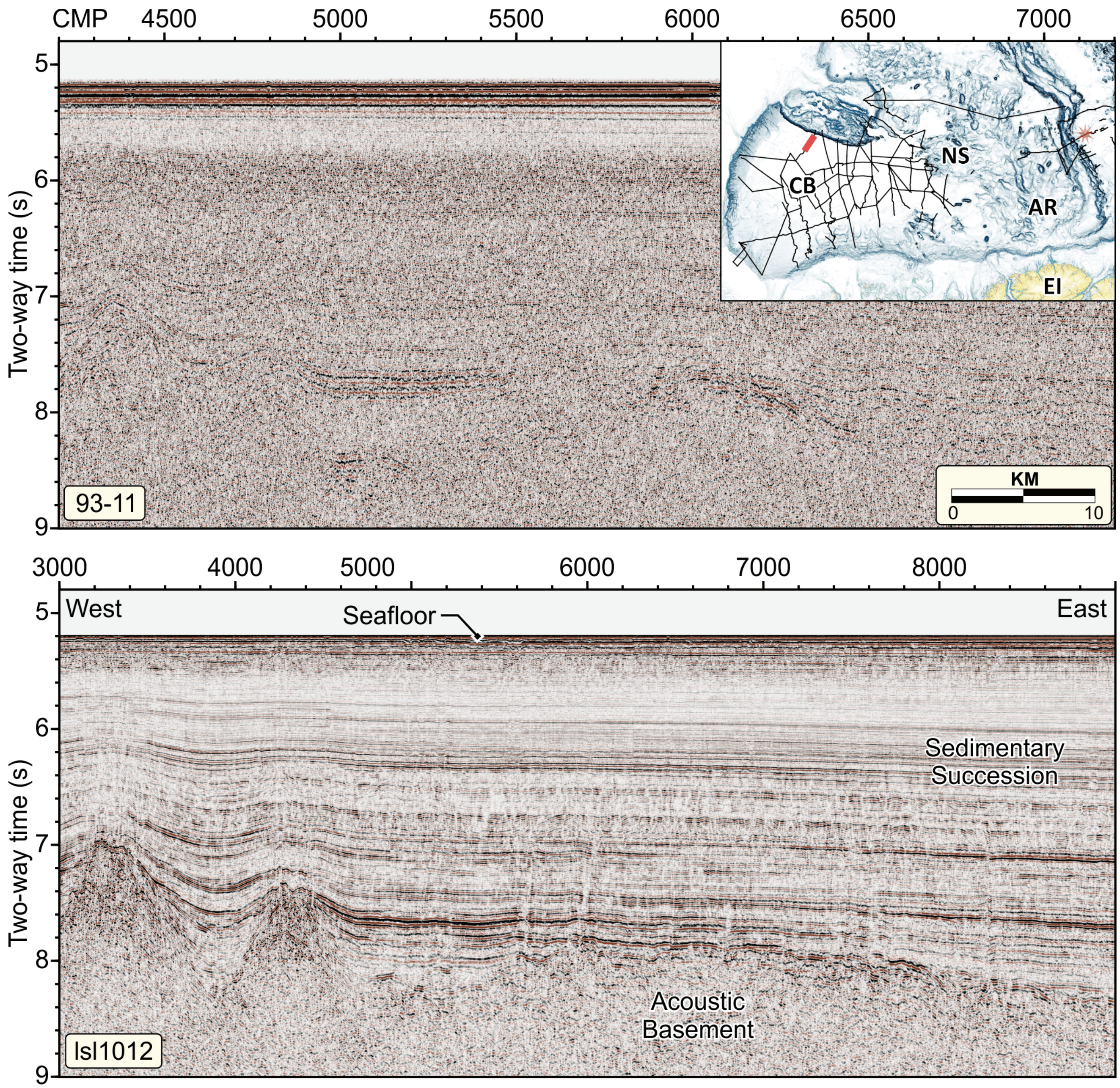

Figure 3: Example seismic reflection lines collected using icebreakers in the Arctic Ocean. In 1993, the US Geological Survey used a single icebreaker with an analogue hydrophone streamer to collect Line 93-11 (top panel). The use of two icebreakers in 2010 for the Canadian ECS program, with a digital streamer and revised processing techniques yielded significant improvements in the signal-to-noise ratio and seismic penetration (bottom panel). The two lines are about 30 km apart at the location indicated with the red line on the inset map. The red star on the inset map indicates the location of the North Pole. Abbreviations: AR–Alpha Ridge;CMP–common mid-point; CB–Canada Basin; EI–Ellesmere Island; NS–Nautilus Spur.

Signal processing

A summary of the seismic processing workflow developed by Shimeld & Boggild (2017) is as follows:

1) input SEG-D shot records with trace debias;
2) assign geometry with receiver statics;
3) bandpass filter;
4) *f*-k filter for suppression of cable noise;
5) turbulence and swell noise suppression;
6) surface related multiple attenuation;
7) zero-phase conversion through wavelet-shaping deconvolution;
8) additional random noise suppression;
9) common midpoint binning, normal move-out correction, trace balance and stacking;
10) finite difference migration;
11) amplitude recovery;
12) time-varying bandpass filter and final output of SEG-Y record sections.

During input, the mean trace value is subtracted from the live samples for each of channels 1 through 16 in each shot record to remove possible stationary bias. Traces containing NaNs or values greater than 1.0E+15 are muted. The geometry is assigned using shotpoint navigation log to design common midpoint bins spaced at a regular 12.5 m interval along the wiggly track of each seismic reflection line. Receiver depths, which fluctuate significantly during icebreaker operations, are calculated through a combination of information from sensors on the streamer and the receiver-ghost signals recorded in the data. The detailed results enable accurate static corrections to be applied for each channel, and also deconvolution of the seismic wavelet in step 7.

Noise filtering starts in step 3 with a minimum-phase Butterworth bandpass applied in the frequency domain using 1.0% additive noise, a 6.5 Hz low-cut with a slope of 24 dB/octave, and a 116 Hz high-cut with a slope of 48 dB/octave. Vibrations along the streamer cause high amplitude linear noise with apparent velocities typically between 200 and 800 m/s, which is eliminated in step 4 through smoothed muting in the *f*-k domain. Step 5 is important in order to filter the significant turbulence noise from icebreaking operations. Noisy traces are identified with a semi-quantitative noise index and are then replaced with *f*-k filtered versions. Swell noise and other random noise bursts are also suppressed in step 5 by an *f*-x domain coherency filter.

After the above noise filtering, a model of the surface-related multiples is constructed and adaptively subtracted from the data in step 6. The data are now ready for deconvolution, in step 7, to remove the receiver ghost and convert the seismic wavelet to zero-phase. The semi-quantitative noise index is re-calculated for each filtered trace, in step 8, and a second round of *f*-k and f-x filtering is applied to the noisiest 5% of the traces in each survey.

In step 9, the shot records are sorted to common midpoint ensembles. Normal move-out corrections are applied but are significant only for records collected in water depths less than 1500 m because of the relatively small source-receiver offsets (<250 m). Residual static shifts of up to 6 ms are caused on some ensembles by uncertainties in the associated receiver depths. These shifts are determined and corrected through cross-correlations with an average pilot trace for each common midpoint ensemble. A surface consistent balance determined within the interval of 0 to 4 s beneath the seafloor is applied to the trace amplitudes, and the ensembles are then stacked.

Finite difference migration is applied in step 10 using sedimentary velocities from the models of Shimeld et al. (2016) and a basement velocity of 4500 m/s. In step 11, a scalar function of the squared velocities and squared two-way travel times is applied to each trace sample in order to compensate for attenuation of the seismic signal due to geometrical spreading and energy dissipation. By avoiding non-linear amplitude recovery techniques, such as automatic gain control, we preserve relative trace-to-trace amplitude characteristics throughout the processing sequence.

Finally, in step 12, a time-varying zero-phase bandpass filter is applied in the frequency domain, limiting the seismic bandwidth to within 4.5–115 Hz near the seafloor and 4.5–55 Hz at 3.5 s below the seafloor. The traces are resampled to a 4 ms time interval and output in digital standard SEG-Y format. Latitude and longitude coordinates are stored, respectively, in byte locations 81 and 85 of the trace headers as arcseconds (x 100). The mid-point bin numbers are in byte location 21, and the shotpoint numbers are in byte location 17.

Accessing the data set

Users of this digital open file report can browse the seismic reflection data set with a map-based graphical interface, and can also access the underlying data files for additional processing and detailed interpretation. Files are stored in the following top-level directories: explorer-files, seismic-nav, seismic-png, and seismic-sgy. The following sections provide further details.

Seismic Explorer

This tool enables the user to select and view individual seismic reflection lines using a map-based interface. Opening the document named "Seismic_Explorer.html" in any modern JavaScript-enabled web-browser presents a track-plot map of all the seismic reflection lines and, to the left of the map, an interactive legend. Hovering the computer mouse-pointer over a seismic track-line of interest will bring up a label with the name of that line, and a single mouse-click selects it. Once selected, a raster image of the seismic reflection line appears below the map. To the right of the map is an information panel with the line name, hyperlink to the data files, and the bibliographic reference for the associated field report. Above the seismic line is a radio-button selector allowing users to toggle between greyscale display of the positive-only seismic amplitudes and colour display of the full-range amplitudes (positive amplitudes appear in reddish-brown shades, negative in blue shades). The greyscale display is intended for viewing the data at regional structural scales, whereas the colour display is designed for viewing enlargements of the sedimentary succession and underlying crustal features.

Clicking items on the interactive legend allows users to filter the track-plot by year and also switch the basemap between regional bathymetry, free-air gravity anomaly and magnetic anomaly. Raster images for these basemaps, encoded with the Joint Photographic Experts Group (JPEG) standard, are stored in the directory named "basemaps." The data sources used to generate the maps are, in order: the International Bathymetric Chart of the Arctic Ocean (IBCAO) version 4.0 (Jakobsson et al., 2020); the DTU17 gravity compilation by Andersen and Knudsen (2019); and, the International Polar Year (IPY) magnetic compilation of Gaina et al. (2011). The free-air gravity and magnetic anomalies are plotted using the perceptually-uniform "batlow" and "batlowW" colourmaps from Crameri (2021) and are overlain with a semi-transparent bathymetric slope map.

Digital data files

The seismic reflection data are supplied as digital binary files in revision 1 of the SEG-Y Data Exchange Format of the Society of Exploration Geophysicists (Barry *et al.*, 1975; Norris and Faichney, 2001). These binary files, written in big-endian byte order, are stored in the subdirectory named "seismic-sgy." The 3200-byte EBCDIC header of each SEG-Y file (Barry *et al.*, 1975) provides associated metadata pertaining to the seismic line (Figure 4). Coordinates of common midpoint positions are stored as arc-seconds in trace-header bytes 73 and 77 for all *Louis* seismic lines, and as projected coordinates in bytes 181 and 185 for *Oden* seismic lines. The coordinates, in decimal degrees, are also stored in ascii-formatted files contained in the "seismic-nav" directory.

Raster images of the seismic reflection lines, encoded in the Portable Network Graphics (PNG) standard, are stored in the subdirectory named "seismic-png". These are rendered at a consistent scale of 4 ms/pixel in the vertical direction, and 3 traces/pixel in the horizontal direction in both greyscale and colour. The greyscale rasters show positive-only amplitudes with a clipping range of 0 to 2.8 standard deviations; colour rasters show the full-range amplitudes with a clipping range –2.8 to +2.8 standard deviations. To reduce file size while maintaining nearly the full resolution of the data, the PNG files were converted from 24-bit red-green-blue format to an indexed (colour-paletted) format.

```
C01 GEOLOGICAL SURVEY OF CANADA    LINE LSL0701a
C02 VESSEL Louis S. St-Laurent     AREA Arctic Ocean   YEAR 2007
C03
C04 SOURCE
C05 3-gun cluster: 500/150/500 in3 (port/midship/stbd) Sercel G-Gun
C06 TOW DEPTH 11.2m   SHOT INTERVALS 14 to 20s depending on water depth
C07
C08 RECEIVER
C09 STREAMER 2x50m Geometrics GeoEel digital active sections, 16 channels total
C10 TOW DEPTH 11.2m attached to gun sled; slight negative buoyancy; no birds
C11 PHONES Benthos RDA Geopoint   GRPSPACING 6.25m   GRPSENSITIVITY 20V/bar
C12
C13 RECORDING
C14 DIGITIZER Geometrics CNT-2 v4.51   WINDOW 13498ms   ACTIVECHN  1-16
C15 AUXCHN none    PREAMPGAIN 18dB chn1-16  FORMAT SEG-D 8058 rev. 1
C16 SAMPLEINT 2ms  SAMPLES/TRC 6750   BYTES/SAMPLE 4   DELAY 0ms
C17
C18 OFFSETS
C19 NAVPT GPS antenna 1.53 m port of ship centreline on ship frame 198
C20 NAVPT/SRC 87.60m   SRC/CHN1 132.625m   SRC/CHN16 226.375m
C21 Navigation is from differential GPS with WGS-84 reference ellipsoid
C22
C23 PROCESSING (John Shimeld, February 2017)
C24  1: input SEG-D shot records;
C25  2: assign geometry;
C26  3: bandpass filter (low: 6.5 Hz @ 24 dB/oct; high: 116 Hz @ 48 dB/oct);
C27  4: cable noise suppression (F-K filter shot gather);
C28  5: turbulence & swell noise suppression (F-K & F-X filter receiver gather);
C29  6: surface related multiple attenuation;
C30  7: deterministic deconvolution to zero-phase Ormbsby wavelet;
C31  8: random noise suppression (F-K & F-X filter receiver gather);
C32  9: surface consistent balance (0:4 s from seafloor), bin and stack;
C33 10: finite difference migration;
C34 11: amplitude recovery (V^2T^2 spherical divergence);
C35 12: time-varying bandpass filter, balance (0:4 s from seafloor),
C36     resample to 4 ms, output SEG-Y files with trace headers as follows:
C37     shotpoint, CMP: byte 17, 21
C38     longitude,latitude [arcsec*100]: byte 73,77
C39     X,Y [m*100]: byte 81,85 (WGS-84/PolarStereo/trueScale 75N/centMerid 0W)
C40 Further details provided in GSC Open File 8239 (Shimeld & Boggild, 2017).
```

Figure 4: Example of a 3200-byte EBCDIC header from the SEG-Y file for seismic line LSL0701a.

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We express our respect and appreciation to the officers, crew, and scientific staff of the Canadian, US and Swedish icebreakers *Louis S. St-Laurent*, *Healy* and *Oden*. Technical staff were exceptionally devoted to their work, enduring seemingly endless hours around-the-clock on cold wind-swept decks, thawing frozen high-pressure airlines, repairing ice-damaged airguns, and improvising replacements for shredded streamer sections (Figure 5). They surmounted formidable Arctic challenges posed by the ice conditions, remoteness, weather, short field season, and complex logistics (Riddell-Dixon, 2017). Managers of the Canadian and US Extended Continental Shelf programs secured requisite funding, coordinated the work and demonstrated extraordinary dedication to the overarching objective of determining the outer limits of the Extended Continental Shelf. In doing so, they made foundational contributions to the collection of new scientific data in the Arctic Ocean. All members of the team may take quiet pride in their contributions toward advancing scientific understanding and promoting the peaceful establishment of international boundaries in the Arctic Ocean under the UN Convention on the Law of the Sea.

Figure 5: Deck crew and GSC technical staff carefully disentangling the hydrophone streamer from broken ice astern of the Canadian Coast Guard Ship Louis S. St-Laurent during the 2009 expedition. Photograph by J. Shimeld. NRCan photo 2021-494.

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