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Characterization of near-surface seismostratigraphy and features of Northeastern Grand Bank: Sea level fluctuations, Glaciation and Slope stability

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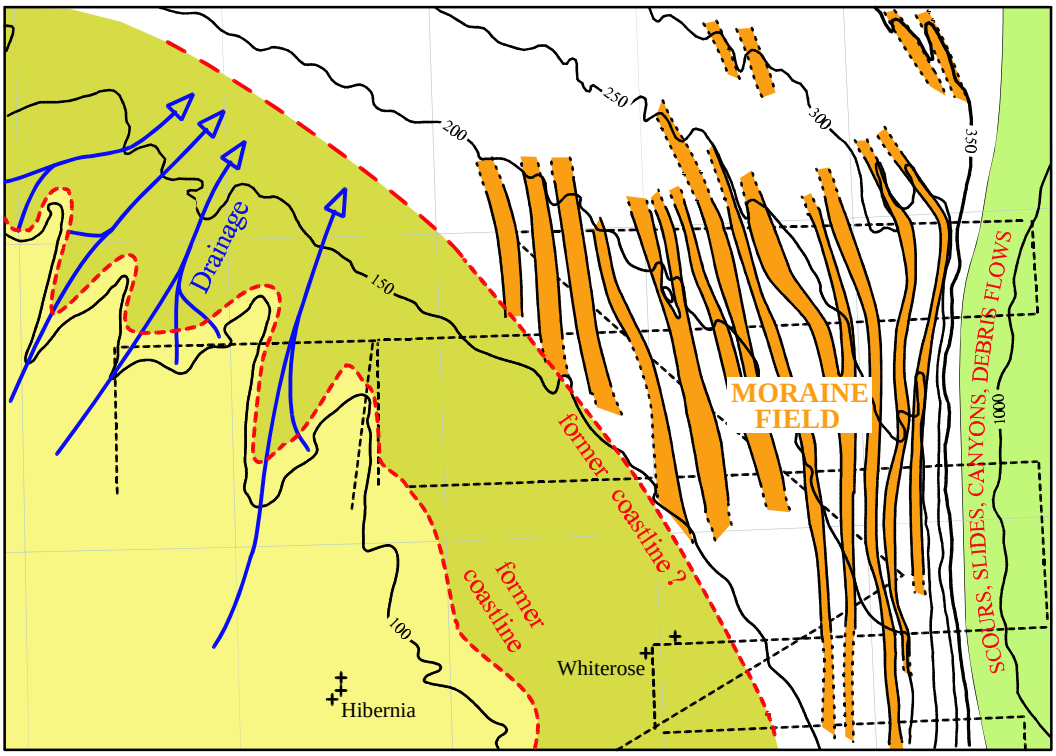

GEOLOGICAL SURVEY OF CANADA COMMISSION GÉOLOGIQUE DU CANADA

OPEN FILE
No. 3886
October, 1999

Canada

Characterization of near-surface seismostratigraphy and features of Northeastern Grand Bank: Sea level fluctuations, Glaciation and Slope stability

Report submitted to the Geological Survey of Canada (Atlantic)
Bedford Institute of Oceanography

June, 1999

Scientific Authority: G.V. Sonnichsen
Contract #:**23420-8-M502/A**

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Funded under the Federal Program for Energy, Research and Development (PERD)

Place on GSC OPEN FILE
No. 3886
October, 1999

TABLE OF CONTENTS

1.0 Scientific Summary 1
2.0 Introduction 3
2.1 Objectives 3
2.2 Regional Setting 3
3.0 Methodology 6
3.1 Geologic Profiles 6
3.1.1 Seismic Pick Precision 7
3.2 Maps 8
3.2.1 Existing Maps 8
3.2.2 Contour Maps 8
4.0 Geological Findings 10
4.1 Summary of Significant New Findings 10
4.2 The Lower Geologic Section; Units 1 to 4 12
4.2.1 Unit 4 12
4.2.2 Unit 3 12
4.2.3 Unit 2 12
4.2.4 Unit 1 14
4.3 The Post Unit 1 Section; Paleoshelf-break and Slope Deposits 15
4.3.1 Slope Features 16
4.3.1.1 Debris Flows 16
4.3.1.2 Canyons/channels/slides 17
4.3.1.3 Possible Faults 18
4.3.1.4 Diapirs 18
4.4 The Glacial Section on the shelf 19
4.4.1 Till Delta 19
4.4.2 Moraine Field 20
5.0 Discussion 22
5.1 Tectonic Subsidence Pattern 22
5.2 Development of the Lower Section: Processes and Age Alternatives 23
5.3 Glacial Processes and Timing 25
5.3.1 A Model for Till Delta and Moraine Field Development 25
5.3.2 The timing of Shelf-edge Glaciation 26
5.3.3 Subaerial Drainage Features 28
5.3.4 Summary of Ice Extent and Retreat 29
6.0 Recommendations for Future Work 31
7.0 Engineering Implications 33
8.0 References 34
9.0 Table 1 37
10.0 Figure Captions 39
11.0 List of Enclosures, Illustrations and Data Files 43
12.0 Reduced Versions of Enclosures (those not shown as figures) 45

1.0 SCIENTIFIC SUMMARY

Recent regional high resolution (10 cu. inch sleeve gun and boomer) seismic coverage on Northeast Grand Bank (Hibernia to Terra Nova sites and eastward to Flemish Pass) provides new insights towards establishing a geomorphic and process framework for the shallow strata (upper 500 m of stratigraphic section). Identification of marked and subtle but regionally extensive angular unconformities in the regularly aggrading and prograding shelf sediments has allowed a stratigraphic breakdown of at least four major units and sub-units (Units 1 to 4 from *top* down).

Unit 4 is a newly identified delta-like progradational body of as yet, unknown extent, very similar to the thick and extensive clinoform body informally known as the "Hibernia Delta" (Unit 2) but nearly 100 m down section and to the west. Rare channels on its surface probably attest to subaerial exposure. The overlying Unit 3 is a relatively featureless parallel-bedded and mildly folded unit at least 90 m thick yet with a subtle internal unconformity. Its upper surface is a well developed angular unconformity, locally dissected and eroded to an observed depth of more than 260 m below sea level. Unit 2 includes the eastward prograding "Hibernia Delta", upwards of 100 m thick and over 200 km long, with local unconformities and at least one major sedimentational break. Distal equivalents are shelf aggradational, locally downlap seaward, and locally exhibit *landward* progradation. A subtle unconformity (erosional to a depth presently 130 m (below sea level) is overlain by a thick (over 100 m stratigraphically) sequence of largely parallel bedded, shelf aggradational and large scale upper slope progradational strata with regional unconformities (Unit 1) which indicate three or four planar, tilting erosional phases interpreted as representing probable lowstands.

Following Unit 1 the sediment record is largely confined to the outer shelf and slope as the progradation steepens. Less well developed seismic stratification and greater bed irregularity points to greater mass failure frequency on the upper slope while mid and lower slope equivalents are uniform and well stratified. The latest few tens of metres of the sediment record on the mid and lower slope indicate a change to greater frequency of relatively small-scale mass failure (debris flow and rotational slide) in an apparently periodic fashion. This periodicity might be a reflection of glacial phases, sea level changes or even climatically induced instability. The late shelf and upper slope record is poorly defined seismically, partially due to local small-scale failures and to a broad zone of iceberg scouring. On the bank top, the entire section is markedly unconformable (more so than anywhere else in the section) within metres or deicmetres of the seabed across most of the map area.

At least part of this marked angular unconformity can be attributed to glacial processes. In the NE portion of the map area it is overlain by a blanket of glacigenic material reaching 35 m thickness. Here, the erosion surface is overdeepened with respect to the shelf break. The blanket is thought to have resulted mainly from subglacial deposition. On its upper surface is a series of sub-parallel and bifurcating recession moraines. They are low (10-20 m), broad (several km) and long ridges (exceeding 100 km) parallel and sub-parallel to bathymetric contours, extending from the shelf break to nearly 100 km westward. At the shelf break the ridge marking the ice maximum exhibits a small scale progradation attributed to sub-glacial water-lain deposition, probably as small failures and debris flows. A backsloping upper surface helps attest to its glacial derivation. It is considered an example of "till-delta" processes inferred below Antarctica's Ice streams (Alley *et al*., 1989). The moraine system is a remnant, having been eroded in water depths shallower than about 150-165 m. The even, planar erosion surface can have resulted from subsequent glacial erosion, but a low sea level stand is the preferred process. A similar mechanism to the latest, better documented late/post glacial low stand is envisioned. Broad erosional valleys in shallow water depths at the seabed NW of Hibernia, disappear below about 170 m present water depth and may have their origin in fluvial processes. Because of the depth relationships either

glacial or low stand erosion mechanisms suggest a *pre*-Late Wisconsinan age for the remnant moraine system. However, a scenario whereby a late glacial forebulge development allows late outer bank subsidence to below the eustatic ca 110 m level is also presented. Moraine deposition may have been a Late Wisconsinan event.

The “old” (pre-Wisconsinan) hypothesis for moraine formation implies considerable (several tens of m) subsidence since that glaciation. Comparisons of degree of splaying in the underlying Unit 1 from north to south suggest a regional tectonic tilting, most pronounced to the north. In addition, local, enigmatic “uphill climbing” Unit 2 delta foresets can be explained by invoking a post depositional regional northward tilt (tectonic subsidence). If this tilting phenomenon is correct, the unconformities on the early Units (4, 3, 2 and possibly 1) can be viewed as the now tilted shelf platforms along whose eastern margins the large deltas of Units 4 and 2 advanced in response to massive reworking on the banks, probably both during lowstands and earlier phases of the subsequent transgression. This process occurred periodically even before the mild deformation phase of Unit 3. This is presented as a possible alternative to the suggested glacial origin of the deltas. An implication of this hypothesis is that the aggrading and prograding Units 1 through 4 can be of Tertiary age. The change in sedimentation style after Unit 1 would correspondingly reflect the glacial influence (mid Pleistocene?).

With respect to engineering problems where consolidated strata are encountered at local development sites, this model lends support to both glacial and diagenetic cementation concepts. The glacial (till) blanket becomes too thin to recognize in the Terra Nova area but trends in the isopach map suggest the possibility of patchy remnants of till just centimetres below the sands and gravels here. Likewise, repeated subaerial exposure with three or four lowstands possibly predating the mid and late Pleistocene fluctuations enhances the possibilities of hardpan or calcrete-like soil developments.

Avenues for future research include application of sequence stratigraphic techniques to the stratigraphic succession, high resolution seismic and strategic short coring on the mid and lower slope for its glacial and paleoceanographic record (which may also establish the moraine field age), further study of the stratigraphy and geometry of the more recent slope mass failures followed by coring, and finally establishment of a seismic tie between the till blanket and moraine field and tills and glacial outwash apron mapped to the northwest of this area.

2.0 INTRODUCTION

King Geological Marine Consulting, under contract to GSC (Atlantic) has conducted an interpretation of seismic reflection data from NE Grand Bank in the area east of the Hibernia and Terra Nova sites. The data were collected by staff of the Geological Survey of Canada at the Bedford Institute of Oceanography during scientific survey HUDSON 98-034. Single-channel sleevegun and Huntec Deep Tow System (DTS) data were acquired in the fall of 1998 and this report represents the initial interpretation of these data. Interpretation involved a refinement of the geologic framework developed for the region (Sonnichsen *et al*., 1994, Sonnichsen & Cumming 1996) and concentrates on the shallow geology (from below the "Hibernia Delta", up to and including the latest glacial deposits, a total of over 500 m of stratigraphic section. This report presents a compilation of over 1300 line km of seismic data, predominantly from BIO Hudson Cruise 98-034. The map area extends from approximately 45º55' to 47º35' N., and from 47º00' to 49º35' W (Fig. 1).

2.1 OBJECTIVES

Apart from direct scientific interests, this study was initialized because cursory examination of the newly collected data showed that the more regional coverage provided potential for better understanding of the much more studied Hibernia/Terra Nova area in terms of stratigraphy and glacial events. An improved framework of this type helps enable near-surface geotechnical/ geoengineering studies to be interpreted in a regional context. Furthermore, an understanding of slope processes in the region will be necessary prior to engineering developments. Both aspects have been successfully addressed in this study. In addition, an immediate sub-seabed hardpan/boulder/overconsolidation phenomenon on outer Grand Bank represents a current problem for engineering installations so a better grasp on sea level and glacial events across the area has the potential for narrowing the possibilities for a genesis of this phenomenon. This study has likewise helped solidify concepts of when and how often conditions which might have given rise to overconsolidation might have periodically arisen.

2.2 REGIONAL SETTING

The outer northern Grand Bank near surface geology is dominated by an east-dipping progradational sequence (Banquereau Fm.) characterized by low amplitude, continuous coherent to discontinuous coherent reflectors with a marked angular unconformity within metres of the seabed and more subtle unconformities and disconformities in the shallow stratigraphy. The seismostratigraphic framework in the sub-surface has gradually evolved (e.g. Zawadski 1991, Stoffyn-Egli *et al.* 1992, Sonnichsen *et al.* 1994, Terraquest Associates 1995, Sonnichsen & Cumming 1996). The much more regional coverage from Cruise 98-034, extending as it does, to the shelf break and covering much of the slope, provided an opportunity to validate and expand upon this framework. The breakdown is based on the seismic character of strata under- and overlying a large delta-like complex which sub-crops beneath late and postglacial surficial sediments. It extends from west of Hibernia across an area tens of km wide and over 180 km in a

north-south sense and locally the delta complex reaches over 100 m thickness (Terraquest Associates, 1995). It is informally known as the "Hibernia Delta" for the site where it was first identified. More monotonous, largely parallel stratified sequences with a slight easterly or east-northeasterly dip are typical of the strata immediately over and underlying the delta as well as the distal components of the delta.

The stratigraphy of Sonnichsen *et al*. (1994) delineates three unconformity-bound main seismostratigraphic units which are also identified and adopted for the more extensive region considered in this report:

- **Unit 1**: *Upper Parallel Reflection Sequence*:
  largely conformable marine shelf aggradation
- **Unit 2**: *Clinoform Reflectors*: including an upper}
  -Unit 2A encompassing the clinoform body ("delta") and its distal equivalents plus post clinoform products, and a lower
  -Unit 2B comprising a less well defined depositional complex but including rare clinoforms and probably related to the later delta.
- **Unit 3**: *Lower Parallel Reflection Sequence*:
  conformable shelf aggradation with minor unconformities

Correlations of the seismic data with several boreholes, although lacking reliable velocity data, provide some groundtruth and are compatible with the broad aspects of the seismostratigraphy (Mosher & Sonnichsen 1992, Taylor *et al*. 1993).

- **Unit 3** includes interbedded sands, silts, and clays which characterize the Lower Parallel Reflection Sequence. Acoustically, it displays a set of near parallel or slightly splaying, continuous to near continuous east-northeast dipping reflections with a spacing of metres to tens of metres. They represent "normal" shelf aggradation but local unconformities recognized in the general region are attributed to some sea level changes (Mosher and Sonnichsen 1992). Terraquest Associates (1995) maps delineate broad, open flexures with a NNE axial trend in the Terra Nova region, yet largely confined to Unit 3.

- **Unit 2** is a wedge-shaped body comprising clinoform (S-shaped) strata with a local angular unconformity at its top. The sediments comprise coarse sands, gravel and minor silt and clay (Stoffyn-Egli *et al*. 1992 and unpublished reports therein). The wedge thins greatly a short distance distal to the youngest clinoforms and its distal equivalents and overlying strata assume a depositional style much like the under and overlying units. This extensive "delta-like" body is attributed to a deposition during a former low sea level stand.

- **Unit 1** exhibits slight ENE-dipping parallel to slightly seaward splaying strata consisting of semi-consolidated interbedded silt and clay (Stoffyn-Egli *et al*. 1992 and unpublished reports therein). It is attributed to shelf aggradation and more distally to progradation.

The age of the uppermost prograding sequence in this region remains uncertain. This is a shortcoming because it presents numerous possibilities in terms of depositional environments. These shallow subsurface strata may originate from early-mid Quaternary aged processes, as some investigations might suggest (A. Miller, C.F.M. Lewis, and G.V. Sonnichsen, GSC, Atlantic, pers. comm.). As such, the origin and properties of sediment packages and their bounding surfaces can be interpreted in terms of short term sea level shifts and widely variable climate fluctuation, including proximity to glaciers. Alternatively, early Pleistocene or late Tertiary environments at this site were also likely subjected to glacial climatic and associated sea level influences but direct sedimentation from glaciers is unlikely and the genesis of sedimentation and erosion events must then be viewed from a different perspective.

The effects of glaciation on outer Grand Bank have been recognized in terms of surficial cobbles and boulders of Avalonian (mainland) affinity, buried and infilled glacial valleys and proglacial sediments (Fader and King 1981, Fader and Miller 1986) and overconsolidated near surface deposits (Long *et al*. 1986). Nevertheless, the timing and extent of the Late Wisconsinan glaciation across the Grand Banks remains unclear. Indirect indications from slope-situated deposits (Flemish Pass) would suggest a limited ice extent during the last (Late Wisconsinan) glaciation with the last shelf-edge ice cover in early Wisconsinan time (Piper and Pereira 1992). The presumed extent of ice cover for the last glaciation is accordingly placed well west of the Hibernia region, just east of the Eastern Shoals (Piper *et al*. 1990). Recent compilations on the bathymetrically submerged NE Newfoundland shelf (north of 48 deg.) show clear evidence of an ice lobe which emanated northward from Grand Bank (King and Fader, *in prep.*). This includes large scale tunnel valley and morainal bank features. A Late Wisconsinan age is presumed through correlation with another large end moraine on the mid shelf (in Trinity Trough) dated at ca 15 ka. This ice lobe is recognized as either the Late Wisconsinan maximum position or alternatively, a stillstand phase superimposed on overall glacier retreat. Also, undated tills are recognized at the shelf edge in 200 to 300 m water depth at the shelf edge on the NE Newfoundland Shelf. Thus, a thin ice cover over the outer northern Grand Bank, including most of the shelf in the map area during the last glaciation is a real possibility (King and Fader, *in prep.*). Clearly more direct evidence of glaciation and its timing in this region is necessary.

Much of the western part of the map area lies within the influence of coastal processes during the Late Wisconsinan low sea level stand (ca. 105-110 m below present) and subsequent transgression and reworking has modified most surficial glacial deposits beyond recognition (Fader and Miller 1986, Barrie *et al*. 1984). This transgression was the latest process to cut the marked angular unconformity within decimetres or metres below the sea floor and probably crossed the area before ca 15 ka (Barrie *et al* 1984). It has been suggested that this period of subaerial exposure may have allowed sufficient surface weathering to develop scattered effects of diagenetic lower soil horizon evolution including caliche or “hardpan”-like horizons which have proven problematic to drilling installations (Segall *et al*. 1987, Long et al. 1986). An additional or perhaps alternative genesis for the overconsolidation is through glacial loading, and/or significant removal of overlying strata (Moran *et al*. 1988) and presence of coarse glacigenic material is also possible.

3.0 METHODOLOGY

Seismic data were acquired in the summer of 1998 onboard CSS Hudson. Seismic equipment consisting of two 10 cubic inch sleeveguns were used for the majority of the survey. Data were recorded on an NSRF tapered array with 21 elements (1 per ft) and an SE eel with a 100' section (50 elements- 1 every 2 ft) and a 25 'section (16 elements - 1 every 1.5 '). Huntec DTS deep towed sparker data resolved the upper metres on the bank top and provided high resolution (< 0.3 m) on the slope.

Apart from initial reflector tracing of analogue seismic profiles, most of the compilation was achieved through a variety of procedures in Computer Aided Drafting (CAD; vector-based Cartesian coordinate system), mapping, and drawing software. Briefly, nearly all visible reflectors are traced on velum, reduction photocopied (50%) and then scanned on a piecemeal basis, vectorized, re-assembled (aligned and scaled for differing aspect ratio) with CAD software, datum registered (sea level set at “0” Y-value), registered to navigation (integral lateral scale adjustments to fit time-based position references on the profiles to distance-based true geographic position) and key horizons are then correlated throughout the profile data set (assigned colours and specific layers). These profiles maintain all the detail of the original tracings. As they are registered to navigation they are then utilized for ready and accurate map production including zero edges (outcrop patterns), surficial and buried features etc. For contour map production the positions and depths of key horizons are then exported to a spreadsheet and manipulated to calculate true depths and thicknesses (in time units) for equally spaced geographic positions. These digital data are then incorporated into a contouring software package to produce depth and thickness contours of the various units. These are subsequently exported to CAD software for minor or major adjustments and display. Original analogue profiles are scanned only in areas of particular interest for illustrative purposes. The techniques and their error margins are described in more detail below.

3.1 GEOLOGIC PROFILES

The geologic profiles are provided as 2-D drawings at true map scale, with a vertical scale of 25 units per millisecond travel time. As noted above, they were compiled from hand drawn tracings on individual (17 inch long) sheets of velum which were reduced 50% on a photocopier, scanned, vectorized, and then re-assembled in a batch technique in a CAD package.

The seismic (air gun) data were recorded at sea on separate graphic recorders from a short (NSRF) and a 100’hydrophone streamer. The latter records at lower frequency/higher penetration and greater signal/noise and proved most beneficial at outer shelf and slope locations. The higher frequency NSRF streamer profiles were best suited for the bank-top situation. Both profiles were usually recorded at the same scales, enabling simple repositioning of the velum tracings to glean the most information from both data sets. The Huntec DTS profile data, covering the uppermost geology were not traced directly but, where they provided additional near surface data, this information was scaled and directly drawn on the velum tracings.

The tracings were made from half-size continuous paper copies of original ship-board graphic printer outputs. The tracings incorporated, in addition to all reflectors of note, depth registrations (every 100 or 250 ms) and time-based fiducial marks with corresponding day/time annotations (generally every 5 minutes). These are necessary for subsequent depth and geographic positional scaling in the CAD program. Lack of consistent annotation (at sea) of the print delays and travel time lines made for considerable detective work and sometimes assumptions, thus making establishment of the sea surface datum difficult in some cases. This was especially the case for the slope profiles where only the digital versions of the seismic data would have preserved travel time information.
Not all profiles were assembled in their entirety. Occasional data gaps or poor analogue printouts hampered meaningful interpretation. Accordingly, lines 4, 8 and 15 are not presented as interpreted profile; nonetheless, features on these data are incorporated into the appropriate maps.

In the 2-dimensional CAD software the along track axis of a geologic profile corresponds to the X-axis while the Y-axis displays depths (in travel time). For the N-S oriented survey lines, the profiles were oriented such that Y-values correspond to along track distances and X- values, to the depths. *The scanned and vectorized tracings were scaled such that the X axis corresponded directly to the true UTM map Eastings for E-W oriented seismic traverses. Similarly the Y axis corresponded to true UTM Northings for N-S oriented traverses (i.e. not true map scale)*. That is, the horizontal scale of the geologic profile corresponded to only the eastern *component* for E-W oriented seismic lines (northern component for N-S lines). Thus, for E-W or N-S oriented lines the profiles are presented at true horizontal scale but deviations from this projected as shorter profiles. This was performed in order to preserve one component of the map coordinates for purposes of later export of the data to a spreadsheet and contour mapping package. The “lost” or “omitted” Northings or Eastings component was later “recovered” in the spreadsheet as described in Section 3.2.2 (Contour maps). *Final presentation of the geologic profiles (Enclosures 2A and 2B) presents all profiles at a uniform horizontal scale with day/time and Eastings (or Northings) annotation*.

3.1.1 <u>Seismic Pick Precision</u>

As with all seismic data sets, some correlations achieved without direct seismic ties are subject to adjustment and the new data set, with its wide spacing was not without these limitations also. Future surveys, especially in the outermost shelf area, which lacks a good strike oriented tieline, will undoubtedly bear some discrepancies with this compilation (just as this study identified in earlier compilations). For example, along-strike correlations on the outer shelf (mainly the top of Unit 1d horizon) are somewhat imprecise. Eventually relations become too uncertain approaching the shelf break to warrant even an attempt at correlation. Clearly new tielines will remedy this. Even within the same data set, seismic reflector ties displayed discrepancies arising mainly from uncertainties and inconsistencies in picking the same cycle of the pulse signature where closely spaced reflectors result in complex constructive and destructive wave interference. In practice these picks were usually within 5-7 ms.

3.2 MAPS

3.2.1 Existing Maps

CAD digital versions of Canadian Hydrographic Service (CHS)-derived charts were supplied by the scientific authority. Some areas are available at a closer contour interval than others. These were assembled (which brought to light some positional inaccuracies from chart to chart) and serve as a basemap (Fig. 1, Enclosure 1). Likewise ship's navigation files were supplied where seismic coverage exists. All maps are UTM projection, Zone 22, central meridian 51 W (NAD 83). Note that the study area spans two UTM zones (22 and 23) and all map data were "forced" to zone 22 to readily relate to existing maps and data in the Hibernia and Terra Nova areas in zone 22. CAD based contour maps and spreadsheet data for key geologic horizons as assembled from earlier compilations of earlier cruises in the area (Terraquest Associates, 1995) were also supplied. Inspection showed that there were regional discrepancies between seismic picks on these key horizons, obviously stemming from handicaps of sparse distribution and unconnected seismic traverses. The more regional coverage from the 1998 data set allowed improvement on these picks. While it became obvious that some picks between the older and new data sets were in agreement it proved difficult to sort which geographic areas were correct and which needed adjustment. Thus most of the previously existing data could not be readily incorporated into the maps produced in this study.

3.2.2 Contour Maps

While the scanned method of digitizing results in incomparable preservation of most fine detail (shape, relief, features etc.), it contains superfluous amounts of data for contour map purposes. Accordingly, the key horizons were redigitized in a rapid on-screen technique. The output is a depth (ms) value for each of the stacked horizons along a profile at a spacing of exactly 500 m of Eastings component (for E-W profiles) or Northings (for N-S profiles). While this represents a true 500 m of spacing for the E-W and N-S ships track orientations, for obliquely oriented tracks (i.e. Lines 1, 2, 17, 18, 19, and 20) the true spacing is actually greater. This difference is not considered to have any appreciable effect on the final contour maps as along-line spacing remains very tight in relation to line spacing. The depth or thickness (ms) values are also posted on the individual CAD-based contour maps (in separate, switchable layers). The spacing of these is much greater as they are decimated by a factor of 5 (because of presentation space limitations) even though *all* data were used in their compilation.

The digital output format from the CAD package is such that all individual data points are registered *twice*. Editing out of duplicates in the spreadsheets was not performed because the contouring software ignores them. The editing process would have been quite laborious, requiring manual intervention, because complete automation would likely have led to omissions.

As stated above, in the 2-dimensional CAD software the along track axis of a geologic profile corresponds to the X-axis while the Y-axis actually displays depths (in time), which in true (3-D) space are actually Z values. The Y values are simply transposed to Z values when exported to a spreadsheet for further manipulation. The X values are true UTM Eastings values but the

corresponding Y values (Northings) were “lost” in the 2-D CAD format and have to be “recovered”. This is accomplished by calculating the linear equations for straight line sections of the entire ship’s track (Y=mx+b) from the CAD-based track plot. In practice, the entire cruise track was subdivided into numerous straight line approximations of the track and the slope and y-intercepts found. These equations were then solved for “Y” in the spreadsheet with the true UTM Eastings (or Northing) values. The actual ships track usually deviates between 0 and 20 m from these straight line segments but could be as much as 50-60 m locally. Thus, the UTM position for any given depth or thickness value used in map production could have a Northing (or Easting) error within this range. This is considered meaningless in relation to the errors associated with seismic picks on these generally flat-lying horizons.

The entire depth (ms) and thickness spreadsheet database for all reflectors is provided as a deliverable. Table 1 shows a small excerpt. Individual unit thicknesses (in ms) are simply the difference in depths from the top of the unit and top of the underlying unit. However, where the unit outcrops (or nearly so) the spreadsheet required minor modification to define the seabed as top of the unit in question (for ease of calculation). As this is geologically meaningless with respect to a structural depth contour map of the top of that unit, these depth values are flagged through highlighting with a yellow colour in the file.

In some isopach maps the automatic contouring package failed to interpolate the existence of the Hibernia delta across the approx. 80 km between lines 1 and 9. A greater continuity was incorporated through manual editing. Likewise, the isochrons were smoothed manually on many of the maps. The continuity of the deposits is clear from both a geological sense and from earlier seismic coverage whose quantitative data were not incorporated in this study. In many cases this continuity is built into the contour maps with the obvious result of inaccuracies in contour placement. The contours have not been “ranked” in terms of degree of certainty, but rather the survey line spacing and uniformity (or variability) of the posted values provides the reader with sufficient information for this type of evaluation.

Depth to top of Unit and Isopach contour maps of nearly all seismostratigraphic units are included in this study (See list, Section 10). Note that all maps utilize two-way travel time as a vertical scale and are correctly termed isochron maps but for conceptual clarity are simply entitled “Depth to Unit X, ms” or “Thickness of Unit X, ms).

4.0 GEOLOGICAL FINDINGS

4.1 SUMMARY OF SIGNIFICANT NEW FINDINGS

This study has identified:
1. an additional clinoform body, much like the “Hibernia delta”. It lies well to the east of the Terra Nova area, 90 to 100 m stratigraphically below the Hibernia delta, but as yet is of unknown distribution. Perhaps of greatest significance in this find is that this massive progradational process is not a temporally isolated phenomenon and it occurred a long time before the Hibernia delta complex and the mild folding event preceding the Hibernia delta deposition.

2. subtle angular unconformities previously identified in the shallow sub-surface (Mosher and Sonnichsen 1992) are now recognized as having a region-wide distribution. Their erosional nature is recognized to considerable depths. The revised stratigraphic breakdown is provided in Fig. 2 and on the geologic profile sheets. It remains unproved if these are sea level/glacially cut or simply low stand related. All observations can be attributed *without* the need to invoke the properties of glacial erosion. The implications of either are significant; multiple glacial phases and a relatively young age for this thick sequence *or* multiple low stands with progradation and a simple aggradation during intervening highstands. The latter, however, entails a longer history within a regime of regional subsidence. Elements of such a subsidence are examined.

3. a series of previously unrecognized low and broad moraines, the outermost extending over 100 km at the immediate shelf break and at least 12 others sub-parallel to this and stretching 100 km landward (cover illustration). A relatively sharp transition in seabed relief from hummocky terrain, typical of a till surface, to a smooth, slightly seaward inclined plane occurs at about 150 m water depth in the south and 170 m depth in the north. This and the planation of the moraines above the transition indicates the moraines have been erosionally truncated along their landward extent, together with the till blanket on which they are superimposed. If this truncation is due to a low stand, its present depth (below the maximum glacio-eustatic lowstand) implies several tens of metres of subsidence which is difficult to envisage in light of glacio-isostatic and eustatic adjustments during the last glaciation. (The Late Wisconsinan-Holocene low stand at 105-110 m is well documented; see above). This suggests a pre- Late Wisconsinan age but a Late Wisconsinan age is not excluded. An advance during oxygen isotope Stage 4 or 6would provide enough time for subsidence at high but not extreme rates. If the moraines can be dated, it would help establish the validity of longer term subsidence and the chronological conjecture invoked in this study to explain the thick sequence underlying the till blanket.

4. slope-situated mass failure features including thin, lensoid debris flow deposits, larger, rotational slides, infilled and open canyons, a broad mid to upper slope iceberg scoured zone with associated small surficial failures, possible faults, and possible soft sediment diapiric structures. With only 2-D visualizations their geometries are not yet defined. A largely unexamined lower slope stratigraphy shows the potential for further understanding of paleoclimate/glaciation history.

Figure 2 shows the revised stratigraphic breakdown. The geologic profile enclosures (2A and 2B) show a similar column, but with units bounded by coloured lines corresponding to the same boundaries in the geologic profiles. Unit numbering follows the scheme of Sonnichsen *et al*. 1994, with additions. A revised numbering system is warranted but in light of stratigraphic uncertainties in the upper part of the section this awaits further data gathering. Accordingly, the outermost shelf and near-surface slope deposits are described in terms of seismic facies with little or no implied stratigraphic relationships. Major subdivisions are thick, clearly erosion-bound units, each with a loosely defined geometry/seismic character. Minor subdivisions are between units of similar geometry but bounded by unconformities which are commonly more subtle. All the units below the marked near-seabed angular unconformity belong to the Banquereau Fm. (c.f. Fig 6.9 of Grant and McAlpine (1990) The surficial sand and gravel facies, related to the post-glacial sea level low stand and rise (from Fader and King, 1981) are not further examined but suggestions in this study of an earlier lowstand would presumably have produced similar facies in deeper water.

The unconformities bounding the major units show clear erosion with locally tens of metres of section removal. The top of Unit 4, for example, displays rare, narrow, infilled channels (Enclosure 2A, between times 1430 and 1500 and Fig. 3B). The top of Unit 3 is a well developed, dissected horizon (Enclosure 2A and Fig. 3B) displaying erosion to a present depth (below sea level) of at least 350 ms (at least 260 m) on the southernmost transect. The dissected and unconformable relationship is less distinct on the more northern traverses (Fig 3A).

The subtle unconformities, especially in Unit 1, are such low angle relationships and with so few truncations that the detailed nature of the unconformity is often unclear. They could be confused with other unit wedge relationships such as onlapping or downlapping. However, the map-wide extent of the horizons displaying similar relationships is indicative of an erosional genesis. The relationship appears conformable across much of the shelf but a progradation is common near the paleo-shelf break.

Figure 4 (Enclosure 4) shows the outcrop patterns of the horizons marking the tops of the major units.

4.2 THE LOWER GEOLOGIC SECTION; UNITS 1 TO 4

4.2.1 Unit 4

The lowermost Unit 4 is a 50 m thick, seaward dipping progradational body with lower angle distal equivalents located well west of and about 100m stratigraphically below the "Hibernia Delta". It is similar in many respects to the Hibernia Delta, with internal downlapping, unconformities and both steep and shallow foresets (Enclosure 2A and Fig. 3B). Encountered on only one seismic transect, its distribution cannot be mapped at present. Enclosure 4 shows an assumed outcrop extent (actually subcrop below post glacial transgression deposits). As noted above, the Unit 4 surface is eroded and locally small channels attest to subaerial exposure.

4.2.2 Unit 3

The overlying Unit 3 is characterized by sub-parallel, relatively closely spaced and high amplitude reflectors. The proximal-most part may also exhibit a prograding style (Fig. 3B and Line 20, Enclosure 2A). A subtle mid-section unconformity allows separation into A and B subunits. As noted above, an angular unconformity marks its top. Surface roughness interpreted as small erosional incisions extend to a depth of at least 260 m (below sea level). The angularity is much less developed on this horizon to the north (e.g. Lines 9, 10, and 11). The geometry of the upper surface of Unit 3 is depicted in Figure 5 (Enclosure 8). It crops out well west of the Hibernia and Terra Nova sites. Trends on the surface are similar to those of the seabed, with a NW strike in the north and S to SW strike in the south. It exhibits no particularly prominent irregularities. Unit 3 has undergone very mild folding over the Jeanne d'Arc Basin in contrast with the overlying units. The position and trends of anticline and syncline axes are shown in Figure 6 (Enclosure 3). Units 2 and 1 also express the same, but more subtle structural trends. This is in part due to the subtle influence that such folding has on subsequent erosional patterns. Structural highs are not always completely removed so subsequent sedimentation in a conformable style also reflects these trends. This is further substantiated in the recognition of local sites where a slight depositional thinning in lowermost Unit 2 occurs across topographic highs. For example, Line 20 (Enclosure 2A) and Fig. 3B, just below and distal to the delta shows deposition patterns governed by the shape of the erosion surface. Similarly, Line 2, Enclosure 2B shows a flexure and thinning distal to the Hibernia delta. These observations contrast somewhat with inferences from earlier data (Terraquest Associates, 1995). It appears likely that the structural flexing event post-dated Unit 3 but was not entirely relaxed following Unit 2 (and possibly some of Unit 1) deposition. This has some implications for age inferences (Section 5.2).

4.2.3 Unit 2

This unit comprises the Hibernia delta and distal equivalents. Its subcrop pattern (below the post-glacial veneer) is shown in Figure 4 and Enclosure 4 (between the top of Units 3 and 2b traces). The contour map of its surface (Fig. 7, Enclosure 12) shows it to depths over 700 ms (below sea level). It strikes approximately N-S in the south and swings rather abruptly to a NNW strike north of the Terra Nova site. This pattern is interrupted locally by the Adolphous salt dome.

The prograding bodies of Unit 2 have thick, expansive equivalents in a seaward direction.

Unit 2 is subdivided into A and B on the basis of an intervening unconformity. This change is exhibited on survey lines 1 and 2 (Enclosure 2B) as an abrupt transition from a thin, non-descript blanket to the downlapping pattern of numerous foresets onto its surface. Lacking the lower blanket on Line 20 (Fig. 3B and Enclosure 2A), a clear angular unconformity *within* the clinoform sets is chosen as this same A-B boundary (despite no strike line ties). Here, erosional processes near the base of the upper subunit (B) clinoforms have completely removed the lower subunit locally (Fig. 3B and Enclosure 2A). To the north (again no strike tie lines), on Lines 9, 10, and 11 the two subunits are clearly distinguished as two broad and relatively thin (20 to 30 ms) prograding bodies. The foresets exhibit less of the "S"-shaped tangential downlapping at their distal ends in comparison to that in the Hibernia area. The prograding extends well seaward (Fig. 4, Enclosure 4 shows extent of distalmost steep foresets). As the upper unit exhibits rare foresets only in its western extent, it was not recognized as part of Unit 2 in the preceding mapping project (Terraquest Associates, 1995) due to lack of seismic coverage.

Figure 8 (Enclosure 10) shows the depth to Unit 2a which has nearly identical trends as the top of Unit 2. Figure 9 (Enclosure 6) presents an isopach (in ms) of the entire Unit 2, while Figures 10 and 11 (Enclosures 9 and 11) show thicknesses of the subunits A and B. The prograding package, Unit 2B, reaches greater thickness in the south (60 ms) than 2A (40 ms) but this is reversed in the north where the lower unit is slightly thicker. Volumetrically there appears to be a migration of the depocentre southward though the change is not great.

As the publications and reports on the Hibernia delta indicate, the distal equivalents of the prograding body are thought to represent the proximal to distal transition to "normal" marine deposits. In the south, the Unit 2 distal equivalents show a downlapping relationship on to the top of Unit 3 unconformity. Terra Nova borehole comparisons indicate finer sediment distally (Terraquest Associates, 1994). Accordingly, Units 2a and 2b should eventually become conformable seaward of the deltas. This is apparently confirmed from the regional data coverage. Interestingly, this 2a-2b boundary commonly exhibits a high reflectivity, which is consistent with the inferred sedimentation interruption. The units eventually thin to under 15 ms.

In conclusion, a two stage prograding event with an intervening depositional hiatus and local erosion is clear for Unit 2. The deposition is clearly low stand related but whether this is directly related to glacial input remains enigmatic. Further understanding is possible in an examination of the more distal pro-clinoform beds. However the exact relationship between clinoforms and distal equivalents is difficult. In the Terra Nova area the question arises as to the stratigraphic position of the transition from clinoforms to similarly dipping (onlapping or conformably overlying) but much later sedimentation. It is this uncertainty which led to discrepancies between maps in this and earlier reports. A shallow, infilled pro-delta basin is expressed in the Terra Nova area but it is unclear if this is related to earlier processes. The delta/pro-delta relationship is different farther south. Line 20 (Fig. 3B, Enclosure 2A) shows a previously excavated basin, as to the north, but here a sizable pro-delta body has prograded *landward* into the basin. This is interpreted as shallow water progradation associated with the rise in sea level following the lowstand which formed the immediately underlying angular unconformity. Continued sea level

rise and transgression of the shallow bank top would result in bank-edge prograding of the Unit 2 clinoforms. Unfortunately, the thin section and resolution limitations preclude establishment of exact stratigraphic relationships with the delta clinoforms, though it is clear they are at least penecontemporaneous.

Thus, the simple concept of a delta and its equivalents is perhaps somewhat simplified. Accordingly, the isopachs (Figs. 10 and 11, Enclosures 9 and 11) demonstrate that the seaward equivalents are thick and voluminous farther to the north, with a clear depocentre centered around lines 3, 18 and 19. The volume of the pro-clinoform deposit (though not calculated) is at least that of the clinoform body. These sediments contribute significantly to the aggradational-style shelf build-up. In terms of a simple prodelta (bottom set) scenario, one would expect a thin, low volume deposit.

4.2.4 Unit 1

This unit displays medium to high amplitude, highly continuous, parallel to slightly seaward splaying reflectors. Subtle angular unconformities within Unit 1 were previously identified in the shallow sub-surface (Mosher and Sonnichsen 1992) but this newer, more regional data set indicate a region-wide distribution. The unit has been subdivided into four unconformity-bound sub-units A to D (Fig. 2). The basis for identifying the horizons as unconformities is generally the angular relationships near the paleo-shelf break. The top of Units 1A and B, exhibit this best. The horizons display different degrees of erosion locally; the top of Unit 1A has the most clearly dissectional nature (Enclosures 2A & 2B). The later (C and D) horizons may be associated with little erosion but rather a transition from a vertical aggradational depositional style on the paleoshelf to a more progradational nature near the shelf break. In either case, the changes require an erosional agent or at least a significant change in sedimentation processes. The erosional horizons must give way to depositional (or disconformable) relationships where they dip to great depths beyond the paleoshelf-breaks and on to their respective paleoslopes.

The top of Unit 1A horizon has erosional elements down to over 350 ms (Line 20), representing present water depths of 270 m, which also corresponds to a gradual shelf break. The erosional nature is greatest in the south (comparable to the Top of Unit 3 situation). A subaerial erosion genesis requires either a very low sea level stand and/or considerable subsequent general tectonic subsidence. Rare *landward* prograding strata at the top of this unit (Line 7), near the paleoshelf-break suggest shallow water processes also preceding the low-stand. The depth structure map (Fig. 12, Enclosure 14) depicts the same N-S to NW-SE swing in strike direction at about the Terra Nova latitude that underlying units possess. The paleoshelf-break is typically at greater than 450 ms present depth (below sea level). The isopach map (Fig. 13, Enclosure 13) shows a typical shelf thickness of 20 to 40 ms, partially a function of preferential infilling in broad subtle basin forms. A substantial thickening at and below the paleoshelf-break is registered as exceeding 130 ms

Unit 1b is similar to the underlying unit but with a lesser degree of section obviously removed by erosion. The top of Unit 1b horizon is smooth, uniformly dipping until about 450 ms depth where, at least in the north, a clear paleoshelf-break is present (Fig. 14, Enclosure 16). The

blanket deposit thickens gradually seaward to about 40 ms at the shelf break except where it has since been partially removed at the present seabed, as is the case over much of the shelf north of Hibernia. Beyond the paleoshelf-break registered thickness is over 70 ms (Fig. 15, Enclosure 15).

Unit 1c crops out in a narrow band well east of the Terra Nova and Hibernia sites (Fig. 4, Enclosures 4). It displays an even more marked swing in strike direction at about the latitude of Terra Nova (NNE-SSW to NW-SE) (Fig. 16, Enclosure 18). It varies between 20 and 50 ms thickness on the paleoshelf and thickens to over 120 m on the paleoslope (Fig. 17, Enclosure 17).

Unit 1d is clearly a mappable unit bound by subtle unconformities but, as stated earlier, mapping precision based on existing data coverage (lack of strike tieline) is somewhat suspect. Nevertheless, Figure 18 (Enclosure 19) shows the geometry of the top of this unit. Outcrop pattern is dominated by a thin inlier (western ends of lines 5 and 7) where erosion at the present seabed was slightly less than to the N and S. Similarly, an outlier has survived later erosion in the region surrounding the Adolphous salt diapir. Doming created a basin west of the diapir while slight subsidence east of the dome might have resulted from the salt migration (Geologic Profile, Line 9, Enclosure 2A). The horizon is recognized to great depth (over 1500 ms) on the paleoslope.

Unit 1 as a whole thickens uniformly eastward until the combined paleoshelf-break prograding deposits contribute to a thick deposit, exceeding 325 ms thickness (Fig. 19, Enclosure 5). The shelf break is generally gradual in the south while north of the strike swing (north of Terra Nova latitude), paleoshelf-breaks are more marked and slope-situated deposit thicknesses are great. These factors are probably more a reflection of the underlying paleogeography and subsidence history than the depositional processes pertaining during Unit 1 time. Section 5.2 contains a brief depositional process and age interpretation.

4.3 THE POST UNIT 1 SECTION; PALEOSHELF-BREAK AND SLOPE DEPOSITS

Stratigraphically above Unit 1 is a change to primarily shelf edge progradation and a more homogeneous (less layered) sedimentation style, (much less continuity in the seismic signature). This transition is not sharp except on Line 20 (Fig. 3b, Enclosure 2A) where a truncation relationship is present. As the top of Unit 1 is poorly defined, the stratigraphic column (Fig. 2) identifies this section as largely undifferentiated Post-1 shelf-break deposits. It is attributed to greater influence of glacial processes. Figure 6 (Enclosure 3) shows the distribution of this zone of relatively amorphous character. Figure 20 (Enclosure 20) shows the total thickness of the post Unit 1 section, including the surficial till blanket. While a thin remnant is present over much of the outer bank, it has a primarily a shelf-edge distribution. The paleoshelf-break and upper slope is characterized by thick seismically homogeneous beds with a large scale prograding aspect. Bed surfaces are rough and discontinuous. (See geologic sections, Enclosure 2A & 2B.) In contrast, the mid and lower slope equivalents (below approx. 550 m water depth) are well to moderately stratified. Periodic changes in current/sedimentological regime are indicated by local unconformities and local ponding. The climbing wave geometry of contourite packages are not observed. The presence of turbidity channels or overbank turbidites is a possibility, especially in

light of previous high resolution seismic and shallow core studies (Piper and Sparks 1986, Armstrong, *et al*. 1988, Piper & Pereira 1992). Although a meaningful seismostratigraphic subdivision seems possible in this mid and lower slope section, line spacing and to some degree, resolution capabilities preclude this presently. Accordingly, the Stratigraphic Table (Fig. 2) differentiates seismic facies and features only with no implied stratigraphic order of succession. In fact the facies are locally both contemporaneous and stratigraphically separated. The previous investigations (above) identified features, stratigraphy and a rough late glacial chronology in parts of this slope and the floor of Flemish Pass. The cursory study from the 98-034 data adds little to this except to identify similar features and processes over a broader area.

4.3.1 Slope Features

Almost all the underlying Unit 1 horizons become rougher (mesorelief, in the order of 5 m) associated with steeper slopes beyond the shelf break. This roughness is interpreted as small scale gravity failures. Yet the prevalence within Post-Unit 1 of small to medium scale failures nearly completely obliterates reflector continuity. This may, in part, be related to the even steeper upper slope in this uppermost unit. Mesorelief is approximately of the same scale presently exposed at the seabed along a continuous zone of iceberg scour/failure (Piper & Pereira 1992, and Fig. 6, Enclosure 3). In contrast to Unit 1 deposition, the upper slope post-Unit 1 deposits form a “bulge” with a convex seabed profile giving way to a concave profile on the mid and lower slope. This might be because of enhanced shelf-break-located deposition as opposed to more dispersive shelf sedimentation processes in the earlier units. The change in depositional style is interpreted to represent the onset or enhanced activity of glaciation. Piper & Pereira (1992) and Armstrong, *et al*. (1988) recognized a change in depositional and erosional processes (valley cuts, turbidites, debris flows etc.) at approximately this stratigraphic interval (or shallower) in the deeper water Flemish Pass. Below this (down to Miocene or Pliocene horizons) a more uniform depositional pattern prevailed. Piper and Sparkes (1986) interpreted the upper slope acoustically incoherent deposits as till or coarse ice-contact sediments. While the authors generally concur with this, only the uppermost stratigraphic unit (located in the NE) is confidently interpreted as a predominantly till blanket (see Section 5.3).

The mid to lower slope section is characterized mainly by continuous, conformable, closely spaced strata of uniform thickness and a concave geometry. However within this section there is a transition approximately midway *within* the Post-Unit 1 section. In the upper half a greater frequency of medium scale mass failure features occurs (the upper ca. 150 m of the unit, see, for example Geologic Profiles 7, 9, 14). These are characterized by buried failure scarps and (more commonly) lenticular bodies with a homogeneous seismic character in contrast to conformable under and overlying blankets displaying fine seismic stratification. Other features include open and filled channels/canyons and lower slope diapir-like features.

4.3.1.1 Debris flows: Figure 6 and Enclosure 3 show the size, distribution and depth (below seabed) of these bodies. Figures 21 and 22 show examples in Huntec boomer profiles. They are interpreted as the constructional depositional lobes of debris flows. They were also recognized

from deep-towed boomer profiles in Flemish Pass by Piper and Pereira (1992) who recognized a crude stratigraphic periodicity to their occurrence. A similar periodicity is recognized in the most recent data. Though their sizes are depicted as circles in Figure 6 (Enclosure 3), this represents only their extent at the position of the seismic profile. They likely have a downslope elongate geometry (many references) and similar bodies on the Norwegian slope have been shown to have upwards of 100's of km runout distances (King *et al*, 1996, 1998, Laberg and Vorren 1995). King *et al*. (1998) demonstrated a close connection between the occurrence of such deposits, termed Glacigenic Debris Flows (GDF's) and glacial ice extending to the shelf break. This need not be the case in the Flemish Pass setting and alternative sources and failure triggers are possible (e.g. a possible ice-free shelf-break during last glacial maximum, lower frequency of failure features, associated turbidites, glaciated shelf-break, iceberg scouring, and possible gas influence).

4.3.1.2 Canyons/channels/slides: Owing to scant seismic coverage the geometry of many failures is unknown, often precluding definitive differentiation of canyons, channels or mass failure slides. Local rotational failures of various scales are identified on the slope (Fig. 6, Enclosure 3). Figure 21 illustrates perhaps the largest of these slide scars. Here, two erosional scarps, probably slide sidewalls, represent two consecutive failures, widely separated in time and space. Figure 23 shows another example of a large slide. A clearly erosional headwall is identified. It flattens out downslope to a strata-parallel glideplane. No equivalent depositional lobe is recognized. Strata on top of the glideplane are disrupted and secondary failures are a possibility. Earlier surveys allowed identification of two major canyon/slide features (Piper & Pereira 1992) termed the Gabriel and Kyle valleys. Both are expressed at the seabed and have associated depositional lobes. The Gabriel valley is considerable larger (10 km wide) and the failure identified in this survey at the intersection of lines 14 and 15 (Fig. 6, Enclosure 3) is probably part of this complex, multi-stage system. A continuous, laminated blanket of about 10 ms thickness covers the slide/canyon. This is the blanket identified as lying above the regional "alpha" reflector of Piper and Pereira (1992) which they tentatively date as a little younger than 23 ka. Local ponding at this horizon on line 15 is suggestive of turbidite activity, likely associated with the Gabriel Valley failure.

A more deep-seated failure scarp is located north of this at the northern edge of line 15. Without additional traverses, its geometry is unknown. It likely represents the sidewall of an older valley. The scarp is larger than the Gabriel scarp with upwards of 30 m of material removed. The affected strata lie well stratigraphically below those of the Gabriel valley. In fact, the Gabriel failure removed much of the infill over this older failure scar. This might represent isolated failure events but there is a possibility of long term channel/canyon migration. The upper part of the sedimentation record between the two scar events (immediately pre- "alpha") is a well laminated deposit which thins to only half the "normal" over a local topographic high (northernmost end of Line 15). This preferential valley infill might be further evidence of a turbidite origin for much of this interval, in accordance with interpretations from scattered core investigations (Piper & Pereira 1992 and Armstrong, *et al*. 1988).

A sharp, "V'-shaped mid-slope, completely infilled valley is present much farther south (Line 7, Enclosure 2B). Incision is upwards of 225 m, much deeper than other features, and the flanks

reach nearly to the seabed. The course of the valley is unknown. The near-surface flanks (poor Huntec boomer registration on analogue record here) suggest a relatively recent age and surficial mass movement at the same site might be related although it is also coincident with the intense iceberg scouring zone (Fig. 6, Enclosure 3). Farther downslope are three rotational-type failures whose headwalls cut between 40 and 55 m of section. Their strata-parallel glideplanes are visible for distances of over 8 km. The largest (lower slope) encompasses three nested slides, each with subsequent infill. Their shallow headwalls reach to within 15 to 20 m of the seabed.

Smaller scale channel-like depressions are common on the lower slope in the north (Line 15) and central (Line 8) map areas (Fig. 6, Enclosure 3). Figure 22 shows a typical channel. Their erosional flanks and base are covered with the regional laminated blanket (less than 5 m thick) over the "alpha" horizon of Piper and Pereira (1992) suggesting a last glacial maximum or slightly older age. Though lenses on either flank are acoustically identical to other bodies interpreted as debris flows, they might also be turbidity channel levées. They immediately overlie the erosional flanks. A proposed core might help identification.

The shallowness of some of the headwall scarps and the smaller channels indicates relatively recent activity (upper post-Unit 1). Armstrong *et al*. (1988) infer a glacial stage incision for some shallow gullies, supplied by shelf-derived, cold density currents. The canyon like feature may be nearly directly glacially fed during an ice maximum at the shelf break or simply a low stand canyon/turbidite channel system not directly associated with a glacier presence.

A further understanding of the processes and the chronology could be attained with a precisely placed core of 10 m or longer recovery at the upper flank of the Gabriel Slide (Fig. 21) and/or the valley farther south (Fig. 22) (See Recommendations for Future Work, Section 6.0).

4.3.1.3 Possible faults: Two of the slope-situated survey lines traverse buried but marked and sharp, strike-parallel inflections in stratification on the mid slope (Fig. 6, Enclosure 3 and Figure 24). Three such features are mapped. The inflections approach to within ca 50 m of the seabed. There appears to be little or no offset of the reflections. Nonetheless, their apparent continuity over 25 km or more raises the suspicion of faulting. Yet the features may be benign as the result of fairly deep-seated differential compaction. Lower slope faulting is recognized on the Flemish Cap (opposite) side of Flemish Pass (Armstrong *et al*. 1988).

4.3.1.4 Diapirs: Figures 21 and 22 show sub-surface acoustically homogeneous and amorphous mounds. Diameters of several hundred metres and heights of 10 to 15 m are common. Occasionally they have a seabed expression. Though they exhibit a diapiric morphology, it is not clear from where the mobilized sediment originates. Identical features identified from earlier surveys (Piper & Pereira 1992, Armstrong, *et al*. 1988) are likewise interpreted as diapirs and their recognition of gas in scattered cores introduces the possibility of a gas or gas hydrate degeneration related origin. They also note an increased abundance of such features ringing the Gabriel lobe, a thick slide or turbidity flow induced depositional lobe. They attribute rapid loading from this lobe to the diapir activity. In a similar lower slope setting in the Faeroe-Shetland Channel, King *et al*. (*in prep.*) attribute rapid loading of thick mid and late Pleistocene

glacigenic debris flow sequences to (larger scale) soft sediment diapirism near the depositional feather edge.

4.4 THE GLACIAL SECTION ON THE SHELF

The uppermost mappable seismic unit has a distribution largely restricted to the northeastern map area (Fig. 25, Enclosure 21). On the outer shelf the angularity of the erosional contact at its base is clear (Enclosures 2A & 2B). It is rare that the erosional surface itself gives rise to a significant reflector (outer Line 9 is an exception) but rather, the unconformity is defined only by the truncation of older beds. This situation is different south and east of this where the glacial unit either thins to beyond recognition on both the high and lower resolution profiles or its lower contact becomes indistinguishable in both its internal character and basal reflection from much older (stratigraphically lower) beds which are essentially parallel bedded. Accordingly the zero edge is poorly defined on the map and the isopach map reflects poor resolution of the glacigenic unit east of the 10 ms contour (Fig. 25). Presumably a thin blanket, becoming dissected, and with outliers, is present west of this. If the rate of westward thinning, as defined by the isopach map, remains about the same then outliers might be encountered 20 or 30 km east of the 10 ms contour, approaching, for example, the vicinity of the Terra Nova site.

The blanket of glacially derived material reaches well over 25 m thickness. Its upper surface is developed into a series of long, continuous ridges interpreted as moraines (Section 4.4.2). The glacial material is interpreted as predominately *till* based on several observations and associated inferences. Though the large “IKU” type grab was unsuccessful in recovering much more than gravel and cobbles, their varied lithology (including Avalonian rocks) attest to their glacial transport. The consolidated nature and/or gravel/cobble armour and a greater preserved iceberg scour incision depth are also consistent with glacigenic sediment. The acoustic character (on boomer profiles) is amorphous/homogeneous, characteristic (though not diagnostic) of till. The moraine system and associated shelf-break till delta are best explained by a sub-glacial genesis as developed in the discussion (Section 5.3.1). Finally, the base of the uppermost glacial unit indicates substantial (metres or 10’s of m) erosion and the shape of this angular unconformity indicates an overdeepening with respect to an inferred E or ENE ice flow direction (Fig 26, Enclosure 22). The substantial body of circumstantial evidence all points to a predominantly till genesis.

4.4.1 <u>Till Delta</u>

A prominent, continuous ridge is evident in the CHS bathymetric chart, extending along the shelf break a distance of at least 70 km from water depths of 230 to 310 m. This is the outermost of a series of at least 15 such ridges generally from 3 to 6 km wide and up to 15 m high (Fig. 6, Enclosure 3). The southernmost seismic traverse (Line 9) indicates a rather structurally homogeneous internal character on the outermost ridge, much as in all the other ridges, but on the two northern traverses a coarsely prograding structure is displayed (Figure 27, and Geologic Profiles, Lines 14 and 16, Enclosure 2A). This delta like structure differs from a typical delta or shelf-edge spill-over in that its upper surface has a *landward* slope. No topsets are resolved so, if

present, they are less than 75 cm thick. As noted earlier, the glacially-carved angular unconformity rarely displays a reflective horizon of its own and such is the case here. However, the landward tilt on top of the "delta" can be projected westward to the glacial erosional unconformity surface (see Geologic Profiles, Lines 14 and 16, Enclosure 2A).

The great water depth precludes a fluvial origin for these "delta" bodies (without invoking unrealistic subsidence rates). Though prograding can develop as a result of bank-top sediment migration and spill-over this is mainly a sandy phenomenon and also it is difficult to envisage how a landward tilt on the delta surface could develop. Rather, a subglacial origin is suggested. This is compatible with an observed gravel/cobble surface, the overdeepened erosion, the crude progradation (probably typical foreset small scale debris flow), and the obvious association with the moraine field. The delta feature is thought to have formed much like a "till delta" found below a low gradient Antarctic ice stream at the grounding line (c.f. Alley *et al*. 1989). A model for the till delta and moraine field is further developed in Section 5.3.1.

4.4.2 Moraine Field

A series of elevations at the seabed on the seismic traverses in the NE of the map area (Fig. 28) is reflected faithfully in the CHS chart (Fig. 1, Enclosure 1). The chart demonstrates that the elevations can be correlated from line to line with the benefit of the much more closely spaced bathymetric control. Figure 29 presents the easterly component of seabed profiles from the seismic lines in the area. The morphology of the ridges is shown as well as their chart-aided line to line correlation. The northern ridges are best developed, with relief in the order of 10 to 15 m while the southern extremities have very low elevations, including those as low as 2 m high. The presence of moraines north of the northernmost survey line can be inferred from the bathymetric charts showing that the field extends another 50-60 km north, to the nose of the bank. The pattern of ridges as mapped from these profiles and CHS chart is shown in Figure 30.

The ridges are interpreted as moraines in light of their pattern, the association with the till delta ridge and the seismic character and geometry of the till blanket in which they are developed. The moraines at the shelf break are oriented N-S, parallel to depth contours, yet farther landward they cut rather obliquely to the depth contours describing a NNW-SSE orientation. A number of the moraines north of the map area lie seaward of the shelf-break ridge farther south. In addition, several of the moraines bifurcate to the north.

The moraine field is conspicuously truncated along the southwest margin (Figs. 29 and 30) The seismic profiles show a thinning and eventual (but not well defined) pinchout of the till blanket along this margin. This is less evident in the south but the seabed expression of well developed moraines along the northwestern margin become subdued and disappear on their southern ends over a span of a few kilometres (Fig. 29). Though it is possible that the glacial regime was such that no moraines ever developed, this seems unlikely in light of the extreme continuity of the outer shelf ridges. The truncation is roughly water depth dependent, following along the 150 to 170 m water depth contours. Figure 29 shows the transition from the rough or rolling topography

of the moraine field and superimposed iceberg scours (high frequency roughness in this figure) to the smoother and evenly rising seabed west of the moraines. On the southern profiles, this transition is also marked as an inflection in the general seabed profile. Lines 18 and 5 depict a seaward steepening while Line 3 has a flattened zone. The nature of truncation and its cause has implications for inferences concerning the age of the moraines (Section 5.3.2).

5.0 DISCUSSION

5.1 TECTONIC SUBSIDENCE PATTERN

A tectonic influence is obvious in the mild folding of Unit 3. As the flexure is largely recognized over the Jeanne d'Arc Basin it probably originates from late, deep seated adjustments. The later units appear little affected and the regime was largely relaxed after the subsequent erosional event that modified the paleo-seabed across the top of this unit. Other than this, a local diapiric feature, the Adolphous salt diapir is displayed on Line 9 (Enclosure 2A and Fig. 31)

The evidence for subsequent tectonic tilting or differential subsidence is addressed because it apparently affects depositional patterns and introduces an element of (long term) timing in an otherwise poorly age-constrained sequence. The setting also has bearing on speculation about the age of surficial erosion and deposits. Several observations point to a regime where relatively uniform, long term tilting is indicated.

The continental shelf to the north of the map area is atypical of shelves in that it is bathymetrically depressed. Subsidence rate has long outpaced depositional rate such that build-up to a base level is not achieved. Accordingly, much of the product from the last glacial is preserved here.

The unconformities within the upper unit (Unit 1) generally display a seaward splaying as illustrated schematically in Figure 32. This figure was generated by applying a straight-line approximation of the dip trend to the most extensive, near planar portion of the unconformity. These dipping horizons are normalized through extrapolation east and west in order to compare from line to line. The degree of splaying shows a definite trend to greater splaying in the northern part of the map area. Splaying indicates greater accommodation space at the thick end of the wedge (seaward end). Accommodation space on this flat shelf environment arises from raised sea level or substrate subsidence. While some depositional wedging might result during lowstands associated with the unconformities it is interpreted as subsidence related because of the differential splaying across the site. Thus, though subsidence is occurring across most of the area, a greater subsidence rate in the north is indicated. This is compatible with the bathymetrically depressed NE Newfoundland shelf.

Another suggestion of the attitude and degree of tectonic tilting arises from an enigmatic arrangement of clinoform strata in Unit 2b. A N-S transect in the northern part of the map area (Line 10) approaching strike direction (Fig. 33) displays the dipping foresets. Successive foresets appear to be climbing in elevation (with a southerly progradation component). This unnatural phenomenon should not arise simply as a result of profile orientation. Rather it is interpreted as a post-depositional tilting to the north. An attempt at reconstruction requires, as a minimum, that the Unit 2b body as a whole be tilted until its top and base are nearly flatlying, thus restoring a natural progradation. This requires a tilting "back" of ca 1: 525 or 0.11 degrees. Perhaps coincidentally, 0.1 degrees is a typical (easterly) dip magnitude on the Unit 1 a, b, and c unconformities. This lends some credence to the tilting concept as the northerly component, though greater, is of the same general magnitude.

On conventional seismic data Grant and McAlpine (1990) recognize a pronounced, pervasive Tertiary subsidence to the north of the Jeanne d'Arc Basin and our observations reflect the same process.

With respect to surficial deposits, Section 5.3.1 discusses a glacial moraine field which has been erosionally truncated, apparently during a lowstand to 150 - 170 m present water depth. In order to reconcile this with assumed isostatic and eustatic conditions, a considerable post-truncation subsidence must have occurred. The above discussion provides for such a setting although timing of events remains unclear.

Presumably such a tectonic tilt represents a fairly long term and relatively constant process. However, subsequent elevated glacial deposition rates may have enhanced subsidence through extra loading. Establishment of direction and magnitude of tectonic tilt or differential subsidence can be more useful if a crude timing can be established (e.g. even one date) to provide *rates* of tilt. We do not have any reliable dates presently.

5.2 DEVELOPMENT OF THE LOWER SECTION: PROCESSES AND AGE ALTERNATIVES

The stratigraphic breakdown of Units 4 to 1 is based on their bounding planar unconformities. These are interpreted as lowstand phenomena but the relative influence of fluvial, marine transgression or glacial erosion is difficult to ascertain. The fluvial influence is apparent at least locally on the top of Units 4, 3 and 1a in the form of small scale relief and incisions. None of the large scale (tunnel valley-like) incisions indicative of glacial overriding are present in the map area. The distribution of such features lies well to the west and northwest (Piper et al. 1990, King and Fader, in prep.) and there is no apparent connection to shelf edge canyons. Tunnel valleys on the NE Newfoundland shelf are clearly a later phenomenon (King and Fader, in prep.). However, this does not necessarily preclude a glacial sheet erosion. The presence of a surficial moraine field at the shelf break (Section 4.4.2) indicates that glacier overriding at the present seabed has occurred without a record of tunnel valleys.

The seabed represents the most marked unconformity of the entire section. It is clear that, for the western part of the map area this erosion represents the cumulative effect of numerous superimposed erosional phases (west of Unit 1d outcrop). These observations can be attributed to marine relative lowstand processes. However, the near surface glacial component of erosion becomes clear in the sculpting and overdeepening in the NE map area (Fig 26.). Though only one phase is evident, it can also represent the cumulative result of previous glacial phases. The explanation for the enhanced unconformity development at the seabed appears to be the cumulative affect of both marine transgression and this glacial component.

It remains unproved if the unconformities are sea level/glacially cut or simply low stand related. With the exception of the present seabed, all observed unconformities could have developed from marine processes without the need to invoke the properties of glacial erosion. This applies

to nearly all horizons with little erosion or fluvial features (i.e. top of Units 4, 3, 1a, b, c and d) . Furthermore, there is nothing in the deposits between the unconformities which suggests other than a “normal” marine deposition process. The *age* implications of either alternative are significant; multiple glacial phases and a relatively young age for this thick sequence or multiple low stands and a simple marine aggradation and progradation during intervening transgressions and highstands. The latter, however, entails a longer history within a regime of regional subsidence. Elements of such a subsidence have already been discussed. The slight folding/flexure event which appears to have preceded Units 1 and 2 also suggests a significant time span. This is probably related to further adjustments associated with salt tectonics (Grant and McAlpine (1990).

In their study of slope features and history in Flemish Pass, Piper and Pereira (1992) site a recognition of the mid-Miocene unconformity (Gradstein 1981) at 610 m below sea floor in the Gabriel C-60 well situated at the base of slope (between the outer ends of Lines 9 and 14). On a seismic section through this well, they suggest a Plio-Pleistocene boundary at ca 300 m below sea floor. Despite the inaccuracies of a distant strike projection to Line 9, the Miocene horizon occurs at least 100 m below the deepest strata recognized in this study. However, provided the underlying geology has a similar geometry, this horizon could conceivably project landward to a position as high as the vicinity of the top of Unit 4 or even the extensive top of Unit 3 unconformity. Their 300 m Plio-Pleistocene boundary projects to very close to the Top of Unit 1d, coincident with the interpreted onset of glacial conditions (or at least change in deposition style) arrived at independently in this study on seismostratigraphic grounds.

The possibility of an “old” age for the marked, deep and extensive unconformity at the base of Unit 2 means that an alternative to a glacial origin for the Hibernia delta complex must be considered. This holds even more so with recognition of the similar delta body in the even older Unit 4 strata. Progradational bodies of a similar scale are also recognized on the NE Newfoundland shelf (north of 48º 45’N), at 350 m below sea level and stratigraphically below a marked unconformity which underlies multiple phases of glacial advances (King and Fader, in prep.) This suggest an apparent ubiquity. Unless these deep occurrences were glacially deposited, they suggest shallow water phenomena which have since subsided. The glacial hypothesis for delta genesis has its merits in explaining a rapid, voluminous sediment influx along an extensive depositional margin, and a sparse, reworked fauna. In contrast, a fluvial origin would result in point source depocentres. Even more problematic is that the fluvial catchment area, even considering the entire bank, is small compared to the deposit (G. Sonnichsen, pers. comm.). This issue would diminish somewhat if the delta is so old as to predate evolution of the Avalon and Halibut Channels.

Perhaps the deltas represent a lowstand bank spill-over phenomenon. Using the Line 20 profile as a model, a sequence of events is proposed. The delta lies directly on the top of Unit 3 unconformity which represents the deepest, most extensive lowstand. Subsequent transgression was slow or erosive enough to mobilize voluminous sediment and deposit the *landward* prograding package situated distally to the Hibernia delta. Some component of fluvial input would occur. As sea level rise progressed, marine inundation of the entire bank subjected an expansive area to erosion and remobilization. Provided the transgression was long-lived or

involved fluctuations, a seaward progradation of the entire eastern bank edge could develop (Unit 2a). A superimposed regression/transgression of lower magnitude caused the Unit 2a/2b hiatus. This was followed by further rapid, extensive bank-edge progradation (Unit 2b). With continued rise Unit 1 blanket deposition began.

An "old" age for Units 4 through 1 would require reconciliation with a number of contradicting age indicators (Miller 1992, 1999, M. Lewis, pers. comm.). Though an observed reworked fauna is expected with bank spillover, the presence of some apparently Pleistocene *age* foraminifera is clearly contradictory, as are specific ostracods which are suspected to have evolved in the Pleistocene. A single magnetic polarity is not unlikely, given the envisaged rapid mode of deposition. A normal polarity is chronologically inconclusive on its own but together with an amino acid analysis from within the delta which indicates little racemization, a Bruhnes chron (< 780 ka) deposition is suggested. Clearly further work is necessary.

5.3 GLACIAL PROCESSES AND TIMING

5.3.1 A Model for Till Delta and Moraine Field Development

The outermost (shelf-edge) morainic ridge, as presented earlier, has a prograding nature similar to the "till-delta" envisaged by Alley *et al* (1989). In the Antarctic case, the delta is forming beneath a low gradient Antarctic ice stream at the grounding line (transition to a broad ice shelf). In that case, a thin, shearing, dilatent, water saturated till layer (topset equivalent) is continuously fed at the glacier sole to the grounding line where it fails, forming foresets. The foresets provide a stable substrate across which the ice can advance farther, coincident with build-out.

Figure 34 shows the conceived evolution of till delta and moraine development for the Grand Bank example. The seabed and sub-till surface are derived from the situation along Line 16. Net erosion in an up-ice position would eventually develop the slightly overdeepened basin and give way to sediment bypass and then net deposition (Panels 1-3, Fig. 33). In this situation, the surface of angular unconformability represents an erosion surface landward of the till delta but a largely depositionally generated angularity (foresets), on the delta top. Note that the continuity of this surface from (up-ice) base of till to top of delta is *assumed*; no reflector is present. This surface represents a lateral transition from net erosion to net deposition at the till delta (Panel 1). The transition between the two would be a zone of sediment bypass only. An acoustic impedance contrast might not develop under such conditions in constant flux between deposition and erosion. Deposition on the steep paleo-margin would begin as the ice reached the shelf-break (Panel 1), most likely as small debris flows. The ice would advance over this progradational body (Panels 2 and 3), and a thin, mobile topset (unresolved) would feed (bypass) to the margin. Some delta-top erosion might occur. The till blanket infilling the overdeepened basin but below the base of the constructional moraines is thick (10-15 m) and must have an *unresolved* vertical stratigraphic buildup (Panel 3) to an indefinite level after which the positive morphology of the first moraine developed (Panel 4). The Antarctic till delta example has a flat top, conforming to the glacier sole at the flat-lying ice stream to ice shelf transition. The contrasting *landward* tilt on top of the Grand Banks example (Panel 3) would have developed because, without the very

gradual transition to an extensive ice shelf, as in the Antarctic situation, buoyant affects would become important at the grounding line, just upstream of the calving margin. With late-stage glacial waning, one or a combination of subsidence, ice thinning and eustatic sea level rise would provide a greater subglacial accommodation space (effectively raising the base level) at and immediately proximal to the ice margin. This space would readily fill with till through the "conveyor belt" sediment feeding action. With greatest accommodation space generated just proximal to the grounding line, and continued waning, a grounding line ridge would eventually develop. The present delta top is envisaged as an approximate time line delineating the configuration of the glacier sole immediately preceding retreat. With sufficient glacial waning the margin would become unstable, retreat from the shelf break in periodic grounding line jumps (Panel 4), while maintaining a similar subglacial sediment feeding mechanism. The absence of prograding foresets in the shelf-situated moraines reflects the flat, immediate proglacial substrate as opposed to a steep, debris flow characterized margin at the shelf break. Rather, a more homogeneous moraine would develop in part sub-glacially as accommodation space was made available, and possibly in part proglacially (Panel 4, stage B). The extreme surface roughness is in part due to scouring of locally calved icebergs, probably after the margin retreated to the western side of the overdeepened basin. The larger scale roughness might reflect minor ice front fluctuations or sub-glacial irregularity.

As noted earlier, the southern ends of the long morainic ridges lie in shallower water depth than their northern ends (Fig. 29). This allows some inferences to be drwan about the moraine genesis and ice behavior. Though it is possible the entire field developed penecontemporaneously in a sub-glacial regime tens of kilometres behind the margin, one would suspect that the field represents a pattern of ice margin retreat. The glacier in the deeper water depths to the north would probably be thinner and faster flowing than that to the south, as the result of marine drawdown. (A faster flowing ice in the north might also have been capable of greater sediment supply, resulting in the observed greater ridge height.) The margin position would be more sensitive to early sea level rise and/or ice thinning than to the south. Continued sea level rise and/or thinning would force landward retreat but the ice sheet in shallower water to the south would be less sensitive to this and slower to react. This could explain the bifurcation pattern as a new moraine developed in the north whose position remained unchanged in the south. Inherent in this explanation is that the moraines formed relatively near the ice margin and that the pattern does, in fact, reflect an ice margin retreat.

5.3.2 <u>The Timing of Shelf-edge Glaciation</u>

The moraine field provides proof of a glacial ice sheet extending to the edge of the NE Grand Bank. Yet, the timing of this advance is uncertain. Its present seabed exposure suggests the last glaciation is responsible. This, however, contradicts conclusions of some workers (e.g. Piper *et al*. 1990, Piper & Pereira 1992) who suggest a mid-shelf Late Wisconsinan maximum ice extent, implying a pre-Late Wisconsinan age for the moraine field. One might expect, with a mid-shelf Late Wisconsinan position, a proglacial blanket cover on the moraines, which is not observed. However, Late Wisconsinan sedimentation on the slope is quite minimal (5 m to "alpha" reflector, Piper & Pereira 1992) and sediment bypass or low sediment supply may have pertained

during the latest low-stand, a situation maintained up to the present time as the seabed lag indicates.

Perhaps the most important phenomenon pertaining to the age of the moraine field is the apparent erosional truncation at the western margin of these features. The erosion is either a result of marine (wavebase and coastal processes) or subsequent glacial sheet erosion. The glacial erosion scenario is not favoured because it is unlikely that the field could be overridden (or partially so) without also having some depositional record superimposed on the moraines. The latest (Late Wisconsinan/Holocene) lowstand is well documented and best depicted by a grainsize distribution with a strong fines tail in sub-littoral sediments below 105-110 m present water depth (Fig. 29) which is absent in beach-washed sediment above this depth. This paleo-shoreline is located in shallower depths than the moraine truncations 40 km to the west. At that time low-stand wave base erosion would have considerable erosive ability across the shallowest moraines, in what was then 40 to 60 m water depth. Yet complete removal (or nearly so) of the till sheet requires vigorous erosive processes (such as transgression) in order to remove a protective boulder/cobble lag which commonly quickly develops and protects from further wave erosion. Thus, the preferred mechanism for partial removal of the moraine field is by coastal processes and subsequent transgression. As this apparently occurred well seaward of the Late Wisconsinan shoreline an *earlier* low-stand associated with a previous glaciation or glacial stade is a possibility (Fig. 29). The setting suggests a pre-Late Wisconsinan age for the moraine formation; two low-stand erosion events separated by an appropriate long period of subsidence.

It is unlikely that eustatic sea level lowering exceeded 120 m during preceding stades or even during the latest Illinoian glaciation. Thus a marine transgression at a present depth of 150 to 165 m suggests subsequent subsidence. The magnitude of this subsidence is poorly constrained because of the unknown component of glacio-isostatic depression (or even uplift from the bulge effect). If the crust were relatively stable following ice retreat (as seems the case for the Late Wisconsinan/Holocene transgression), then 30 to 50 m subsidence since a possible pre- Late Wisconsinan transgression is likely. The subsidence probably reflects continued post-rifting cooling, but superimposed regional basin effects may apply. The findings regarding regional tectonic subsidence in preceding Section 5.1 can be examined in this light.

The two likely periods of extensive glacial ice on the Grand Banks previous to the Late Wisconsinan are during the “heavy” global oxygen isotope periods in the early Wisconsinan (isotopic Oxygen Stage 4) and the latest Illinoian (Stage 6). Thirty to fifty metres subsidence over the shorter of these time spans translates to between 55 and 75 cm/kyr and for the longer, 25 to 40 cm/kyr. These are high, though not unprecedented subsidence rates (e.g. North Sea graben locally displays 50 cm/kyr in Quaternary times). If the preceding arguments for erosion of the moraine field hold, then the implication is that it is unlikely the moraines formed during the Late Wisconsinan and possibly even an earlier Wisconsinan stade. They may originate from the Illinoian glaciation. This is compatible with little evidence for shelf-edge glaciation from previous slope studies and also a general (global) tendency to a larger glacial distribution at that time.

Another possible explanation for the truncated moraine field is, as mentioned above, an isostatic uplift and subsequent subsidence following ice retreat. Let us hypothesize a thin Late Wisconsinan ice sheet which reached the shelf break at some time between 22 and 18 ka, but then quickly receded to the mid shelf to excavate the complex of tunnel valleys and build morainal banks (King and Fader, in prep.) by about 15 ka. This provides a time window during which glacioisostatic depression largely recovers on the outer shelf. Further ice retreat and outer-mid shelf crust stabilization would involve subsequent landward migration of the forebulge. Subsidence of the outer bank in the order of 30-40 m is possible, thus placing the shallowest, truncated moraine remnants in 160 –170 m present water depth (Fig. 35). In this scenario the two shoreline positions (panels B and C, Fig. 35) differ only slightly in age and represent two points on a continuous transgression. However, the model apparently fails to explain the marked sediment textural change at the present 105 m water depth, attributed to the Late Wisconsinan lowstand.

The two hypotheses accommodate quite different age constraints. Dating of the moraine field is of utmost importance in this context. The absence of a recognized proglacial blanket on the moraines precludes a direct minimum date. Part of the blanket of sediment on the slope represents distal equivalents of the till delta foresets. The lowermost might be tied to the approach of the ice margin to the shelf break. This blanket might contain a correlative datable planktonic (non-reworked) assemblage but their stratigraphic connection with the delta remains seismically vague and the stratigraphic tie with the well laminated mid-slope blanket is destroyed by the intervening intensive zone of iceberg scours. Furthermore a mid Wisconsinan or older age presents a technical dating challenge.

5.3.3 Subaerial Drainage Features

Another implication of an interpreted pre-Late Wisconsinan lowstand is that such a setting helps explain enigmatic broad erosional features NE of Hibernia (NE part of map area). In profile, these features are broad erosional valleys, stretching 15 to 20 km across and 40 m deep, as shown on the western end of lines 9 and 11 (Enclosure 2A). They are cut into Unit 2 and early Unit 1 strata. In plan view (Fig. 1, Enclosure 1 and Fig. 29) they are V-shaped with a NNE long axis and resemble wide canyon heads. Unlike canyons there is no seaward continuity of the erosion below approximately 160 or 170 m present water depth. They are closed on their upper end (at about 85 or 90 m water depth) and open ended at their seaward extent where they merge into the relatively topographically featureless seabed. (Note that they should not be confused with large, post-transgressive paleo-shoreface connected sand ridges lying to the south but with a similar crestline orientation.)

Either a glacial or a subaerial erosion mechanism is apparent though submarine canyon-like development in its infancy cannot be ruled out. Glacial erosion would suggest a north-northeasterly ice flow, in contrast to a dominant easterly flow as indicated from the (probably later stage) moraine pattern. The data are inconclusive. However, the fluvial erosion hypothesis is compatible with the proposed 160 m lowstand (pre-Late Wisconsinan) event which truncated the moraines. An hypothetical drainage pattern is shown in Fig. 30. The upper reaches of the same

valley systems would have been inherited during the latest lowstand which might explain the sharp contour inflections in the 100 m contour. Voluminous fluvial erosion products would presumably be deposited through delta and coastal processes at the valley mouths (Fig. 30). Provided coastal processes allowed preservation here, one test of this "fluvial" hypothesis is further surveying to identify possible related deposits. One problem with this interpretation is the apparent absence of preserved large-scale subaerial features to the south and east of these features at similar water depths across Grand Bank. It is possible that they have since been destroyed or buried, or that fluvial systems did not develop to the same extent there.

5.3.4 Summary of Ice Extent and Retreat

The glaciation history of outer Grand Bank has been poorly understood to date. Some effects of glaciation were obvious early on, as the abundance of coarse material from the mainland attest (Fader and King 1981). The marked angular unconformity at the seabed was attributed largely to glacial erosion, though marine transgression above 110 m was also recognized (Fader and King 1981, Barrie et al. 1984, Fader and Miller 1986). Buried valleys extending to the mid shelf were attributed to glacial overdeepening processes and their outer limit has been interpreted to represent a glacial front position of yet unproved age, but it is generally attributed to the Late Wisconsinan maximum (Piper *et al*. 1990). This is compatible with sparse sedimentation and little evidence for the presence of a shelf-edge glacier in slope deposits along the Flemish Pass (Piper & Pereira 1992). The record of glaciation is much better preserved on the Northeast Newfoundland shelf, NE of the map area. A tunnel valley and associated morainal bank system there represents an ice lobe emanating from northern Grand Bank, and a dated moraine in deeper water confirms ice on the mid shelf until 15.3 ka (King and Fader, in prep.). However a till blanket continues to the shelf break here. The recognition of an extensive moraine system NE of Hibernia represents the best evidence to date for glaciation across the bank and to the shelf break. The timing of this is uncertain and a Late Wisconsinan age is not excluded, but a pre-Late Wisconsinan age is suggested, perhaps Stage 4 or a late Illinoian advance are possibilities. What is more clear is the sequence of events in the late stages of this glacial phase.

At the ice maximum in this region, the glacier was grounded all along the shelf break (within the map area) in water depths presently ranging from nearly 400 to 250 m. A linear ridge with a till delta structure developed along much of this margin, probably because of repeated gravity failure on the steep depositional substrate. Retreat is interpreted to have begun at the nose of the Bank (near Sackville Spur) in the deepest water, presumably because of instability of a thin ice sheet sensitive to sea level rise and/or thinning ice and associated increased ablation through calving. The margin remained stable at the shelf break to the south. Eventually retreat began in the southern area, however the margin there remained more stable throughout the retreat process. Periodic retreat events in the north formed a series of at least 16 ridges but many fewer in the higher ground to the south. An ice front trending NNE-SSW to the northeast of the Hibernia region indicates that much of Grand Bank had to have been ice covered.

The ice sheet would most likely have been quite thin; emanating from a banktop ice cap. Ice retreat most likely preceded significant eustatic sea level change at this extreme ice extent so subsequent transgression would have begun erosion relatively soon after deposition.

Outside the map area, ice extent and flow pattern becomes much more speculative. Of note, however, is a major geomorphic change in the bank margin about 100 km south of the map area (see insert map, Fig. 30). Here, apart from an inflection in trend of the shelf break, the slope becomes much more heavily incised by canyons, possibly reflecting a difference in glacial extent or regime.

6.0 RECOMMENDATIONS FOR FUTURE WORK

Hibernia Delta: Results from this study, benefiting from a regional coverage, allows the discussion surrounding the age and mode of deposition of the delta to be viewed in a different light. A process not directly influcenced by glacial deposition is suggested and an age considerably older than that of proponents of the glacial mode is possible. The merit of further seismic coverage in this immediate area is questionable yet perhaps a more stringent analysis in terms of "classical" sequence stratigraphic techniques and a resulting sea level history has the potential of indirect dating through sea level curve matching. Direct dating has the inherent problems of partially or entirely reworked fauna but the (deeply buried) distalmost delta equivalents might have a more readily identified *in situ* fauna.

An alternative approach to age dating is a rigorous tie to well stratigraphy, notably the more eastern locations where the deep section has been examined. The extreme of this is the Gabriel C-60 site located beyond the shelf break (between lines 9 and 14) where a mid Miocene unconformity is present at only 610 m below sea floor (Gradstein, 1981). Existing seismic data (or alternatively a new survey tieing lines 9 and 14) should provide this.

Glacial and other process history: A detailed seismic stratigraphy must be established from the Huntec DTS profiles on the mid and lower slope. This was beyond the scope of this work but with a modest time investment, the relative timing of periodic laminated deposits and periods of significant shifts in their style, periodic debris flow horizons, and punctuated canyon/slide/turbidity channels can be clearly established. This should be followed up in the next cruise to the region, with a strategic/precision coring program. The canyon/slide erosion character affords several locations where a nominal length piston core can provide the means of studying the sedimentologic and chronologic history of these events. Studies on the North Sea margin, for example, demonstrate a lithologic and chronologic tie between debris flow deposits (Glacigenic Debris Flows, GDF's), similar to those present here, and glacial maximum positions (King *et al*. 1998). This illustrates the potential for establishing a regional history from study of these slope sediments. Figure 22 shows an example whereby a 10 m core could penetrate a buried debris flow (ice maximum?) horizon, canyon/slide sidewall, and the draping cover with the potential for dating (AMS C-14 on unispecific foraminifera) all three events. The presence of gas in some Flemish Pass cores led Piper and Pereira (1992) to suggest some features might have a gas related genesis. The core sub-sampling technique should be planned accordingly.

Slope Stability: Further high resolution surveying should probably also concentrate on the slope instability features and history, not the least because of near future engineering applications here. Topics to address include the nature of the large-scale failures. Are they canyons/turbidity channels or large rotational or translational slides? Are they only periodically active (e.g. during lowstands/glaciations) as the data might suggest? Do they, in fact, migrate as the preliminary data might indicate? Regarding the smaller features, is there a relationship between the smaller debris flow horizons and shelf-edge build-out? Are they related to specific events (sea level/glaciation) and perhaps through climate change to gas release? A better three-dimensional picture must first be established. Within the framework of limited survey time constraints, one or two specific features should be surveyed and perhaps core-sampled.

Slope history: An understanding of the slope history might also benefit greatly by a tie with a long core # 11 (R/V Marion du Fresne) located in about 900 m water depth on Sackville Spur.

Till delta: An improved understanding of the stratigraphic relationships between the delta foresets and the upper slope laminated sediment and debris flow bodies is necessary. More seismic sueveying will help establish the connection between shelf processes and slope processes as well as help make the chronological connection which is important because the slope deposits are likely to be more readily dateable.

Moraine field age: The suggestion that the retreat moraines are of Stage 4 or Stage 6 age is based largely on geomorphic inferences. Eventual swath bathymetry coverage here will undoubtedly improve the geological picture. Direct dating of the moraines, however, might prove difficult as attempts at their sampling were largely unsuccessful. Apparently there is little or no sediment cover, this region having either been starved or undergoing bypass. The strategy with most potential for success might be the upper slope till delta/pro-delta stratigraphic correlation and dating of cored pro-delta material, as stated above.

Correlations with the southern NE Newfoundland shelf: Seismostratigraphic and core studies in this area (King and Fader, in prep.) have established ice margin positions, some clearly ice retreat related, but others potentially related to the Late Wisconsinan maximum at a mid-shelf position (a morainal bank complex associated with a north-flowing ice lobe). The latter remains undated but clearly dating could be pivotal to understanding the age of the moraines/till deltas identified in *this* study. Minimum dates on the morainal bank complex can be provided from existing cores sampling post-morainal bank glacimarine sediments. Also, expansive till blankets are recognized beneath a sub-aqueous outwash plane/wedge. The stratigraphic relationship between this till blanket and the blanket making up the moraine field to the southeast should be established through regional seismic surveying. An east-west seismic traverse well to the north of this study area (from 1989) depicts, for example, a similarly morainic or at least complex topography.

Low sea level stand: A simple compilation of existing seabed grab sample grain size analyses in the Hibernia region (King, 1989) demonstrated the transition from transgressed to sub-littoral surficial sediments, marking a sea level stand at 105 m for the Late Wisconsinan period. There is some potential that a similar compilation for the deeper region (150 to 170 m) could test the pre-Late Wisconsinan shoreline inferred in this study.

7.0 ENGINEERING IMPLICATIONS

A problem with difficult near-surface geotechnical conditions at some engineering sites (e.g. Terra Nova) has been variously attributed to “hardground” and/or glacial till (boulder clay). The hardground phenomenon, it is reasoned, developed through a diagenetic (weathering) soil process during sub-aerial exposure, causing a calcrete or caliche development. Alternatively cobble/boulder concentrations can lead to “refusal” in shallow subsurface installations. In this setting such clasts can only arise in glacigenic sediments or their erosional remnants (lags). These conceptualizations are not new to this study. However, this study lends credence to the probability of both processes.

Though glacigenic sediment remnants have been suspected, the recognition of a continuous blanket of these sediments to the east and north is now confirmed. In the Terra Nova area this blanket is too thin to differentiate seismically from underlying strata and is probably locally absent as subsequent marine transgression planed it off. There may be local erosional remnant outliers. Nevertheless, the till blanket was in all likelihood present across much of the NE Grand Bank. Subsequent transgression, both immediately after the till blanket deposition and during the latest lowstand effectively removed most of the till. This would effectively concentrate the coarse clast population on top of any till remnants or leave only a coarse, surficial lag. Neither the thin till remnants, outliers, or the inferred lag are properly resolved in the seismic data.

The hardground occurrence development requires sufficient time for a weathering (soil) profile to develop during subaerial exposure (local leaching and resulting precipitates). Such development would likely be variable and laterally sporatic. The setting established here whereby subaerial exposure was recurrent provides ample opportunity for soil development. If the four lowstands associated with Unit 1 indeed predate the major onset of frequent global glaciations then the climate might also have been more conducive to hardground development. Again, no direct indications from the seismic profiles are recognized.

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9.0 TABLE 1

Table 1. (following page) Excerpt from an extensive “Excel” spreadsheet format database derived (exported) from equally spaced (horizontally) digitized depths from the scanned geologic section line interpretations (in a CAD program). Depths (travel time, ms, below sea level) to boundaries of the seismostratigraphic units were organized to be suitable for export to an automated contouring package (Surfer) for isopach map production. They were further manipulated to provide unit thicknesses for individual units and combined unit packages. These combined thickness packages include Unit 1 total, Unit 2 total, Units 1 and 2 total Post Unit 1 total. The data are organized on a line by line basis (separate sheet for each line). All data are from the 98-034 cruise with the exception of additional values for the Top of Unit 3 horizon, excerpted from the Terraquest Associates (1995) report.

TABLE 1

Easting	Northing	Raw Depths of various units									Depths in milliseconds below sea level										Thicknesses in milliseconds below sea level									
		seabed	top3	top2a	top2	top1a	top1b	top1c	top1d	g-uncor	seabed	w depth	Top 3	Top2a	Top2	Top1a	Top1b	Top1c	Top1d	Glacial Uncon.	Unit 2a	Unit 2b	Unit 2	Unit 1a	Unit 1b	Unit 1c	Unit 1d	Unit 1	Glacial	Units 1 Post- 1d
727898	5173500	-3900		-7925	-6625	-6050	-5525	-5175	-4250		-156	-117		-317	-265	-242	-221	-207	-170			52		23	21	14	37	109		14
727881	5174000	-3950		-7950	-6625	-6075	-5575	-5250	-4225		-158	-119		-318	-265	-243	-223	-210	-169			53		22	20	13	41	107		11
727881	5174000	-3950		-7950	-6625	-6075	-5575	-5250	-4225		-158	-119		-318	-265	-243	-223	-210	-169			53		22	20	13	41	107		11
727863	5174500	-3950		-8000	-6675	-6075	-5600	-5275	-4250		-158	-119		-320	-267	-243	-224	-211	-170			53		24	19	13	41	109		12
727863	5174500	-3950		-8000	-6675	-6075	-5600	-5275	-4250		-158	-119		-320	-267	-243	-224	-211	-170			53		24	19	13	41	109		12
727845	5175000	-4000		-8025	-6725	-6100	-5650	-5300	-4275		-160	-120		-321	-269	-244	-226	-212	-171			52		25	18	14	41	109		11
727845	5175000	-4000		-8025	-6725	-6100	-5650	-5300	-4275		-160	-120		-321	-269	-244	-226	-212	-171			52		25	18	14	41	109		11
727828	5175500	-3975		-8025	-6700	-6125	-5725	-5375	-4300		-159	-119		-321	-268	-245	-229	-215	-172			53		23	16	14	43	109		13
727828	5175500	-3975		-8025	-6700	-6125	-5725	-5375	-4300		-159	-119		-321	-268	-245	-229	-215	-172			53		23	16	14	43	109		13
727810	5176000	-4050		-8075	-6675	-6125	-5725	-5375	-4325		-162	-122		-323	-267	-245	-229	-215	-173			56		22	16	14	42	105		11
727810	5176000	-4050		-8075	-6675	-6125	-5725	-5375	-4325		-162	-122		-323	-267	-245	-229	-215	-173			56		22	16	14	42	105		11
727792	5176500	-4025		-8100	-6700	-6150	-5725	-5400	-4375		-161	-121		-324	-268	-246	-229	-216	-175			56		22	17	13	41	107		14
727792	5176500	-4025		-8100	-6700	-6150	-5725	-5400	-4375		-161	-121		-324	-268	-246	-229	-216	-175			56		22	17	13	41	107		14
727775	5177000	-3975		-8125	-6700	-6175	-5775	-5400	-4350		-159	-119		-325	-268	-247	-231	-216	-174			57		21	16	15	42	109		15
727775	5177000	-3975		-8125	-6700	-6175	-5775	-5400	-4350		-159	-119		-325	-268	-247	-231	-216	-174			57		21	16	15	42	109		15
727757	5177500	-3975		-8175	-6750	-6250	-5725	-5425	-4300		-159	-119		-327	-270	-250	-229	-217	-172			57		20	21	12	45	111		13
727757	5177500	-3975			-6750	-6250	-5725	-5425	-4300		-159	-119			-270	-250	-229	-217	-172					20	21	12	45	111		13
727739	5178000	-3975			-6750	-6275	-5725	-5450	-4325		-159	-119			-270	-251	-229	-218	-173					19	22	11	45	111		14
727739	5178000	-3975			-6750	-6275	-5725	-5450	-4325		-159	-119			-270	-251	-229	-218	-173					19	22	11	45	111		14
727722	5178500	-3950			-6800	-6250	-5725	-5475	-4300		-158	-119			-272	-250	-229	-219	-172					22	21	10	47	114		14
727722	5178500	-3950			-6800	-6250	-5725	-5475	-4300		-158	-119			-272	-250	-229	-219	-172					22	21	10	47	114		14
727704	5179000	-3950			-6850	-6200	-5725	-5425	-4275		-158	-119			-274	-248	-229	-217	-171					26	19	12	46	116		13
727704	5179000	-3950			-6850	-6200	-5725	-5425	-4275		-158	-119			-274	-248	-229	-217	-171					26	19	12	46	116		13
727686	5179500	-3950			-6850	-6225	-5725	-5475	-4275		-158	-119			-274	-249	-229	-219	-171					25	20	10	48	116		13
727686	5179500	-3950			-6850	-6225	-5725	-5475	-4275		-158	-119			-274	-249	-229	-219	-171					25	20	10	48	116		13
727669	5180000	-3975			-6850	-6225	-5725	-5425	-4300		-159	-119			-274	-249	-229	-217	-172					25	20	12	45	115		13
727669	5180000	-3975			-6850	-6225	-5725	-5425	-4300		-159	-119			-274	-249	-229	-217	-172					25	20	12	45	115		13
727651	5180500	-4000			-6850	-6250	-5750	-5475	-4300		-160	-120			-274	-250	-230	-219	-172					24	20	11	47	114		12
727651	5180500	-4000			-6850	-6250	-5750	-5475	-4300		-160	-120			-274	-250	-230	-219	-172					24	20	11	47	114		12
727633	5181000	-4025			-6850	-6250	-5750	-5475	-4325		-161	-121			-274	-250	-230	-219	-173					24	20	11	46	113		12
727633	5181000	-4025			-6850	-6250	-5750	-5475	-4325		-161	-121			-274	-250	-230	-219	-173					24	20	11	46	113		12
727616	5181500	-4025			-6900	-6250	-5800	-5500	-4375		-161	-121			-276	-250	-232	-220	-175					26	18	12	45	115		14
727616	5181500	-4025			-6900	-6250	-5800	-5500	-4375		-161	-121			-276	-250	-232	-220	-175					26	18	12	45	115		14
727598	5182000	-4025			-6900	-6325	-5875	-5525	-4475		-161	-121			-276	-253	-235	-221	-179					23	18	14	42	115		18
727598	5182000	-4025			-6900	-6325	-5875	-5525	-4475		-161	-121			-276	-253	-235	-221	-179					23	18	14	42	115		18
727581	5182500	-4050			-6950	-6350	-5925	-5550	-4450		-162	-122			-278	-254	-237	-222	-178					24	17	15	44	116		16
727581	5182500	-4050			-6950	-6350	-5925	-5550	-4450		-162	-122			-278	-254	-237	-222	-178					24	17	15	44	116		16
727563	5183000	-4075			-6950	-6400	-5925	-5575	-4450		-163	-122			-278	-256	-237	-223	-178					22	19	14	45	115		15
727563	5183000	-4075			-6950	-6400	-5925	-5575	-4450		-163	-122			-278	-256	-237	-223	-178					22	19	14	45	115		15
727545	5183500	-4075			-6975	-6475	-5925	-5600	-4525		-163	-122			-279	-259	-237	-224	-181					20	22	13	43	116		18

10.0 FIGURE CAPTIONS

Figure 1. The study area, showing data coverage from HUDSON cruise 98-034 and figure locations. (see Enclosure 1 for greater detail).

Figure 2. Revised seismo-stratigraphic breakdown of NE Grand Bank, based primarily on unconformity-bound units of various internal seismic character. The upper part of Unit 1 and the overlying glacially dominated section is largely undifferentiated stratigraphically but several features and facies are recognized. Suggested ages are preliminary, based on inferences discussed in text.

Figure 3. Selected geologic profiles from lines 14, Panel A and 20, Panel B showing features and unit/sub-unit breakdown.

Figure 4. Outcrop patterns of the top horizons of the Seismostratigraphic units in Fig. 2 (Reduced version of Enclosure 4, 1: 600 000 scale sheet in back envelope).

Figure 5. Depth to Unit 3, in milliseconds (Reduced version of Enclosure 8).

Figure 6. Geologic features, Surficial and Buried (Reduced version of Enclosure 3, 1: 600 000 scale sheet in back envelope).

Figure 7. Depth to Unit 2b, in milliseconds (Reduced version of Enclosure 12).

Figure 8. Depth to Unit 2a, in milliseconds (Reduced version of Enclosure 10).

Figure 9. Thickness of Unit 2, in milliseconds (Reduced version of Enclosure 6).

Figure 10. Thickness of Unit 2a, in milliseconds (Reduced version of Enclosure 9).

Figure 11. Thickness of Unit 2b, in milliseconds (Reduced version of Enclosure 11).

Figure 12. Depth to Unit 1a, in milliseconds (Reduced version of Enclosure 14).

Figure 13. Thickness of Unit 1a, in milliseconds (Reduced version of Enclosure 13).

Figure 14. Depth to Unit 1b, in milliseconds (Reduced version of Enclosure 16).

Figure 15. Thickness of Unit 1b, in milliseconds (Reduced version of Enclosure 15).

Figure 16. Depth to Unit 1c, in milliseconds (Reduced version of Enclosure 18).

Figure 17. Thickness of Unit 1c, in milliseconds (Reduced version of Enclosure 17).

Figure 18. Depth to Unit 1d, in milliseconds (Reduced version of Enclosure 19).

Figure 19. Thickness of Unit 1 (all subunits combined) (Reduced version of Enclosure 5).

Figure 20. Thickness of Post Unit 1 deposit (Reduced version of Enclosure 20).

Figure 21. Huntec deep towed boomer profile from lower slope (Line 15, time 1735 to 1801) showing an erosional scarp cut in mainly draping glacigenic sediments. This is the sidewall of the Gabriel Valley (Piper and Pereira 1992). A similar, but older (deeply buried) slide cut several kilometres to the south suggests canyon migration or multiple slide failure events on relatively long time scale. Isolated, lensoid debris flow bodies are common at least three horizons along the entire slope. Local unconformities are present within the layered sequences.

Figure 22. Huntec deep towed boomer profile from lower slope (Line 8, time 2335 to 0009) showing an erosional scarp of a channel or small slide cut in laminated sediments with an overlying draping unit. Isolated, lensoid debris flow bodies at three horizons are identified. Local unconformities are present within the layered sequences. A core at the selected site has the potential for better sedimentologic and chronologic characterization. The mounded features with partially draping laminites might result from mud diapiric action.

Figure 23. Air gun profile from mid slope (Line 7, time 1018 to 1054) showing a buried slide, including the headwall and near bedding-parallel glideplane, disturbed sediment, and later infill.

Figure 24. Air gun profile on mid-slope (Line 9) showing inflections which might represent faulting. Surficial iceberg scour zone is restricted to this approximate water depth. Some downslope failure is locally indicated. There is no apparent relationship inferred between this and the disturbances at depth.

Figure 25. Thickness of the Glacigenic Unit, in milliseconds (Reduced version of Enclosure 21).

Figure 26. Depth to the *base* of the Glacigenic Unit, in milliseconds (Reduced version of Enclosure 22).

Figure 27. Huntec Deep-Towed boomer profile from northeastern shelf break (Line 16, time 2058 to 2120) showing progradational body comprising small, irregular debris flows, and landward-sloping upper surface. This probably marks where the glacier sole lay. This surface projects landward to the till-covered glacial erosional unconformity at depth, immediately to the west. The feature is interpreted as a near-margin, sub-glacially formed "till delta".

Figure 28. Huntec Deep-Towed boomer profile from northeastern shelf (Line 16, time 427 to 645) showing series of moraines in till/glacigenic sediments whose base is marked by a diffuse reflector on an angular unconformity.

Figure 29. Bathymetric profiles across the moraine field showing their character and correlation, (with the aid of the bathymetric chart). The ridges to the south are lower relief, with the

exception of the shelf-break "till-delta". The heavy dashed line separates the till/morainic field from a much more subdued, nearly planar topography in the shallow areas. In the south this is marked by an inflection in the profile, best developed on lines 3, 5 and 18. Line 17 has been divided into segments as it intersects the northern lines.

Figure 30. Pattern of retreat moraines on NE Grand Bank. The outermost ridge has a prograding nature similar to “till deltas”. The Late Wisconsinan lowstand is shown along with a deeper inferred Pre-Late Wisconsinan lowstand, believed responsible for erosional truncation of the moraine field on its eastern edge. The erosional valleys in the NW do not continue below the interpreted Pre-Late Wisconsinan lowstand and it is suggested that they represent fluvial development.

Figure 31. Sleeve gun profile in Adolphous area (Line 9, time 1151 to 1316) showing up-turning of strata resulting from salt doming. The presumed top of salt is visible slightly below the seabed.

Figure 32. Approximated dip trends of unconformities at top of Units 1 a to d, 2 and 3. Uppermost panel demonstrates the approximations. Upper panels from the north and lower panels from southern lines. In an attempt at normalization, the dip trends are extrapolated equally to the east and west and corrected for apparent dip using strike trends from contour maps of their surfaces. The numerals to the right are ratios of thickness between unconformities on the east and west extremities, for purposes of line to line comparison. The seabed and uppermost sediment sequence is not included because of the complications with glacial-dominated erosion and deposition. Note a general trend to more splaying to the north, interpreted as reflecting a greater rate of general subsidence.

Figure 33. Interpreted seismic profile (Line 10) approximately along strike, showing foresets in the Hibernia delta. The foresets exhibit an unusual climbing pattern to the south. A simple tectonic reconstruction involving a minimal tilt restores a more natural horizontal delta top and prograding foresets. A regional tilt of this magnitude is similar to tilts in unconformities of similar age in comparison to younger unconformities.

Figure 34. Interpreted ice configuration responsible for formation of the shelf-break till deltas and subsequent moraine development. Present configuration of the seabed is shown for points of reference. 1. Erosion of underlying strata in progress; unknown development of delta. 2. Sub-glacial net erosion gives way to sediment bypass towards the margin with till delta (small debris flows on foresets) deposition immediately proximal to margin. 3. With ice slowing, thinning and/or sea level rise, the base level of the delta is elevated through a slight lifting of the ice margin, allowing a higher vertical build-up of the most distal delta foresets. 4. With further retreat, a till sheet accumulates vertically an uncertain amount, building the moraines at times of relative margin stability. Some late stage proglacial moraine development is possible. Simultaneous calving and margin fluctuation is probably responsible for much of the smaller scale topographic irregularity. Northward bifurcation of moraines in deeper water depths attests to less stable/higher retreat rate while the ice remained better grounded in the shallower area to the south (Figure 30).

Figure 35. Hypothetical model to explain formation of the moraine field during a Late Wisconsinan retreat from the shelf break. Moraines formed during ice retreat from the shelf break to a mid shelf stillstand position where the regime changed and subglacial meltwater channels dominated. Truncation/removal of the moraines above a present water depth of 160 - 170 m along with eroding of deep fluvial valleys to this depth can be explained through a mechanism of relative sea level lower than the eustatic low stand. This can have resulted from their position on the forebulge which experienced subsidence associated with landward migration of a glacial forebulge.

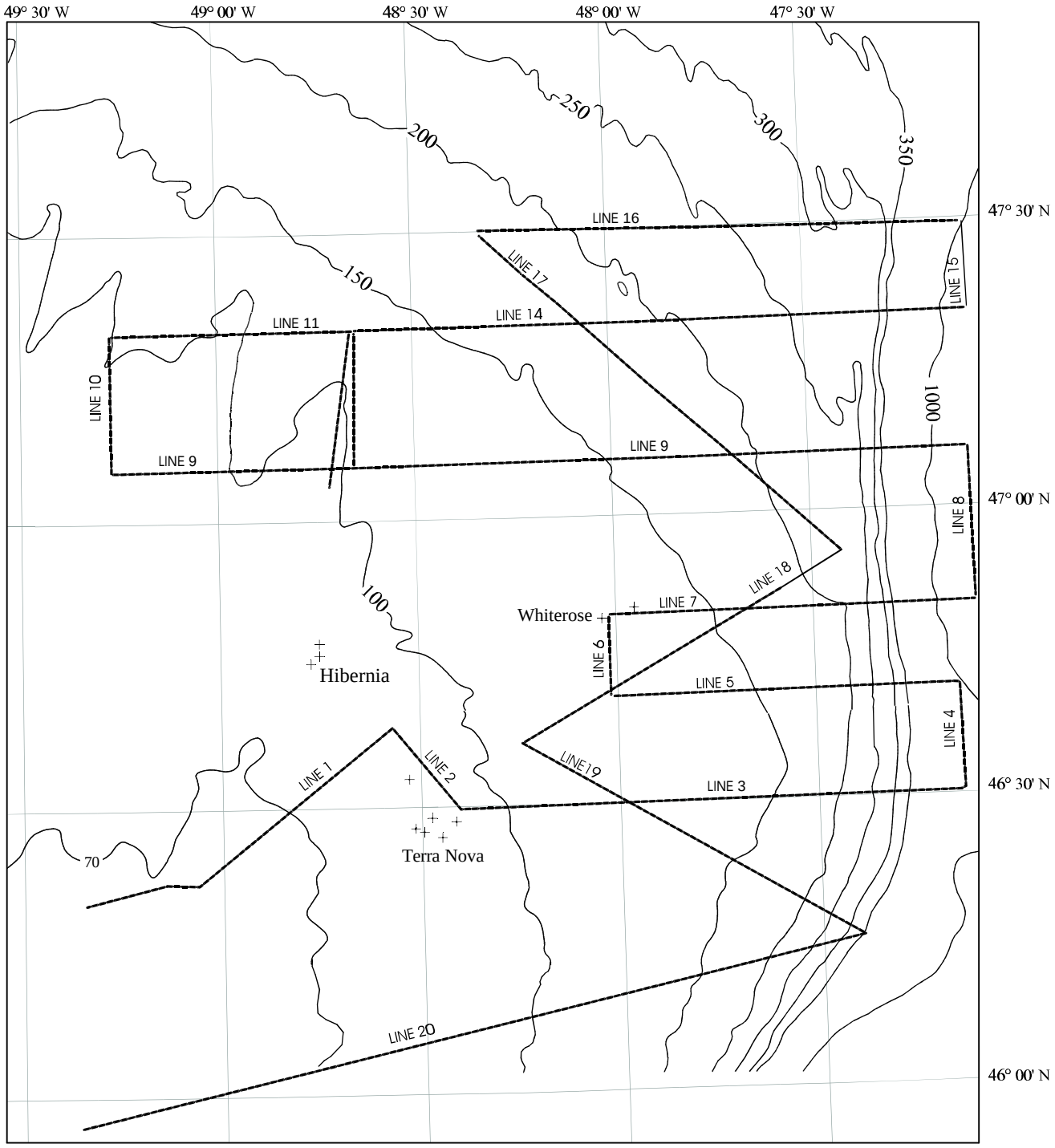


Figure 1. Location of seismic traverses (Lines 1 to 20) on northeast Grand Bank, Cruise HN98-034, utilized in this study. Some wellsites provided for reference. See Enclosure 1 for greater detail.

Previous Unit designations		New Unit designations*		Unit Description/Interpretation	Suggested Age
Grand Banks Sand & Gravel Formation**	Sand facies			Post-transgressive sands *reworked into thin veneer and bedforms of all scales*	18? to -10? ka
	Gravel facies			Basal transgressive lag *formed during low-stand and post-glacial sea level rise*	
				MARKED ANGULAR UNCONFORMITY	
Banquereau Formation	1	Glacially-dominated shelf & slope	Facies *iv*	Shelf-situated glacigenic deposits *moraine system, unconfirmed proglacial veneer*	pre-Late Wisconsinan, Stage 4 or 6
				MARKED ANGULAR UNCONFORMITY	
			Facies *iii*	Shelf-situated glacigenic deposits *sub-glacial shelf-break "deltas"*	
			Facies *ii*	Slope-situated laminites *glacimarine, hemipelagites, contourites? & turbidites?*	At least three depositional phases with locally unconformable relationships
			Facies *i*	Shelf-edge and slope failure-dominated *slides, debris flows, canyons and non-descript failures*	
		1	undiffer-entiated	Shelf edge progradation (sparse data coverage precludes mapping) *thick, multi-phased shelf progradation and mass wasting*	Early to mid Pleistocene (onset of glaciatons)
				UPPER SLOPE STEEPENING AND MASS FAILURE	
			D	Shelf aggradation, shelf edge progradation *correlations imprecise due to sparse data coverage*	Plio-Pleistocene?
			C	Shelf aggradation, shelf edge progradation	
			B	Shelf aggradation, shelf edge progradation	
			A	Shelf aggradation, shelf edge progradation *locally dissected surface, local landward progradation*	
	2B	2	B	Expansive p rogradational body and distal equivalents *multi-phase lobes with high-angle, delta-like foresets*	
	2A		A	Expansive progradational body and distal equivalents *multi-phase lobes occasionally with low angle foresets*	Late Tertiary?
	3	3	B	Parallel to slightly splaying aggradational beds *downlaps on top of Unit 3a*	
			A	Parallel to slightly splaying beds *low angle foresets at western end*	
		4	B	Aggradational to progradational *low angle delta-like foresets and distal equivalents*	
			A	Progradational body *steep delta-like foresets and distal equivalents*	

*a revised numbering system is recomended but probably notwarranted until outer-shelf and slope data coverage better establishes stratigraphic/mapping relationships

**From Fader andMiller (1986)

Figure 2. Revised stratigraphic column for the upper hundred metres of northeast Grand Bank. All units are unconformity-bound with the exception of some of the glacial facies. There is no implied age relationship among the slope glacial facies (*i*, *ii* and *iii*)..

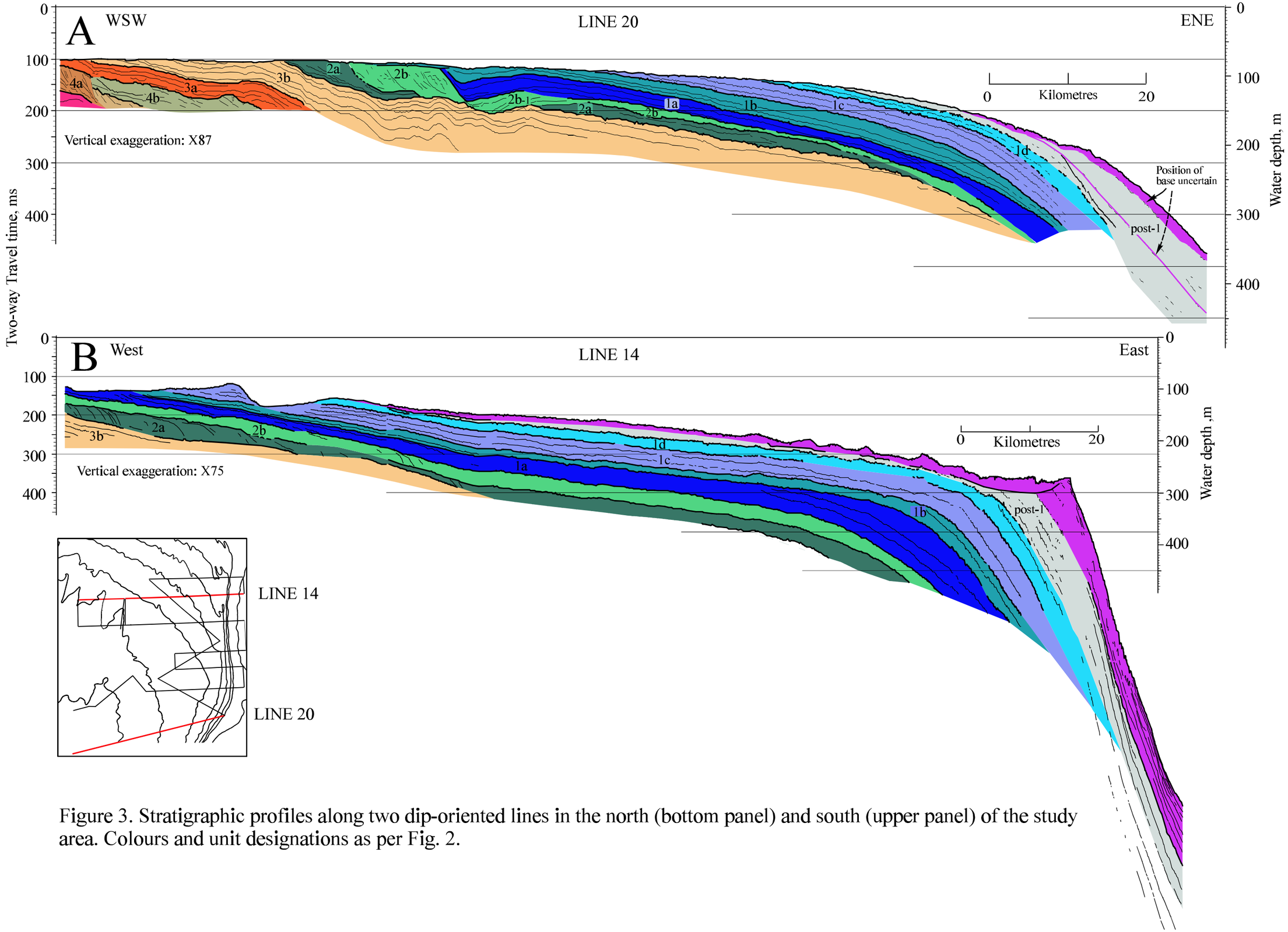


Figure 3. Stratigraphic profiles along two dip-oriented lines in the north (bottom panel) and south (upper panel) of the study area. Colours and unit designations as per Fig. 2.

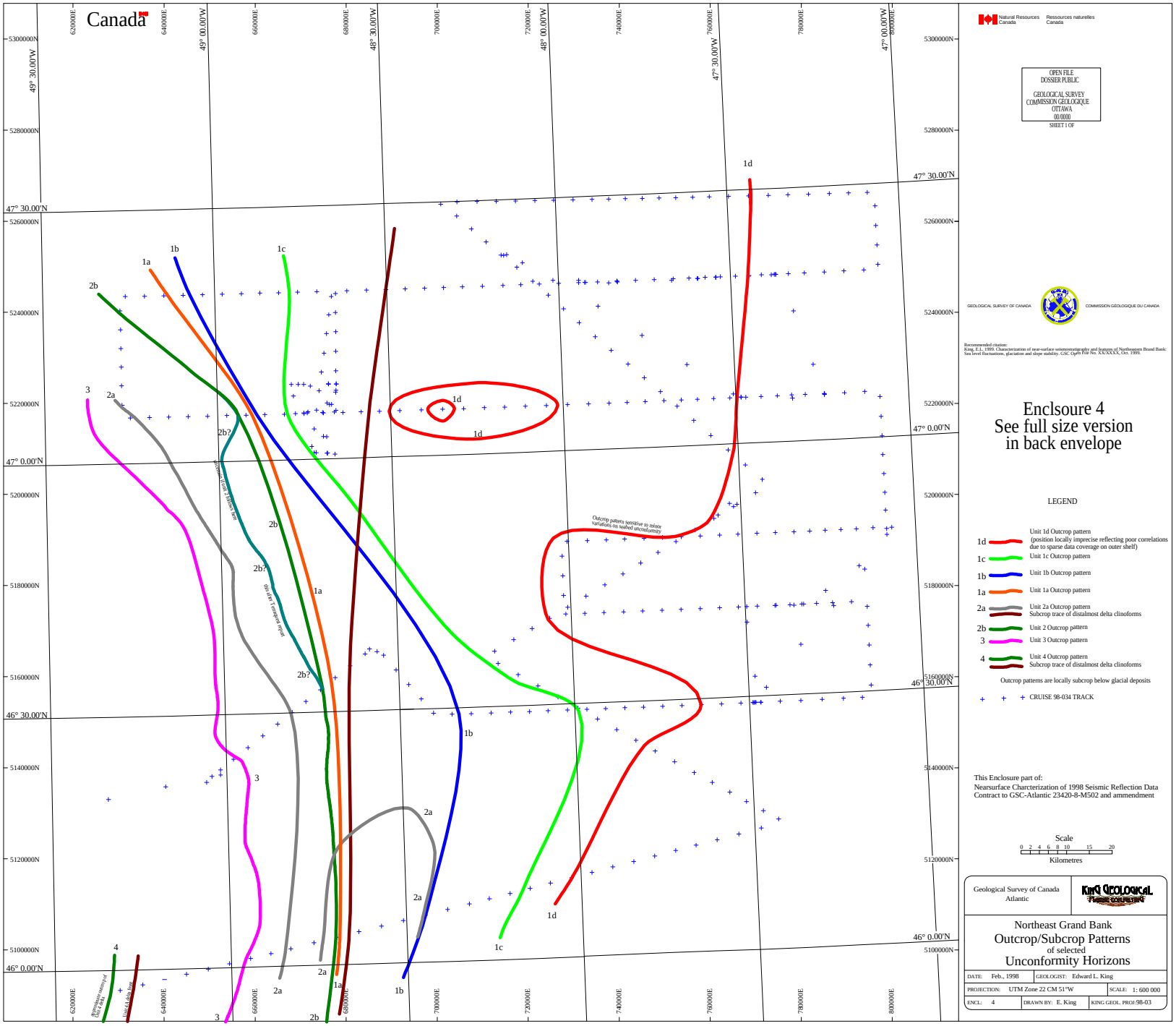
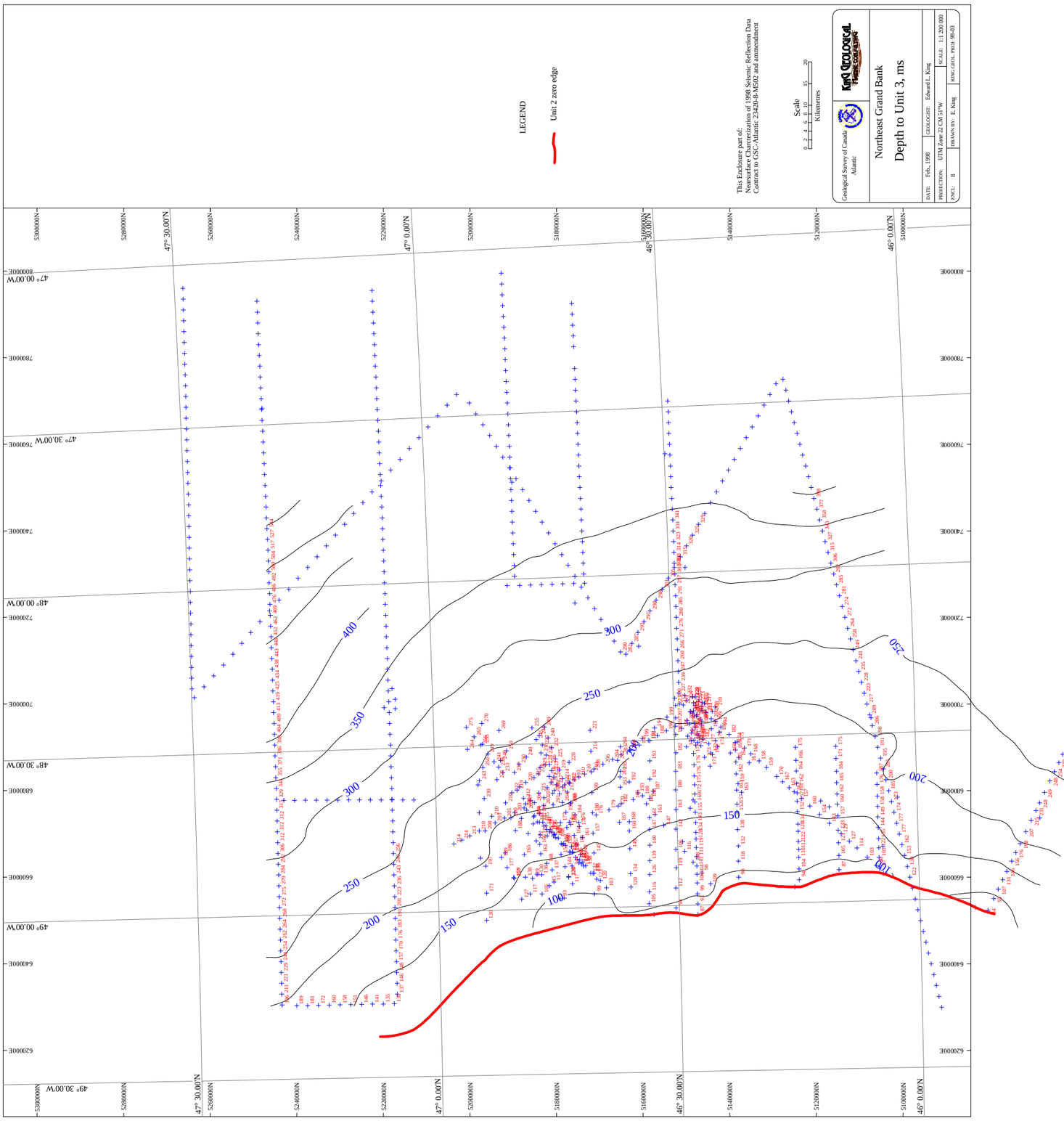


Figure 4. Outcrop patterns of the top horizons of the seismostratigraphic units in Fig. 2. (Reduced version of Enclosure 4, 1 : 600 000 scale sheet in back envelope) .

Figure 5. Depth to Unit 3, in milliseconds (Reduced version of Enclosure 8).



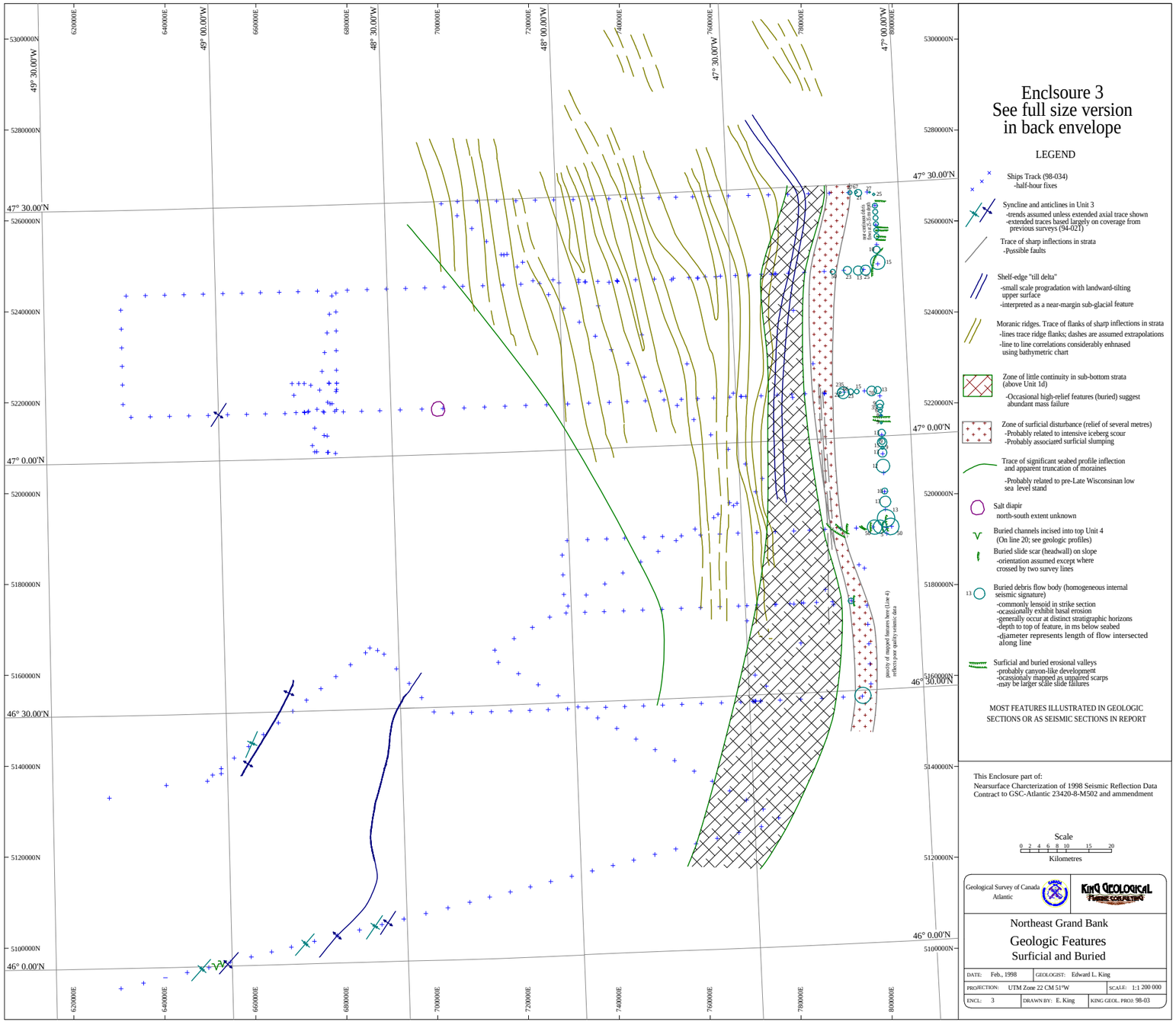
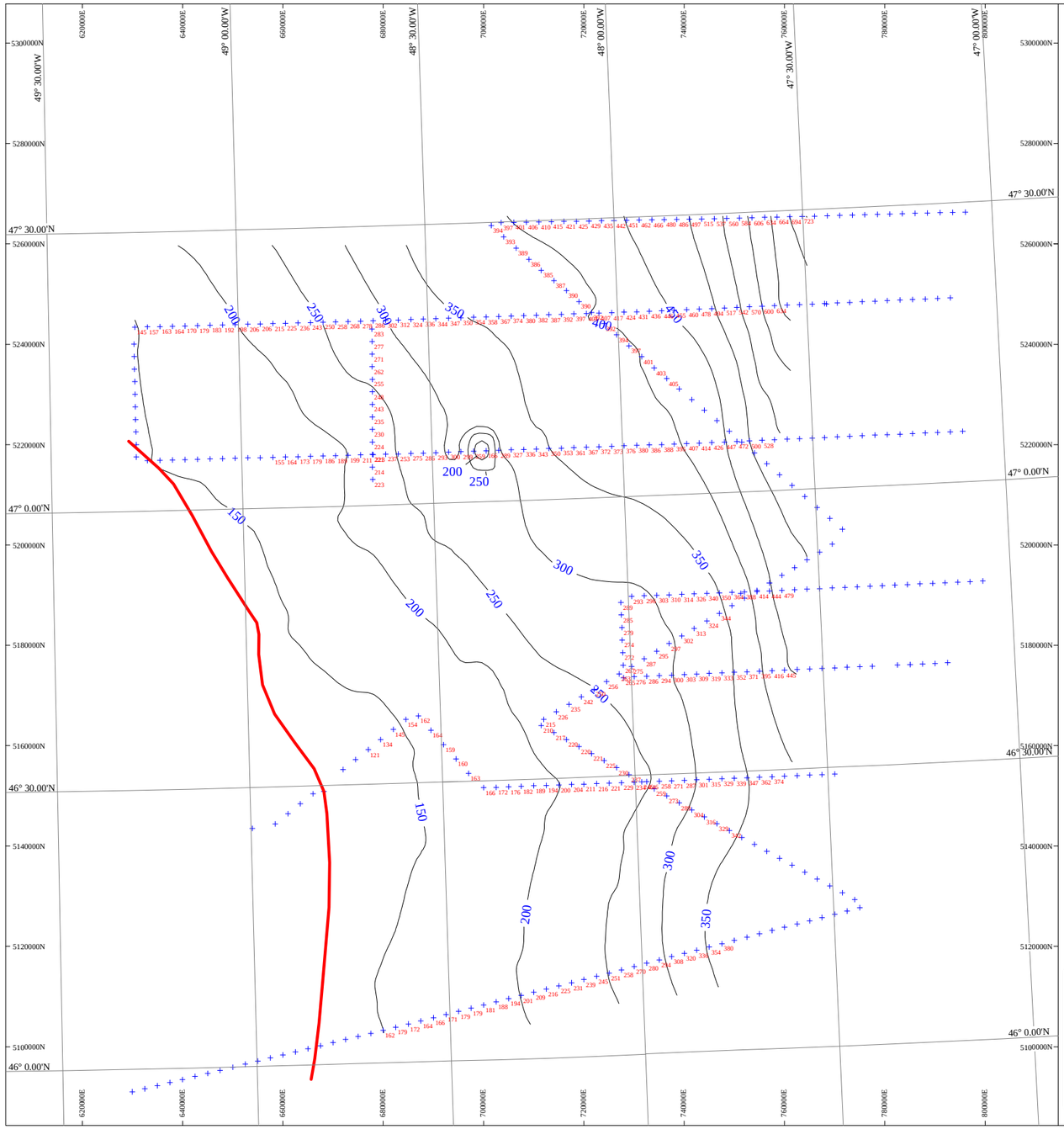


Figure 6. Geologic features, Surficial and Buried (Reduced version of Enclosure 3, 1: 600 000 scale sheet in back envelope).



LEGEND
Cruise 85005

Unit 2 zero edge

This Enclosure part of:
Nearsurface Charcterization of 1998 Seismic Reflection Data
Contract to GSC-Atlantic 23420-8-M502 and ammendment

Scale
0 2 4 6 8 10 15 20
Kilometres

Geological Survey of Canada
Atlantic

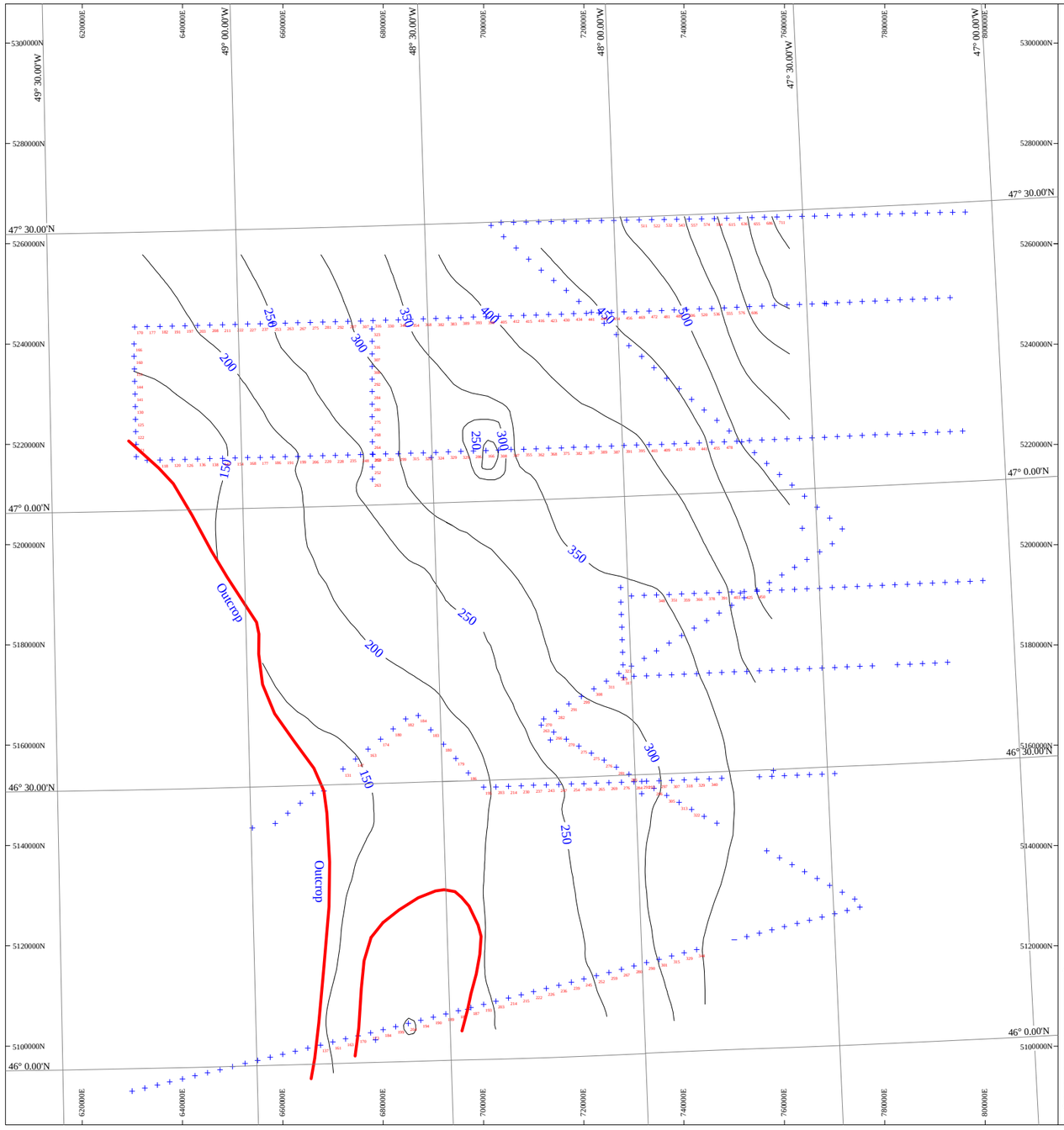
King Geological
Marine Solutions

Northeast Grand Bank

Depth to Top Unit 2, ms
(Top of Hibernia Delta)

DATE: Feb., 1998	GEOLOGIST: Edward L. King	
PROJECTION: UTM Zone 22 CM 51°W		SCALE: 1:1 200 000
ENCL: 12	DRAWN BY: E. King	KING GEOL. PROJ: 98-03

Figure 7. Depth to Unit 2b, in milliseconds (Reduced version of Enclosure 12).



LEGEND

Unit 2a zero edge

This Enclosure part of:
Nearsurface Charcterization of 1998 Seismic Reflection Data
Contract to GSC-Atlantic 23420-8-M502 and ammendment

Scale
0 2 4 6 8 10 15 20
Kilometres

Geological Survey of Canada
Atlantic

KING GEOLOGICAL

Northeast Grand Bank

Depth to Unit 2A, ms

DATE: Feb., 1998	GEOLOGIST: Edward L. King	
PROJECTION: UTM Zone 22 CM 51°W		SCALE: 1: 1 200 000
ENCL: 10	DRAWN BY: E. King	KING GEOL. PRO#: 98-03

Figure 8. Depth to Unit 2a, in milliseconds (Reduced version of Enclosure 10).

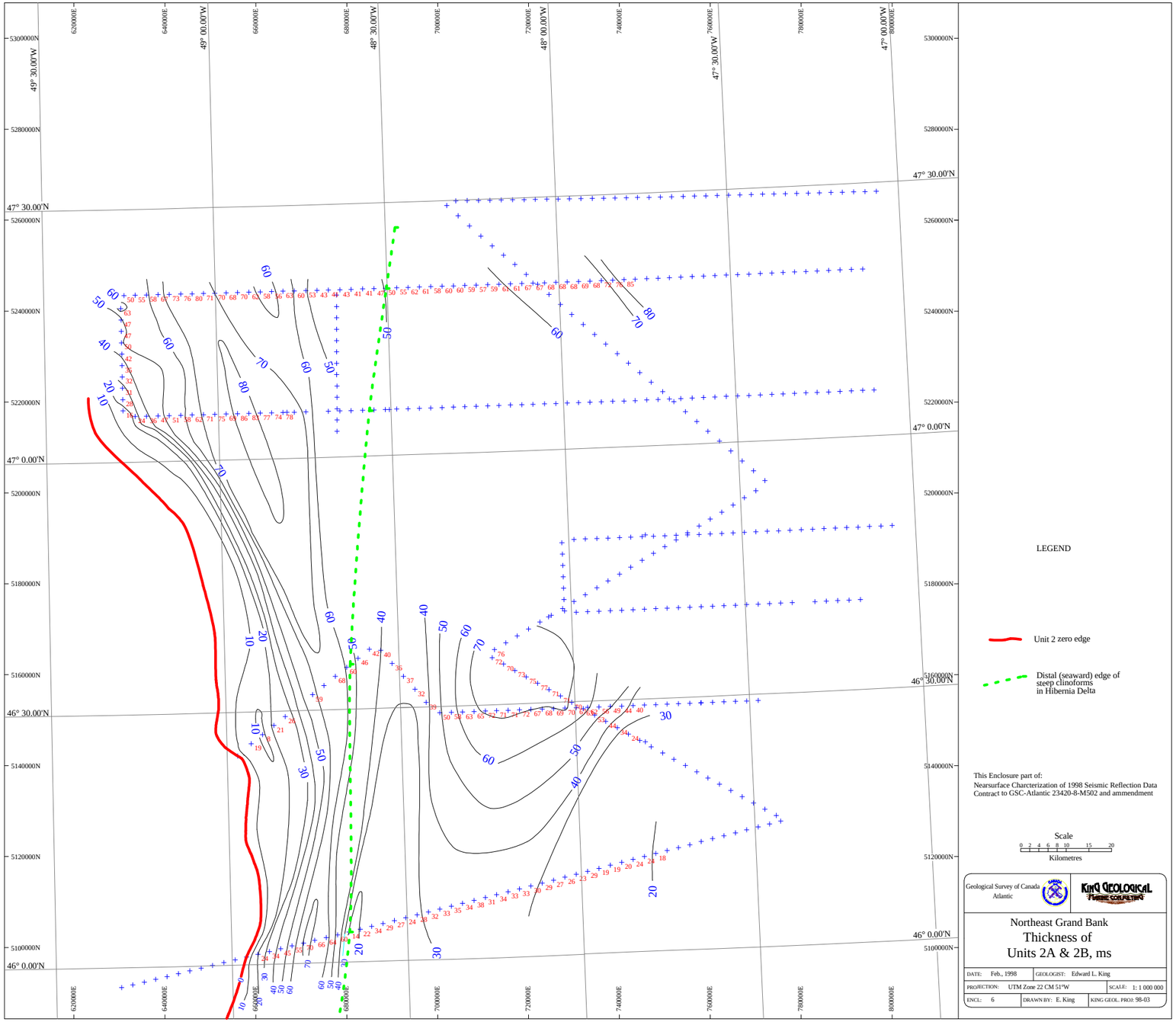


Figure 9. Thickness of Unit 2, in milliseconds (Reduced version of Enclosure 6).

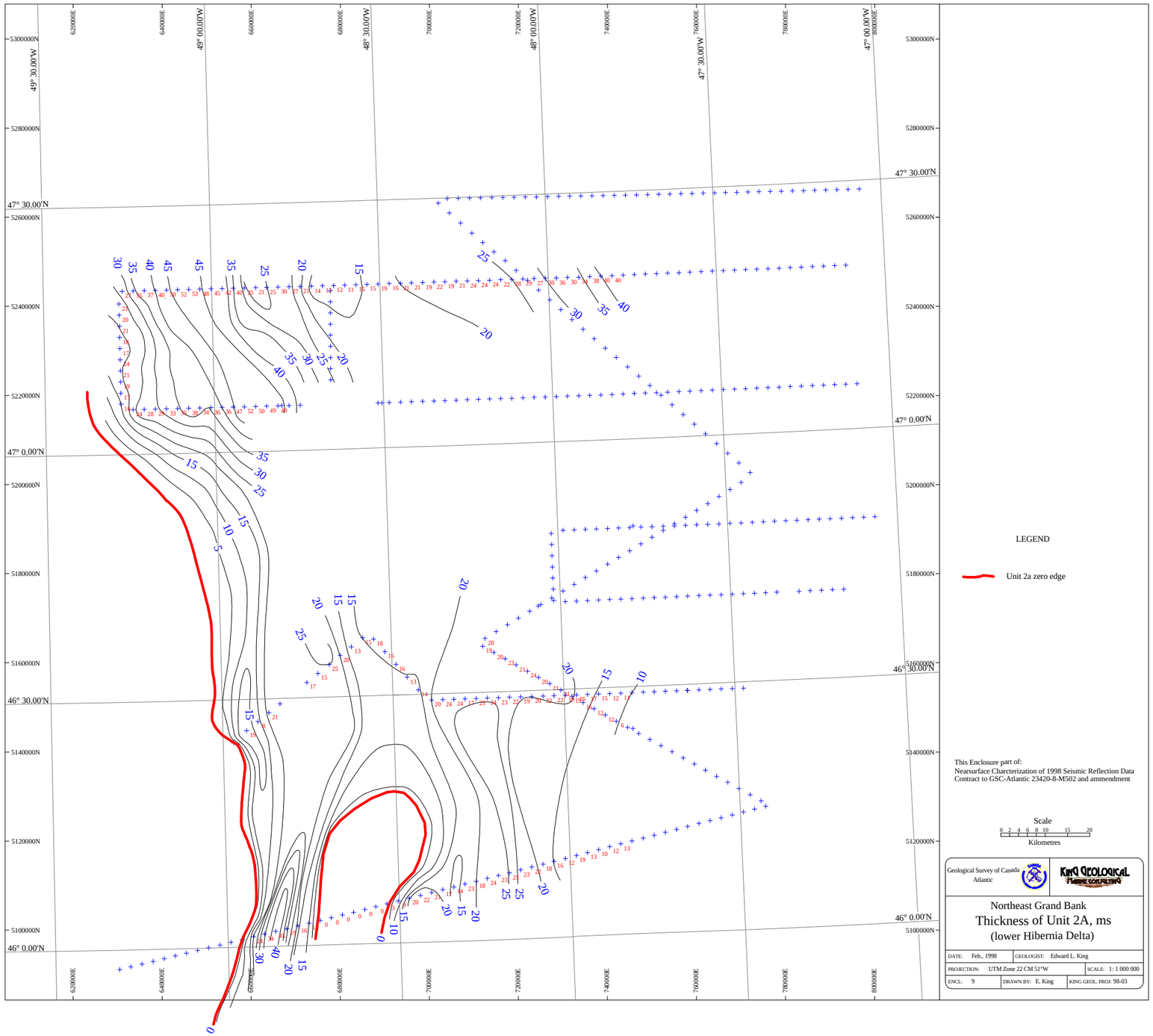


Figure 10. Thickness of Unit 2a, in milliseconds (Reduced version of Enclosure 9).

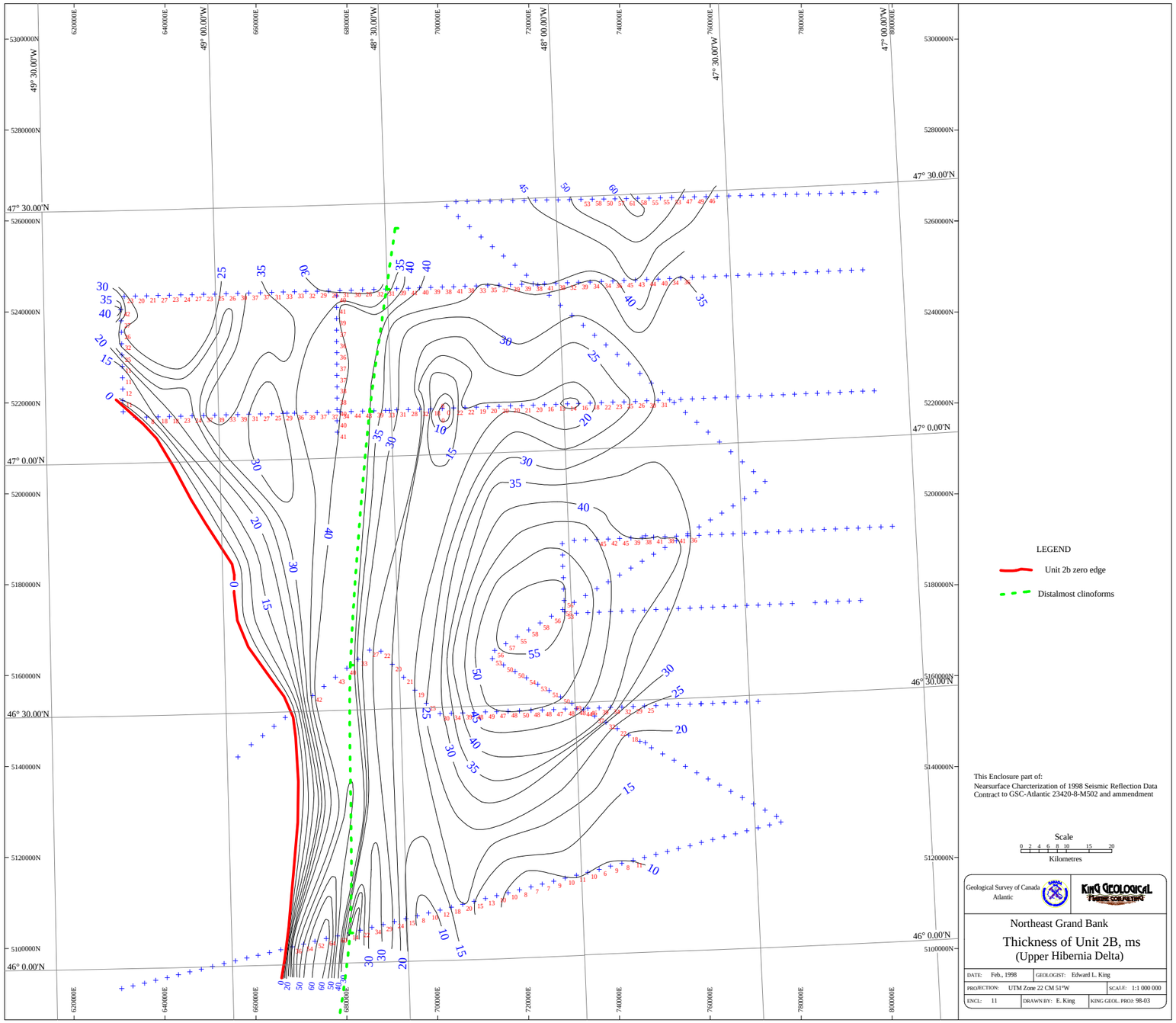
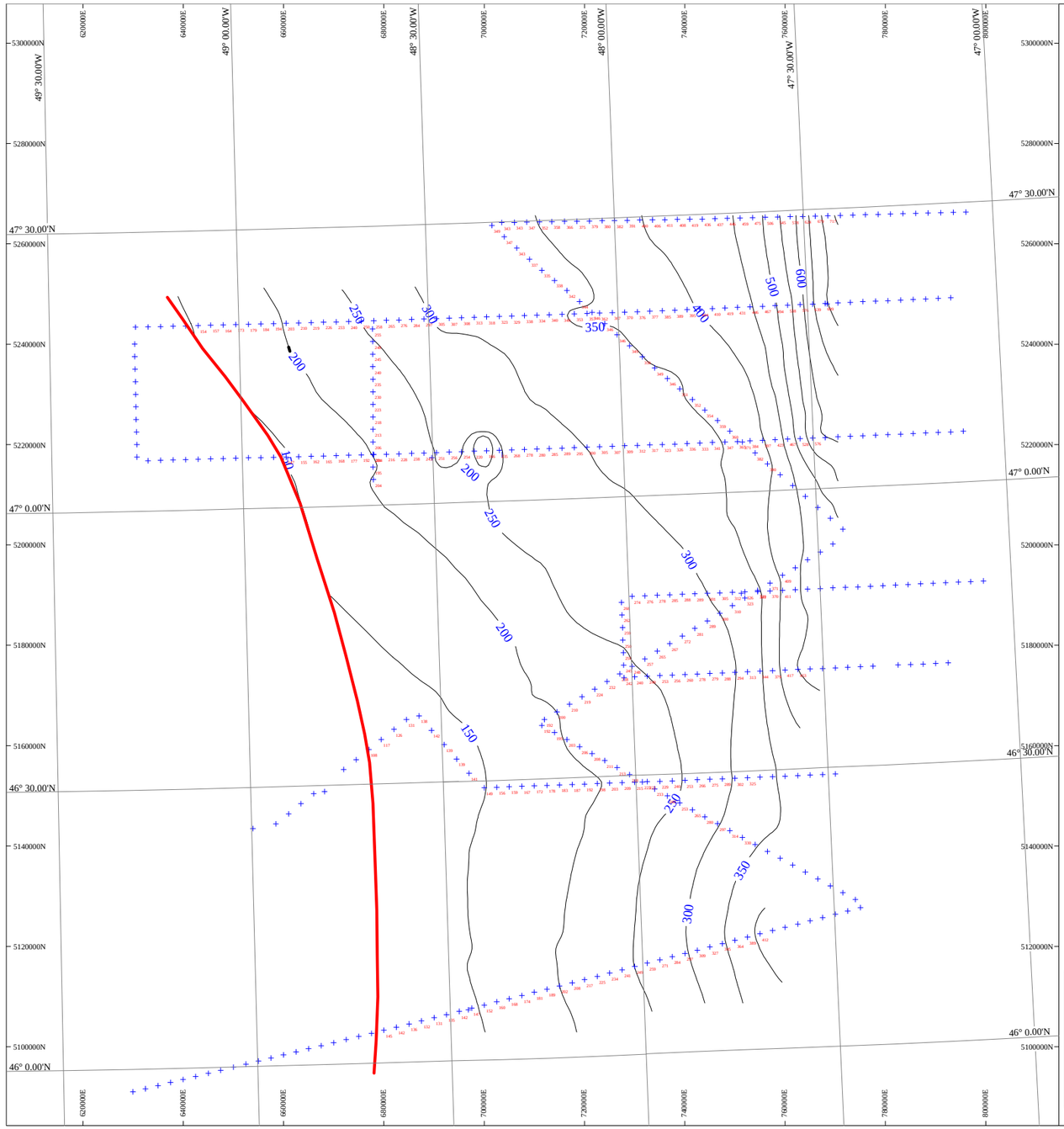


Figure 11. Thickness of Unit 2b, in milliseconds (Reduced version of Enclosure 11).

Figure 12. Depth to Unit 1a, in milliseconds (Reduced version of Enclosure 14).



LEGEND

Approximate Zero Edge of deposit

This Enclosure part of:
Nearsurface Charcterization of 1998 Seismic Reflection Data
Contract to GSC-Atlantic 23420-8-M502 and ammendment

Scale
0 2 4 6 8 10 15 20
Kilometres

Geological Survey of Canada
Atlantic

King Geological
Marine Consulting

Northeast Grand Bank

Depth to
Unit 1A ms

DATE: Feb., 1998	GEOLOGIST: Edward L. King	
PROJECTION: UTM Zone 22 CM 51°W		SCALE: 1:850 000
ENCL: 14	DRAWN BY: E. King	KING GEOL. PROJ: 98-03

Figure 12

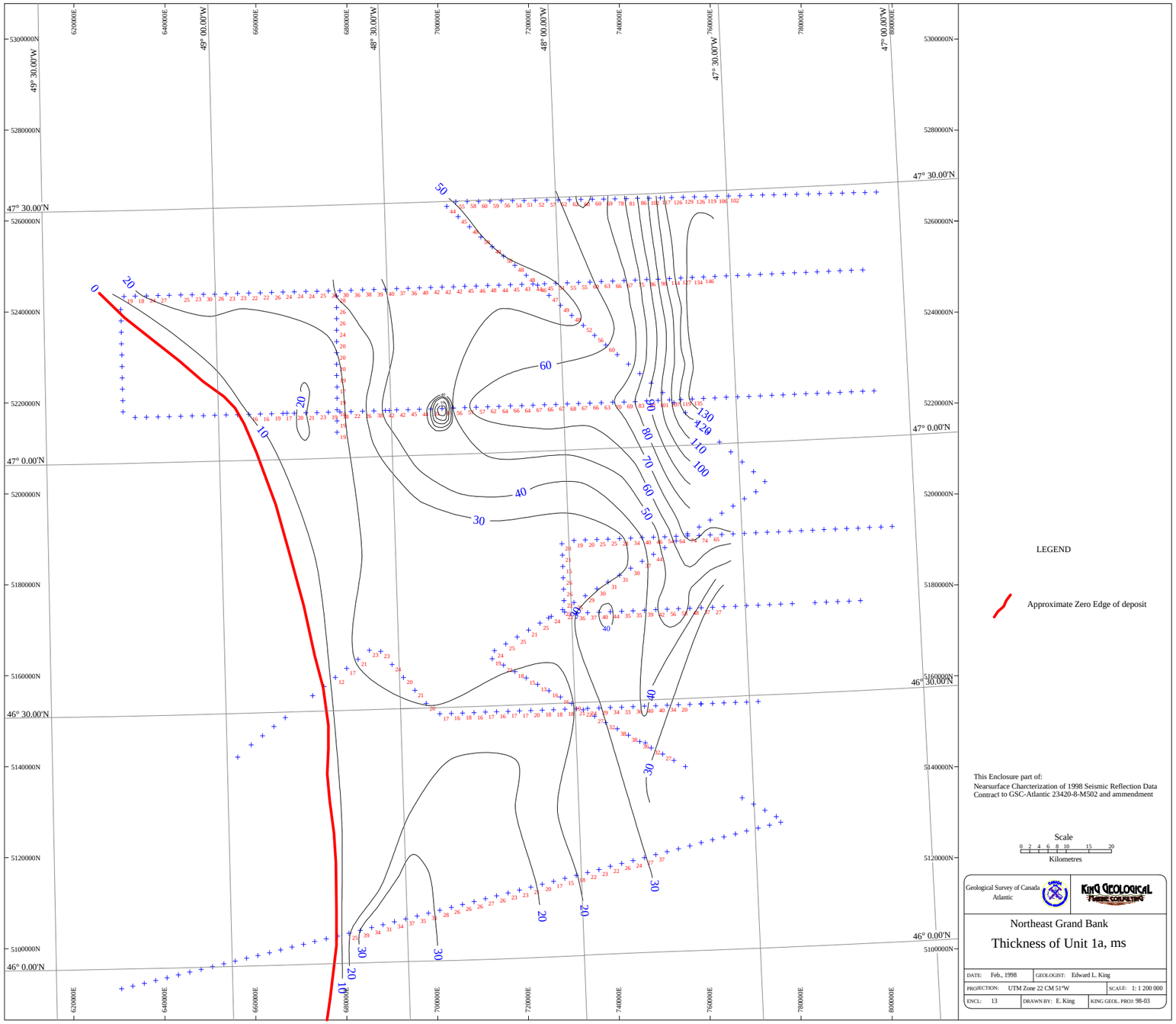


Figure 13. Thickness of Unit 1a, in milliseconds (Reduced version of Enclosure 13).

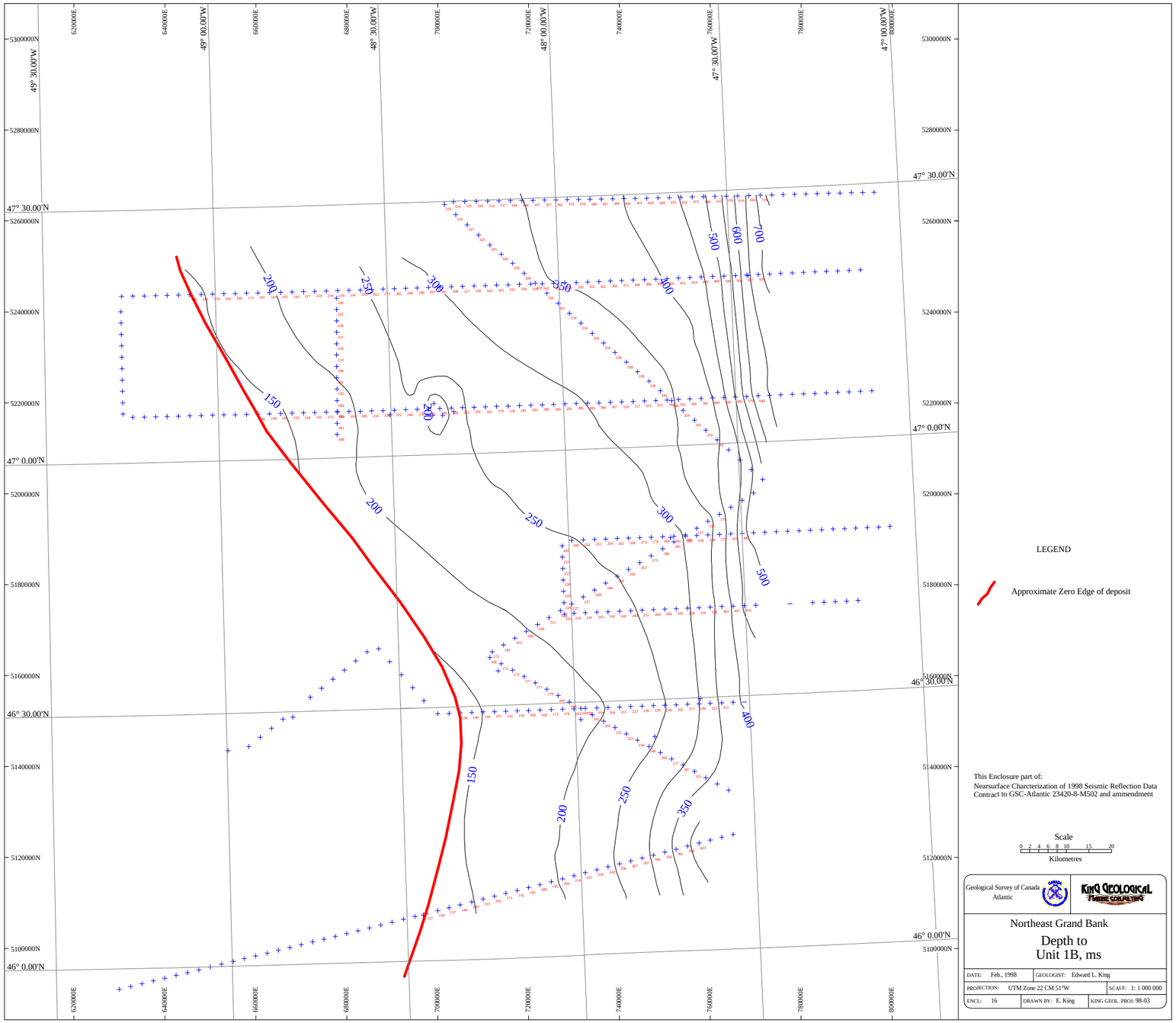
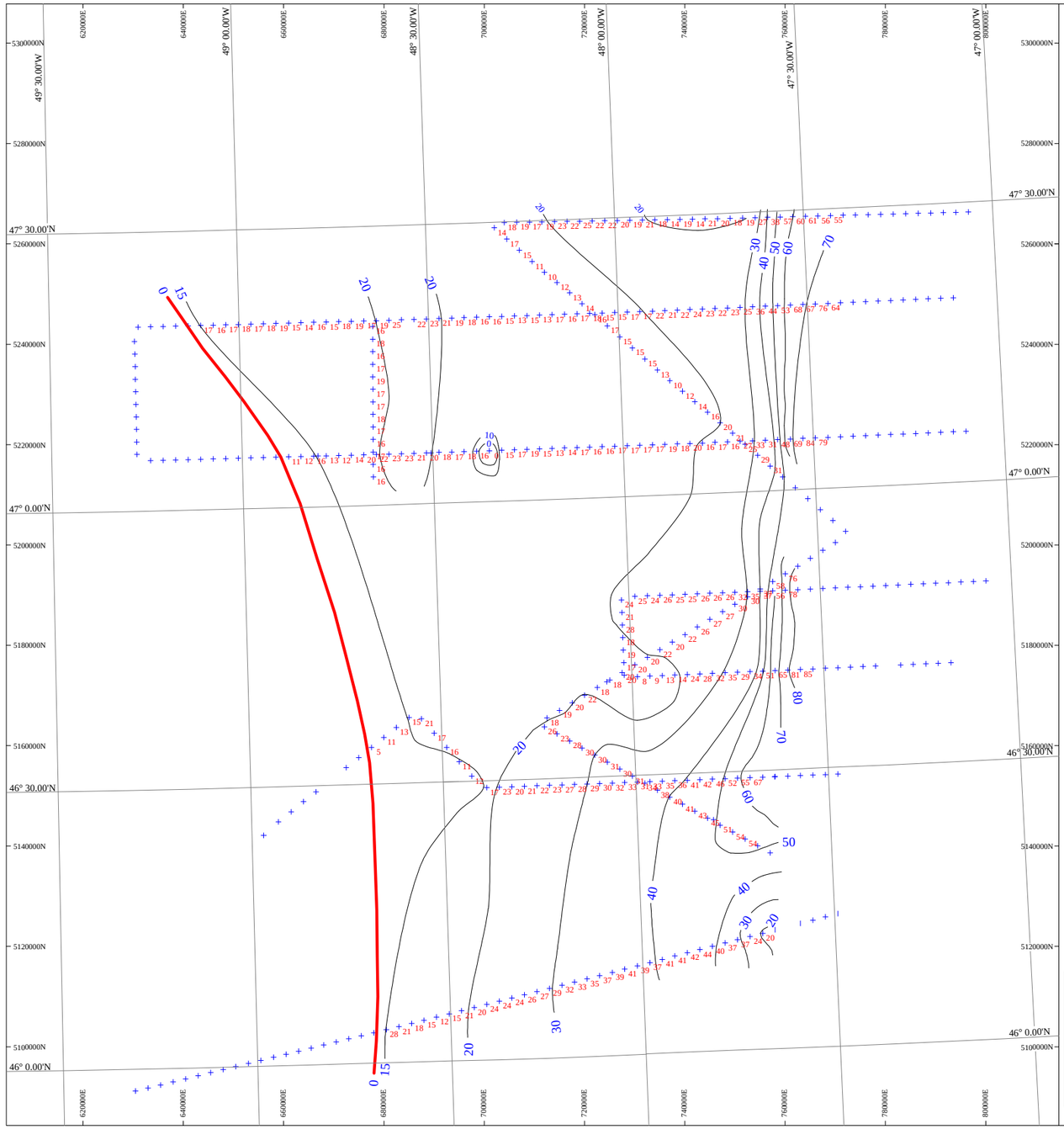


Figure 14. Depth to Unit 1b, in milliseconds (Reduced version of Enclosure 16).



LEGEND

Approximate Zero Edge of deposit

This Enclosure part of:
Nearsurface Charcterization of 1998 Seismic Reflection Data
Contract to GSC-Atlantic 23420-8-M502 and ammendment

Scale
0 2 4 6 8 10 15 20
Kilometres

Geological Survey of Canada Atlantic

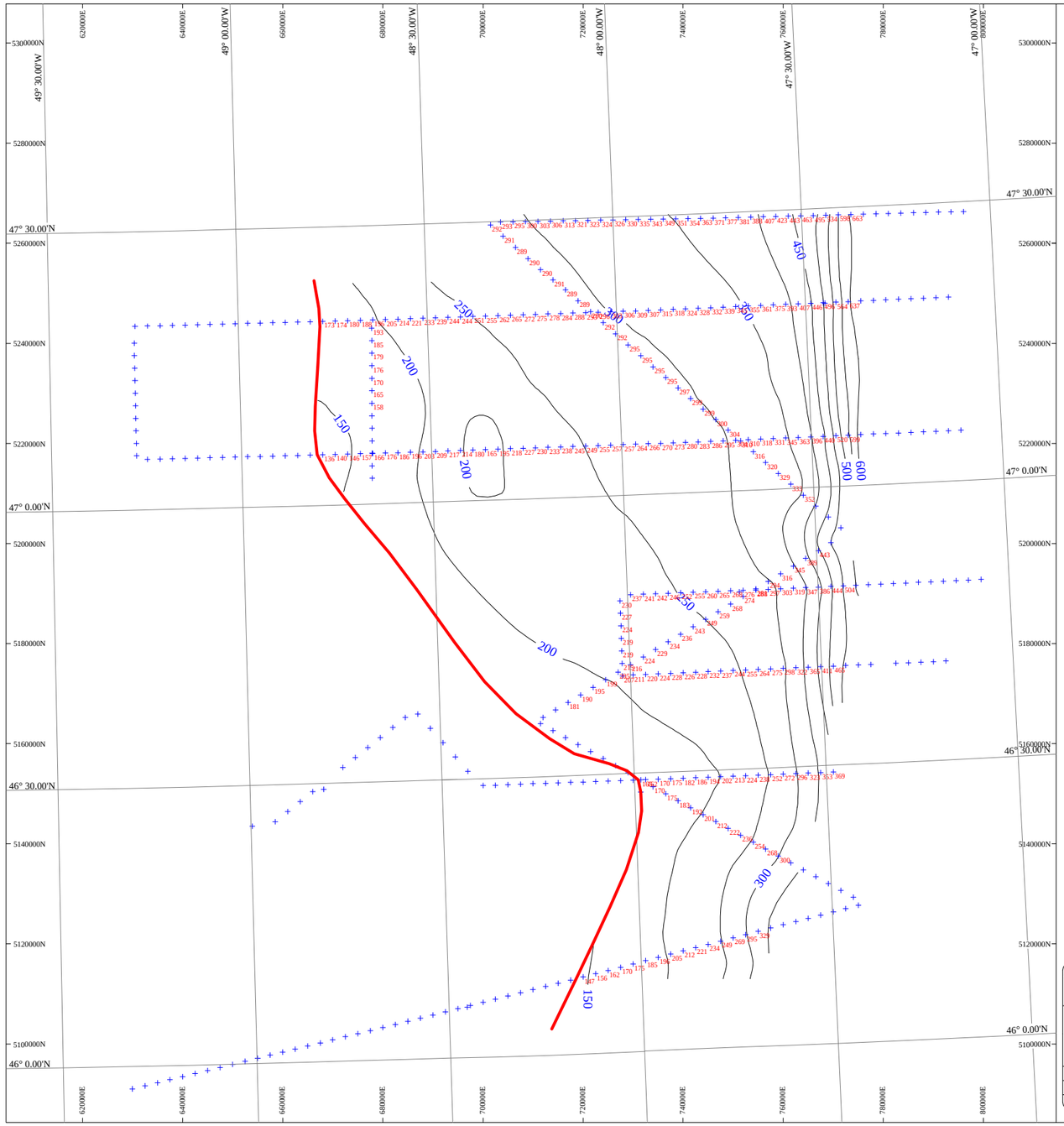
KING GEOLOGICAL PLANNING CONSULTANTS

Northeast Grand Bank

Thickness of Unit 1b, ms

DATE: Feb., 1998	GEOLOGIST: Edward L. King	
PROJECTION: UTM Zone 22 CM 51°W		SCALE: 1: 1 000 000
ENCL: 15	DRAWN BY: E. King	KING GEOL. PRO#: 98-03

Figure 15. Thickness of Unit 1b, in milliseconds (Reduced version of Enclosure 15).



LEGEND

Approximate Zero Edge of deposit

This Enclosure part of:
Nearsurface Charcterization of 1998 Seismic Reflection Data
Contract to GSC-Atlantic 23420-8-M502 and ammendment

Scale
0 2 4 6 8 10 15 20
Kilometres

Geological Survey of Canada
Atlantic

King Geological

Northeast Grand Bank
Depth to
Unit 1c, ms

DATE: Feb., 1998	GEOLOGIST: Edward L. King	
PROJECTION: UTM Zone 22 CM 51°W		SCALE: 1: 1 200 000
ENCL: 18	DRAWN BY: E. King	KING GEOL. PROJ: 98-03

Figure 16. Depth to Unit 1c, in milliseconds (Reduced version of Enclosure 18).

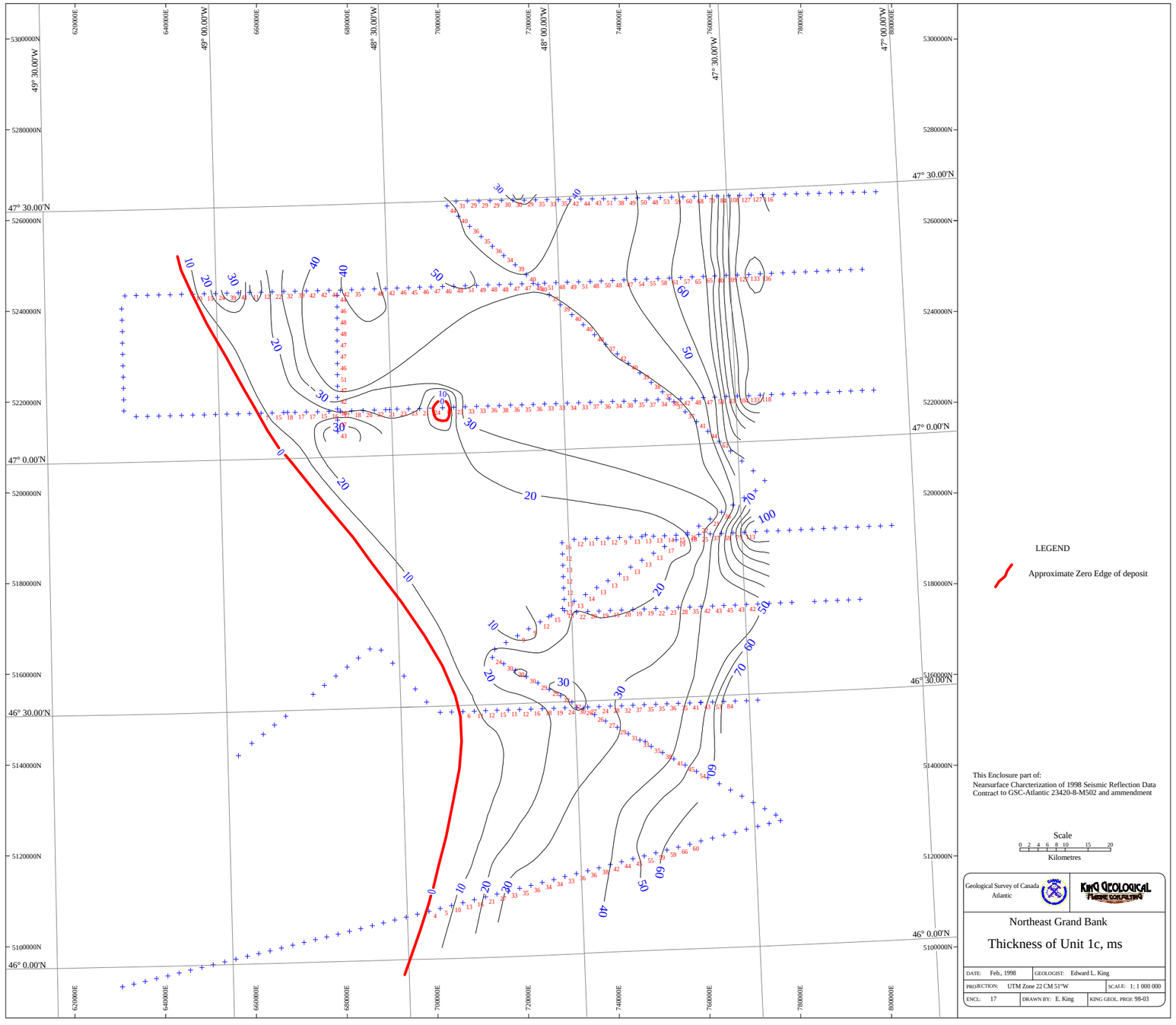


Figure 17. Thickness of Unit 1c, in milliseconds (Reduced version of Enclosure 17).

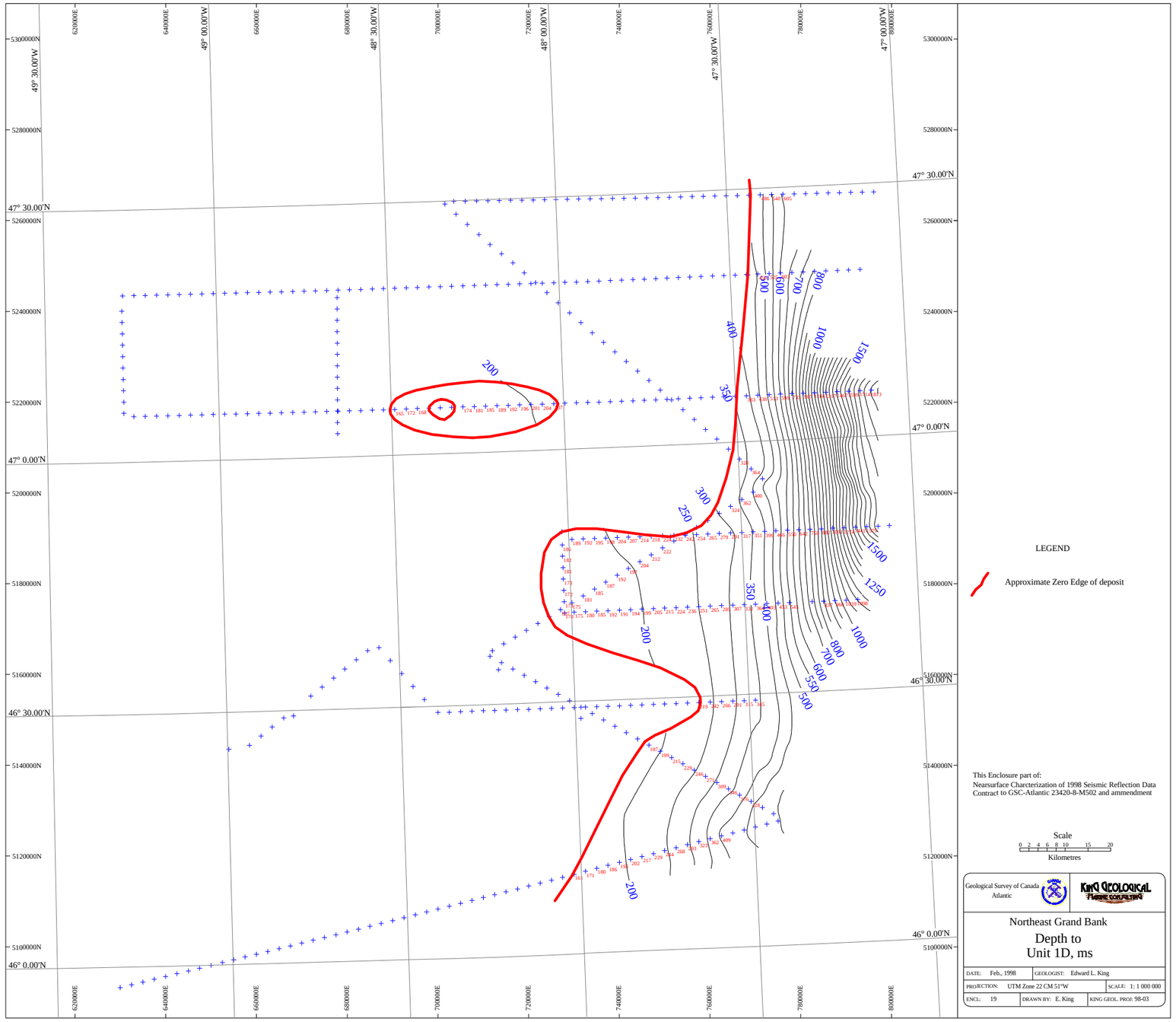


Figure 18. Depth to Unit 1d, in milliseconds (Reduced version of Enclosure 19).

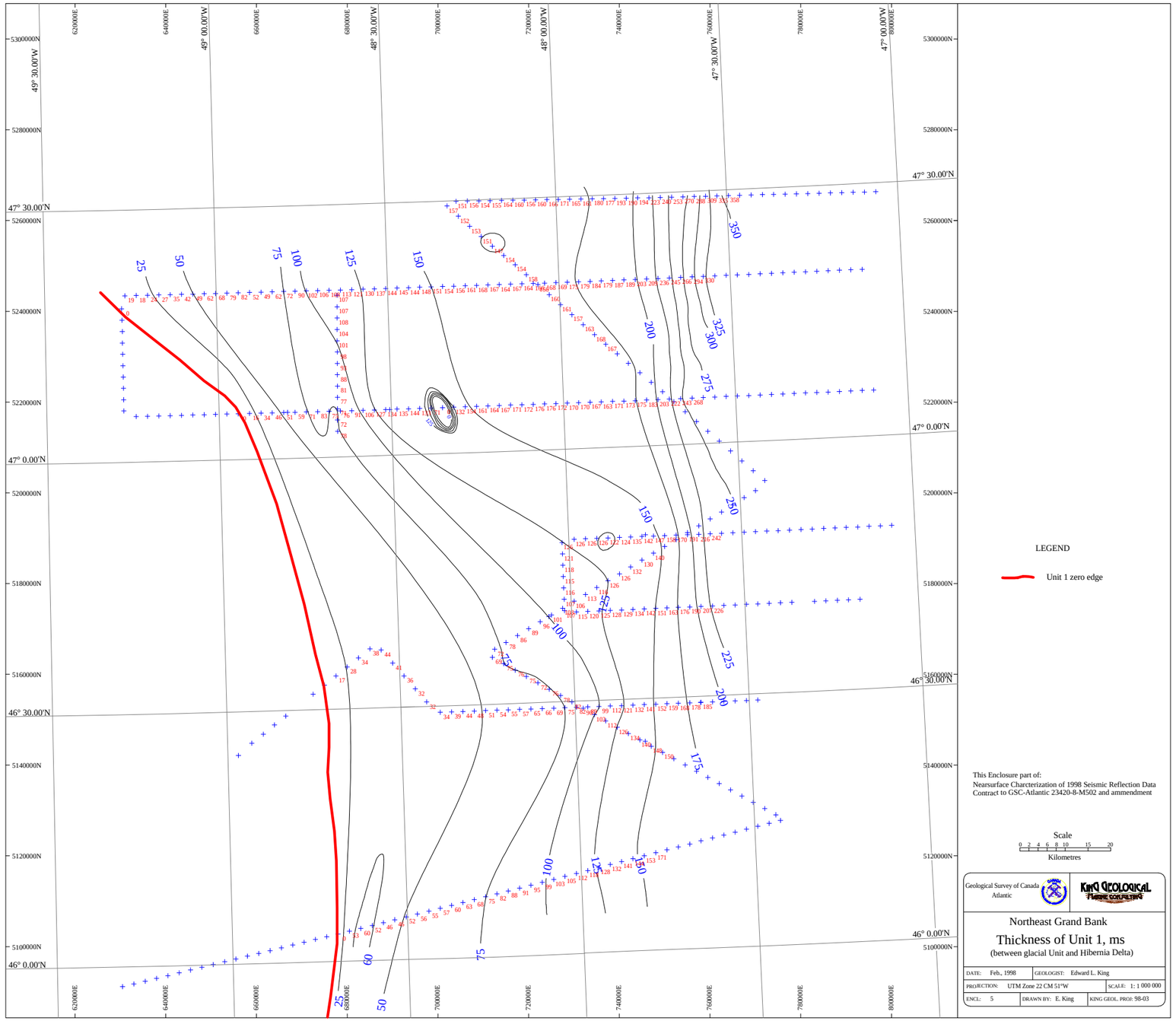


Figure 19. Thickness of Unit 1 (all subunits combined) (Reduced version of Enclosure 5).

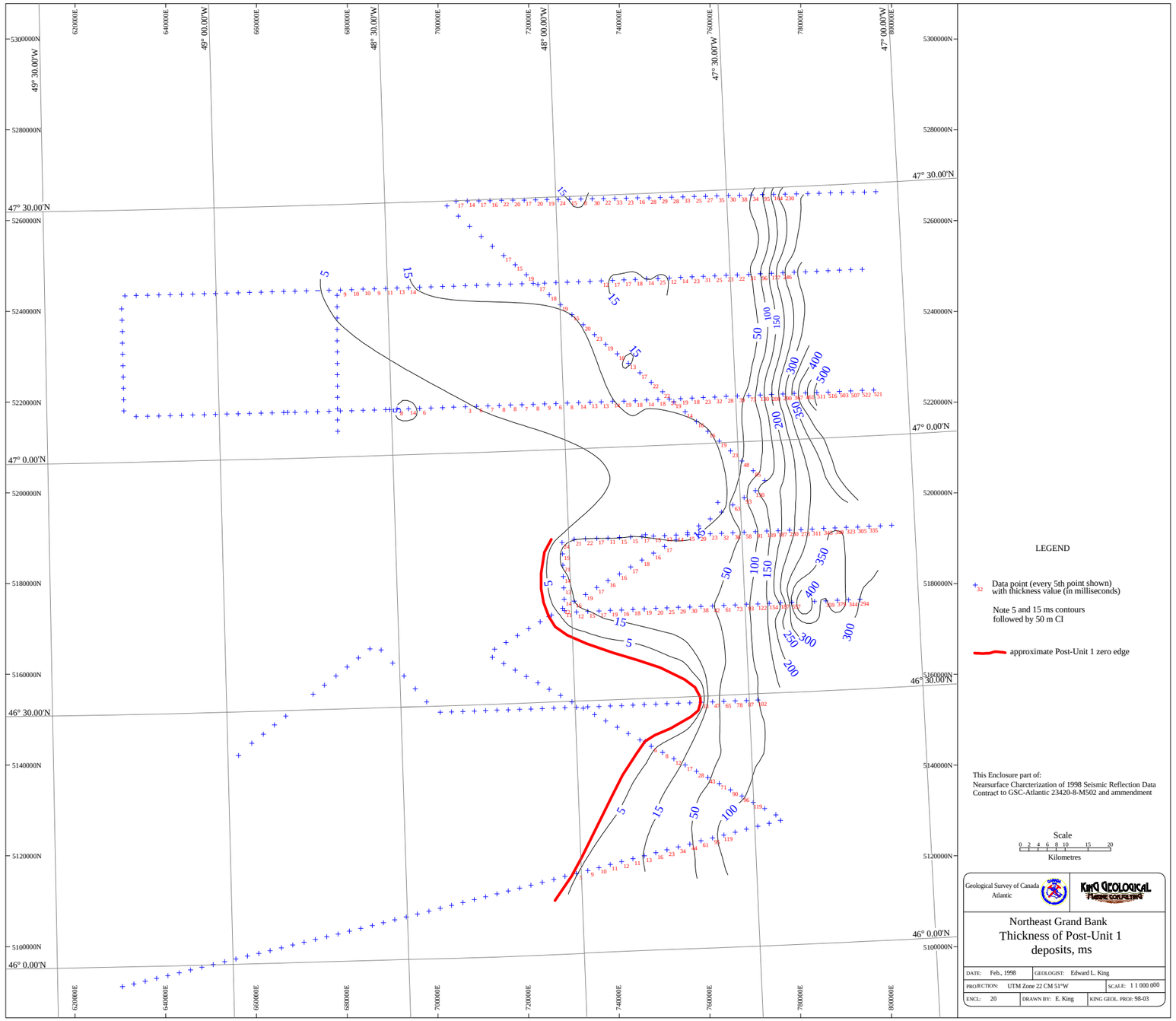


Figure 20. Thickness of Post Unit 1 deposit (Reduced version of Enclosure 20).

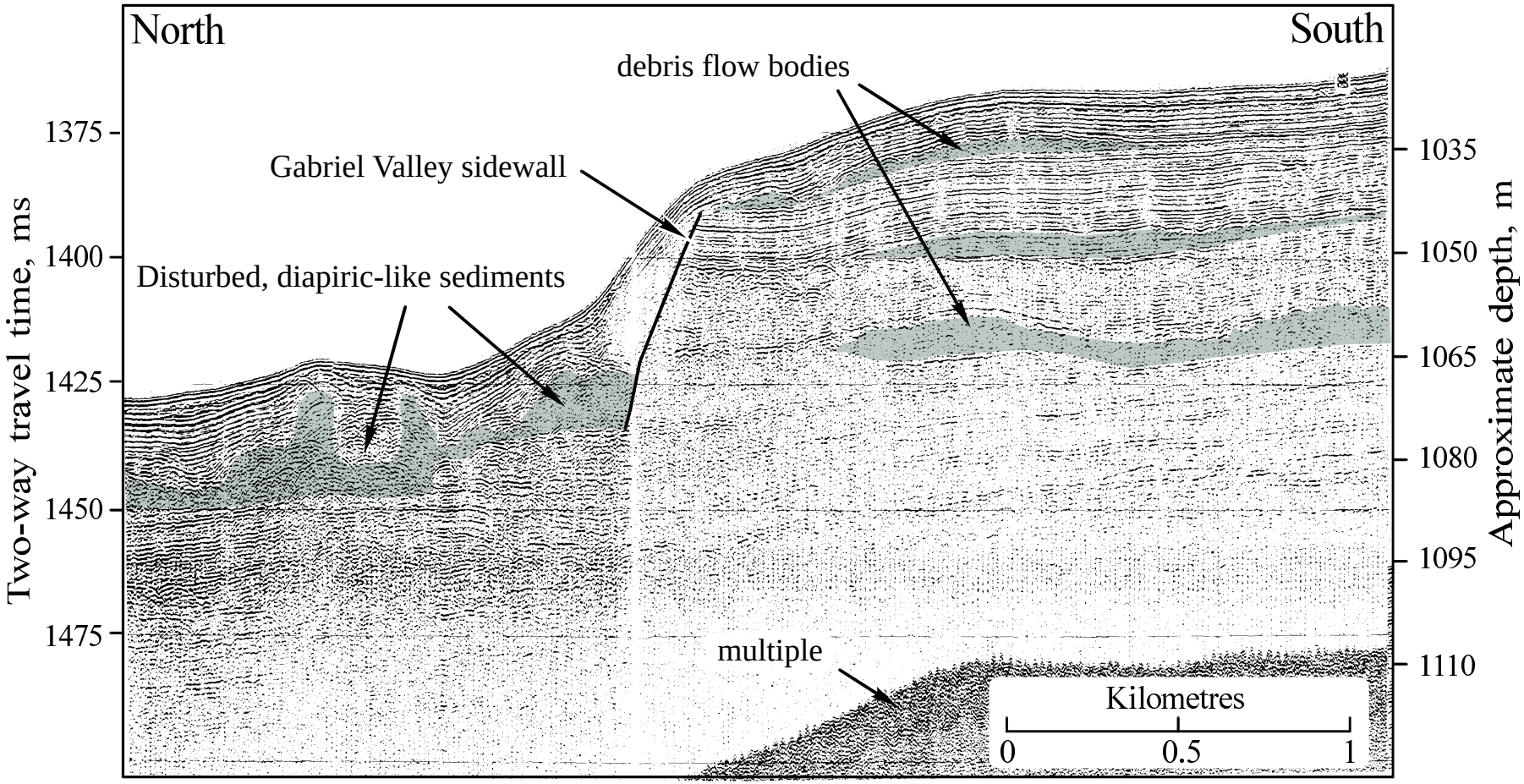


Figure 21. Huntec deep towed boomer profile from lower slope (Line 15, time 1735 to 1801) showing an erosional scarp cut in mainly draping glacigenic sediments. This is the sidewall of the Gabriel Valley (Piper and Pereira 1992). A similar, but older (deeply buried) slide cut several kilometres to the south suggests canyon migration or multiple slide failure events on relatively long time scale. Isolated, lensoid debris flow bodies are common at least three horizons along the entire slope. Local unconformities are present within the layered sequences.

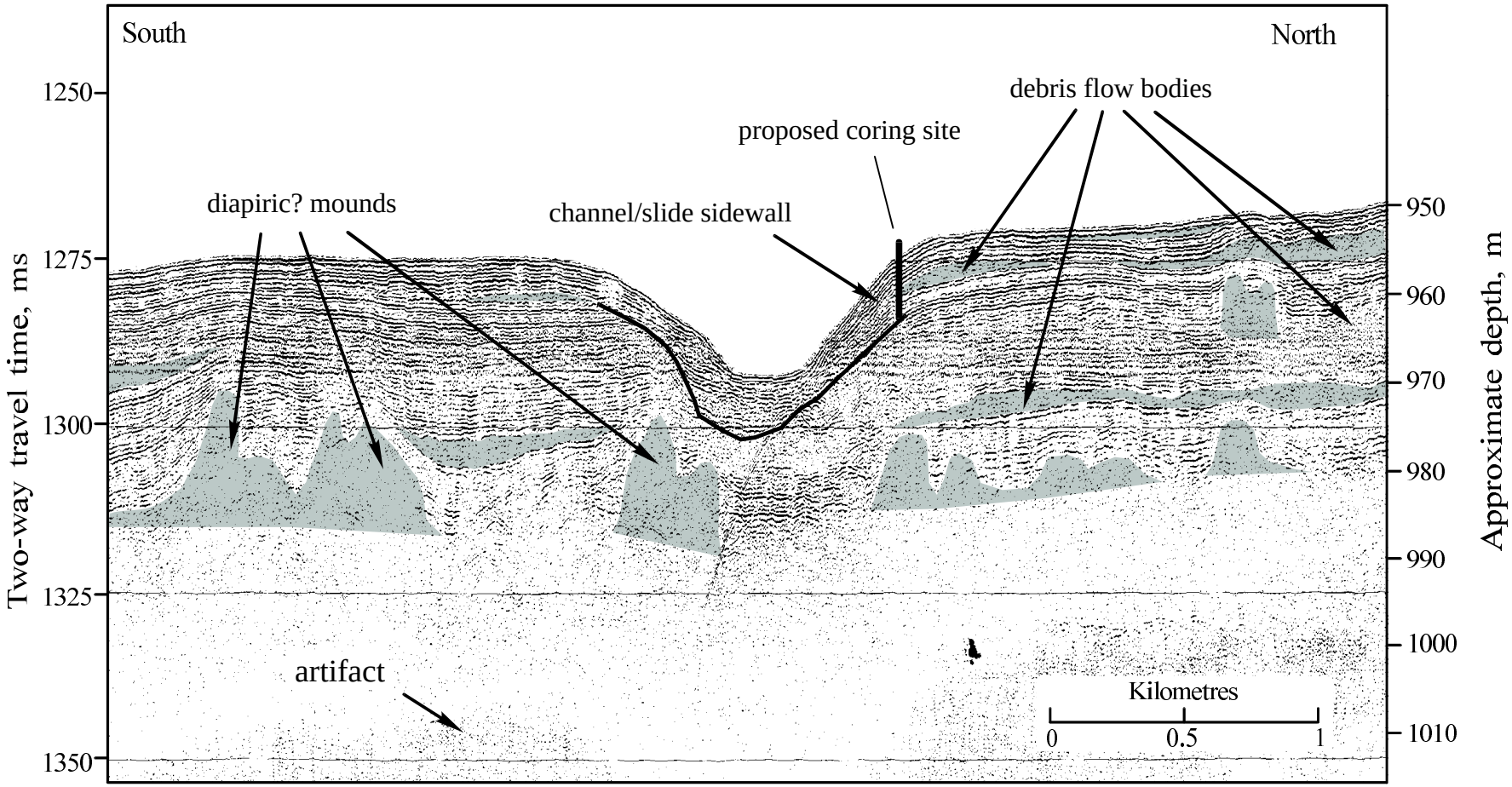


Figure 22. Huntec deep towed boomer profile from lower slope (Line 8, time 2335 to 0009) showing an erosional scarp of a channel or small slide cut in laminated sediments with an overlying draping unit. Isolated, lensoid debris flow bodies at three horizons are identified. Local unconformities are present within the layered sequences. A core at the selected site has the potential for better sedimentologic and chronologic characterization. The mounded (ridge?) features with partially draping laminites might result frommuddiapiric action.

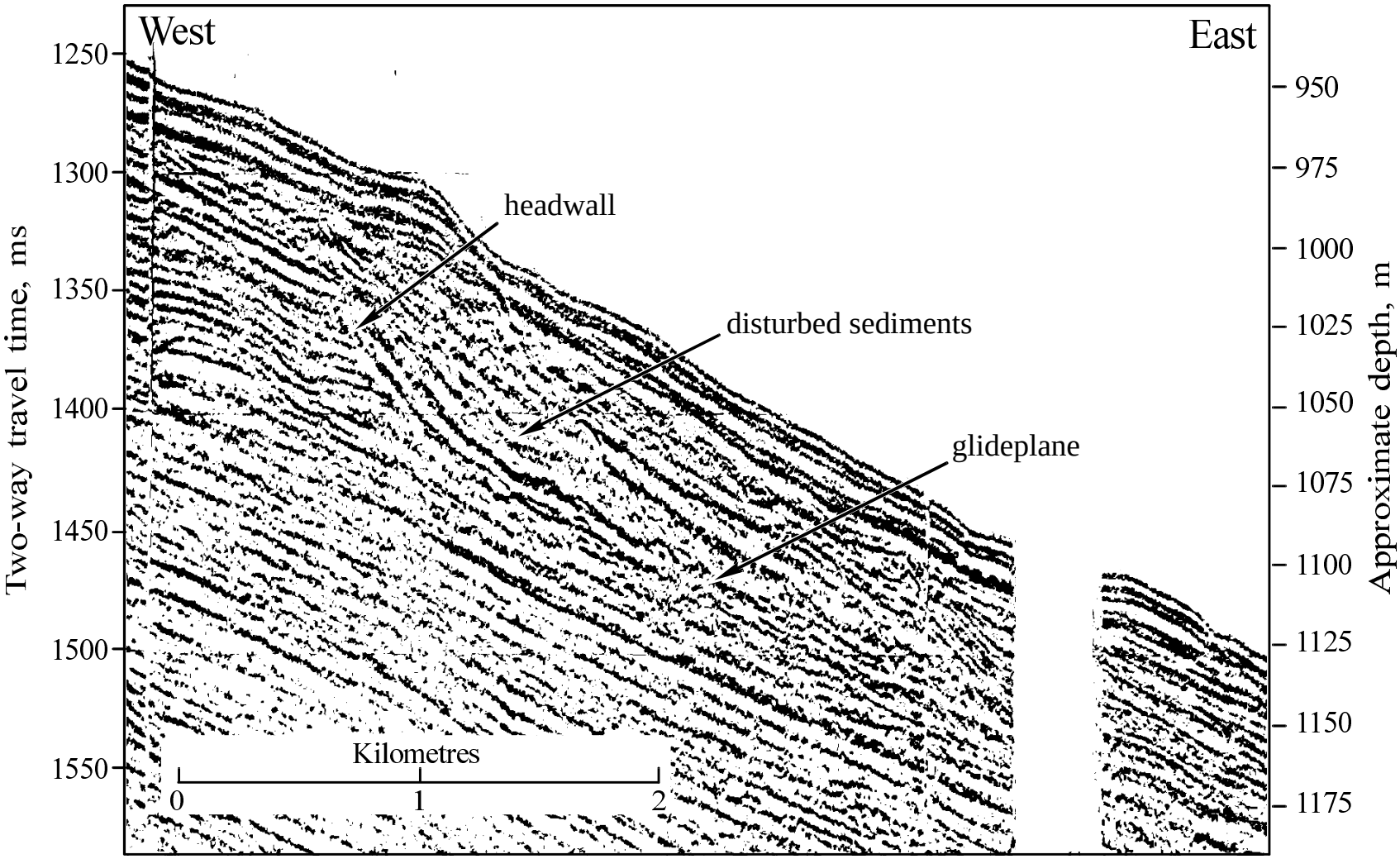


Figure 23. Air gun profile from mid slope (Line 7, time 1018 to 1054) showing a buried slide, including the headwall and near bedding-parallel glideplane, disturbed sediment, and later infill.

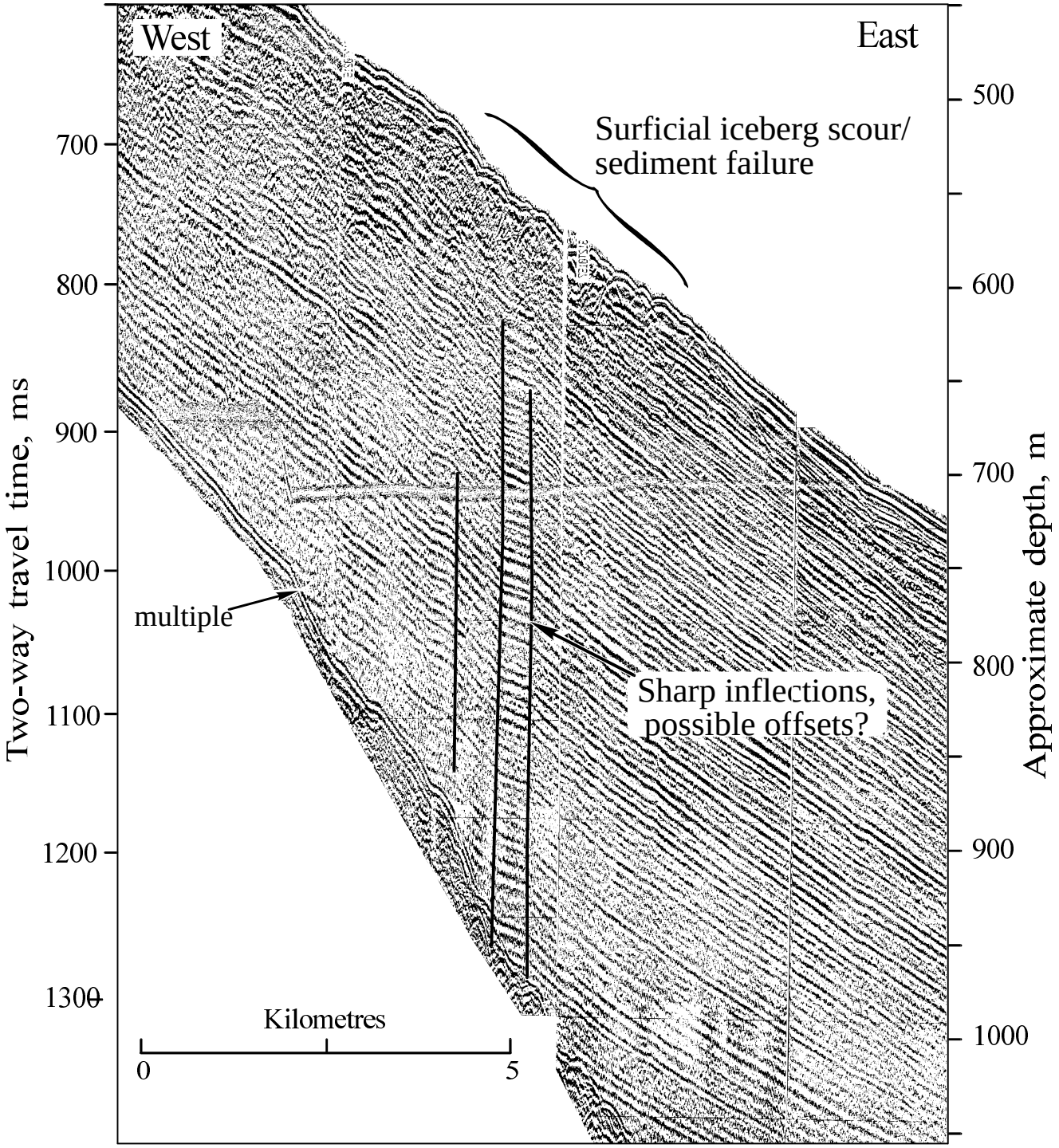


Figure 24. Air gun profile on mid-slope (Line 9) showing inflections which might represent faulting. Surficial iceberg scour zone is restricted to this approximate water depth. Some downslope failure is locally indicated. There is no apparent relationship infered between this and the disturbances at depth.

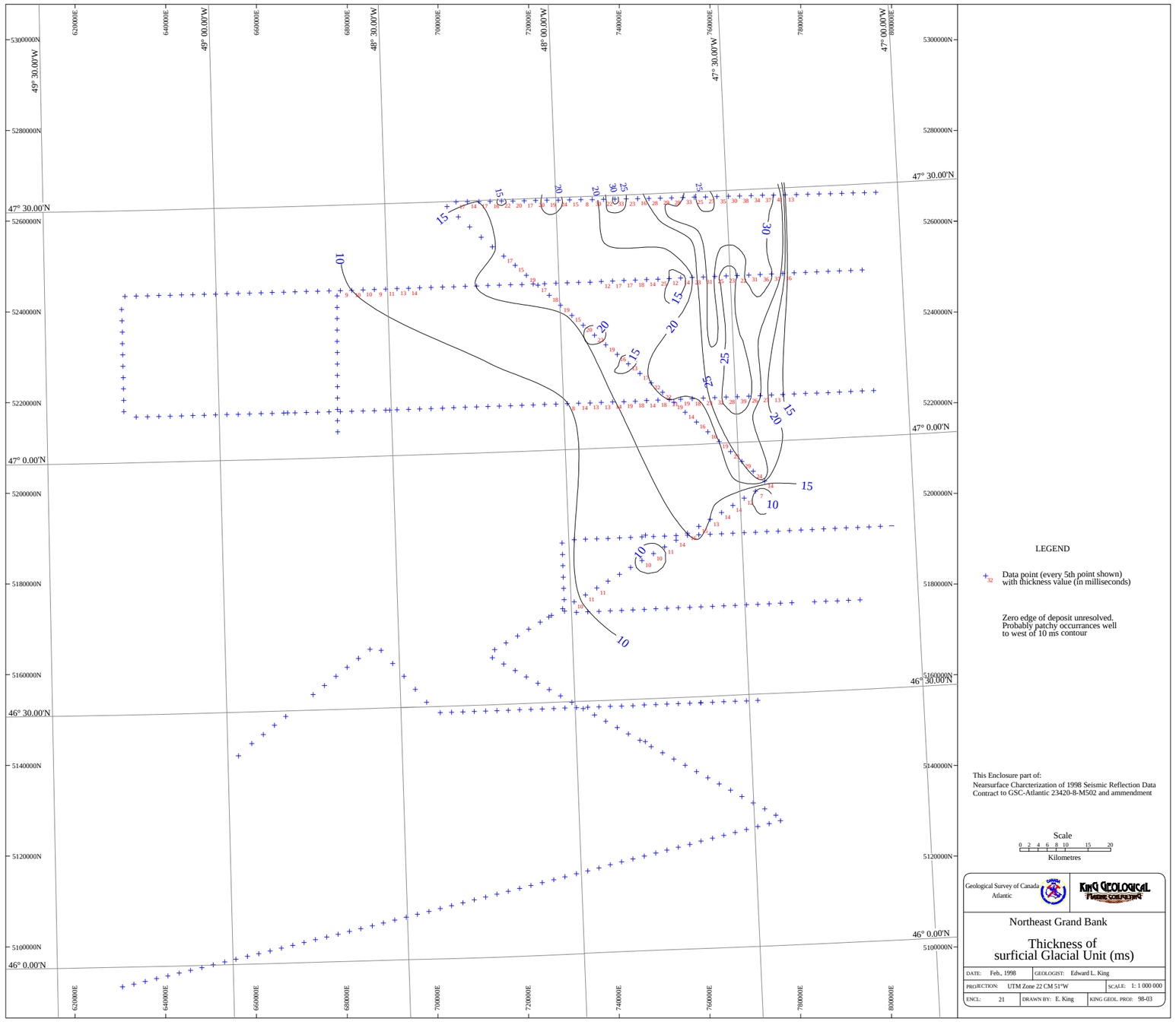


Figure 25. Thickness of the Glacigenic Unit, in milliseconds (Reduced version of Enclosure 21).

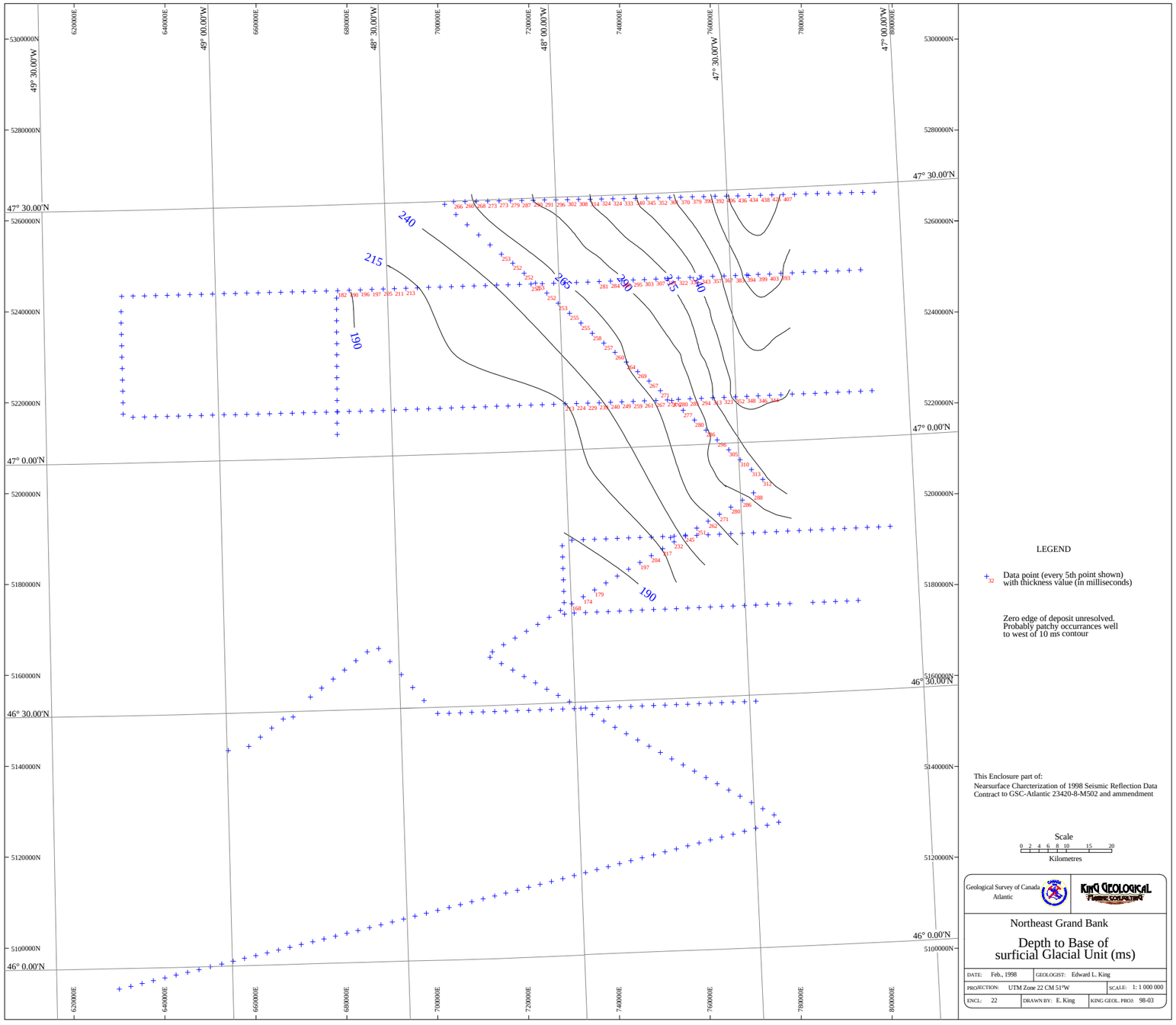


Figure 26. Depth to the base of the Glacigenic Unit, in milliseconds (Reduced version of Enclosure 22).

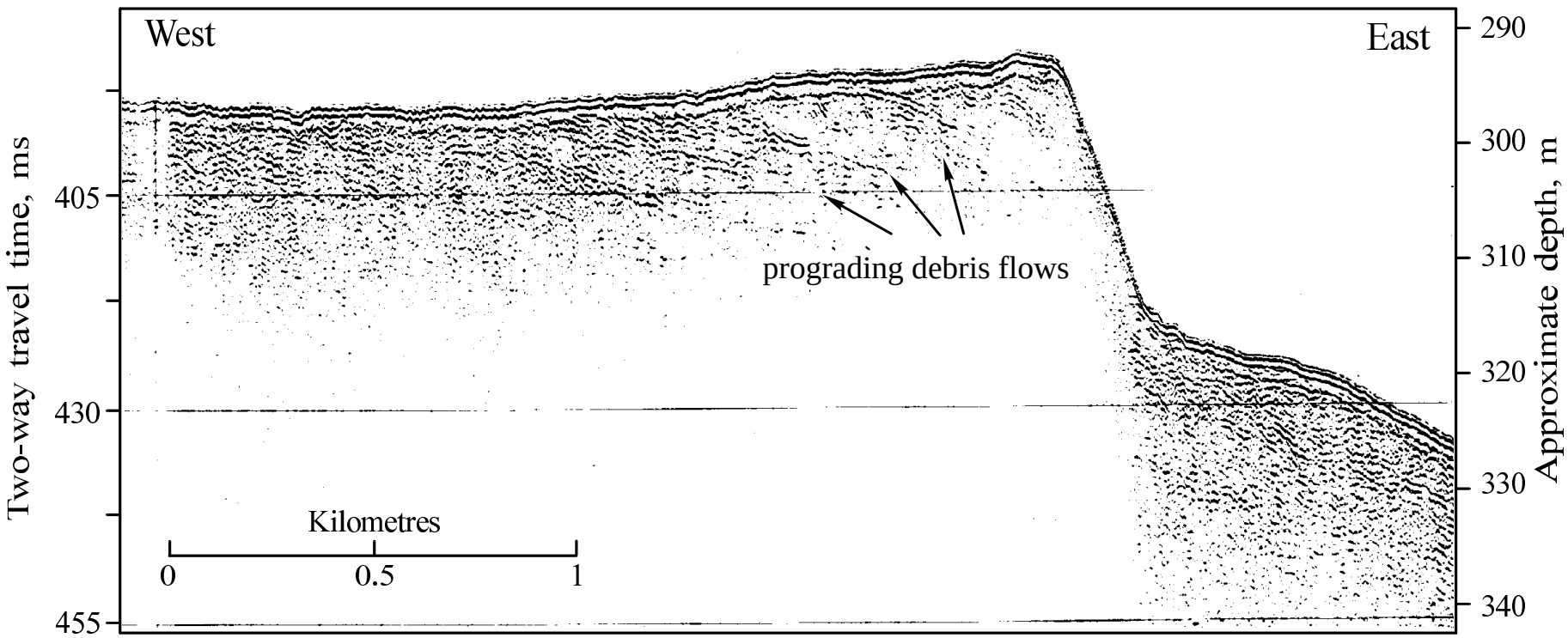


Figure 27. Huntec Deep-Towed boomer profile from northeastern shelf break (Line 16, time 2058 to 2120) showing progradational body comprising small, irregular debris flows, and landward-sloping upper surface. This probably marks where the glacier sole lay. This surface projects landward to the till-covered glacial erosional unconformity at depth, immediately to the west. The feature is interpreted as a near-margin, sub-glacially formed "till delta".

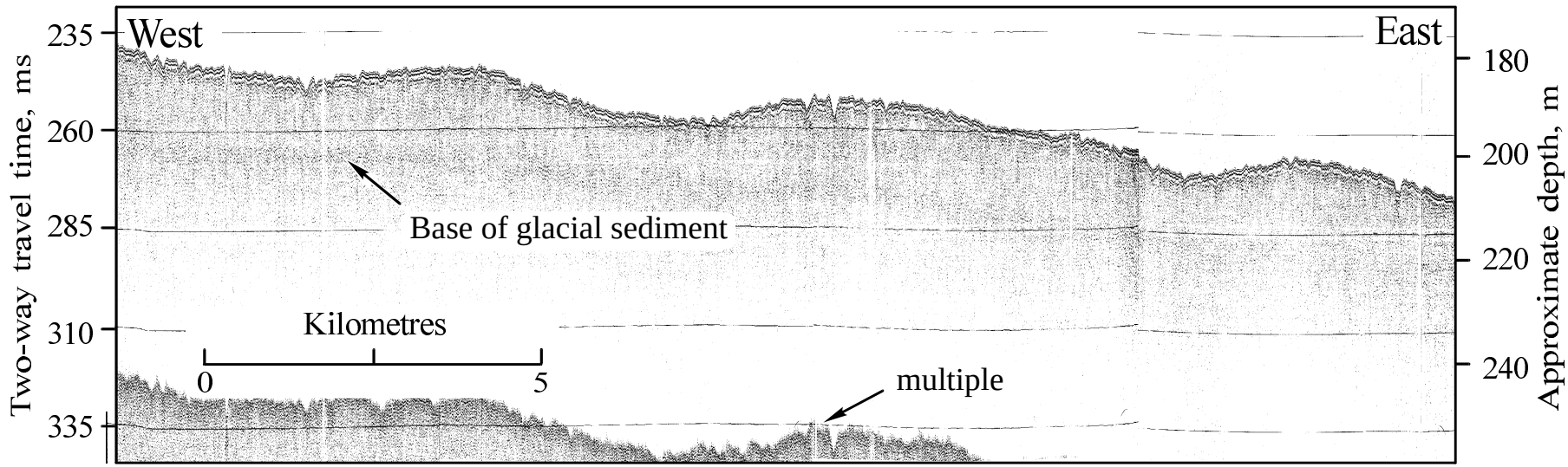


Figure 28. Huntec Deep-Towed boomer profile from northeastern shelf (Line 16, time 427 to 645) showing series of moraines in till/glacigenic sediments whose base is marked by a diffuse reflector on an angular unconformity.

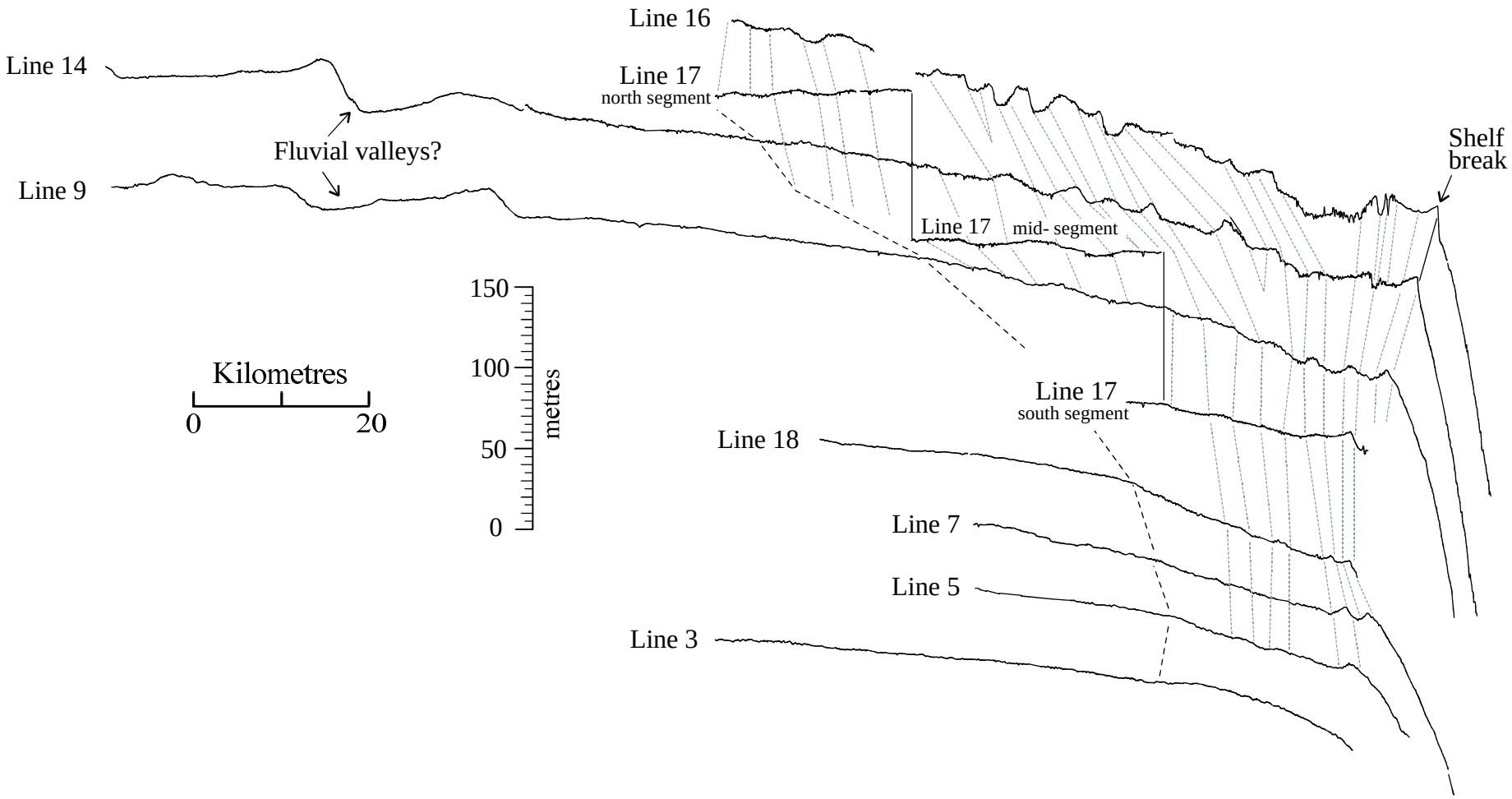


Figure 29. Bathymetric profiles across the moraine field showing their character and correlation, (with the aid of the bathymetric chart). The ridges to the south are lower relief, with the exception of the shelf-break moraine. O n the northern three profiles this moraine has a prograding structure interpreted as a “till delta“ (see also Fig. 27). The heavy dashed line separates the till/moranic field from a much more subdued, nearly planar topography in the shallow areas. In the south this is marked by an inflection in the profile, best developed on lines 3, 5 and 18. Line 17 has been divided into segments as it intersects the northern lines.

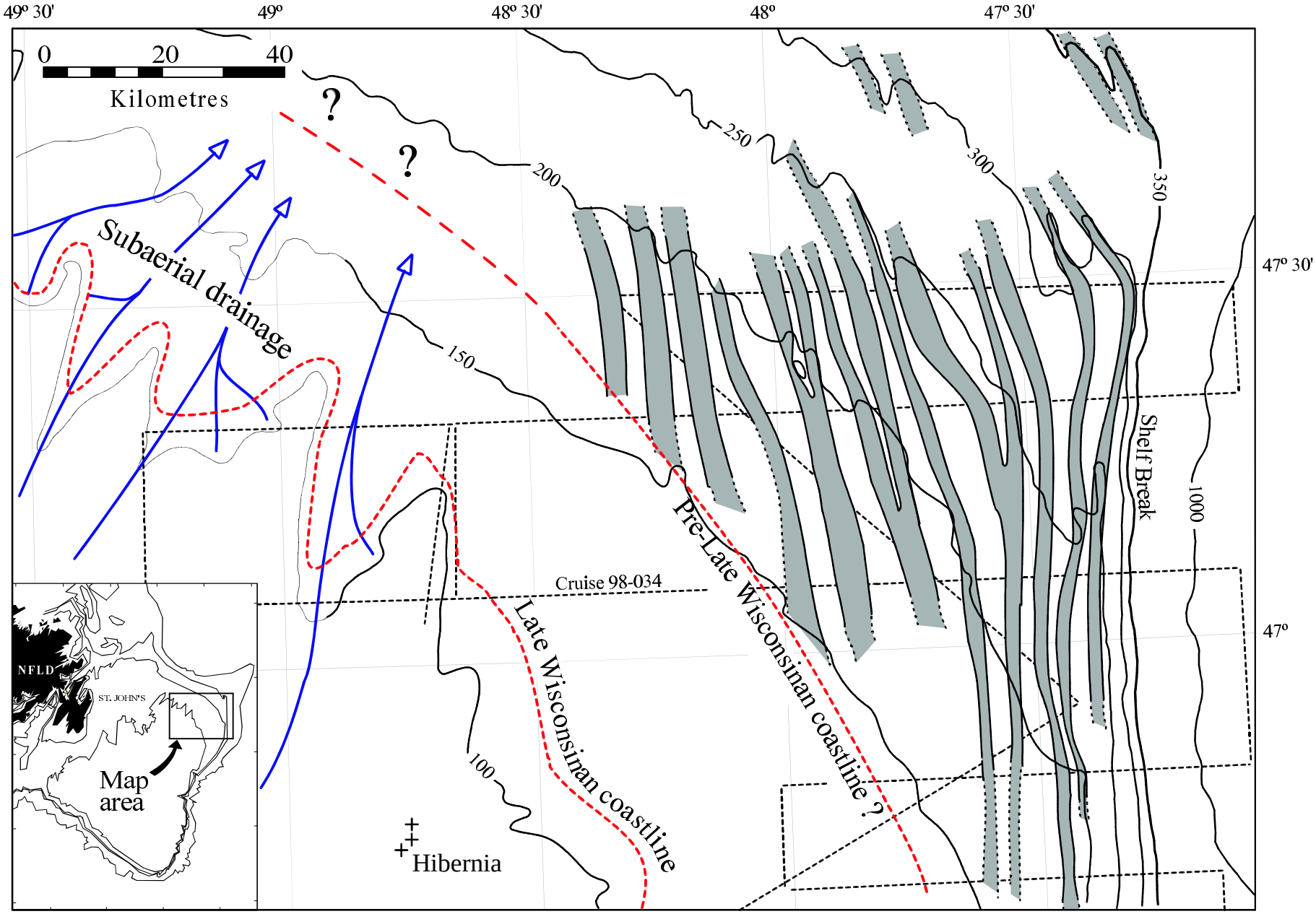


Figure 30. Moraine pattern on NE Grand Bank. They reach over 15 m height north of the survey area but are much more subdued in height to the south. Their western boundary is apparently eroded. Lacking any evidence for subsequent glacial erosion their truncation during a lower sea level is invoked. Its erosive effects to between 150 and 170 m present water depth at least 50 m below the Late Wisconsinan lowstand, suggest an *earlier* lowstand. Another possibility is relatively shortlived elevation on a periferal bulge while the Late Wisconsinan ice margin retreated but lay in stillstand on a mid shelf position. Subaerial fluvial erosion would explain the erosion-formed valleys which end in 165-170 m water depth.

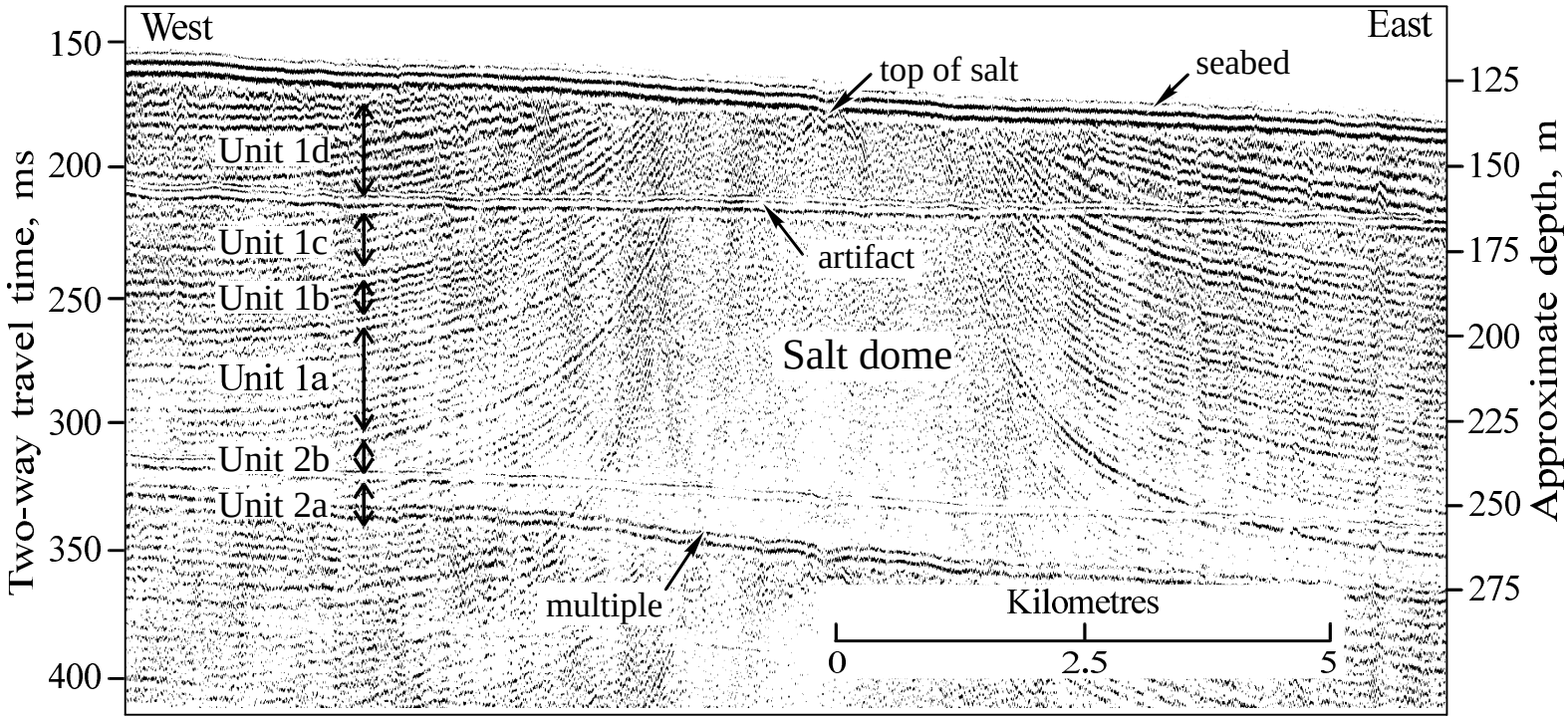


Figure 31. Air gun profile in Adolphus area (Line 9, time 1151 to 1316) showing upturning of strata resulting from salt doming. The presumed top of salt is visible slightly below the seabed.

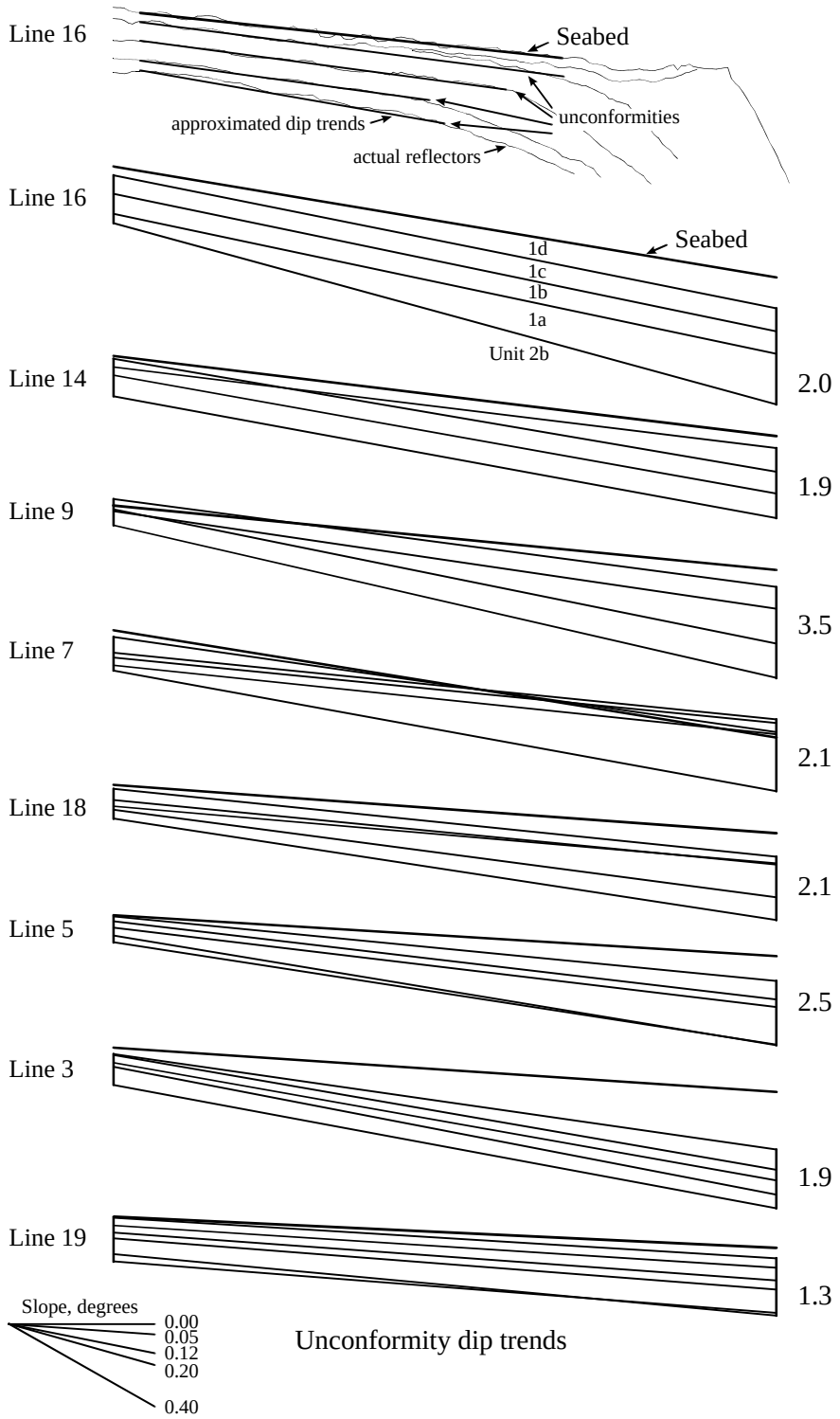


Figure 32. Approximated dip trends of unconformities at top of Units 1 a to d, 2 and 3. Uppermost panel demonstrates the approximations. Upper panels from the north and lower panels from southern lines. In an attempt at normalization, the dip trends are extrapolated east and west and corrected for apparent dip using strike trends from contour maps of their surfaces. The numerals to the right are ratios of stratigraphic thickness between unconformities on the east and west extremities, for purposes of line to line comparison. The seabed and uppermost sediment sequence is not included because of the complications with glacial-dominated erosion and deposition. Note a general trend to more splaying to the north (greater ratios), interpreted as reflecting a greater rate of general subsidence.

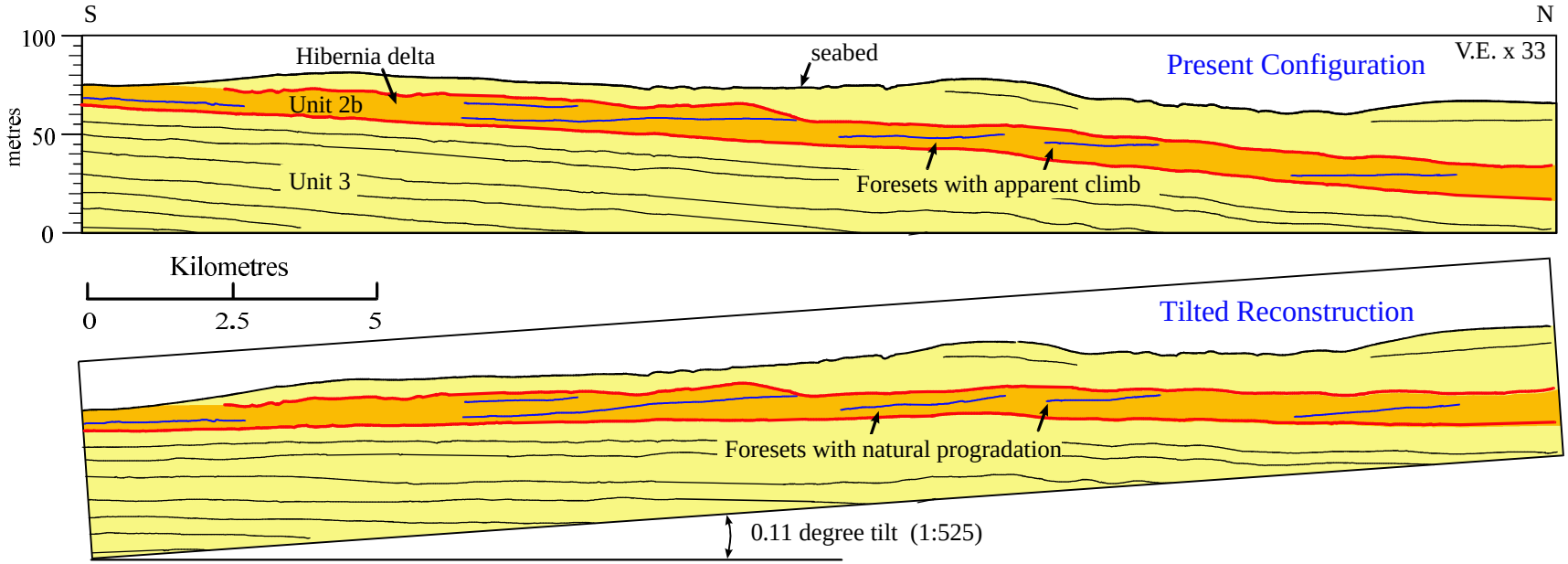


Figure 33. Interpreted seismic profile (Line 10) approximately along strike, showing foresets in the Hibernia delta. The foresets exhibit an unusual/apparently unnatural southward climbing pattern whereby successive foresets lie at higher elevations than previous ones. A simple tectonic reconstruction involving a minimal tilt restores a more natural horizontal delta top and prograding foresets. A regional tilt of this magnitude (0.1 degree) is similar to tilts in unconformities of similar age in comparison to younger unconformities.

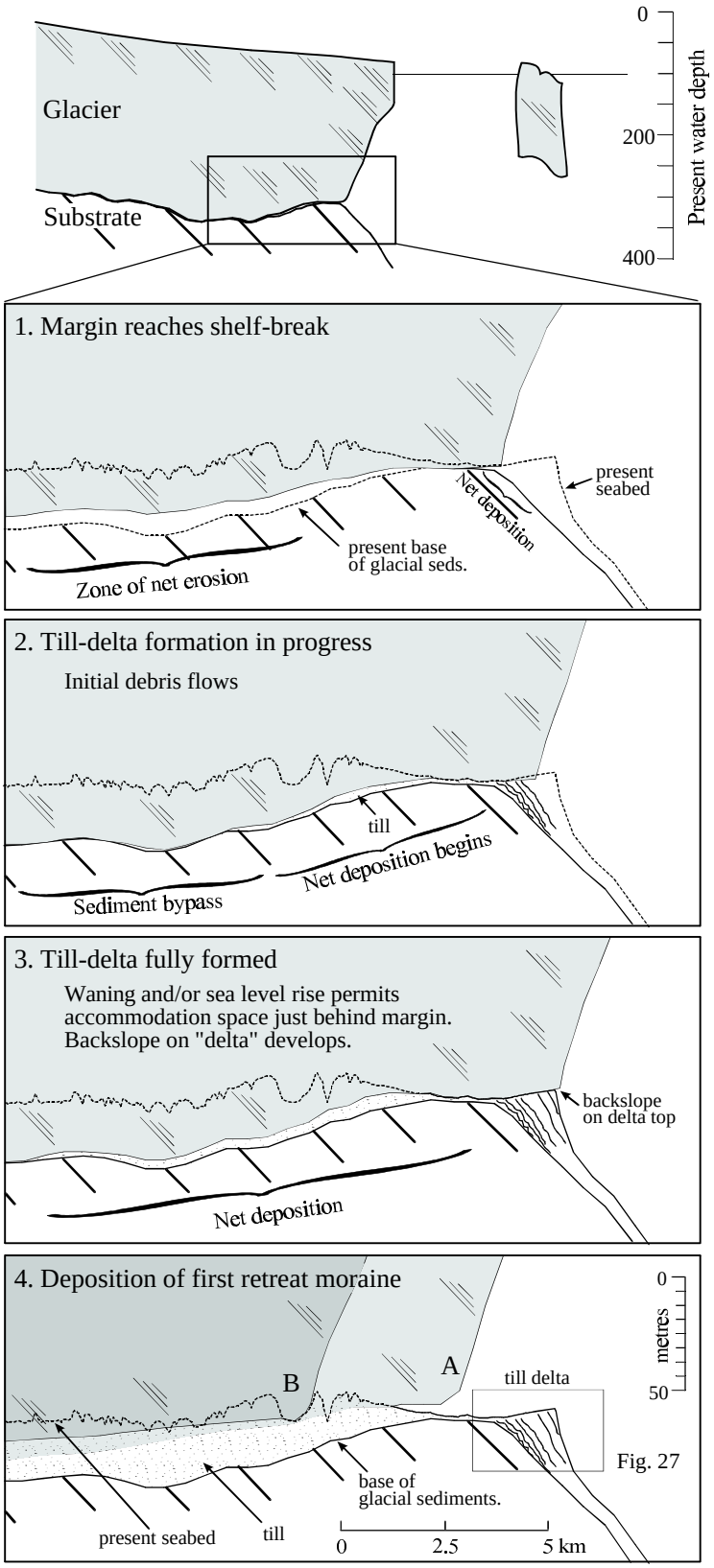


Figure 34. Interpreted ice configuration responsible for formation of the shelf-break till deltas and subsequent moraine development. Present configuration of glacigenic sediments shown for points of reference. 1. Erosion of underlying strata in progress; unknown development of delta. 2. Sub-glacial net erosion gives way to sediment bypass towards the margin with till delta (small debris flows on forsets) deposition immediately proximal to margin. 3. With ice slowing, thinning and/or sea level rise, the base level of the delta is elevated through a slight lifting of the ice margin, allowing a higher vertical build-up of the most distal delta forsets. 4. With further retreat, a till sheet accumulates vertically an uncertain amount, building the moraines at times of relative margin stability. Some late stage proglacial moraine development is possible. Simultaneous calving and margin fluctuation is probably responsible for much of the smaller scale topographic irregularity. Northward bifurcation of moraines in deeper water depths attests to less stable/higher retreat rate while the ice remained better grounded in the shallower area to the south (Figure 30).

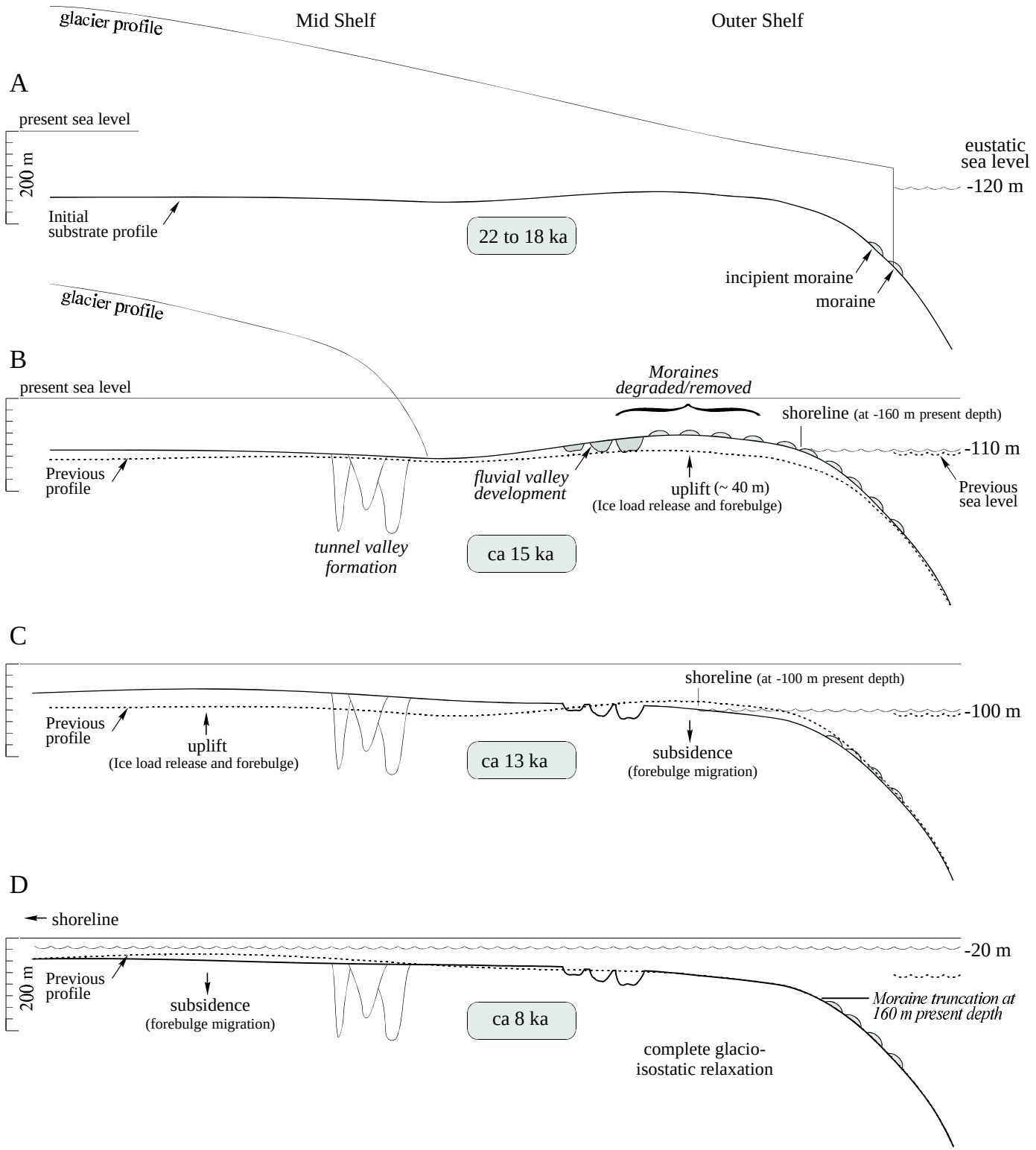


Figure 35. Hypothetical model to explain formation of the moraine field during a Late Wisconsinan retreat from the shelf break (alternative to pre Late Wisconsinan age). Moraines formed during ice retreat from the shelf break to a mid shelf stillstand position where the regime changed and subglacial meltwater channels dominated. Truncation/removal of the moraines above a present water depth of 160 -170 m along with eroding of deep fluvial valleys to this depth can be explained through a mechanism of outer shelf uplift during the eustatic low stand. This can have resulted from their position on the forebulge which subsequently experienced subsidence associated with landward migration of a glacial forebulge. This model does not explain the sharp upper limit of the (sub-littoral) Adolphous Sand Fm. at 105 m present water depth.

11.0 LIST OF ENCLOSURES, ILLUSTRATIONS AND DATA FILES

Note: Hard copies of Enclosures 1, 2A & B, 3 and 4 (Bathymetry and track plot, Geologic sections, Geologic features, and Outcrop patterns) are presented as separate map sheets at 1 : 600 000 scale. The only hard copies of Enclosures of Isopach and Structural Contour Maps are presented as letter page sized Figures (Figs. 5, 7 through 20, 25 and 26) at 1 : 1 200 000 scale. The corresponding Adobe Acrobat PDF files are at 1 : 1 000 000 scale (17'' x 11'') and the corresponding CAD map files are at true scale.

All text and maps are presented on CD in *Adobe Acrobat Exchange, (3.0)* PDF format in addition to the original formats shown listed below.

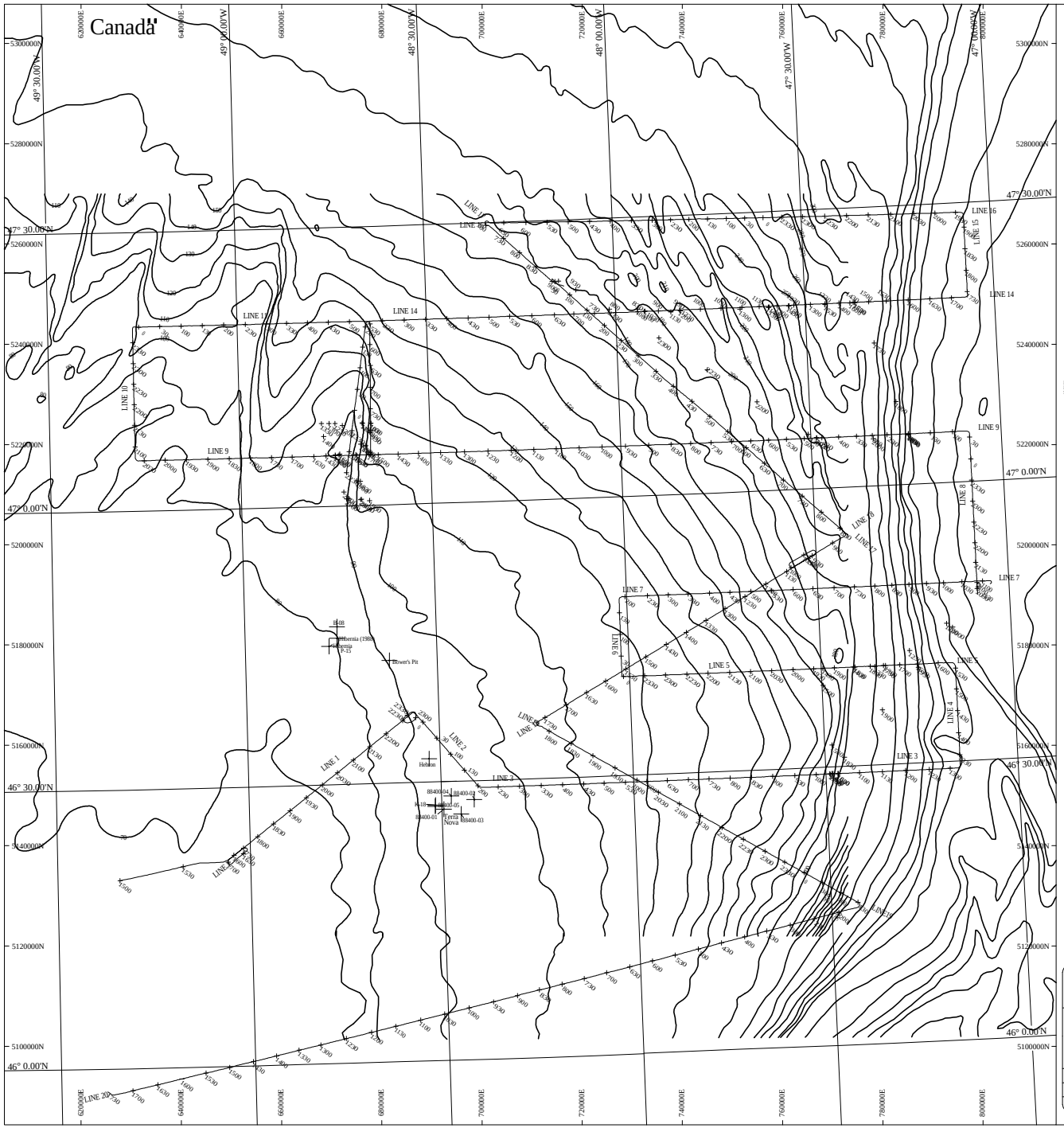
There may be minor editing discrepancies (scale, colours, line widths, some labeling etc.) between the PDF maps and the Acad maps as they were originally compiled in *IMSI Visual CADD (3.0.0.036)* and converted to *Acad* drawing files.

Corel Draw Version 7, Excel Version 97 SR-2, AutoCad Release 12, MS Word Version 97 SR-2
Enclosure 1. (1: 600 000 scale sheet enclosed in back) Bathymetry and Cruise 98-034 Ship's track, Acad File: *gbbathy3.dwg*
Enclosure 2A. (1: 200 000 scale sheet enclosed in back) Geologic Profiles, Survey Lines 9, 11, 14, 16, 17, 18, 19 & 20.
Separate Acad Files: *Line9.dwg*, *Lin11-14.dwg*, *Line16.dwg*, *Line17a.dwg*, *Line18a.dwg*, *Line19a.dwg*, *Line20a.dwg* and finally *Profil-a.dwg* (a title block and legend for all the geologic profiles)
Enclosure 2B. (1: 200 000 scale sheet enclosed in back) Geologic Profiles, Survey Lines, 1, 2, 3, 5, 6, 7 & 10.
Separate Acad Files: *Line1a.dwg*, *Line2a.dwg*, *Line3.dwg*, *Line5.dwg*, *Line6.dwg*, *Line7.dwg* & *Line10.dwg*.
Enclosure 3. (1: 600 000 scale sheet enclosed in back) Geologic features, Surficial and Buried, Acad File: *Features.dwg*
Enclosure 4. (1: 600 000 scale sheet enclosed in back) Outcrop patterns, Acad File: *Outcrop.dwg*
Enclosure 5. Thickness of Unit 1 (all subunits combined), Acad File: *Unit1map.dwg*
Enclosure 6. Thickness of Unit 2 (all subunits combined), Acad File: *Unit2map.dwg*
Enclosure 7. Thickness of Units 1 and 2 (all subunits combined) , Acad File:*U1-2map.dwg*
Enclosure 8. Depth to Unit 3 (ms) , Acad File: *Unit3map.dwg*
Enclosure 9. Thickness of Unit 2a, Acad File: *Unit2map.dwg*
Enclosure 10. Depth to Unit 2a (ms) , Acad File: *Unit2map.dwg*
Enclosure 11. Thickness of Unit 2b, Acad File: *Unit2map.dwg*
Enclosure 12. Depth to Unit 2 (ms) , Acad File: *Unit2map.dwg*
Enclosure 13. Thickness of Unit 1a, Acad File: *Unit1map.dwg*
Enclosure 14. Depth to Unit 1a (ms) , Acad File: *U1depth.dwg*
Enclosure 15. Thickness of Unit 1b, Acad File: *Unit1map.dwg*
Enclosure 16. Depth to Unit 1b (ms) , Acad File: *U1depth.dwg*

Enclosure 17. Thickness of Unit 1c, Acad File: *Unit1map.dwg*
Enclosure 18. Depth to Unit 1c (ms) , Acad File: *U1depth.dwg*
Enclosure 19. Depth to Unit 1d (ms) , Acad File: *U1depth.dwg*
Enclosure 20. Thickness of Post-Unit 1, Acad File: *Post1map.dwg*
Enclosure 21. Thickness of Glacigenic Unit, Acad File: *Glac-map.dwg*
Enclosure 22. Depth to Base of Glacigenic Unit (ms) , Acad File: *Glac-map.dwg*
Figure 1. Bathymetry outline and seismic traverses, Corel Draw File: *Figurel.cdr*
Figure 2. Stratigraphic column, Corel Draw File: *Stratcol.cdr*
Figure 3. Geologic profile, Lines 14 & 20, Corel Draw File: *figure3.cdr*
Figure 21. Huntec profile; Lower slope canyon, debris flows, Corel Draw File: *Canyon.cdr*
Figure 22. Huntec profile; Lower slope channel, debris flows, diapirs, Corel Draw File: *Channel.cdr*
Figure 23. Sleeve gun profile; Lower slope rotational slide, Corel Draw File: *L7-slide.cdr*
Figure 24. Sleeve gun profile; Slope situated faults, Corel Draw File: *L9-fault.cdr*
Figure 27. Huntec boomer profile; Shelf break till delta, Corel Draw File: *Tildelta.cdr*
Figure 28. Huntec profile; Outer shelf moraines, Corel Draw File: *L16-mora.cdr*
Figure 29. Moraine profile correlations, Corel Draw File: *Morain2.cdr*
Figure 30. Moraine map and low stand, Corel Draw File: *Moraine.cdr*
Figure 31. Sleeve gun profile; Adolphous salt dome, Corel Draw File: *L9-dome.cdr*
Figure 32. Regional unconformity tilts, Corel Draw File: *Dips.cdr*
Figure 33. Reconstructed tilted clinoforms (Line 10), Corel Draw File: *L10-tilt.cdr*
Figure 34. Glacial depositional model, till delta and moraines, Corel Draw File: *Ice-conf.cdr*
Figure 35. Hypothetical NE Grand Bank forebulge model, Corel Draw File: Bulgemodel.cdr
File. Seismic picks: unit depths, thicknesses, Excel File: *98-34pics.xls*
File. Report text: MSWord File: *98-34rep.doc*

12.0 REDUCED VERSION OF ENCLOSURES
(Those not shown as figures)

Enclosure 1: Bathymetry and 98-034 track plot
Enclosure 2A: Selected Geologic profiles 9, 11, 14, 16, 17, 18, 19 & 20
Enclosure 2B: Selected Geologic profiles 1, 2, 3, 5, 6, 7 & 10
Enclosure 7: Thickness of Units 1 and 2 combined, ms



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GEOLOGICAL SURVEY OF CANADA / COMMISSION GÉOLOGIQUE DU CANADA

Recommended citation:
King, E.L. 1999. Characterization of near-surface seismostratigraphy and features of Northeastern Grand Bank: Sea level fluctuations, glaciation and slope stability. GSC Open File No. XXXXXX, Oct. 1999.

Enclsoure 1
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LEGEND

CONTOUR INTERVAL
10 m above 350 m water depth in most areas

50 m to 500 m
250 m below 500 m

Selected Wellsite

This Enclosure part of:
Nearsurface Charcterization of 1998 Seismic Reflection Data
Contract to GSC-Atlantic 23420-8-M502 and ammendment

Scale
0 2 4 6 8 10 15 20
Kilometres

Geological Survey of Canada
Atlantic

King Geological Consulting

Northeast Grand Bank
Bathymetry
Cruise 98-034 track

DATE: Feb., 1998	GEOLOGIST: Edward L. King	
PROJECTION: UTM Zone 22 CM 51°W		SCALE: 1:600 000
ENCL: 1	DRAWN BY: E. King	KING GEOL. PROJ:98-03

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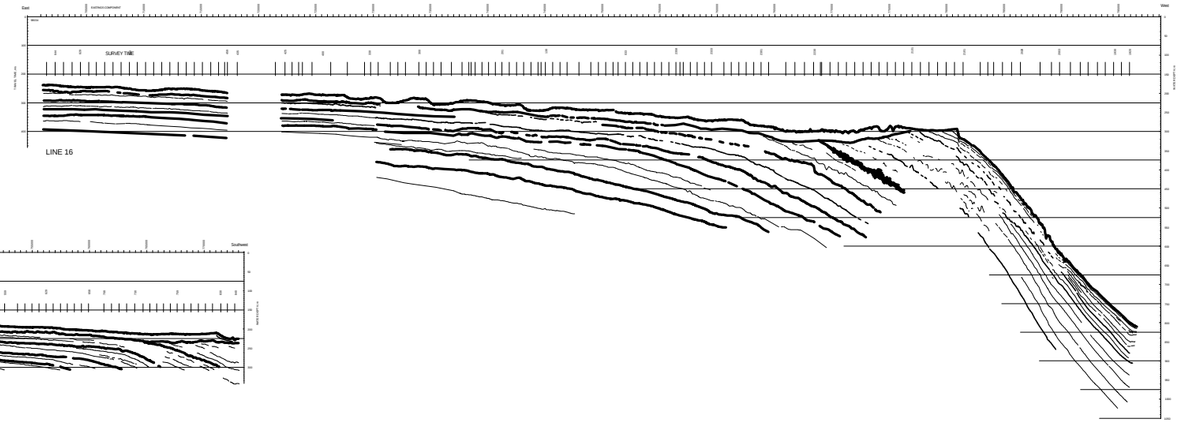
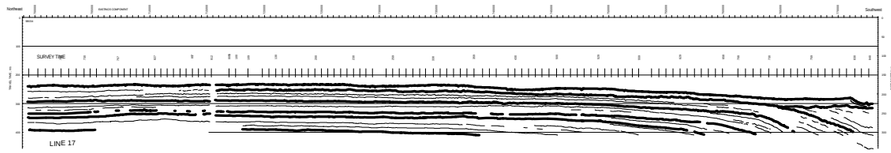
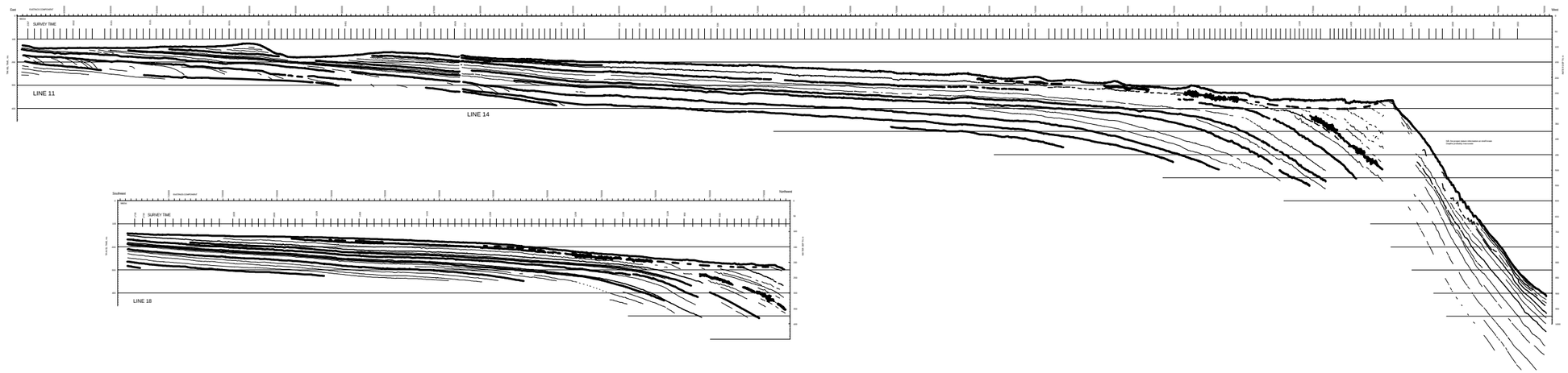
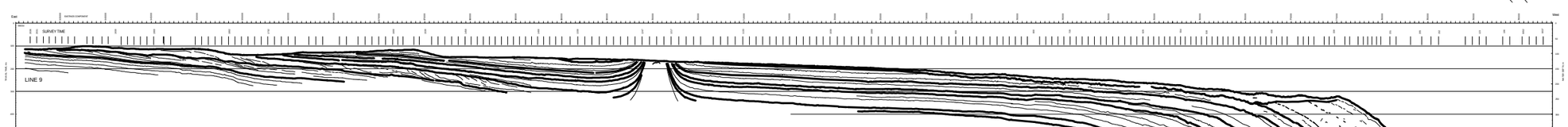
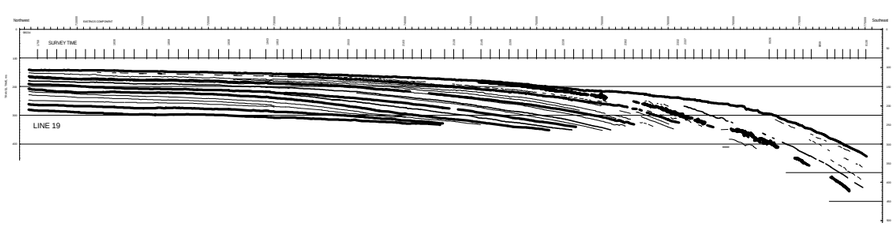
Recommended citation: King, E.L. 1999. Characterization of near-surface seismostratigraphy and features of Northeastern Brand Bank: Sea level fluctuations, glaciation and slope stability. GSC Open File No. XX/XXXX, Oct. 1999.

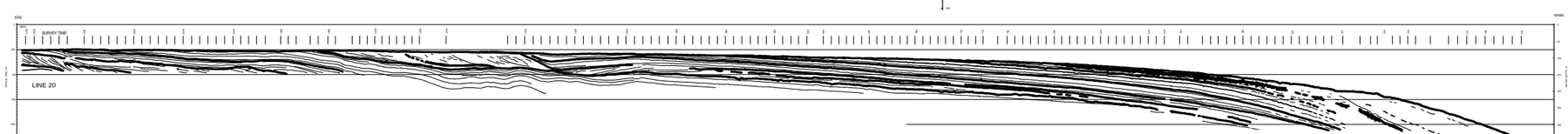












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Enclosure 2A

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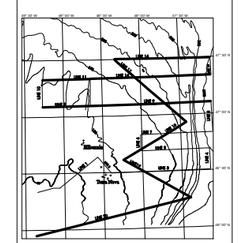


This Enclosure part of:
Nearsurface Characterization of 1998 Seismic Reflection Data
Contract to GSC-Atlantic 23420-8-M502 and amendment

Seismic stratigraphy of shelf sediments based on seismic reflection characteristics and coring data			Unit Description/Interpretation
Regressive Cycle	1	undifferentiated	**Glacial-transported deposits** Diamicton, till ridges, glaciomarine muds, sediment-laden ice, glacial outwashes Glacial and Holocene
		D	**Shelf-edge progradation** Muds, muddy prodeltaic and prograding sandy and coarse-clastic wedges Late Quaternary
		C	**Shelf-edge progradation** Muddy prodeltaic and prograding sandy and coarse-clastic wedges Late Quaternary
		B	**Shelf aggradation, shelf-edge progradation** Muddy prodeltaic and prograding sandy and coarse-clastic wedges Late Quaternary
		A	**Shelf aggradation, shelf-edge progradation** Muddy prodeltaic and prograding sandy and coarse-clastic wedges Late Quaternary
			Shelf aggradation, shelf-edge progradation Muddy prodeltaic and prograding sandy and coarse-clastic wedges Late Quaternary
	2	B	**Aggrading progradational body and distal equivalents** Muddy prodeltaic and prograding sandy and coarse-clastic wedges Late Quaternary
	Marine Stage	A	**Aggrading progradational body and distal equivalents** Muddy prodeltaic and prograding sandy and coarse-clastic wedges Late Quaternary
	3	B	**Parallel to slightly splaying aggradational beds** Muddy prodeltaic and prograding sandy and coarse-clastic wedges Late Quaternary
		A	**Parallel to slightly splaying aggradational beds** Muddy prodeltaic and prograding sandy and coarse-clastic wedges Late Quaternary
	4	B	**Shelf aggradation to progradation** Glaciomarine muds, sandy muddy prodeltaic and distal coarse-clastic wedges Late Quaternary
		A	**Progradational body** Muddy prodeltaic and distal coarse-clastic wedges Late Quaternary

Scale
0 2 4 6 8 10
Kilometres

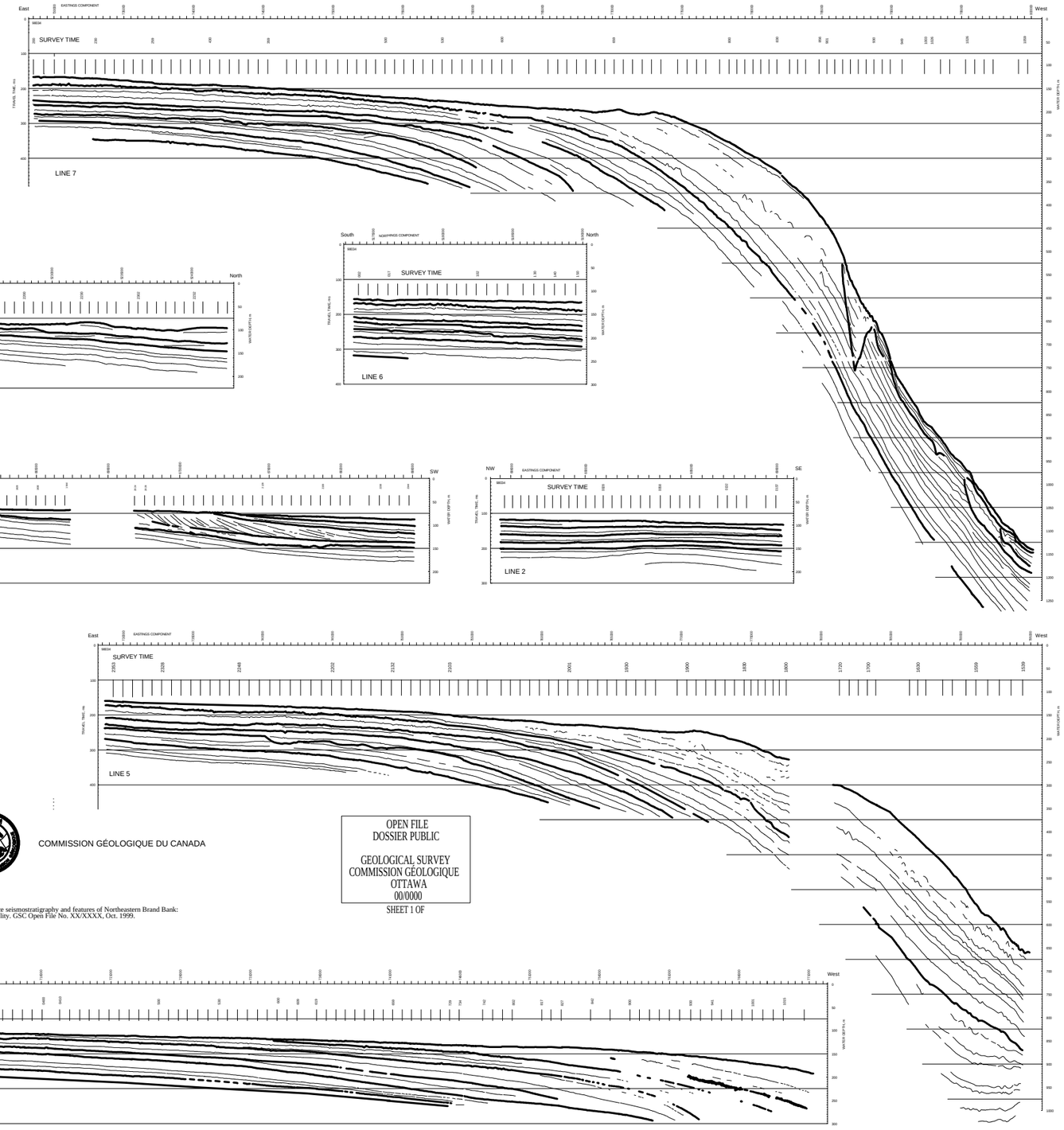
Geological Survey of Canada
Atlantic

King Geological Profile Collection

Northeast Grand Bank
Selected Geologic Profiles
Cruise 98-034

DATE: Feb., 1998	GEOLOGIST: Edward L. King		
PROJECTION: UTM Zone 22 CM 51°W		SCALE: 1: 200 000	
ENCL: 2A	DRAWN BY: E. King	KING GEOL. PROD: 98-03	

Canada



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OTTAWA
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SHEET 1 OF

Recommended citation: King, E.L. 1999. Characterization of near-surface seismostratigraphy and features of Northeastern Brand Bank: Sea level fluctuations, glaciation and slope stability. GSC Open File No. XX/XXXX, Oct. 1999.

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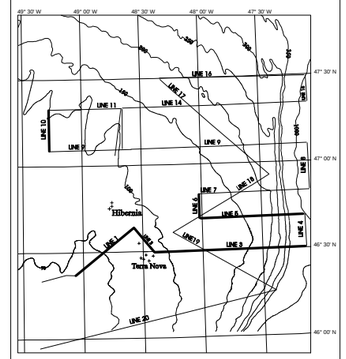
Enclosure 2B

See full size version
in back envelope



Colours at top of Unit correspond with same coloured reflection in profile			Unit Description/Interpretation
Banquereau Formation			Glacial-dominated deposits moraines, till-delta, till blanket, undifferentiated pro-glacial sediments UNCONFORMITY
	1	Undifferentiated	Shelf edge progradation thick, multiphased shelf progradation and mass wasting UNCONFORMITY
		D	Shelf edge progradation correlations imprecise due to sparse data coverage UNCONFORMITY
		C	Shelf aggradation, shelf-edge progradation UNCONFORMITY
		B	Shelf aggradation, shelf-edge progradation UNCONFORMITY
		A	Shelf aggradation, shelf-edge progradation locally dissected surface, local landward progradation UNCONFORMITY
	2 Hibernia Delta	B	Expansive Progradational body and distal equivalents multiphase lobes with high-angle, delta-like foresets UNCONFORMITY
		A	Expansive Progradational body and distal equivalents multiphase lobes occasionally with low angle foresets UNCONFORMITY
	3	B	Parallel to slightly splaying aggradational beds downlaps on top of Unit 3a UNCONFORMITY
		A	Parallel to slightly splaying aggradational beds low angle foresets at western end UNCONFORMITY
	4	B	Shelf aggradation to progradation occasional low angle delta-like foresets and distal equivalents UNCONFORMITY
		A	Progradational body deep delta-like foresets and distal equivalents

This Enclosure part of:
Nearsurface Charcterization of 1998 Seismic Reflection Data
Contract to GSC-Atlantic 23420-8-M502 and ammendment

Scale
0 2 4 6 8 10
Kilometres

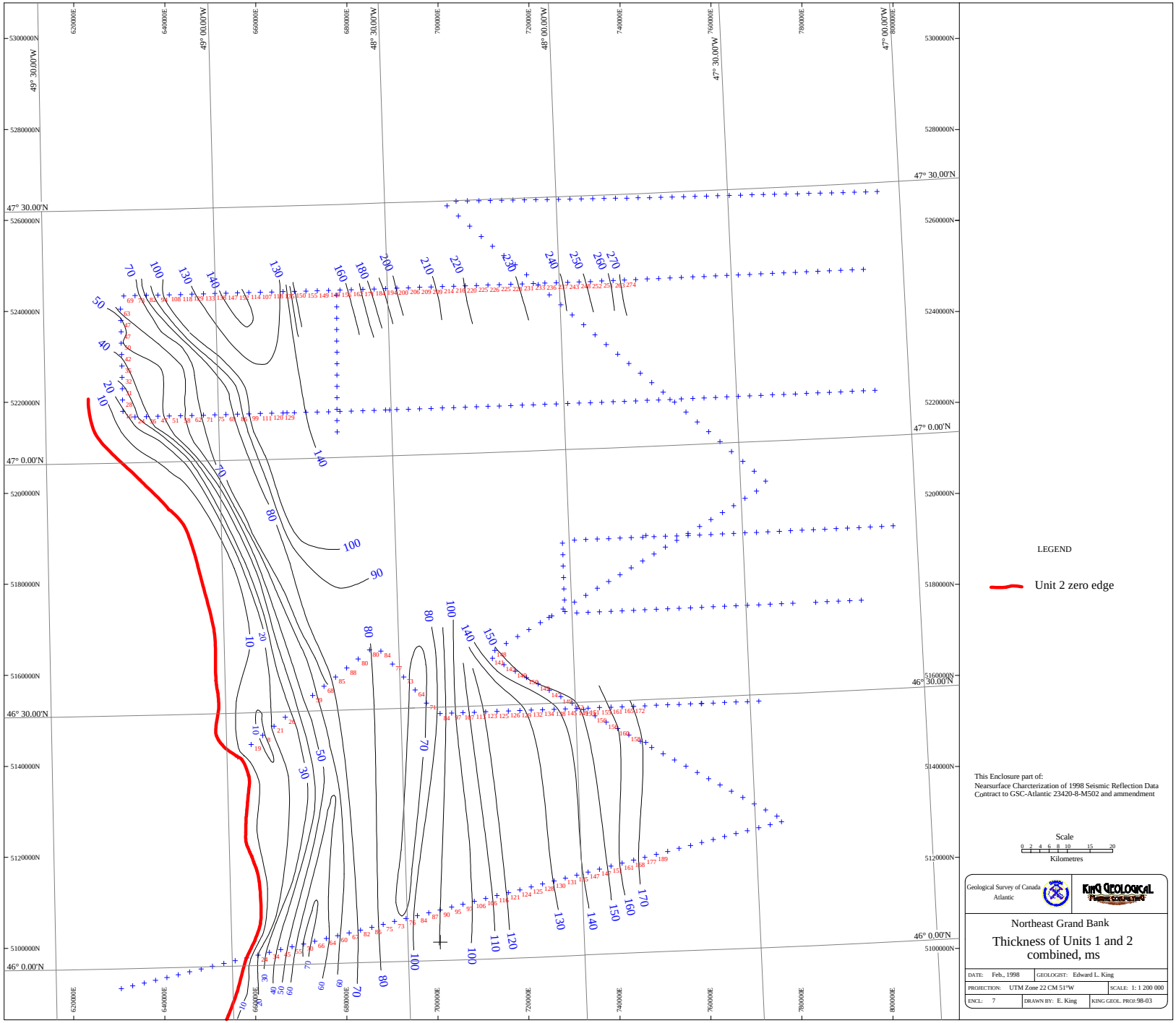
Geological Survey of Canada
Atlantic

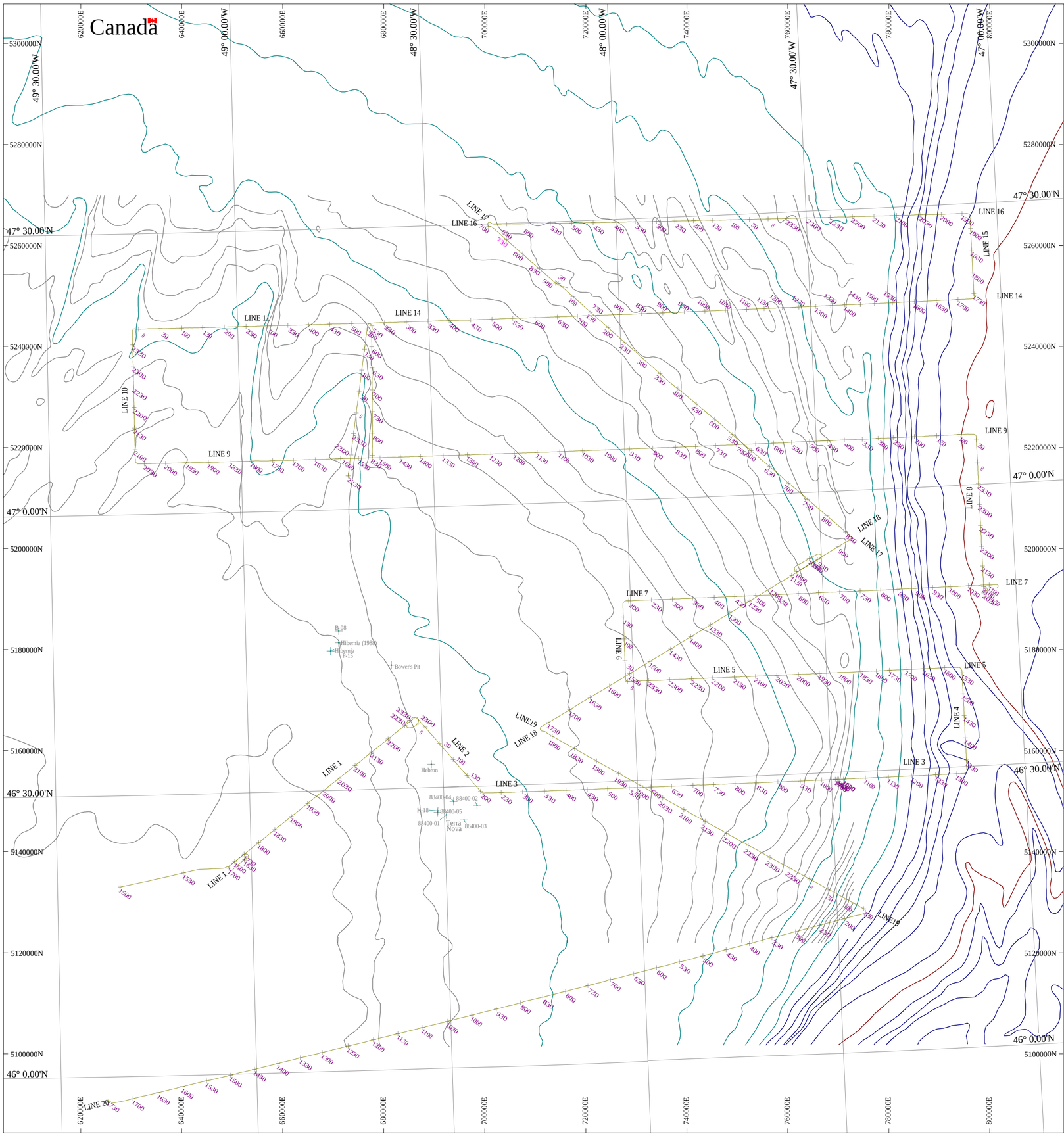
KING GEOLOGICAL MARINE CONSULTING

Northeast Grand Bank
Selected Geologic Profiles
Cruise 98-034

DATE: Feb., 1998	GEOLOGIST: Edward L. King	
PROJECTION: UTM Zone 22 CM 51°W		SCALE: 1: 200 000
ENCL: 2B	DRAWN BY: E. King	KING GEOL. PROJ 98-03

Enclosure 7. Thickness of Units 1 and 2 combined, in milliseconds.





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SHEET 1 OF 5

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Recommended citation:
King, E.L. 1999. Characterization of near-surface seismostratigraphy and features of Northeastern Brand Bank: Sea level fluctuations, glaciation and slope stability. GSC Open File No. 3386, Oct. 1999.

LEGEND

CONTOUR INTERVAL
10 m above 350 m water depth
in most areas
50 m to 500 m
250 m below 500 m

88400-03 Selected Wellsite

This Enclosure part of:
Nearsurface Charcterization of 1998 Seismic Reflection Data
Contract to GSC-Atlantic 23420-8-M502 and ammendment

Scale
0 2 4 6 8 10 15 20
Kilometres

Geological Survey of Canada
Atlantic

KING GEOLOGICAL MARINE CONSULTING

Northeast Grand Bank
Bathymetry
Cruise 98-034 track

DATE: Feb., 1998	GEOLOGIST: Edward L. King	
PROJECTION: UTM Zone 22 CM 51°W		SCALE: 1:600 000
ENCL: 1	DRAWN BY: E. King	KING GEOL. PROJ: 98-03

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Recommended citation: King, E.L. 1999. Characterization of near-surface seismostratigraphy and features of Northeastern Brand Bank: Sea level fluctuations, glaciation and slope stability. GSC Open File No.3886, Oct. 1999.

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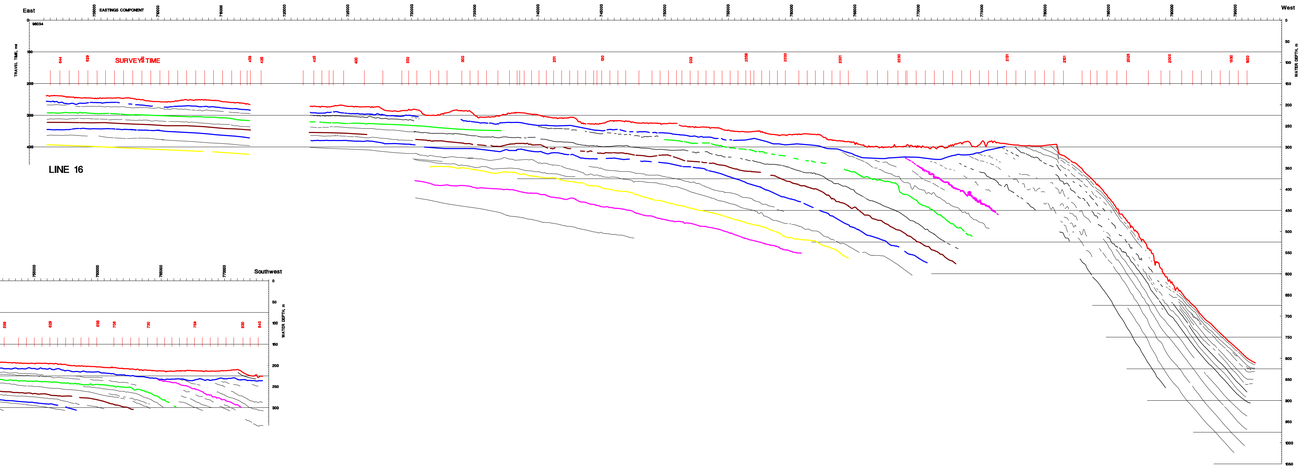

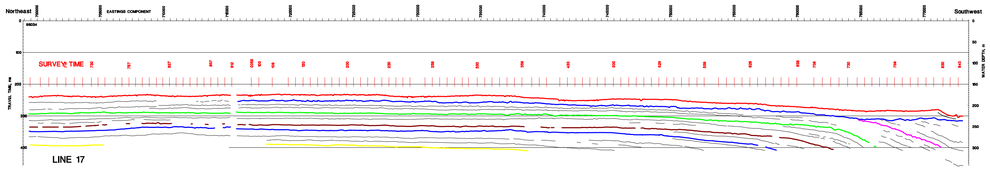

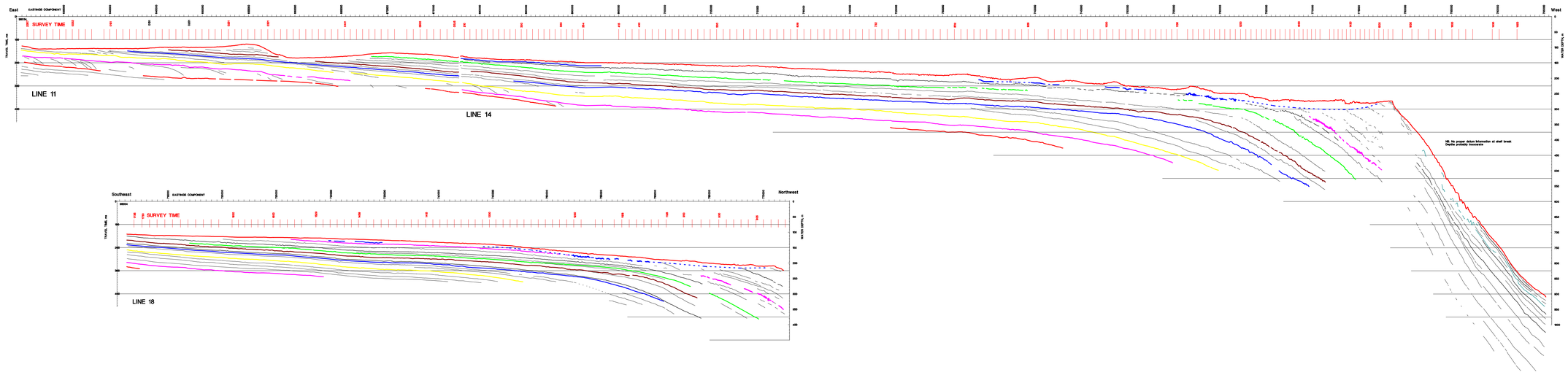

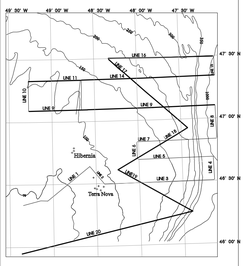

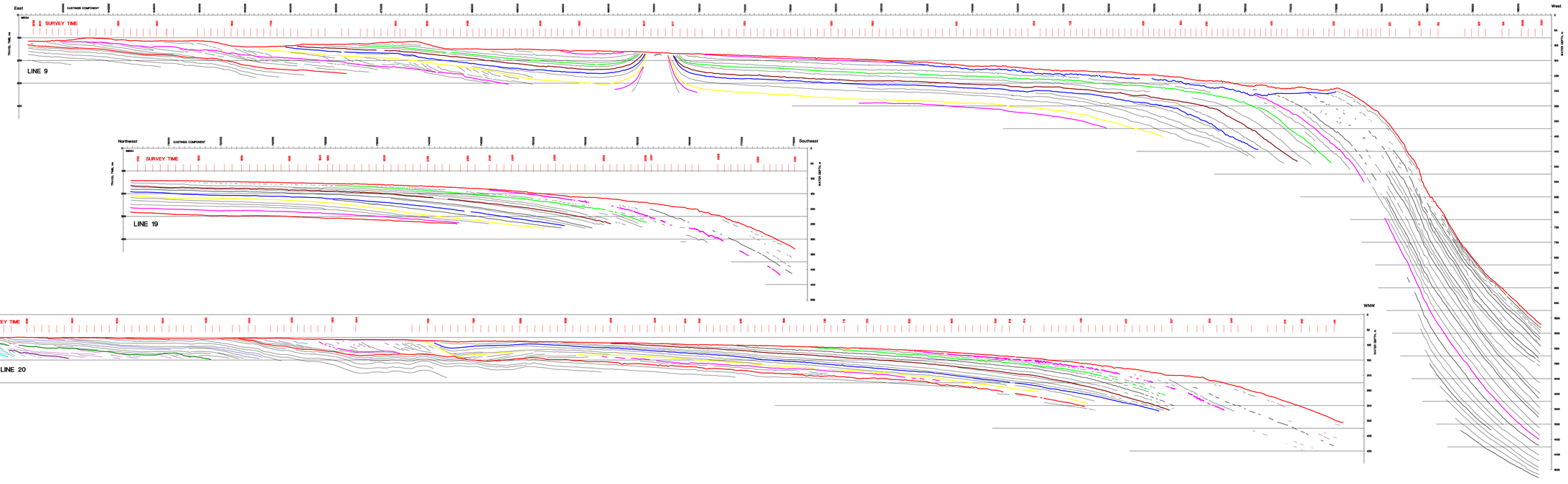

This Enclosure part of:
Nearsurface Characterization of 1998 Seismic Reflection Data
Contract to GSC-Atlantic 23420-8-M502 and amendment

Colours at top of Unit correspond with same colours in profiles			Unit Description/Interpretation
			Glacial-dominated deposits moraines, till-deltas, till blanket, undifferentiated pre-glacial sediments
			UNCONFORMITY
Banquereau Formation	1	Undifferentiated	Shelf edge progradation thick, multi-phased shelf progradation and mass wasting
			UNCONFORMITY
		D	Shelf edge progradation thin, multi-phased progradation due to sparse data coverage
			UNCONFORMITY
		C	Shelf aggradation, shelf-edge progradation
			UNCONFORMITY
		B	Shelf aggradation, shelf-edge progradation
			UNCONFORMITY
		A	Shelf aggradation, shelf-edge progradation locally dissected surface, total backward progradation
			UNCONFORMITY
	2	B	Extensive Progradational body and distal equivalents multi-phase lobes with high-angle, delta-like foresets
	2 thinner beds	A	Extensive Progradational body and distal equivalents multi-phase lobes occasionally with low angle foresets
			UNCONFORMITY
	3	B	Parallel to slightly splaying aggradational beds downlap on top of Unit 3a
			UNCONFORMITY
		A	Parallel to slightly splaying aggradational beds low relief, top of western bulge
	4	B	Shelf aggradation to progradation occasional low angle delta-like foresets and distal equivalents
			UNCONFORMITY
		A	Progradational body steep delta-like foresets and distal equivalents

Scale
0 2 4 6 8 10
Kilometres

Geological Survey of Canada
Atlantic

KING GEOLOGICAL MARINE CONSULTING

Northeast Grand Bank
Selected Geologic Profiles
Cruise 98-034

DATE: Feb., 1998	GEOLOGIST: Edward L. King	
PROJECTION: UTM Zone 22 CM 51°W		SCALE: 1: 200 000
ENCL: 2A	DRAWN BY: E. King	KING GEOL. PROJ:98-03

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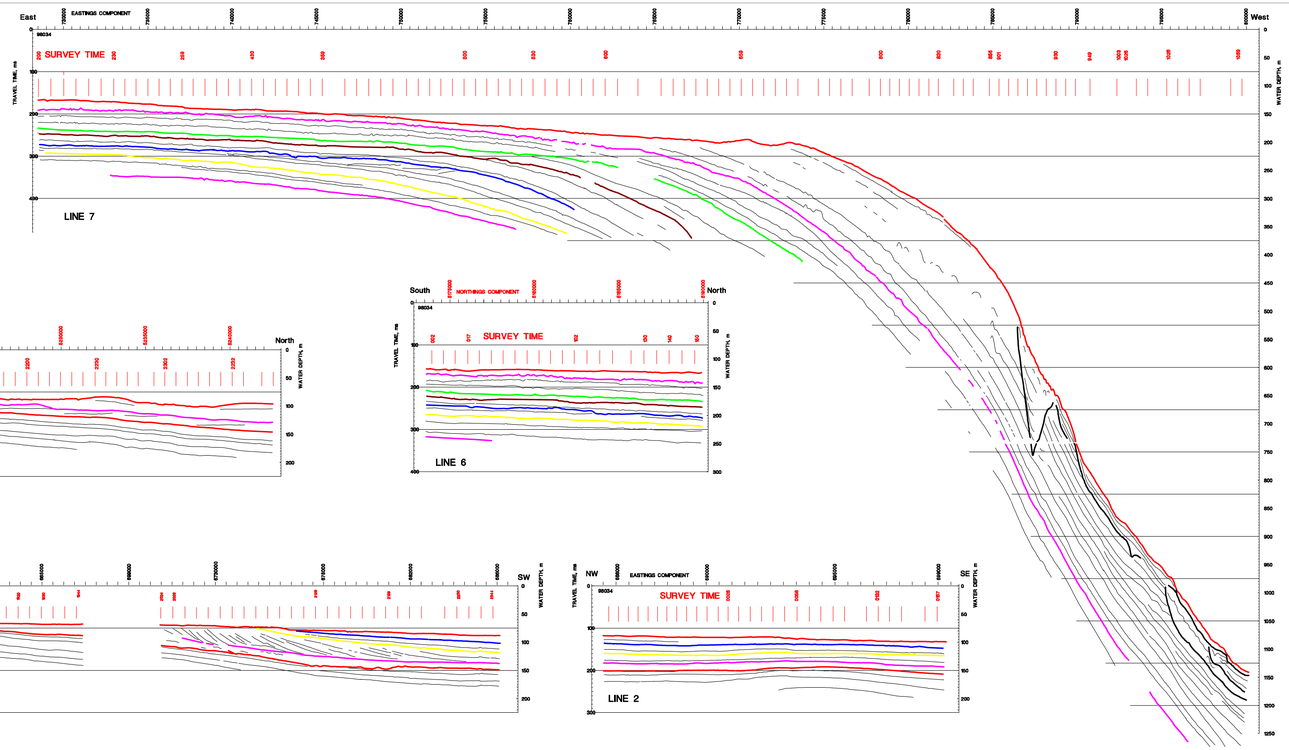

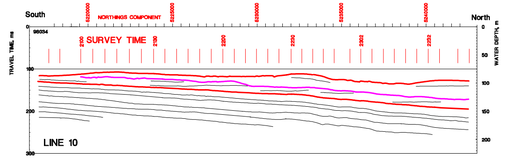

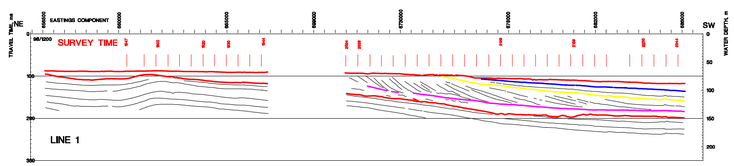

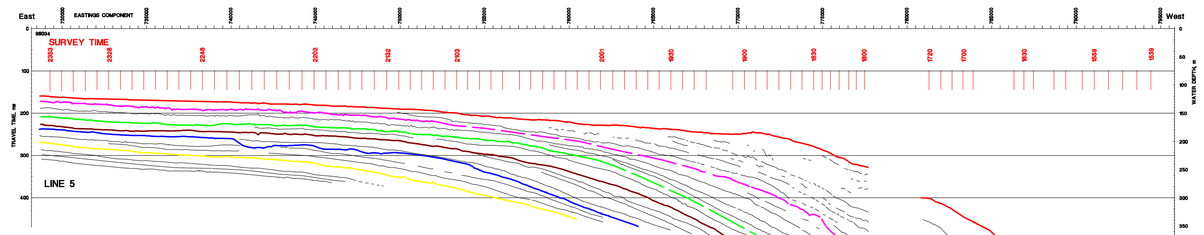

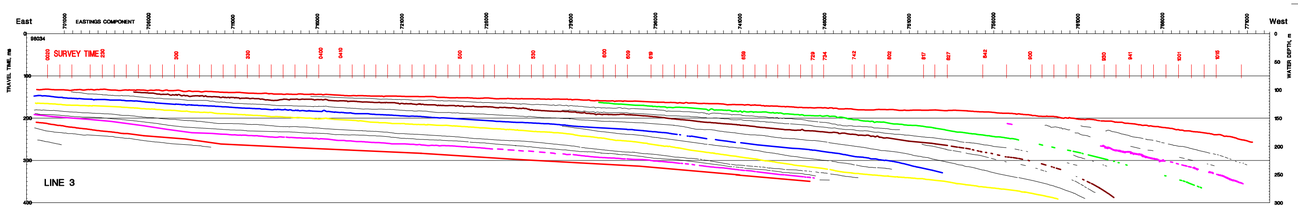

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3886

SHEET 3 OF 5

Recommended citation: King, E.L. 1999. Characterization of near-surface seismostratigraphy and features of Northeastern Brand Bank: Sea level fluctuations, glaciation and slope stability. GSC Open File No.3886, Oct. 1999.

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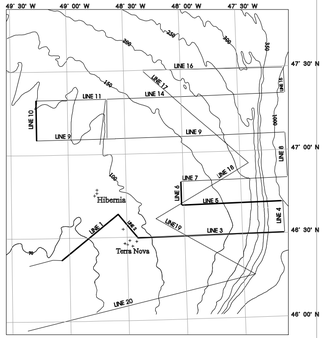


Colours at top of Unit correspond with same coloured reflectors in profile			Unit Description/Interpretation
Barquereau Formation			Glacial-dominated deposits moraines, till-debris, till blanket, undifferentiated pro-glacial sediments
			UNCONFORMITY
	1	Undifferentiated	Shelf edge progradation thick, multi-phased shelf progradation and mass wasting
			UNCONFORMITY
	1	D	Shelf edge progradation correlations impredise due to sparse data coverage
			UNCONFORMITY
	1	C	Shelf aggradation, shelf-edge progradation
			UNCONFORMITY
	1	B	Shelf aggradation, shelf-edge progradation
			UNCONFORMITY
	1	A	Shelf aggradation, shelf-edge progradation locally dissected surface, local backward progradation
			UNCONFORMITY
	2	B	Expansive Progradational body and distal equivalents multi-phase lobes with high-angle, delta-like foresets
			UNCONFORMITY
	2	A (Alberta Delta)	Expansive Progradational body and distal equivalents multi-phase lobes occasionally with low angle foresets
			UNCONFORMITY
	3	B	Parallel to slightly splaying aggradational beds downlapping on top of Unit 3a
			UNCONFORMITY
	3	A	Parallel to slightly splaying aggradational beds low angle foresets at western end
			UNCONFORMITY
	4	B	Shelf aggradation to progradation occasional low angle delta-like foresets and distal equivalents
			UNCONFORMITY
	4	A	Progradational body steep delta-like foresets and distal equivalents

This Enclosure part of:
Nearsurface Charcterization of 1998 Seismic Reflection Data
Contract to GSC-Atlantic 23420-8-M502 and ammendment

Scale

0 2 4 6 8 10

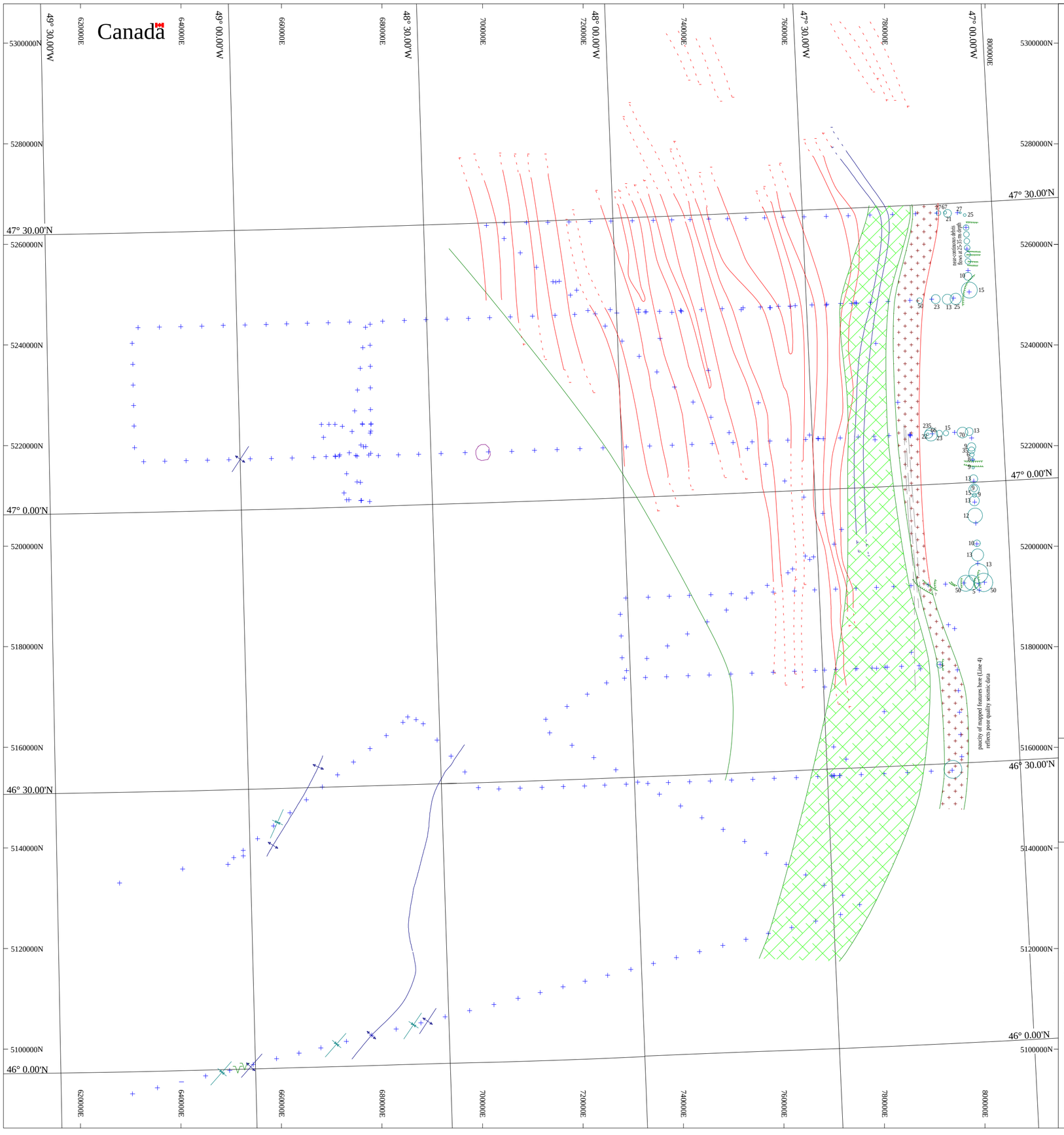
Kilometres

Geological Survey of Canada
Atlantic

King Geological
Marine Consulting

Northeast Grand Bank
Selected Geologic Profiles
Cruise 98-034

DATE: Feb., 1998	GEOLOGIST: Edward L. King	
PROJECTION: UTM Zone 22 CM 51°W		SCALE: 1: 200 000
ENCL: 2B	DRAWN BY: E. King	KING GEOL. PROJ:98-03



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OTTAWA
3886

SHEET 4 OF 5

LEGEND

Ships Track (98-034)
-half-hour fixes

Syncline and anticlines in Unit 3
-trends assumed unless extended axial trace shown
-extended traces based largely on coverage from previous surveys (94-021)

Trace of sharp inflections in strata
-Possible faults

Shelf-edge "till delta"
-small scale progradation with landward-tilting upper surface
-interpreted as a near-margin sub-glacial feature

Moranic ridges. Trace of flanks of sharp inflections in strata lines trace ridge flanks; dotted lines are assumed extrapolations line to line correlations considerably enhnased using bathymetric chart

Zone of little continuity in sub-bottom strata (above Unit 1d)
-Occasional high-relief features (buried) suggest abundant mass failure

Zone of surficial disturbance (relief of several metres)
-Probably related to intensive iceberg scour
-Probably associated surficial slumping

Trace of significant seabed profile inflection and apparent truncation of moraines
-Probably related to pre-Late Wisconsinan low sea level stand

Salt diapir
north-south extent unknown

Buried channels incised into top Unit 4
(On line 20; see geologic profiles)

Buried slide scar (headwall) on slope
-orientation assumed except where crossed by two survey lines

Buried debris flow body (homogeneous internal seismic signature)
-commonly lensoid in strike section
-ocassionally exhibit basal erosion
-generally occur at distinct stratigraphic horizons
-Depth to top of feature, in ms below seabed
-diameter represents length of flow intersected along line

Surficial and buried erosional valleys
-probably canyon-like development
-ocassionally mapped as unpaired scarps
-may be larger scale slide failures

MOST FEATURES ILLUSTRATED IN GEOLOGIC SECTIONS OR AS SEISMIC SECTIONS IN REPORT

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This Enclosure part of:
Nearsurface Charcterization of 1998 Seismic Reflection Data
Contract to GSC-Atlantic 23420-8-M502 and ammendment

Scale
0 2 4 6 8 10 15 20
Kilometres

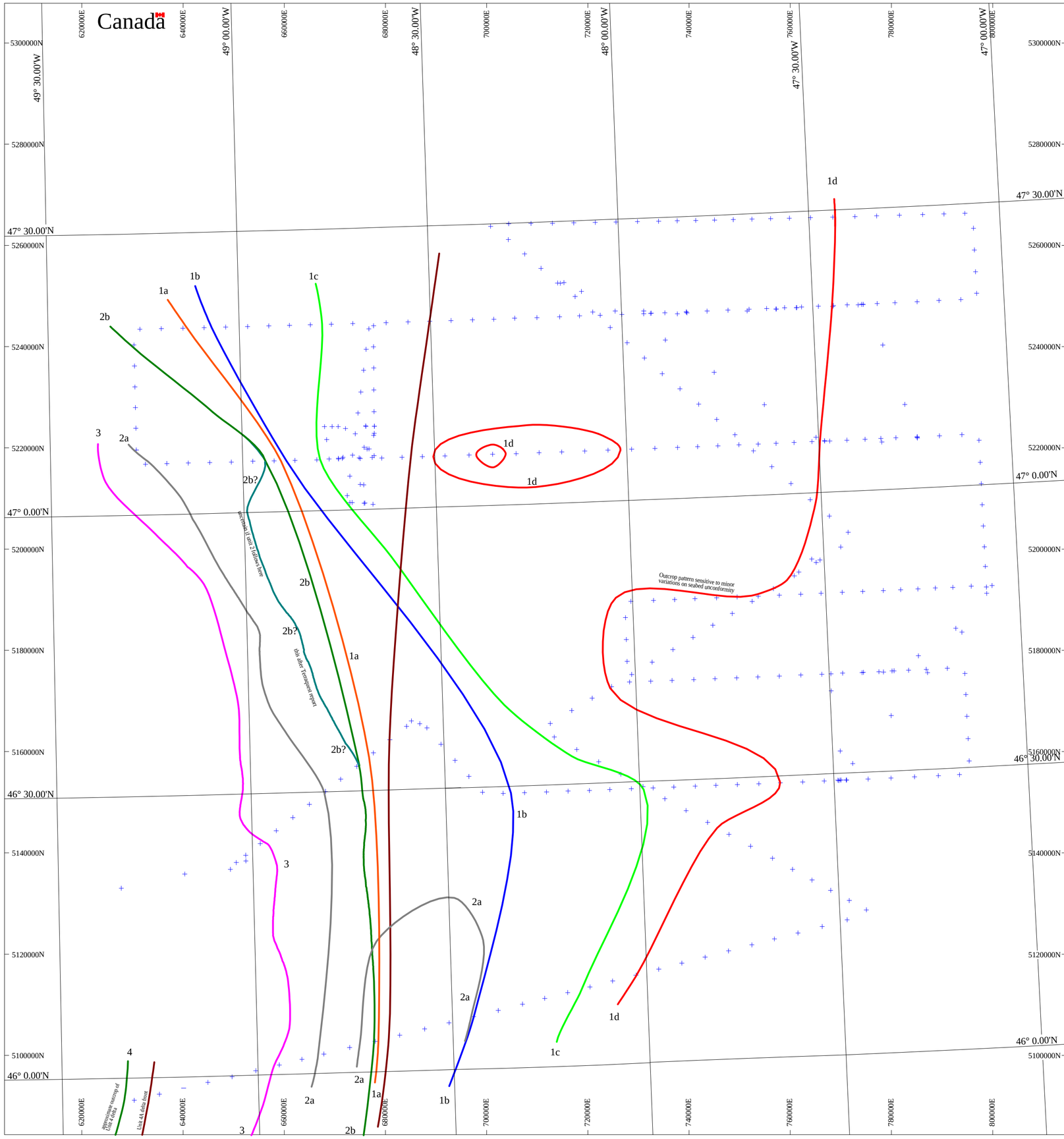
Geological Survey of Canada
Atlantic

KING GEOLOGICAL MARINE CONSULTING

Northeast Grand Bank

Geologic Features
Surficial and Buried

DATE: Feb., 1998	GEOLOGIST: Edward L. King		
PROJECTION: UTM Zone 22 CM 51°W		SCALE: 1:600,000	
ENCL: 3	DRAWN BY: E. King	KING GEOL. PROJ: 98-03	



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LEGEND

- 1d — Unit 1d Outcrop pattern (position locally imprecise reflecting poor correlations due to sparse data coverage on outer shelf)
- 1c — Unit 1c Outcrop pattern
- 1b — Unit 1b Outcrop pattern
- 1a — Unit 1a Outcrop pattern
- 2a — Unit 2a Outcrop pattern; Subcrop trace of distalmost delta clinoforms
- 2b — Unit 2 Outcrop pattern
- 3 — Unit 3 Outcrop pattern
- 4 — Unit 4 Outcrop pattern; Subcrop trace of distalmost delta clinoforms

Outcrop patterns are locally subcrop below glacial deposits

CRUISE 98-034 TRACK

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Scale
0 2 4 6 8 10 15 20
Kilometres

Geological Survey of Canada
Atlantic

King Geological Marine Consulting

Northeast Grand Bank
Outcrop/Subcrop Patterns
of selected
Unconformity Horizons

DATE: Feb., 1998	GEOLOGIST: Edward L. King	
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ENCL: 4	DRAWN BY: E. King	KING GEOL. PROJ: 98-03