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Abstract: High-resolution geophysical surveys of northern Grand Bank document sea-level fluctuations and an extensive glaciation. Multiple erosion-bounded progradational and aggradational sediment packages include two clinoform bodies deposited during the late Cenozoic as bank spillover rather than from glacial meltwater. A change from aggradation to shelf-break progradation with oversteepening and sediment failure apparently reflects increased sediment flux in the Pliocene–Pleistocene. A pervasive near-surface glaciogenic blanket interpreted as mainly till and related recessional moraines are evident to 400 m water depth. This represents the only clear evidence for glaciation extending to the shelf break. Abrupt truncation of the moraines in the southwest may indicate a pre-Late Wisconsinan transgression that eroded the till above about 160 m water depth leaving only remnants shallower than this. A Late Wisconsinan glaciation is not ruled out. Localized occurrences of hardground, likely relating to subaerial exposure, may be widespread above 160 m water depth.

Résumé : Des levés géophysiques à haute résolution effectués dans la partie nord du Grand Banc attestent de fluctuations du niveau de la mer et d'un englacement généralisé. Parmi la multitude d'ensembles de sédiments de progradation et d'aggradation dont les limites sont définies par des surfaces d'érosion, on en distingue deux qui sont caractérisés par des surfaces progradantes et qui se seraient déposés au Cénozoïque tardif sous forme de dépôt débordement de banc plutôt que par l'action d'eaux de fonte glaciaires. Le passage d'un régime d'aggradation à un régime de progradation de la bordure de la plate-forme continentale qui a eu pour conséquence d'augmenter l'inclinaison de la pente du talus et de déclencher des glissements de terrain témoigne d'une augmentation de l'apport de sédiments au Pliocène–Pléistocène. Jusqu'à des profondeurs d'eau de 400 m, on peut reconnaître une nappe de sédiments glaciogéniques généralisée, enfouie à faible profondeur sous la surface, qui serait composée surtout de till et de moraines de retrait apparentées. Cet élément est le seul témoin manifeste de l'extension de la glaciation au-delà de la bordure de la plate-forme continentale. Vers le sud-ouest, la terminaison abrupte des moraines témoigne probablement d'une transgression antérieure au Wisconsinien supérieur. Cette transgression aurait érodé le till qui était présent au-dessus d'une profondeur d'eau d'environ 160 m et n'aurait laissé que des lambeaux d'érosion dans les zones moins profondes. La possibilité d'une glaciation au Wisconsinien supérieur ne peut être éliminée. La présence localisée de surfaces de sol induré, qui seraient probablement associées à une exposition subaérienne, est peut-être commune au-dessus d'une profondeur d'eau de 160 m.

INTRODUCTION

In 1998 and 1999 GSC Atlantic undertook reconnaissance geophysical and geological surveys to the east and north of the Jeanne d'Arc Basin and into Flemish Pass (Fig. 1) in order to extend a geological framework developed for the near-surface sediments of the Jeanne d'Arc Basin across the shelf break. Our goal was to assess the presence and characteristics of seabed geohazards, information required by both regulatory bodies and petroleum engineers to ensure safe, cost-effective development of offshore resources. The new data have provided key insights into the role of Quaternary glaciation and sea-level fluctuation on sediment distribution and characteristics, as well as on difficult soil conditions encountered in recent construction of oil field facilities. This knowledge will improve our ability to predict sediment conditions in areas of future oil and gas development and to extrapolate these findings more regionally.

Reconnaissance geophysical profiles totaling 2500 km were collected aboard *CCGS Hudson* in 1998 and 1999 (Fig. 1). The two expeditions connect a relatively dense pattern of seismic-reflection data on the bank (Sonnichsen et al., 1994) to much sparser coverage across newly announced petroleum lease blocks in Flemish Pass. Two simultaneously towed profiling systems helped resolve the near-surface geology. Single-channel seismic reflection data from two 10 cubic inch sleeveguns provided penetration to a maximum of about 500 m below seabed with reflector resolution of

approximately 5 m. Huntect (DTS™) sparker profiles provided high resolution (<0.3 m) and penetrated more than 50 m on the slope but often less on the bank.

In this paper, we describe new insights and introduce models for sea-level fluctuations and Quaternary glaciation on Grand Bank. Some of the engineering implications will be discussed.

REGIONAL SETTING

Grand Bank is the largest and easternmost of six banks off Newfoundland, separated from the island by Avalon Channel. The northeastern part of Grand Bank dips gently to the east and northeast to a shelf break at about 220 m water depth in the south and over 350 m in the north. To the east, Flemish Pass is over 1000 m deep and separates Grand Bank from Flemish Cap (Fig. 1). Our understanding of the near-surface seismostratigraphy has evolved from regional geological descriptions (Fader and King, 1981; Fader and Miller, 1986) to characterizations more focused on shallow foundation conditions within the Jeanne d'Arc Basin (Lewis et al., 1987; Taylor et al., 1993; Sonnichsen et al., 1994, Sonnichsen and Cumming, 1996). The shallow (upper 200 m) subsurface geology of Grand Bank is dominated by near-parallel, very low-angle seaward-dipping ($\sim 0.1^\circ$) reflections of the Banquereau Formation which are truncated near the seabed (Lewis et al. 1987). Sonnichsen and Cumming (1996) described a simple three-unit stratigraphy for the upper 100 m of the Jeanne d'Arc Basin consisting of wedge-shaped

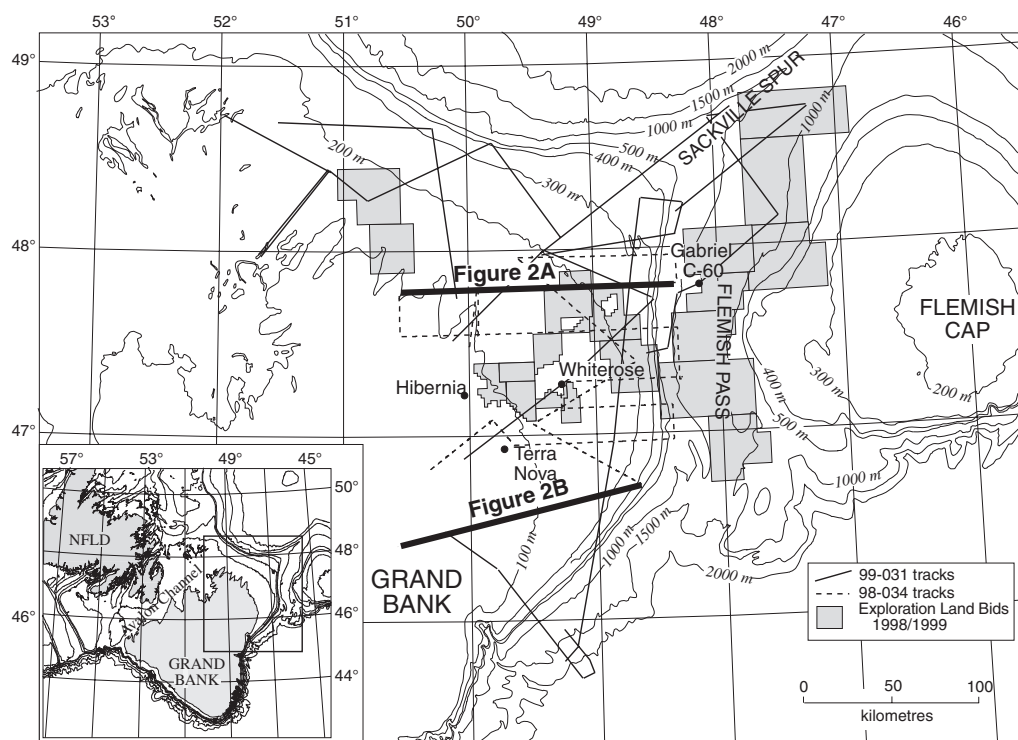


Figure 1. Location of well sites, seismic tracks, and Figure 2 profiles.

sequences of progradational clinoforms (unit 2) which separated younger and older reflectors above (unit 1) and below (unit 3). The unit 2 clinoform body subcrops below thin surficial sands west of Hibernia and dips eastward below unit 1 for tens of kilometres. It extends 200 km from north to south, locally reaching over 100 m thickness (Terraquest Associates, 1995). Its origins have been attributed to glacial erosion and deposition during a low sea-level stand of unknown Quaternary age (Sonnichsen and Cumming, 1996). Both the underlying unit 3 and overlying unit 1 consist of subparallel or slightly splaying, near-continuous east-northeast-dipping reflections. They represent 'normal' shelf aggradation but local unconformities were attributed to sea-level changes (Mosher and Sonnichsen, 1992). Unit 1 was thought to represent a gradual transition from the proglacial sedimentation of unit 2 to normal marine aggradation and progradation. Correlations of the seismic data with several boreholes are compatible with the broad aspects of the seismostratigraphy (Mosher and Sonnichsen, 1992; Stoffyn-Egli et al., 1992; Taylor et al., 1993). The prominent angular unconformity which truncates these units at or just below the seabed across much of Grand Bank has been attributed to a 15 ka low sea-level stand at 100–110 m (Barrie et al., 1984; Fader and Miller, 1986).

The effects of glaciation on outer Grand Bank have been recognized on the basis of the distribution of surficial cobbles and boulders of Avalonian affinity, buried and infilled glacial valleys, 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 Wisconsin glacial remains unclear.

REFINED REGIONAL SEISMOSTRATIGRAPHY

The new data allowed a more detailed subdivision of the Sonnichsen et al. (1994) stratigraphic units and identified new units below unit 3 and above unit 1 (E.L. King and G.V. Sonnichsen, unpub. report, 1999). A brief description of the new units (unit 4 and units postdating unit 1) and revisions follows.

Unit 4 (Fig. 2B) is a 50 m thick, seaward-dipping progradational body with lower angle distal equivalents. It includes clinoform progradational packets with internal downlapping, unconformities, and both steep and shallow foresets; the unit is remarkably similar to unit 2 located to the east and about 100 m higher in the section (Fig. 2B). With only one seismic transect, its distribution is unknown. The unit 4 surface is eroded and, locally, small channels attest to subaerial exposure.

The overlying unit 3 is characterized by subparallel, relatively closely spaced and high-amplitude reflections (Fig. 2). A subtle mid-section unconformity allows separation into a and b subunits and a distinct angular unconformity defines its top. A surface roughness, interpreted as small erosional incisions, extends along this horizon to at least 260 m (below sea level). Unit 3 outcrops west of the Hibernia and Terra Nova discoveries. It strikes to the northwest in the north and south-southwest in the south. Units 3 and 4 have undergone mild folding over the Jeanne d'Arc Basin in contrast with the overlying units.

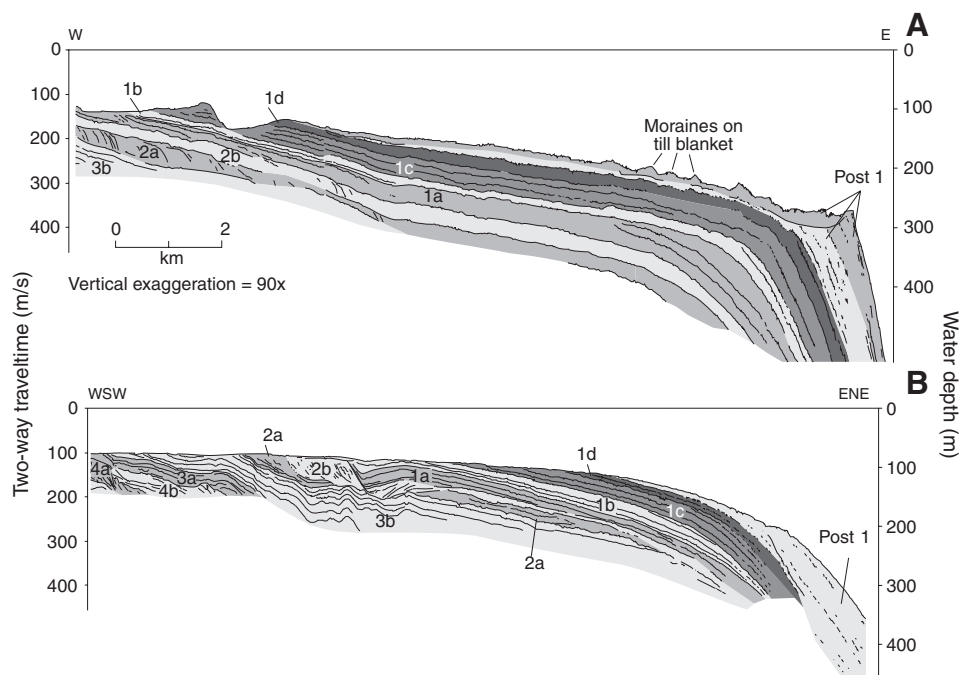


Figure 2. Geological sections interpreted from seismic profiles (location, Fig. 1).

Unit 2, a large clinoform progradational body, is now recognized as extending north to 47°40' and south more than 200 km. It is 35 km wide in the south, ranging to over 65 km in the north. While the clinoforms extend to over 300 m depth below sea level, its distal, more aggradational equivalents can be traced to depths over 500 m (E.L. King and G.V. Sonnichsen, unpub. manuscript, 1999). Two subunits, a and b, separated by a depositional hiatus and local erosion, represent two prograding phases (Fig. 2). To the north, the two subunits are clearly distinguished as two broad and relatively thin (20–30 ms) prograding bodies. There appears to have been a modest migration of the depocentre from one phase to the next. The volume of the more-aggradational proclinoform deposit (though not calculated) is at least that of the clinoform body so its simple classification as including a delta and its distal equivalents is perhaps oversimplified. Unit 2 was deposited during a low stand of sea level, but whether this was synchronous with glaciation is discussed later.

Unit 1 exhibits medium- to high-amplitude, highly continuous, parallel or splaying reflections with subtle angular unconformities which were identified by Mosher and Sonnichsen (1992). The new, more regional data set provides the basis for subdivision into four regional unconformity-bound subunits a to d (Fig. 2) separated by horizons with angular relationships near a paleoshelf break. Each of the unit 1 subunits displays a modest eastward thickening shelf aggradation (15–35 m thick) and marked thickening at a clear paleoshelf break, beyond which unit 1 exceeds 250 m thickness. The horizon at the top of unit 1a has the most clearly dissected nature (down to present water depths of 270 m) while the tops of units 1c and d may be associated more with a transition from shelf aggradation to paleoshelf progradation than with erosion. Either case represents a significant change in sedimentation processes.

Sediments postdating unit 1 show three distinct changes in depositional style (Fig. 2) including early shelf-break progradation, a slope-situated increase in the incidence of mass failure, and a shelf-situated glaciogenic surficial cover (discussed in the next section). Lower deposits postdating unit 1 display much less continuity (rough bed surfaces) in seismic reflection character than underlying unit 1 deposits. The unit becomes better stratified at mid-slope and lower slope depths. This is attributed to small- to medium-scale failures which almost completely obliterate reflector continuity, possibly related to the trend toward progressively steeper paleoslopes. Also in contrast to unit 1, the upper slope deposits postdating unit 1 form a 'bulge' with a convex seabed profile (Fig. 2A) suggesting enhanced shelf-break deposition as opposed to more dispersive shelf sedimentation processes observed in earlier units.

A greater frequency of medium-scale, mass-failure features occurs in the upper 150 m of deposits postdating unit 1 on the mid-slope to lower slope below 450 m water depth (Fig. 2A). These are characterized by buried failure scarps, valleys, and numerous lenticular bodies with a constructional but internally homogeneous seismic character in contrast to surrounding stratified sediments. They are interpreted as the depositional lobes of debris flows. These were identified by

Piper and Pereira (1992) who recognized a crude stratigraphic periodicity to their occurrence. Other failure features include open and filled channels and/or canyons and lower slope diapir-like features (Piper and Pereira, 1992; E.L. King and G.V. Sonnichsen, unpub. report, 1999).

SHELF GLACIAL SEDIMENTS

Till blanket

In uppermost deposits postdating unit 1, a subtle unconformable relationship between 10 and 30 ms depth below seabed across the northeastern study area indicates the presence of a surficial cover unit. The angularity of the unconformity is best evident on the outer shelf (Fig. 2A). The erosional surface rarely gives rise to a reflector so the unconformity is usually defined by the truncation of older unit 1 strata. The surficial blanket is largely restricted to the northeast where its thickness exceeds 25 m (Fig. 3B). It may be present in water depths less than about 120 m but here the near-parallel nature of the seabed to the underlying strata and their similar interbed acoustic character precludes recognition of its base. In contrast, it is largely absent where unit 1 and 2 strata extend up to the surficial sand and gravel south and west of the Terra Nova site.

The surficial blanket unit is interpreted as predominately till based on several observations and associated inferences. The large 'IKU' type grab sampler was unsuccessful in recovering much more than gravel and cobbles but their varied lithology includes long-transported Avalonian rocks. The consolidated nature of the sediment, the gravel-cobble armour, and a greater preserved iceberg scour incision depth compared with those in surficial sands suggests a stiff, cohesive consistency, common in glaciogenic sediment. The acoustic character (on sparker profiles) is amorphous and incoherent, a common characteristic of till (though not diagnostic). The upper surface forms a series of long, continuous ridges interpreted as moraines superimposed on a continuous till blanket. Finally, the angular unconformity at the base of this glacial unit indicates substantial (locally tens of metres) erosion and a near shelf-edge overdeepening (Fig. 2A).

Moraine field

A series of subtly elevated seabed mounds on the till (Fig. 2A, 3C) in the northeastern study area can be correlated between seismic profiles with the benefit of regional bathymetric control. This indicates a series of linear and bifurcating ridges whose pattern suggests a field of recessional moraines (Fig. 3A). The morphology of the northern ridges is best developed with relief of 10–15 m (Fig. 2A) while the southern extremities have elevations only as high as 2 m. In the deeper water they exhibit a rough surface relief due partially to the presence of superimposed iceberg scours. The moraines have little sedimentary cover, commonly with only partial infilling of the iceberg scour troughs.

The moraine field is conspicuously truncated at its southwest margin (Fig. 3A). Though it is possible that the glacial regime was such that no moraines ever developed, it seems

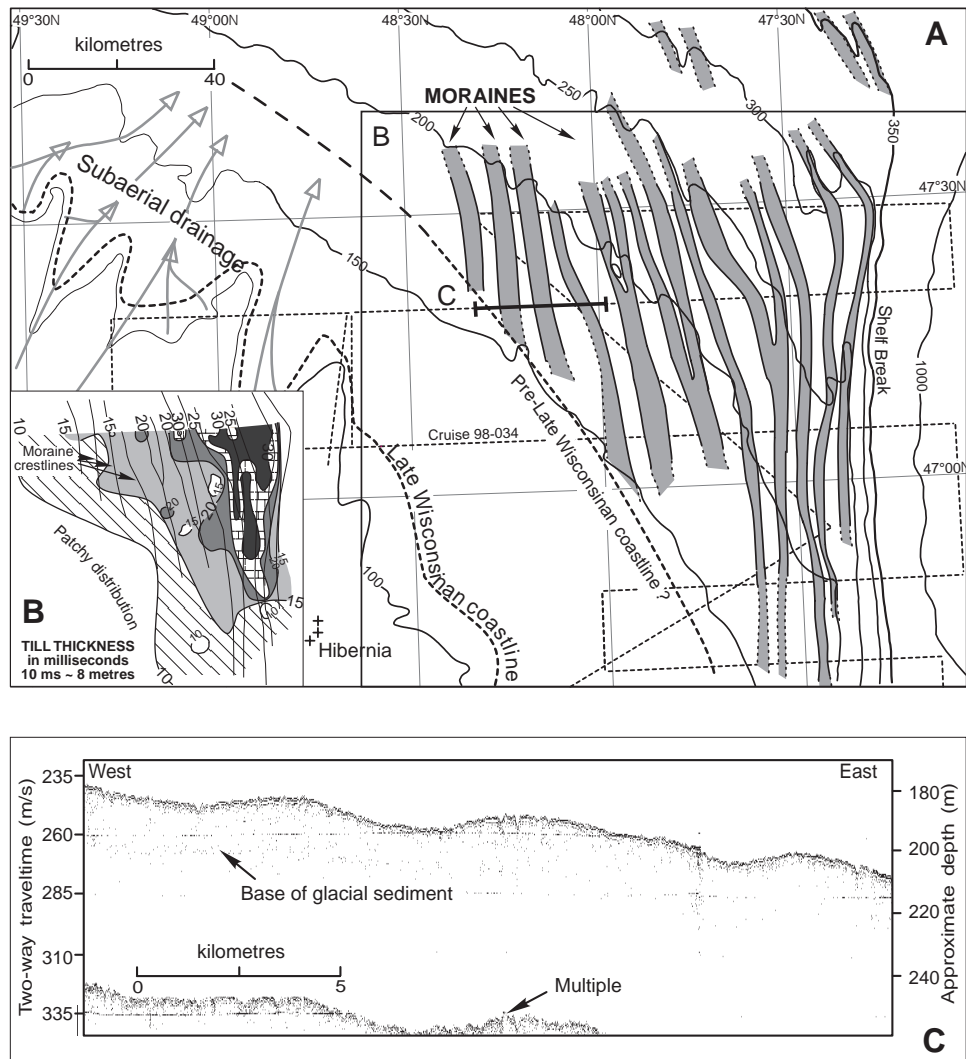


Figure 3. Surficial elements of northeast Grand Bank; **A)** moraines, paleocoastlines, and valleys, **B)** till blanket thickness, and **C)** high-resolution sparker profile across the moraines.

unlikely in light of the extreme continuity of the outer shelf ridges. The seismic profiles also show a thinning and eventual (but not well defined) pinchout of the till blanket along this margin (Fig. 2A). The truncation coincides with water depths of 150–170 m (Fig. 3A). The truncation is considered erosional. There is also a transition from a rough or rolling topography on the moraine field to a smoother seabed in shallower water to the west, commonly with an associated inflection in the general seabed profile.

DISCUSSION

Lower geological section — units 1 to 4

The seaward-dipping section below the near-seabed unconformity across much of middle to outer areas of Grand Bank was originally designated Tertiary, based largely on integration of well and seismic data south of here (King and MacLean, 1975; Fader and King, 1981). Later efforts in the

Hibernia area (unit 2) indicated glacial erosion and proglacial meltwater deposition rather than fluvial processes to account for the widespread, rapid deposition of sand within unit 2 (Sonnichsen et al., 1994; Parrott et al., 1995; Sonnichsen and Cumming, 1996). A mid-Pleistocene (or younger) age was suggested, citing the microfaunal assemblage and a horizon yielding a “young” amino acid racemization (Miller et al., 1992; Miller, 1999). However, the presence of unit 4 confirms that large-scale progradational processes were not a temporally isolated phenomenon. Given the similarities in geometry and internal reflection character with unit 2, deposition was likely under similar conditions. These two bodies are widely separated in time considering not only their stratigraphic separation but also the mild folding in intervening unit 3 and widespread erosion at its top.

In their study of slope features and geological history in Flemish Pass, Piper and Pereira (1992) recognized a mid-Miocene unconformity (F' in their Fig. 2) and overlying Pliocene–Pleistocene sediments (Gradstein, 1981) in the

Gabriel C-60 well situated at the base of the slope (Fig. 1). Preliminary seismic correlations suggest that this mid-Miocene unconformity projects landward to either the top of unit 2 or 3. The latter exhibits the most marked erosion. This tentative correlation implies an early Miocene or considerably older age for unit 4 clinoforms and presumably a nonglacial origin. This diminishes the likelihood of a glacial origin for the younger unit 2 clinoform body, assuming its similar genesis. A shallow-water environment of deposition is inferred, possibly a long-lived or multistage, bank spillover phenomenon, with subsequent subsidence. A late Tertiary age is suggested for units 2 to 4 and this is supported by a late Pliocene palynological marker (Peta Mudie, pers. comm., 1990 in Piper and Pereira, 1992) in geotechnical borehole samples from unit 2. However this remains unreconciled with other indications of a much younger age (Miller, 1999).

Subtle angular unconformities in units 1 and 2, previously identified in the shallow subsurface (Mosher and Sonnichsen, 1992), are now recognized as having a region-wide distribution warranting a further stratigraphic subdivision of the bounding units, especially in unit 1. The unconformities are interpreted as low-stand phenomena but the relative influence of fluvial, marine transgression, or glacial erosion is difficult to ascertain. A 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. These incisions contrast with a dense network of glacial tunnel valley-type features located well to the west of the study area (Fader and Miller, 1986; E.L. King and G.B.J. Fader, unpub. report, 1999). However, with the exception of the erosional surface below the surficial till blanket, all features can result from marine processes without the need to invoke glacial erosion. Depositional features suggestive of processes other than 'normal' marine are absent. Low-stand erosion is therefore the preferred mechanism for the formation of the regional unconformities. Phenomena such as regional splaying indicate tectonic tilting to the north which must also influence present-day depth distribution of the unconformities.

The Pliocene–Pleistocene boundary is not recognized in the area and neither the sediment signal nor the timing of the initial onset of glaciation are clear. Sediments postdating unit 1 mark a change in depositional style and may signal general climate deterioration and elevated sediment flux. The presence of the mid-section change (to frequent mass failure) could mark a more direct influence from nearby ice or sea-level fluctuations. Only one record of ice sheet advance to the shelf break (with basal erosion and till) is preserved.

Shelf glaciation

The moraine field provides proof of an ice sheet extending to the edge of northeastern Grand Bank yet its timing is uncertain. King and Fader (1992; E.L. King and G.B.J. Fader, unpub. report, 1999) suggest that Late Wisconsinan maximum ice reached the shelf break through a large cross-shelf trough 200 km to the northeast (beyond a dated ca. 15 ka mid-shelf moraine). They also recognized a north- and east-flowing ice lobe emanating from central or west-central Grand Bank, presumably of Late Wisconsinan age, but it is

unclear if it represents the maximum extent. Shelf-edge ice was also maintained until late Late Wisconsinan time on the banks south of Newfoundland (Moran and Fader, 1997; Miller, 1999). The present seabed exposure of the moraines might suggest formation by the latest glaciation but outer shelf and slope sedimentation is minimal and sediment bypass may have occurred since their formation. This introduces the possibility of a pre-Late Wisconsinan age. Flemish Pass and slope studies (Piper et al., 1990; Piper and Pereira, 1992) demonstrate little Late Wisconsinan sedimentation and infer an Early Wisconsinan (or older) shelf-break ice extent.

Lacking direct dates from overlying sediment, information pertaining to the age of the moraine field is in the apparent erosional truncation at their southwestern margin. The erosion resulted either from marine or subsequent glacial sheet erosion. Glacial erosion is less favoured because it is unlikely that the field could be overridden (or partially so) without simultaneously having some superimposed depositional record. The preferred mechanism for partial removal of the moraine field is by coastal processes and subsequent transgression. The latest (Late Wisconsinan–Holocene) low stand is well documented (Barrie et al., 1984; Fader and Miller, 1986) at 105–110 m present water depth (Fig. 3A). However, truncation of the moraines occurred 40 km seaward and 40–60 m deeper than the -105 m low stand. Assuming wavebase erosion was incapable of moraine removal, because of the expected development of a coarse protective lag, then an earlier low stand at -160 m associated with a previous glaciation or glacial stage is implied. As this exceeds the eustatic low stand, an appropriate period of subsidence must be invoked. The moraines would be older or penecontemporaneous. Enigmatic deep (40 m) and broad (20 km) erosional valleys exposed at the seabed between 85 m and 160 m water depth well west of the moraine field (Fig. 3A) can then be explained by fluvial processes during such a low stand.

An alternative age and/or process scenario is possible whereby a Late Wisconsinan shelf-break ice extent followed by retreat to a mid-shelf still stand results in an associated landward migrating glacial peripheral bulge. Transgression of the bulge and wavebase erosion can also account for many of the observations (E.L. King and G.V. Sonnichsen, unpub. report, 1999). A definitive age for the moraine-till cover requires further study.

ENGINEERING IMPLICATIONS: COHESIVE TILLS, BOULDERS, AND HARDGROUND

The presence of a near-surface till blanket on parts of northeastern Grand Bank below approximately 120 m water depth has been demonstrated but where it thins to less than 7 m or 8 m toward the southeast its recognition from seismic reflection profiles is ambiguous. This includes the area of proposed subsea developments for the Whiterose and Terra Nova discovery sites. We assume a degree of original continuity of this till blanket into shallower water and suggest that the same erosional mechanism which destroyed the moraines in deeper areas acted to remove the top of the till blanket above 120 m water depth. Here the cumulative affect of coastal and

transgression processes from both low stands would have been greater. Limited undercutting on this flat surface would lead to development of a protective lag, effectively impeding complete till removal. Thus, a thin or patchy remnant till cover between approximately 100 m and 120 m water depth is likely. This conclusion remains valid regardless of the erosional mechanism and the speculation regarding a deep-water pre-Late Wisconsinan coastline. Recent engineering operations at the Terra Nova site (Fig. 1) have indeed identified boulders and cohesive clay matrix (probably till) up to several metres below the seabed (G. Lever, pers. comm., 1999, Terra Nova Alliance). In progressively shallower water, transgression following the low stand(s) could have allowed more complete reworking and removal of the fine-grained sediment. A till blanket and its remnants substantiate the inferences of Fader and Miller (1986) who documented shallow-water boulder concentrations which they attributed to glacial transport. In the shallow water, unit 2 and 3 strata generally extend up to the base of loose surficial deposits of the Grand Banks sand and gravel formation (Fader and Miller, 1986) which would largely represent the reworked glacial remnant.

At the Terra Nova site, situated in water depths just above the Late-Wisconsinan low stand, a patchy, massive layer more than 1.5 m thick comprising overconsolidated, weakly cemented granular shelly material (hardground), often described as 'hardpan' in engineering reports, is documented just below the surficial sands and gravels (Sonnichsen and Zevenhuizen, 1996). The hardground has proven problematic to glory hole excavations (Long et al., 1986; Segall et al., 1987; Sonnichsen and Zevenhuizen, 1996). Hardground was most recently encountered in 1999 dredging operations (G. Lever, pers. comm., 1999) apparently overlying the till remnant. Based on our present understanding of history and processes, the hardground could be explained as the product of repeated subaerial exposure and one or a combination of desiccation, meteoric water and groundwater exposure, partial soil profile development, and possibly overconsolidation processes on beach deposits of coarse granular and shell material. Typically the effects of these processes are localized and resulting hardground could be patchy but likely widespread throughout the Jeanne d'Arc Basin area, possibly to water depths of 160 m. It would be best developed in the shallower areas which have experienced more numerous cycles of exposure. Moran et al. (1988) indicate an additional or perhaps alternative genesis through overconsolidation with glacial loading and/or significant removal of overlying strata. This would only apply west of the till blanket coverage or between till patches.

CONCLUSIONS

Shallow sediments on the northeastern area of Grand Bank record cyclic shelf aggradation and progradation controlled by sea-level fluctuations. Large clinoform bodies are interpreted as former shallow-water bank spillover events, rather than glacial meltwater deposits and date back to the Miocene. The age of the younger of these remains problematic.

On the outer shelf and upper slope, thick prograding deposits were built, probably without direct glacial influence. This evolved to a sedimentary record (upper 150 m) on the mid-slope and lower slope dominated by medium-scale mass failures. This might relate to increased magnitude of sea-level fluctuations and sediment flux induced by the intensification of episodes of Pleistocene glaciation.

The most conclusive evidence for a shelf-crossing glaciation is a preserved series of recessional moraines which occur in 160 m to over 400 m water depth. In shallower water, postglacial transgression left only erosional remnants of the associated till blanket which extends to about 120 m water depth, becoming thin and/or patchy above this. The age of this till remains uncertain.

The regional seabed unconformity in the study area represents erosion related to at least one glaciation and one or more sea-level transgressions. Seabed soil conditions for subsea facilities vary with location and water depth related to till distribution and processes of hardground formation.

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