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Geology of the nearshore and coastal Presumpscot Formation from high resolution seismic profiling and vibracores

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ABSTRACT

The Presumpscot Formation is of glaciomarine origin, composed of clay, silt, sand, and scattered gravel. It was laid down approximately 16 cal. ka to 12.5 cal. ka over much of Maine's coastal lowlands, and extends into the deep Gulf of Maine. The offshore record of remote sensing, because of continuous lines, gives a more complete record of the geometry and stratigraphic record than on-land exposures and gravel pits. The Presumpscot Fm. directly overlies bedrock or till in a uniform blanketing manner, concentrically draping underlying structures, a consequence of rapid sediment accumulation rate and less reworking. Three seismic facies subdivide Presumpscot Fm.: 1) GM-M, glaciomarine-massive, which is a near-grounding line deposit, 2) GM-D, having a well-stratified draped character in proglacial basins, and 3) GM-P, with a ponded geometry found more distal from the grounding line. Characterization of these stratigraphic variations is important for understanding geologic and engineering properties of the Presumpscot Fm.

1 INTRODUCTION

We discussed the geology of the uppermost Pleistocene Presumpscot Formation in the first Presumpscot Symposium in 1987 (Belknap, 1987; Schnitker and Borns, 1987). Since then there have been numerous theses and other research studies, including advances in equipment and understanding, that provide the basis for a reexamination of the stratigraphy of the Presumpscot Fm. as determined from submerged deposits and their onshore extensions.

1.1 Geologic Setting

At the end of the latest glaciation the Laurentide Ice Sheet retreated from its greatest extent on Georges Bank and in the Gulf of Maine (Schnitker et al., 2001), reaching present-day coastal Maine ca. 17 thousand calendar years ago (cal. ka). The weight of the glacial ice depressed the landscape hundreds of meters, thus allowing waters of the DeGeer Sea to inundate the coastal lowlands of Maine between 16 and 12 cal. ka, (Stuiver and Borns, 1975; Thompson, 1979, 1987, 2015). Crustal warping due to glacio-isostatic rebound resulted in the tilting up to the north of this paleoshoreline from present elevations of 60-70 m on the coast to greater than 122 m inland (Thompson et al., 1989).

The deep proglacial marine system received abundant glacial outwash sediments as well as ice-rafted debris, which were deposited at a thick blanket over much of the coastal lowlands (Thompson and Borns, 1985) and in the nearshore and offshore basins of the Gulf of Maine (Fader et al., 1977; King and Fader, 1986; Schnitker et al., 2001). These sediments are dominated by a bluish-gray mud, with associated sandy layers and dropstones, known as the Presumpscot Formation (Bloom, 1963) in Maine and the northern Gulf of Maine, the Boston Blue Clay in Massachusetts (Kaye, 1961), and the Emerald Silt on the Scotian Shelf (King and Fader, 1986). All are near equivalent in composition and paleoenvironmental settings, and roughly the same age, with deposition starting in the south and rolling northward with the retreat of the ice edge. Other evidence identifying the Presumpscot Fm. as glaciomarine includes abundant iceberg dropstones, and locally abundant fossils that indicate cold, turbid water conditions found today in Labrador and Greenland (e.g., Bloom, 1960; Stuiver and Borns, 1975; Thompson, 2015). The Presumpscot Fm. is Pleistocene in age, on the basis of stratigraphy and radiocarbon dates of its marine fossils, all older than 12.5 cal. ka (Stuiver and Borns, 1975; Borns et al., 2004). As the ice sheet retreated farther north, Maine rebounded rapidly, resulting in a relative fall of sea level to -60 m offshore (Schnitker, 1974; Belknap et al., 1987) approximately 12.5 ka (Barnhardt et al., 1995; Kelley et al., 2013). This sea-level fall caused deep incision of the Presumpscot Fm. in paleovalleys, as well as general erosion off higher topography by littoral and fluvial processes (Belknap et al., 1986). It also produced lowstand deltas (Belknap et al., 1986, 1989; Hein et al, 2014) and shoreline terraces (Shipp et al., 1989, 1991) that form a major part of the interpretation of the sea-level lowstand position.

The sedimentary composition of the Presumpscot Fm. is a mix of clay, silt and sand, with wide local variations (Thompson, 2015). It is often referred to as "clay" because of its compact stiff plastic nature (e.g., Andrews, 1987), but is actually a mix of sand, silt and clay-sized sediment, and sometimes gravel. Goldthwait (1951) analyzed 43 samples in southwestern Maine, obtaining grain sizes of 23.5% sand, 37.5% silt and 39% clay. Caldwell (1959) and Borns and Hagar (1965) found similar values in central Maine (Thompson, 1987). It is thus strictly a "mud" or "sandy mud" in geologic terms (e.g., Folk, 1968). Davies (1992) found values of 3 to 14% sand, 97 to 86% mud in Presumpscot Fm. samples from vibracores in the Damariscotta River. Offshore in Jordan Basin piston core CH-10-90-03, Schnitker et al. (2001) found in the upper, distal glaciomarine (DGM) values of 1-9% gravel, 10-19% sand, 19-27% silt, and 52-62% clay. Water content in this unit was 20-28% (note that this uses the sedimentological definition, the difference in wet versus dry sediment weight divided by the initial wet weight $(M_w\text{-}M_d)/M_w$, e.g., Lewis and McConchie,1994). The Jordan Basin core was well below the sea-level lowstand, and represents unmodified conditions of water content, other than sediment compaction, and no changes in oxidation/ reduction conditions.

Kelley (1989) discussed the mineralogical composition of the Presumpscot Fm. It is primarily "rock flour," the mechanically ground fine mineral particles produced by glacial movement, carried to the glacial terminus, and in this case into the adjacent marine environment primarily by glacial meltwater. The composition is strongly controlled by sand, silt and finer quartz and feldspar grains. The clay minerals illite and chlorite are indicative of the metamorphic rock terrain of Maine. The Bay of Fundy provides a component of kaolinite clays, from tropical weathering in ancient sedimentary rocks of New Brunswick and Nova Scotia.

Bloom (1960, 1963) pointed out the differences between the deeper, unweathered Presumpscot Fm., with its blue-gray color, higher water content, and greater plasticity, as compared to the oxidized and fractured yellow-brown sediments as much as 10 m thick at the top of the unit (see: Thompson, 2015, Fig. 3.19). Caldwell's (1959) analyses showed that the brown color is from the oxidation of iron-bearing minerals. Bloom (1960, 1963) associated this oxidation with the fall in sea level and exposure to terrestrial conditions. This results in over-consolidation, and is an important factor in recognition of this surface as a greater impedance contrast in seismic reflection surveys. Below 60 m offshore, the Presumpscot Fm. was not exposed, and thus shows a more gradual change to postglacial and modern sediments.

1.2 Methods

We have conducted seismic surveys, coring, and other sampling in Maine estuaries and the Gulf of Maine since 1983, through a series of graduate student theses and funded research projects. This published and archived database provides the basis for the summary shown in this paper.

In the 1980's and 1990's we used analogue records produced by an ORE Geopulse boomer system, usually at 105 joules power, and peak frequency response of 1.5 ± 0.7 kHz, on 1/8 s sweep (thus ca. 100 m depth scale). This resulted in a theoretical vertical resolution better than 25 cm, and routinely allowed high-resolution imagery for penetration of as much as 100 m of post-glacial sediments, to crystalline bedrock. In addition, we did reconnaissance with a Raytheon RTT1000 3.5 kHz system, over lower power and penetrating capability. Navigation employed Loran-C, which was later converted to latitude-longitude coordinates. For the purpose of this study, the paper records were scanned and rectified, then interpreted with graphics software (Photoshop CS3 and Canvas 10).

For 1999 and subsequent work we used a digital Triton-Elics system, employing an AAE boomer at 100 joules, 20-element hydrophone, and hard-drive recording of data. Navigation was by GPS, which was georeferenced to the geophysical record. The frequency, resolution and penetration of the AAE boomer is similar to the

Geopulse, but the ability to digitally manipulate the record through filtering, and direct georeferencing of each shot point, are major advantages.

Geophysical data was "ground-truthed" with vibracores and piston cores, as well as grab samples. Interpretation of seismic facies was also facilitated by bridge boring logs (Belknap et al., 1986) and examination of outcrops of bedrock, till, and glaciomarine sediments throughout coastal Maine.

1.3 *Significance*

As developed in the 1987 Symposium volume and the current Symposium, the Presumpscot Fm. is important in many ways in Maine. It is the substrate for much of the agricultural and forest soils in the coastal lowlands. It is an important part of groundwater and septic systems, acting either as an aquaclude, or as a more permeable zone where sandier units are interlayered. It is an important low-permeable material for lining and capping landfills. Major slumps occur in the Presumpscot Fm. (e.g., Novak, 1987; Berry et al., 1996), and the role of stratigraphy and sedimentology in the slumping process are poorly understood. Study of Presumpscot Fm. in test borings and borrow pit exposures can provide important details of sediment makeup and stratigraphic relationships, but these are generally limited in extent. Seismic profiling, on the other hand, provides proxy reflection relationships of the Presumpscot Fm. over tens of kilometers, revealing subtle changes in geometry and texture not available in any pit, or even a series of disconnected pit or core observations.

2 SEISMIC STRATIGRAPHY

Seismic stratigraphy is based on acoustic impedance contrasts and geometry of reflectors. Shipp (1989), Belknap and Shipp (1991) and Barnhardt et al. (1997) established the fundamental seismic stratigraphic framework for Maine coastal and nearshore work. Similar approaches were used in the deeper Gulf of Maine (Bacchus, 1993; Bacchus and Belknap, 1997; Schnitker et al., 2001), but because of complexities of ice-shelf formation and decay, and other glacial grounding-line processes, are not specifically relevant to this paper, and are not discussed further. The specific sequence of analysis proceeds from an identification of reflectors (acoustic impedance contrasts) in the record, based on: 1) intensity, then 2) geometry of internal reflection characteristics, 3) geometry of external bounding surfaces, and 4) frequency or position of occurrence, particularly the position within a sequence (Belknap and Shipp, 1991). There are approximately 12 seismic facies in the coastal Maine successions, with some variation from embayment to embayment. The facies interpreted as glaciomarine are ubiquitous and consistent along the coast.

2.1 *Seismic Stratigraphic Bounding Surfaces*

Any identification of seismic facies begins with the identification of reflectors that form bounding surfaces. These may be conformable or disconformable, and they may be intense, moderate, or subdued transitions (Belknap and Shipp, 1991, Fig. 4). The greatest acoustic impedance contrasts (reflector strengths) occur at the water-sediment boundary, and at the sediment-bedrock boundary. In the figures illustrating the facies below, it is important to remember that these are relative relationships, and although the processing equipment automatically adjusts the gain with depth (TVG: time-variable gain), return strength and distinction of reflections decreases with thickness of overlying sediment. It is a basic assumption that many reflectors correspond to changes in sediment grainsize or degree of consolidation. However, there are artifacts that can obscure this basic relationship (multiples, natural gas deposits, migration and side echoes, etc.; see Payton, 1977) but the examples chosen below are mostly free of these distractions.

2.2 *Glaciomarine Seismic Facies*

Seismic facies GM, interpreted as glaciomarine sediments (Belknap et al., 1986, 1989; Shipp, 1989; Belknap and Shipp, 1991; Barnhardt et al., 1997), occur throughout coastal Maine and the northern Gulf of Maine. They occur in succession above bedrock (at a nonconformity), till (at a conformity), and sometimes stratified drift (at a conformity and/or interfingering relationship – see Kelley and Belknap 1991, Fig. 8). The glaciomarine facies are capped by a distinct erosional unconformity in water shallower than 60 m present water depth (Kelley and Belknap, 1991,

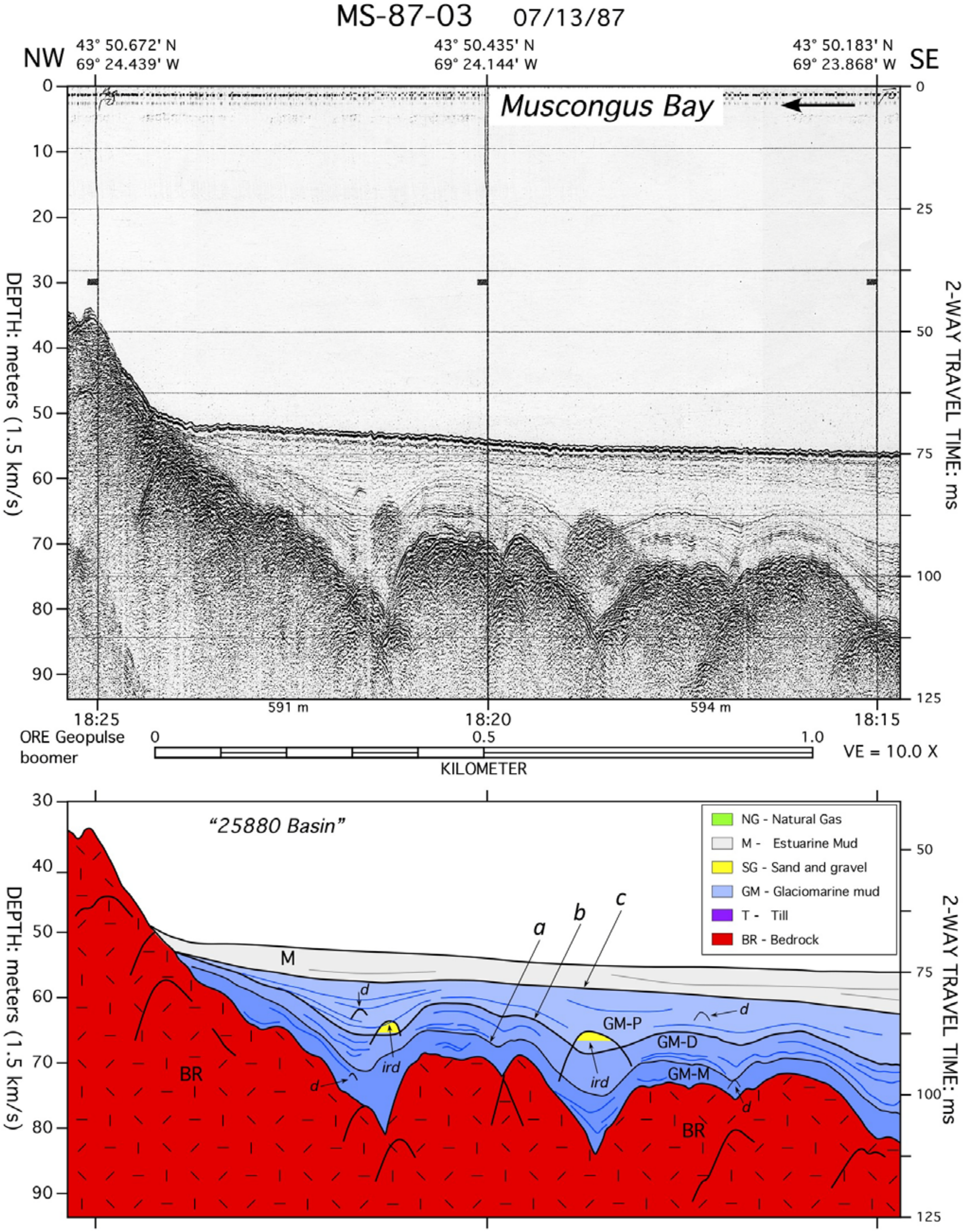

Figure 1 – Short segment of ORE Geopulse seismic line MS-87-03, western Muscongus Bay, 7 km ESE of New Harbor, ME. See also Kelley and Belknap (1991, Fig. 7). Subfacies GM-M: glaciomarine massive, GM-D: glaciomarine draped; and GM-P: glaciomarine ponded. Unit boundaries a, b and c are discussed in the text. Feature labels d: dropstone and ird: ice-rafted detritus.

Fig. 7), while in deeper water the relation- ship with overlying post-glacial sediments is conformable (Kelley and Belknap, 1991, Fig. 10). Figure 1 illustrates GM facies draping nonconformably over bedrock over much of this basin in Muscongus Bay. However, the truncation of GM at the bedrock ridge illustrates erosional processes both during the fall to sea-level lowstand and ongoing current and wave activity. Note that even the modern marine mud (M) is truncated, and shows a slight moat near the bedrock, suggesting current scour. GM in this location is capped by a moderate intensity, low-slope disconformity (c), suggesting little or no incision at this depth, near the sea-level lowstand. The three subfacies of GM described below were identified by Belknap and Shipp (1991) but are further refined here.

2.2.1 GM-M

Seismic facies GM-M is massive, with little distinct stratification. It is always the lowest unit in the GM succession, when present. It is found in most embayments along the Maine coast, but usually in the deepest parts of the paleovalleys, and may not continue to shallower sections. Figures 1 and 2 show well-developed, thick GM-M, while Figure 3 shows a thinner, less distinct, and discontinuous unit. In Muscongus Bay (Fig. 1) GM-M is slightly stratified, and separated from overlying GP-D by a transitional zone of variable stratification (a). In Eastern Penobscot Bay, GM-M shows a lateral variation in stratification, and the definition of the interface with GM-D does not follow one single continuous reflector (Fig. 2). It is important to note that the MS-87-03 data (Fig. 1) are ORE Geopulse, and in deeper water than the AAE boomer data in PB-01-09a and PB-00-203, and the latter two were in extremely calm conditions (as can be seen from the smoothness of the (c) reflector. The higher resolution of Figure 2 and Figure 3 may be due to any of these factors, but the sea state is probably the largest control. This places constraints on the distinction between GM-M and GM-D in data sets taken in average or rougher seas. It is possible that the lower, southeastern portion of the unit labeled GM-D in PB-00-203 (Fig. 3) is equivalent to GM-M in PB-01-09a (Fig. 2), or is a transitional case.

2.2.2 GM-D

GM-D is the most common and distinctive of the three glaciomarine seismic facies. It is found in every locality with glaciomarine units along Maine coast and inner shelf. It can overlie GM-M, or lie directly over bedrock and/or till. Its most distinctive feature is the long, continuous internal reflectors that drape concentrically over underlying topography. Thompson (2015, Figs. 3.17 and 3.18) illustrates such draping geometry in terrestrial exposures. Individual reflectors can be traced for kilometers or more (10’s of kilometers in the deeper Gulf of Maine: Bacchus and Belknap, 1997), demonstrating a widespread process of simultaneous variations, most likely in sediment grainsize. Piper et al. (1983) show that the draped configuration indicates sedimentation from suspension at a very rapid rate of sediment accumulation, while the rhythmic fluctuations in grainsize are typical of proximal proglacial overflow-interflow transport and deposition processes (e.g., Smith and Ashley, 1985; Pfirman and Solheim, 1989; Powell and Molnia, 1989). Presumpscot Fm. is very well exposed at Bunganuc Bluff in Maquoit Bay (northern Casco Bay) in Brunswick, ME (Fig. 4). The long parallel beds correspond to the reflectors seen in seismic facies GM-D. This exposure contains numerous rhythmites – sets of sandy units that fine upward to silt-clay sediments in repetitive packages 10-15 cm thick (Fig. 5). Within the sandy portions of these packages are a dozen or more repetitive successions that fine upward from coarse sand to silt to mud (Fig. 6). These units superficially resemble lake varves, but there is insufficient dating or other control to support or refute that idea. The rhythmites do suggest seasonal or shorter-term pulses of meltwater-carried sediment into the glaciomarine basin.

The upper surface of GM-D may be a relatively abrupt change in intensity of reflection, frequency of reflectors, and/or geometry, as shown in Figure 1, interface (b), overlain by GM-P. More commonly GM-D is capped by an erosional, often angular unconformity (Figs. 2, 3), caused by littoral and fluvial erosion above the lowstand. In PB-01-09a and PB-00-203 the fluvial incision was caused by the paleo-Penobscot river at lowstand ca. 12.5 ka, and

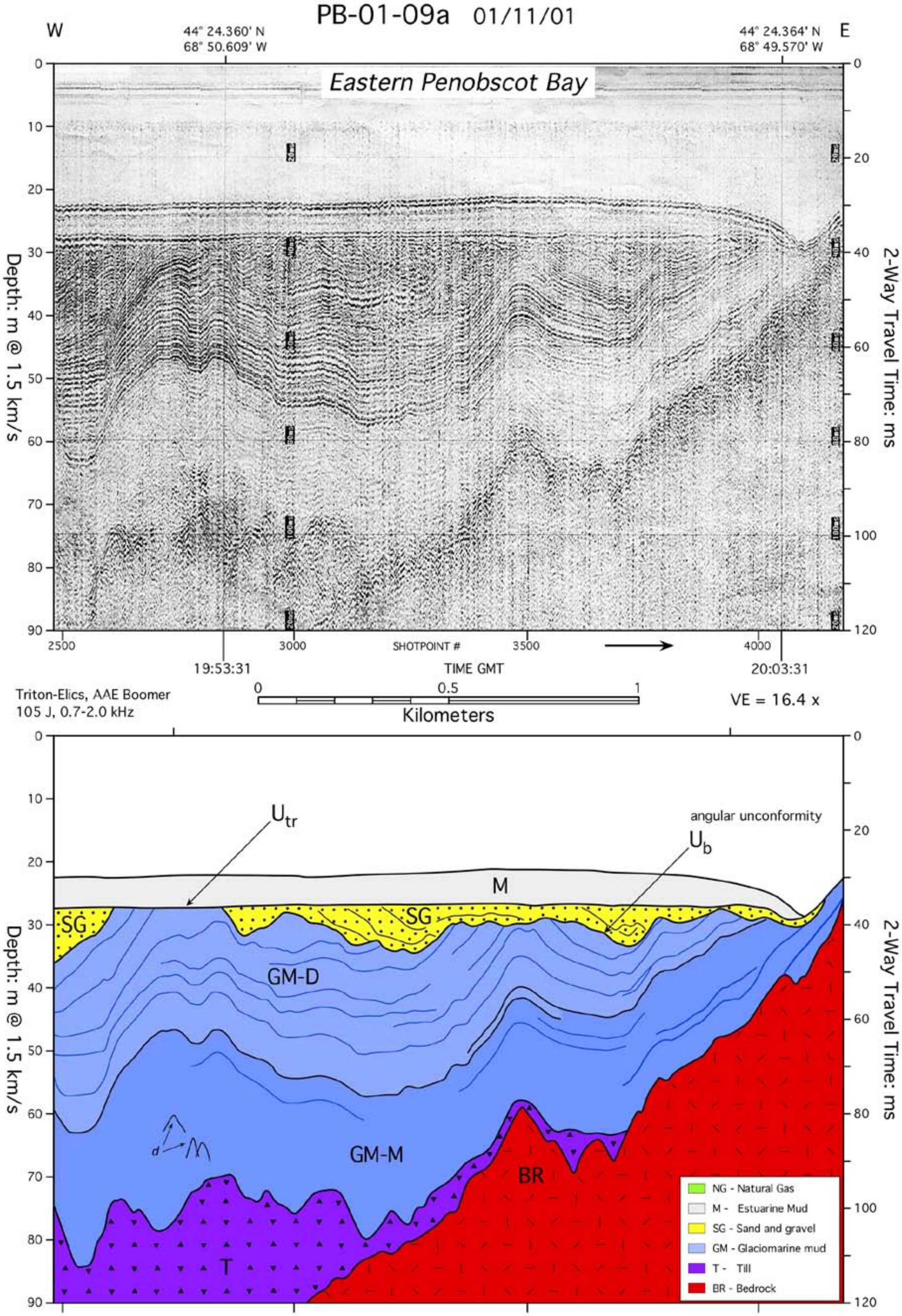

Figure 2 – Short segment of Triton-Elics AAE seismic line PB-01-09a in Eastern Penobscot Bay, 1 km W of Perkins Point, Castine, ME. An adjacent section of this line is depicted in Belknap et al. (2005, Fig. 7), showing SG incised valley fill up to 20 m thick.

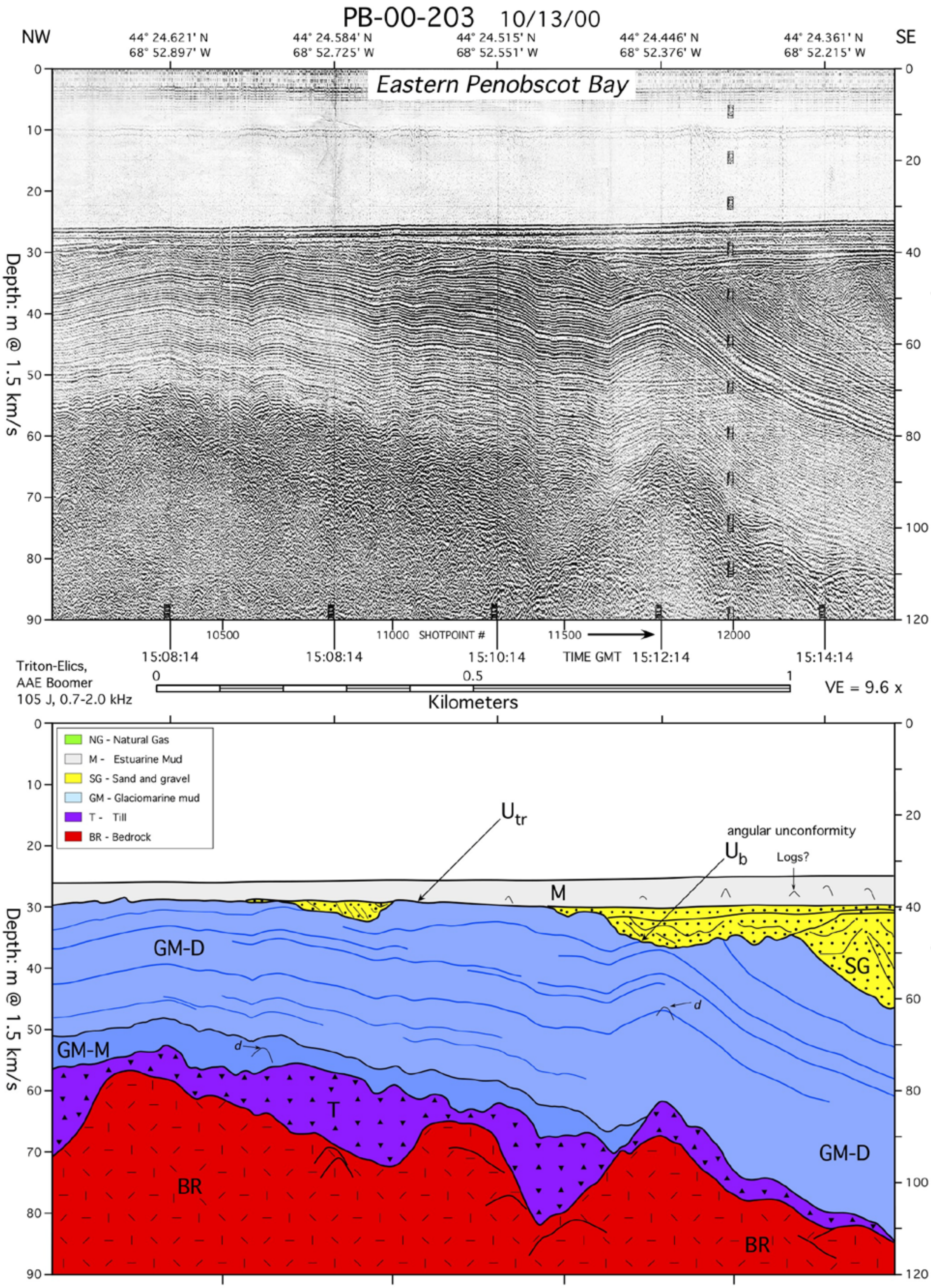

Figure 3 – Short segment of Triton-Elics AAE seismic line PB-00-203 in Eastern Penobscot Bay, 4 km W of Perkins Point, Castine, ME. An adjacent section of this line is depicted in Belknap et al. (2005, Fig. 4), showing SG incised valley fill up to 30 m thick.

Figure 4 – Bunganuc Bluff view from the south. The total relief of the m bluff section is approximately 8 m. The majority of the exposure is Presumpscot Fm. with a thin sandy cover. Photo 05/18/86 by J.T. Kelley.

filled in by the Penobscot Paleodelta (Belknap et al., 2002, 2005) when sea level was between -30 and -26 m, ca. 9 to 8 ka. This incision forms the basal unconformity (U_b of Belknap et al., 2005, in Figs. 2 and 3). Away from the incised valleys, transgressive estuarine and bluff erosional processses created a planar transgressive unconformity (U_{tr} of Figs. 2 and 3).

2.2.3 *GM-P*

GM-P is characterized by a ponded geometry of reflectors, infilling lows left at the top of GM-D. It is the highest in stratigraphic succession of the three GM facies, and generally the least common along the Maine coast and shelf. It is generally less well stratified than GM-D, with a lenticular geometry thickest near the center of low spots in the underlying GM-D, pinching out towards the margins of these basins. The interface between GM-D and GM-P can be sharp, defined as an abrupt drop-off in frequency of high-amplitude reflectors (Fig. 1, surface (b)), or sometimes more gradational, but the distinctive change from highly draped to ponded internal geometry is the basis of the distinction of the two subfacies. Piper et al. (1983) show that the ponded geometry reflects a slower rate of sediment accumulation and greater influence of reworking by waves and currents, especially in shallower sections, and primarily reflects a position more distant from the proglacial sediment sources (Shipp, 1989; Belknap and Shipp, 1991). The uppermost portions of the Presumpscot Fm. may not actually be of direct glacial influence, lacking cold-water fossils and dropstones, but the lower and middle portions of GM-P as shown in Figure 1 do exhibit dropstones and IRD.

2.3 *Associated Seismic Facies*

The glaciomarine units are close to or associated with several other seismic facies or characteristic reflections. These identifications place the GM units in their proper stratigraphic position, and help identify paleoenvironments.

2.3.1 BR – bedrock

Bedrock (BR) is always the base of the section, and is characterized by a highly reflective upper surface of rugged topography. Scattering of the seismic wave and lack of strong internal acoustic impedance contrasts in this crystalline metamorphic and igneous rock give a chaotic, unstratified internal character. Apparent internal reflectors in Figure 1 and 3 are actually hyperbolic returns from rough surface topography. Overlapping appearance of reflectors is due to side echoes out of the plane of the seismic profile line.

Figure 5 – Rhythmites in the upper Presumpscot Fm. Bunganuc Bluff, northern Casco Bay, ME, 06/10/88 by D. F. Belknap. Scale bar is 10 cm.

2.3.2 T –Till

Till (T) overlies BR, and gives a slightly less strong surface reflection. It has a mounded or irregular surface, and a chaotic internal geometry in most cases (Fig. 2). A weak stratification can be observed in some places, however (Fig. 3). This facies is interpreted as basal till, directly deposited from glacial ice. Other locations in Maine show distinct moraines built of till (e.g., Kelley and Belknap, 1991, Fig. 8), but in the examples used here it is discontinuous or absent (Fig. 1). The interface between BR and T is of low contrast, and is sometimes difficult to distinguish.

Figure 6 – Detail of rhythmite sandy layers. Bunganuc Bluff, northern Casco Bay, ME, 06/10/88 by D.F. Belknap. Scale bar is 10 cm.

2.3.3 Ice-rafted detritus – ird, and Dropstones - d

A clear indication of glaciomarine conditions is individual dropstones or even iceberg dumps carried to sea from the calving front of a glacier, or melted out of the base of an ice shelf (Ovenshine, 1970; Thomas and Connell, 1985; Schnitker et al., 2001). Due to the nature of seismic profiling a single point source reflection will appear as a hyperbola on the record due to lateral migrations of the signal. Individual dropstones may be below the level of horizontal resolution, but still give a strong reflection centered at the peak of the hyperbola. Figure 7, a detail from Figure 1, shows several examples of dropstones within GM, and a particularly strong reflection in GM-P. Similar reflectors are found in Figures 1, 2 and 3. A large iceberg dump may be more resolvable, but may still demonstrate definite hyperbolic migration effects on its margins, and disrupt the underlying reflectors to some degree by diffraction effects. The feature labeled (ird) in Figures 1 and 7 is interpreted as an iceberg dump deposit. Alternatively, this could be a distant side-echo from a bedrock peak, but we would expect it to be more connected to the BR signal at its base if that were the case. The third possibility is natural gas in the section, as seen elsewhere on this same line (Kelley and Belknap, 1991, Fig. 7), but that interpretation is rejected because the diffractions do not wipe out underlying reflectors, as is the case with natural gas deposits (Belknap and Shipp, 1991). These (ird) units were in fact interpreted as natural gas by Kelley and Belknap (1991, Fig. 7), but upon further consideration, the present interpretation is favored. Belknap and Shipp (1991) discuss seismic facies TGL (thin gravel lens) that has similarities to the (ird) shown here, but the geometry and stratigraphic position is different.

2.3.4 SG – Sand and gravel, incised valley fill

Seismic facies SG (sand and gravel) is characterized by a moderate upper reflector and irregular to well stratified, dipping internal reflectors. Its base is of low contrast with underlying GM, and is best identified in most cases by angular unconformable relationships. The upper surface of SG is conformably overlain by M (estuarine mud). Facies SG is confined to the fill of incised channels cut into GM in Eastern Penobscot Bay (Figs. 2 and 3) in this study, and constitute the fluvial and delta facies of the Penobscot Paleodelta (Barnhardt et al., 1997; Belknap et al., 2002, 2005). However, facies SG is found in similar settings all along the coast of Maine (Belknap and Shipp, 1991; Barnhardt et al., 1997).

2.3.5 M – Marine and nearshore mud

Seismic facies M is Holocene age mud, in nearshore shelf and estuarine settings. It is usually the uppermost stratigraphic unit, and exposed at the seafloor. The upper reflector is strong due to the large impedance contrast with seawater. Internal reflectors are subdued and discontinuous. The basal boundary reflector varies from setting to setting. In MS-87-03 (Fig. 1 and 7) this interface is conformable and shows only a subtle change from the underlying GM-P. This is due to the position near local relative post-glacial sea-level lowstand, lack of exposure, and thus a conformable, continuous sedimentation. In PB-01-09a (Fig. 2) and PB-00-203 (Fig. 3) the boundary overlies an erosional angular unconformity cut into the Presumpscot Fm., but it is a conformable surface overlying the Paleodelta SG unit. In the latter case, estuarine mud was deposited over the sandy delta as sea level rose, the sandy deposition ceased, and eventually the Paleodelta was overtopped by 6 to 7 m of mud. The M facies demonstrates ongoing depositional and erosional processes including the scour moats near bedrock ridges (primarily due to tidal currents). This moat is subtle in MS-87-03 (Fig. 1 and 7), but very well developed in PB-01-09a (Fig. 2). (The section of PB-00-203 shown in Figure 3 is not near a bedrock ridge, and thus does not show a moat). Within facies M in PB-00-203 (Fig. 3) are hyperbolic reflectors indicative of point sources. We interpret these as submerged and buried logs, as might be expected at the mouth of the Penobscot River. These are not common features in the seismic data of the Maine coast and shelf.

3 SUMMARY AND CONCLUSIONS

3.1 Relationship of Facies and Paleoenvironments

The GM seismic facies are indicative of glaciomarine conditions in the northern Gulf of Maine, and extending onto the submerged Maine coastal lowlands immediately after retreat of the Laurentide Ice Sheet between 17 and 12.5 ka. Observations in natural bluffs, borrow pits and road exposures in many areas of Maine's coastal lowlands (e.g., Thompson, 1987, 2015) inform our interpretation of the estuarine and offshore facies. Conversely, the more continuous seismic

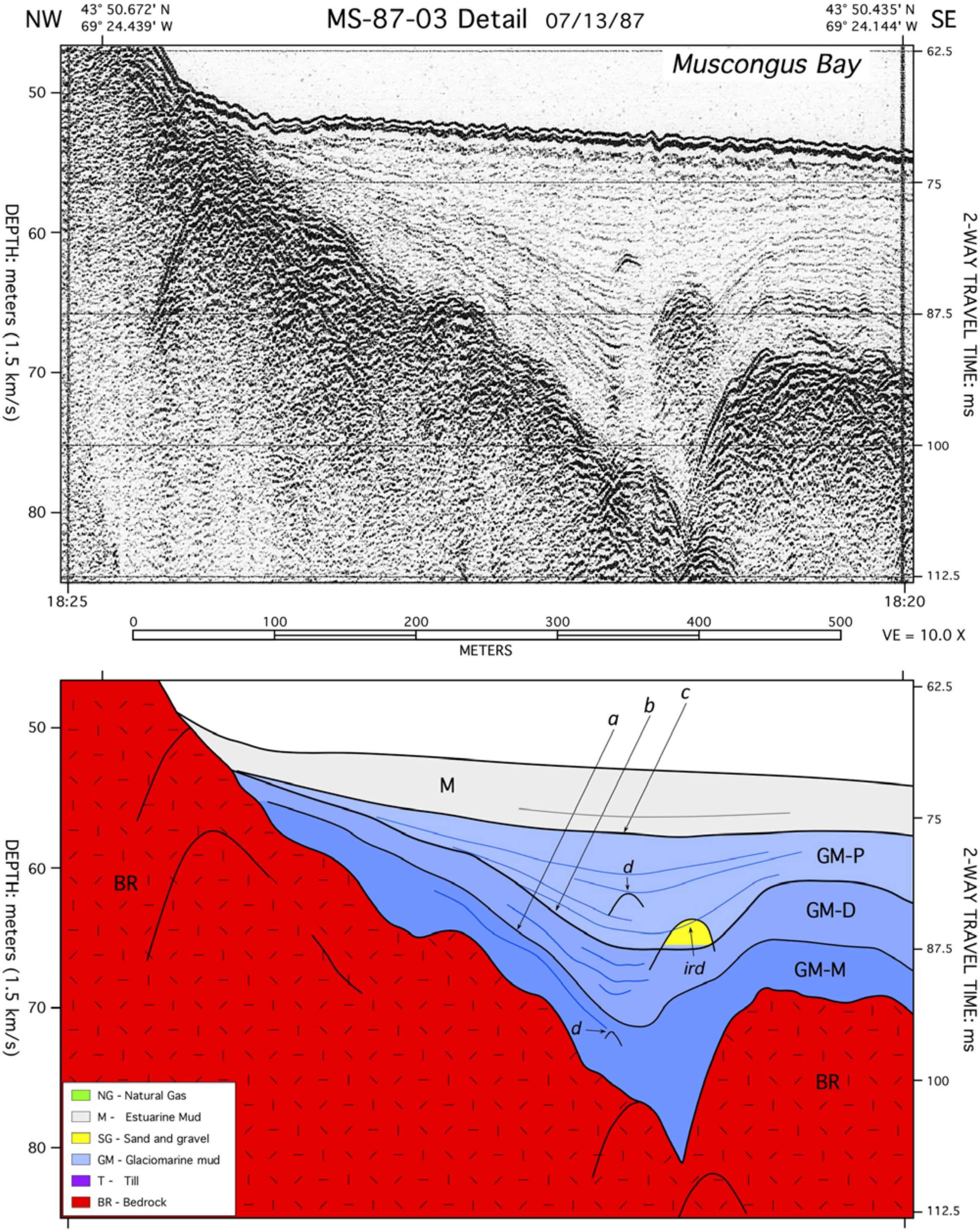

Figure 7 – Detail of ORE Geopulse seismic line MS-87-03, depicted in Figure 1.

lines give a better sense of thickness, length, and continuity of units that can inform interpretation of the terrestrial sections. GM-M is deposited directly over and adjacent to till, and is interpreted as a proximal glaciomarine unit. It most likely is coarser and accumulated most rapidly of the three subfacies. Variations may be due to proximity to or distance from glacial grounding-line meltwater flow concentrations (e.g., Ashley et al., 1991). GM-D demonstrates continuity of deposition over kilometers or greater scale, and rhythmic cycles of coarser and finer sediment beds. The exposure at Bunganuc Bluff (Figs. 3, 5, 6 and 7) is a close model for the submerged seismic facies. The concentric draping nature of GM-D represents very rapid sediment accumulation, blanketing pre-existing topography with little influence of current or wave reworking. This suggests a glaciomarine embayment, or general ice-front environment, proximal to a calving ice front, or perhaps under an ice shelf. The ponded geometry of GM-P on the other hand suggests slower accumulation and greater influence of tide and wave reworking. This suggests more distal conditions, and/or later deposition as sea level began to fall. However, all three subfacies contain dropstones or ice-rafted detritus, indicating a glacial source and at least seasonal iceberg activity.

3.2 Importance of Presumpscot Formation Facies

The societal implications of building infrastructure, homes and businesses on the widespread Presumpscot Fm. in Maine requires better understanding of the geologic and engineering properties of the “blue clay.” Rotational slump failures, for example, are dependent in part on thickness of the Presumpscot Fm. and the degree of undermining of the toe of a coastal bluff, such as in the Rockland landslide of 1996 (Berry et al., 1996). However, the up to 10 m of blue clay was not of uniform composition, and layers of more permeable could have played a part in the event. The layering demonstrated in offshore seismic facies may also help inform issues of groundwater flow and pollution infiltration. Recent proposals for offshore dredging and dredge-spoils disposal, such as off Sears Island, might also be better informed by an understanding of the properties of the Presumpscot Fm., as can any underwater project, such as cables, pipes, or wind generation. Although there is a large database currently available in our archives, further research is prudent, especially for site-specific offshore projects.

4 ACKNOWLEGEMENTS

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5 REFERENCES CITED

Andrews, D.W., 1987, The engineering aspects of the Presumpscot Formation: In: D.W. Andrews, W.B. Thompson, T.C. Sandford and I.D. Novak, eds., Geologic and Geotechnical Characteristics of the Presumpscot Formation, Maine's Glaciomarine "Clay." Maine Geological Survey, Augusta, p. 4-1 to 4-17.

Ashley, G.M., Boothroyd, J.C. and Borns, H.W., Jr., 1991, Sedimentology of late Pleistocene (Laurentide) deglacial-phase deposits, eastern Maine; an example of a temperate marine grounded ice-sheet margin: In: Anderson, J.B. and Ashley, G.M., eds., Glacial marine sedimentation: paleoclimatic significance, Geological Society of America Special Paper 261, p. 107-125.

Bacchus, T.S., 1993, Late Quaternary Stratigraphy and Evolution of the Eastern Gulf of Maine: Ph.D. Dissertation, Dept. Oceanography, University of Maine, Orono, 347 pp.

Bacchus, T.S. and Belknap, D.F., 1997, Glacigenic features and shelf basin stratigraphy of the eastern Gulf of Maine: In: Davis T.A., Bell, T., Cooper, A.K., Josenhans, H., Polyak, L., Solheim, A., Stoker, M.S. and Stravers, J.A., eds., Glaciated Continental Margins: An Atlas of Acoustic Images, Chapman-Hall Pub. Co., New York, p. 213-216.

Barnhardt, W.A., Belknap, D.F. and Kelley, J.T., 1997, Stratigraphic evolution of the inner continental shelf in response to late Quaternary relative sea-level change, northwestern Gulf of Maine: Geological Society of America Bulletin, v. 109, p. 612-630.

Barnhardt, W.A., Gehrels, W.R., Belknap, D.F. and Kelley, J.T., 1995, Late Quaternary relative sea-level change in the western Gulf of Maine: evidence for a migrating glacial forebulge: Geology, v. 23, p. 317-320.

Belknap, D.F., 1987, Presumpscot Formation submerged on the Maine inner shelf: In: Andrews, D.W., Thompson, W.B., Sanford,T.C., and Novak, I.D., eds., Geological and Geotechnical Characteristics of the Presumpscot Formation, Maine's Glaciomarine "Clay": Symposium

Proceedings, March 20, 1987, Augusta, Maine Geol. Survey, 7 pp. (p. 153-166).

Belknap, D.F., Andersen, B.G., Anderson, R.S., Anderson, W.A., Borns, H.W., Jr., Jacobson, G., Jr., Kelley, J.T., Shipp, R.C., Smith, D.C., Stuckenrath, R. Jr., Thompson, W.B., and Tyler, D.A., 1987, Late Quaternary sea-level changes in Maine: In: D. Nummedal, O.H. Pilkey, Jr. and J.D. Howard, eds., Sea-Level Fluctuation and Coastal Evolution, Society of Economic Paleontologists and Mineralogists Special Pub. 41, p. 71-85.

Belknap, D.F., Gontz, A.M., and Kelley, J.T., 2005, Paleodeltas and preservation potential on a paraglacial coast – evolution of eastern Penobscot Bay, Maine. Chapter 16. In: D.M. FitzGerald and J. Knight, eds., High Resolution Morphodynamics and Sedimentary Evolution of Estuaries. Springer, Dordrecht, The Netherlands, p. 335-360.

Belknap, D.F., Kelley, J.T. and Gontz, A.M., 2002, Evolution of the glaciated shelf and coastline of the northern Gulf of Maine, USA: Journal of Coastal Research Special Issue 36, p. 37-55.

Belknap, D.F. and Shipp, R.C., 1991, Seismic stratigraphy of glacial-marine units, Maine inner shelf: In: J.B. Anderson and G.M. Ashley, eds., Glacial-Marine Sedimentation; Paleoclimatic Significance, Geological Society of America Special Paper 261, p. 137-157.

Belknap, D.F., Shipp, R.C. and Kelley, J.T., 1986, Depositional setting and Quaternary stratigraphy of the Sheepscot Estuary, Maine: Géographie physique et Quaternaire, v. 40, p. 55-69.

Belknap, D.F., Shipp, R.C., Kelley, J.T. and Schnitker, D., 1989, Depositional sequence modeling of late Quaternary geologic history, west-central Maine coast: In: R.D. Tucker and R.G. Marvinney, eds., Studies in Maine Geology - Vol. 5: Quaternary Geology, Maine Geological Survey, Augusta, p. 29-46.

Berry, H.N. IV, Dickson, S.M., Kelley, J.T., Locke, D.B., Marvinney, R.G., Thompson, W.B., Weddle, T.K., Reynolds, R.T. and Belknap, D.F., 1996, The April 1996 Rockland Landslide: Maine Geological Survey Open File Report 96-18, Augusta, 55 pp. + 1 Plate.

Bloom, A.L., 1960, Late Pleistocene changes of sea level in southwestern Maine: Maine Geological Survey, Augusta, ME, 143 pp.

Bloom, A.L., 1963, Late-Pleistocene fluctuations of sea level and postglacial & crustal rebound in coastal Maine: American Journal of Science, v. 261, p. 862-879.

Borns, H.W., Jr., Doner, L.A., Dorion, C.C., Jacobson, G.L., Jr., Kaplan, M.R., Kreutz, K.J., Lowell, T.V., Thompson, W.B. and Weddle, T.K., 2004, The deglaciation of Maine, U.S.A., in: J. Ehlers and P.L. Gibbard, eds., Quaternary Glaciations - Extent and Chronology, Part II, Elsevier B.V., p. 89-109.

Borns, H.W. Jr. and Hagar, D.J., 1965, Late-Glacial stratigraphy of a northern part of the Kennebec River Valley Western Maine: Geological Society of America Bulletin: v. 76, p. 1233-1250.

Caldwell, D.W., 1959, Glacial lake and glacial marine clays of the Farmington area, Maine: Maine Geological Survey, Department of Economic Development, Special Geologic Studies, Series No. 3, 48 pp.

Davies, C.P., 1992, Estuarine preservation potential model for archaeological sites in coastal Maine: M.S. Thesis, Inst. Quaternary Studies, University of Maine, Orono, 195 pp.

Fader, G.B., King, L.H. and MacLean, B., 1977, Surficial geology of the eastern Gulf of Maine and Bay of Fundy: Marine Sciences Paper 19, Geological Survey of Canada Paper 76-17, 23 pp.

Folk, R.L., 1980, Petrology of Sedimentary Rocks, Hemphill's, Austin, TX. 182 pp.

Goldthwait, L.G., 1951, The glacial-marine clays of the Portland-Sebago Lake region, In Report of the State Geologist, 1949-1950, Augusta, ME, Maine Development Commission, p. 24-34.

Hein, C.J., FitzGerald, D.M., Buynevich, I.V., Van Heteren, S. and Kelley, J.T., 2014, Evolution of paraglacial coasts in response to changes in fluvial sediment supply; In: Martini, I.P. and Wanless, H.R., eds., Sedimentary Coastal Zones from High to Low Latitudes: Similarities and Differences, Geological Society, London, Special Publications, 388, 34 pp.

Kaye, C.A., 1961, Pleistocene stratigraphy of Boston, Massachusetts: U.S.G.S. Professional Paper 424-B, p. B73-B76.

Kelley, J.T., 1989, A preliminary analysis of the mineralogy of glaciomarine mud from the western margin of the Gulf of Maine: Northeastern Geology, v. 11, p. 141-151.

Kelley, J.T., Barber, D.C., Belknap, D.F., FitzGerald, D.M., van Heteren, S., and Dickson, S.M., 2005, Sand budgets at geological, historical and contemporary scales for a developed beach system, Saco Bay, Maine: Marine Geology, v. 214, p. 117-142.

Kelley, J.T. and Belknap, D.F., 1991, Physiography, surficial sediments and Quaternary stratigraphy of the inner continental shelf and nearshore region of central Maine, United States of America: Continental Shelf Research, v. 11, p. 1265-1283.

Kelley, J.T., Belknap, D.F., Kelley, A.R. and Claesson, S.H., 2013, A model for drowned terrestrial habitats with associated archeological remains in the northwestern Gulf of Maine, USA: Marine Geology, v. 338, p. 1-16.

King, L.H. and Fader, G.B.J., 1986, Wisconsinan glaciation of the Atlantic continental shelf of southeast Canada: Geological Survey of Canada Bulletin, 363, 72 pp.

Lewis, D.W. and McConchie, D., 1994, Analytical Sedimentology, Chapman Hall, New York, 197 pp.

Novak, I.D., 1987, Geology of the September, 1983 landslide at Gorham, Maine: In: D.W. Andrews, W.B. Thompson, T.C. Sandford and I.D. Novak, eds., Geologic and Geotechnical Characteristics of the Presumpscot Formation, Maine's Glaciomarine "Clay." Maine Geological Survey, Augusta, p. 10-1 to 10-9.

Ovenshine, A.T., 1970, Observations of iceberg rafting in Glacier Bay, Alaska, and the identification of ancient ice-rafted deposits: Geological Society of America Bulletin, v. 81, p. 891-894.

Payton, C.E., 1977, Seismic Stratigraphy - applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, Tulsa, OK, 516 pp.

Pfirman, S.L. and Solheim, A., 1989, Subglacial meltwater discharge in the open-marine tidewater glacier environment: observations from Nordaustlandet, Svalbard Archipelago: Marine Geology, v. 86, p. 265-281.

Piper, D.J.W., Letson, J.R.J., DeIure, A.M., and Barrier, C.Q., 1983, Sediment accumulation in low sedimentation, wave dominated, glaciated inlets: Sedimentary Geology, v. 36, p. 195-215.

Powell, R.D. and Molnia, B.F., 1989, Glacimarine sedimentary processes, facies and morphology of the south-southeast Alaska shelf and fjords: Marine Geology, v. 85, p. 359-390.

Schnitker, D., 1974, Postglacial emergence of the Gulf of Maine: Geological Society of America Bulletin, v. 85, p. 491-494.

Schnitker, D., Belknap, D.F., Bacchus, T.S., Friez, J.K., Lusardi, B.A. and Popek, D.M., 2001, Deglaciation of the Gulf of Maine, In: Weddle, T.K. and Retelle, M.J., eds., Deglacial History and Relative Sea-Level Changes, Northern New England and Adjacent Canada, Boulder Colorado, Geological Society of America Paper 351, p. 9-34.

Schnitker, D. and Borns, H.W., Jr., 1987, Depositional environment and composition of the Presumpscot Formation: In: D.W. Andrews, W.B. Thompson, T.C. Sandford and I.D. Novak, eds., Geologic and Geotechnical Characteristics of the Presumpscot Formation, Maine's Glaciomarine "Clay." Maine Geological Survey, Augusta, p. 3-1 to 3-13.

Shipp, R.C., 1989, Late Quaternary sea-level fluctuations and geologic evolution of four embayments and adjacent inner shelf along the northwestern Gulf of Maine: Ph.D. Dissertation, Oceanography Program, Univ. of Maine, 832 pp.

Shipp, R.C., Belknap, D.F. and Kelley, J.T., 1989, A submerged shoreline on the inner shelf off the Maine coast, Northwestern Gulf of Maine: In: Tucker, R.D. and Marvinney R.G., eds., Studies in Maine Geology, v. 5, Quaternary Geology, Maine Geological Survey, Augusta, ME, p. 11-28.

Shipp, R.C., Belknap, D.F., and Kelley, J.T., 1991, Seismic-stratigraphic and geomorphic evidence for a post-glacial sea-level lowstand in the northern Gulf of Maine: Journal of Coastal Research, v. 7, p. 341-364.

Smith, N.D. and Ashley, G.M., 1985, Proglacial Lacustrine Environment, Chapter 4, In: Ashley, G.M., Shaw, J. and Smith, N.D., eds., Glacial Sedimentary Environments, SEPM Short Course No. 16, Society of Paleontologists and Mineralogists, Tulsa, OK, p. 135-216.

Stuiver, M. and H.W. Borns, Jr., 1975, Late Quaternary marine invasion in Maine: Its chronology and associated crustal movement: Geological Society of America Bulletin, v. 86, p. 99-104.

Thomas, G.S.P. and Connell, R.J, 1985, Iceberg drop, dump and grounding structures from Pleistocene glaciolacustrine sediments, Scotland: Journal of Sedimentary Petrology, v. 55, p. 243-249.

Thompson, W.B., 1979, Surficial Geology Handbook for Coastal Maine, Maine Geological Survey, August, 68 pp.

Thompson, W.B., 1987, The Presumpscot Formation in southwestern Maine: In: Andrews, D.W., Thompson, W.B., Sandford, T.C. and Novak, I.D., eds., 1987, Geologic and Geotechnical Characteristics of the Presumpscot Formation, Maine's Glaciomarine "Clay", Maine Geological Survey, Augusta, p. 7-29.

Thompson, W.B., 2015, Surficial Geology Handbook for Southern Maine, Bulletin 44 (Third Edition), Maine Geological Survey, Augusta, ME, 97 pp.

Thompson, W.B. and Borns, H.W., Jr., 1985, Surficial Geologic Map of Maine, Maine Geological Survey, Augusta, Maine 1:500,000.

Thompson, W.B., Crossen, K.J., Borns, H.W., Jr. and Andersen, B.J., 1989, Glaciomarine deltas of Maine and their relation to Late Pleistocene-Holocene crustal movements: In: W.A. Anderson and H.W. Borns, Jr., eds., Neotectonics of Maine, Studies in Seismicity, Crustal Warping, and Sea-level Change, Maine Geological Survey Bulletin 40, p. 43-67.