Reservoir distribution and characterization: Shelf to slope linked depositional systems

FINAL REPORT

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EXECUTIVE SUMMARY

All passive continental margins have an underpinning geologic platform that dictates their broad geomorphologic character and exerts control on sedimentation patterns. A significant issue in recent hydrocarbon exploration activities in deep water on the Scotian margin is the detection of reservoir rock, distributed by these sedimentation patterns. The objectives of this study are 1) to understand the complexities of shelf-to-slope and slope sedimentation patterns using Neogene to Recent analogues offshore Nova Scotia, the Grand Banks of Newfoundland and Suriname, South America, and 2) to understand the controls, inherent in mixed siliciclastic and carbonate shelf-edge depositional systems, particularly the inter play between the Abenaki carbonate platform and the Sable delta. In the first objective, younger analogues are studied where spatial and temporal resolution is not at issue and geologic events are better age-constrained.

It has been found that existing models of deep water sedimentation, particularly on passive continental margins, have greatly underestimated the linkages between shelf to slope sedimentation, the role of sediment mass failure and along slope sediment transport in redistributing sediment, and the role of canyon development leading to base of slope sediment distribution. These processes indicate that reservoir-grade sediments can be reworked, relocated and transported to great water depths and offer significant challenges to reservoir detection along the Scotian margin.

New play concepts were developed that identified significant reworking of the margin that has not been recognised in the past. Our preliminary estimates suggest that over 50% of the Cenozoic margin has been reworked and in many instances the sediment has been remobilised and transported some distance from the shelf margin through canyon delivery systems, mass transport deposits, contourites, salt control on sediment redistribution, carbonate platform and mixed siliciclastic carbonate depositional systems. A thorough understanding of the interplay and complexity of these processes is necessary to develop and apply exploration models. The consequence of these sedimentary processes is movement of potential reservoir rock to greater depths than previously anticipated. Deciphering forcing functions, sediment pathways and depositional processes provide insights into exploration models for passive clastic margins. Validation of these hypotheses indicates that exploration must move to deeper water where shelf-equivalent rocks are transported and deposited.

Deep Panuke is possibly unique, situated in a thick platform of continuous carbonate, adjacent to a large delta. Over time the Sable delta buries some of the Abenaki platform. The hydrocarbon history has capping prodelta beds to give lignitic-humic source rock and seal. The reservoir and trap are the reef margin. Due to early cementation from rapid and deep burial in deltaic sediments; the updip platform limestone is non-porous and acts as a lateral seal forming a partial stratigraphic trap. The shelf margin position develops fracturing and faulting but the occurrence is highly variable. These provided migration conduits for dolomitizing fluids and later hydrocarbons that result in a deeply buried reservoir with gas accumulation.

Though the worldwide dissemination of the results of the research through scientific publications and presentations at academic and industry forums (e.g. American Association of Petroleum Geologists and Canadian Society of Petroleum Geologists) and the organization of the largest petroleum research conference ever held in Eastern Canada (1st Conjugate Margins Conference of the Central Atlantic, Dalhousie University, Halifax), we have ensured the widest possible exposure of the Scotian Margin to the Petroleum Industry. There have been over 70 publications, abstracts and presentations that have culminated from this research project and this is continuing past the end of the project with presentation at the 2nd Conjugate Margins Conference of the Central Atlantic, Lisbon, Portugal, in September, 2010. Over 1/3 of the presentations on the Scotian Margin at Lisbon CMC will be results from this research project. Our student graduates will continue this legacy with their roles as new employees in Industry and Government. A key component of this project was the development of HQP and this has proved highly successful with the completion of 3 MSc theses and 2 PhD dissertations in final stages.

Concepts identified through this research project provide previously unrecognized opportunities on the Scotian margin that should be investigated further, and are applicable to other passive margins around the globe. New insights on the Cenozoic stratigraphic framework are applicable worldwide.

TABLE OF CONTENTS

SUMMARY REPORT

INTRODUCTION

Offshore Nova Scotia, there have been 7 deep water wells since 2000 with only one non-commercial discovery (Enachescu and Wach 2005). This lack of success stems from insufficient understanding of continental shelf-to-slope and slope geologic processes. The Shubenacadie H-100 and Shelburne G-29 wells were drilled on mounded seismic morphologies, interpreted as depositional fans. In post-drill analysis with modern seismic coverage, it is apparent that these structures are erosional remnants resulting from canyon cutting across the slope (Kidston et al., 2007). More recently, the Torbrook C-15 well was drilled into a presumed Tertiary fan; an interpretation using modern 3D seismic data. In this case, a mass transport deposit was encountered. The Annapolis B-24 well (Fig. 1) targeted a turbidite fan; again an interpretation based on modern 3D seismic data. It was the only discovery well in deep water, but was non-commercial. Kidston et al. (2007) admit uncertainty as to the origin of the reservoir facies within the conceptual submarine fan body and suggest that the Annapolis area may represent an overall bypass zone on the slope. Our studies suggest it may be an interval of contourites. On the Abenaki carbonate platform, Queensland M-88 was drilled on the carbonate slope basinward of the Deep Panuke field to test for by-pass sands that turned out to be shale. The last wells drilled by EnCana-Marauder, Dominion J-14 and J-14A, were plugged and abandoned. The expected reservoir facies (seismically-inferred porosity anomaly) along the carbonate platform was not found with shale encountered rather than porosity. When whipped near horizontally southwest the technical success of finding stromatoporoid reef limestone unfortunately did not find the anticipated porosity.

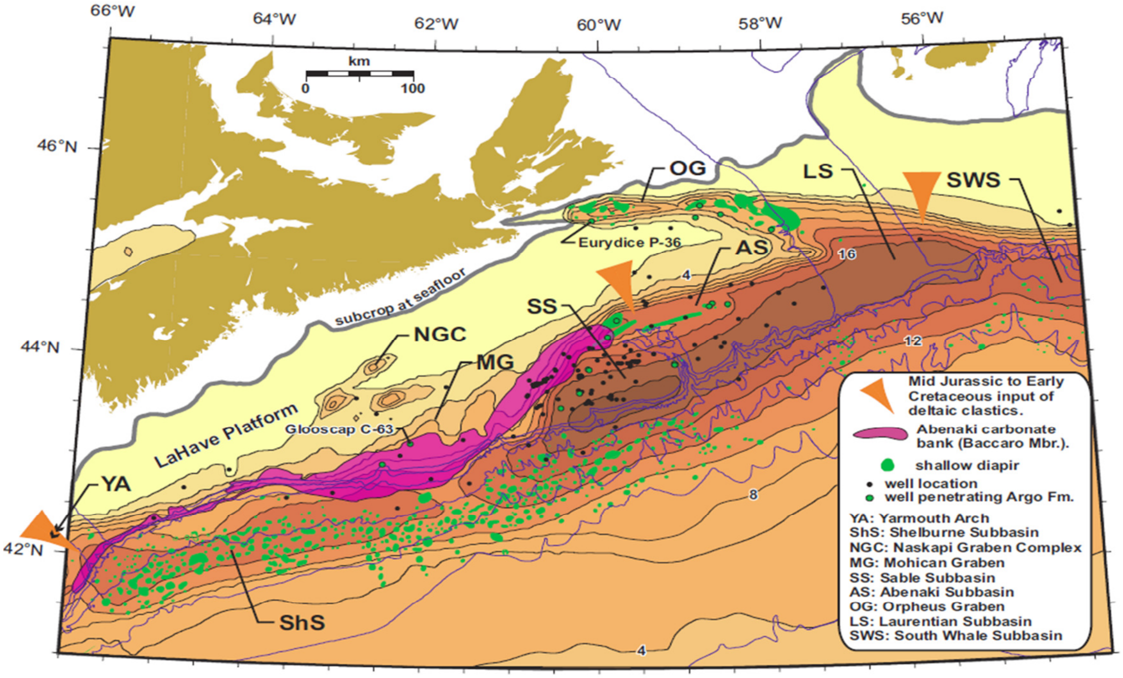


Figure 1: Scotian margin with basin geometries (Shimeld, 2004).

These examples highlight a need not only on the Scotian margin, but also globally in oil and gas exploration, to recognize and understand continental shelf-to-slope and slope sedimentary processes and depositional systems and the complexities associated with mixed carbonate-siliciclastic systems in order to identify potential source, reservoir and seal facies. The purpose of this study is to refine depositional models of these environments along the Scotian margin. This purpose will be accomplished through study of Neogene to Recent analogues on the Scotian margin, development of a stratigraphic framework within which these depositional models apply, and investigate the Mesozoic carbonate platform and Sable delta mixed depositional system through core and seismic analysis. Other Atlantic margin examples will also be incorporated for comparative purposes.

GEOLOGIC SETTING

The Scotian Slope is part of the Scotian basin, a passive margin sequence that developed after North America rifted from the African continent in the Late Triassic to Early Jurassic. The rift phase was characterized by deposition of continental clastic sediment and evaporites, while the drift phase was characterized by clastic progradation with periods of carbonate deposition (Wade and Maclean 1990). The Abenaki carbonate platform developed in the western part of the basin during the Late Jurassic (Eliuk, 1978) with limited extent in the east due to the presence of a major clastic deltaic depocentre near the position of the present day Sable Island (Eliuk and Wach, 2008). Transgression continued throughout the Late Cretaceous and Cenozoic punctuated by major sea level lowstand sequences (Wade and MacLean 1990; Kidston et al. 2002). The Scotian margin accumulated prodeltaic shales during this time and was deeply incised by canyons during major sea level lowstands through the Tertiary. In the later Miocene, the Western Boundary Undercurrent influenced sediment distribution on the margin. There was rapid sedimentation on the Laurentian Fan and Scotian Slope with the onset of terrestrial glaciation. Widespread gully cutting took place in the early Pleistocene, but the overall style of sedimentation continued to be prodeltaic (Piper and Normark 1989; Newton et al., 2003). The first shelf-crossing glaciation occurred about 0.5 Ma, and since that time, the continental slope has been dominated by proglacial sediment deposition, with little sediment accumulation at highstands.

The modern Scotian Slope extends approximately 1000 km from the Laurentian Channel in the northeast to the Northeast Channel in the Southwest (Fig. 1). It is broadly divided into two distinct morphological provinces (Uchupi and Swift 1992; Campbell et al. 2004). West of Verrill Canyon, the regional slope is 1.5° to 3° and the seabed is relatively smooth. From multibeam bathymetry, shallow submarine channels and linear escarpments tens of kilometres long and tens of metres high are observed superimposed on the smooth seabed. East of the Verrill Canyon the regional slope is steeper, 2.5° to 4°, and the seabed is deeply incised by submarine canyons, several of which cut back tens of kilometres into the continental shelf edge (Mosher et al. 2004).

BASIN EVOLUTION

Structurally, the East Coast of Canada is divided into three distinct regions: The Scotian margin in the south, the Newfoundland margin in the centre and east, and the Labrador margin in the north (Louden 2002; Hall et al., 2002)). The Scotian margin developed as a result of the break-up of the Pangean supercontinent in the Middle Triassic when North America and Africa rifted to form separate continents. Rifting occurred throughout the Late Triassic to Early Jurassic (~230-190 Ma) (Wade and McLean 1990), during which time the landmass comprising Nova Scotia occupied a near equatorial position adjacent to Morocco (Schenk 1973, 1981, 1997).

The final separation of North America and Africa is marked by the Break-up Unconformity (BU). The BU is manifested by complex faulting and erosion of Late Triassic and Early Jurassic rock as well as the creation of oceanic crust by volcanism with the opening of the proto-Atlantic Ocean (Keen and Beaumont 1990). The resultant Scotian basin consisted of a complex terrain of grabens and basement highs defined by the landward extensions of oceanic fracture zones onto continental curst (Welsink et al. 1990). From southwest to northeast the platforms and depocentres along the Scotian margin include the Georges Bank/Shelburne Basin, La Have Platform, Sable and Abenaki Subbasins, Banquereau Platform and the Orpheus Graben/ Laurentian subbasin.

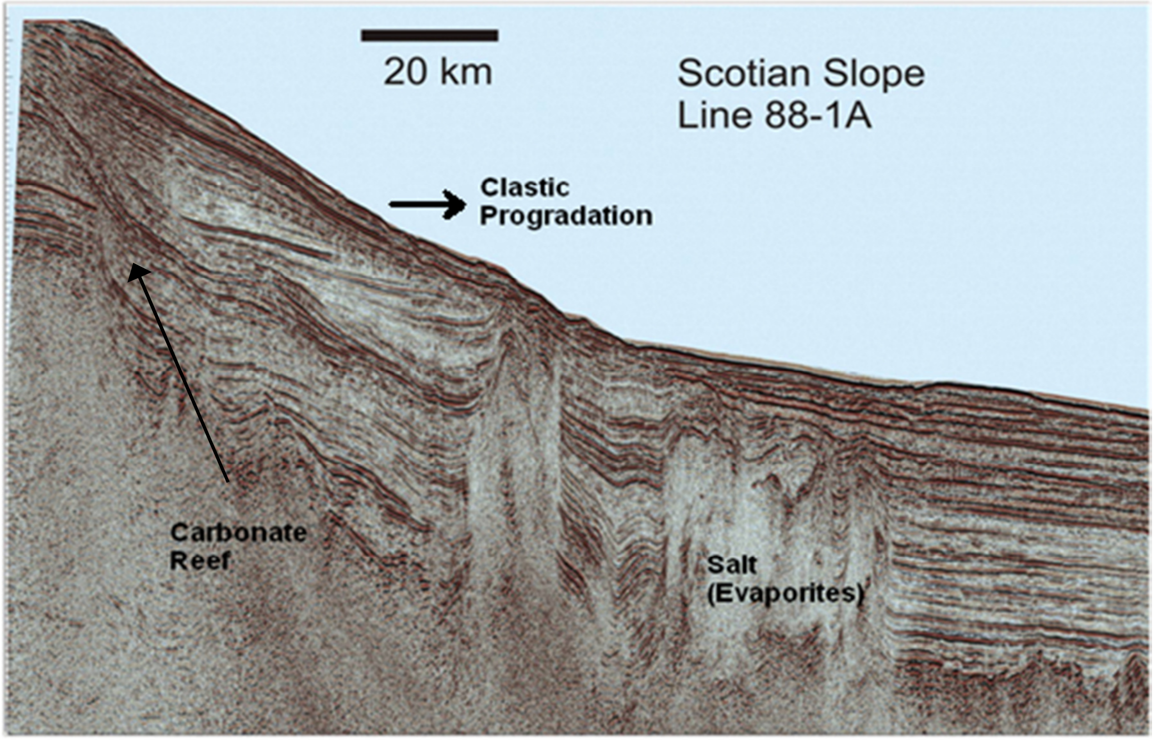


Figure 2: : Scotian slope rifted margin. Line 88-1A illustrating the carbonate reef and platform, and salt diapirs (Data from Lithoprobe).

Periods of basement subsidence during the Jurassic, Cretaceous and Cenozoic, (likely due to subsequent rifting events on the Grand Banks (Louden 2002), deepened the interconnected subbasins, resulting in the accumulation of strata 12 km or greater in thickness (Wade and MacLean 1990). The distribution of salt suggests that the subbasins were initially the loci of evaporate deposition although the timing of deposition is enigmatic and remains open for discussion (pers. comm. P. Post and J. Adam, 2010). Large synsedimentary faults are a prominent feature of the sedimentary section in Abenaki and Sable Subbasins resulting mainly from salt movement at depth. Many faults extend upward, well into the Cenozoic section, indicating long-term subsidence in the basin (Wade et al. 1995).

Strike-slip motion along the Cobequid – Chedabucto - Southwest Grand Banks fault system during the Cretaceous and Early Cenozoic was influential in shaping the landforms and depositional patterns on the Scotian margin; including rapid subsidence of the eastern Scotian basin in the mid-Cretaceous. Tilting of the Scotian Shelf during the Early Cenozoic led to erosion and reworking of Cretaceous inner shelf facies and deposition of deep water facies beneath the outer shelf (Wade et al. 1989) and possible Oligocene uplift of the eastern Scotian Shelf (Grist and Zentilli (2003; Pe-Piper and Piper 2004).

STRATIGRAPHY

Cenozoic and Mesozoic

Lithostratigraphic and structural evolution of the Scotian margin was first proposed by McIver (1972) and subsequently modified by Jansa and Wade (1975), Wade and MacLean (1990), Wade et al. (1995) and Kidston et al. (2002; 2007), through the study of Scotian Shelf wells and seismic data. Mesozoic, and in part, Cenozoic sedimentary rocks of the Scotian basin overlie a crystalline basement consisting of Paleozoic metasedimentary rocks and granites (Fig. 2). Restricted shallow marine conditions led to the deposition of continental redbeds of the Eurydice Formation in many of the deeper grabens, overlain and interfingered with evaporites of the Argo Formation (McIver 1972). The accumulation of extensive evaporate (salt and anhydrite) deposits perhaps up to 1-2 km in thickness, continued into the Early Jurassic as marine transgression covered the basin with a shallow sea (Wade and MacLean 1990; Kidston et al. 2002; Ings and Shimeld 2006; Adam and Krezsek, in press).

Restricted shallow water to tidally influenced marine conditions in the Early Jurassic led to deposition of continental clastic and evaporitic dolostones of the Iroquois and Mohican formations (Given 1977), unconformably overlying the Argo and Eurydice formations (Jansa and Wade 1975; Wade and MacLean 1990; Kidston et al. 2002). The dolomite sequence was followed by a thick succession of coeval fluvial sandstone and shale of the Mohican Formation, which completed the process of filling the rift grabens and onlapped basement highs along the post-breakup surface (Wade and MacLean 1990).

Normal marine conditions were established across the basin during the Middle and Upper Jurassic, represented by continental clastics of the Mohawk Formation (McIver 1972), shallow marine sandstones, shales and limestones of the MicMac Formation (McIver 1972), a shelf carbonate facies, the Abenaki Formation (McIver 1972; Eliuk 1978) and a basinal shale facies, the Verrill Canyon Formation (Wade and MacLean 1990). Continuous sediment loading during this period initiated the mobilization of deeply buried Jurassic salt causing the vertical and lateral intrusion of overlying sediment that continues to the present day (Ings and Shimeld 2006).

The Early Cretaceous was characterized by deposition of fluvial-deltaic Missisauga and Logan Canyon formations. The Missisauga Formation (McIver 1972) consists of a series of thick deltaic packages of sand-rich sediment with broad alluvial plain, adjacent delta and prodelta facies. The deltaic facies are best known in the Sable Island area but likely occur in parts of the Laurentian and South Whale subbasins (Wade and MacLean 1990; Kidston et al. 2002). Deposition of deltaic sediment ceased following a late Early Cretaceous marine transgression. The result of marine transgression was the accumulation of shales of the Logan Canyon Formation and transgressive marine shales and minor limestones of the Dawson Canyon Formation.

Late Cretaceous sea level rise and basin subsidence resulted in deposition of marine marls and chalky mudstones of the Wyandot Formation (McIver 1972; Wade and MacLean 1990; Kidston et al. 2002; Kettanah et al. 2010). Cretaceous sediments and the entire Cenozoic sedimentary succession above the Wyandot are designated the Banquereau Formation (McIver 1972). Marine shelf mudstones, sands and conglomerates of the Banquereau Formation were influenced throughout the Cenozoic by several major unconformities related to sea level fall. Unconformities are noted during the Paleocene, Oligocene and Miocene intervals where fluvial and deep water currents eroded largely unconsolidated sediments, subsequently depositing them on the abyssal plain (Wade and MacLean 1990; Kidston et al. 2002). Winnowing and reworking of deep-water sediment by bottom currents began in the Oligocene (Gradstein et al. 1990; Piper 2005), providing the earliest evidence of thermohaline circulation. Sediment distribution of Miocene successions were strongly influenced by the Western Boundary Undercurrent with periods of intensified bottom current activity also occurring in the Late Pliocene (Myers and Piper 1988; Piper 2005), followed by widespread gully cutting in the Early Pleistocene. During the Quaternary to recent, several hundred metres of glacial and marine sediment were deposited on the outer shelf and slope (Piper et al. 1987; Mosher et al., 1994; Kidston et al. 2002).

On the Scotian Shelf and Grand Banks the widespread hiatus eroding either the upper part or all of the Oligocene is marked by a regional unconformity; the nature of which includes canyon formation. Canyon incision at the shelf edge initiated during the Eocene and was extensive by the Oligocene (Fensome et al. 2008). Pe-Piper and Piper (2004) noted that although Oligocene strata are absent on the Scotian Shelf and Grand Banks, they are present both on the Labrador Shelf (Balkwill and McMillan 1990) and on the New Jersey margin where small hiatuses are correlated with the global eustatic 1987 sea-level curve of Haq (Miller et al. 1985; Mountain and Tucholke 1985; Tucholke and Mo*untain 1986). Wade et al. (1995) attributed the missing Oligocene strata on the eastern Scotian Shelf to a broad southeasterly trending canyon associated with a sea level lowstand although Grist and Zentilli (2003) argued for thermal inversion in the Late Cretaceous to Early Cenozoic based on results from apatite fission track analysis.

The late Cenozoic regional stratigraphy of the southeastern Canadian margin was synthesized by Piper and Normark (1989). They suggested that several marker horizons could be recognized in places as disparate as Flemish Pass, St. Pierre Slope, and the central Scotian Slope. Reflector E marks a sea level lowstand in the middle Pliocene, with valley cutting on the slope, followed by a return to draped sedimentation on the continental slope during the succeeding highstand. An early Pleistocene lowstand (reflector C) was marked by widespread gully cutting, and in many parts of the continental margin, these gullies persisted through the Quaternary. Reflector B marked a pronounced change in the style of slope sedimentation associated with the onset of shelf-crossing glaciation in the middle Pleistocene (Piper et al., 1994). On the central Scotian Slope, a more detailed seismic stratigraphy was interpreted by Piper et al. (1987), with modifications by Piper and Sparkes (1990) and Piper et al. (2002) and used for Brake's study (2009) (Fig. 3).

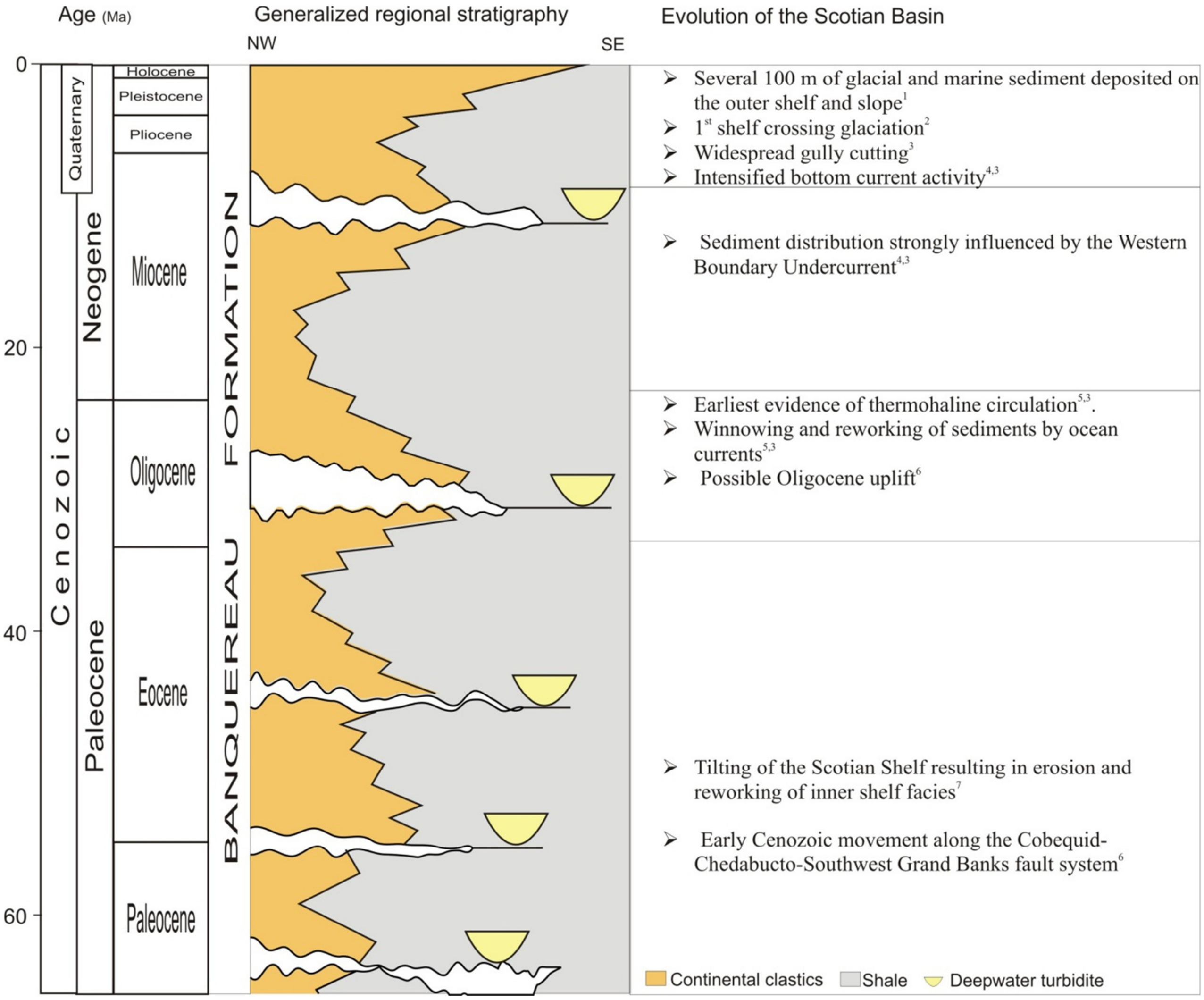


Figure 3: Cenozoic lithostratigraphic chart identifying key units and seismic markers of Brake's 2009 study area as well as equivalent Deep Sea Drilling Program (DSDP) markers (Tucholke and Mountain, 1979). The generalized regional stratigraphy (CNSOPB call for bids 2008-2009), closely corresponds to the Eustatic sea level curve (Haq et al. 1987). 1=Kidston et al. 2002; 2=Mosher et al 2004; 3=Piper 2005; 4=Myers and Piper 1988; 5=Gradstein et al. 1990; 6=Pe-Piper and Piper 2004; 7=Wade et al. 1989.
*Influence of salt movement throughout the Cenozoic section influences sedimentation patter and sediment delivery pathways
*inferred deepwater turbidite

Biostratigraphic picks are based on ties to the Shubenacadie H-100 and Acadia K-62 exploration wells. Piston cores from the continental slope have a distinctive Holocene and late Pleistocene sedimentary sequence. Holocene olive-gray muds pass down into early Holocene–late Pleistocene silty muds and thin sand beds that are believed to reflect lowered sea level at that time on the outer shelf. Distinctive ice-rafted marker horizons date from 12 and 14 ka (all ages are reported in radiocarbon years, including a 400-yr reservoir effect) (Piper and Skene 1998). Older sediment is proglacial mud with dropstones on the continental slope and related fine-grained mud turbidites downdip on the continental rise, with distinctive color changes probably related to changing glacial sources. Previous radiocarbon dating of these strata (Piper, 2001; Gauley, 2001) means that an approximate chronology can be applied to new cores that show this regular lithostratigraphy.

Jurassic and Cretaceous Sequence Stratigraphy

For the Abenaki Eliuk's thesis work uses a transgressive-regressive sequence stratigraphic framework rather than Exxonian model developed with EnCana even though there are minor inconsistencies within it (EnCana 2006, Weissenberger et al. 2006). In the Deep Panuke trend schematic lithologs are used to show facies changes vertically between sequences and for well to seismic control. The sequences are being extended southwestward to the western Shelf margin wells. Intraformational subdivision in the thick Abenaki carbonates, aside from the original three lithological members – Scatarie limestone, Misaine shale and thick Baccaro (McIver 1972) with an additional uppermost sponge-facies-defined Artimon Member (Eliuk 1978), must be based on sedimentological and subtle lithologic changes. At least 4 shoaling-deepening sequences above Misaine culminating in sponge-reef drowning were noted and showed the potential for subdivision. Increased numbers of relatively closely-spaced wells at Deep Panuke with reliance on thin sandstones (interpreted to be unconformities based on examination mixed carbonate-siliciclastic core outside the Panuke area and close to Sable Island) and 3D seismic allowed 7 stratigraphic sequences to be correlated above the Misaine (Weissenberger et al 2006). Unfortunately the thin sandstones are not developed to the southwest of the Panuke trend, but an attempt to extend these sequences using shoaling-deepening trends onto the western Shelf. In that area carbonate sedimentation continued into younger Early Cretaceous time (Jansa 1993), after the carbonate sedimentation cessation and drowning closer to the Panuke trend. Detailed logging has shown effects of long periods of slow to non-deposition with identification of thin red geopetal linings in Neptunian dykes and several wells with red iron oolite capping or above shallow Abenaki limestone on the Western Shelf. These findings that corroborate seismic data on the slope showing relatively thin overburden, have significant implications for lack of seal and continued sub-seafloor cementation relative to carbonate reservoirs. In the other direction, application of the Deep Panuke sequences is possible to Marquis L-35 area. But further northeast into the Sable delta area even larger scale correlation and biostratigraphic dating is extremely difficult. A thin condensed limestone (#9 in W. Venture C-62) examined in long core beneath the West Venture field also demonstrates paleoecological shallowing-up changes that appear to corroborate the argument (Cummings and Arnott 2005) for forced regression during the establishment of a Late Jurassic shelf margin delta. This new insight shows the potential power of using thin limestones in deltas to aid in understanding their sequence stratigraphic development (Eliuk and Wach 2008).

Stratigraphic controls and modifiers

From the Mesozoic through the Cenozoic there have been significant events and processes that have contributed to the evolution of the Scotian margin that impact the stratigraphic framework of the margin.

Salt Tectonics: Salt underlying thick sedimentary successions in the Scotian Basin has flowed extensively during periods of its geologic history, due to sediment loading and possibly due to periodic reactivation of the rift fault system during later stages of continental breakup (Shimeld, 2004; Adam and Krezsek, in press). Allochthonous and autochthonous salt pillows, diapirs and canopies are common along the lower Scotian Slope (see Figs. 1 and 2). Although salt can produce mini-basins and many hydrocarbon trap structures, creating suitable exploration targets, they also affect sediment distribution and margin stability, leading to a far more dynamic margin than would otherwise be the case. Late Cenozoic rates of salt deformation are low; yet faulting related to salt tectonics reaches the seabed in many places, locally producing fault-line scarps (Bennett, 2000; Newton et al., 2003). Some salt diapirs have positive bathymetric features above them, and the courses of canyons are, in many places, are influenced by the underlying presence and syndepositional location of salt.

Seismicity: Although the western Atlantic is a passive margin, significant magnitude earthquakes have occurred within the historical record (e.g., 1929 Grand Bank earthquake, M7.1). Mazzotti and Adams (2005) suggest a seismic moment of 1.0-1.2 x 10^{17} Nm/yr (a >M7 earthquake every 50 years) for the entire Eastern Continental Margin. This elevated seismic potential along the margin Mazzotti (2007) attributes to be in part related to remnant glacial rebound strain and in part inherited from old tectonic terrains (Mazzotti 2007). In this slope environment, ground shaking can remobilize sediment and cause massive landslides (Mosher et al., 1994), as it did in the 1929 event (Piper et al. 1988, 1999). Mosher et al (2004) imply glacial isostatic rebound influenced seismicity rates and patterns, leading to increased rates of sediment mass failure on the slope during this period. In the Jurassic collapse of the reef margin has often been attributed to “over steepening” of the reef margin perhaps in association with reef aggradation during sea level rise; however seismic events may also have been a trigger mechanism contributing to failure and collapse.

Glaciation: The first shelf-crossing glaciation occurred about 0.5 Ma along the Scotian margin, and since that time, the continental slope has been dominated by proglacial sediment deposition, with little sediment accumulation at highstands. On the eastern Scotian Slope, the numerous canyons appear to be the continuation of subglacial meltwater channels (tunnel valleys) on the eastern Scotian Shelf (Flynn, 2000), probably derived from meltwater issuing from ice in the Gulf of St. Lawrence. These canyons appear to have been significantly deepened in the past 0.5 m.y., although many were present in the late Tertiary. Ice sheets extended close to the shelf edge at the last glacial maximum (18 ka) and had retreated to the present shoreline by about 12 ka (Stea et al., 1998). Since that time, and with subsequent sea level rise, continental slope sedimentation has been slow, dominated by pelagic and hemipelagic deposition (Mosher et al., 1994).

Major debris-flow and mass-wasting deposits on the continental rise date back at least to the late Pliocene (Piper et al., 1999; Shimeld et al., 2003; Mosher et al, 2010). It is therefore difficult to propose that their origin is closely linked to glaciation. Since the deepening of the canyons on the eastern Scotian Slope in the past 0.5 m.y., the size of debris-flow deposits on that sector of the continental rise appears to have decreased. One reason for this observation may be that canyon cutting permitted better drainage of excess pore pressures on the margin.

Interglacial periods are typically characterised by high sea level stands with hemipelagic deposition of fine-grained sediment that tends to blanket underlying strata, for example at present (a sealevel highstand), there exists a drape of about 1.5 to 2.0 m of Holocene mud across the Scotian Slope (Mosher et al. 1994).

OBJECTIVES

Reservoir distribution is the greatest risk element facing development of the "deepwater" offshore Nova Scotia. There is a proven petroleum system in the region; Annapolis showed hydrocarbon-bearing sands but had limited net to gross and a delineation well failed to refine understanding of the system; Crimson failed to find appreciable sands. Sediment delivery to continental margins is highly dependent on sea level systems tracts and processes inherent in them. Conceptual models for marine clastic passive margin settings have underestimated the role of shelf-slope interplay and slope processes in delivering potential reservoir rock to the continental margin. Understanding the linkages between shelf sediment capture/delivery, the role of shelf margin deltas, the interplay of carbonate and siliciclastic depositional systems, sea level and slope processes is critical to detecting reservoir rock distribution in deep and ultra-deep water. The Scotian Slope demonstrates a history of canyon and channel cut and fill, and sediment mass transport. These processes likely link to a variety of relative sea level stands in combination with seismicity and other causative factors.

In most offshore basins around the globe, sequence stratigraphic approaches have been applied to develop basin models with respect to source and reservoir rock distribution (Mitchum and Wach, 2002). Application of these principals in the case of the Scotian margin has not been entirely successful; in part because efforts have been fragmented within different license blocks and in part because of the complexities presented in the *Geologic Setting* discussion above. It is an objective of this study to help minimize reservoir risk for hydrocarbon exploration offshore of Nova Scotia by using existing stratigraphic understanding and new seismic 3D data sets to study depositional system analogues on the Scotian margin. This infers understanding the relative importance of depositional processes in their stratigraphic context, and how these processes and resulting deposits affect development of a sequence stratigraphic framework. This study examined the Cenozoic sedimentary section as a depositional and stratigraphic analogue, because spatial and temporal resolution is not at issue and geologic events are better age-constrained.

In addition to these scientific objectives, it was the intent of this project to contribute to training of highly qualified personnel in latest technologies and concepts that would be readily applicable to industry and provide grass roots experience in the exploration basins offshore Nova Scotia. A total of five MSc and PhD studies were directly supported through this project.

METHODOLOGIES

The primary method of investigation for this study was interpretation of industry-supplied confidential multi-channel seismic reflection data. Five 3D seismic volumes distributed across the Scotian margin, and an extensive grid of 2D seismic data were interpreted for this study (Fig. 4). In addition, 2D and 3D seismic data from offshore Suriname, as a modern analogue margin, were studied. 3D seismic volumes were supplied by Encana, ConocoPhillips and Repsol USA. 2D seismic data were supplied by TGS-Nopec, Repsol USA and the Geological Survey of Canada (GSC). Seismic interpretation licenses were supplied by Seismic MicroTechnology (SMT), Schlumberger and the GSC. Interpretation workstations were provided via funding in this proposal and by the GSC. Additional data included a regional grid of multibeam data for the Scotian margin, supplied by the GSC, and sediment core and well results also largely supplied by the GSC. The Abenaki and Sable data were provided by Shell, Encana, and IOL-ExxonMobil. We are grateful to the CNSOPB for access to the CNSOPB Geoscience datacentre to view public data, including, seismic, logs, cuttings, and cores.

Seismic interpretation techniques involved seismic facies analysis and conventional horizon correlation to establish sequence boundaries with ties to well control where feasible. They also included utilization of modern techniques of attribute analysis (for example semblance, coherency, and maximum dip), particularly for the 3D seismic volumes. Additionally, developmental principles of seismic geomorphology were applied; utilizing detailed surface renderings extracted from 3D seismic volumes in order to use geomorphological elements to interpret sedimentary processes. Biostratigraphic picks are based on ties, for example, to the Shubenacadie H-100 and Acadia K-62 exploration wells.

As an example of the seismic data analysis methodology, the study of the Greater Laurentian Channel region involves interpretation of multibeam and 2D and 3D seismic reflection data. Multibeam data are available in the greater Laurentian Fan region, from the shelf break to about 3000 m water depth. Resolution varies with water depth but on average sounding density is on the order of one sounding every 100 m2. These data allow interpretation of surficial geologic processes. Both industry and GSC 2D seismic reflection data were used in this investigation. These data provide the regional stratigraphic and structural framework and/or high resolution sub-bottom imaging. The Laurentian East 3D seismic volume is a 1505 km2 area in the Halibut Channel region on the east side of the study area. Data were acquired with a 25 x 6.25 m bin size, a record length 5.5 s (for this investigation), and a sample rate of 2 ms. These data, although restricted in area, allow detailed 3D visualization of sedimentary deposits to fully understand processes of formation and stratal/lithologic relationships.

For the Abenaki carbonate platform and Sable delta analysis a transgressive-regressive sequence stratigraphic framework rather than Exxonian model was employed. Schematic lithologs are used to show facies changes vertically between sequences on sections, laterally within a sequences on maps and for well to seismic control. Detailed logging and interpretation of cuttings and sparse conventional and sidewall cores control provided critical information for depositional modeling. In carbonates with their uniform mineralogy it is only by closely looking at the rock, not just petrophysical logs or seismic, that depositional and diagenetic conclusions can be made. All SWC's had thin sections that also were examined.

A Leitz binocular microscope with a polarizer substage option was used to examine cuttings at the usual sampling depth intervals (10 feet, 5 metres). Petrophysical logs assisted in interpretation of the cuttings and over lost circulation intervals. In the Abenaki Formation all available cores, post-1998 sidewall cores were logged and photographed, and also all cores from the Baltimore Canyon wells. Thin sections from the Deep Panuke area were examined and photographed. Well litholog plots using a custom Excel spreadsheet were made with plots of key frame builder fossils and transferred to schematic depictions. Schematic logs of important litho/biofacies were compared to mechanical logs and standard and digital cross sections were constructed of various vintages to establish correlations, sequence breaks and lithofacies relationships. Publicly available seismic particularly from Kidston et al. (2005) and published EnCana sections were used for well correlation. Lithofacies data were plotted as pie diagrams using principal lithologies, Dunham classification, certain allochems (oolite, microbial/peloidal) and key frame builder content. These pie diagrams were grouped by sequence intervals for display next to schematic logs on well sections and on sequence stratigraphic layer maps.

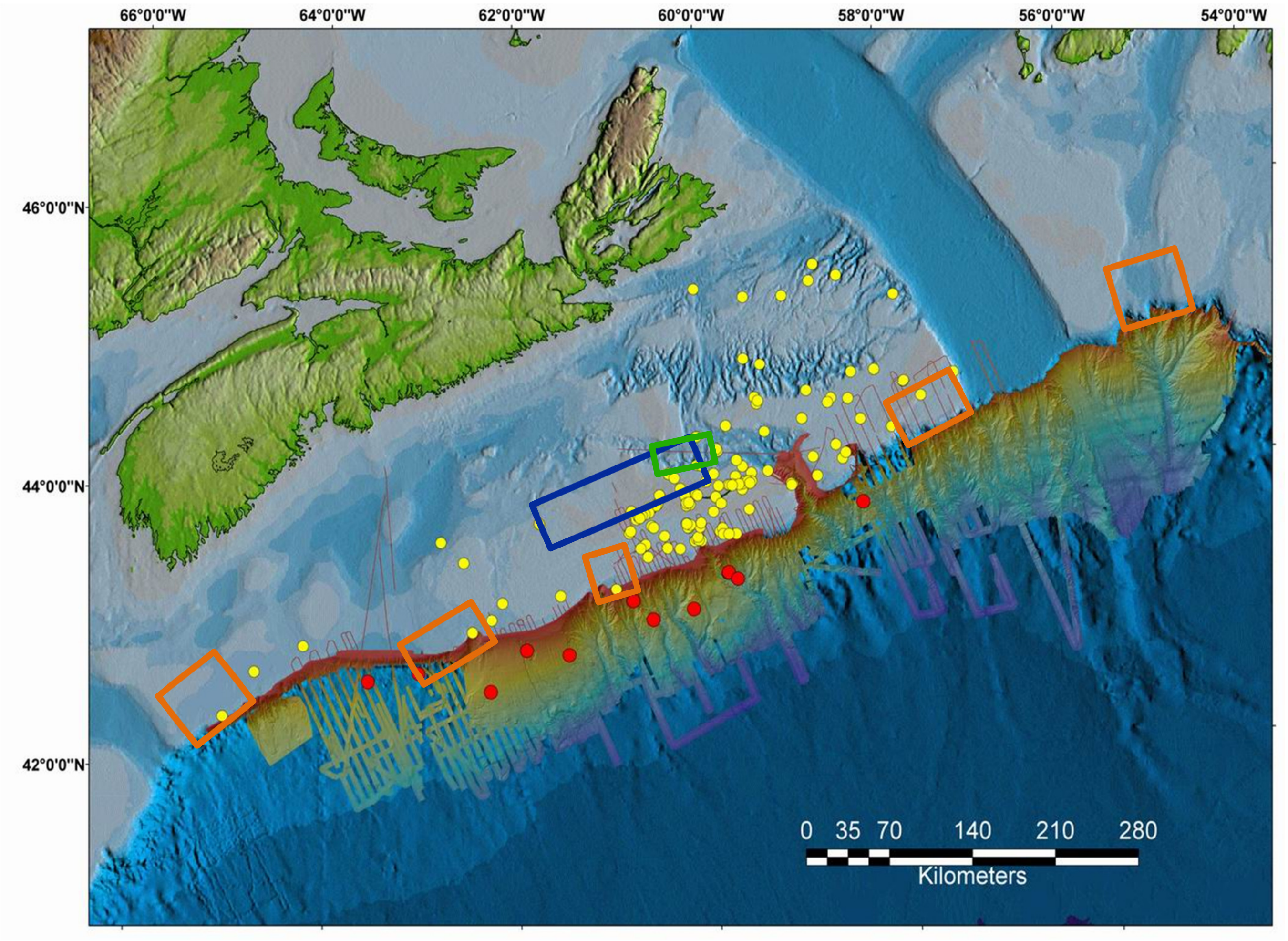


Figure 4. The modern seafloor bathymetry of the Scotian margin shows numerous canyons. Red polygons are 3D seismic volumes used in this study. Black lines are 2D seismic track lines (TGS-NOPEC). Yellow dots are exploration wells on the slope.

RESULTS

Activities

To achieve the objectives outlined above, the project was divided into activities, each activity delivered by graduate student research as a thesis or dissertation topic, or by the principal investigators and the summation of the research conducted by the PIs. Research activities included:

I Shelf to Slope Linkages: establishing the regional sequence stratigraphic framework.

The research objectives within this activity included:

1) temporal and spatial distribution of sedimentary facies, and
2) delivery/sedimentation processes through discovery of analogue systems.

Calvin Campbell (PhD candidate) is conducting the principal component of this research with a tentative dissertation topic entitled " *Investigation of middle Cenozoic unconformities along the western Scotian margin: The interplay of down-slope and along-slope processes*". Additionally, a related study to investigate an analogous margin was undertaken. The Suriname margin is the last vestige of the proto-Atlantic and its post-rift sedimentary sequence is young and unaffected by subsequent tectonic processes. Shawn Goss, as part of his MSc thesis, completed a study on the "*Cenozoic seismic stratigraphic analysis of the Suriname margin, South America"*

II Laurentian Channel/Fan depositional system.

Research objectives within this activity included study of an area of known high sedimentation rates and historic mass failure to study mass transport process, frequency, and contribution to slope and base of slope sediment accumulations. Michael Giles completed an MSc thesis entitled "*Mass Transport Processes in the Greater Laurentian Channel Region*" as a significant contribution to this activity. In addition, Mosher et al (2009, 2010 and in press) documented several mass transport deposits along the Scotian margin, providing understanding to the process and its relevance in this region.

III Canyon depositional systems: Stonehouse 3D cube, eastern Scotian Slope

This activity was meant to increase understanding of the role of erosional systems, such as canyon formation, on the movement of material to base-of-slope regions and the subsequent provision as a corridor for sediment slope by-pass. Virginia Brake conducted her MSc thesis on the "Evolution of an Oligocene Canyon System on the Eastern Scotian Margin", providing evidence of multiple phases of canyon cut and fill.

IV Relationship of the Abenaki Reef and Sable Delta

The complex interplay of a carbonate/siliciclastic depositional system such as the Sable delta is the subject of this investigation. This environment is atypical in the geologic record and not well known to exploration geologists. The "*Abenaki Formation Carbonate Margins and Sable Island Delta Influence – offshore Nova Scotia, Canada and Baltimore Canyon Trough, USA"* is the subject of a PhD dissertation by Les Eliuk.

DISCUSSION

For the Scotian margin, application of conventional seismic sequence stratigraphic methods has proven difficult to apply because of the dominance of erosive processes. Such processes include numerous episodes of canyon cut and fill coupled with slope bypass, mass transport reworking and re-deposition, and along-slope sediment erosion and transport by deepwater contour currents (contourites). These poorly understood processes dominate over sediment input and sea level controls and greatly impact the preserved stratigraphic record with significant spatial and temporal variation.

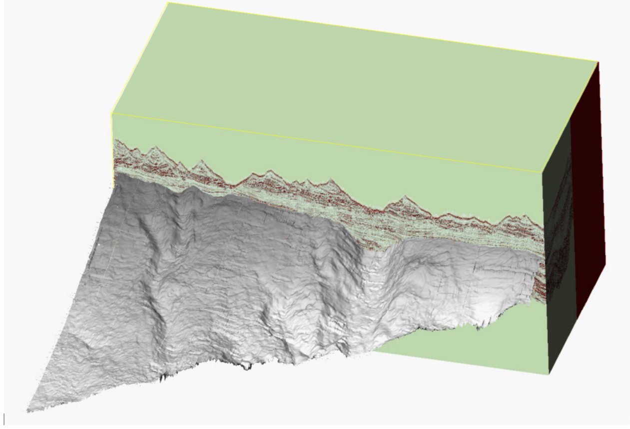


Figure 5. A 3D surface render of a presumed Oligocene canyon system on the Scotian Slope (from Brake, 2009)

The modern seafloor of the eastern Scotian Slope is heavily incised by canyons and valleys, providing recognizable conduits for off-shelf sediment transport, slope by-pass and deposition on the continental rise and abyssal plain (Fig.1; Mosher et al., 2004; Jenner et al., 2006). Canyon incision appears to have been episodic throughout the Cenozoic, involving multiple phases of cut-and-fill with new systems often re-occupying old, perhaps in response to underlying

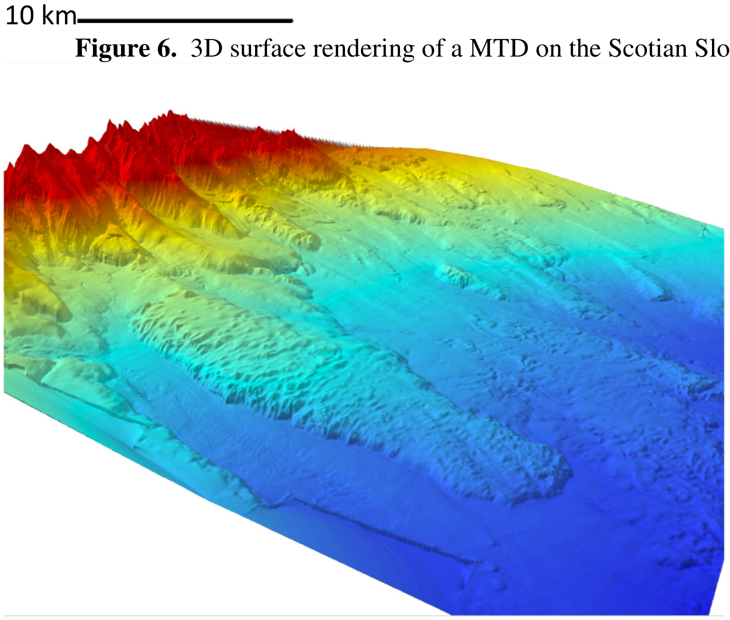


Figure 6. 3D surface rendering of a MTD on the Scotian Slope.

basement control (Brake, 2009) (Fig. 5). This episodic canyon incision indicates a limited residence period of sediments on the shelf and slope, having implications for potential reservoir distribution.

Mass transport processes (Fig. 6) are a fundamental aspect of continental slope construction (Mosher et al., 2010; Giles et al. 2010). Their deposits are enigmatic depending on hydrocarbon type (gas or oil). They may produce a good seal to reservoir facies, dependent upon sand, silt and clay content and may lead to down-dip high density turbidite facies which may form reservoirs. The magnitude of sediment redistribution by contour-currents (Fig. 7) was only recently recognized along this margin (Campbell et al., 2009, 2010). This process leads to difficulty in predicting sediment distribution patterns and ultimate prospectivity for hydrocarbons. The prospectivity of the base-of-slope is unknown but it is a region dominated by mass transport and turbidite deposition (e.g. Fig. 8).

Despite these complexities in sedimentary processes, there are consistencies in depositional patterns across the margin and Atlantic-wide paleoceanographic events permit establishment of a broad stratigraphic framework. For example, a major Eocene canyon cutting period and a mid-Miocene bottom current intensification period provide stratigraphic markers despite having varying depositional signatures across the margin. These results indicate the need for regional comprehension of the margin that includes ties to global paleoceanographic events.

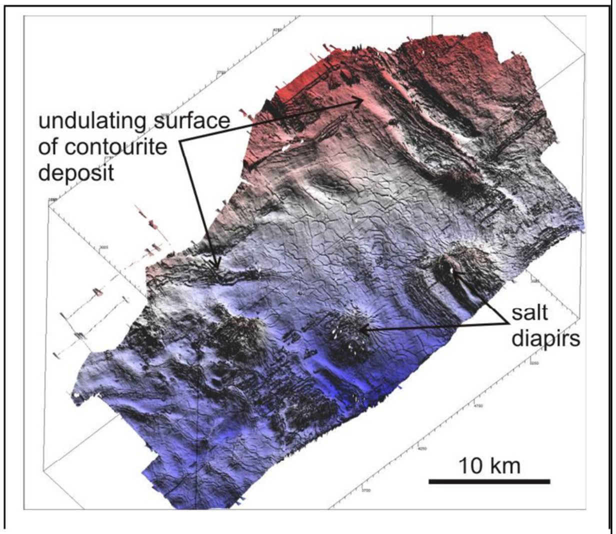


Figure 7. 3-D surface rendering of a seismic horizon illustrating contourite deposits and salt diapirs (from Campbell, in prep.).

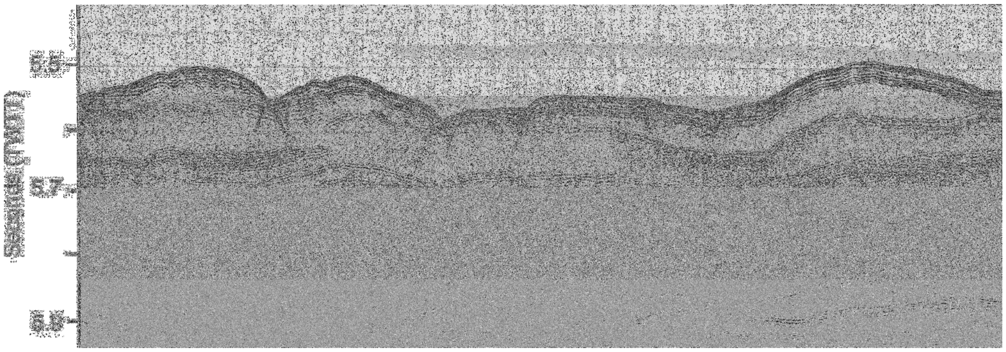


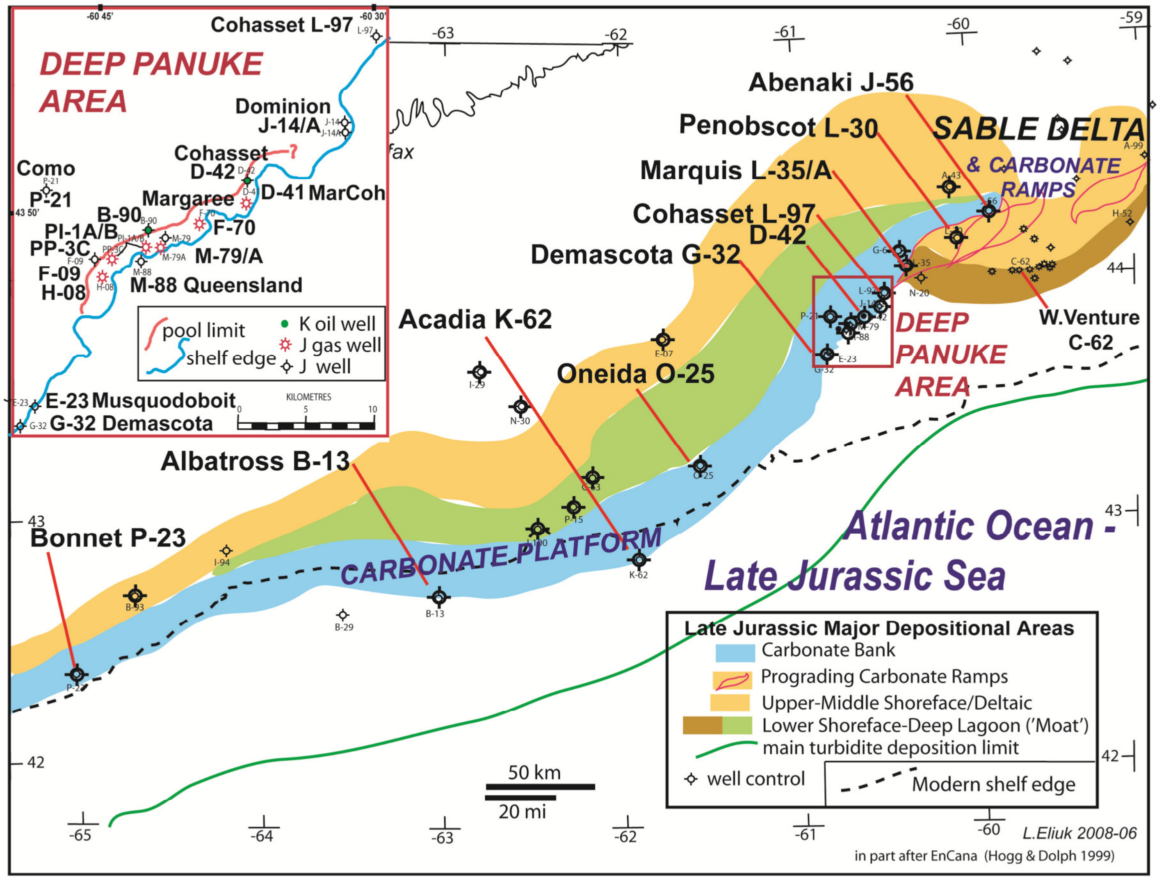
Figure 8. Seismic profile of stacked MTDs on the Scotian continental rise.

Carbonate Platform- Sable Delta relationship

Offshore Nova Scotia's most recent gas discovery at Deep Panuke (Fig. 9) has doubled the amount of near margin well control. Recent reviews and publications on the petroleum geology, sequence stratigraphy and reservoir diagenesis has put in the public domain data an understanding of the field itself. But its broader regional setting and the seemingly anomalous location of thick clean carbonates beside one of the largest paleodeltas on the North American Atlantic offshore remain to be understood. Rock data and interpretation from well core and especially cuttings were compared to petrophysical logs and integrated with publicly available seismic to update and further understand the Abenaki Formation carbonate platform margin particularly in proximity to the contemporaneous Sable island delta. The carbonate platform has an aggrading relatively stationary margin in contrast to the Sable delta area (Fig. 9) where prograding mixed carbonates-siliciclastics flank the Sable deltaic depocentre. The trace of the modern shelf edge is a first order approximation of the varying influence of Jurassic and subsequent Early Cretaceous deltaic sedimentation that encroaches then buries Deep Panuke but wanes to the southwest.

Vertical changes occur over more than a kilometre of carbonate where standard dip-oriented carbonate facies template can be updated and applied. But along-strike lateral variation occurs away from the delta. Facies parameters represent a variety of margin facies-associations from oolitic to margin reefal to carbonate slope. Most obvious are systematic color changes but include types of reefs and indicate that the close juxtaposition of delta had a significant influence on carbonate platform and its margin reservoirs.

At the other scale extreme within the deltaic complex, in less than 10 m of core, a reef type change vertically with thin condensed limestones that aid in understanding the sequence stratigraphy of the Venture shelf margin delta. Deep Panuke is in the centre of these changes along the margin. So not only is it a unique gas accumulation for the North American continental shelf, it may constitute a unique or at least very rare hydrocarbon system worldwide. Understanding the depositional facies relationships and process controls that allowed this close association of reefal-oolitic carbonate platform margin and large deltaic complex will help increase its relevance as an analogue for further exploration on the Nova Scotian shelf and elsewhere in the world.



L.Eliuk 2008-06

in part after EnCana (Hogg & Dolph 1999)

FIGURE 9. Study area with Abenaki Formation wells in bold and generalized major depositional areas. Newer wells (1998+) are in the Deep Panuke area (inset map) with one of the first margin wells Cohasset D-42 actually in the pool and the other Demascota G-32 that cored all 3 reef types downdip. The only post-1998 Abenaki wells outside the inset map are Marquis L-35 and its basinward whipped follow-up L-35A.

Queensland M-88 (Fig. 10) was drilled on the carbonate slope basinward of the Deep Panuke field to test for by-pass sands that turned out to be shale. Depositional sequences approximate those of Weissenberger et al. 2006. M-88 is located immediately in front of the Deep Panuke gas field on the forereef slope and has a mixed carbonate-siliciclastic composition with fine clastic content increasing upward and sometimes coarsening. The transgressive-regressive (deepening-shoaling) cycles are interpretive. Note that the thicker carbonates are dominated by microbial and peloidal textures that with the seismic can be used to identify distal deep carbonate slope setting. The sequence transitions are identified by thin, deeper-water reefal beds such as lithistid sponges but by typically shallower stromatoporoid coralline sponges for AB4. These are very unlikely to be unconformities but rather the shallowest events in transgressive-regressive successions. Minor oolite at 9620m (AB6) likely is lowstand shed debris from the shelf. Typically thin limestones are considered condensed maximum flooding surface marker. The basal dark shales indicate a rapid deepening with some carbonate also part of the transgressive event.

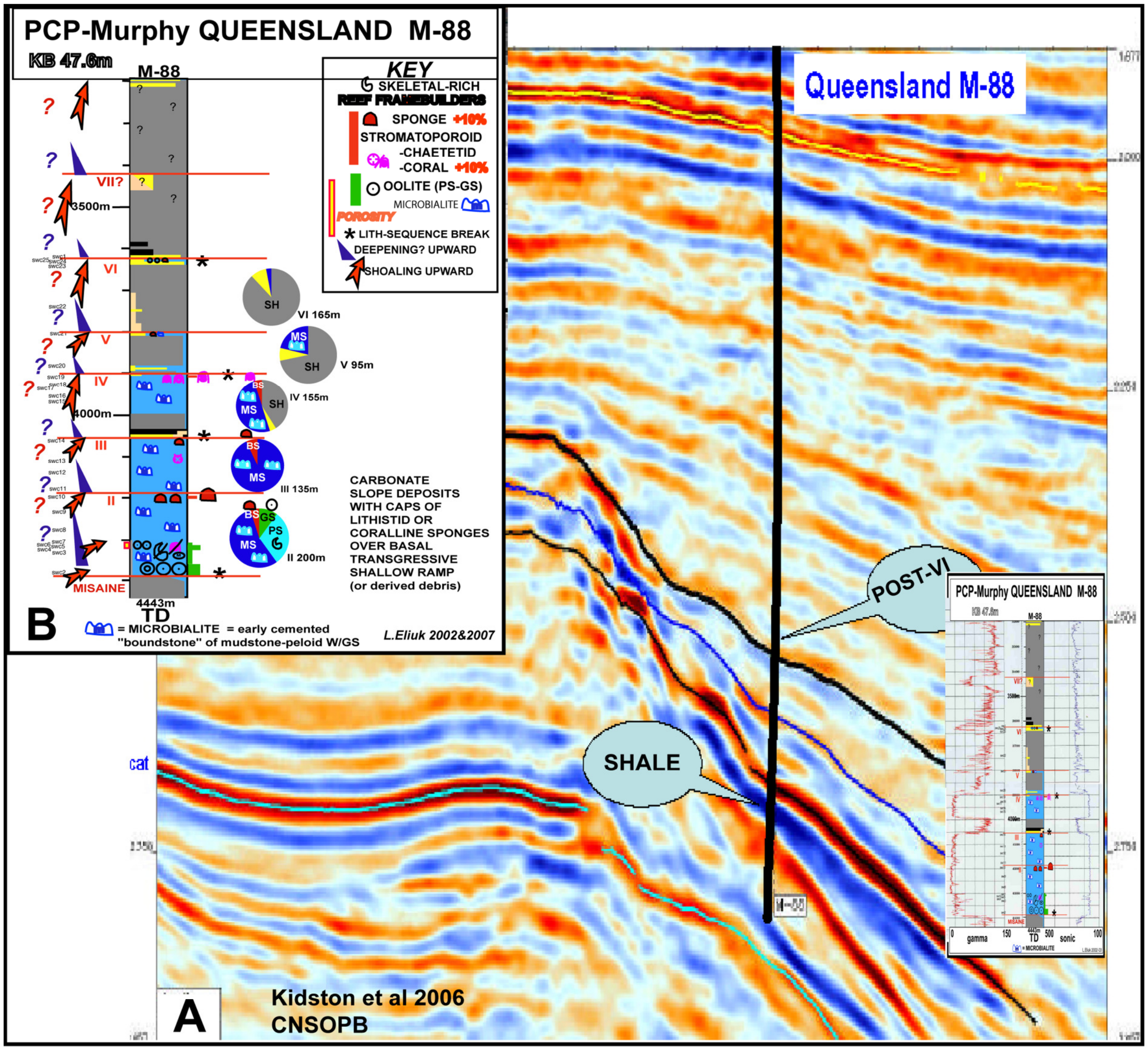


Figure 10. Queensland M-88 of Deep Panuke area - **A**) dip seismic section (Kidston et al. 2005) with lithology-gamma-sonic log insert, and **B**) schematic lithologic column with pie charts of lithofacies.

The Abenaki Formation AB is the main reservoir-bearing sequence in the Deep Panuke field (Fig. 11). The data show significant variation within the field area and even adjacent wells. On a near well basis the main changes are often dolomite content and thus reservoir. Oolite and reefal boundstone (e.g. M-79) if not dolomitized are often not porous. But in M-79A the far end of the whipped well encountered significant porous dolomite re-interpreted post-well on the 3D seismic. Beyond the field to the northeast, Dominion J-14 drilled shale rather than seismically-inferred porosity and when whipped near horizontally southwest, the technical success of finding stromatoporoid reef limestone did not find porosity. The importance of this local highly-variable dolomite porosity is highlighted by the oldest Abenaki margin well Cohasset D-42 abandoned within the field in 1973. At an areally more extensive level, four major areas can be defined by the lithofacies– 1) distal slope shales and microbial lime mudstones/mounds at M-88 and J-14), 2) tight oolitic limestones on the inboard flexure at F-09, B-90 (discovery well of shallow Panuke oil) and P-21 (shelf interior), 3) carbonate-encased reefal pinnacles-ridges and proximal upper foreslope dolomitized grain/packstones (dipping landward) at M-70 shows a deepening-upward series of thin reeflets on dipping carbonate slope sands, D-41 (topmost Abenaki faulted out) and J-14A and finally 4) at D-42 and the remainder of the field wells to the southwest a variety of margin lithologies including oolite, reefs and proximal slope-reef flat sands deposited as a series of shoaling parasequences (Weissenberger et al. 2006).

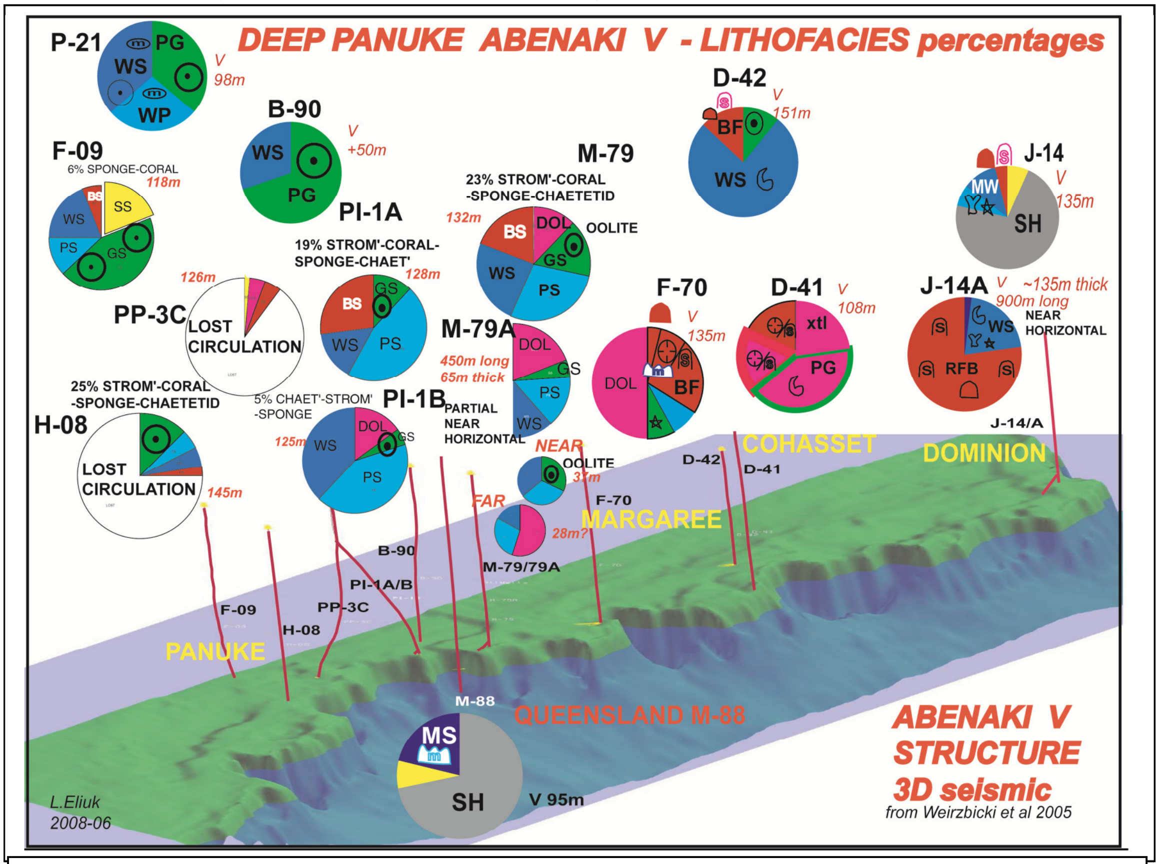


Figure 11. Map of Abenaki Formation AB 5 - the main reservoir-bearing sequence, in the Deep Panuke field shown by 3D seismic structure with lithofacies pie diagrams above the well locations (after Weirzbicki et al 2005).

DISSEMINATION AND TECHNOLOGY TRANSFER

Though the worldwide dissemination of the results of the research through scientific publications and presentations at academic and industry forums (e.g. American Association of Petroleum Geologists and Canadian Society of Petroleum Geologists) and the chairing of the largest petroleum research conference ever held in Eastern Canada, we have ensured the widest possible exposure of the Scotian Margin to the Petroleum Industry. Our student graduates will continue this legacy with their roles as new employees in Industry and Government.

Efforts at disseminating the results of this projects research have been highly successful. Technology transfer has been achieved not only through these efforts, but through the training of five M.Sc. and Ph.D. graduate students and student research assistants in advanced stratigraphic, sedimentologic, seismic and petroleum technologies. The training and skills they have received are highly sought by Industry and all received offers of full employment prior to graduation and completion of their theses. Employment includes ExxonMobil (Houston), Geological Survey of Canada and McGregor Geoscience.

Several of these students have won awards and scholarships in recognition of their achievements. There have been over 70 publications, abstracts and presentations that have culminated from this research project and this is continuing past the end of the project with presentation at the 2nd Conjugate Margins Conference of the Central Atlantic, Lisbon, Portugal, in September, 2010.

Conjugate Margins Conference- Halifax 2008; August 13-15, 2008, Dalhousie University, (Grant Wach Co-Chair and Co-Organiser).
The second year of the Project began with the resounding success of the Conjugate Margins Conference. This was a key venue for presentation of interim results and the project team met their targets with 16 oral and poster presentations related to project research that were appended to earlier reports.

A total of 93 presentations were given at the Conference: Oral (45; 6 keynotes), Poster (41), and Core Workshop (7). Approximately 215 delegates were registered for the conference coming from 17 countries. Over half were from the petroleum industry representing 26 E&P companies, and twenty (20) seismic, research, service and consultancy firms. Other delegates represented government surveys, agencies and departments (7), universities (19) with the remainder either unaffiliated, emeritus or retirees. We were particularly pleased with the number of students, their participation and excellent presentations. Participants taking in the two field trips, two short courses and the core workshop were unanimous in praise for the high quality of these events.

A complete list of publications, abstracts and presentations is included with this report.

CONCLUSIONS AND RECOMMENDATIONS

Stratigraphic Framework: : Conventional sequence stratigraphic models developed and tested on other passive margins (e.g. Niger Delta and Fan, Mitchum and Wach, 2002) are difficult to apply along the Scotian Slope. Correlating beyond the Cenozoic and present-day shelf breaks, with the dominance of canyon cutting, mass transport reworking and re-deposition, and along-slope sediment transport by deepwater contour currents (contourites) make conventional sequence stratigraphic concepts difficult to apply. These poorly understood processes dominate over sediment input and sea level controls and greatly impact the preserved stratigraphic record with significant spatial and temporal variations. Nonetheless, there are consistencies in depositional patterns across the margin that provide the basis for a stratigraphic framework. For example, canyon cutting events, episodes of contour current intensification, and periods of sediment infill appear to correlate along the margin. Additionally, global oceanographic events, such as large eustatic sea level excursions and bottom current intensification, are apparent along the margin and throughout the Atlantic such as at the equatorial Atlantic site (ODP, site investigations and Suriname margin studies). Along the Suriname margin, Cenozoic sedimentation is controlled by sediment supply and relative sea level position. These control events provide broad stratigraphic markers along the Atlantic margin that assist in the establishment of the stratigraphic framework.

Analogue Margin Studies: Data from analogue studies from the Suriname and Grand Banks margins demonstrate that a sequence stratigraphic model is possible to develop on a continental slope-shelf transition; however, subsequent subsidence (salt tectonics), compaction (Sable Delta) and erosional episodes (canyons) may overprint the original stratigraphic architecture. In contrast, the Suriname margin demonstrates relatively complete stratigraphic successions with correlatable bounding surfaces and a well-developed Cenozoic sequence architecture (Fig. 8). With completion of each of our in-depth studies along the Scotian margin, a better understanding of the relationships of stratigraphic elements has unfolded.

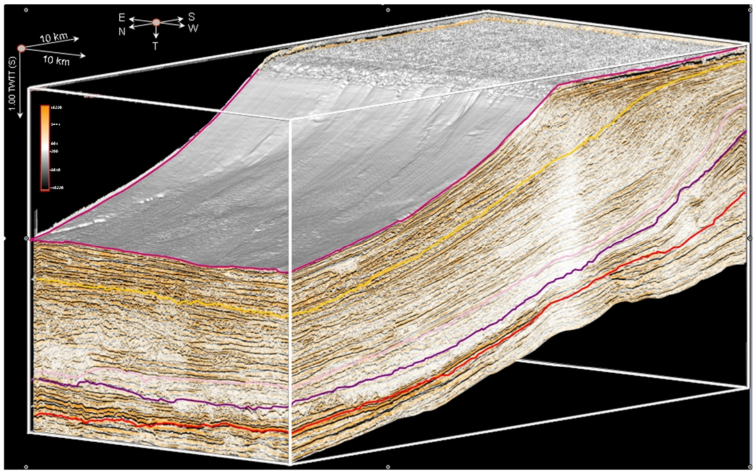


Figure 8. 3D perspective view of the seafloor and subsurface reflection patterns, outer shelf and uppermost slope, offshore Suriname.

Mixed Carbonate Platform and Deltaic Successions: All passive continental margins have an underpinning geologic platform that dictates their broad geomorphologic character and to some extent controls subsequent sedimentation patterns. These building blocks can control the margin's hydrocarbon potential. The Abenaki Carbonate platform underpinning the Scotian margin controls subsequent sedimentation patterns. Sea level is recorded within the platform with subsequent unconformities and deltaic bypass sands. **Sediment loading** of the platform has and continues to play a significant role in controlling underlying **salt migration** that impacts sediment pathways along and across the slope. The relationship of reefs and deltas is generally thought to be one of complete incompatibility, but the Scotian margin is an exception. Detailed examination of all well and seismic data, coupled with outcrop and subsurface analog studies are providing the scales of the architectural elements and identifying stratigraphic anomalies to help address the fundamental question, is there adequate high resolution stratigraphic age control? Our research has improved the quality of the stratigraphic and facies control.

Abenaki Carbonate Platform and Sable Delta Petroleum System: Deep Panuke is possibly unique, situated in a kilometre thick attached platform of continuous carbonate, adjacent to a large delta (Fig. 12). Typically, bathymetric or tectonic lows act as siliciclastic sinks to prevent burial or environmental deterioration of the carbonate. Over time the delta does bury some of the Abenaki platform and proximal burial seems to occur in shallow water where oolite occurred. But in the Deep Panuke area there is a zone of capping sponge reefal beds that grew in deeper water adjacent to prodeltaic shales. In the distal settings the platform drowned prior to onset of sponge-rich sediments or even in their absence as indicated by red coated ironstone ('Fe-oolite') beds. On the Western Shelf far from the delta, carbonates growth continued even as they were temporarily drowned or exposed on the seafloor before eventual burial in by younger shales.

The hydrocarbon history has aspects of a delta, such as capping prodelta beds to give lignitic-humic source rock and seal with the reservoir and trap the carbonate reef margin itself. But perhaps due to early cementation in the highly saturated late Mesozoic calcite seas and burial cementation from the rapid and deep burial in deltaic sediments; the adjacent updip platform limestone, even the oolite, is non-porous. Thus it acts as a lateral seal giving a partial stratigraphic trap. Prior to deposition of the prodelta shales, the argillaceous sponge reefal beds also performed as a top seal. At the Dominion J-14 well, there is an anomalous shale pod in the shelf margin that acts as a lateral 'plug'. Dominion J-14A side-tracked near horizontally from J-14 found shallow reef but no dolomite nor porosity over one kilometre. The shelf margin position localized by probable underlying tectonic paleohighs makes fracturing and faulting both likely but highly variable. This provided migration conduits for dolomitizing fluids and later hydrocarbons resulting in a deeply buried reservoir and gas accumulation.

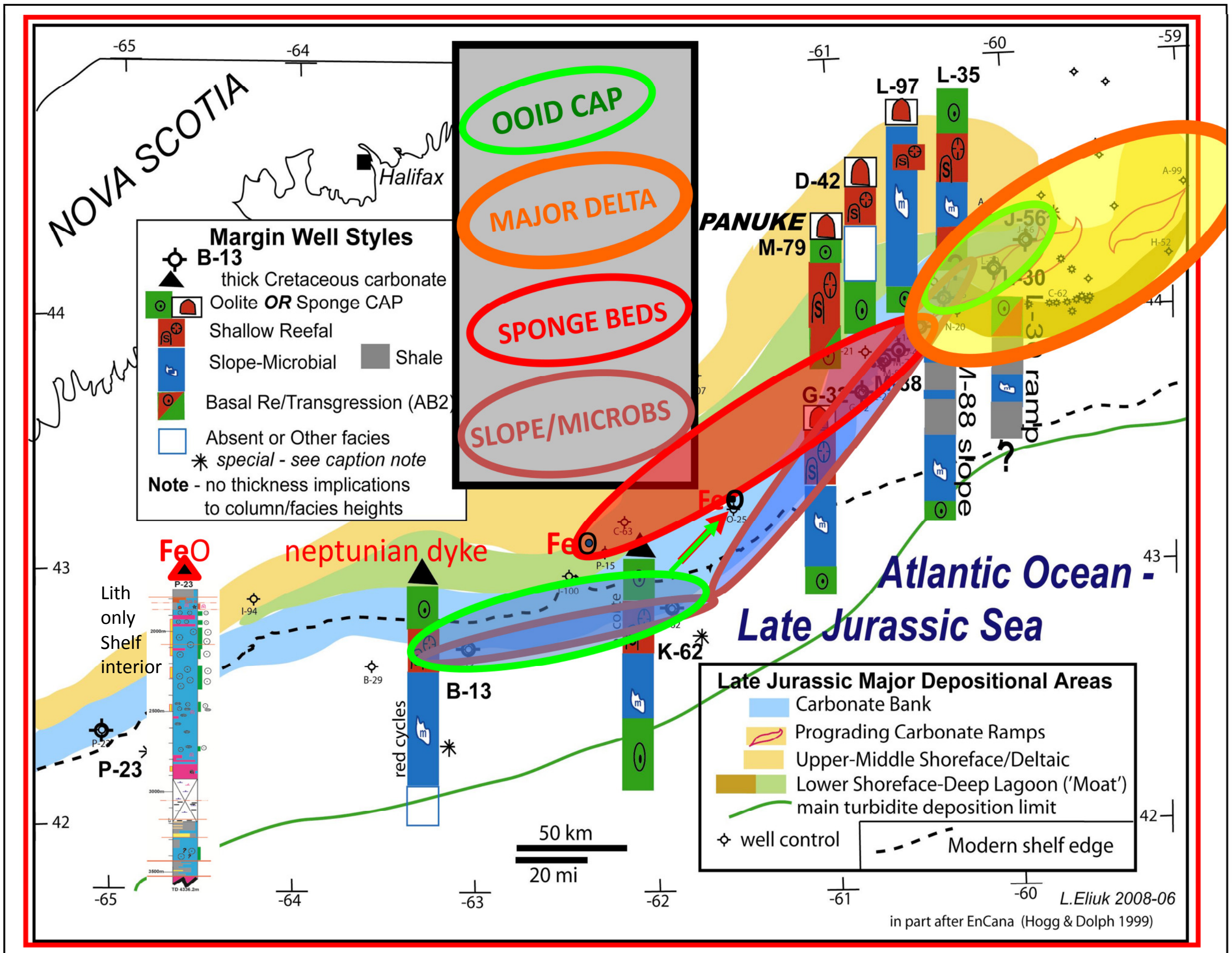


Figure 12. Map of carbonate margin well styles and major capping facies showing the large scale shoaling pattern in most wells after an initial transgressive oolitic limestone above the Misaine Shale Member. In the Panuke area and in some interior wells further southwest, the Abenaki is capped by thin argillaceous sponge-rich beds that are younger away from the delta. These formed in deeper water over a drowned carbonate platform. Oceanographic-deltaic stresses may be indicated by the oncolitic zone. In contrast to the capping older (?Late Jurassic) oolite beds that are interbedded with sandstones near the Sable delta, the Western shelf oolite beds are much younger (possibly Barremian which is the age of the O Limestone within the Missisauga Formation Sable deltaic sediments), lighter-coloured to even white and lack sandstones. Near vertical open fractures in oolitic limestone with thin red geopetals are interpreted as neptunian dykes from eroded capping marine redbeds. In P-23 the carbonate platform is capped by red iron oolite indicating younger drowning and slow seafloor sedimentation/diagenesis. These relationships can be interpreted to indicate long-continued north-eastward-directed currents that winnow and even erode the carbonate platform after its drowning during at least two different times. Such currents would also keep fine clayey sediment of the Sable delta away from the carbonate platform during its growth. Such an oceanographic or wind-driven flow may help explain the much different style of the Abenaki carbonate shelf northeast of the Sable Delta where thick sandstones interbed with yet thicker carbonates. These lateral changes along the margin controlled in large part by the adjacent Sable delta that also gave early burial at Deep Panuke resulted in a possibly unique hydrocarbon system for that reef margin gas accumulation.

Reservoir distribution and quality: The principal source of sediment for continental slopes is the adjacent shelf with sediment is delivered during low sea level stands. The **Sable shelf margin delta** provides reservoir sands to deeper water. Progradation of the Sable delta to the shelf edge was controlled in part due to localized accommodation controls from differential mobilization of the underlying salt.

Margin erosion and reworking: Along the Scotian margin, sediment distribution is influenced predominantly by **mass transport deposition**, **sediment by-pass through canyons**, and sediment redistribution by strong **deep-water contour currents.** Canyons and mass-transport processes provided mechanisms for slope bypass and delivery to the rise and abyssal plane. **Mass transport deposits** are enigmatic depending on hydrocarbon type (gas or oil). They may in fact produce a good seal facies to reservoir facies, dependent upon sand, silt and clay content within stratigraphic intervals. Sediments deposited by contour-currents were only recently identified along the margin, leading to difficulty in predicting sediment distribution patterns, and ultimately prospectivity for hydrocarbons. Significant deep water margin erosion occurred at certain periods, apparently related to development of strong along-slope bottom currents. These currents were responsible for removal and redistribution of vast amounts of material. The prospectivity of the base-of-slope is unknown but it is clear that this too is dominated by mass transport deposition which strongly affects the stratigraphic distribution and sedimentary architecture. The broad correlation of sedimentary processes across the margin provides for some consistency in interpretation with reasonable predictability of sediment type on the large scale.

These processes indicate that reservoir-grade sediments can be reworked, relocated and transported to great water depths and offer significant challenges to reservoir detection along the Scotian margin. A thorough understanding of the interplay and complexity of these processes is necessary to develop and apply exploration models. The obvious consequence if such hypotheses are validated through this study is that exploration must move to deeper water where shelf-equivalent rocks are transported and deposited.

Recommendations

The following recommendations support the need for regional understanding for hydrocarbon exploration and development along the Scotian Margin.

Seismic and Well Data Integration- For example, Eliuk has made extensive use of the Kidston et al. (2005) seismic-based Abenaki study with well summaries and has noted the seismic geometries and interpretation are usually compatible with Eliuk's lithofacies but occasionally a significant difference may indicate an area of late structure or even an overlooked prospect. A means of disseminating comparative well and seismic analysis would be helpful to explorationists.

Depositional processes- The impact of depositional processes such as canyon cut and fill coupled with slope bypass, mass transport reworking and re-deposition, and along-slope sediment erosion and transport by deepwater contour currents (contourites) are poorly understood and need further investigation for the impact and control they have for reservoir distribution along the margin. This study shows that these processes dominate over sediment input and sea level controls and greatly impact the preserved stratigraphic record with significant spatial and temporal variation.

Mass Transport Deposits (MTDs)- Potential hydrocarbon exploration on the southwestern could use the preserved turbidite deposits as an analogue for deeper reservoir targets along the Margin. Turbidite deposits within stacked MTDs and are typically preserved in "minibasins" associated with salt withdrawal. These deposits may be small but they could occur as several stacked reservoir targets and should be further investigated as reservoir targets for hydrocarbon exploration.

Some of the Cenozoic MTDs from the margin may be sand-rich deposits and suggests MTDs in the deeper basin may have reservoir potential but this is unknown until the interval is sampled during future exploration programs.

Another play concept for reservoir-prone sediments would be on the lower slope. Evidence of channels on the top of Plio-Pleistocene MTDs suggests that sediment bypassed the middle slope through channels between failure events and was deposited further downslope.

Lithofacies Studies and Depositional Studies- Further carbonate lithology and depositional studies in conjunction with biostratigraphic studies that support sequence subdivision and dating within carbonates should progress southwest of the Sable delta to the Abenaki platform and for example, investigate the stratigraphic significance thin limestones within the deltaic sediments as facies-and-sequence-stratigraphic indicators. Differences in the major lithologies and the processes that control their distribution and in their biota, will improve detailed correlation between the delta and carbonates, and coupled with biostratigraphic and absolute dating could tie the whole shelf together.

Mesozoic stratigraphy- In all areas future biostratigraphic dating research perhaps in concert with Sr87/Sr86 stable isotope curve dating would give much greater reliability to any proposed sequence stratigraphic framework. This is particularly relevant to Nova Scotia Late Jurassic-earliest Cretaceous dating which has been very problematic because of carbonate-versus-siliciclastic (and Tethys-versus-boreal biorealms) biota differences (for instance see Poag 1991).

Biostratigraphy and Sr87/Sr86 Dating - In all areas increased biostratigraphic control is needed for the Jurassic-Cretaceous intervals. Any new biostratigraphic effort should be coupled with Sr87/Sr86 stable isotope dating to the Phanerozoic curve in early formed stable allochems/fossils with results corroborated to the sequence stratigraphic framework. Calibration to the world-wide curve from early Jurassic to early Cretaceous is problematic as the Western Shelf has an absence of both seismically correlative intra-Abenaki markers and of thin sandstone beds such as used at Deep Panuke.

Mixed Carbonate Siliciclastic Depositional Systems- There is a systematic geographic change in obvious features of those microbialites as related to delta proximity but more detailed analysis on many facets should be completed (see preliminary studies of Dromart 1986; Jansa, Pratt and Dromart 1988/9).

Between the Abenaki platform and areas northeast adjacent to the Sable delta, there are major changes in both the geometric style (aggrading platform versus prograding ramps) and major lithologies (nearly continuous carbonate with only thin or no sandstones near the margin versus interbedded sandstones-shales and limestones). This subdivision, split by the Sable delta depocentre, is such that the name Abenaki should not be applied northeast of the Sable delta. Instead individual ‘unit’ or member names should be applied to the diachronous limestones as they develop on younger prograding Sable delta sediments. But older Late Jurassic dating in some of the furthest northeast wells and the great thickness of the limestones makes this interpretation for the whole area suspect. A study of the limestones and how they relate to the siliciclastics might be a great assistance in understanding the relationship of the Sable and Laurentian paleodeltas. Wells in the South Whale Basin should be included in such a study. Cuttings studies should be undertaken within a team that also includes both a biostratigrapher and seismic interpreter since the relationship across faults and the non-correlative nature of at least the limestone units closest to the Sable depocentre was demonstrated by Wade and MacLean (1990). Recent Dalhousie studies on the timing and style of salt movement relative to Sable delta sedimentation indicate a possibly important component in understanding the lithologic and depositional relationships and alternation. The approach of (Eliuk and Wach 2008) at West Venture in applying an analysis of thin condensed limestones to understanding the facies and sequence stratigraphy of the surrounding deltaic clastics should be applied.

Laurentian Basin- A refined stratigraphic framework should be expanded to the northeast to investigate and test the relationship of the mixed thick siliciclastics -limestones northeast of the Sable delta, to the Laurentian Channel and Laurentian paleodelta area.

Abenaki Carbonates- The paleontological identification of the macrofossil frame builders and their encrusting and cavity dwelling micro fossils has only been attempted in a very limited manner and deserves detailed study. Reef paleoecology and effects of bioerosion suggest broader application to regional studies such as in the case of microsolenids corals.

Carbonate Diagenesis- specialist studies could be pursued on the deposition and early diagenesis of features such as the condensed red iron oolites, early diagenesis of various reefs, e.g. some microsolenids corals-microbialites form limestone in dolomites, Neptunian dyke infill-history and early diagenesis in the sponges-rich beds.

Geohazards Hydrocarbon Exploration and Population Density and Infrastructure- Mass transport deposits on the Scotian Margin and southwestern Newfoundland slope are serious geohazards for hydrocarbon exploration with the potential of blowouts associated with increased overpressure and trapped gas. Submarine landslides are a significant threat to coastal communities and could result in the initiation of a tsunami. The southwestern Newfoundland coast experienced a historic tsunami in 1929 (initiated by the Grand Banks Landslide) which devastated the Burin Peninsula. Today the effects of tsunamis could be far greater with increased population density and infrastructure amongst the coastal communities of Atlantic Canada. Further studies are needed to determine the risk to the people and infrastructure, and procedures and development policies put in place to mitigate or eliminate risks from these geohazards.

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Campbell, D.C., and Mosher D.C. (2010) Middle to late Miocene slope failure and the generation of a regional unconformity beneath the western Scotian Slope, eastern Canada. In: Mosher, D.C., Shipp, C., Moscardelli, L., Chaytor, J., Baxter, C., Lee, H. and Urgeles, R. (eds). Submarine Mass Movements and Their Consequences IV; Advances in Natural and Technological Hazards Research, Vol 28, DOI 10.1007/978-90-481-3071-9, Springer, The Netherlands, p. 645-656.

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March 2010
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March 2010
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(*=illustrated and extended abstracts)

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***Eliuk, L**. and Wach, G. **2009.** Carbonate and Siliciclastic Sequence Stratigraphy- Examples from the Late Jurassic Abenaki Limestone and West Venture Deltaic Beds, Offshore Nova Scotia, Canada (ext. abstr. with 3 figs). Frontiers + Innovation – CSPG-CWLS Convention (Calgary), 4p. for poster May 4-5th (also shown informally at AAPG-SEPM convention in New Orleans on April 12, 2010).

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Wach. G.D. Mosher, D.C., ***D.C. Campbell***, ***M.K. Giles***, ***V.I. Brake*** 2010, Margin evolution and reservoir distribution- examples from Cenozoic of the Central Atlantic margin, American Association of Petroleum Geologists Annual Convention and Exhibition, Program with Abstracts, New Orleans, April 2010.

RPS Play Fairway Analysis Workshop, Halifax, Nova Scotia, May 11-12, 2009.

- **Mosher, D.C.** and **Wach, G.D.*** “Passive” margin sedimentation and reservoir distribution along the Scotian margin.
- **Eliuk, L.** , Abenaki Formation carbonate margin- regional setting of the Later Jurassic Deep Panuke Field.- Presented by **Grant Wach**

University of Malaysia, Kula Lumpur, Malaysia, April 28, 2009.

- **Wach, G.D**. Deepwater reservoir distribution and characterization. Invited Lecture.

Petroleum Exploration Society of Australia (PESA), Perth, W. Australia, April 22, 2009

- **Mosher, D.C**. **Wach, G.D**.* “Passive” margin sedimentation and reservoir distribution along the Scotian margin. Invited Lecture.

Joint GSC-Industry Workshop, February 19, 2009, Calgary Alberta

Mosher presented research to industry representatives (54 in attendance) on east coast activities including student research under OETR

SPE-Petroleum Society Technical Seminar, OTANS 2009 CORE Conference, Tuesday, October 6, 2009, Halifax, Nova Scotia

- *Passive margin evolution and reservoir distribution* David Mosher (Geological Survey of Canada – Atlantic) & Grant D. Wach (Dalhousie University)
- *Continental slope sedimentation models: Laurentian Channel and Halibut Channel regions, Eastern Canada* Michael Giles (Dalhousie University), David Mosher

(Geological Survey of Canada-Atlantic), David J.W. Piper (Geological Survey of Canada-Atlantic), Mladen Nedimovic (Dalhousie University) & Grant D. Wach (Dalhousie University)

- *Middle Cenozoic depositional processes along the western Scotian Margin* Calvin Campbell (Dalhousie University), David Mosher (Geological Survey of Canada-Atlantic) & Grant D. Wach (Dalhousie University
- *Sequence stratigraphic evolution of the Demerara Rise, Suriname, South America: Transition from a rifted to passive margin and possible analogue to the Scotian Slope* Shawn Goss, Grant D. Wach (Dalhousie University) & David Mosher (Geological Survey of Canada-Atlantic)
- *Reservoir quality, diagenetic history and provenance of the Late Triassic sandstones of the Wolfville formation, Bay Of Fundy, Nova Scotia* Yawooz Kettanah & Grant D. Wach (Dalhousie University)
- *Abenaki formation carbonate margins and Sable Island Delta influence, offshore Nova Scotia, Canada and Baltimore Canyon Trough, USA* Leslie Eliuk & Grant D. Wach (Dalhousie University)
- *Biostratigraphic study of Cenozoic strata of the Grand Banks, Newfoundland* Deborah Skilliter (Nova Scotia Museum of Natural History / Dalhousie University), Graham Williams, Robert A. Fensome (Geological Survey of Canada-Atlantic), G.R. Guerstein (Universidad Nacional del Sur), R. Andrew MacRae (Saint Mary's University), & Grant D. Wach (Dalhousie University)

Atlantic Geoscience Society, Wolfville, February 5-6, 2010

- **Wach and Mosher et al**, Margin evolution and reservoir distribution- examples from Cenozoic of the Central Atlantic margin
- **Giles, M., Mosher, Wach** Mass Transport Processes on Slope Sedimentation: Sediment Distribution on the SW Newfoundland Slope, Eastern Canada

American Association of Petroleum Geologists, New Orleans, April 11-14th, 2010

- **Wach and Mosher et al**, Margin evolution and reservoir distribution- examples from Cenozoic of the Central Atlantic margin
- **Giles, M., Mosher, Wach** Mass Transport Processes on Slope Sedimentation: Sediment Distribution on the SW Newfoundland Slope, Eastern Canada
- **Mosher, D**. Regional Slope Stability Assessment: Challenges in Spatial and Stratigraphic Geologic and Geotechnical Data Integration,
- Piper, D.J. Tripsanas, E.K. **Mosher, D.C.** MacKillop, K. Seismic Hazard in Passive Margin Frontier Basins: Geological Estimates of the Frequency of Large Earthquake-Triggered Submarine Landslides in Orphan Basin, Offshore Canada
- **Eliuk, L. and Wach, G**. Large-scale mixed carbonate-siliciclastic clinoform systems: three types from the Mesozoic North American offshore.

GeoCanada 2010; Canadian Society of Petroleum Geologists, Calgary, May 10-14, 2010.

- **Mosher, Wach et al**, Passive margin evolution and reservoir distribution
- **Giles, Mosher and Wach** Mass Transport Processes on Slope Sedimentation: Sediment Distribution on the SW Newfoundland Slope, Eastern Canada
- **Eliuk, L. and Wach, G**. Carbonate-siliciclastic depositional systems
- **Eliuk, L**. Regional Setting of the Late Jurassic Deep Panuke Field, offshore Nova Scotia, lateral changes of a platform adjacent to a delta

Nova Scotia Energy Research and Development Forum, Halifax, May 26&27th, 2010

- **Wach and Mosher et al**, Margin evolution and reservoir distribution- examples from Cenozoic of the Central Atlantic margin
- **Giles, M., Mosher, Wach** Mass Transport Processes on Slope Sedimentation: Sediment Distribution on the SW Newfoundland Slope, Eastern Canada
- **Goss, Mosher, Wach.** Cenozoic seismic stratigraphic analysis of the Suriname margin, South America
- **Brake, Mosher, Wach.** Evolution of an Oligocene canyon system on the eastern Scotian Margin.

Future dissemination

2nd Conjugate Margins Conference of the Central Atlantic, Lisbon, Portugal, September, 2010.

- **Wach and Mosher et al**, Margin evolution and reservoir distribution- examples from Cenozoic of the Central Atlantic margin
- **Campbell, Mosher, Wach**. The formation of Miocene deepwater unconformities and the effects on subsequent deposition patterns on the western Scotian Slope, Canada
- **Eliuk, L. and Wach, G. -** Regional Setting of the Late Jurassic Deep Panuke Field, offshore Nova Scotia, Canada II: Part 1 - Distant and fractal analogues and possible process controls for a thick carbonate platform flanked by a large delta.
- **Eliuk, L**. Regional Setting of the Late Jurassic Deep Panuke Field, offshore Nova Scotia, Canada II: Part 2 - cuttings-based synthesis of a reef margin gas pool set within the lateral changes of a platform adjacent to a delta – a unique(?) hydrocarbon system and play type

Bulletin, Canadian Society of Petroleum Geologists (in preparation)

- **Mosher, Wach et al.** Passive margin evolution and reservoir distribution along the Scotian Margin (in preparation)

Marine and Petroleum Geology Journal (in preparation)

- **Mosher, Goss, Wach.** Seismic Stratigraphy of the Demerara Rise, Suriname, South America (in preparation)

APPENDIX A: LAURENTIAN FAN STUDY- M.K. GILES (M.SC.)

INTRODUCTION

Continental margin slopes form 5.9% of the surface area of the Earth and are location of the thickest sections of unconsolidated sediment. Nearly 9% of the World's hydrocarbon supplies now come from slope environments and this value is likely to increase as deep water exploration and development continues into these frontier regions. It is, therefore, critical to understand geologic processes of slope environments to know depositional patterns, structural controls, and geohazard and engineering constraints in this complex region. The Laurentian Fan area of the SW Newfoundland Slope is an active exploration frontier and an area of a historic submarine mass-movement.

It is the purpose of this study to investigate sediment mass failure deposits and structural controls in this region, to understand causal mechanisms of slope failure and assess the significance of slope failure processes in margin construction and sediment redistribution.

STUDY AREA AND BACKGROUND GEOLOGY

The Laurentian Channel and Fan Region are located off of Canada's eastern continental shelf (Fig. 1), between Nova Scotia's rifted continental margin and the inactive transform margin of the southwest Grand Banks (Piper et al., 1984). The Laurentian Channel is a shelf crossing trough which acted as an outlet for the Laurentide Ice Sheet during the Late Pleistocene. The Laurentian Fan, at the mouth of the Laurentian Channel, is the deep water depo-centre for sediment transported by glaciers and glacial outwash through the Laurentian Channel. It is bounded to the north by the Grand Banks and merges to the south and east with Sohm Abyssal Plain (Skene and Piper, 2003).

A major mass transport event occurred in the Laurentian Channel and Fan Region in recent history: the 1929 Grand Banks Landslide resulted from a M7.2 earthquake (Adams 1986, Piper and Aksu 1987, Piper et al. 1999 and Fine et al. 2005). The fault was a strike-slip event at about 30 km depth (Bent, 1995). Significant seismic activity has occurred in the immediate vicinity since this event – probably as aftershocks. The tectonic causes of this earthquake are not well known. Mazzotti et al. (2005) describe latent tectonic stresses remaining as a result of glacial loading and rebound. Although the 1929 earthquake was undoubtedly the trigger for a subsequent landslide and tsunami, there were contributing or pre-conditioning factors that this investigation will study.

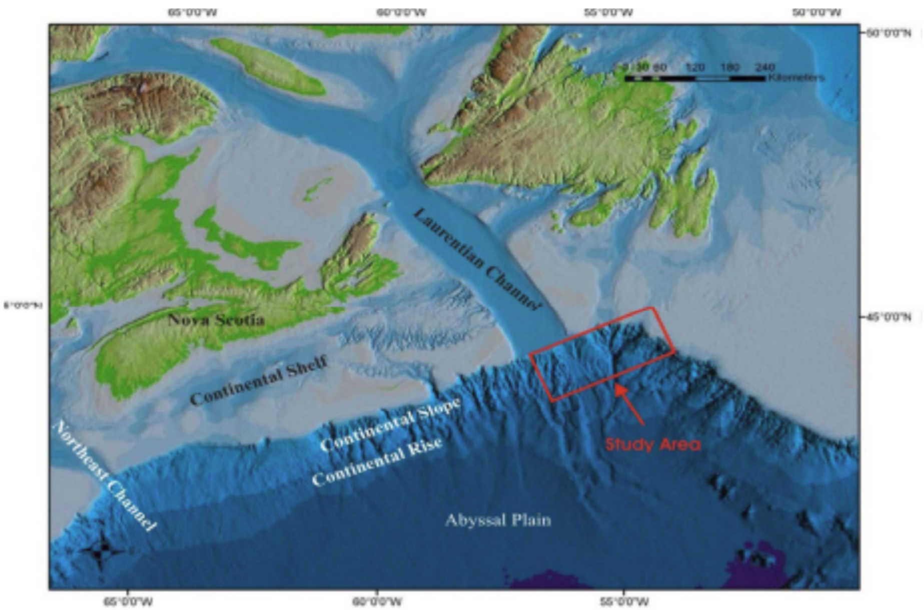

Figure 1 – Location map of the study area. The box outlined in solid red indicates the coverage of the 2D and 3D seismic reflection data from the Laurentian Fan in the southwest to Halibut Slope in the northeast.

METHODS

The study of the Greater Laurentian Channel region involves interpretation of multibeam and 2D and 3D seismic reflection data. Multibeam data are available in the greater Laurentian Fan region, from the shelf break to about 3000 m water depth (Fig. 2). Resolution varies with water depth but on average sounding density is on the order of one sounding every 100 m^2. These data allow interpretation of surficial geologic processes. Both industry and GSC 2D seismic reflection data were used in this investigation. These data provide the regional stratigraphic and structural framework and/or high resolution sub-bottom imaging. The Laurentian East 3D seismic volume is a 1505 km^2 area in the Halibut Channel region on the east side of the study area. Data were acquired with a 25 x 6.25 m bin size, a record length 5.5 s, and a sample rate of 2 ms. These data, although restricted in area, allow detailed 3D visualization of sedimentary deposits to fully understand processes of formation and stratal/lithologic relationships.

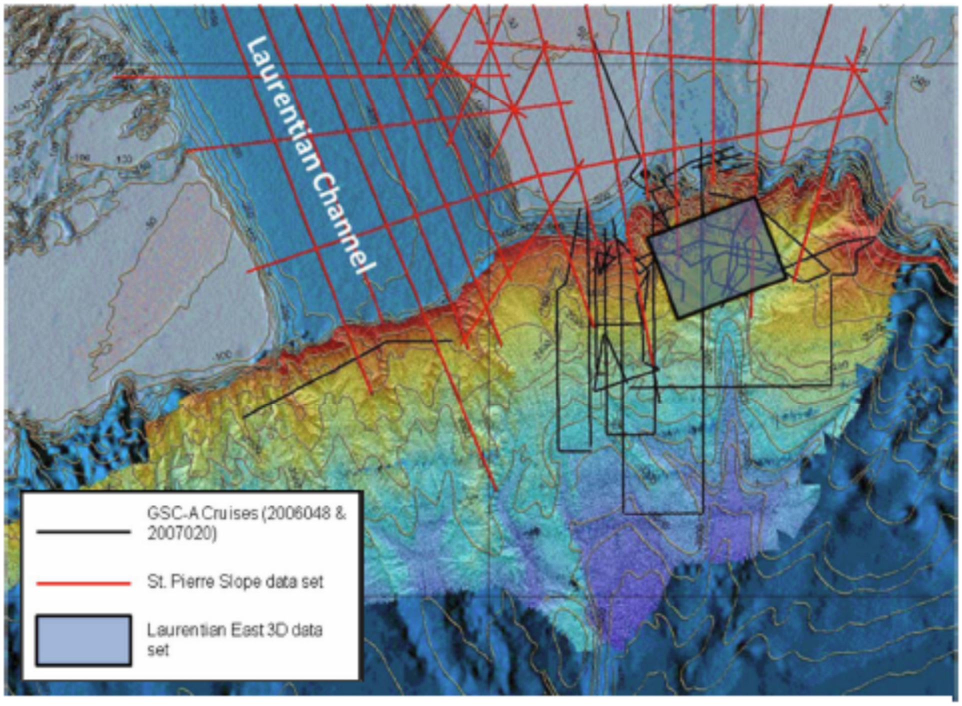

Figure 2 – Regional data coverage for the Greater Laurentian Channel region. The Laurentian East 3D data set is highlighted by the translucent blue box, outlined in black. Black lines indicated the location of the 2D seismic reflection data collected on cruises 2006048 and 2007020 by the Geological survey of Canada (Atlantic). The St. Pierre Slope data set are shown by the red lines.

RESULTS

MULTIBEAM DATA- Multibeam data of the greater Laurentian Fan area reveal the following general aspects of this part of the continental margin: (1) the overall slope angle on the Laurentian Fan is two degrees, being steepest (up to six degrees) near the shelf break, and 2) the most prominent features are the numerous canyons and valleys with complex upslope tributary systems. These features are described in detail by Mosher and Piper (2007). At the regional scale these features are somewhat typical of the continental slope along the eastern Canadian margin (see Mosher et al., 2004). Specific to the 1929 landslide, no major headscarp related to the event is recognized (cf. the Storegga Slide). Most significant are a series of shallow gullies with small headwalls about mid-slope. Upslope from these is a series of shallow escarpments that probably represent upslope retrogression of the failure. The landslide appears to have been relatively shallow (top 5-100 m) and laterally extensive. There is no evidence of a single massive submarine landslide with major headscarp and debris lobe.

REGIONAL 2D HIGH RESOLUTION 3d SEISMIC DATA- High resolution seismic data that escarpments observed on the seafloor relate to extensional listric faults in subbottom. This faults sole within a sediment package interpreted as sedimentary waves as seen on regional industry seismic data. The termination of listric faults in these sedimentary waves provides evidence that these packages possible act as detachment surfaces resulting in failure and mass transport of sediment further downslope. These regional industry seismic reflection data also show numerous intervals of chaotic reflections, typical of mass transport deposits, throughout the section. As well, they show large rotated and displaced blocks. These features provide evidence for a history of sediment mass-failure in the Laurentian Channel and Fan region.

3D VOLUME - Four seismic horizons have been correlated across the Laurentian East data set including the seafloor, (Fig. 3). These three surfaces relate to mass transport deposits are laterally extensive but don't span the entire area of the Laurentian East data set.

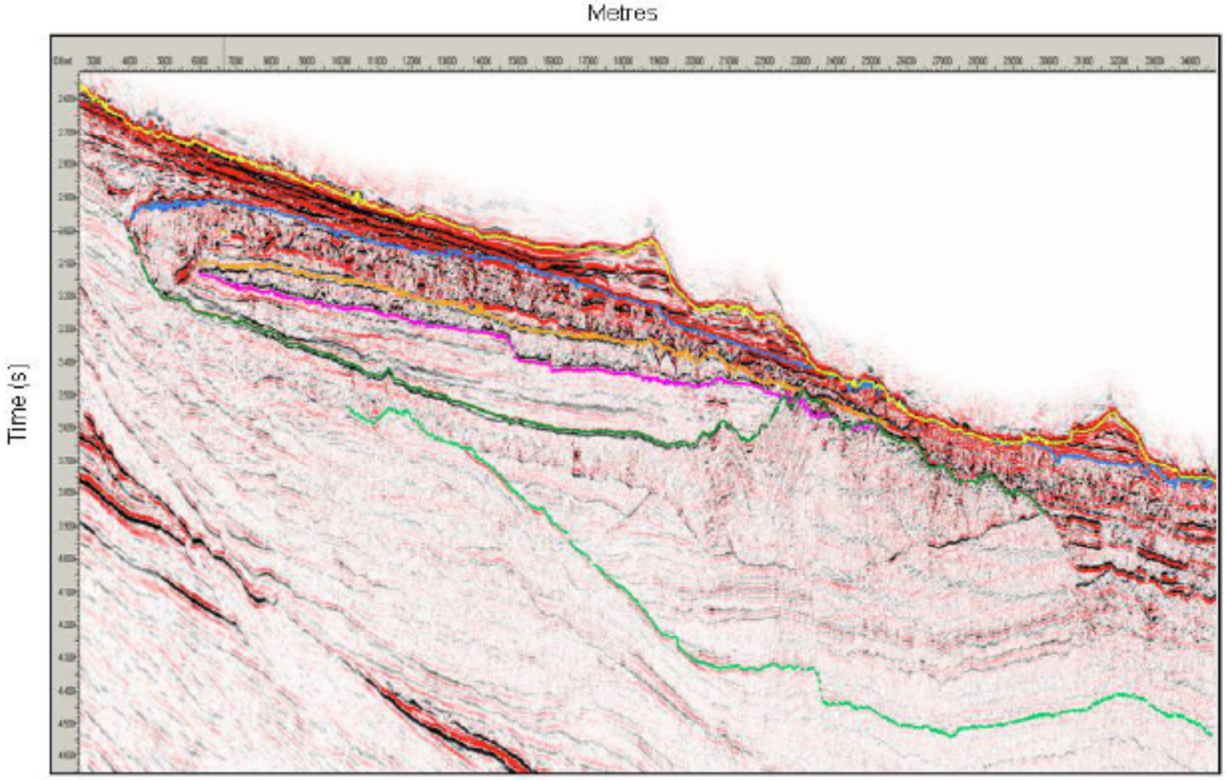

Figure 3- Inline shows the seafloor (yellow horizon), tops of two MTDs (blue and orange horizons) and a base of a mass transport deposit (pink). Dark green and light green horizons are rendered surfaces.

The 3D render of the seafloor reflector indicates the slope on this portion of Canada's Southeast margin is heavily incised with large scale canyons that empty into one major corridor. These canyons may provide a conduit for modern sediment to travel from the shelf to the deep ocean, by-passing the slope (Fig. 4).

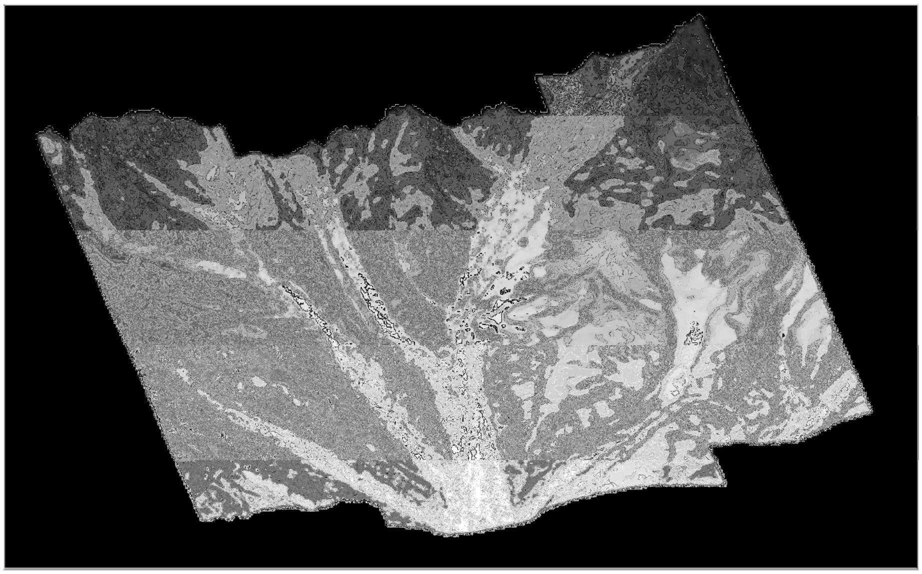

Figure 4 – Seafloor render from the Laurentian data set.

The yellow horizon (Fig. 3) represents the seafloor of the Laurentian 3D volume. It is easily correlated across the data set and when rendered (Fig. 4) provides a surface for comparison with the multibeam data. The blue horizon (Fig. 3) is interpreted as the top of a mass transport deposit as it caps a seismic facies characterized by discontinuous, low to moderately high amplitude incoherent reflectors. The orange horizon (Fig. 3) represents the top of a smaller mass transport deposit which is concentrated in the center of the Laurentian East data set. The pink horizon (Fig. 3) represents the base of a smaller mass transport deposit, capped by the orange horizon.

DISCUSSION

Seismic facies analysis of the greater Laurentian Channel region on Canada’s southeast continental margin shows that there are successive sediment mass failures at a variety of scales, suggesting that this process is an integral component to slope sedimentation in this area. The study area of this project overlies the Cobequid-Chedabucto fault, a former transform margin, and appears to have a higher level of seismicity than most of the Canadian east coast margin. Seismicity plays a critical role in the initiation of sediment failures, as evidenced in the 1929 Grand Banks landslide. Generally, continental slope sediments are statically stable and sediment is "pre-conditioned" by a variety of factors to be susceptible to fail. In the case of the greater Laurentian Channel region, factors potentially affecting slope stability include sediment loading, generation of excess pore pressures, and intra-formational gas.

Glaciation- Canada’s Eastern margin has been influenced by past glaciations from the mid-Pleistocene to the Late Wisconsinan as described by King and Fader (1986), Piper and Normak (1989) and Mosher et al. (2004). During glacier times, large amounts of sediments were deposited along the slope creating unstable areas. The deposition of glacier deposits as well as the retreating ice sheet may have created higher then normal pore pressure leading the deposits to be fluidized and subject to failure (Imbo et al., 2003).

Gas hydrate was recognized in the Halibut Slope region and free gas is evident in cores recovered from the St. Pierre Slope. Gas generation within sediments reduces its strength properties setting up a situation for potential mass failure.

Geohazard assessment- This is of particular importance for the exploration and development of hydrocarbon resources as this is an ongoing process in the area. Mass transport processes are also a concern to the population of the surrounding provinces in terms of a threat of a tsunami as a result of another large scale event like the 1929 Grand Banks Landslide. The importance of such events is highlighted by a recent announcement of the establishment of a North Atlantic tsunami warning system.

CONCLUSIONS

Seismic facies analysis of the Laurentian Channel and Fan Region shows that there are successive sediment mass failures at a variety of scales, suggesting that this process is integral to slope sedimentation in the area. The investigation of recently acquired seafloor multibeam, and 2D and 3D seismic reflection data of the St. Pierre and Halibut Slope regions, east of the Laurentian Fan, provides the opportunity to study modern seafloor features and related underlying structures. This area overlies the Cobequid-Chedabucto fault, a former transform margin, and appears to have a higher level of seismicity than most of the Canadian east coast margin. As evidenced in the 1929 Grand Banks landslide, seismicity played a critical role in initiating sediment failure. Generally, continental slope sediments are statically stable and sediment is "pre-conditioned" by a variety of factors to be susceptible to fail. In the case of the greater Laurentian Slope region, factors potentially affecting slope stability include sediment loading, generation of excess pore pressures, and intra-formational gas. High rates of sedimentation occurred during glacial episodes that created a thick Quaternary sediment mass on the upper slope in this area. High sedimentation rates potentially lead to sediment under consolidation. An interval of buried sedimentary bedforms with likely sandy intervals is recognizable in seismic reflection profiles of the St. Pierre and Halibut Slope areas. Listric faults extending from surface escarpments to these sedimentary bedforms provide evidence that these intervals act as detachment surfaces, perhaps in response to generation of overpressures and liquefaction during seismic shaking. Gas hydrate was recognized in the Halibut Slope region and free gas is evident in cores recovered from St. Pierre Slope. Generation of gas within sediment reduces its strength properties thus increasing the potential for potential mass-failure. Mass transport processes are a significant mechanism for sediment delivery in the shelf to slope setting of the greater Laurentian Channel region. Improving our understanding of the triggering mechanisms and associated structural and lithological factors will be fundamental in geohazard assessments for potential industrial development and identifying the possibility of other large-scale landslides for this area of the Scotian margin.

The Cenozoic evolution of the southwestern Newfoundland margin documents periods of slope erosion linked to channel development and mass transport processes. A composite seismic stratigraphic framework derived from the Laurentian East 3D seismic volume and adjacent 2D seismic reflection data was completed for the southwestern Newfoundland slope. Five key seismic reflection events are recognized across the study area in the 3D and 2D data. These seismic reflection events are age-constrained for the last 65 Ma through biostratigraphic ties to industry wells on the adjacent shelf. The reflection events are top Cretaceous (K99), middle Oligocene (O50), late Miocene (M70), Middle Pleistocene (Q50) in age. Regional mapping within the southwestern Newfoundland slope reveals nine mass transport deposits (MTDs) that occur between the top Cretaceous and Middle Pleistocene. These MTDs are regionally extensive events that cover areas up to 900 km2 and have volumes up to 225 km3. MTDs are identified by their incoherent and chaotic seismic character and are represented by failures which include rotated and deformed slump blocks, slides and debris flows.

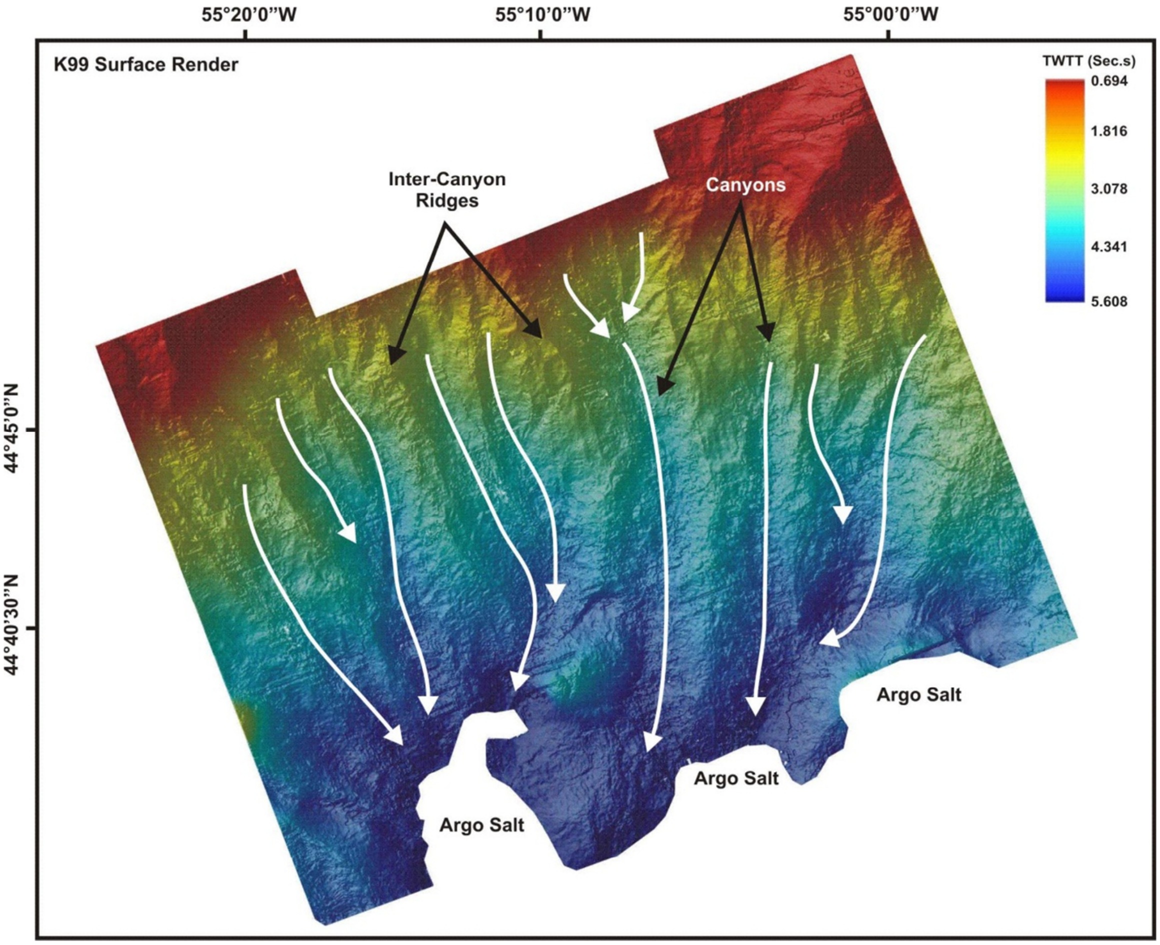

Figure 5: The rendered K99 horizon shows Late Cretaceous canyons (the areas of which are represented by white arrows) and inter-canyon ridges.

During the Upper Cretaceous and early Paleocene, the upper slope of the southwestern Newfoundland margin experienced canyon incision (Fig. 5), likely in response to sealevel lowering (Miller et al., 2005). A significant shift in sedimentation style occurred on the margin during the Miocene where more constant, predictive sedimentation rates associated with sealevel fluctuations, were replaced with large scale, regionally extensive sediment failures. It was during late Miocene and Middle Pleistocene when high sedimentation rates associated with periods of sealevel lowering deposited large amounts of sediments on the upper and middle slope).

In the late Miocene and early Pliocene, bottom water currents affected the southwestern Newfoundland slope which reworked bottom sediments and deposited seismic scale bedforms.

Regionally extensive sediment failures became less frequent during the Lower-Middle Pleistocene as sedimentation styles changed once again on the margin in association with decreasing global sealevel. The onset of shelf-crossing glaciation began in the Middle-Upper Pleistocene and resulted in the deposition of 200 m of proglacial sediment on the continental margin. This stratigraphic section is represented by a mixed combination of turbidite deposits and thin, localized MTDs. Finally, the southwestern Newfoundland margin was incised by glacial melt waters which created the canyonized slope and dendritic ridges of the modern seafloor.

A significant proportion of the Cenozoic stratigraphy on the southwestern Newfoundland margin is composed of mass transport deposits, indicating that these processes are important mechanisms in the construction and evolution of the margin. Nine MTDs are identified between the top of a Cretaceous unconformity and the Middle Pleistocene section of the margin. MTDs represents between 30 - 40 % of the entire section and up to 60 % of the mid Miocene to recent section. Late Miocene MTDs are larger than Plio-Pleistocene MTDs, but the latter appear to be more frequent. Above the Middle Pleistocene marker, thin localized failures alternate with turbidite deposits and represent an additional 5 % of the sedimentary column. The preserved MTDs between M70 and Q50 correspond to a relatively thin section of stratigraphy for the 7 Ma it represents. The presence of channel systems on the uppermost MTD suggests that between failures, sediment bypassed the mid slope via these channels and was deposited further downslope. This is an explanation for the minimal amount of sediment preserved during this time. The process of sediment mass failure on continental margins can represent a significant proportion of the sedimentary column and therefore should to be considered as a major component of sedimentation models for passive continental margins.

The southwestern Newfoundland margin has a history of large scale submarine landslides with one occurring during the late Miocene and the more recent 1929 Grand Banks Landslide. Both are of a similar size, moving ~ 200 km3 of sediment but are two different styles of failure. The late Miocene MTD is classified as a blocky debris flow and the 1929 failure is identified as a turbidity current, each representing opposite end members of sediment mass failure. This indicates that the conditions responsible for these distinctively different failures can occur on one margin and suggests that any style of failure is possible depending on the trigger mechanisms and pre-conditioning factors.

Triggering mechanisms responsible for submarine landslides are hard to pinpoint for a particular margin, let alone a particular failure. Historic earthquake data from the greater Laurentian Fan region demonstrate that the region is susceptible to increased levels of seismicity. The 1929 Grand Banks Landslide was clearly activated by a M7.2 earthquake that occurred in the area. Submarine landslides in the region were initiated by ground accelerations due to earthquakes. However, pre-conditioning factors are required to prepare the sediment for failure in the region and it is believed that these factors are responsible for the areal and volumetric differences of MTDs on the southwestern Newfoundland margin. The preservation of MTDs across the Scotian and southwestern Newfoundland margin suggests that the distribution of seismicity across the eastern Canadian margin may be best described by the random seismicity model (random distribution) suggested by Basham et al. (1983) and Mazzotti (2007).

Mass transport deposits on the southwestern Newfoundland slope are serious geohazards for hydrocarbon exploration with the potential of blowouts associated with increased overpressure and trapped gas. Submarine landslides are a significant threat to coastal communities and could result in the initiation of a tsunami. The southwestern Newfoundland coast experienced a historic tsunami in 1929 (initiated by the Grand Banks Landslide) which devastated the Burin Peninsula. Today the effects of tsunamis could be far greater with increased population density and infrastructure amongst the coastal communities of Atlantic Canada.

Potential hydrocarbon exploration on the southwestern Newfoundland margin could use the preserved turbidite deposits as an analogue for deeper reservoir targets in the basin. These turbidite deposits are found interbedded within stacked MTDs and are typically preserved in “minibasins” associated with salt withdrawal. These deposits may be small but they could occur as several stacked reservoir targets. Another consideration is that some of the Cenozoic MTDs from the margin may be sand-rich deposits. This would suggest the possibility of sandier MTDs in the deeper basin which may have reservoir potential but this will remain unknown until the interval is sampled. One other potential location for reservoir type sediments would be in deeper water on the lower slope. Evidence of channels on the top of Plio-Pleistocene MTDs suggests that sediment bypassed the middle slope through channels between failure events and was deposited further downslope.

In summary, mass transport processes on the southwestern Newfoundland margin are significant mechanisms for transporting large amounts of sediments (up to 225 km3) in the slope environment. These processes have greatly influenced the construction and the evolution of the margin since the Miocene and can represent as much as 60 % of the sedimentary column since the Cenozoic. Their initiation is linked to the increased levels of seismicity in the region where pre-conditioning factors such as, seaward dipping faults, sealevel lowering, high sedimentation rates, bottom currents, and over-steepening of sediments control the size of the failure. Finally, mass transport processes and their deposits can create implications for the development of offshore resources as well as impose a possible risk to the population of Atlantic Canada.

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Mass Transport Deposits on the Southwestern Newfoundland Slope

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Abstract

Sediment mass failure is a major process during Cenozoic development of the southwestern Grand Banks of Newfoundland margin. Recently acquired seafloor multibeam and seismic reflection data provide evidence of stacked and regionally extensive mass transport deposits (MTDs) since the middle-late Miocene. MTDs with volumes between 30 and 150 km3 lie between the top of a Cretaceous Unconformity and mid-Pleistocene and MTDs with volumes less than 1 km3 are recognized since the mid Pleistocene. Seaward dipping faults at the base of the mid Miocene MTD suggest zones of weakness and increase the susceptibility to failure. Sediment stability is also reduced by ongoing shallow salt deformation. These factors and sealevel lowering are key ingredients leading to sediment failure during the mid-Miocene to Middle Pliocene. During the Pleistocene, high sedimentation rates following glaciations may have generated underconsolidated sediment profiles with interbedded sandy horizons, explaining more frequent and smaller MTD sizes in the Plio-Pleistocene section. Although these factors "precondition" the sediment column to mass failure, seismicity, such as occurred in 1929, is likely the ultimate triggering mechanism.

Keywords Mass Transport Processes • mass failure • mass transport deposit (MTD) • slope sedimentation • multibeam • 3D seismic • seismicity

1 Introduction

The southwestern Newfoundland slope outboard of the Laurentian and Halibut Channels on the Canadian east coast margin is a prospective region for hydrocarbons and an area of a historic submarine landslide. The modern seafloor geomorphology shows evidence for significant canyon and channel development and abundant evidence of mass failure deposits. The late Cenozoic section offshore southwestern Newfoundland is highly dissected by extensive mass transport deposits suggesting that this is an integral process of sediment transport for the shelf to slope region.

Understanding the geological processes of slope environments through depositional patterns and structural controls is essential for knowing geohazard and engineering constraints in this complex region. Mass transport processes are also a concern to the population of the surrounding coastlines in terms of tsunami threat, as occurred in the historic 1929 Grand Banks landslide and tsunami (Mosher and Piper 2007).

In this paper, new results from bathymetric and high quality seismic data are presented. Evidence of sediment mass-failure supports the idea that mass transport processes are an important factor in the evolution of the southwestern Newfoundland margin. It is the purpose of this paper to evaluate the volume and seismic character of mass transport deposits and the stratigraphic interval within which they occur in order to assess their significance as a process in contributing sediment to the margin, as a geohazard to offshore development and surrounding coastal society infrastructure and perhaps to identify potential trigger mechanisms or at least development of pre-conditioning factors that lead to mass-failure.

1.1 Regional Geology

The Canadian east coast margin is a passive continental margin that extends from the Labrador Sea, across the Grand Banks and the Scotian margin to Georges Bank (Wade and Maclean 1990). During the Jurassic, the central North Atlantic Ocean opened and transform margin formed along the southwestern Grand Banks of Newfoundland. This tectonic feature extends to the east as the Newfoundland Fracture Zone and to the west as the Cobequid – Chedabucto southwest Grand Banks Fault system (Jansa and Wade 1975). Seaward of southwestern Newfoundland, the continental slope lies in water depths from 100 to 2500 m with mean gradients between 2° and 10°. It is incised by several large valley systems, the largest of which is Haddock Valley. Further west, the Laurentian Channel is a 700 km long, 80 km wide, glacial trough that cuts over 300 m into the continental margin (Fig. 1) (Piper et al. 1984). This feature acted as a major sediment delivery conduit and ice stream corridor for the Laurentide ice sheet. At the mouth of the Laurentian Channel lies the Laurentian Fan that is bounded to the east by the continental margin of the Grand Banks, to the west by the Scotian Shelf and Slope, and to the south by the Sohm Abyssal lain (Skene and Piper 2006).

1.2 Methods

32,150 km2 multibeam sonar bathymetry data were acquired in the region in September, 2006. Details of this acquisition are reported by Mosher and Piper (2007). Seismic reflection data in the region come from a variety of vintages and resolution. 3,100 km of 2D MCS data (STP) were acquired by the Geological Survey of Canada in 1984 and 1985. Industry (TGS-Nopec) collected 34,000 line km of 2D MCS data across the Scotian and SW Newfoundland Margins in 1999. The grid spacing for the survey was 8 by 8 km. In 2002, approximately 1,500 km2 of 3D seismic data with a bin spacing of 25 × 6.25 m, were collected over the southwestern Newfoundland margin in an area referred to as the Laurentian 3D prospect. Finally, a further 3,200 line-km of high resolution SCS data were acquired by the Geological Survey of Canada in 2003 and 2007. An average velocity of 2,100 m/s was used to convert from time to depth in the shallower parts of these seismic data.

Key reflection horizons were mapped throughout the study area and correlated to exploration wells. Age control for the study was established through ties to the Pliocene section on the Laurentian Fan by Piper and Normark (1989) as well as from till tongue stratigraphy.

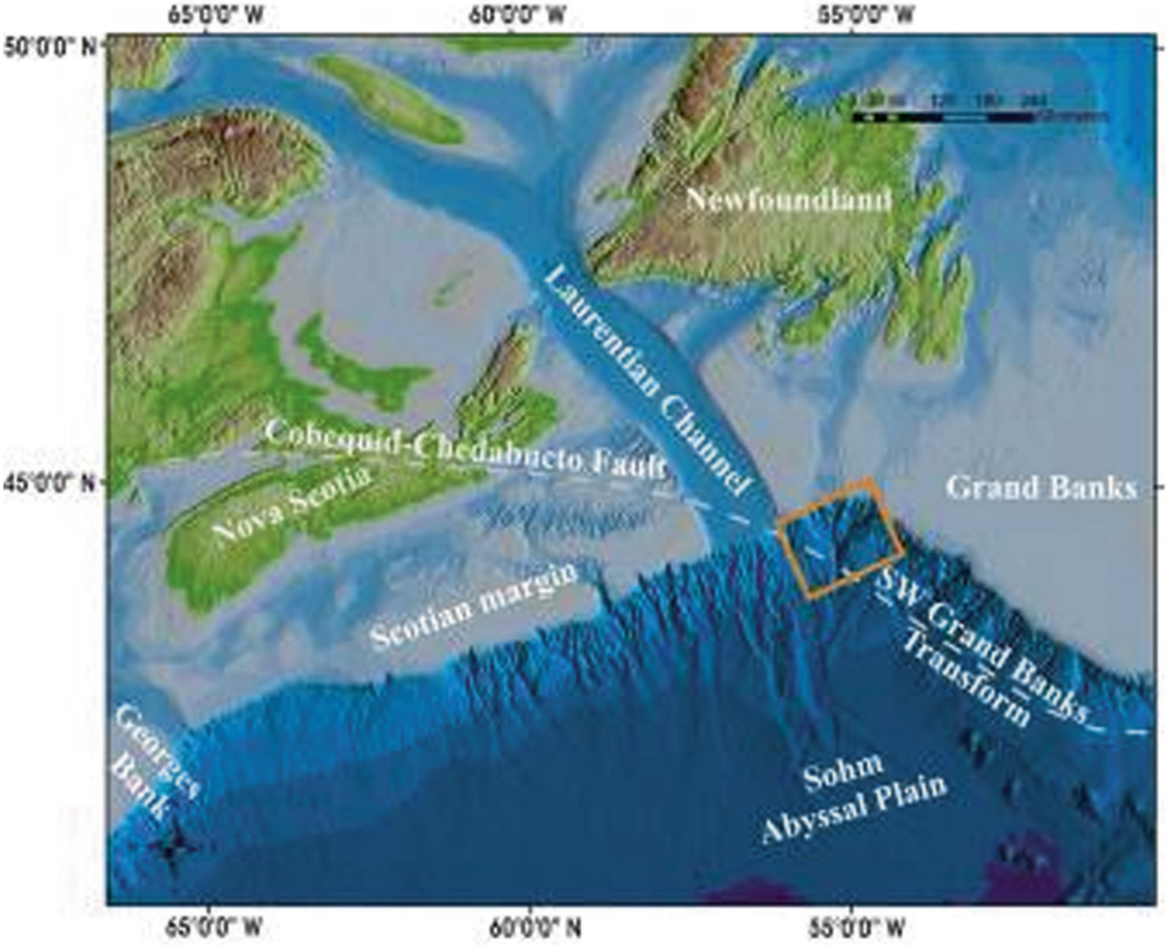

Fig. 1 Location of the study area (orange box) positioned on Canada's East coast.

Major geographic and structural features labelled in white (Shaw and Courtney 2002) on the St. Pierre Slope by Piper et al. (2005). Based on work by Piper et al. (2005), new biostratigraphic analysis from the industry well Hermine E-94 were completed and correlated to seismic data from the STP data set. Age correlations were interpreted down the St. Pierre Slope and east into the study area using STP and TGS-NOPEC data.

2 Results

A seismic stratigraphic framework for the study area was established based on published literature and data from the surrounding shelf and slope. A marker coeval for the top Cretaceous (K99) was correlated into the study area. Three other stratigraphic markers were also correlated into the study area based on the work done by Piper et al. (2005). The middle Oligocene unconformity (O50) and a middle-late Pliocene marker (M90) are both defined by biostratigraphy from the Hermine E-94 well. A mid-Pleistocene marker (Q50) has also been correlated into the study area and is based from the deepest till tongue on the St. Pierre Slope (Piper et al. 2005) (Fig. 2).

The sediment column in the Halibut channel region of the southwestern Newfoundland margin is divided into three units based on seismic facies. The lower unit, Unit 1, is the interval between the top Cretaceous unconformity (K99) and the middle-late Pliocene (M90) marker. This unit is present across the study area and has a variable thickness ranging from 900 to 1750 m, with thicker sections in the western portion of the study area. The base of this unit consists of sub-parallel to parallel, moderate amplitude reflectors which are vertically offset in some parts of the study area.

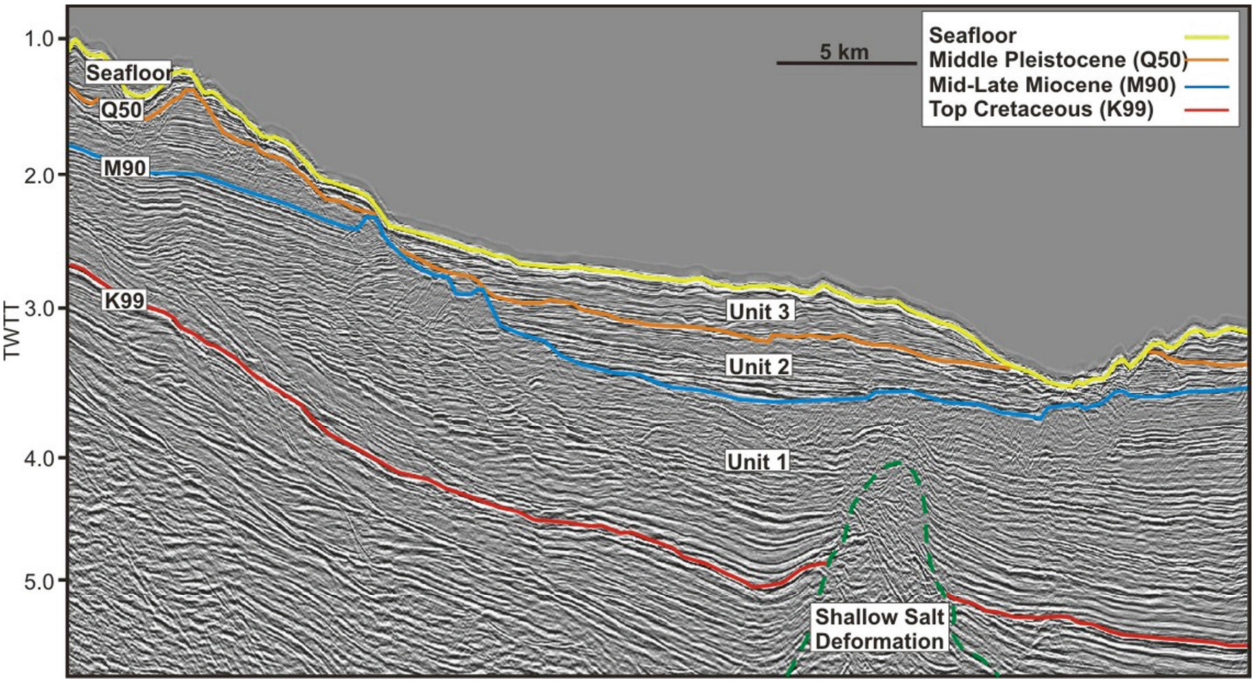

Fig. 2 Line 15 from the STP survey showing the stratigraphic framework for the Halibut Channel region of the Southwestern Newfoundland Slope.

Above these reflectors, there are a series of discontinuous, chaotic, moderate amplitude reflectors that continue to the M90 marker. The second unit, Unit 2, is the interval between the middle-late Pliocene (M90) marker and the mid Pleistocene (Q50) marker. Thickness varies between 150 to 500 m and consists of moderate to high amplitude, parallel reflectors at the base of the unit. On top of these reflectors, there are moderate-high amplitude packages that alternate between chaotic and fairly continuous reflectors. The upper unit, Unit 3, is not present throughout the entire data set. It is the interval between the mid Pleistocene marker (Q50) and the modern seafloor and consists of high and low amplitude, parallel to mounded reflectors with thin chaotic reflections through the section. Unit 3 varies in thicknesses ranging from 50 to 500 m and includes areas where none of the stratigraphy is preserved.

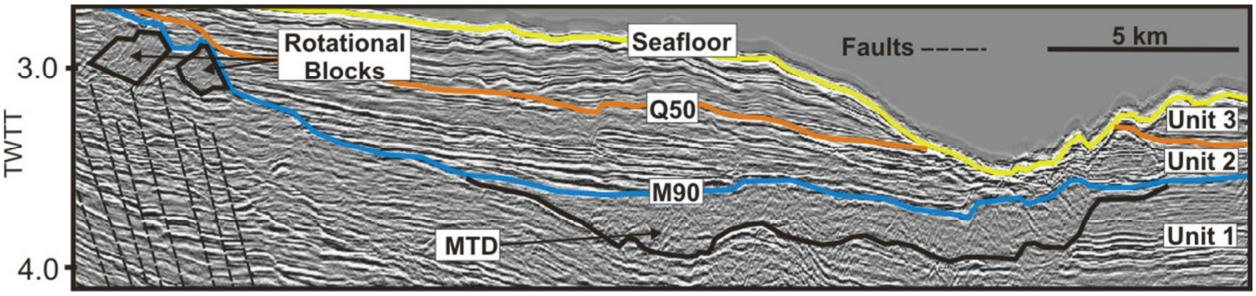

Fig. 3 STP line 15 showing the middle-late Miocene MTD and associated upslope rotational slump blocks. Seaward dipping faults are observed in the lower left corner of the figure.

In the subsurface of the Halibut Channel region, mass transport deposits are identified by their incoherent and chaotic acoustic character. The bases of these MTDs are typically erosional with the upper surface having an undulating character. MTDs occur in Units 1, 2, and 3 at a variety of scales. In Unit 1, there is one large scale MTD that has an area of 670 km2 and thicknesses as much as 400 m (Fig. 3). Using an average thickness of 250 m, the volume for this MTD is 167 km3. In Unit 2, the alternating packages of chaotic and parallel reflectors are interpreted as stacks of MTDs (Fig. 4). These MTDs overlie the mid Miocene MTD in some parts of the study area. Two of the larger MTDs have been mapped in this unit. The lower MTD has a thickness between 75 and 85 m and covers an area of 400 km2 resulting in a volume of 35 km3. The second MTD mapped in this unit has a thickness of about 150 m, covers an area of 375 km2 and has a volume of between 50–60 km3. In Unit 3, the largest of the MTDs are between 20–30 m thick with volumes less than 1 km3, reaching the limit of resolution for the Industry data.

3 Discussion

Data from the study areas show that mass transport processes occur on the southwestern Newfoundland margin in a variety of styles and magnitudes and suggest that this is an integral process of slope sedimentation in this region. In the Halibut Channel area MTDs on the scale of 30 to 150 km3 are preserved from the top of the Cretaceous unconformity (K99) to the mid Pleistocene marker (Q50) (Unit 1 and 2) (Fig. 2), while from the mid Pleistocene marker (Q50) to the modern seafloor (Unit 3) MTDs are 20 to 30 m thick and have volumes less 1 km3.

In Unit 1, the middle-late Miocene MTD displays 300–350 m thick rotational slump blocks in the mid-slope region, followed downslope by a blocky deposit that becomes more chaotic in the seaward direction. The blocky nature of the MTD suggests three things about this deposit: (1) the failed sediment has some structural integrity and was able to move downslope distance before it transitioned to a disturbed sediment package, likely representing a more fluidized flow, (2) an escarpment of equal size to the rotated slumps is required to provide the intact blocks, and (3) accommodation space to allow the rotated blocks to fail. The vertical offsets seen in Unit 1 have been interpreted as seaward dipping faults and are cut by middle to late Miocene MTD (Fig. 3). It could be possible that these seaward dipping reflectors have pre-conditioned the sediment and made it susceptible to failure.

The presence of shallow salt deformation in the western portion of the study area could be one mechanism that has caused the middle-late Miocene MTD to have frontally confined characteristics (Fig. 5). As the failure moved downslope, it encountered a bathymetric high, in this case a result of shallow salt deformation of the overlying sediment. East of the shallow salt deformation, the middle-late Miocene MTD follows bathymetric lows. The erosional character of this MTD indicates that it failed into a previous depression, creating a channelized flow. It is likely that the volume of the middle-late Miocene MTD is larger than 167 km3 as the MTD likely extends outside of the region covered by the data. In Unit 2, MTDs are smaller with volumes between 30 and 50 km3 compared to the large middle-late Miocene MTD but occur more frequently.

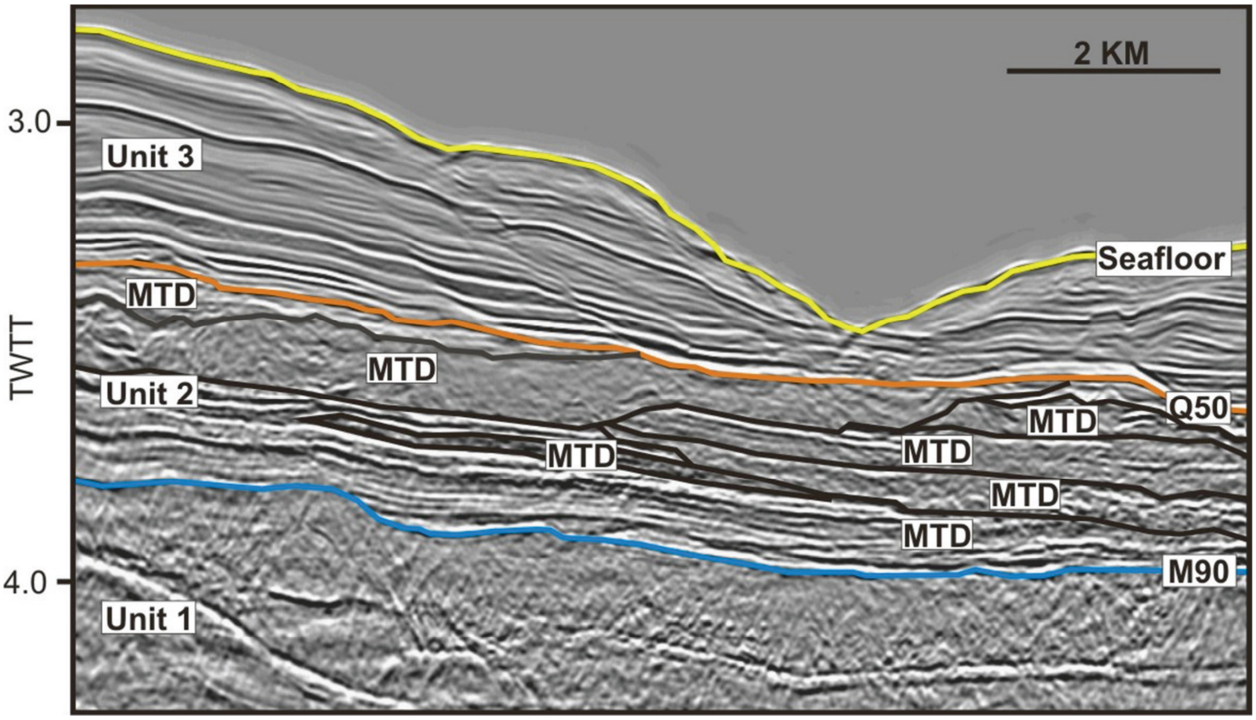

Fig. 4 Stacked MTDs observed in the TGS-NOPEC line 1306-100 from the middle-late Miocene marker to the Middle Pleistocene marker. MTDs are outlined in black.

A possible explanation for having repeated failures in this area could be that the scars created by previous submarine landslides create over steepened and unstable slopes leading to retrogressive behaviour. The remnant scars create accommodation space for subsequent sedimentation, leading to sediment overloading and increasing the susceptibility of failure for the area (Masson et al. 2006). Other possibilities include salt tectonics with recurring seismic activity. Seismic facies of Unit 1 suggests that the alternating high and low amplitudes represent fine and coarse grained material deposited by proglacial plumes and turbidity currents (c.f. Armitage 2009) where the smaller, chaotic packages represent local failures. In the Halibut Channel region of the study area, MTDs make up 30–40% of the sedimentary column since the top of the Cretaceous unconformity marker (K99). The influence of MTDs in this region would be higher if you account for turbidity currents and local failures that have occurred since the mid Pleistocene marker (Q50).

As shown by Mosher et al. (1994), near surface sediment (top 25 m) on the Scotian Slope is stable under static conditions. Marsters (1986), in a geotechnical study, showed that most samples from the St. Pierre Slope demonstrated apparent over-consolidation; although it was noted that there is a high percentage of silt in the samples leading to poor test quality in many instances. If sediments are statically stable on the St. Pierre Slope, having many analogues to the Scotian Slope, it is expected that an external factor is required to either increase the stress acting on seafloor sediments (Lee at el. 2007), reduce the strength of the sediment (increase the pore pressure), or some combination of the two in order to trigger a slope failure. There are several possible triggering mechanisms believed to be associated with the Newfoundland's southwestern margin: (1) Earthquakes – The Cobequid-Chedabucto fault system runs under the Laurentian Channel and Fan and along the southwestern margin of Newfoundland (Fig. 1). Seismicity is relatively low along the Canadian east coast but is slightly higher in the region of the Cobequid-Chedabucto fault (Mazzotti and Adams 2005); (2) Sediment loading – During Late Wisconsinan glaciations, glacial outwashes rapidly deposited large amounts of sediment on the upper continental slope (King and Fader 1986), potentially generating higher pore pressures and increasing the susceptibility of sediment failure; (3) sedimentary bedforms and faults – buried sedimentary bedforms interpreted from regional seismic data suggest sandy intervals underlie St Pierre and Halibut Slope areas.

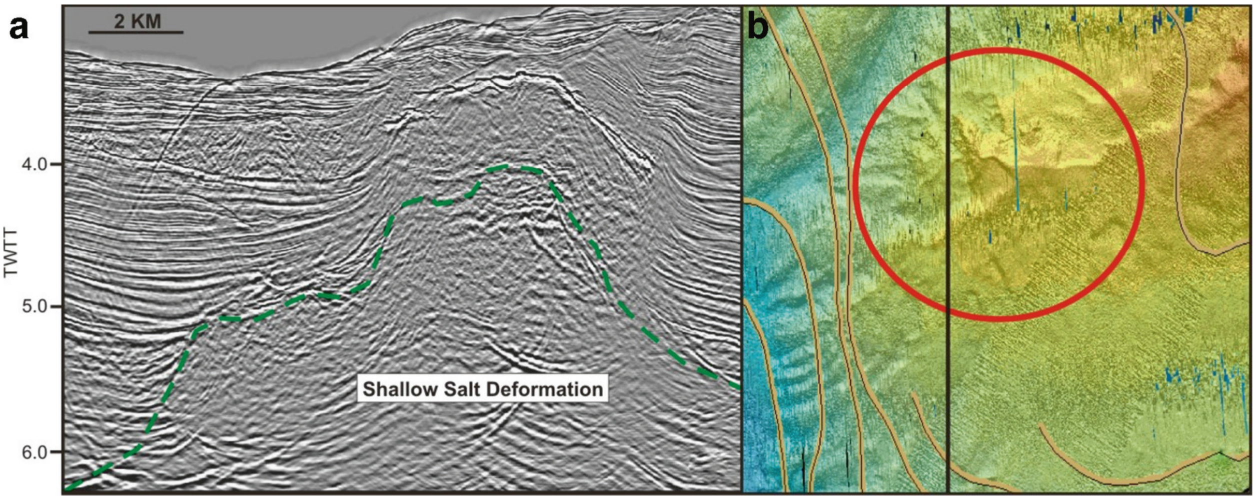

Fig. 5 Shallow salt deformation in the greater Halibut Channel region. Image A shows a seismic interpretation of shallow salt. Image B displays shallow salt deformation on the modern seafloor in multibeam sonar bathymetry data with the black line representing the seismic line.

Listric faults, extending from surface escarpments to these possible sand packages, provide evidence that these intervals may act as detachment surfaces, perhaps in response to generation of overpressures during seismic shaking; (4) shallow free gas is evident in cores recovered from St. Pierre Slope. Generation of gas within sediment reduces its strength properties setting up a situation for potential mass-failure; and (5) shallow salt deformation can play a role in the weakening of sediments by steepening slopes, directing fluid flow, and removing downslope support.

4 Conclusions

Mass transport processes are excellent mechanisms for transporting large volumes of sediment from the continental shelf to the abyssal plain. It is evident from seismic reflection data that the southwestern slope of Newfoundland was highly influenced by mass transport processes since at least the early Miocene. Evidence of frequent occurrence of these processes indicates that models of continental margin stratigraphy and sedimentation need to consider this process as a major contributing factor. Sediment mass failure is also a concern for the coastal communities of Atlantic Canada and for industry development in the area in terms of geohazard and tsunami risk. The size and frequency of such events is critical to understand in order to accurately assess the modern risk factor.

The conditions required for large scale submarine mass failures are not fully understood and the exact triggering mechanism responsible for a particular failure is hard to recognize with certainty. The presence of seaward dipping faults at the base of the mid Miocene MTD suggests that they create zones of weakness within the sediment column and increase the susceptibility of failure. Sediment stability is also reduced in some regions as a result of ongoing shallow salt deformation. It is probable that the seaward dipping faults, shallow salt deformation and sealevel lowering are key factors leading to sediment failure during the mid-Miocene to Middle Pleistocene. During the Pleistocene, high sedimentation rates following the various glaciations may well have established conditions for failure in the region by generating underconsolidated sediment profiles. In addition, there is evidence of horizons influenced by bottom currents, generating sedimentary bedforms; likely sandy in nature. These horizons could well be susceptible to liquidfaction in event of ground accelerations. Although these factors "precondition" the sediment column to mass failure, seismicity, such as occurred in 1929, is likely the ultimate triggering mechanism.

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APPENDIX B: CENOZOIC STRATIGRAPHY – D. CALVIN CAMPBELL

Cenozoic Geology Offshore Nova Scotia- A review of studies of the seismic, litho-, and sequence stratigraphy and comparison to the Cenozoic history of the North American Basin and New Jersey margin

INTRODUCTION

The Scotian margin consists of the continental shelf, slope and rise south of Nova Scotia and is part of the Scotian Basin, a 1200 km long basin offshore Nova Scotia. The basin formed during the late Triassic and early Jurassic rifting of Pangea and the opening of the North Atlantic Ocean (Wade and MacLean 1990). It comprises a number of interconnected grabens and half-grabens that are divided into sub-basins of the Scotian Basin. Cenozoic (Paleocene to Pliocene) deposits offshore Nova Scotia are understudied (Gradstein et al .1990; Piper 2005) despite exceeding kilometres in thickness and contributing significantly to the overall sediment column. In contrast, similar age deposits in the North American Basin and along the continental margin of the eastern United States have been extensively studied (Figure 1); for example, several Deep-Sea Drilling Program (DSDP) and Ocean Drilling Program (ODP) drilling transects have been conducted along the New Jersey margin to test theories on continental margin evolution and sequence stratigraphy. This paper presents a brief overview of the Cenozoic stratigraphy of the North American Basin. It then reviews the results of previous studies of Cenozoic deposits off Nova Scotia and summarizes the current state of knowledge regarding the lithostratigraphy, seismic stratigraphy, and sequence stratigraphy. In the discussion, the stratigraphy of the Scotian margin is compared to the stratigraphy of the North American Basin and New Jersey margin and differences are highlighted. Finally, directions for future research are suggested.

OVERVIEW OF THE CENOZOIC GEOLOGY OF THE NORTH AMERICAN BASIN

Mesozoic and Cenozoic deposits of the North American Basin are described by Jansa et al. (1979) and interpretations are based on extensive DSDP holes. The North American Basin is the large bathymetric depression in the northwest Atlantic Ocean centered on the Bermuda Rise (Figure 1). It is confined to the north by the Scotian margin, Grand Banks and Newfoundland Ridge, to the east by the Mid-Atlantic Ridge, to the south by the Antilles and Barracuda fracture zones, and to the west by the North American continental margin.

Lithostratigraphy

The lithostratigraphy of the North American Basin is shown in figure 2. The Late Cretaceous to Quaternary deposits comprise the Plantagenet, Bermuda Rise, and Blake Ridge formations. The Plantagenet Fm spans Late Cenomanian to Late Paleocene sediments and is described as

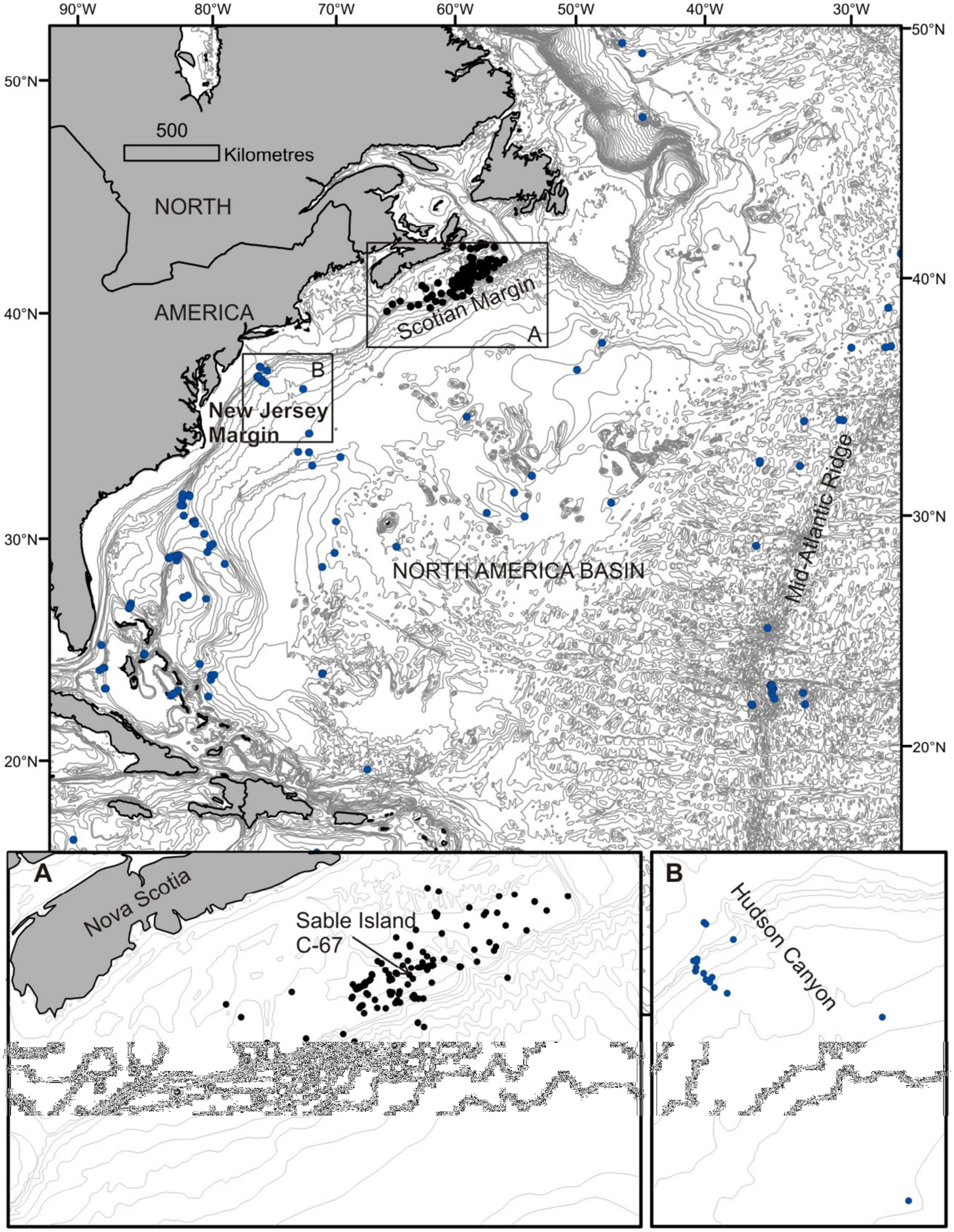


Figure 1- Maps of the study area. Main map shows North American Basin and adjacent continental margins with positions of ODP and DSDP drill sites, along with exploration drill sites for the Scotian margin. Inset A shows detail of drill sites along the Scotian margin. Inset B shows detail of ODP and DSDP sites on the outer New Jersey margin.

variegated, non-calcareous claystone interpreted as a pelagic deposit which accumulated in an oxygenated environment below carbonate compensation depth (CCD). A relatively thin but conspicuous interval of nannofossil chalks, marls and limestones is found in the upper part of the Plantagenet Fm. and has been designated the Crescent Peaks Member. The age of the Crescent Peaks Member is Middle Maastrichtian to earliest Eocene. It is interpreted to have formed via pelagic deposition in quiescent conditions above the CCD. The Bermuda Rise Fm spans latest Paleocene to Middle Eocene sediments and is described as a suite of sediments enriched in biogenic silica and chert. The Bermuda Rise Fm. is interpreted to be deposited in an environment where biogenic silica deposition predominated over biogenic carbonate in the deep basin below the CCD, and where significant biogenic silica contributed significantly to deposits above the

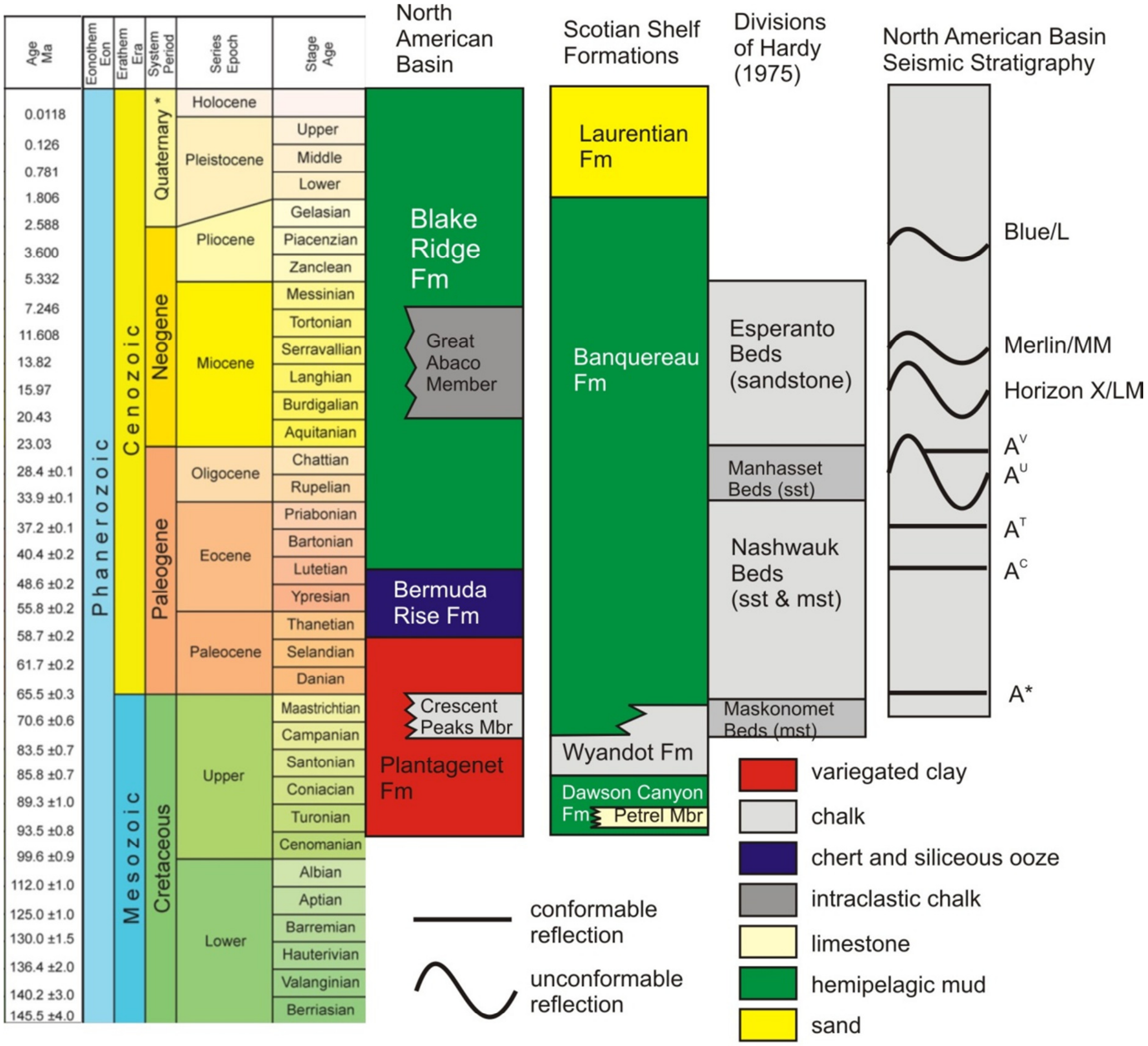


Figure 2- Lithostratigraphy and seismic stratigraphy of the North American and Scotian basins. North American Basin lithostratigraphy from Jansa et al. (1979). Scotian Shelf lithostratigraphy from McIver (1972), Jansa and Wade (1975), and Hardy (1975). Seismic stratigraphy from Tucholke and Mountain (1979), Tucholke and Mountain (1989), and Ebinger and Tucholke (1988).

Paleocene to Middle Eocene sediments and is described as a suite of sediments enriched in biogenic silica and chert. The Bermuda Rise Fm is interpreted to be deposited in an environment

where biogenic silica deposition predominated over biogenic carbonate in the deep basin below the CCD, and where significant biogenic silica contributed significantly to deposits above the CCD. The Blake Ridge Fm spans Middle Eocene and younger sediments. It is a widespread, greenish-grey and brown hemipelagic mud. It is interpreted to have been deposited in very similar environment as what currently prevails in the Northwest Atlantic. Much of the formation was deposited directly from turbidity currents and reworked by bottom currents. Within the Blake Ridge Fm, a massive interval of intraclastic chalk has been mapped and is designated the Great Abaco Member. The Great Abaco Member is Early to Middle Miocene age and is interpreted to be a mass transport complex.

Seismic Stratigraphy

Seismic reflection profiles are an important tool for evaluating basin histories and allow the extension of very local information (i.e., data collected at a single borehole) to a regional scale (Tucholke and Mountain 1979). In the North American Basin, a regional grid of seismic reflection profiles tied to DSDP and ODP holes resulted in the development of a basin-wide seismic stratigraphic framework. Since seismic reflection character is dependant on impedance contrast in sedimentary layers, which is directly dependant on changes in sediment bulk density and acoustic velocity, the seismic stratigraphy is intimately tied to the lithostratigraphy.

The seismic stratigraphy of the North American Basin is presented by Tucholke and Mountain (1979) and has been refined by subsequent researchers (e.g. Tucholke and Mountain 1986; Ebinger and Tucholke 1988) (Figure 2). Late Cretaceous and Cenozoic reflections have been assigned to the Horizon-A complex. Horizon A* correlates with the top of the Crescent Peaks Member of the Plantegenet Fm, a marly nannofossil rich chalk. Its age is late Maastrichtian. Horizon A^C correlates with the top of the Bermuda Rise Fm, with strong reflectivity associated with the cherts of this formation. Its age is Middle Eocene. Horizon A^T correlates with the top of a turbidite interval within the Blake Ridge Fm. Its age is Middle to Late Eocene and is attributed to widespread terrigenous input into the basin. Horizon A^U is a basin-wide erosional unconformity attributed to erosion by abyssal currents. Its age is variable and in many areas represents a hiatus from Late Eocene to Early Miocene. Horizon A^V correlates to an apron of volcanoclastic turbidites deposited around Bermuda. The age of the horizon is upper Oligocene and is attributed to subaerial weathering of the Bermuda pedestal which emerged above sealevel by middle Eocene time. In addition, a number of additional Miocene and Pliocene seismic reflection unconformities have been widely referenced in the literature (e.g. Tucholke and Mountain 1986; Swift 1987; Ebinger and Tucholke 1988; Locker and Laine 1992 and others). These are Horizon X/Unconformity/LM of Early to Middle Miocene age, Horizon Merlin/MM of Middle Miocene age, and Horizon Blue/L of Pliocene age.

STUDIES OF THE CENOZOIC GEOLOGY OFFSHORE NOVA SCOTIA

Details of the Cenozoic geology of the Scotian margin have been interpreted from direct sampling by hydrocarbon exploration wells, well log data, and seismic reflection data. The various studies that have looked at the geology of this area can be divided geographically into studies of deposits buried below the modern continental shelf and deposits buried below the modern continental slope and rise. This division is due to technological, economic and practical reasons. Early studies used data from areas accessible by the drill rigs of the day, either onshore rigs in the case of Sable Island, or jack-up rigs that were only capable of drilling in shallow water depths. Successful drilling results led to a focus of exploration in the Sable Sub-basin and therefore geographically constrained any new data.

Little was known about the Mesozoic and Cenozoic geology of the Scotian margin prior to drilling of the Sable Island C-67 exploration well by Mobil Oil Co. in 1967 (McIver 1972; Fensome et al. 2008). Early studies by McIver (1972) and Jansa and Wade (1975) divided the Mesozoic and Cenozoic deposits of the Scotian margin into a series of thirteen formations that represented the syn-rift and post rift depositional history of the area. The studies were based on wells drilled on the continental shelf, either into deposits of the Sable delta or into the Jurassic carbonate bank (Abenaki Formation). Of the thirteen formations, Cenozoic age deposits comprise the Banquereau (Late Cretaceous to Early-Mid Pleistocene) and Laurentian formations (Early-Mid Pleistocene to Recent)(Figure 2). Hardy (1975) proposed a four unit informal division of the Banquereau Formation (Figure 2, Figure 3), however these divisions have rarely been adopted because of difficulty distinguishing the units on seismic data and in regional correlation (Wade and MacLean 1990; Fensome et al. 2008).

Apart from Quaternary deposits, little is known about the Cenozoic history of the outer Scotian margin (Gradstein et al. 1990; Piper 2005), the zone below the modern continental slope and rise, primarily because it has not been of economic interest to petroleum exploration companies and no scientific drilling has been conducted in the area. In particular, the correlation of proximal and distal facies of the Scotian Basin formations is poorly known (Wade and MacLean 1990) and there are many uncertainties tying the abyssal North American Basin stratigraphy into the area (Swift et al. 1986; Ebinger and Tucholke 1988; Wade et al. 1995). In general, two approaches have been applied in correlating the Scotian Basin with the rest of the North American Basin. The first approach has been to correlate using seismic reflection data from the continental shelf basinward onto the slope while incorporating sparse well information from the continental slope (e.g. Jansa et al. 1979; Wade and MacLean 1990; Wade et al. 1995; MacDonald 2006). Despite abundant well and seismic reflection data from the shelf, correlation across the shelf break onto the upper to middle slope is difficult because it is an area of high sediment flux, with sediment bypass and erosion, and steeply dipping artificial reflections (multiples) interfere with true reflection data (Wade et al. 1995; MacDonald 2006).

The second approach has been to correlate seismic reflection horizons from the Sohm Abyssal Plain across the continental rise to the continental slope (e.g. Uchupi and Austin 1979; Swift 1987; Ebinger and Tucholke 1988). Ocean Drilling and Deep-Sea Drilling Program sites on the abyssal plain provided stratigraphic and age control, however tenuous seismic reflection correlation through the New England Seamounts and poor seismic reflection continuity between the abyssal plain and the continental slope made this approach difficult (Swift et al. 1986; Ebinger and Tucholke 1988) leading to errors in the correlation of Sohm Abyssal Plain seismic markers on the Scotian Slope (Wade et al. 1995).

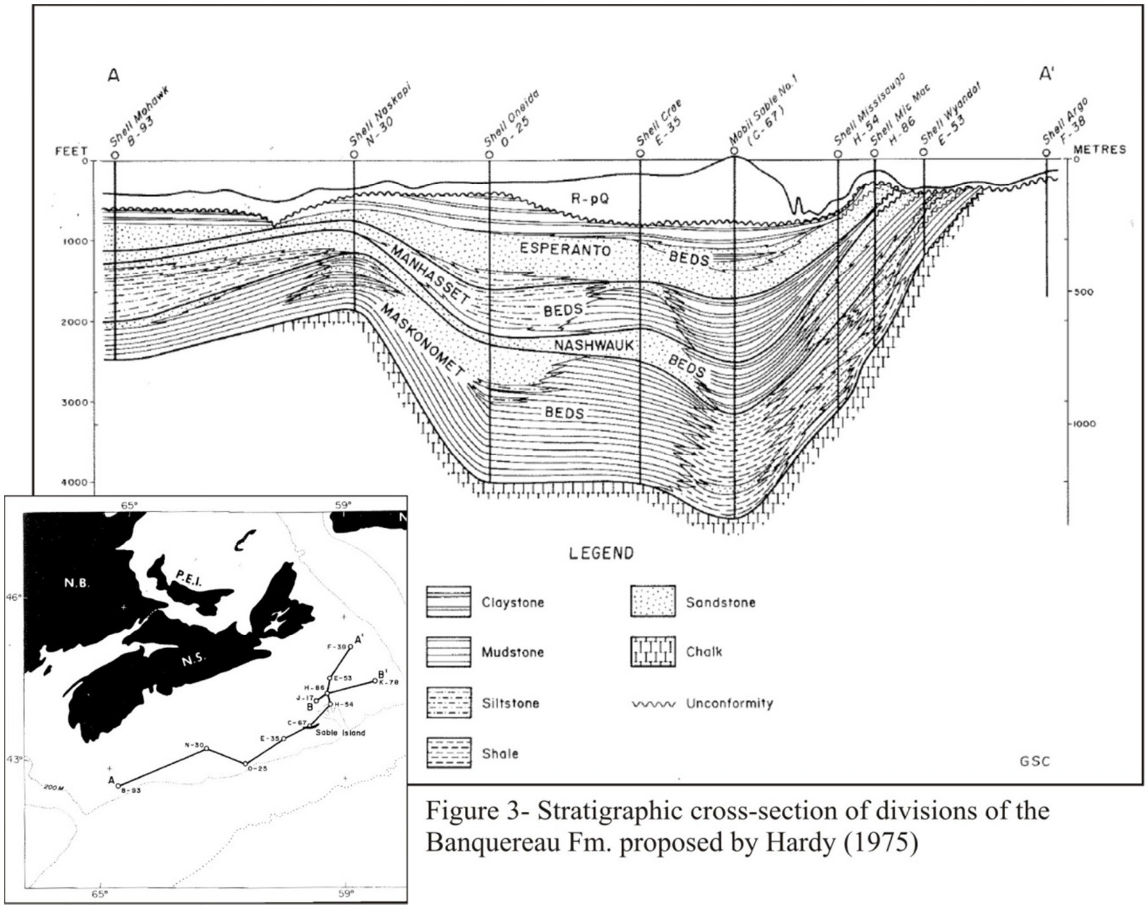


Figure 3- Stratigraphic cross-section of divisions of the Banquereau Fm. proposed by Hardy (1975)

LITHOSTRATIGRAPHY OF BANQUEREAU FORMATION

The type section for the Banquereau Formation below the Scotian Shelf is at the Sable Island C-67 well (McIver 1972; Hardy 1975; Wade and MacLean 1990) (Figure 1B). At this well, the formation is 1190 m thick and across the shelf it ranges from 1500 m thick in some wells to a zero thickness at the middle part of the shelf (Wade and MacLean 1990). This thickness variation was shown by Hardy (1975) (Figure 3).

The lithology of the Banquereau Formation is predominantly mudstone with lesser sandstones and thin chalk beds (Wade and MacLean 1990; Fensome et al. 2008). The most up-to-date lithologic summary is given by Fensome et al. (2008) (Figure 2, Figure 4). In the central Scotian Shelf, the formation consists of a lower interval of prograded deltaic clinoforms that built basinward over the underlying Wyandot Formation. Within this interval, clinoform topsets consist of sandstone, while foresets and bottomsets are mainly mudstone. The clinoform wedge spans the Maastrichtian through Paleocene. It is overlain by a mudstone and chert unit, then a thin, early Eocene chalk which is regionally mappable on seismic reflection data over much of the outer shelf and slope. Canyon

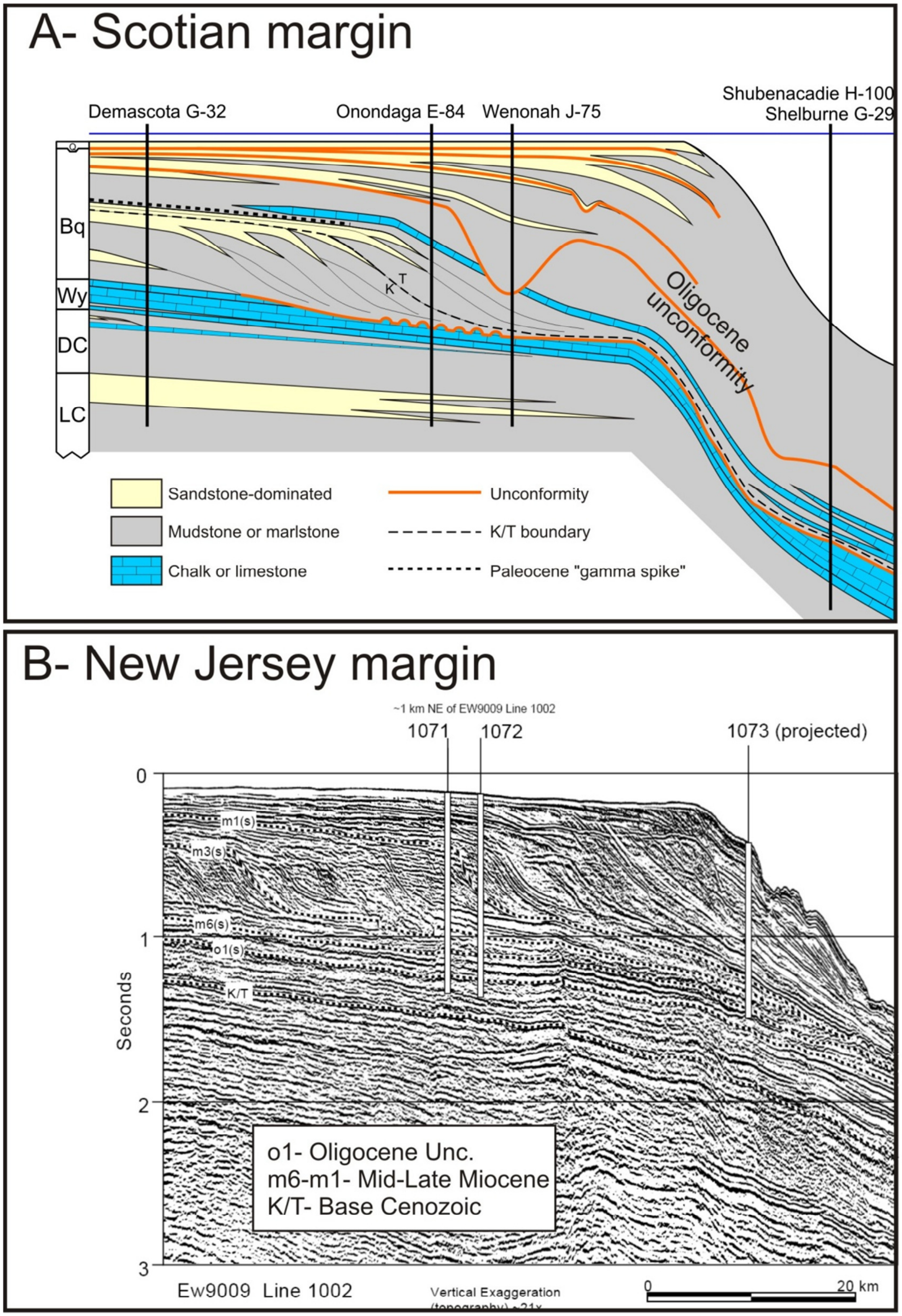


Figure 4- Depositional architecture of the outer shelf of the Scotian and New Jersey margins. A) Cartoon of the outer Scotian Shelf showing a buried late Cretaceaous and Paleocene delta and an Oligocene erosion surface (modified from Fensome et al. 2008). B) Seismic reflection profile of the outer New Jersey Shelf showing a buried Mid to Late Miocene delta over an Oligocene age unconformity (modified from Christie-Blick et al. 1998).

incision at the shelf edge started in the Eocene, but became particularly extensive in the Oligocene. Above the Oligocene erosion surface, the Banquereau Formation becomes increasingly sandy landward and consists of seaward-stepping progradational episodes punctuated by canyon incision and broader erosion, culminating with the effects of Pleistocene glacial erosion.

The lithostratigraphy of the Banquereau Formation along the outer Scotian margin is based on well cuttings and sidewall cores (small plugs sampled from the side of the well bore during drilling). There are no post-Oligocene conventional cores. Due to a paucity of data, no detailed lithostratigraphic summary exists. Samples show that the formation is mud-dominated, but like the shelf, has a general coarsening up pattern of deposition. Paleocene and early Eocene chalks, similar age to those on the shelf (Fensome et al. 2008), are recognized in a number of wells. Fine sandy intervals, tens of metres in thickness, are recognized in the Shelburne G-29 and Shubenacadie H-100 and are of Late Miocene age.

CENOZOIC SEISMIC STRATIGRAPHY OF THE SCOTIAN MARGIN

Previous authors have attempted to correlate the North American Basin seismic stratigraphy into the Scotian margin area (Jansa et al. 1979; Uchupi and Austin 1979; Swift et al. 1986; Swift 1987; Ebinger and Tucholke 1988; Wade and MacLean 1990; Wade et al. 1995). Major impediments to this correlation are the New England Seamounts and the Scotian Slope salt diaper province which disrupt seismic reflection continuity. Prior to Swift et al. (1986), seismic correlation across the New England seamounts was inferred or “jump-correlated” based on reflection characteristics. Only horizons A* and A^U were correlated with confidence across the New England Seamounts by Swift et al. (1986).

The top of the Wyandot Fm forms a regionally correlatable seismic reflection below the continental shelf and slope, and marks the base of the Banquereau Fm. The Wyandot Fm is considered to be equivalent to the Crescent Peaks Member of the Plantagenet Fm, and therefore the reflection created at its upper surface is equivalent to A* in the North Atlantic Basin. A number of erosion surfaces have been recognized on the shelf within the Banquereau Fm and have been attributed to sealevel fluctuations (Wade and MacLean 1990; Fensome et al. 2008) (Figure 4). These date from Paleocene and Eocene age to Late Miocene but have not been correlated regionally. On the outer Scotian margin, Swift (1987) and Ebinger and Tulcholke (1988) reported a number of seismic unconformities produced by bottom current erosion of the continental rise and abyssal plain with inferred ages of Oligocene, Lower Miocene, Middle Miocene, and Pliocene.

CENOZOIC SEQUENCE STRATIGRAPHY OF THE SCOTIAN MARGIN

Sequence stratigraphy has its origins in the early work by the Exxon Corporation (Payton 1977) and the sequence stratigraphic model is based on the idealized sediment sequence deposited during a single sealevel cycle (fall and rise). Sequence stratigraphy as a field of study has suffered from an inability to be properly defined (Embry 2002). Embry (2002) provides a working definition that removes the uncertainties in distinguishing tectonic versus eustatic changes in sealevel: “Sequence stratigraphy consists of the recognition and correlation of changes in the depositional trends in the rock record. Such changes, which were generated by the interplay of sedimentation and shifting base level, are now recognized by sedimentological criteria and geometrical relationships.” Base level is defined as the imaginary equilibrium point between erosion and deposition and is typically close to sealevel, however one can easily imagine scenarios where base level is below sealevel, for example where large rivers meet the coast, or along storm dominated shelf areas where base level occurs at storm wave base.

There have been only three published studies of the Cenozoic sequence stratigraphy of the Scotian margin. The first was by Wade et al. (1995) and was located in the Banquereau area. They utilized data from three exploration wells and a single regional, dip-oriented seismic reflection profile. The second study was an M.Sc. thesis by Long (2002) located in the outer shelf area near Sable Island. The study utilized over 265 strike- and dip-oriented seismic reflection lines and data from 41 wells. The most recent study was an M.Sc. thesis by MacDonald (2006) and was located on the continental slope southwest of Sable Island. The study utilized a regional 3D seismic reflection dataset and data from four exploration wells. The results of the studies compare favourably (Table 1), with discrepancies explainable by data limitations and geographic variability.

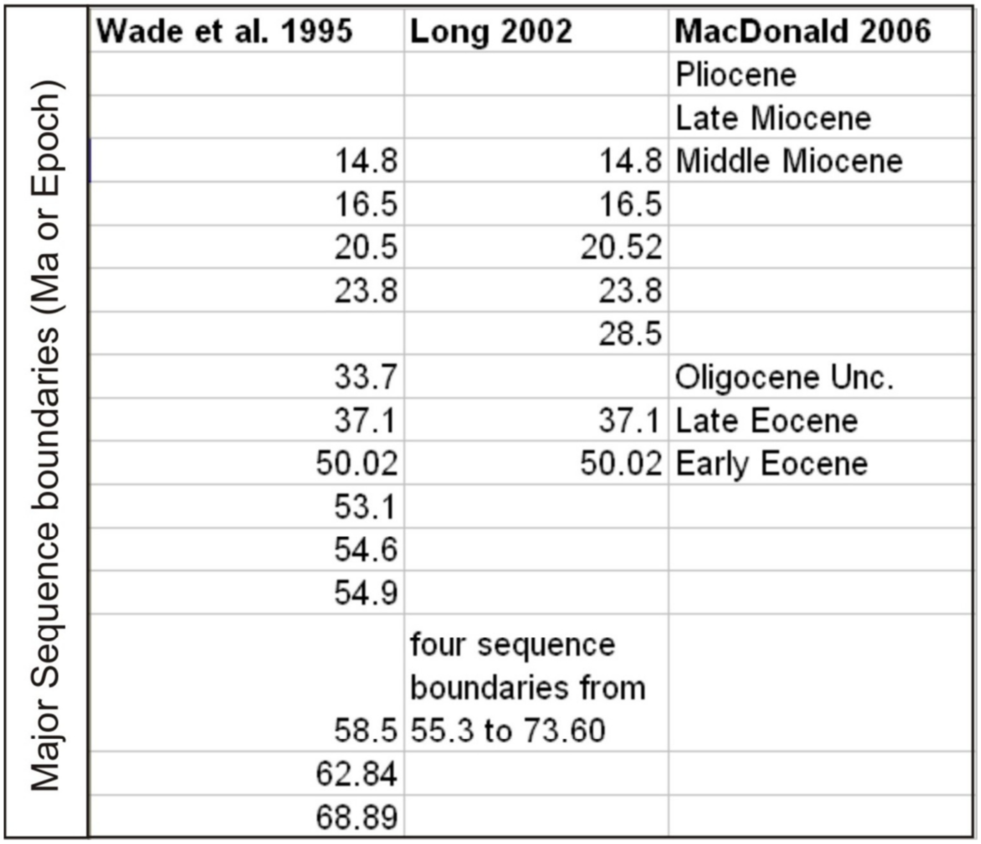
DISCUSSION

Comparison of the North Atlantic Basin with the New Jersey and Scotian margins

The New Jersey margin is the most extensively sampled and studied passive margin in the world. Four scientific drilling legs have been conducted over a relatively small area just south of Hudson Canyon and a fifth is planned for 2009 (Figure 1C). For the purpose of comparison, it is convenient that the Scotian margin is geographically close to the New Jersey margin. The two areas are separated by the Yarmouth Arch, a structural high, and the New England Seamounts. Major similarities between the two areas include a passive continental margin setting, progradational architecture, and the development of a major carbonate bank in the Jurassic. Major differences are the lack of Cenozoic deposits on land on the Scotian margin compared to extensive deposits of Cenozoic deposits on the Atlantic Coastal Plain. The New Jersey margin lacks the widespread Triassic salt deposits (Argo Fm) of the Scotian margin. Geodynamic models of Keen and Beaumont (1990) outlined differences between the Scotian margin and Baltimore Trough areas, identifying a much wider lithospheric-oceanic crust transition zone for the Scotian margin.

In terms of lithostratigraphy, Jansa et al. (1979) described the differences between North American Basin formations and coeval deposits on the US and Canadian margins. For the Plantagenet Fm, no lithologically similar deposit has been recognized on either the US margin or Scotian margin. The chalks and marls of the Crescent Peaks Mbr. are correlatable with chalks on the Scotian margin (Wyandot Fm) and chalk formations along the US coastal plain. The silica rich and cherty Bermuda Rise Fm is coeval with marls and chalks with variable biogenic opal content on the US continental shelf. Although Jansa et al. (1979) indicate that coeval deposits on the Scotian margin comprise glauconitic mudstones, subsequent exploration drilling revealed chalk units of this age (Fensome et al. 2008). Deposits of similar age to the Blake Ridge Formation along the US and Canadian continental margins are much more variable than the rather monotonous greenish-grey sediments that comprise the formation in the deep basin (Jansa et al. 1979). On the Scotian margin, Oligocene and Miocene sediments are dark yellowish-brown and brownish-grey mudstones with lesser sandy intervals. In contrast, more than a kilometre of Oligocene and Miocene fine-grained sandstone was deposited on the New Jersey margin.

Table 1- Major Late Cretaceous and Cenozoic sequence boundaries recognized on the Scotian margin.



Major Sequence boundaries (Ma or Epoch)	Wade et al. 1995	Long 2002	MacDonald 2006
			Pliocene
			Late Miocene
	14.8	14.8	Middle Miocene
	16.5	16.5	
	20.5	20.52	
	23.8	23.8	
		28.5	
	33.7		Oligocene Unc.
	37.1	37.1	Late Eocene
	50.02	50.02	Early Eocene
	53.1		
	54.6		
	54.9		
	58.5	four sequence boundaries from 55.3 to 73.60	
	62.84		
	68.89		

Mapping of elements in seismic reflection data has revealed other differences between the two areas. On the New Jersey margin, a major post-Oligocene prograding clinoform wedge of Miocene-Pliocene age is preserved below the modern shelf (Christie-Blick et al. 1998; Metzger et el. 2000) (Figure 4). A morphologically similar wedge is recognized on the Scotian margin west of Sable Island, however the age is Maastrichtian through Paleocene (Fensome et al. 2008), indicating that the margin prograded to the shelf break much earlier than New Jersey. In the Neogene, pre-Pleistocene canyons are rare on the New Jersey margin, with earliest canyons having a Mid to Late Miocene age. In contrast, the Scotian margin has experienced multiple phases of canyon development, in the Eocene, Oligocene, and Miocene (Kidston et al. 2007; Fensome et al. 2008). On the continental rise off New Jersey, Miocene to Pliocene age, widespread contour-current derived deposits (contourites) are recognized in seismic reflection data, namely the Hatteras Outer Ridge and the Lower Continental Rise Hills. Off Nova Scotia, no major contourite drifts of this age are reported, although erosion of the slope and rise by bottom currents during this time has been suggested by a number of authors (Swift 1987; Ebinger and Tucholke 1988).

Directions for future work

Research on the Cenozoic evolution of the Scotian margin benefits from a recent round of hydrocarbon exploration that resulted in the collection of regional 2D seismic reflection data, a number of 3D seismic reflection datasets, and the drilling of seven new deepwater exploration wells. Such extensive and high quality geophysical datasets do not yet exist on the adjacent New Jersey margin because the area has been under moratorium to hydrocarbon exploration since the early 1980s. These datasets provide a uniform "sampling" of the margin and allow recognition of true spatial variability, whereas previous studies of the outer Scotian margin utilized sparse geophysical data collected in a non-systematic manner. It is an opportune time to revisit previous studies and challenge and revise pre-existing ideas in light of new data.

There are a number of future directions for study which would utilize currently available data and address knowledge gaps identified from previous studies. First, the relationship between sedimentation in the deep basin and adjacent margins needs to be better understood. Differences between coeval deposits of the two areas were highlighted above. The continental slope and rise is the transition zone between these two areas and new geophysical datasets have been focused over this transition zone. Analysis of these datasets will lead to new concepts on passive margin evolution, for example the concept of gradual margin progradation versus periodic synchronous mass-wasting, or the relative importance of down-slope and along-slope processes.

Another area is the impact of Cenozoic tectonics on regional erosion and deposition patterns. There is evidence for occasional tectonic activity due to changes in intracrustal stress (Cloetingh et al. 1990), salt migration (Shimeld 2004; MacDonald 2006), movement along the Cobequid-Chedabucto- Southwest Grand Banks fault system (Pe-Piper and Piper 2004), and post-Paleocene exhumation and cooling from fission track analysis (Grist and Zentilli 2003). The New Jersey margin is the type-section for the Late Cretaceous global sealevel curve (Miller et al. 2005), however there are differences between the sequence stratigraphy off New Jersey and Nova Scotia. Whereas the scientific drilling transect off New Jersey provides an unparalleled level of groundtruth, the transect covers a narrow sector of the continental margin and does not capture along-slope variability. Although comparisons with more distal margins, such as the European and Australian records, have been made, preliminary work by Long (2002) shows discrepancies between the sequence stratigraphy of the Nova Scotia and New Jersey margins, with only three of eight Cenozoic sequences in agreement. On the New Jersey margin, the signal of sealevel change due to tectonic changes (i.e. subsidence and uplift) has supposedly been stripped out (Miller et al. 2005), and so differences with the Scotian margin record implies differences in sediment supply and/or tectonics. This discrepancy warrants further investigation.

SUMMARY

Sediments of the North American Basin record changes in depositional modes and sediment type that are a response to changing oceanographic conditions, climate, sediment supply, tectonics, and relative sealevel change. Despite experiencing similar climate and oceanographic conditions throughout the Cenozoic, differences are apparent in progradational history and timing of depositional elements between the New Jersey and Scotian margins. This suggests differences in other factors, such as sediment supply, basin configuration, and tectonic history.

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APPENDIX C: ABENAKI CARBONATE PLATFORM AND SABLE DELTA - LESLIE ELIUK

OUTLINE

Introduction with explanation of report format

Summary of Eliuk's proposed PhD research (Does a large siliciclastic delta have identifiable and significant influence on the margin and reefs of an adjacent thick carbonate platform?)

Database and methodology (Table of wells – Study area – Illustration of cuttings/litholog)and Tabulated Chronological Comparison of Advances in Understanding Abenaki

Sequence Stratigraphy, correlation, non-deposition effects and other new such contributions

Summary Conclusions 1: Regional Setting of the Late Jurassic Deep Panuke Field, offshore Nova Scotia, Canada: - cuttings-based synthesis of a reef margin gas pool set within the lateral changes of a platform adjacent to a delta – a unique(?) hydrocarbon system and play type

Summary conclusions 2: Regional Setting of the Late Jurassic Deep Panuke Field, offshore Nova Scotia, Canada: - Distant and fractal analogues and possible process controls for a thick carbonate platform flanked by a large delta; two possible analogues for the Abenaki – Sable delta near the Deep Panuke trend

Summary conclusions 3: Carbonate and Siliciclastic Sequence Stratigraphy- examples from the Late Jurassic Abenaki limestone and West Venture deltaic beds, offshore Nova Scotia, Canada

Significance to Hydrocarbon Exploration-Development

Future Work Possibilities

References cited

Chronological Selected Bibliography of Abenaki-Atlantic margin and adjacent carbonates

Rock data and interpretation from well core and especially cuttings are compared to petrophysical logs and integrated with publicly available seismic to update and further understand the Abenaki Formation carbonate platform margin particularly in proximity to the contemporaneous Sable island delta. Offshore Nova Scotia's most recent gas discovery at Deep Panuke has doubled the amount of near margin well control. Recent seismically-based review and very timely publications on the petroleum geology, sequence stratigraphy and reservoir diagenesis has put in the public domain data and a good understanding of the field itself. But its broader regional setting and the seemingly anomalous location of thick clean carbonates beside one of the largest paleodeltas on the North American Atlantic offshore remain to be understood. Vertical changes occur over more than a kilometre of carbonate where standard dip-oriented carbonate facies template can be updated and applied. But along-strike lateral variation occurs away from the delta in intra-facies parameters in a variety of margin facies-associations from oolitic to margin reefal to carbonate slope. Most obvious are systematic color changes but include types of reefs. These indicate that the close juxtaposition of delta and carbonate platform had a significant influence. At the other extreme, even within the deltaic complex, thin condensed limestones have a complex story to unravel as component reef types change vertically over less than 10m. Deep Panuke is in the centre of these changes along the margin. So not only is it a unique gas accumulation for the North American continental shelf, it may constitute a unique or at least very rare hydrocarbon system worldwide. Understanding the depositional facies relationships and process controls that allowed this close association of reefal-oolitic carbonate platform margin and large deltaic complex will help increase its relevance as an analogue for further exploration on the Nova Scotian shelf and elsewhere in the world.

INTRODUCTION

This report summarizes aspects of Mr. Leslie Eliuk's Dalhousie Earth Science PhD Abenaki carbonate research (2007-2010...advisor Prof Grant Wach) relevant to offshore Nova Scotia hydrocarbon exploration and development. The Abenaki carbonates were generally considered economic basement until EnCana (PanCanadian) drilled below a depleted margin-drape sandstone oil accumulation. The discovery of the Deep Panuke Abenaki margin reef gas field changed that. Their 1998 platform deepening eventually resulted in possibly one TCF or more of gas in place justifying a pipeline to come on-stream in late 2010. Truly the understanding of the Abenaki could be divided into "before and after Deep Panuke". Nova Scotia offshore is unique in having the only carbonate gas accumulation on the North American Atlantic continental shelf and the youngest reefal accumulation in Canada famed for its Paleozoic reef hydrocarbon accumulations. Geologically Deep Panuke's setting may also be rare if not unique.

Abenaki margin well control more than doubled following the discovery with 15 new wells. Relative to those activities, studies of the thick Abenaki Formation carbonate platform can be divided into an earlier pre-Deep Panuke gas field discovery-and-development period prior to 1998 and a subsequent period post-dating the discovery. In fact, studies from the period from 2000 to 2006, which culminated in operator-sponsored publications in the AAPG on Deep Panuke petroleum geology-sequence stratigraphy (Weissenberger, Wierzbicki and Harland 2006) and reservoir diagenesis (Wierzbicki, Dravis, Al-Aasm and Harland 2006) respectively plus the EnCana field development report (2006, available on the CNSOPB website), and earlier data in core conference articles (Wierzbicki et al. 2002, 2005) and a CNSOPB seismic-based regional Abenaki review (Kidston et al. 2005) are a fairly complete summary on the field and its immediate setting, particularly the importance of late burial diagenesis to dolomitization and porosity. However a broader regional view concentrating on the initial setting and probable controls, depositional environments and early diagenesis relative to the unusual close juxtaposition of a thick carbonate platform and a large delta is the subject of Eliuk's thesis. In other words, what set up the Abenaki at Deep Panuke for late diagenesis to make it a gas accumulation. To demonstrate the advances made in our Abenaki knowledge as a result of the EnCana discovery and the continuing increase in understanding; a three-fold chronological comparison is **Table 2** and the Bibliography/References are similarly subdivided. Based on that timing, the table briefly reviews what was generally known about the Abenaki prior to 1998, what was put in the public domain by Deep Panuke operator workers in 2000-2006 when the last well to date was drilled in the play (limited by 2 year confidentiality) and what could be considered additional learnings during the time of OETR funding from 2007 on and is expanded upon.

Eliuk's PhD research is cuttings- and core-based (over 25 wells with 15 post-Panuke), uses Kidston et al. (2005) seismic mainly and concentrates on the depositional and very early diagenetic aspects of the Abenaki to address the problem – does a large siliciclastic delta have identifiable and significant influence on the margin and reefs of an adjacent thick carbonate platform. But this report concentrates on contributions relevant to offshore energy through the threefold chronological comparison (**Table 2**) going from aspects of smaller to larger scale for the following topics: a) litho/bio/reef facies, b) prospect and well analysis, c) reservoir characterization and variability, d) diagenesis and porosity, e) regional setting as related to the adjacent Sable Island paleodelta, f) analogues and process controls and g) play fairway analysis and hydrocarbon system. After the 3 summary conclusions there is a short listing of how the preceding work has specific relevance to hydrocarbon exploration and development. Finally some suggestions for future follow-up research are given.

SUMMARY OF ELIUK'S PROPOSED PHD RESEARCH (DALHOUSIE EARTH SCIENCES – G. WACH):

The Abenaki Formation is near the stratigraphic base of the offshore Nova Scotia passive margin. It occurs at the northern end of a carbonate gigaplatform extending from the Grand Banks to Florida in the Middle Jurassic-earliest Cretaceous (Poag 1991). The Abenaki is unique in Canada as the youngest carbonate platform with the youngest 'typical' reefs in a spectrum that includes all three Jurassic reef and reef mound end-members (coral reef, sponge and microbial-mud mound; Leinfelder 1994, Eliuk 1978, 1989). It also is the youngest gas-bearing fossil-reef reservoir in a nation noted for its Paleozoic reef reservoirs (Wierzbicki et al. 2006, EnCana 2006). The Abenaki at Deep Panuke is so far unique in the North American Atlantic offshore as being the only hydrocarbon field in carbonates. The Abenaki may be unique or at least very rare in the world in being a thick reef-bearing carbonate platform laterally adjacent to and dissected by a large delta – the Sable Island paleodelta. This juxtaposition is opposed to the not uncommon mixed carbonate-siliciclastic situations of relatively thin carbonate layers or small buildups within thick siliciclastic-volcaniclastic regimes or isolated carbonate banks or platforms across deeps from major siliciclastic influxes or carbonate shelves with nearshore siliciclastics. The Abenaki and its correlatives are these too. Though these mixed carbonates-siliciclastics are interesting in themselves, they are not the problem to be addressed here.

This thesis will argue that these unusual features are not a coincidence but result from a "natural experiment" cataloguing the influence (increased nutrients and turbidity; reduced salinity, oxygen and illumination; potential fouling, hard substrate loss and burial – modified from Leinfelder 1997 and Mount 1984) of the Sable Island siliciclastic depo-centre in modifying other paleo-oceanographic controls on the Abenaki carbonate platform and its reef margin to the southwest. Core and particularly well cuttings in about 25 wells tied to published seismic (Kidston et al. 2005) will be used to identify vertical changes in the facies architecture as a whole and between individual sequences (Weissenberger et al., 2006). Similarly, lateral changes will be followed at increasing distances from the Sable Island delta using all margin wells within sequences for the major depositional facies associations such as 1) ooid shoal margin top, 2) varied reef subtypes in the upper margin front with the lithistid sponge reefs being deepest and/or most turbid, and 3) microbial-mound-rich deeper slope with possibly the youngest red microbial stromatactis mounds. These changes involve features from rock color to skeletal/non-skeletal composition to microbial content to bioerosion amount to reef type and may include all three carbonate factory types of Schlager (2005). The Nova Scotian Basin relationship will be contrasted with the contemporaneous carbonate margin in the Baltimore Canyon Trough off Delaware USA. There, small deltas occur behind a seismically well-imaged margin that also shows all three of the Jurassic end-member reef-reef mound types plus pinnacle reefs. Using both data sets it will be argued that the shelf-edge geometries, carbonate margin sediment types and interpreted reduced-to-condensed sedimentation vary systematically as a function of lateral proximity to the delta. Thus the facies distribution across the margin will show more dynamic changes than can be depicted in the simplification of a carbonate platform facies template (Wilson 1975, Eliuk 1978, Eliuk and Levesque 1989, Wierzbicki et al 2002) or the pattern of reef promontory versus inter-reef channel of the nearly stationary aggrading platform margin contrasted with the prograding ramp margin associated with the Sable Island delta proper (Eliuk 1978, Wade and McLean 1990).

In short the problem is **- does a large siliciclastic delta have identifiable and significant influence on the margin and reefs of an adjacent thick carbonate platform? And that apparently academic problem is also the relationship that gives the highly economic Deep Panuke reef gas field its possibly unique hydrocarbon system.**

DATABASE-METHODOLOGY AND TABULATED CHRONOLOGICAL COMPARISON OF ABENAKI UNDERSTANDING

The main basis and contribution of Eliuk's thesis is the information derived from cuttings logging and interpretation, critically supported by very sparse core control. In carbonates with their uniform mineralogy it is only by closely looking at the rock, not just petrophysical logs or seismic, that depositional and diagenetic conclusions can be made. The area of study is shown in **Figure 1** and the wells logged for cuttings (and core indicated by number in furthest right column) in **Table 1**. The key data in this thesis are the cuttings as illustrated in **Figure 2** along with the resulting schematic log and interpretation. There is a long history of cuttings examination going back to 1973-1974 studies for Shell Canada with detailed lithologs eventually published in Eliuk (1978; wells indicated by date in **Table 1**). However most wells were logged or relogged (indicated in red of **Table 1**) in the last decade to assist the EnCana and other operators exploration and development campaign. Then followed some additional examination for an update on older wells that post-dated the earliest drilling but pre-dated Deep Panuke. Because of modern turbo drilling with PDC (polycrystalline diamond compact) bits the cuttings are mostly but not all chalkified and sheared. Though less adequate than one would like, it is the only rock fabric/texture data available except for the few and rare cores that cover less than 3 % of the section drilled. Rock image logs were used by Wierzbicki (eg. Wierzbicki et al. 2005, Weissenberger et al. 2006) and were calibrated by drilled sidewall cores examined by Eliuk (indicated by 's' in the last column of **Table 1**. All SWC's had thin sections that also were examined; Albatross had 'blasted' SWC's that had been made into thin section by PetroCanada.

A Leitz binocular microscope with a polarizer substage option was used to examine cuttings at the usual sampling depth intervals (10 feet, 5 metres) in the wells indicated in **Table 1**.

Mechanical logs assisted in interpretation of the cuttings and over lost circulation intervals. In the Abenaki Formation all available cores (over 25 core intervals between 1 and 25m long plotted in various logging formats) and all post-1998 sidewall cores (over 200) were logged and photographed and also all cores (15) in the 3 Baltimore Canyon Trough shelf margin wells. In addition many cuttings thin sections and all thin sections from drilled sidewall cores in the Deep Panuke area were examined and photographed. Detailed well litholog plots using a custom Excel spreadsheet were made for more recent wells; some older ones are in the public domain (Eliuk 1978) and those done for the Deep Panuke play operators are in part confidential (posters done for Wierzbicki et al. 2005 on Margaree F-70 cuttings and core are in the public domain and illustrate the Excel format). Plotting key framebuilder fossils in an approximate relative depth order was a particularly useful procedure and was often transferred to schematic depictions. Schematic logs showing important litho/biofacies have been done for most of the wells as indicated on **Table 1**. These data were compared to mechanical logs and standard and digital cross sections were constructed of various vintages to establish correlations, sequence breaks and lithofacies relationships. Publicly available seismic particularly from Kidston et al. (2005) and published EnCana sections were used extensively for additional understanding and comparison of the wells. The lithofacies data were plotted as pie diagrams using principal lithologies, Dunham classification, certain allochems (oolite, microbial/peloidal) and key framebuilder content. These pie diagrams were grouped by sequence intervals for display next to schematic logs on well sections and on sequence stratigraphic layer maps.

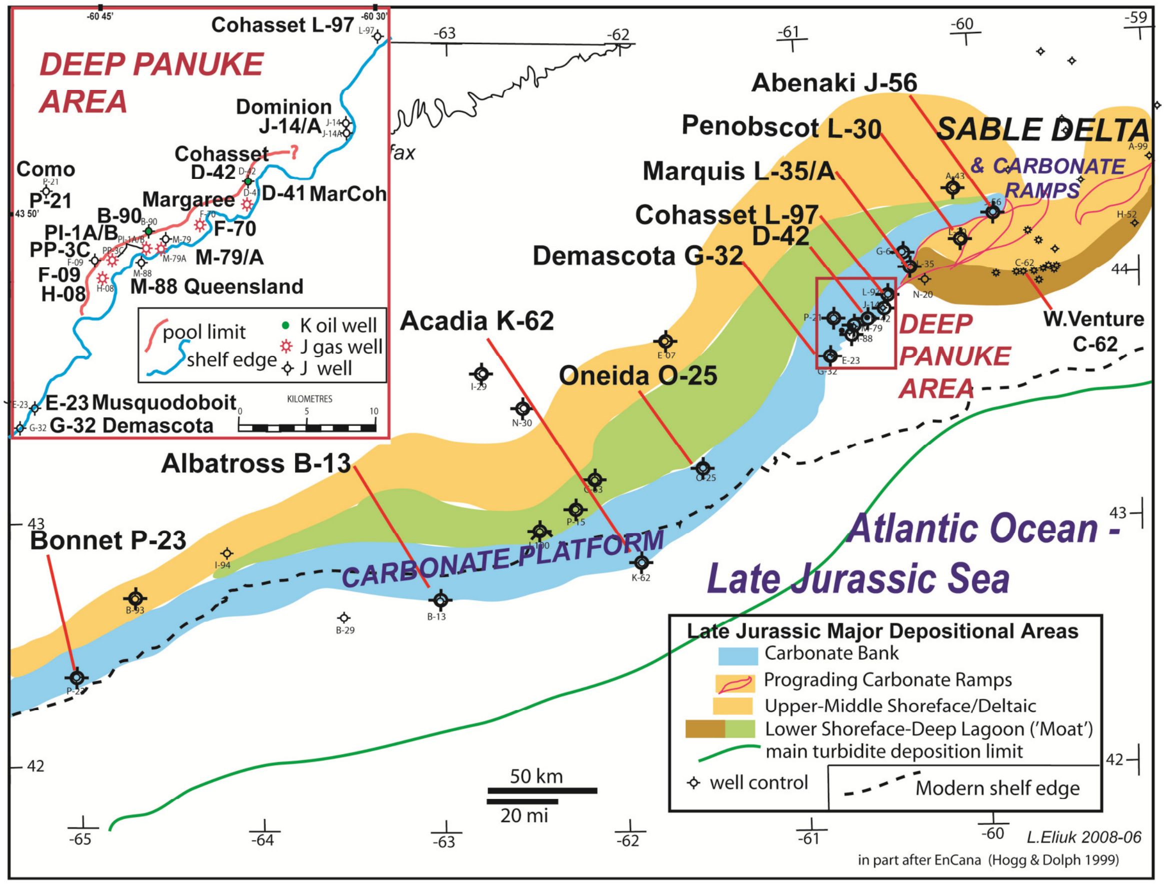


FIGURE 1. Study area with Abenaki Formation wells in bold and generalized major depositional areas. Newer wells (1998+) are in the Deep Panuke area (inset map) with one of the first margin wells Cohasset D-42 actually in the pool and the other Demascota G-32 that cored all 3 reef types downdip. The only post-1998 Abenaki wells outside the inset map are Marquis L-35 and its basinward whipped follow-up L-

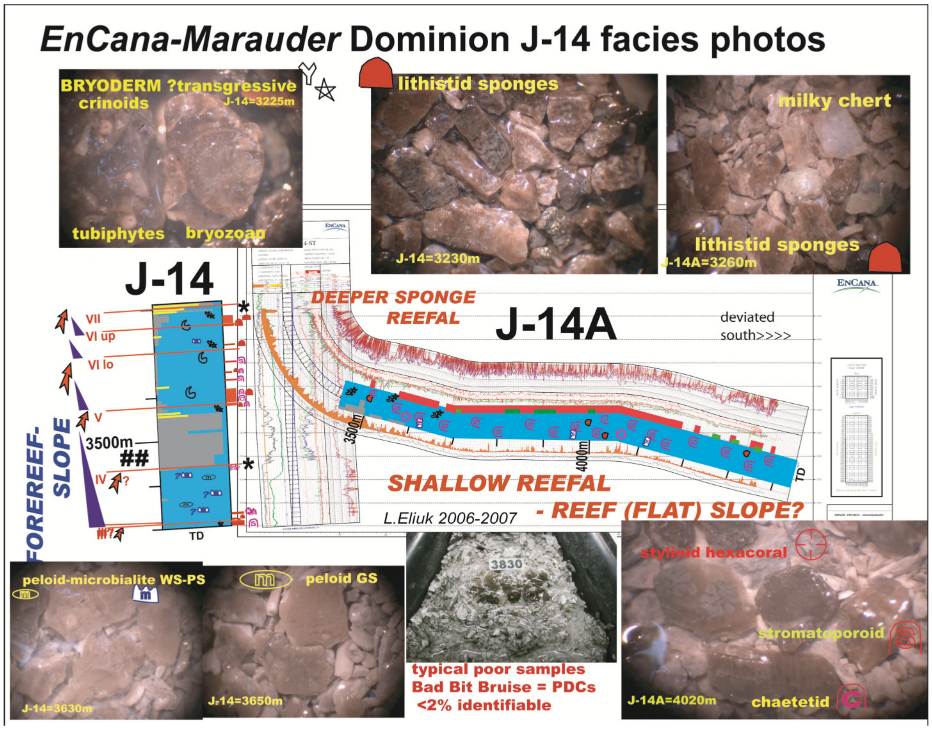


Figure 2. Photographs of cuttings used to gather depositional information for the schematic logs of the last wells in the Deep Panuke play. This was the only rock data in the latest wells which found shale at the AB 5 reservoir zone instead of the expected porosity. Unlike all the other Deep Panuke wells AB 4 had microbial-peloidal slope lithofacies indicating an originally deeper depositional setting.

TABLE 1. ABENAKI MARGIN WELLS –litho/depofacies Versus CNSOPB (Kidston et al 2005) Leslie Eliuk 2010-08

Year	Operator	Name	ID	FTD (m)	Status (m of gas)	Comments (of Kidston et al 2005)	Litholog Eliuk	S=Schematic Seismic>x	I=Sequence ID P=%s,	Core S=SWC
1970	Shell	Oneida	O-	4110	D&A	Platform-on basement	1978, d	x		
1971	Shell	Abenaki	J-56	4569	D&A	Platform-salt diaper	1978, d	x		
1972	Shell	Mohican	I-	4393	D&A	Platform-over salt swell	1978, d	x		5
1973	Mobil	Cohasset	D-	4427	D&A	Bank edge/back reef-some ϕ, Koil	1978, d, s	S x	I(E) P	
1974	Shell	Demascota	G-	4672	D&A	Bank edge- 186m ϕ, test	1978, d, s	S x	P	5
1976	PetroCanada	Penobscot	L-30	4267	D&A	*Bank edge/back reef- no ϕ	1981/85, s	S x		
1977	PetroCanada	Moheida	P-	4298	D&A	Platform-basement	1978, p-	x		2
1978	Chevron	Acadia	K-	5283	D&A	Bank edge-good ϕ	1981, s, p	S x	I?	5
1978	Mobil	Cohasset	L-97	4872	D&A	(*)Bank edge-some ϕ	d, s,	S x	I	1
1984	Husky	Glooscap	C-	4542	D&A	Platform,-salt swell		x		
1984	PetroCanada	Bonnet	P-	4336	D&A	Back reef- major lost	d,s	S x	I?	
1984	PetroCanada	Dover	A-	4525	D&A	Platform-fault block	d, W	x		
1985	Mobil	W.Venture	C-		gas	Shelf lime beds under	Core only	x	See Cummings	2+
1985	PetroCanada	Albatross	B-	4046	D&A	(*)Bank edge-some ϕ	d, s	S x	I?	1,(s)
1986	Shell	Panuke	B-	3445	D&A-oil	(*)Bank edge- no ϕ, K oil disc	d,	S x	I (E)	
1987	Shell	Kegeshook	G-	3540	D&A	Platform-basement	d,s	S x	I	
1987	PetroCanada	Como	P-	3540	D&A	Platform-basement	d,	S x	I	1
1998	PanCanadian	Panuke (PP-3C)	J-99	4163	Gas -97	Bank edge- Ab5 gas disc'	d, s	x	I(E) P	
1999	PanCanadian	Panuke (PI-1A)	J-99	4030	Gas -6.9	Bank edge-thin gas	d, s	S? x	I(E) P	1, s
1999	PanCanadian	Panuke (PI-1B)	J-99	4046	Gas -49	Bank edge-24.2m pay	d, s	^x	I(E) P	
2000	PanCanadian	Panuke	H-	3682	Gas -112	Bank edge-108m pay	d, s	x	I(E) P	1
2000	PanCanadian	Panuke	M-	4598	D&A-14	Bank edge-no gas	d, s W	S ?	I(E) P	1,s
2000	PanCanadian	Panuke	M-	3935	Gas -21	Bank edge-11.4m pay	d, s	^x	I(E) P	
2000	PanCanadian	Panuke	F-09	3815	D&A-27	(*)Back reef-low ϕ,	d, s	S x	I(E)	s
2001	PanCanadian	Musquodoboit	E-	3818	D&A	Bank edge- no ϕ	d, s	S x	I(E)	s
2002	PanCanadian	Queensland	M-	4401	D&A	Fore reef- no ϕ, by-pass	d, s	S x	I?	s
2002	ElPaso	Marquis	L-	4501	D&A	Bank edge - no ϕ,	d, s	S x	I?	
2003	EnCana	Margaree	F-70	3677	Gas-76	Bank edge – 70m pay	d, s 2006	S x	I(E)	1, s
2003	EnCana	Marcoh	D-	3625	Gas-	Bank edge – 100m pay	d, s	S x	I(E)	s
2006	EnCana	Dominion	J-		D&A	Bank edge –confidential, whipped	d, s	S	I PW	
Deep Panuke Gas Field = all gas wells and M-79, F-09. NOTE: Dauntless D-35, Sauk A-57, Mohawk B-93 logs in Eliuk 1978; *=lithofacies not in agreement with geometry-based interpretation of Kidston et al 2005; ϕ = porosity 'year'=published with year, d=detailed log, s=schematic log, p=preliminary/partial/text, W = needs more work								Seismic in Kidston et al or EnCana	(E)=EnCana infoS=sidewall cores	<<<<

TABLE 2. Advances in Abenaki understanding before and after the Deep Panuke discovery

TIME PERIOD TOPIC	PRE-DEEP PANUKE Pre-1998 Eliuk 1978, 1981, 1988,1998; Ellis 1984 etc Jansa 1981,1993, Jansa&Lake 1991, Jansa, Pratt & Dromart 1988, Jansa, Termier & Termier 1981, etc Wade & McLean 1990,	DEEP PANUKE E&D 2000-2006 Wierzbicki et al 2002,2005,2006, Weissenberger et al 2006 EnCana 2006 workers or ex- & consultants including Eliuk and CNSOPB Kidston et al 2005	RECENT STUDY 2007-continuing See Bibliography divided into 3-fold chronology for references
Litho/Bio/Reef Facies	Carbonate template (Eliuk 1978) showed major facies with oolite and 3 reef/mound types – coral, sponge, mud/microbial (former peloid-several short studies) various but similar dip facies schematics Double margin flexure & channels vs reefs on seismic. Minor but intriguing macropaleontological and microbialite studies on reef and reef-microbial mound facies	Updated facies template (Wierzbicki et al 2002) with finer slope and reef subdivisions but no major changes BUT 3D seismic & later well control eg F70, D14,J14 showed complex topography along margin. Bioerosion (Eliuk & Pemberton 2002) was used to help characterise different facies relative to their position to the margin	Due to confidentiality last Panuke-reef play wells shown by Eliuk and dip-oriented facies layer-cake model compromised by landward dipping ridge & pinnacle wells. Microsolenid corals distribution may aid facies understanding. Sub-Venture thin #9 Lst vertical facies changes clue to forced-regression shelf-margin delta sequence strat. Apparent lack of bioerosion in lithistid sponges may show need for early shallow burial to be lithified (sea chemistry control ie Calcitic seas -may also explain tite ooids)
Individual Wells & Prospects	Lack of porosity widespread even in oolites; mainly structures drilled without success. G32 (non structure at margin) found reservoir in dolm & LS, similarly3 Western Bank (&slope) wells.	Beneath depleted margin-draped oil pool - partial strat trap reef found by seismic porosity character (Harvey 1993 insight); Doubling of wells albeit in a local shelf margin area high variability (=whips). CNSOPB Abenaki seismic-well study good review	Relating detailed well lithofacieslogs to Kidston et al seismic shows that geometry may not be enough to define even margin facies eg. L97 slope lith but in structure so maybe late movement. J14 shows seismic porosity character may be anomalous shale
Reservoir Character & Variability (Diagenesis & Porosity)	Widespread oolite cementation so Dunham depofacies not applicable except in shallow burial eg. salt domes (Orpheus, S.Whale). Margin reefs with dolomite porous but slope often submarine cemented. Mixing zone dolomite model applied suggesting search for early paleohigh prospects	EnCana studies of Deep Panuke showed Eliuk's 1978 mixing zone model better replaced by burial dolomitization and limestone corrosion (Eliuk 2004). So key to reservoir is faulting-fracturing and more likely at margin since may be tectonic. But tight wells show not always and numerous whips show problems. Applied sequence strat and layered modelling along strike in Deep Panuke (Weissenberger et al 2006)	Eliuk 2004 give a historical review of his failed mixing zone dolomite model replaced by better explanation of Wierzbicki et al. 2006. Although Eliuk PhD concentrates on deposition and very early diagenesis - the effect of late diagenesis cannot be avoided and H08 core chaetetid-crinoid reef may be refractory 'diagenetic reef'. Reefal zone between double flexures and seismically irregular so correlation (& dolomite distribution) problematic.
Sequence Stratigraphy	At least 4 shoaling-deepening sequences above Misaine culminating in sponge-reef drowning (Eliuk 1978) seen as far as Baltimre Canyon (Eliuk et al 1986) so interpreted as circum-Atlantic eustatic	Increased and closely spaced well control with reliance on thin sandstones & 3D seismic allowed finer 6 to 7 fold Abenaki sequence strat above Misaine (Weissenberger et al 2006; EnCana 2006) who used mixed carb-clastic core far from Panuke to show interpreted sequence contacts. F70 showed complex deepening up reeflets on local slope but these occurred with a single sequence AB 5 (Eliuk).	EnCana sequence strat is followed even given inconsistencies in the various versions & use regressive-transgressive rather than Exxonian model. Based on facies (no thin SS), an attempt is made to extend sequences SW. A thin condensed limestone (#9 W.Venture C-9) below a shelf margin delta is used through detailed facies changes to support forced regression =utility in siliciclastics.
Regional Setting (??Analogues??)	The distinction of a platform profile carbonate shelf lateral to mixed carb-clastic system by the Sable delta with prograding ramps has been the initial and continuing subdivision with Wade & McLean (1990) suggesting that Eliuk's (1978) use of Abenki for limestones of both areas be	Deep Panuke is areally restricted southwest of Sable delta but cores from near the delta were nevertheless included to demonstrate sequence breaks (Weissenberger et al 2006) and relationships were shown schematically and delta sourced shales were suggested as source rocks. The sponge-rich beds first	With completion of all margin well logging, a lateral pattern of color changes from dark to light to even cyclic reds SW away from the Sable delta, limited central distribution of sponge-rich beds, condensed red iron ooid carbonate top beds and Neptunian dykes with red geopetals shows that lateral changes

	abandoned to the northeast. Thicker carbonates on the Western Shelf and newer biostrat led Jansa (1991, 1993) to subdivide the upper carbonates in K62 and P23 as a early Cretaceous Roseway unit. Kidston et al (2005) used a 3 fold geographic subdivision for the Abenaki but mostly did not include much on the delta area. William (in Eliuk 1986) dated the Artimon Member sponge-rich beds diachronously younging away from the Sable delta.	seen as reef mounds at G32 cap the Abenaki and help seal the Deep Panuke reservoir. Similar sponge-rich capping facies were seen at the top of the J-K carbonates in the Baltimore Canyon trough (Eliuk & Levesque 1988, Eliuk & Prather 2005) so this was seen as a regional carbonate drowning event that related to the offsetting prodelta shales.	from a near-delta with prodeltaic shale area to deeper water sponge reefs to starved carbonate sedimentation to continued shallow-water platform growth far to the SW away from deltaic shale or nutrient influence. This proximity of large delta and thick carbonate platrom was thought to rare or even unique in modern and ancient sediments. But two possible analogues that while having many differences are instructive because they suggest process controls – a larger scale "fractal" analogue or the N. American Atlantic shelf itself and a "distant" in time and place analogue the Bulf of Papua Miocene to Recent Fly R delta.-Great Barrier reef confluence (see Table 4)
Hydrocarbon System and Play Fairway Analysis	After tight reservoir difficulties in drilled structures and apparent limited structures or too young seals along the margin where there was porosity, the Abenaki was considered economic basement. Eliuk's (1978) comment seemed to apply – "..unless source rocks occur in LtJ-EK shales immediately seaward... and shelf-edge fracturing is adequate as a migration path, the HC potential of the Abenaki must be considered very low."	EnCana's Deep Panuke Abenaki margin discovery showed that high relief structures or build-ups are not necessary for reefal gas accumulations. The tight platform oolite actually contributes to lateral seal. Since porosity is late and deep, fracture and faulting are needed. Potentially the whole Abenaki margin could be the play fairway.	If Eliuk's regional setting is correct with its large areas of slow sedimentation away from the Deep Panuke trend near the Sable delta; then the prodelta proximal platform margin capped by sponge-rich beds constitute a more self-contained but areally limited hydrocarbon system. The play fairway is thus smaller - too close to the delta and structures are required due to porous sandstone thief zones and too far then source and seal become problematic (but there are other plays)

SEQUENCE STRATIGRAPHY, CORRELATION, NON-DEPOSITION EFFECTS AND OTHER NEW SUCH CONTRIBUTIONS

Eliuk's thesis work accepts and uses the recent EnCana Abenaki sequence stratigraphic framework even though there are minor inconsistencies within it (Weissenberger et al. 2006). But a transgressive-regressive rather than Exxonian model is followed. In the Deep Panauke trend schematic lithologs are used to show facies changes vertically between sequences on sections (**Fig. 3**), laterally within a sequences on maps (**Fig. 4**) and for well to seismic control (**Fig. 5**). The sequences are being extended away from the references areas as an attempt is made to extend them southwestward into the Western Shelf margin wells. Intraformational subdivision in the thick Abenaki carbonates, aside from the original three lithological members – Scatarie limestone, Misaine shale and thick Baccaro (McIver 1972) with an additional uppermost sponge-facies-defined Artimon Member (Eliuk 1978), must be based on sedimentological and subtle lithologic changes. At least 4 shoaling-deepening sequences above Misaine culminating in sponge-reef drowning (Eliuk 1978) were noted and showed the potential for subdivision. Increased numbers of relatively closely-spaced wells at Deep Panuke with reliance on thin sandstones (interpreted to be unconformities based on examination mixed carbonate-siliciclastic core outside the Panuke area and close to Sable Island) and 3D seismic allowed 7 stratigraphic sequences to be correlated above the Misaine (Weissenberger et al 2006). Unfortunately the thin sandstones are not developed to the southwest of the Panuke trend, but an attempt to extend these sequences using shoaling-deepening trends onto the Western Shelf is part of the thesis project. In that area carbonate sedimentation continued into younger Early Cretaceous time (Jansa 1993) after the carbonate sedimentation cessation and drowning closer to the Panuke trend. In fact the sponge-rich Artimon beds appear to diachronously young away from the Sable delta area (according to biostratigraphic dating by Williams in Eliuk 1985). Detailed logging has shown effects of long periods of slow to non-deposition with identification of thin red geopetal linings in Neptunian dykes and several wells with red iron oolite capping or above shallow Abenaki limestone on the Western Shelf. These findings, that corroborate seismic on the slope showing relatively thin overburden, have significant implications for lack of seal and continued sub-seafloor cementation relative to carbonate reservoirs. In the other direction, application of the Deep Panuke sequences is possible to Marquis L-35 area. But further northeast into the Sable delta area even larger scale correlation and biostratigraphic dating is extremely difficult. There is a hope of correlating from the Sable delta area to the slope in front of Deep Panuke using sequence stratigraphy (Eliuk and Wach 2008). A thin condensed limestone (#9 in W, Venture C-62) examined in long core beneath the West Venture field also shows paleoecological shallowing-up changes that appear capable of corroborating the argument (Cummings and Arnott 2005) for forced regression during the establishment of a Late Jurassic shelf margin delta. This new insight shows the potential power of using thin limestones in deltas to aid in understanding their sequence stratigraphic development. In all areas future biostratigraphic dating research perhaps in concert with Sr87/Sr86 stable isotope curve dating would give much greater reliability to any proposed sequence stratigraphic framework. This is particularly relevant to Nova Scotia Late Jurassic-earliest Cretaceous dating which has been very problematic because of carbonate-versus-siliciclastic (and Tethys-versus-boreal biorealms) biota differences (for instance see Poag 1991).

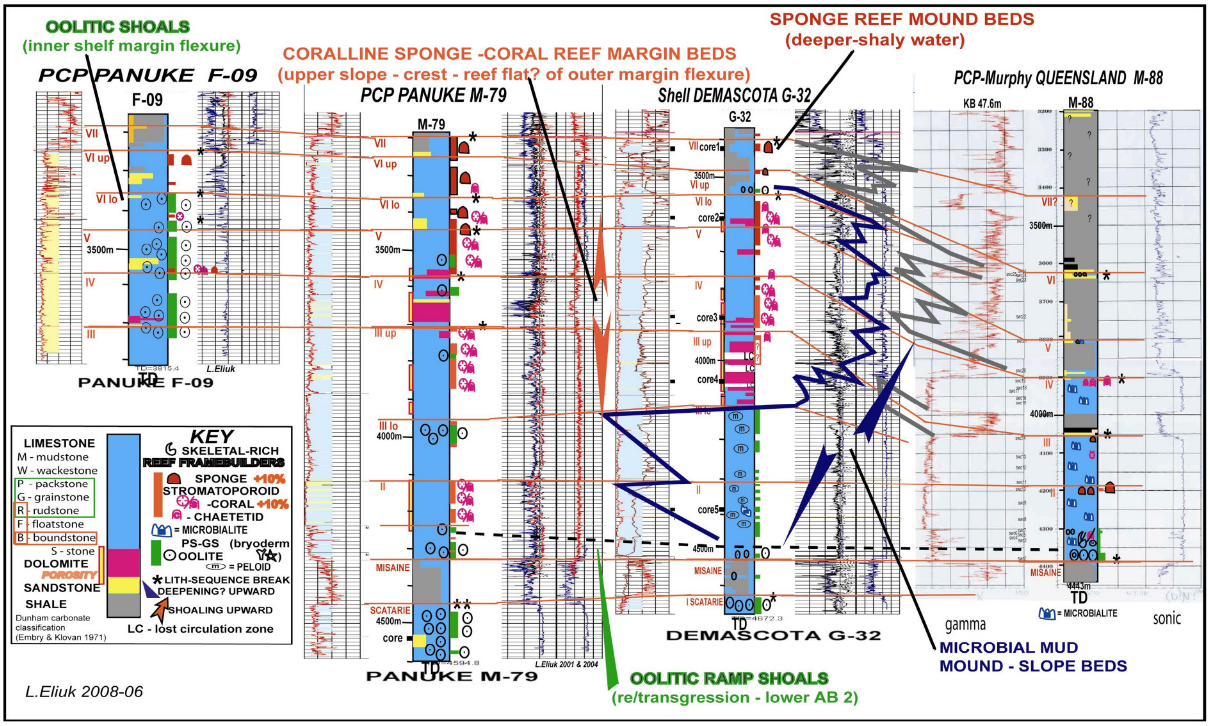


Figure 3. Dip section through Deep Panuke (G-32 projected in) of schematic logs show key lithofacies changes with large scale shoaling before reversal to deeper sponge-rich beds.

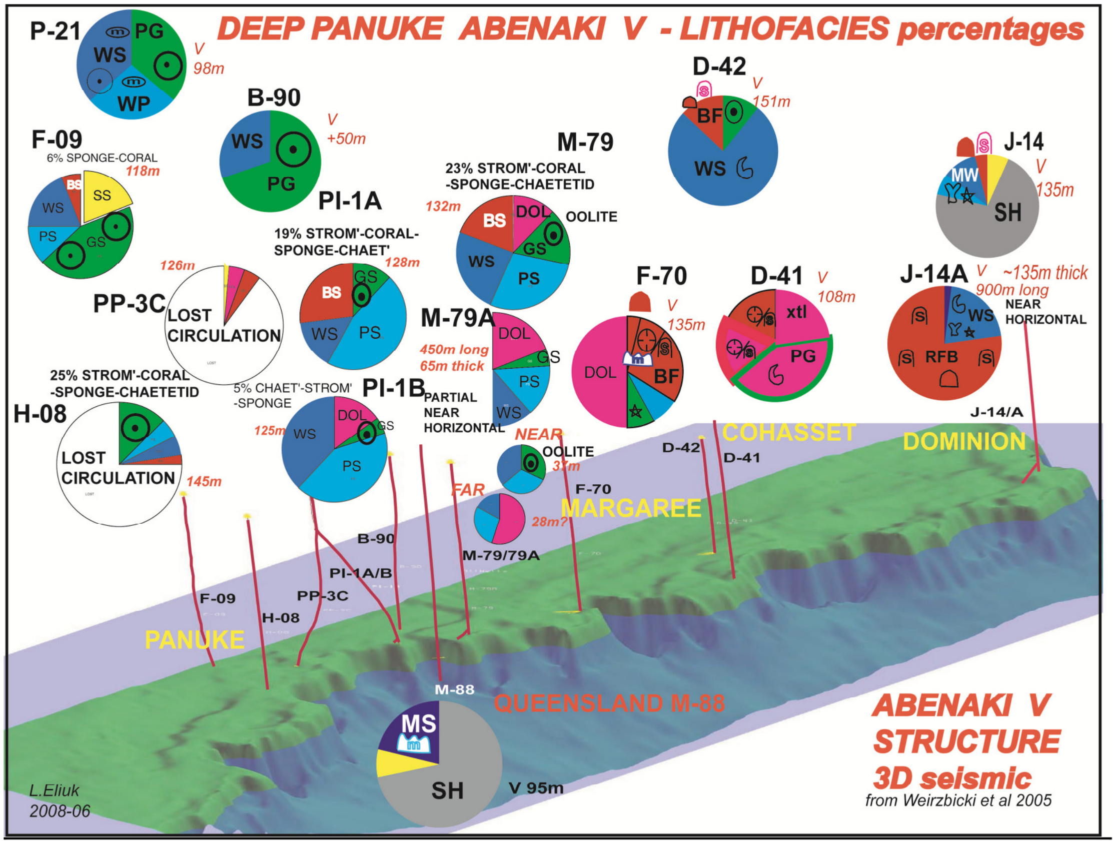


Figure 4. Lithofacies pie diagrams (see legend in Fig. 2) for sequence AB V which is the main reservoir zone in Deep Panuke to illustrate another use for and depiction of the cuttings data.

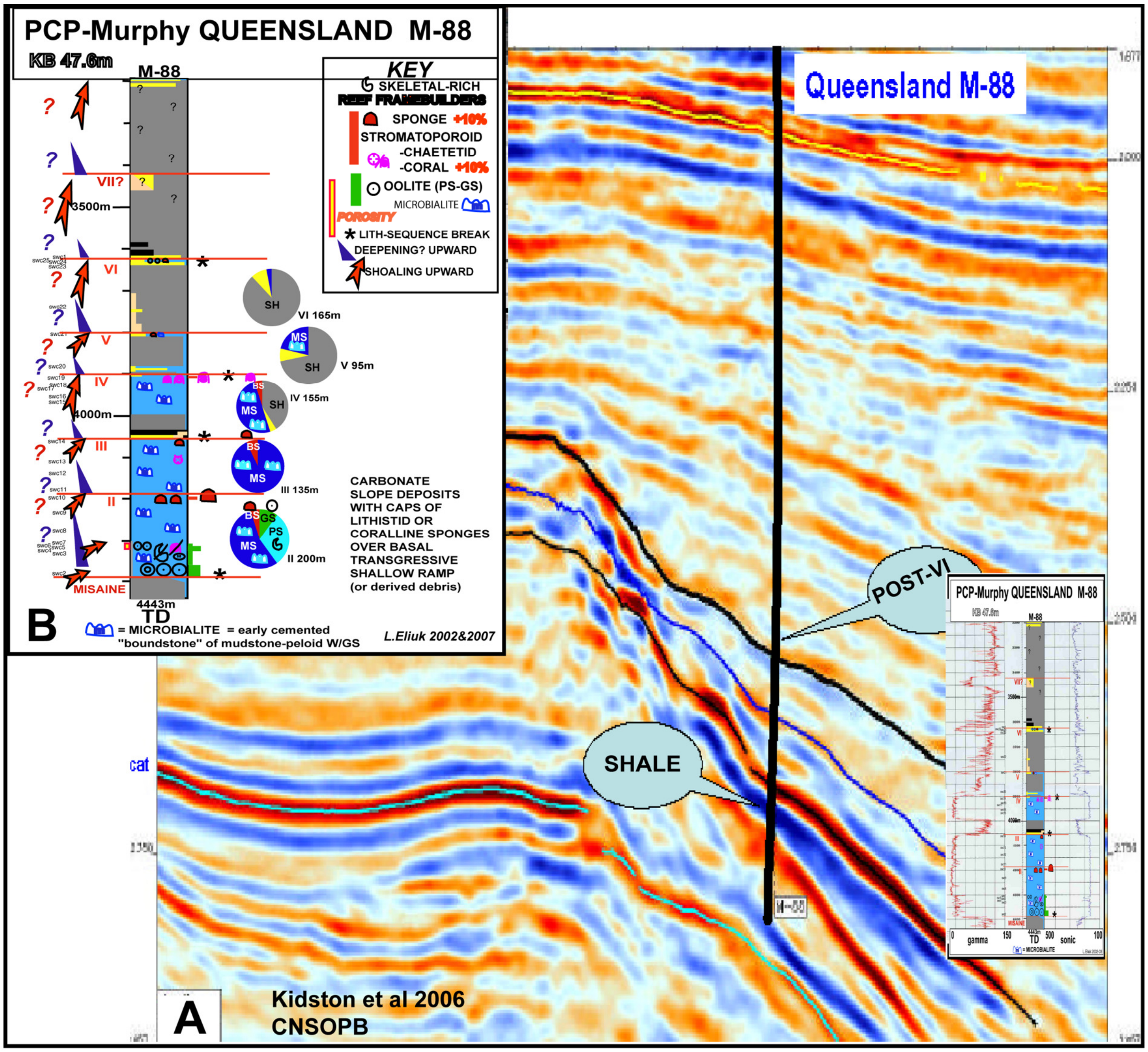


Figure 5. Queensland M-88 of Deep Panuke area - A) dip seismic section (Kidston et al. 2005) with lithology-gamma-sonic log insert, and B) schematic lithologic column with pie charts of lithofacies. M-88 was drilled on the carbonate slope basinward of the Deep Panuke field to test for by-pass sands that turned out to be shale. Depositional sequences approximate those of Weissenberger et al. 2006 and EnCana 2006 which differ slightly. M-88 is located immediately in front of the Deep Panuke gas field on the forereef slope and has a mixed carbonate-siliciclastic composition with fine clastic content increasing upward and eventually coarsening. As indicated by the question marks the transgressive-regressive (deepening-shoaling) cycles are highly interpretive. Note that the thicker carbonates are dominated by microbial and peloidal textures that with the seismic can confidently be used to identify distal deep carbonate slope setting. The sequence transitions are identified by thin deeper-water reefal beds such as lithistid sponges but by typically shallower stromatoporoid coralline sponges for AB4. These are very unlikely to be unconformities but rather the shallowest event in a transgressive-regressive succession. Minor oolite at 9620m (AB6) likely are lowstand shed debris from the shelf. Typically thin limestones are considered condenses maximum flooding markers but here perhaps the basal dark shales are those indicating a rapid deepening with some carbonate part of the transgressive event. This is an example of understanding and sequence analysis only possible with the logging of cuttings supplemented very helpfully by limited drilled sidewall cores. See Eliuk and Wach (2008 and 2009 given below in the summary) for how this data was compared to a thin condensed limestone below the West Venture shelf margin delta.

SUMMARY CONCLUSIONS 1: REGIONAL SETTING OF THE LATE JURASSIC DEEP PANUKE FIELD, OFFSHORE NOVA SCOTIA, CANADA: - CUTTINGS-BASED SYNTHESIS OF A REEF MARGIN GAS POOL SET WITHIN THE LATERAL CHANGES OF A PLATFORM ADJACENT TO A DELTA – A UNIQUE(?) HYDROCARBON SYSTEM AND PLAY TYPE (ELIUK 2010)

Published studies (Weissenberger et al., 2006; Wierzbicki et al., 2005, 2006; EnCana 2006) give details on the hydrothermally-dolomitized reef margin gas field discovered below a depleted oil pool in 1998 and starting production in 2010. Expanding on those studies using cuttings and core data in over 25 Abenaki Formation wells, Panuke is placed in a larger context between the northeast contemporaneous major Sable Island paleodelta prograding ramp shelf and the southwest thick aggrading carbonate platform. Wells can be grouped based on geometry and position relative to the shelf margin as follows (**Fig. 6 A & B**): prograding ramp margin (only a few of the numerous wells in the Sable Island paleodelta are included), margin slope, margin with full shoaling sequence, margin with paleohighs and encased pinnacles (typical of Deep Panuke area) developed between an inner and outer margin flexure, margin inboard flexure with oolite shoals, interior platform oolitic shoals and shaly lagoon-'moat' and near-shore siliciclastic-rich ridge. The large-scale (second order?) vertical full-shoaling stratigraphic sequence is seen in nearly all margin wells (**Fig 7**). It comprises a basal transgressive oolite usually, then forereef with microbial mud mounds, then shallow coral-coralline sponge reefs, then oolites and two types of capping beds – either oolites or lithistid sponge-rich beds. Laterally there is a curious pattern to the argillaceous sponge-rich cap beds in being flanked by wells with oolite caps both nearer the delta with sandstone interbeds and south-westward of the Panuke area wells but lacking sandstone (**Fig. 7 & 8 section**). The older proximal oolite was buried in shallow deltaic siliciclastics while the distal oolite forms younger platform carbonates that continued growing after the intervening platform was drowned. In some cases the southwest platform top has red iron oolite then thin glauconitic sponge-rich beds indicating slow sedimentation (P-15; O-25 and P-23 have iron/Fe oolite only; see **Fig. 8**). There is also a regional trend in the limestone color relative to the Sable Island delta from proximal darker to distal lighter both in oolite and in slope microbial-rich beds (**Fig.7 B&C**) that even become red and white in the most distal margin well (B-13). In that same well (B-13) the upper white oolite is cut by near vertical fractures with thin red geopetals interpreted as Neptunian dykes fed from eroded capping marine red beds (red iron oolite still occurs capping the carbonate in well P-23, **Fig. 8**). Some reef types and microsolenid coral occurrences also show lateral changes. As listed and schematically shown on a section (**Fig. 9**), these facies trends relative to the Sable Island delta and the associated early, deep prodeltaic burial are key factors that contributed to Deep Panuke's possibly unique hydrocarbon system of reservoir (fractured reef with deep burial dolomitization), trap (stratigraphic and structural), seal (cemented oolite, sponge-rich limestone, prodeltaic shale) and charge (gas prone lignitic prodelta shale) properties. Early deltaic burial promoted early cementation of the likely calcitic oolite that then formed updip stratigraphic seals.

PROGRADING RAMP MARGIN	Northeast to Southwest Penobscot L-30 (to NE numerous wells with 'younger' limestone beds developed younging across growth faults cf. Wade and MacLean 1990). Dauntless D-35 and Sauk A-57 near NE margin but older limestone ages suggest different setting or developed on older NE delta (Laurentian?). West Venture C-62 cores 12&13 #9 Lst below Lower Missisauga delta
MARGIN SLOPE	Queensland M-88 (still has basal oolite even if mostly slope peloids-microbial carbonate sediment then shales above with dark MFS?OMZ? shales capping thin framebuilders)
MARGIN – full shoaling sequences with basal oolite (or shallow reef)	(**capping beds sponge-rich**, then oolite, shallow reef, forereef & mud mounds downward but usually basal oolite) Cohasset L-97*, Dominion J-14 & 14A (anomalous shale over microbial beds) , Musquodoboit E-23, Demascota G-32* (**capping beds oolite-rich**, then shallow reef, forereef & mud mounds) Marquis L-35(top=prograding oolite-SST) & 35A, PANUKE GAP, Acadia K-62*, Albatross B-13* (red microbial Mud Mound & no basal oolite, upper oolite has interpreted neptunian dykes with thin red geopetals prior to fracture fill)
MARGIN – paleohighs and encased pinnacles	MarCoh D-41 (faulted out top Abenaki), Margaree F-70, Panuke M-79* &79A, Panuke J-99s (PP-3C, PI-1A, PI-1B), Panuke H-08(chaetetids-crinoids in core) (lower distal forereef & mud mounds not developed; D-41 & F-70 lack ooids & have landward FR dips)
MARGIN – inboard flexure and margin shoal	Cohasset D-42*, Panuke B-90, Panuke F-09, Bonnet P-23*(mostly oolite & peloids of shelf interior but upper beds stromatoporoid-rich and capped by thin red iron oolite)
INTERIOR PLATFORM – oolitic shoals	Abenaki J-56*, Kegeshook G-67, Como P-21, Oneida O-25* (top eroded/reddened)
INTERIOR PLATFORM – shaly lagoon/ 'moat'	Glooscap C-63*, Moheida P-15 (above top -red iron ooids then sponge beds), Mohican I-100* (post-Misaine sequences = 4 at least, well developed)
NEARSHORE RIDGE &/or SILICICLASTIC RICH	Dover A-43, Ojibwa E-7, Naskapi N-30, Mohawk B-93, ***= penetrates Scatarie**

TABLE 3. Abenaki Formation wells subdivided by major facies tracts southwest of the Sable Island paleodelta. This study includes all the margin and slope wells listed but only Kegeshook and Como from the Interior Platform and Nearshore Ridge areas. Penobscot L-30 and West Venture C-62 included for illustration of ramp end member and intra-deltaic carbonates with microbialites (in core).

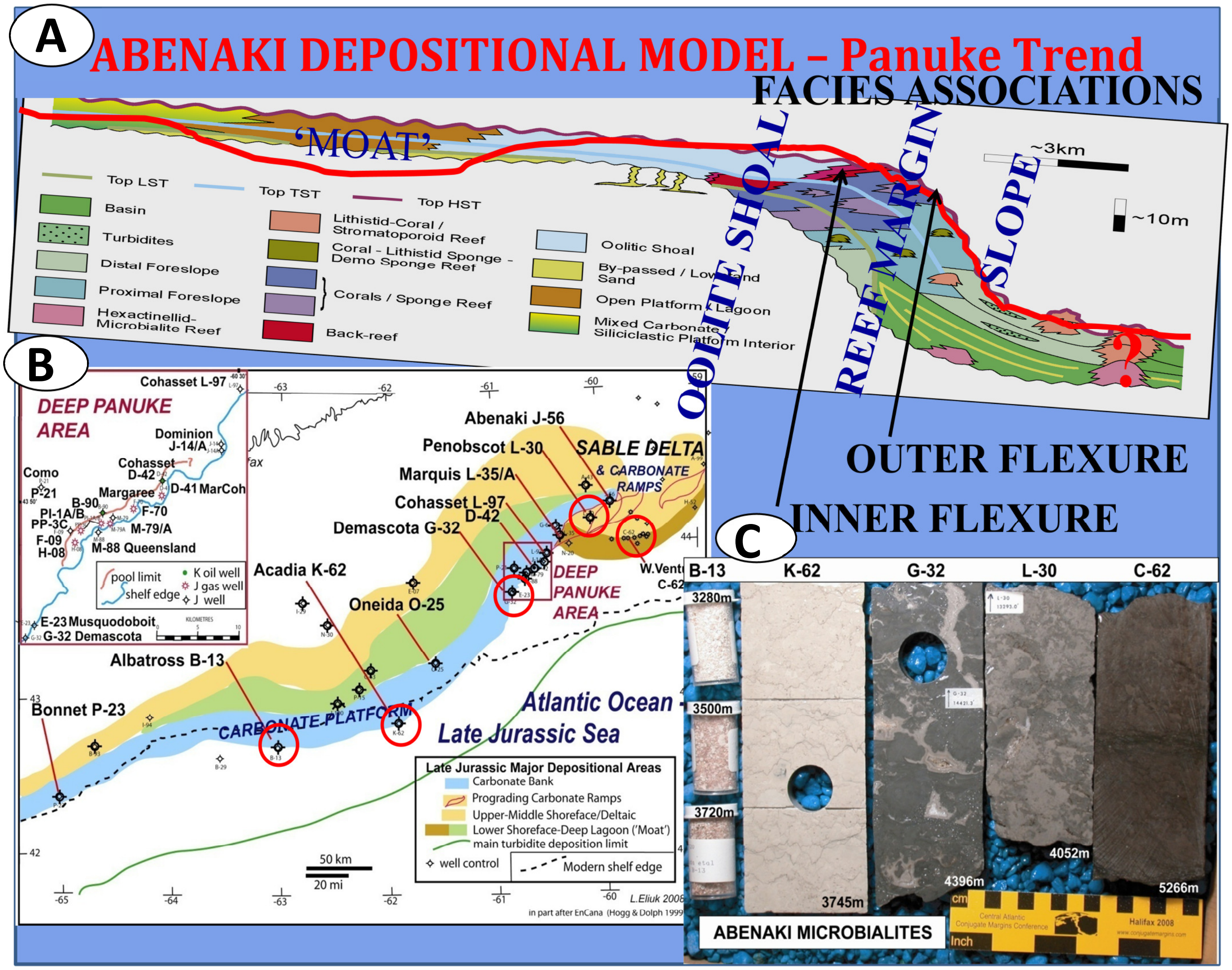


Figure 6. A- Facies association model (modified from Wierzbicki et al. 2002) with red line showing schematic bathymetry including margin double flexures and deep lagoon/moat that helped isolate nearshore siliciclastics from carbonate platform. Note that thin sandstones helping define sequence breaks eventually are absent southwest of Sable Island paleodelta. **B.** Well location and major facies map with location of illustrated microbialites circled in red. **C.** Systematic color changes in slope microbialites away from major delta. Note the classic stromatactis in G-32 and the red and white colors that occur cyclically in most distal B-13 indicating highly-oxidizing slow(?) seafloor sedimentation.

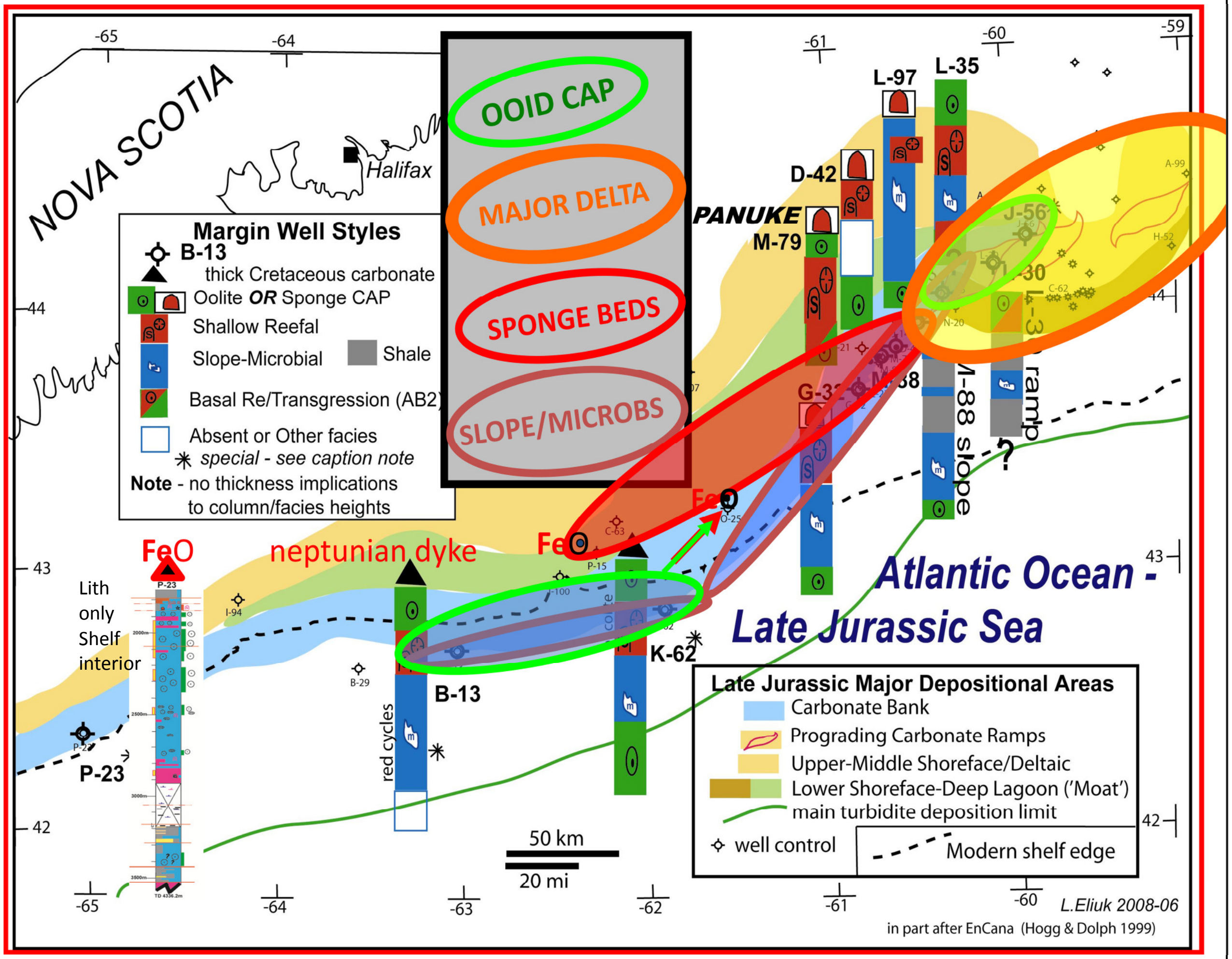
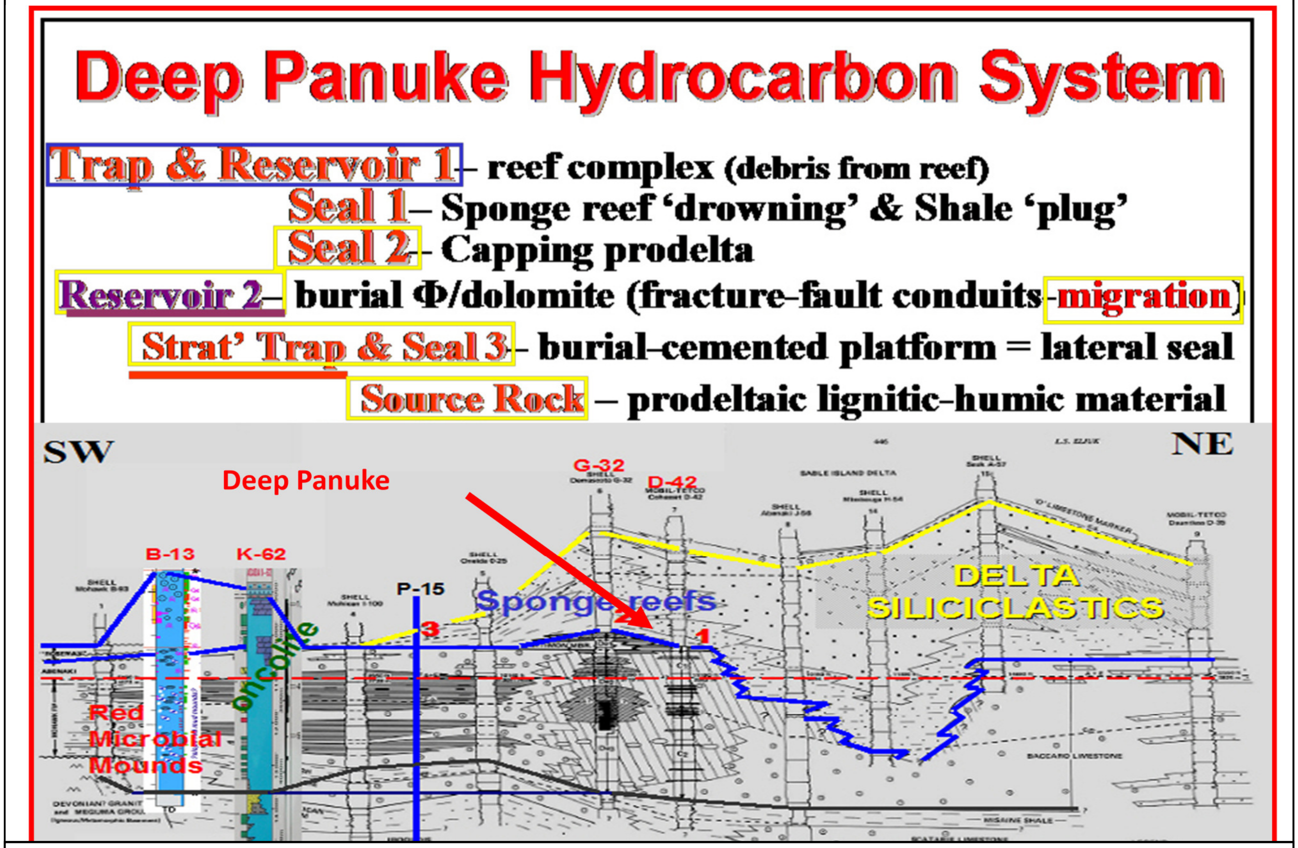


Figure 7. Map of carbonate margin well styles and major capping facies showing the large scale shoaling pattern in most wells after an initial transgressive oolitic limestone above the Misaine Shale Member. Microbialites are characteristic of the slope everywhere and pass upward into coral reefal beds then oolites. But in the Panuke area and in some interior wells further southwest the Abenaki is capped by thin argillaceous sponge-rich beds that are younger away from the delta (see Fig.3 section also). These formed in deeper water over a drowned carbonate platform with several instances of iron oolite formation either below sponge beds (P-15) or in the absence of sponge beds (O-25 and P-23). On the western shelf (K-62, B-13, P-23) carbonate sedimentation re-established or continued with an intervening drowned zone to the northeast (shown on Fig 3 section also). This same style is seen in age equivalent carbonates in a dip direction in Baltimore Canyon Trough. Oceanographic-deltaic stresses may be indicated by the oncolitic zone in K-62 (see Fig. 3 section also). In contrast to the capping older (?Late Jurassic) oolite beds that are interbedded with sandstones near the Sable delta, the Western shelf oolite beds are much younger (possibly Barremian which is the age of the O Limestone within the Missisauga Formation Sable deltaic sediments), lighter-colored to even white and lack sandstones. Near vertical open fractures in uppermost B-13 oolitic limestone with thin red geopetals are interpreted as neptunian dykes from eroded capping marine redbeds. In P-23 the carbonate platform is capped by red iron oolite indicating younger drowning and slow seafloor sedimentation/diagenesis. These relationships can be interpreted to indicate long-continued north-eastward-directed currents that winnow and even erode the carbonate platform after its drowning during at least two different times. Such currents would also keep fine clayey sediment of the Sable delta away from the carbonate platform during its growth. Such an oceanographic or wind-driven flow may help explain the much different style of the Abenaki carbonate shelf northeast of the Sable Delta (not shown on the maps but indicated on the Fig.3 section) where thick sandstones interbed with yet thicker carbonates (Dauntless D-42, Sauk A-57).



Deep Panuke Hydrocarbon System

Trap & Reservoir 1– reef complex (debris from reef)

Seal 1– Sponge reef ‘drowning’ & Shale ‘plug’

Seal 2- Capping prodelta

Reservoir 2– burial Φ/dolomite (fracture-fault conduits-**migration**)

Strat’ Trap & Seal 3- burial-cemented platform = lateral seal

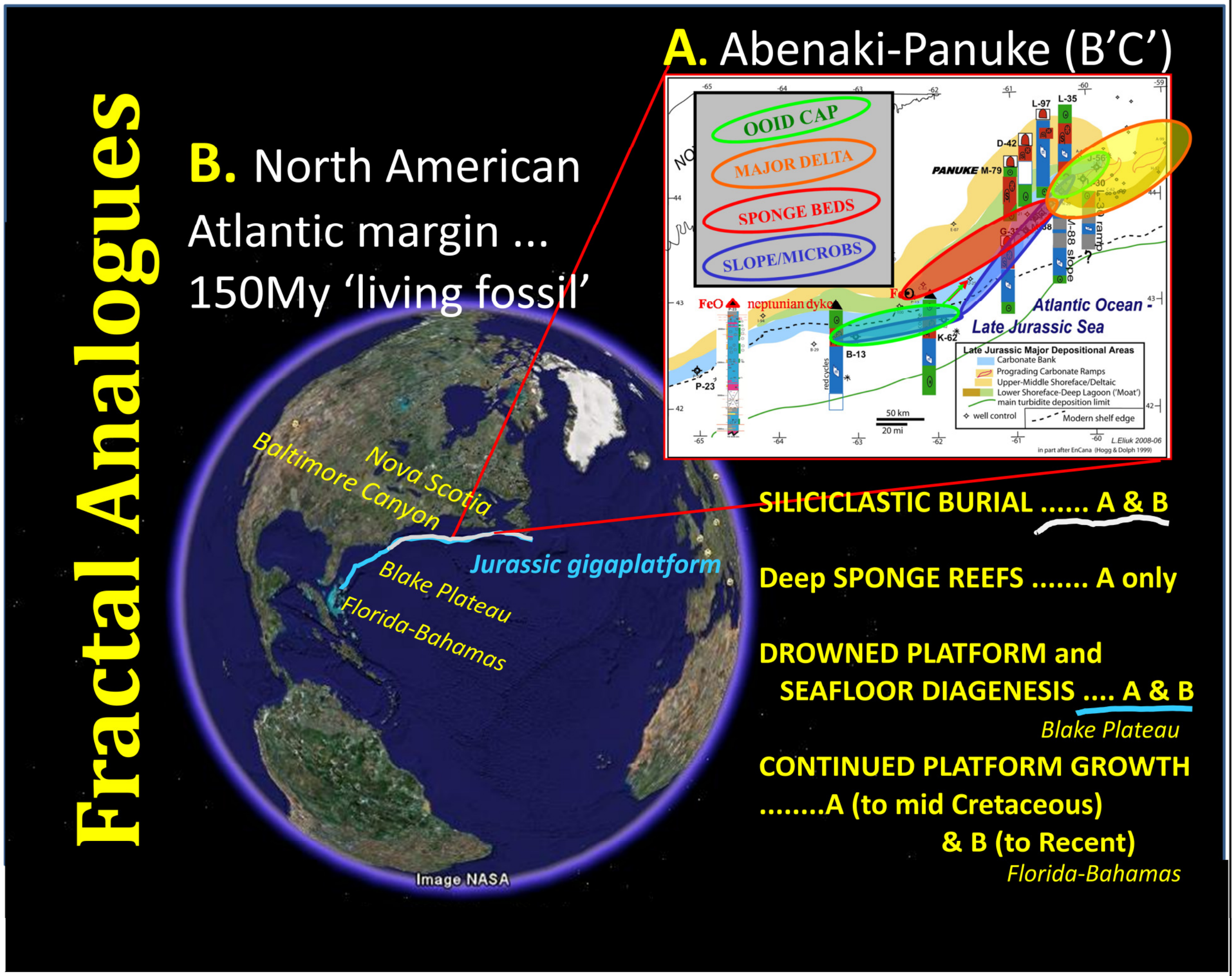
Source Rock – prodeltaic lignitic-humic material

Figure 8. Deep Panuke hydrocarbon system summary and regional dip section (section modified from Eliuk 1978). As indicated by the section, Deep Panuke is possibly uniquely situated in a kilometre thick attached platform of continuous carbonate that is adjacent to a large delta apparently without intervening bathymetric or tectonic lows that typically act as siliciclastic sinks to prevent burial or environmental deterioration of the carbonate. Overtime the delta does bury some of the Abenaki platform and proximally burial seems to occur in shallow water where oolite occurred. But in the Deep Panuke area there is an intervening zone of capping sponge reefal beds that grew in deeper water adjacent to prodeltaic shales. In the most distal settings the platform drowned prior to onset of sponge-rich sediments or even in their absence as indicated by red iron oolite beds. On the Western Shelf far from the delta, carbonates continued growing even if temporarily drowned or exposed and finally were long exposed on the seafloor before eventual burial in much younger shales. The consequence of this setting and history is an hydrocarbon history that has aspects of a delta such as capping prodelta beds to give lignitic-humic source rock and seal. But the reservoir and trap is the carbonate reef margin itself. But perhaps due to early cementation in the highly saturated late Mesozoic calcite seas and burial cementation from the rapid and deep burial in deltaic sediments; the adjacent updip platform limestone, even the oolite, is non-porous. So it acts as a lateral seal giving a partial stratigraphic trap. Even prior to prodelta shale, the argillaceous sponge reefal beds also gave a top seal. At the Dominion J-14 well, there is an anomalous shale pod in the shelf margin that acts as a lateral ‘plug’. The shelf margin position localized by probable underlying tectonic paleohighs makes fracturing and faulting highly likely. This provided migration conduits for dolomitizing fluids and later hydrocarbons resulting in a deep burial reservoir and gas accumulation.

SUMMARY CONCLUSIONS 2:

Regional Setting of the Late Jurassic Deep Panuke Field, offshore Nova Scotia, Canada: - Distant and fractal analogues and possible process controls for a thick carbonate platform flanked by a large delta; two possible analogues for the Abenaki –Sable delta near the Deep Panuke trend (Eliuk and Wach 2010)

Deep Panuke, discovered in 1998, is the only carbonate gas field in the eastern North America continental shelf. This shelf margin reef complex pool occurs between the northeast contemporaneous Sable Island paleodelta prograding ramp shelf and the southwest aggrading carbonate platform. This juxtaposition of a thick continuous carbonate platform so close to a large delta is extremely rare in the geological record and was thought to be unique. However at least two analogues are possible. The utility of analogues is not exact duplication; rather similar patterns may help infer similar control processes and principles at work. This better understanding aids future exploration and exploitation. From north to south, the Panuke pattern to match in the uppermost Abenaki (Latest Jurassic-early Neocomian age) is a large delta burying the shallow carbonates and passing laterally from prodelta shales to diachronous deeper sponge reefs to starved sediments (iron oolite) on a drowned shelf to continued shallow platform oolite and coral reef growth (**Fig. 8A**). The fractal analogue (self-similar at different time and space scales) is the North American eastern continental shelf margin itself (**Fig. 8B**). The Jurassic gigaplatform (Poag 1991) is mostly buried in siliciclastics until the deep Blake Plateau that is thinly covered in starved sediment with major evidence of seafloor diagenesis (and even minor deep-water coral reefs) where shallow carbonates drowned in the Aptian but continue growing off Florida and in the Bahamas. Some relevant process controls are northward plate tectonic drift (paleo-latitude/climate changes), erosive-inhibitory oceanic currents (Gulf Stream), subsidence and eustatic sea-level changes. The distant analogue in both time and space is the Neogene northern Great Barrier reef system in the Gulf of Papua with the large Fly River delta siliciclastics input that buried a drowned Miocene carbonate platform and southward the world's largest barrier reef continues growing (Andre Droxler pers. comm. AAPG short course 2010 & references especially Tcherepanov 2008). For varied time including to the present day, proximal shelf margin reefs and outboard atolls continued growing. One encased in deltaic clastics reservoirs the undeveloped Pandora reef gas pool. Control processes on carbonate platforms involved are (in part based on Davies et al. 1989) in long term – plate motions northward and subsidence; in short term – rifting (pre-existing topography), eustacy, climate (variations through Neogene), oceanography (for instance Miocene phosphate inhibition of reefs and particularly East Australian Current that swept deltaics northward from carbonates), collision (change from passive to active margin of Papua-New Guinea). Both these analogues have lessons to help understand the Abenaki platform-Sable delta justaposition. Differing sea-water chemistry of Neogene aragonitic seas versus Jurassic-Cretaceous calcitic seas (much greater oolite) is a key difference.



Fractal Analogues

B. North American Atlantic margin … 150My ‘living fossil’

A. Abenaki-Panuke (B’C’)

SILICICLASTIC BURIAL …… A & B

Deep SPONGE REEFS ……. A only

DROWNED PLATFORM and SEAFLOOR DIAGENESIS …. A & B

Blake Plateau

CONTINUED PLATFORM GROWTH ……..A (to mid Cretaceous) & B (to Recent)

Florida-Bahamas

Figure 8. Fractal analogue comparison. **A.** Abenaki-Panuke (Late Jurassic-early Neocomian) near end of carbonate sedimentation with deltaic burial on NE through deep sponge reefing on drowned platform with iron-ooid starved seafloor diagenesis to continued carbonate growth on SW (see Eliuk 2010 Fig. 2 this conference for details). **B.** Modern North American Atlantic continental margin with Late Jurassic gigaplatform from Grand Banks to Bahamas buried in siliciclastics as far south as Blake Plateau where it is drowned but thinly buried or exposed with seafloor diagenesis but still growing in the Florida-Bahamas as a 150 million year old ‘living fossil’. Probably the north-flowing Gulf Stream that winnows and erodes the Blake Escarpment and Plateau had an early equivalent in the Latest Jurassic that aided growth of the Abenaki platform by keeping Sable paleodelta clays-nutrients off the carbonates. This suspect current may also explain the margin profile seaward of Oneida O-25 of a distally-steepened ramp and O-25’s abrupt Late Jurassic termination of Abenaki Formation limestone with a red iron oolite cap.

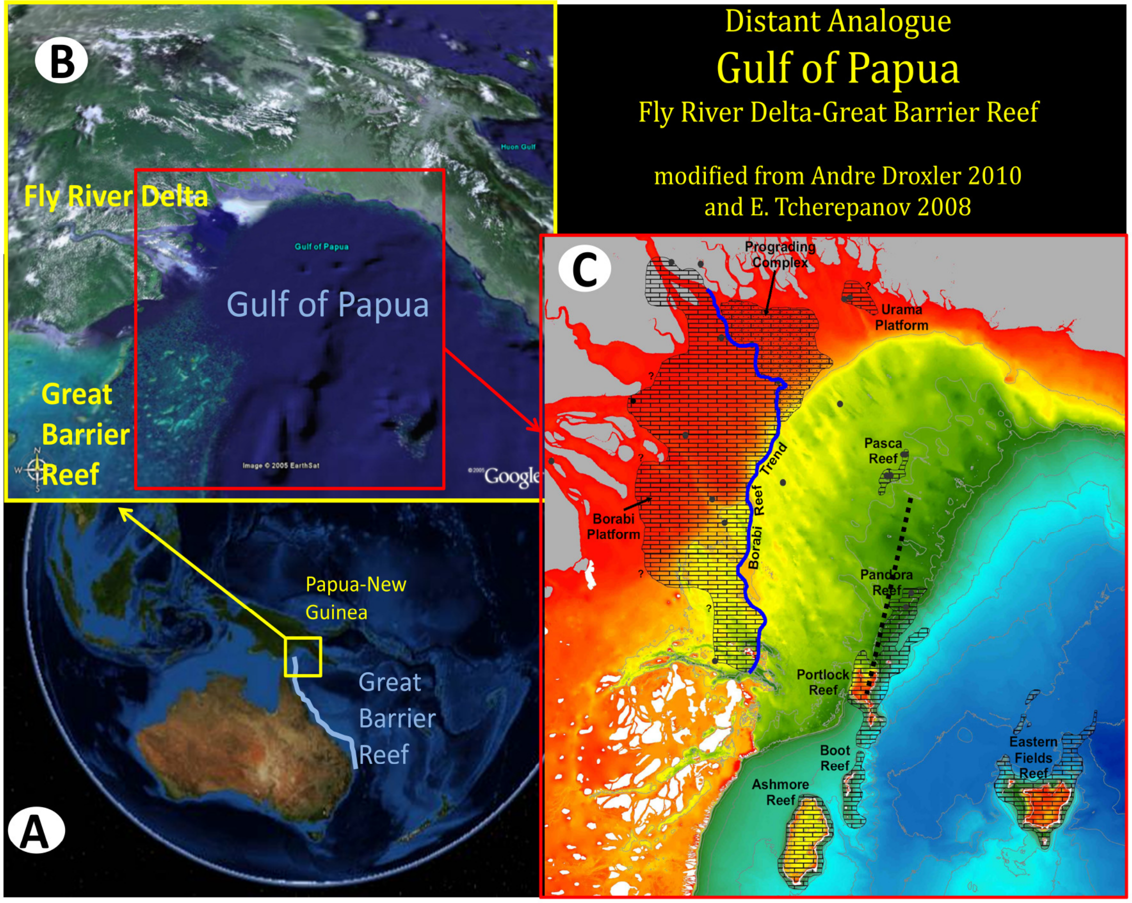


Figure 9. Distant Analogue - Gulf of Papua. **A.** Southern hemisphere showing Australian Great Barrier Reef that goes north into Gulf of Papua. The equator is just north of Papua-New Guinea. Globe is about the same scale as in Fig. 1 thus showing the Late Jurassic gigabank was perhaps twice as long initially. But over geologic time plate tectonic drift northward took the Abenaki out of reef-favourable climates as it took the Great Barrier Reef further into them. **B.** Satellite view of Gulf of Papua showing contemporaneous existence of isolated reef complexes (Portlock, Boot, Ashmore, Eastern Fields mainly growing on earlier Miocene reefs) separated by deep water from the Fly River Delta and also Great Barrier Reef patch reefs on the adjacent shelf. **C.** Map showing drowned Late Miocene platforms in blue block symbol with attached Borabi platform partially buried (red) at a slightly later time by Fly River Delta. Dashed line indicates seismic line going through Pandora reef gas discovery from deltaic foresets south to still growing Portlock Reef that is shown in Appendix Ia.

Figures 6B and 6C are from Prof. Andre Droxler's 2010 AAPG Short Course. Andre and his student Dr. E. Tcherepanov are heartily thanked for them and for introducing me to a fascinating story that has some extremely enlightening similarities to the Abenaki carbonate platform-Sable Island delta relationship. Interestingly, drowning of the Miocene platform occured well before burial in the Fly River Delta sediments and is contemporaneous with several other Neogene carbonate platform drownings so that global eustacy and oceanographic changes (not specified) are given as the ultimate causes rather than proximity to a delta. There is no apparent sponge reef facies equivalent associated with the Fly Delta-drowned carbonate platform. Also oolite is much rarer in the Gulf of Papua Neogene limestones than in the Abenaki platform (pers. comm. J.Packard of Talisman).

SUMMARY CONCLUSIONS 3:

Carbonate and Siliciclastic Sequence Stratigraphy- examples from the Late Jurassic Abenaki limestone and West Venture deltaic beds, offshore Nova Scotia, Canada (Eliuk and Wach 2010)

Relative to their occurrence in thick siliciclastic sections, thin carbonates show utility as sensitive indicators of the surrounding sand and shale sedimentation. When composed of *in situ* framebuilders (microbial and skeletal) as demonstrated by inter-growth position, bioerosion, associated submarine cements and marine geopetals, the carbonates are particularly helpful for environmental inferences. Within the Sable Island paleodelta, cores in Penobscot L-30 and West Venture C-62 show both dark colors and limited biotic diversity with microbial textures. The C-62 cores are particularly interesting because they provide an independent check on the shelf-margin delta model and sequence stratigraphic scenario presented by Cummings and Arnott for the Venture gas field. In less than 7 metres, facies and fauna in limestone change upward from a biotically depauperate marl to a microbial mud mound which is succeeded by an argillaceous sponge-microsolenid coral reef mound with some stromatoporoids and possible red algae. The sequence is interpreted to reflect a forced regression and falling sea level. This closely supports the published deltaic sequence stratigraphy as long as it is appreciated that the "condensed limestone facies" is actually a distal composite, recording changes in sea level, nutrient supply, and ultimately sediment type that replaces the carbonate as the delta progrades. The maximum flooding surface (MFS) occurs during the microbial mound stage, below an abrupt lithologic change across a pyritized hardground which is overlain by laminated black shale. This placement of the MFS reflects problematic differences in sequence stratigraphic concepts of carbonates versus siliciclastics. Relative to understanding the Abenaki platform, the C-62 core provides insights into relationships seen only in cuttings and sidewall cores in Queensland M-88 which drilled the slope and basin facies immediately in front of the Deep Panuke (Abenaki reservoir) gas field. M-88 and C-62 may be potential links for correlating and dating the massive (Abenaki) carbonates and the deltaic siliciclastics**.**

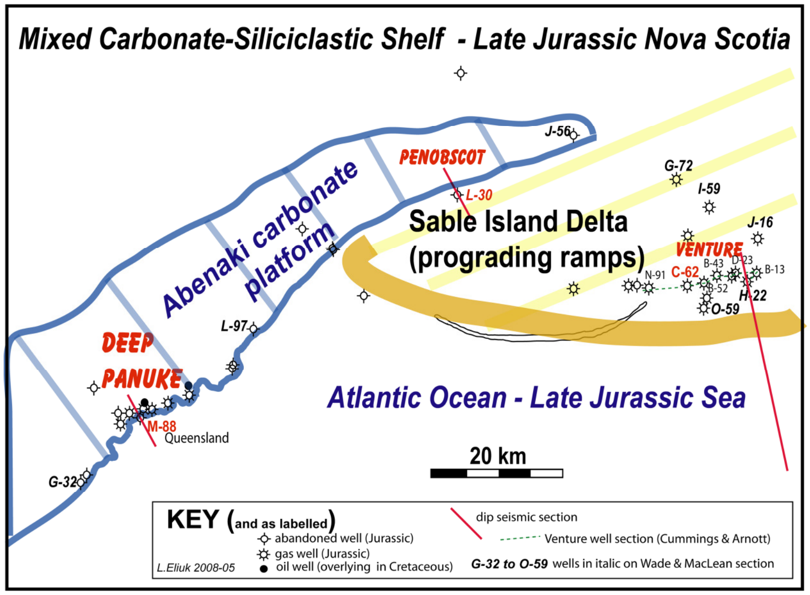
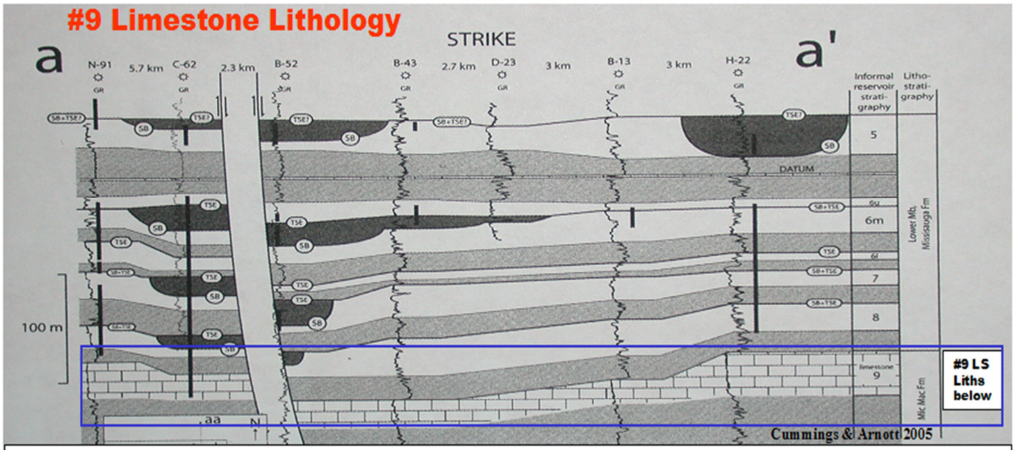


Figure 10. Regional setting of Late Jurassic carbonate platform and Sable Island delta with intervening prograding ramp showing three key locations, wells and seismic lines approximately – Venture area with West Venture C-62, Penobscot L-30 and Deep Panuke with Queensland M-88 on adjacent reef slope. Seismic in L-30 and M-88 show clinoforms and support a deeper water setting for microbialites recovered in whole and sidewall cores that then can be used for supporting a deeper-water setting for microbialites seen in the #9 limestone core in C-62. Seismic can be seen in Eliuk and Wach 2008 and Kidston et al. 2005



N-91	**C-62(core)**	**B-43**	**B-13**	**H-22**
SH dk grey	SH black lam	siltst qtz	SS	SS-sltst shaly
5m FWS frg-bry				**5m WS spg-bryoderm**
35m F(B)S spg	**3m SpgCor BS**	**15m MS marl**	**10m GS ool**	**15m WS frag skel**
	4m Microb BS	**15m dk ool GS**	**15m PWS pel-frg**	**15m FWS strm-spg-micob**
+5m sdy LS-SSf	+9m marl		**5m FWS spg-skel**	**5m GS ool**
		SS qtz vf-f	SS qtz vf	SS qtz vf

LS=limestone, SH=shale, SS=sandstone (f=fine, v=very), lam=laminated, qtz=quartz, sdy=sandy (Dunham) **BS=boundstone**, F'=float', M'=mud', W'=wacke', P'=pack'. **GS=grain' st=stone** bryoderm= bryozoa-echinoderm, cor=coral, frg=fragmental, **microb=microbial** (thrombolitic), **ool=oolite**, pel=peloid, skel=skeletal, spg=sponge. strm=stromatoporoid, bry=bryozoa (+echinoderm)

Figure 11. Venture area #9 Limestone lithologies – based on 5m cuttings samples for all but C-62 well. Colors indicate either red for reefal (10% or greater framebuilders - lithistid/siliceous sponges, stromatoporoids, corals mainly microsolenid) or green for oolite grain/packstones. In Venture B-52 most of the #9 Limestone is faulted out except for 10 m of marl-argillaceous mudstone with minor black ooids. Section is from Cummings and Arnott 2005 showing their sequences and facies of 'dark grey'= strongly tidally influenced estuarine incised valley fill, 'light grey'= storm dominated delta front sandstone, 'medium grey'= prodelta mudstone and 'limestone symbols'= condensed shelf limestone

Model-Shelf margin delta: Facies 1-
Lime MS, condensed

Shelf ?Margin Carbonate mound

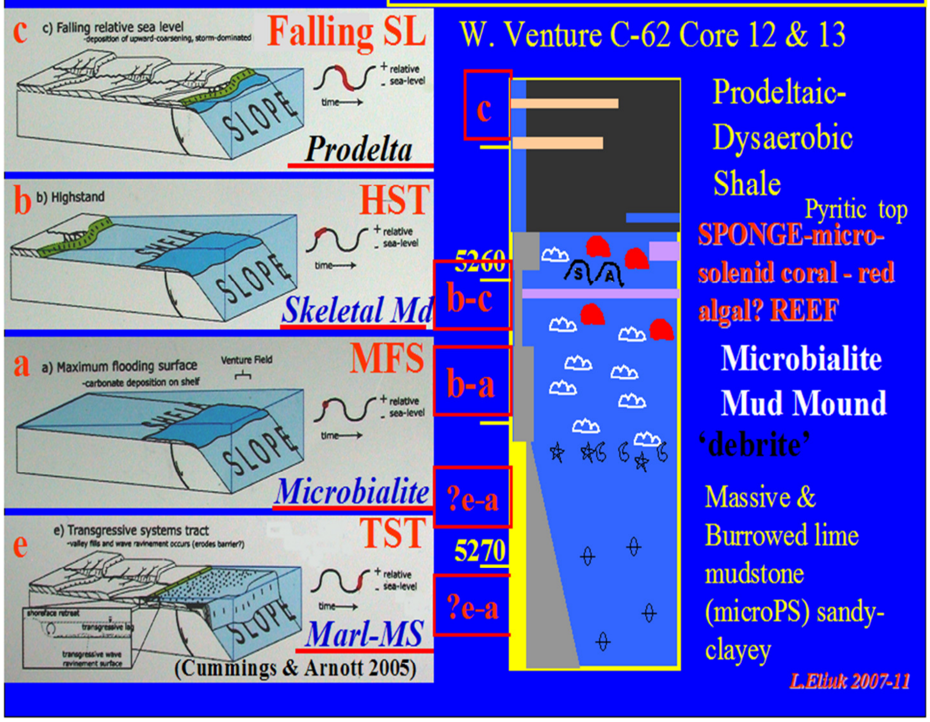


Figure 12. West Venture C-62 #9 Limestone core depo-lithofacies compared to depositional model of Cummings and Arnott (2005) – note the interpreted transgressive or deepening trend in the relatively thin limestone facies from highly bioturbated deeper-shelf calcareous shale/marl up to massive marl (micro-packstones) then microbial boundstone ("mud mound") compatible with the model's transgressive (TST), maximum flooding (MFS) and highstand (HST) systems tracts then the reversal to a regressive or shoaling trend of microbial-microsolenid coral-lithistid sponge-red algal? (solenoporid?) reef mound abruptly overlain by laminated prodeltaic or lower shoreface shales/mudstones with a pyritized hardground contact that is the most abrupt lithologic change, but not the deepest deposition. Given the thinness of the limestone making depositional elevation into photic and less nutrient-rich depths unlikely, this reversal is best explained by falling relative sea-level that allowed skeletal framebuilder replacement of the pure microbialites in spite of the increasing clay content (see Eliuk and Wach 2008 Appendix for core gamma log and additional facies illustrations).

Significance to Hydrocarbon Exploration-Development

From a detailed core to regional setting level, Eliuk's thesis work, including his earlier cuttings and core studies released by operators, significantly contributes to understanding of the Deep Panuke reef margin gas discovery and play. Advancements in understanding of the Abenaki could truly be dated as before and after the Deep Panuke discovery. That chronology used above for a three-fold comparison (**Table 2**) for 6 topics on litho/bio/reef facies, individual wells & prospects, reservoir character & variability (diagenesis & porosity), sequence stratigraphy, regional setting (?analogues), and hydrocarbon system and play fairway analysis. Just a few examples are given here of Eliuk's contributions resulting from the EnCana's discovery and generosity in letting its geoscientists and consultants put data and publications in the public domain (EnCana 2006, Weissenberger et al. 2006, Wierzbicki et al 2002, 2005, 2006). Indeed Eliuk's thesis and earlier work is a major benefactor of EnCana (and Shell before).

On a cuttings-core scale, a specially-adapted framebuilder, microsolenids corals, can now be used even in cuttings to help infer particular deeper-water conditions, an unusual association of chaetetid coralline sponges and crinoids in the little-understood high-porosity 'vuggy limestone' segment of the Deep Panuke reservoir may not be a depositional reef but rather a 'diagenetic reef' of refractory poorly-soluble fossils, and understanding the paleoecological mini-reefal changes in a condensed limestone may be used for understanding sequence stratigraphy in the overlying delta (Eliuk and Wach 2008).

On a single prospect or reservoir-development scale, detailed cuttings lithologs are compared to seismic geometries (Kidston et al. 2005) or reservoir depositional facies-stratigraphy models (Weissenberger et al. 2006, fig. 15). For instance, Cohasset L-97 on seismic is a shelf margin structure; in cuttings it is dominantly distal microbial slope with some deeper in-situ reef in core suggesting both later structural movement and the potential for a bank-ward gas accumulation. And while a correlative layer-cake reservoir stratigraphy may be appropriate for the southern part of Deep Panuke; it is not for the north end. The northern wells Margaree F-70 and MarCoh D-41 both have depositional dips landward. F-70 in core shows dolomitized proximal slope and deepening-upward series of thin limestone reefs indicating that the reservoir is composed of carbonate-encased pinnacles or reef ridges in a drowning succession. The porosity variability between nearby wells and common need to whip or deviate wells is then not so surprising and not simply due to haphazard burial dolomitization. Dominion J-14 and follow-up J-14A north of the pool with only cuttings available was even more extreme in having shale rather than the expected seismically-inferred porosity notch at the sequence AB 5 reservoir level. L-14 is the only well close to the pool to have a distal slope microbial reef mound facies which can be used to argue that unlike most wells drilled at the margin that do have that microbial slope facies, Deep Panuke was initiated on a paleohigh certainly at Panuke M-79 where the whole Abenaki is drilled.

But it is on the regional scale and the relationship of the Abenaki platform and adjacent Sable delta that perhaps the unique nature of the Deep Panuke reef discovery is most evident. Continuing work on the regional setting (Eliuk 2008, 2010) shows that there is a major effect of the delta on the platform margin. From proximal to distal relative to the delta particularly in the uppermost Abenaki these changes can be observed in the near margin oolite shoals, the margin reef zone and the carbonate slope. There are systematic changes in siliciclastic content, color, reef type, submarine cementation and early fracturing, slope microbialites, possibly bioerosion, seafloor diagenesis including red iron oolite, and even the ability to a grow carbonate at all change (the carbonates on the Western Bank continue to grow into possibly the Barremian but those at Oneida O-25 stop abruptly at the top Jurassic while at Demascota G-32 and Deep Panuke the sponge reefs are at least earliest Cretaceous Berriasian). Deep Panuke is located in the middle of all these changes. And with the early prodeltaic burial and likely gas-prone source rock, it constitutes a unique hydrocarbon system with aspects of platform-edge reef and shelf-margin delta. From a play fairway perspective, Deep Panuke-like plays are not transportable to areas lacking large deltas adjacent to thick carbonates. Baltimore Canyon Trough carbonate margin could be considered a test of this hypothesis. It has all the Abenaki reef margin attributes plus high relief pinnacles and even large closed structures but the deltas while numerous were small and never even covered the shelf margin. But bank interior to the west with faulting and early shale burial was the only place where non-commercial gas was at least tested.

Future Work Possibilities

Suggested further carbonate studies (and biostratigraphic studies that support sequence subdivision and dating within carbonates) include possible work within the Abenaki platform area southwest of the Sable delta (Eliuk's thesis area), follow-up to further understanding on using thin limestones within the deltaic sediments as facies-and-sequence-stratigraphic indicators, and further northeast the relationship of the mixed thick siliciclastics -limestones northeast of the Sable delta to the Laurentian Channel (and paleodelta) area.

In all areas, better and more biostratigraphy is needed for the Jurassic-Cretaceous intervals. In concert with new biostratigraphic effort, Sr87/Sr86 stable isotope dating to the Phanerozoic curve in early formed stable allochems/fossils might give further confidence in using sequence stratigraphy. Some calibration would be needed and interpretation is made difficult by the shape of the world-wide curve from early Jurassic to early Cretaceous On the Western Shelf absence of both seismically correlative intra-Abenaki markers and of thin sandstone beds such as used at by EnCana at Deep Panuke make extension of their sequences suspect. In the other direction the differences in the major lithologies, in what processes control their distribution and in their biota, continue to make detailed correlation between the delta and carbonates problematic. Improved dating could only help tie the whole shelf together.

Many topics and features in the Abenaki carbonates might prove fruitful for further specialist research. The paleontological identification of the macrofossil framebuilders and their encrusting and cavity dwelling micro fossils has only been attempted in a very limited manner and deserves detailed study (only some coralline sponges have been studied, Jansa, Termier and Termier 1982) since a classic spectrum of Jurassic reef types has been sampled. Similarly the reef paleoecology and effects of bioerosion (or in the case of the lithistid sponges reefs the strange absence of bioerosion) is only dealt with in a limited survey-like manner. Mainly these were briefly undertaken where widespread distribution capable of being seen in cuttings suggested broader application to regional studies such as in the case of microsolenids corals. Microbialite and mud mounds occur commonly as part of that framebuilder spectrum. Eliuk's thesis will show the systematic geographic change in obvious features of those microbialites as related to delta proximity but more detailed analysis on many facets could be done (see brief preliminary studies of Dromart1986, Jansa, Pratt and Dromart 1988, Pratt 1982, 1985). Similarly specialist studies could be pursued on the deposition and early diagenesis of features seen on Eliuk's regional survey such as the condensed red iron oolites, early diagenesis of various reefs (why are some microsolenids corals-microbialites still limestone in dolomites), Neptunian dyke infill-history and early diagenesis in the sponges-rich beds. These perhaps more academic studies often supply supporting detail for regional understanding and even hydrocarbon exploration. The following is a more exploration focussed contribution that is already started. Eliuk has made extensive use of the Kidston et al. (2005) seismic-based Abenaki study. As indicated on **Table 1** a number of well summaries have been completed incorporating their seismic Most often their geometries and interpretation are compatible with Eliuk's lithofacies but occasionally a significant difference may indicate an area of late structure or even an overlooked prospect. Some means of disseminating that comparative well analysis and completing it would be helpful to explorationists. A fuller collaboration with CNSOPB interpreters such as Brent Smith using the most recent seismic including 3D and Eliuk's well lithofacies columns and interpretations would be even more useful.

Between the Abenaki platform and areas northeast adjacent to the Sable delta, there are major changes in both the geometric style (aggrading platform versus prograding ramps) and major lithologies (nearly continuous carbonate with only thin or no sandstones near the margin versus interbedded sandstones-shales and limestones that may be thin to 100's of metres). This subdivision, split by the Sable delta depocentre, has been known since Eliuk (1978) and even better shown by Wade and MacLean (1990). They felt it was so fundamental that that the name Abenaki should not be applied northeast of the Sable delta. Instead individual 'unit' or member names should be applied to the diachronous limestones as they develop on younger prograding Sable delta sediments. But older Late Jurassic dating in some of the furthest northeast wells (eg. Dauntless D-35) and the great thickness of the limestones makes this interpretation for the whole area suspect. A study of the limestones and how they relate to the siliciclastics might be a great assistance in understanding the relationship of the Sable and Laurentian paleodeltas (also see John Harper CSPG talk 2007). Wells in the South Whale Basin including the recently drilled Conoco-Phillips Wolverine G-37 (RR2010-04-23) and ExxonMobil-Gulf et al Bandol #1, in French territorial waters (to be released in 2011 according to Enachescu 2006 C-NLOPB website and report) might eventually be included in such a study. Cuttings studies should be undertaken within a team that also includes both a biostratigrapher and seismic interpreter since the relationship across faults and the non-correlative nature of at least the limestone units closest to the Sable depocentre was well shown by Wade and MacLean (1990). Recent Dalhousie studies on the timing and style of salt movement relative to Sable delta sedimentation indicate a possibly important component in understanding the lithologic and depositional relationships and alternation. Another possible follow-up study is within the Sable delta itself. There might be additional places to use the approach of (Eliuk and Wach 2008) at West Venture in applying an analysis of thin condensed limestones to understanding the facies and sequence stratigraphy of the surrounding deltaic clastics.

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