"Passive" Margin Sedimentation and Reservoir Distribution Along the Scotian Margin

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Summary

Conceptual models for 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 links between shelf sediment capture and delivery, the role of shelf margin deltas, sea level and slope processes are critical to detecting reservoir rock distribution in deep and ultra-deep water. Models of these processes must account for the inter-twined complexities of continental margin processes, including salt tectonics, deep ocean currents, sediment mass-failure and channel and canyon incision.

Introduction

A significant issue in recent hydrocarbon exploration in the deep water on the Scotian margin is the detection of reservoir rock. Existing models of deep water sedimentation have greatly underestimated the linkages between shelf and slope sedimentation and the various roles of sea level, salt tectonism, canyon formation as sediment transport pathways, mass failure and along-slope sediment transport processes in passive continental margin development. The overall consequence of these sedimentary processes is movement of potential reservoir rock to different locations and to greater depths than previously anticipated. The objectives of this study are to understand the complexities of shelf to slope sedimentation patterns using

Neogene to Recent analogues offshore Nova Scotia. In younger sections, spatial and temporal resolution is not at issue and geologic events are better age-constrained (Mitchum and Wach, 2002). Deciphering forcing functions, sediment pathways and depositional processes are expected to improve exploration models for passive clastic margins. Validation of these hypotheses would indicate that exploration must move to deeper water where shelf-equivalent rocks are transported and deposited.

Geologic Setting

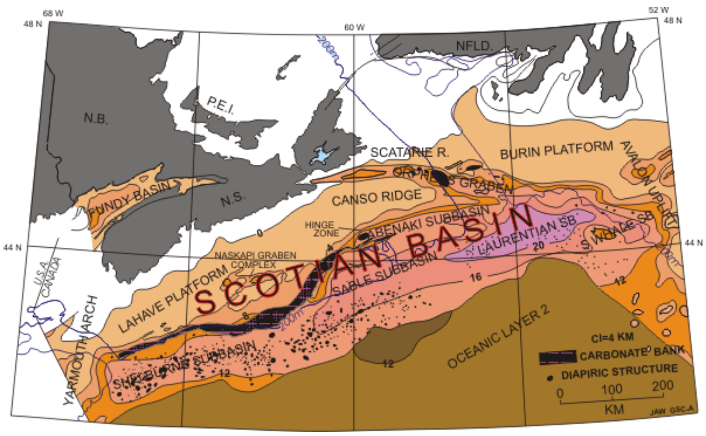

Figure 1. Scotian margin sediment thickness and structure map. Note the carbonate platform and outboard salt diapirs.

The Nova Scotia margin was formed within the Appalachian Orogen by the separation of Africa from North America during the Mesozoic breakup of Pangaea (Jansa and Wade 1975; Wade and Maclean, 1990). Rifting of the Nova Scotia margin began in the Middle Triassic to Early Jurassic (230-175 Ma) (Welsink et al. 1989), followed by Jurassic seafloor spreading (Klitgord and Schouten 1986). The oldest syn-rift deposits in the Sable Basin are nonmarine Triassic red beds, which are generally found between fault blocks (Wade and MacLean 1990). These are overlain by shallow marine sediments of Late Triassic-Early Jurassic age, including extensive salt diapirs. Thick Jurassic and Cretaceous strata overlie this Triassic salt (Wade and Maclean, 1990). Rifting of the Nova Scotia margin began in the Middle Triassic to Early Jurassic (230-175 Ma) (Welsink et al. 1989), followed by Jurassic seafloor spreading (Klitgord and Schouten 1986). The oldest syn-rift deposits in the Sable Basin are nonmarine Triassic red beds, which are generally found between fault blocks (Wade and MacLean 1990). These are overlain by shallow marine sediments of Late Triassic-Early Jurassic age, including the extensive salt diapirs. Thick Jurassic and Cretaceous strata overlie this Triassic salt (Wade and Maclean, 1990). Underpinning the Scotian margin is a Jurassic carbonate platform, over which prodeltaic shales accumulated. Back from the margin a thick deltaic section was deposited during the later Jurassic and Cretaceous. This Mesozoic succession 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. Rapid sedimentation on Laurentian Fan and Scotian Slope ensued with the onset of terrestrial glaciation during the Pliocene. On the eastern Scotian Slope numerous canyons appear to be the continuation of sub-glacial meltwater channels (tunnel valleys) on the updip Scotian Shelf (Flynn, 2000), but these modern canyon systems follow buried Tertiary systems for which glaciation was not a factor. Ice sheets extended close to the shelf edge at the last glacial maximum (18 ka) and retreated to the present shoreline by about 12 ka (Piper, 2005; Piper et al., 2002; Stea et al., 1998).

Stratigraphic complexity

Predicting and identifying the location of shelf equivalent facies (reservoir rocks) in deep and ultra-deep water is fundamental to understanding the distribution and characterization of margin sedimentary facies including potential reservoir sediments. Sequence stratigraphic concepts were developed as predictive capabilities to understand continental margins and model lithologic distribution. These models rely on the interplay of relative sea level and sedimentation. The Scotian margin demonstrates a number of extraneous factors that make sequence stratigraphic correlation difficult. These factors include: 1) salt tectonics, 2) a unique carbonate platform, 3) significant canyon incision, 4) erosion and along slope sediment transport, and 5) large mass-failures.

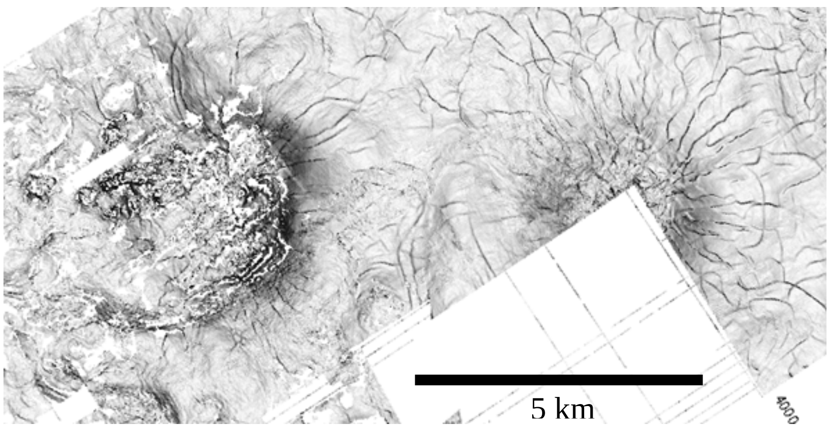

Figure 3. Salt domes imaged on a 3D seismic surface, showing radial fault pattern emanating from the uplifting structure.

Salt tectonics

The early stages of rifting along the Scotian margin (late Triassic – Early Jurassic) included deposition of thick successions of salt. This salt has flowed extensively due to subsequent sediment loading and possibly, due to periodic reactivation of the rift fault system during later stages of continental breakup (Shimeld, 2004). Allochthonous and autochthonous salt pillows, diapirs and canopies, are common along the deeper portions of the Scotian Slope (Fig. 1). 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. There are many examples along this margin where salt affects even the modern seafloor topography. Complex fault patterns surrounding salt structures are observed (Fig. 2) and there is evidence of re-routing of sediment pathways around salt structures. These factors force deviation from a classic margin development (Vail et al., 1977).

Carbonate margins and Sable delta influence

The Deep Panuke gas discovery in the platform margin has paradoxical features that result from the unique setting of the large Sable delta dissecting a carbonate platform. The upper Abenaki has two expressions - prograding mixed siliciclastic-carbonate ramps associated with the Sable Island paleodelta and relatively stationary aggrading oolitic carbonate platforms to the southwest and arguably northeast. Surprisingly, worldwide, the Upper Jurassic has few hydrocarbon fields in reef settings despite huge numbers of reefs and carbonate-hosted reserves.

The Sable shelf margin delta: Shelf margin deltaic sequences are notoriously difficult to correlate in the subsurface. Delta lobe switching contributes to stratigraphic complexity. Numerous permeability baffles and barriers create complex reservoir heterogeneities. An extensive network of non-marine channels and incised valleys cut into deltaic and shelf deposits during the falling stage and lowstand systems tracts and are recognized at multiple stratigraphic levels, particularly the Logan Canyon formation. Progradation of the Sable delta to the shelf edge was constrained, in part by localized accommodation controls from differential mobilization of underlying salt (Fig. 3). Shelf margin sediments can be trapped at the margin or may contribute directly to downslope fans.

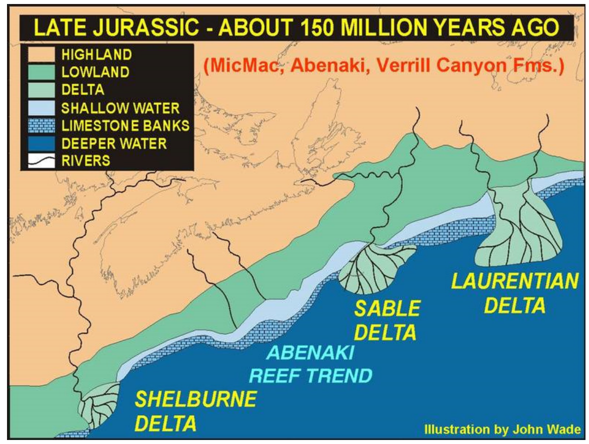

Figure 3. Simplified paleogeographic reconstruction of the Scotian Basin during the Late Jurassic. This period is the final stage of the Abenaki carbonate margin, with incision and development of shelf margin deltas by a rapidly prograding clastic system . Copyright © Atlantic Geoscience Society – used with permission.

Canyon formation

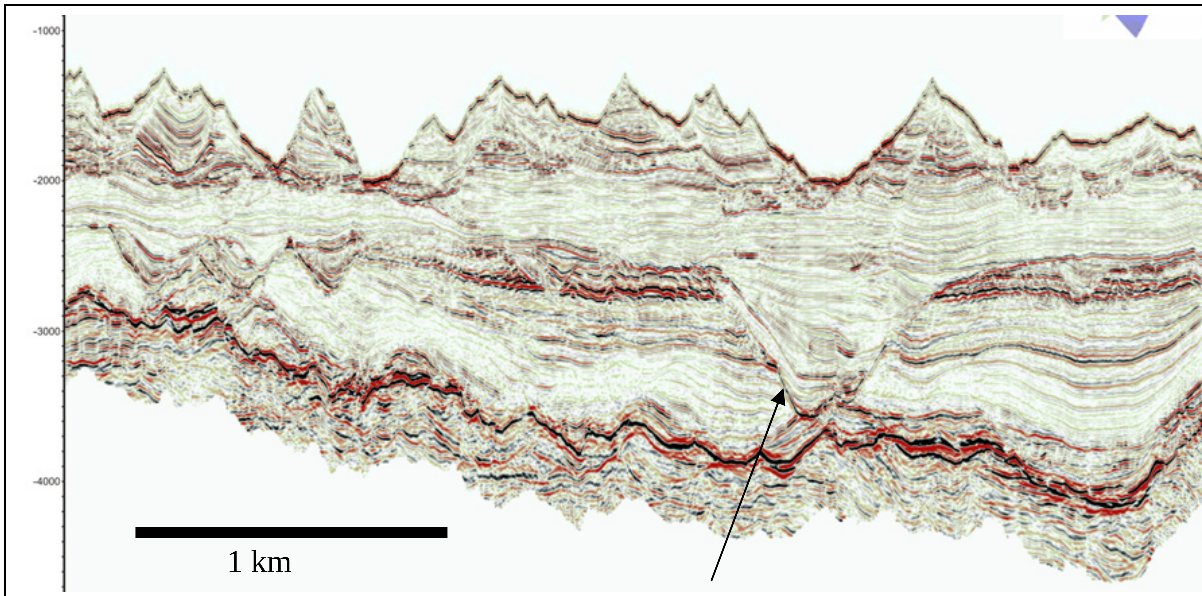

Figure 4. Seismic profile showing the heavily canyoned modern seafloor topography as well as a buried Oligocene(?) canyon system indicated by the arrow.

The modern seafloor of the eastern Scotian Slope is heavily incised by canyons and valleys, providing conduits for off-shelf sediment transport, slope by-pass and deposition on the continental rise and abyssal plain. 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 basement control (Brake et al., 2008) (Fig. 4). This episodic canyon incision indicates a limited residence period of sediments on the shelf and slope, having implications for potential reservoir distribution. Causes of this canyon incision are not entirely clear. Modern canyons may be related to sea level fall and high sediment transport during deglaciation, but older systems are perplexing as glaciation was not a causative factor. Major sea level regressions are required to initiate the depth of canyon incision observed, suggesting either large eustatic sea level fall or tectonic inversion (Grist and Zentilli, 2003) along this passive margin with the latter complicating the geologic history of the margin. Mapping of these canyon systems shows fill of classic thalweg channels with meander loops. Channel fill and channel overspill may provide reservoir quality sediments. By analogy, mapping of gas hydrate along the Scotian margin clearly shows concentration within channel and channel levee deposits – presumably occurring where porosity and permeability permit hydrate accumulation (Mosher, 2008).

Margin erosion and along slope transport

A prominent Middle to Late Miocene (?) erosional unconformity is recognized over an area of >20 000 km^2 along the lower slope and rise of the western Scotian margin (Fig. 5). This unconformity is the product of a number of erosion events that over-steepened the lower slope. In response there was sediment bypass across the unconformity and sediment aggraded at the toe of the slope. This unconformity is onlapped by slope-derived mass transport deposits and subsequent bottom current deposits in the form of complicated seismic-scale bedforms. In some areas these bedforms built the seabed above grade, trapping subsequent down-slope flows. This evidence of broad scale erosion and sediment transport indicate modification of the lower continental slope outside of the direct influence of changing sea level and sediment supply.

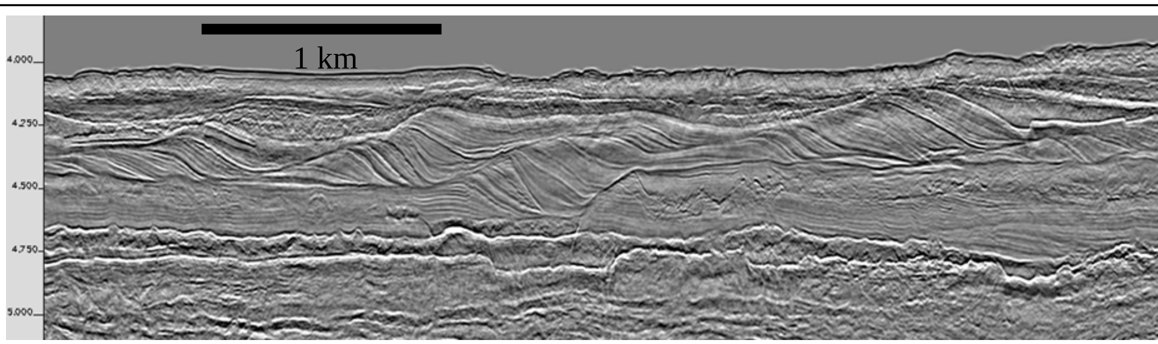

Figure 5. Seismic section from the Scotian Slope showing large sediment waves constructed above a prominent mid-Miocene (?) unconformity.

Mass transport processes

Interpretation of both seismic reflection profiles and surface renders of the modern and ancient seafloors demonstrates the prevalence of mass transport processes in the stratigraphic evolution of the Scotian margin (Mosher et al., 2004; Mosher and Campbell, in press). Mass transport deposits (MTD) appear at all scales of resolution and form an estimated 50% of the sedimentary section. As recently as 1929, an earthquake-initiated mass failure occurred in the Grand Banks region, generating a devastating tsunami (Giles et al., 2008). The late Pleistocene Shelburne mega-slump of the central Scotian Slope maps to some 234 km^2 in area and 140 km^3 in volume (Mosher et al., in press). The associated debrite runs out to the abyssal plain in excess of 100 km and maps over 9,000 km^2. Large events like this destroy much of the pre-existing margin stratigraphy and the sum of mass-transport failures moves massive amounts of sediment from shallow to deep water in a very short period of time. In addition, these processes sculpt the morphology of the margin, determining subsequent sediment pathways and depo-centres.

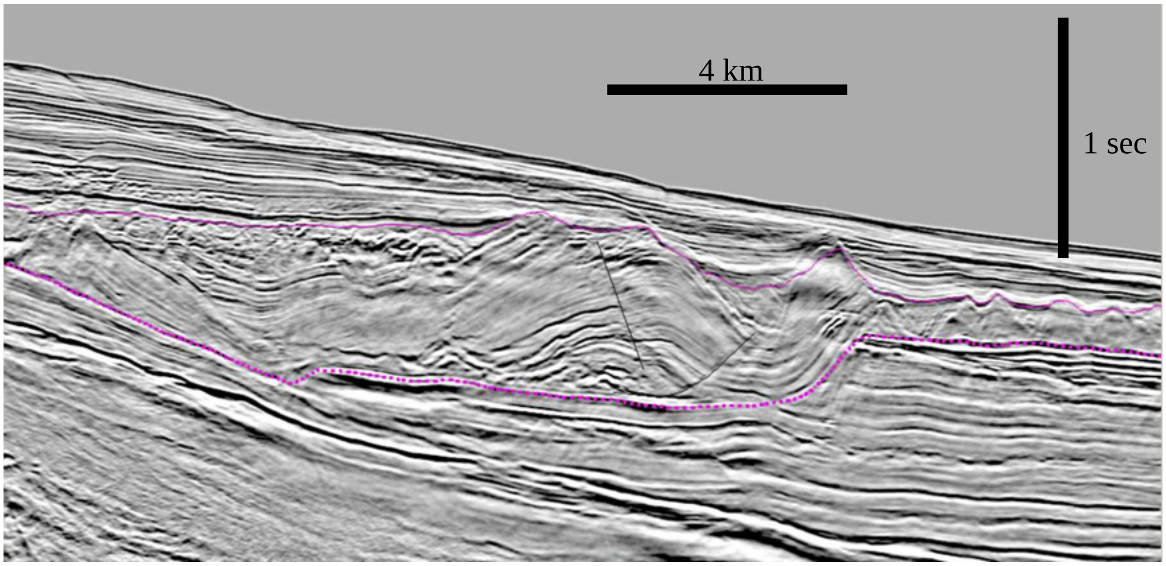

Figure 5. Seismic profile showing large MTD on the central Scotian Slope.

Conclusions

- Along the Scotian margin, canyons and mass-transport processes provide mechanisms for slope bypass and delivery to the rise and abyssal plain. Mechanisms of canyon incision are uncertain and may be related to deglaciation and eustatic sea level change, or in some cases relative sea level changes initiated by tectonic inversion.
- Mass transport processes result in removal of stratigraphic section and transport of significant amounts of sediment downslope.
- Some canyon and channels and their associated levee systems may contain reservoir quality sediments and provide conduits for downdip reservoir potential.
- The presence of salt greatly complicates the margin. Mobile salt may provide significant trapping mechanisms, minibasin formation with sediment ponding, but may also complicate sediment pathways, destroy stratigraphy continuity and cause mass failures through removal of lower slope buttress support.
- Updip deltas and shelf margin deltas provide a source for downslope transport and sediment loading can contribute to mobilization of underlying salt.
- Significant deep water margin erosion occurred at certain periods, apparently related to development of strong along-slope bottom currents. This erosion may have led to undercutting of the base of slope initiating sediment mass failure. These same currents produced large (10's km in wavelength) bedforms which may have reservoir potential and may force capture of down-slope sedimentation, perhaps generating local reservoir rock potential.

Investigation and analysis of these processes demonstrate that reservoir-grade sediments can be reworked, relocated and transported to great water depths, and thus offer significant challenges to reservoir detection along the Scotian margin. A thorough understanding of the interplay and complexity of these processes is necessary to apply effective exploration models on passive margins.

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