Geological Survey of Canada

CURRENT RESEARCH
2005-D3

Major Quaternary mass-transport deposits in southern Orphan Basin, offshore Newfoundland and Labrador

D.C. Campbell

2005

Natural Resources Canada
Ressources naturelles Canada

Canada

CURRENT RESEARCH

ISSN 1701-4387
Catalogue No. M44-2005/D3E-PDF
ISBN 0-662-40824-1

Toll-free (Canada and U.S.A.): 1-888-252-4301

Author's address

D.C. Campbell (ccampbe@nrcan.gc.ca)
Geological Survey of Canada (Atlantic)
1 Challenger Drive
Dartmouth, Nova Scotia B2Y 4A2

Publication approved by GSC Atlantic

Original manuscript submitted: 2005-05-09

Final version approved for publication: 2005-05-31

Major Quaternary mass-transport deposits in southern Orphan Basin, offshore Newfoundland and Labrador

D.C. Campbell

Campbell, D.C., 2005: Major Quaternary mass-transport deposits in southern Orphan Basin, offshore Newfoundland and Labrador; Geological Survey of Canada, Current Research 2005-D3, 10 p.

Abstract: Orphan Basin is a deep-water basin off the northeast coast of Newfoundland that is currently an area of active hydrocarbon exploration. The Geological Survey of Canada has conducted regional high-resolution seismic-reflection and seabed sampling surveys during 2003–2004 to improve understanding of the Quaternary geology and identify potential geohazards. Evidence of past instability includes thick, stacked mass-transport deposits on the basin floor and seabed failure scars on the continental slope. Most of the mass-transport deposition through the Quaternary occurred in the northern part of the study area, although there has been a shift towards the northwest during the Pleistocene. Recurrence of large-scale seabed failure through the Quaternary is on the order of 75 000–100 000 years, but it is not clear if there is a correlation with global sea-level change and glaciations or if the distribution is random.

Résumé : Le bassin Orphan, situé en eau profonde au large de la côte nord-est de Terre-Neuve, est actuellement le lieu de nombreux travaux d'exploration pétrolière. La Commission géologique du Canada y a exécuté des levés de sismique-réflexion haute résolution et effectué une cueillette d'échantillons du fond marin en 2003-2004, afin de mieux comprendre la géologie du Quaternaire et d'identifier les dangers géologiques possibles dans cette région. Les signes d'instabilité passée comprennent des dépôts résultant de mouvements de masse, qui forment d'épais empilements sur le fond du bassin, et des cicatrices de rupture du fond marin sur le talus continental. La plupart des dépôts résultant de mouvements de masse au Quaternaire se sont accumulés dans la partie septentrionale de la région d'étude, quoiqu'un décalage en direction nord-ouest se soit produit au cours du Pléistocène. Durant le Quaternaire, la période de récurrence des ruptures à grande échelle du fond marin a été de l'ordre de 75 000 à 100 000 ans; il n'est pas clair si ces événements sont reliés aux variations eustatiques du niveau marin et aux glaciations, ou bien si leur répartition temporelle est aléatoire.

INTRODUCTION

The recent expansion of oil and gas exploration into the deep-water regions offshore eastern Canada has driven the need to understand continental margin geological processes, with a particular emphasis on seabed stability and geohazard assessment. From 1979 to 1987, six exploration wells were drilled in the deep-water areas of the Grand Banks slope, Flemish Pass, and Orphan Basin. One of the wells, Blue H-28 in Orphan Basin, achieved a world record for drilling water depth at that time, 1486 m. In 2003, two more wells were drilled in Flemish Pass. Also in 2003, an offshore land sale in Orphan Basin covering an area of over 25 000 km^2 (Fig. 1) resulted in work commitments by exploration companies that potentially include the drilling of several exploration wells in water depths of 2000–3000 m in the next four years.

Previous geohazard assessments on the Scotian Slope can provide a model for assessments in other areas. On the Scotian Slope, interpretation of high-resolution seabed bathymetry (either from multibeam sonar or 3-D seismic seabed renders), sedimentological and geotechnical analysis of sediment cores, and interpretation of high- and ultra-high-resolution seismic-reflection data has provided a regional understanding of the upper 500 m of the sediment column (Mosher et al., 2004). This study uses newly acquired high-resolution seismic-reflection data to present evidence of large-scale mass-transport deposits throughout the Quaternary in southern Orphan Basin. The term mass-transport deposits is used here to describe features recognized in seismic-reflection profiles that are interpreted to represent deposits associated with sediment failure and transport as slumps, slides, debris avalanches, or debris flows.

BATHYMETRIC SETTING

Orphan Basin is a bathymetric embayment in 2000–3000 m water depth and forms part of the continental margin off eastern Canada. It is bounded to the west and south by the Newfoundland Shelf and Flemish Cap, and to the northeast by Orphan Knoll (Fig. 1). Sackville Spur is a sediment drift feature that forms much of the southeast mid- to upper slope of Orphan Basin (Kennard et al., 1990). The western slope has a low gradient of 1–2°, is undissected, and is underlain by wedges of mass-transport deposits interbedded with acoustically stratified units that form a large depositional lobe seaward of Trinity Trough (Hiscott and Aksu, 1996). The southeast slope is also undissected, but has a much higher gradient (4–6°) than the western slope. In contrast, much of

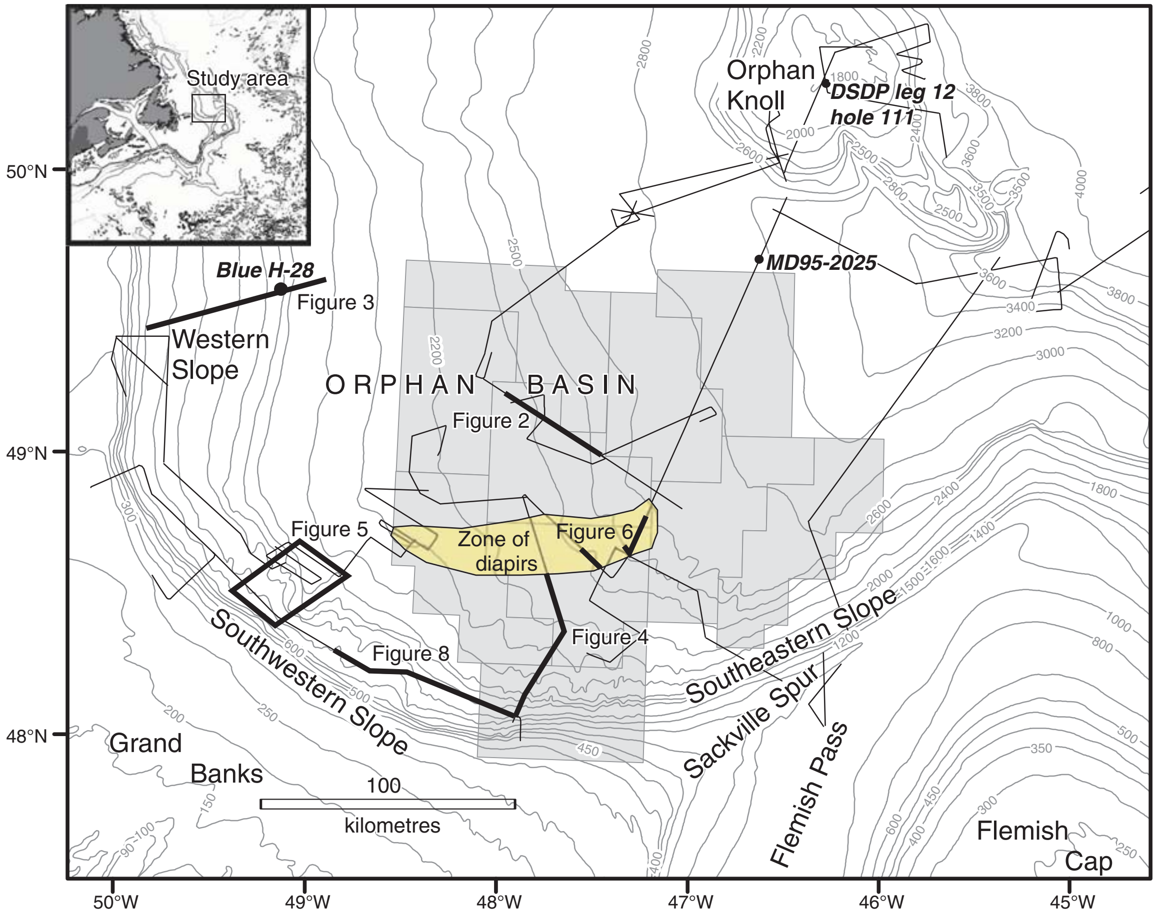

Figure 1. Map of southern Orphan Basin showing regional bathymetry in metres, seismic-reflection profiles (black lines), exploration lease blocks (grey boxes), location of figures, and other features discussed in the text.

the southwestern slope is incised by canyons and is underlain by mass-transport deposits, large sediment drift features, and acoustically stratified units (Piper et al., 2004). Broad submarine channels on the southern Orphan Basin floor appear to coalesce towards the gap between Orphan Knoll and Flemish Pass. Otherwise, the floor of Orphan Basin is relatively flat and gently slopes towards the east.

METHODS

This study is based on high-resolution seismic-reflection profiles collected by the Geological Survey of Canada during CCGS *Hudson* cruises 2003-033 and 2004-024. Approximately 2500 line-kilometres of data were acquired over the western and southern slopes and basin floor of Orphan Basin (Fig. 1).

The seismic-reflection system consisted of an airgun and single-channel streamer. The acoustic source for the seismic-reflection system was a Seismic Systems Inc. Generator Injector (GI) Gun™ (total volume of 3.44 L). The seismic data were recorded using a Teledyne model 28420 single-channel streamer with acceleration-cancelling hydrophones and a 45.2 m long active section (overall length of 61 m). The maximum vertical resolution of the system is on the order of 1 m. The seismic data were digitized onboard using custom in-house software which outputs SEG-Y files with navigation and deep-water delay information written directly to each trace header. The data were imported into a commercial seismic-interpretation software package and some minor processing was applied before interpretation. The software allowed for interpretation of the seismic data, correlation of a seismic stratigraphy throughout the study area, and creation of isopach maps between key horizons.

RESULTS

Analysis of high-resolution seismic-reflection data from southern Orphan Basin shows the following general features: the sediments of the western to southern basin slope record a complex history of cut-and-fill and canyon erosion, the formation of large sediment waves, seabed failure escarpments, sediment accumulation on inter-canyon ridges, but little evidence of mass-transport deposition and the sediments of the basin floor are dominated by mass-transport deposits, in areas comprising up to 90% of the upper 1.0 s two-way traveltime (~750 m) of the sediment column, that are interbedded with acoustically stratified material of variable thickness.

Seismic stratigraphy

A Quaternary seismic stratigraphy was developed in the central Orphan Basin by Hiscott and Aksu (1996). In their study, key horizons were defined within acoustically stratified intervals found at the base of major mass-transport deposits. In this study, only the blue horizon of Hiscott and Aksu (1996) has been correlated widely in the study area. Three new horizons have been defined for the deeper seismic stratigraphy (Fig. 2). The blue horizon was defined as the base of the shallowest wedge-shaped, acoustically incoherent interval (Hiscott and Aksu, 1996) and overlies an acoustically stratified interval in the northern part of the study area. The red horizon marks the base of the acoustically stratified interval below the blue and overlies a widespread mass-transport deposit. The yellow horizon (approximately brown from Hiscott and Aksu (1996)) was defined as the base of the package of wedge-shaped, transparent mass-transport deposits seen in the northern part of the study area and marks a distinct change in acoustic character within the mass-transport deposits (Fig. 2). The deepest horizon, purple, occurs as a prominent unconformity on the southwest slope of Orphan Basin and marks the base of the seismic section examined in this study (Fig. 2).

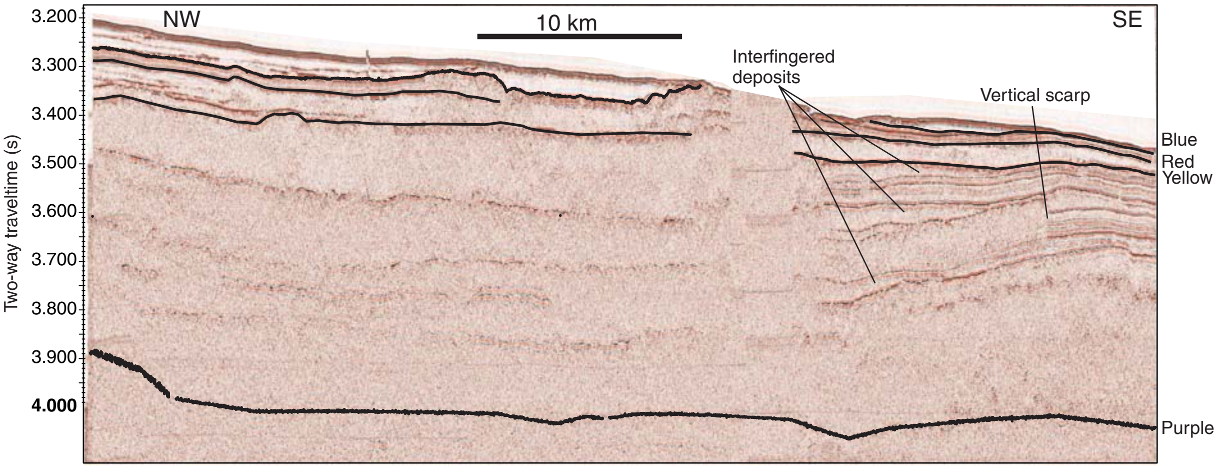

Figure 2. *Seismic-reflection profile showing seismic stratigraphic type section and acoustic character of mass-transport deposits.*

Age determinations and acoustic character of horizons are summarized in Table 1. Hiscott and Aksu (1996) determined the age of the blue horizon to be 30–40 ka based on correlation with Heinrich and ash layers, and oxygen-isotope stratigraphy in piston core 92045-011. The age of the red and yellow horizons can be estimated from correlation to core MD95-2025 on the basin floor (E. Tripsanas, pers. comm., 2005) (Fig. 1) that has been described by Hiscott et al. (2001). Core MD95-2025 penetrates beyond the depth of the red horizon, and based on this correlation, the red horizon occurs at the MIS (marine isotopic stage) 7 to MIS 8 transition, approximately 235 ka. The yellow horizon occurs approximately 10 m below the red horizon and is beyond the depth of penetration of core MD95-2025. Based on an extrapolation of the comparison of the oxygen-isotope stratigraphy from the core and the seismic character seen in Huntec DTS™ high-resolution sparker data, the age of the horizon is estimated to be MIS 12 (ca. 450 ka). Hiscott and Aksu (1996) estimated the age of their brown reflector (approximately yellow in this report) to be MIS 11 (ca. 381 ka), based on extrapolation from a much shorter piston core. The purple horizon can be correlated with the Blue H-28 well in central Orphan Basin (Fig. 1). In the Blue H-28 well, the N21-N22 biozone transition (dated elsewhere at 2 Ma) occurs between 1069 m and 1099 m subsurface (Gradstein and Williams, 1986). Precise depth to time conversion at the well site shows that this biostratigraphic pick lies immediately below the purple horizon, giving the horizon a latest Pliocene–earliest Pleistocene age (Fig. 3).

Mass-transport deposits

Generally, mass-transport deposits have depression-filling geometry, low amplitude, and chaotic internal acoustic character (Posamentier and Kolla, 2003). In many places, the base of deposits appears erosional and the upper surface ranges from smooth to hummocky. At the margins of some deposits, the deposit surface passes laterally into local to regional unconformities that in turn are correlateable with failure escarpments upslope.

In southern Orphan Basin, deposits imaged in high-resolution seismic-reflection data range in thickness from over 100 ms two-way traveltime (~75 m) to the vertical resolution limit of the seismic-reflection system (~2 m). Between the purple reflector and the seafloor, there is a general pattern of thicker

Table 1. Seismic stratigraphy presented in this study.

Reflector	Character	Estimated age (ka)	Reference
Blue	Top of acoustically stratified interval between mass-transport deposits	30–40	Hiscott and Aksu (1996)
Red	Base of acoustically stratified interval between mass-transport deposits	235	This paper
Yellow	Base of transparent mass-transport deposit facies	450	This paper
Purple	Regional unconformity	1800	This paper

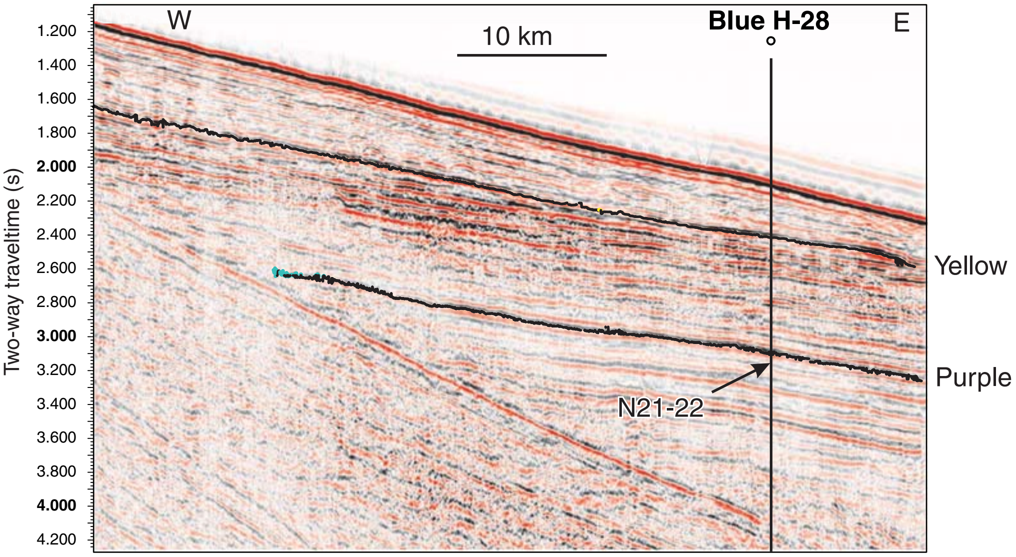

Figure 3. *Multichannel seismic-reflection profile through the Blue H-28 well site, showing biostratigraphic picks and horizons discussed in text.*

and more abundant deposits with increasing subsurface depth (Fig. 2). Most deposits pinch out at the edge of the basin floor where gradient increases (Fig. 4). Some terminate abruptly at near-vertical escarpments (Fig. 2; 5C, D, sections C-C' and D-D'). The margins of some of the deeper and thicker mass-transport deposits interfinger with adjacent acoustically stratified sediment (Fig. 2), that indicates that some of the mass-transport deposits represent multiple events. The tops of some deposits have been eroded (Fig. 4).

Mass-transport deposit corridor on the southwestern slope

A geographically confined zone of repeated seabed failure, informally termed a mass-transport deposit corridor, has been recognized on the southwestern slope of Orphan Basin, similar to the Logan Canyon mass-transport deposit corridor identified on the Scotian Slope (Mosher et al., 2004) (Fig. 5). On the upper slope (Fig. 5A, section A-A'), there is a broad flat zone of evacuation. The subsurface in the evacuation zone consists of acoustically stratified reflections that differ from the cut-and-fill pattern observed in the subsurface adjacent to the corridor. A broad debris-filled channel is developed downslope from A-A'. Profile B-B' only images the northern wall of the channel, whereas profiles C-C' and D-D' image the channel wall and channel floor. In both profiles C-C' and D-D', a near-vertical, buried lateral escarpment is imaged with a height of approximately 200 ms two-way traveltime. The channel is filled with stacked mass-transport deposits that abut the lateral escarpment. The southern limit of the failure corridor (Fig. 5E, inset map) was not surveyed and is speculatively based on the regional bathymetry.

Shallow diapirs on the basin floor

Diapir mounds are found on the southern Orphan Basin floor. They cut stratified sediment immediately above a geographically extensive mass-transport deposit that underlies the yellow reflector. The diapirs have a positive seafloor expression (Fig. 6), are 300–500 m in diameter, and are confined to an area of about 1500 km^2 between 2000 m and 2600 m water depth (Fig. 1). Diapirs have not been recognized in any other mass-transport deposits. It is not known whether the diapirism is due to specific properties of the deposit or due to migration of fluids from depth in the general area. Similar features have been identified previously on Sackville Spur (Campbell et al., 2002) and at the margin of a mass-transport deposit lobe in Flemish Pass (Piper and Campbell, 2005).

Deposition patterns through the Quaternary

Three isochron maps were created for the study area (Fig. 7). The isochron maps represent the variation in two-way traveltime between horizons and are analogous to more traditional isopach maps of sediment thickness assuming uniform sound velocity through the mapped intervals. It is possible to create maps that display time variation between any of the horizons within the study area. However, for illustration purposes the purple to seafloor (approximately earliest Pleistocene to present) (Fig. 7A), purple to yellow (approximately earliest Pleistocene to MIS 12)(Fig. 7B), and yellow to seafloor (approximately MIS 12 to present)(Fig. 7C) are presented. The survey lines used in the map creation appear in grey and show the data control.

The purple to seafloor isochron provides an overview of depositional patterns within southern Orphan Basin throughout the Quaternary (Fig. 7A). The map shows that most of the deposition during the Quaternary within the study area was in

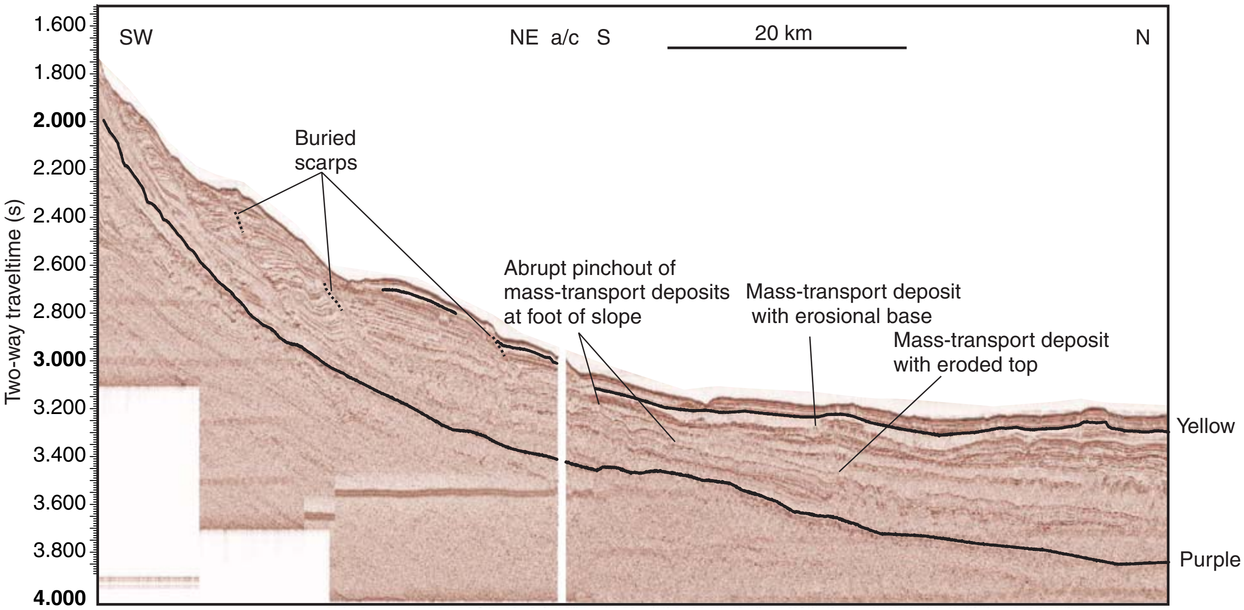

Figure 4. *Dip seismic-reflection profile illustrating pinchout of mass-transport deposits at the edge of the basin floor and buried escarpments on the slope; a/c = alternate course.*

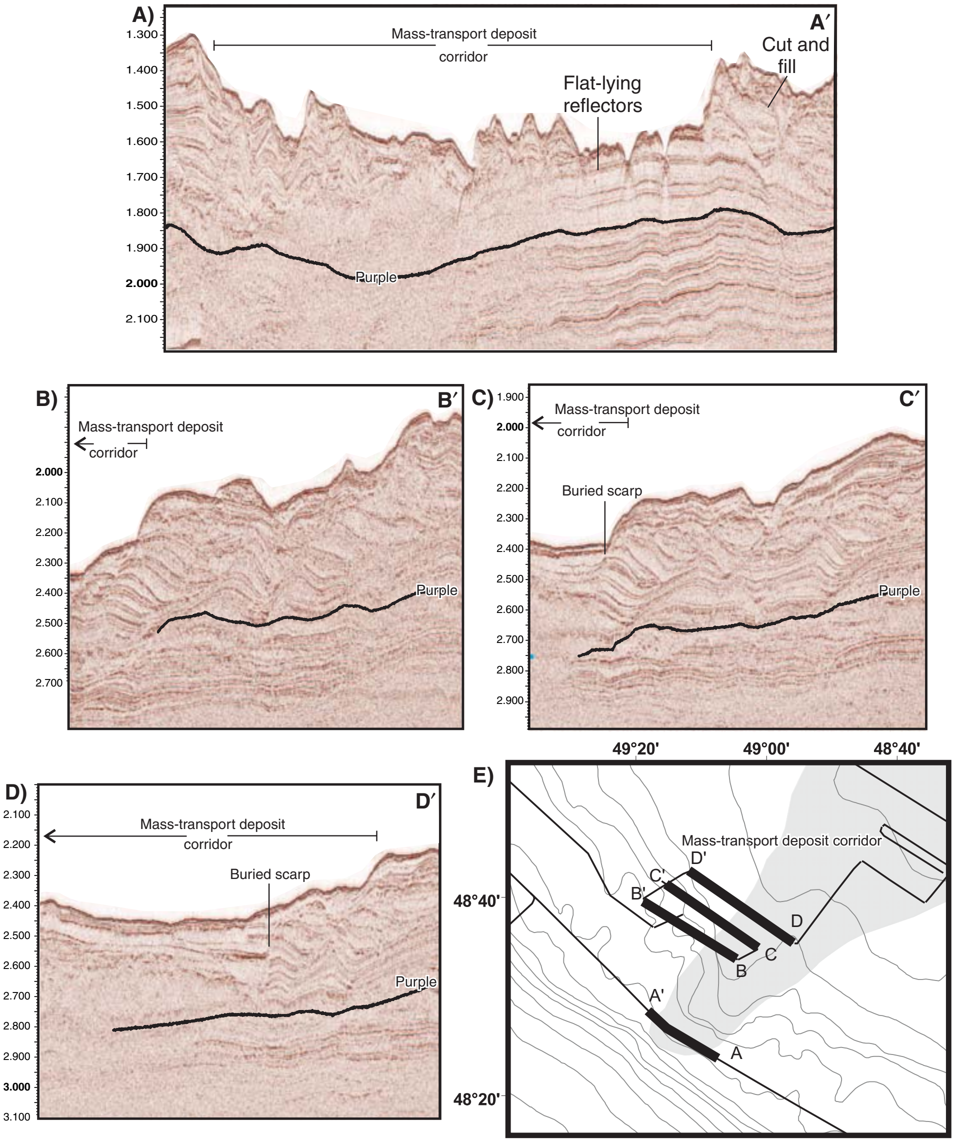

Figure 5. *A)–D) Series of seismic-reflection profiles showing a mass-transport deposit corridor recognized on the western slope of Orphan Basin.* ***E)*** *Inset map shows location of profiles.*

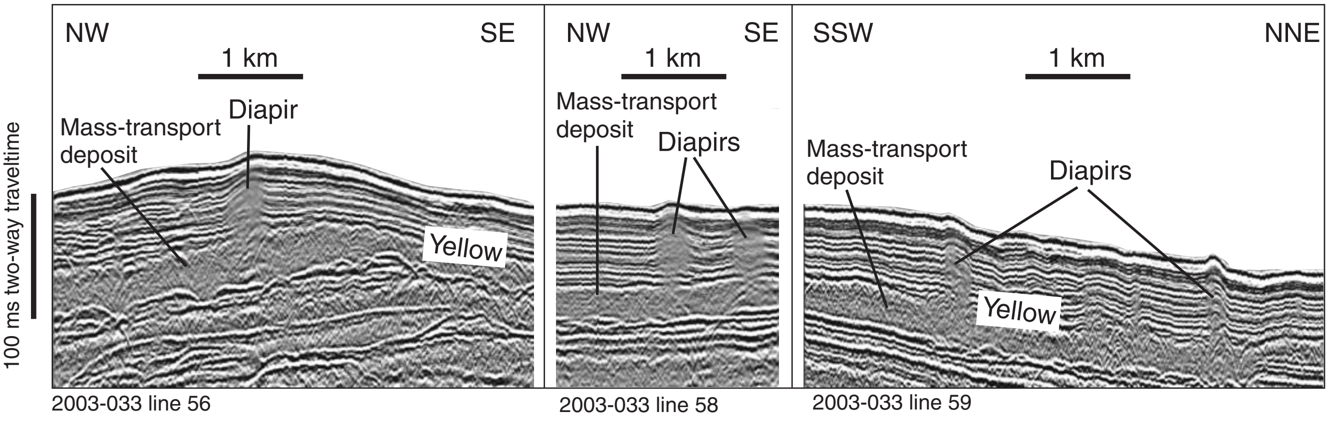

Figure 6. *Seismic-reflection profiles showing diapiric features associated with a regional mass-transport deposit. Figure* modified from *Piper et al. (2004).*

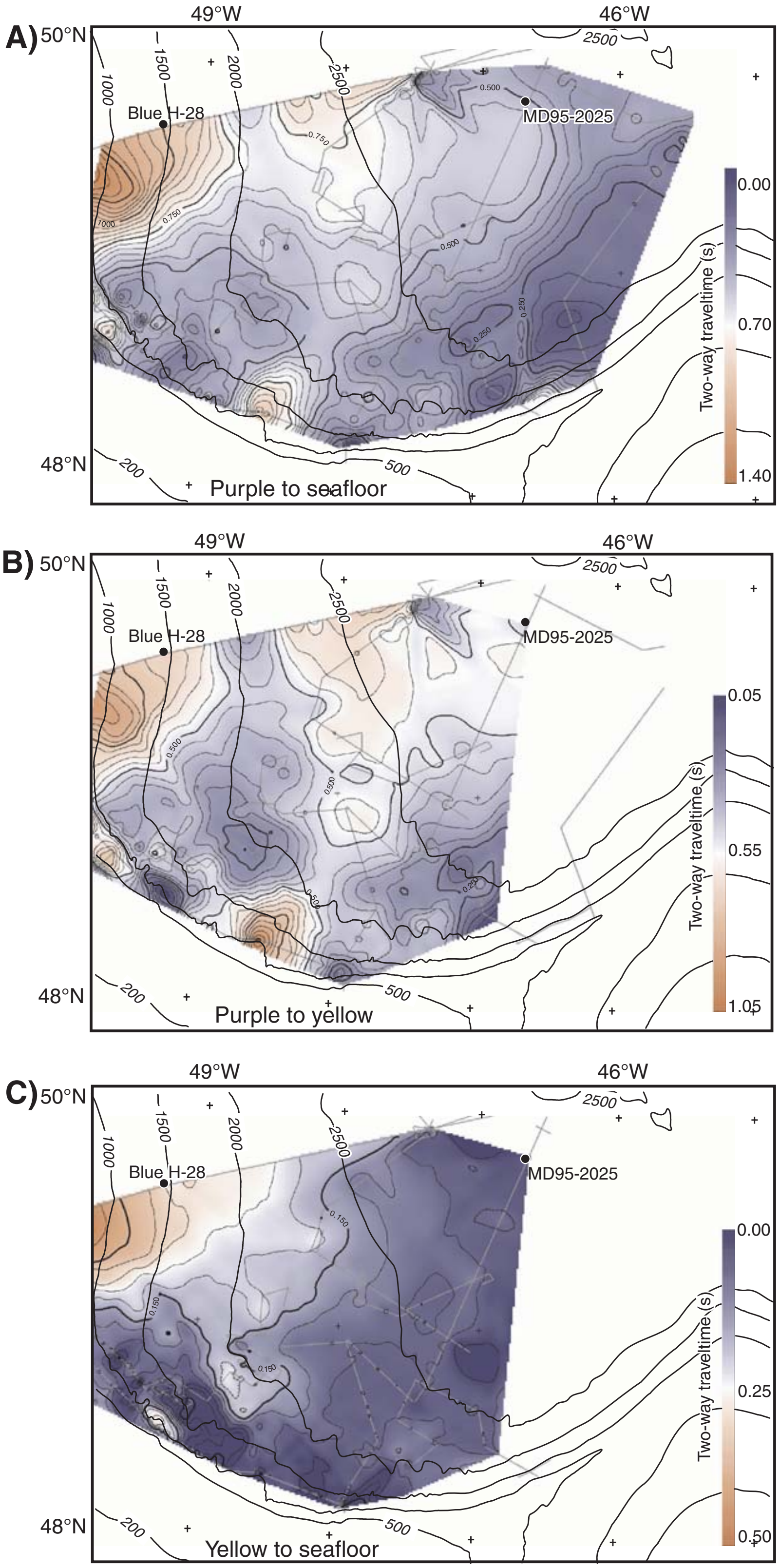

Figure 7.

Isochron maps showing sediment distribution through ***A)*** *the entire Quaternary section,* ***B)*** *the early to middle Pleistocene, and* ***C)*** *the middle Pleistocene to present.*

the north and particularly the northwest, thus apparently derived from Trinity Trough. A smaller depositional lobe appears to be present in the southwest, but there is little data control in this area. Sediment accumulation was least along the base of the modern southern continental slope.

The purple to yellow isochron reveals depositional patterns during the early to middle Pleistocene (Fig. 7B). The extent of the map is limited to the area that the yellow horizon has been mapped and covers a smaller region than Figure 7A. It is apparent from the map that most of the deposition during this period was in the northwest and northeast part of the study area.

The yellow to seafloor isochron reveals depositional patterns during the middle Pleistocene to present (Fig. 7C). The map shows that most of the deposition has been in the northwest part of the study area with relatively little sediment accumulation elsewhere in this area during the late Pleistocene.

DISCUSSION

Large-scale mass-transport deposits have been recognized previously on the eastern Canadian continental rise (summarized *in* Piper and McCall (2003); Piper et al. (2003)). Data from the present study show that much of the upper 500 m of seabed on the basin floor within southern Orphan Basin consists of mass-transport deposits interbedded with typically thin, acoustically stratified deposits. These deposits are laterally extensive on the basin floor and, except for the depositional lobe seaward of Trinity Trough, pinch out rapidly at the base of the continental slope. Assuming that mass-transport events originate on the continental slope (even the lower slope), sediment comprising these deposits has been transported tens of kilometres and is probably true debris-flow or debris-avalanche deposits rather than rotational slumps or slides (Nardin et al., 1979).

The regional-scale geomorphology of southern Orphan Basin forms an amphitheatre that acts as a funnel to collect mass-transport deposits on the basin floor, making it difficult to associate particular deposits with particular failure scars on the slope without more data. A number of features in seismic-reflection profiles from the slope around southern Orphan Basin point to potential source areas for failure deposits. A dip profile from the southwestern slope (Fig. 4) shows a number of buried escarpments on the middle to lower slope. Another strike profile from the same area (Fig. 8) shows numerous escarpments and a thick mass-transport deposit. Further to the north, a mass-transport deposit corridor has been recognized (Fig. 5). It is not clear from the sparse data whether failure initiated on the upper slope or whether failure initiated on the lower slope and retrogressed. On the Scotian Slope, from which there is much more data, there is evidence of failure initiating on the lower slope and retrogressing to the upper slope (Mosher et al., 2004).

The series of maps shown in Figure 7 displays total sediment thickness, both mass-transport deposits and hemipelagic, between different horizons, but because the thickness of mass-transport deposits is so great compared to hemipelagic, the maps essentially show the distribution of mass-transport deposits. Considering this, a major shift in sediment accumulation occurred during the Pleistocene. During the early to middle Pleistocene (Fig. 7B) the pattern of mass-transport deposition indicates that the failed material accumulated seaward of Trinity Trough, seaward of a canyon system on the southwest slope, and on the distal basin floor approximately 100 km seaward of the base of the slope. Besides the Trinity Trough source area, there are a number of large buried escarpments present on the southwestern slope (Fig. 4, 8) that could be source areas for these deposits. Kennard et al. (1990) recognized numerous failure escarpments on the northern side of Sackville Spur, but there is little evidence of failure deposition in this area. Presumably, the material that failed would have accumulated on the basin floor and contributed to the observed deposition pattern.

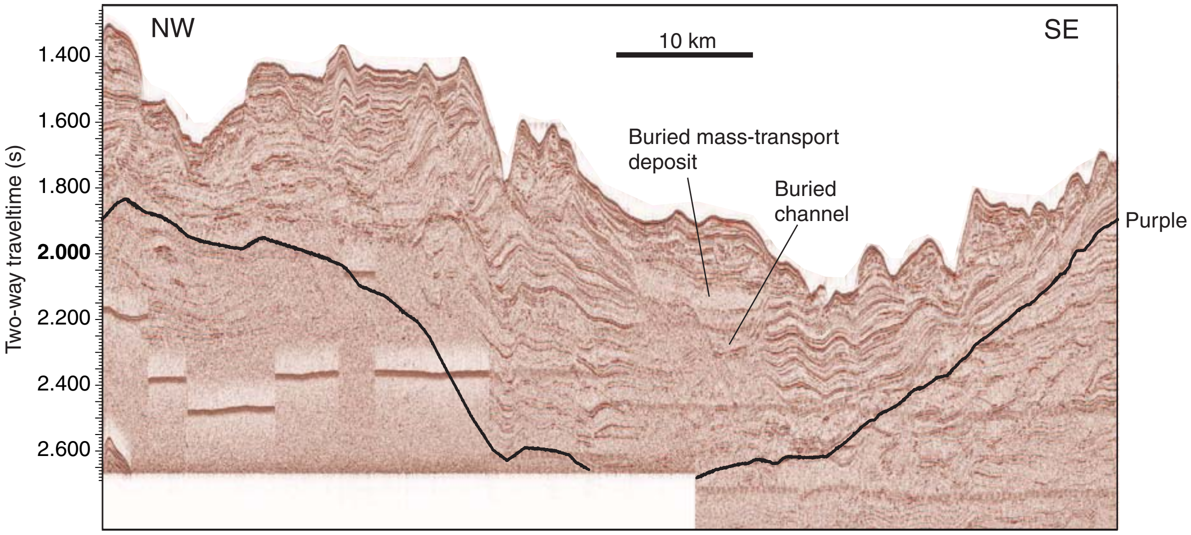

Figure 8. *Seismic-reflection profile along the southwestern slope showing complex history of sediment failure, canyon erosion, and deposition above the purple reflector.*

On the southwestern slope above the purple reflector (Fig. 8) there is abundant evidence of canyon erosion and cut-and-fill sequences. These erosional events would also carry large amounts of sediment to the basin floor.

During the middle to late Pleistocene, the pattern of mass-transport deposition reveals a lobe of deposits originating from the northwest (Fig. 7C). This lobe forms the debris-flow complex discussed by Hiscott and Aksu (1996) and possibly reflects the first major shelf-crossing glaciation and evacuation of Trinity Trough. The unique homogeneous and transparent acoustic character of the mass-transport deposits comprising this interval suggests a different composition than underlying deposits. Nygard et al. (2002) recognized deposits on the North Sea Fan with similar acoustic and geomorphological character, interpreted to be glaciogenic debris flows. Distally and to the southern side of the lobe, the deposits pinch out and overlie the thick-stacked mass-transport deposits of the early to middle Pleistocene section (Fig. 2).

Major mass-transport deposits in Orphan Basin have a slightly higher recurrence than deposits identified in Flemish Pass (Piper and Campbell, 2005). In Orphan Basin, major failures occurred every 75 000–100 000 years during the middle to late Pleistocene (Fig. 9). Major failures occurred less frequently during the early Pleistocene, every 250 000 years, and a similar pattern is seen on the Scotian Margin (Piper et al., 2003; Campbell et al., 2004); however, this pattern may be a technical artifact, since seismic resolution decreases with subsurface depth and the less frequent, but thicker deposits of the early Pleistocene may represent multiple events. Given the potential error in the age estimates for the seismic stratigraphy during the early Pleistocene, it is not clear whether there is a correlation between failure deposits and global sea-level fluctuations and glaciations, or if failure deposits are due to random events such as large passive margin earthquakes. The distribution of mass-transport deposits during the middle to late Pleistocene shows that these deposits are geographically related to Trinity Trough. The similarity of mass-transport deposits in this area to features identified on the North Sea Fan (Nygard et al., 2002) indicate that these deposits were sourced from the upper slope, probably seaward of a calving ice stream situated in Trinity Trough that would provide a relatively continuous supply of sediment.

Implications for hydrocarbon development

The deep-water areas currently under exploration in Orphan Basin differ from the deep-water areas off Nova Scotia. In Nova Scotia, much of the exploratory drilling has taken place on steep areas of the continental slope where seabed failure hazard due to drilling activity may be higher. In Orphan Basin, most of the area to be explored is on the basin floor that lacks incised canyons and has a regional gradient of less than 1°, and therefore has a much lower risk of seabed failure at the drilling site. In Orphan Basin, most of the potential hazard is associated with the actual mass-transport deposits. Mass-transport deposits can carry coarser sand and gravel from the upper slope into deep water. Depending on the

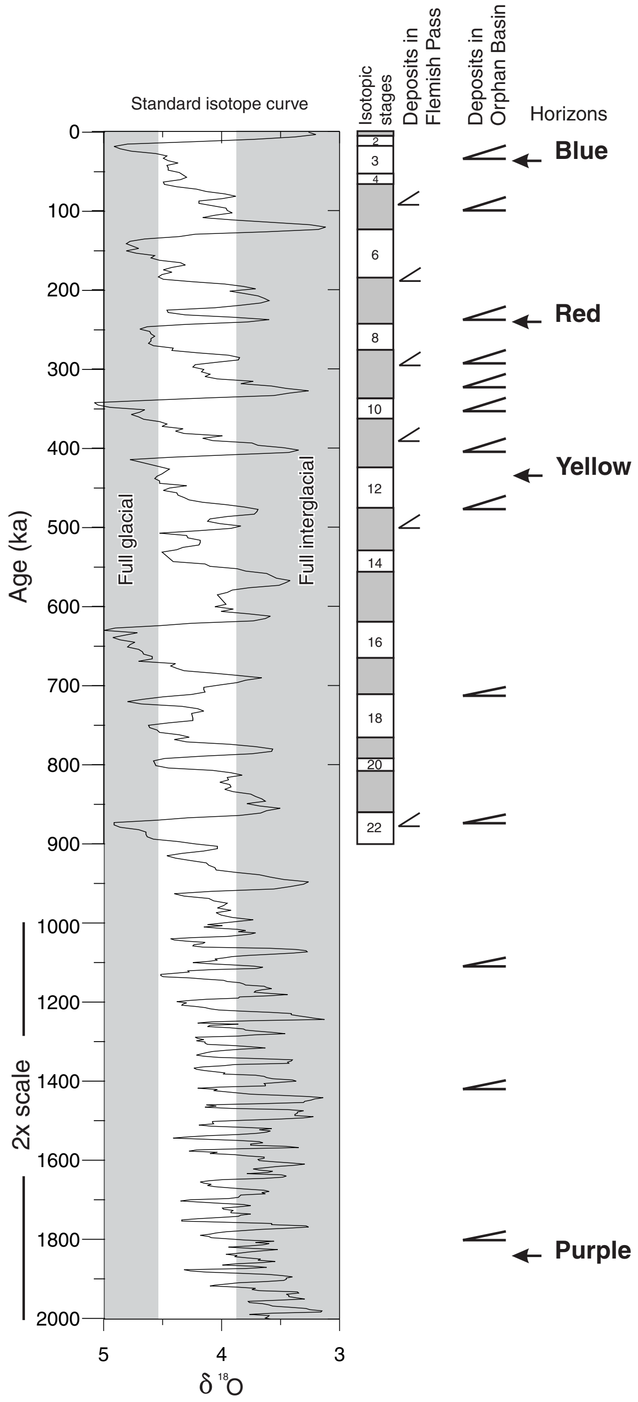

Figure 9. Comparison of chronological relationship of seismic reflectors and mass-transport deposits in Orphan Basin with mass-transport deposits in Flemish Pass; modified from *Piper and Campbell (2005).*

degree of remoulding within the deposit, it can be more consolidated than the surrounding unfailed material (Shipp et al., 2004). Data show that mass-transport deposits may be unstable in areas based on the presence of diapiric features (Fig. 6), and can provide weak layers for the development of seabed creep.

CONCLUSIONS

The floor of southern Orphan Basin records a history of mass-transport deposition throughout the Quaternary. Many source areas for seabed failure are apparent, but it is difficult to associate individual failure deposits on the basin floor with failure scars on the slope. During the Pleistocene, the distribution of mass-transport deposits shifted to the northwest and overall though the Quaternary deposits are thickest in the northern part of the study area. More data are required to provide better age control for the seismic stratigraphy and to accurately map the distribution of mass-transport deposits.

ACKNOWLEDGMENTS

This work was conducted under the Offshore Geohazards project of the Geological Survey of Canada Geoscience for Ocean Management Program and is a contribution to the Program for Energy R&D project 532211. This manuscript was improved through discussions with D.J.W. Piper and E.T. Tripsanas. C. Jauer provided time to depth conversion information for the Blue H-28 well. The author would like to thank the captain and crew of CCGS *Hudson* during expeditions 2003-033 and 2004-024.

REFERENCES

Campbell, D.C., Piper, D.J.W., Douglas, E.V., and Migeon, S.
2002: Surficial geology of Flemish Pass: assessment of hazards and constraints to development; Geological Survey of Canada, Open File 1454, 68 p.

Campbell, D.C., Shimeld, J.W., Mosher, D.C., and Piper, D.J.W.
2004: Relationships between sediment mass-failure modes and magnitudes in the evolution of the Scotian Slope, offshore Nova Scotia; *in* Proceedings of the 2004 Offshore Technology Conference, Houston, Texas, May 2004, Paper 16743, 14 p.

Gradstein, F.M. and Williams, G.L.
1986: Stratigraphy of the Labrador Sea and northern Grand Banks; *in* Geophysical Maps and Geological Sections of the Labrador Sea; Geological Survey of Canada, Paper 85-16, p. 7–8.

Hiscott, R.N. and Aksu, A.E.
1996: Quaternary sedimentary processes and budgets in Orphan Basin, southwestern Labrador Sea; Quaternary Research, v. 45, p. 160–175.

Hiscott, R.N., Aksu, A.E., Mudie, P.J., and Parsons, D.F.
2001: A 340,000 year record of ice rafting, palaeoclimatic fluctuations, and shelf-crossing glacial advances in the southwestern Labrador Sea; Global and Planetary Change, v. 28, p. 227–240.

Kennard, L., Schafer, C., and Carter, L.
1990: Late Cenozoic evolution of Sackville Spur: a sediment drift on the Newfoundland continental slope; Canadian Journal of Earth Sciences, v. 28, p. 863–878.

Mosher, D.C., Piper, D.J.W., Campbell, D.C., and Jenner, K.A.
2004: Near surface geology and sediment failure geohazards of the central Scotian Slope; AAPG Bulletin, v. 88, p. 703–723.

Nardin, T.R., Hein, F.J., Gorsline, D.S., and Edwards, B.D.
1979: A review of mass movement processes, sediment and acoustic characteristics, and contrasts in slope and base-of-slope systems versus canyon-fan-basin floor systems; *in* Geology of Continental Slopes, (ed.) L.J. Doyle and O.H. Pilkey; Society of Economic Paleontologists and Mineralogists, Special Publication, no. 27, p. 61–73.

Nygard, A., Sejrup, H.P., Haflidason, H., and King, E.L.
2002: Geometry and genesis of glacigenic debris flows on the North Sea Fan: TOBI imagery and deep-tow boomer evidence; Marine Geology, v. 188, p. 15–33.

Piper, D.J.W. and Campbell, D.C.
2005: Quaternary geology of Flemish Pass and its application to geohazard evaluation for hydrocarbon development; *in* Petroleum Resources and Reservoirs of the Grand Banks; Geological Association of Canada, Special Paper 43, p. 29–43.

Piper, D.J.W. and McCall, C.
2003: A synthesis of the distribution of submarine mass movements on the eastern Canadian margin; *in* Submarine Mass Movements and Their Consequences, (ed.) J. Locat and J. Mienert; Kluwer, Dordrecht, The Netherlands, p. 291–298.

Piper, D.J.W., Campbell, D.C., Loloi, M., and Mosher, D.C.
2004: Sediment instability in Orphan Basin, offshore eastern Canada; *in* Geo-Engineering for the Society and its Environment; 57th Canadian Geotechnical Conference and the 5th Joint Canadian Geotechnical Society–International Association of Hydrogeologists Conference, October 24–27, 2004.

Piper, D.J.W., Mosher, D.C., Gauley, B.J., Jenner, K., and Campbell, D.C.
2003: The chronology and recurrence of submarine mass movements on the continental slope off southeastern Canada; *in* Submarine Mass Movements and Their Consequences, (ed.) J. Locat and J. Mienert, Kluwer, Dordrecht, The Netherlands, p. 299–306.

Posamentier, H.W. and Kolla, V.
2003: Seismic geomorphology and stratigraphy of depositional elements in deep-water settings; Journal of Sedimentary Research, v. 73, p. 367–388.

Shipp, R.C., Nott, J.A., and Newlin, J.A.
2004: Physical characteristics and impact of mass transport complexes on deepwater jetted conductors and suction anchor piles; *in* Proceedings of the 2004 Offshore Technology Conference, Houston, Texas, May 2004, Paper 16751, 11 p.

Geological Survey of Canada Project X27 OM4100