SHALLOW TERTIARY SEISMOSTRATIGRAPHY AND ENGINEERING GEOLOGY OF THE NORTHEASTERN GRAND BANKS OF NEWFOUNDLAND

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ABSTRACT

The Tertiary sequence of the northeastern Grand Banks of Newfoundland comprises the potential foundation material for most future seabed structures. Recently collected shallow seismic reflection data, supplemented by limited borehole information, show the presence of a 750 sq. km delta within widespread Tertiary shelf units of unlithified, bedded, marine sandy silt-clay. The delta is partly truncated at the seafloor and may be a significant source for the formation and maintenance of sandy bedforms. A shallow fault and a channel infilled with material of probable Pleistocene age also occur within the Tertiary sediments. The elements of a geological framework to classify potential variations of seabed stability and engineering properties are Tertiary stratigraphy, deltas, channels, faults, unconformities, weathered crusts, and Quaternary glacial and sea-level history.

INTRODUCTION

The discovery of oil in commercial quantities at Hibernia in 1979 has brought the need for surficial geology information on northeastern Grand Bank into focus. Information concerning the nature of surficial sediments and the processes affecting their stability may be required to evaluate seabed conditions for the design and potential construction of oil production and transportation facilities.

An ongoing marine geological program by the Atlantic Geoscience Centre (AGC) provides a regional geological framework for studies of both Quaternary and surficial bedrock geology of the Grand Banks of Newfoundland and adjacent areas (King and MacLean, 1975; Fader and King, 1981; Fader et al., 1982; King et al., 1985; King and Fader, 1986; King et al., 1986; Fader and Miller, 1986a and b). Since 1980 much of the engineering-oriented study of the surficial geology of northeastern Grand Bank has concentrated on developing sediment facies models for the surficial sands and gravels (Barrie et al., 1984, 1986; Fader et al. 1985); quantitative evaluation of iceberg scouring (d'Apollonia and Lewis, 1981; 1986; Lewis and Barrie, 1981; Lewis and Parrott, 1987); and sediment transport processes (Barrie et al., 1986). These studies have proven that the Quaternary sediments on northeastern Grand Bank are discontinuous and thin (< 5 m). The underlying Tertiary sediments therefore constitute the foundation zone and would be required to support vertical stresses and to resist relatively large horizontal loads imposed by waves, currents, and ice on potential major structures which might be placed on the seabed. Thus it is appropriate to direct attention to the upper few hundred metres of Tertiary section beneath the seabed. The available information concerning this section is being compiled and new shallow seismic transects were collected across the shelf edge of northeastern Grand Bank in 1986 (Fig. 1)(Parrott and Lewis, 1986).

The deeper structure of the Tertiary section and tectonic elements of the underlying Jeanne d'Arc Basin have been studied in detail using deep reflection seismic data (Grant et al, 1986). While structures and features in the deeper section are expected to affect the shallow Tertiary sediments, resolution of the deep seismic data is insufficient for interpretation of details of the shallow seismostratigraphy.

In this report we present highlights of the new and related existing data for northeastern Grand Bank, and discuss the stratigraphy, structure and lithology of the surficial Tertiary sediments with respect to their potential zonation for seabed engineering properties.

REGIONAL SETTING

The surface of Grand Bank slopes gently, for example, with average gradients of about 1:1,000 - 1:1,500 to the northeast and east, from shallow water at Virgin Rocks and Eastern Shoals near the centre of the Bank to a gentle shelf break at about 100 m (Fig.1). Avalon Channel, locally up to 200 m deep, separates the Bank from Newfoundland. The surface of the Bank is veneered with thin deposits of sand and gravel. These deposits overlie, in places, glacial till or glaciomarine sediment on Cambrian to Devonian bedrock west of the (Hadrynian) Virgin Rocks (Fader, 1986; King et al., 1986; Durling et al, in press). To the south and southeast of Virgin Rocks, muddy sand and glacial sediments occur over Cretaceous-Tertiary bedrock (Fader, 1986; Fader and Miller, 1986b). To the northeast, thin to discontinuous sands and gravels directly overlie a prism of Cretaceous-Tertiary bedrock (Fader and King, 1981), which thickens to about 10 km in the oil-bearing Jeanne d'Arc Basin of northeastern Grand Bank (Jansa and Wade, 1975; Arthur et al., 1982).

PREVIOUS INVESTIGATIONS OF THE SHALLOW TERTIARY SECTION

Fader and King (1981) identified reflections, gently dipping to the east, on airgun seismic profiles from northeastern Grand Bank, and interpreted them as representing Tertiary sediments. The Tertiary reflections are truncated updip at an unconformity which is overlain by a thin discontinuous cover of Quaternary sediments. Fader and Miller (1986b) described the regional surficial geology of southeastern Grand Bank. Numerous infilled channels cutting Tertiary beds to depths of 300 m occur on the eastern margin of Grand Bank. However only one infilled channel (60 m deep) was then known on northeastern Grand Bank, about 55 km west of the Hibernia oil discovery (Vilks,1984; Fader and Miller, 1986b). Fader and Miller (1986b) also note widespread wedge-shaped zones of clinoform reflections (interpreted as bodies of prograded sediment) between major parallel reflections on seismic records of the Tertiary section across southeastern Grand Bank. An additional body of Tertiary prograded sediment is interpreted in the vicinity of the Terra Nova wellsite (site K-18 on Fig. 1) southeast of Hibernia (G.B. Fader, personal communication, 1986).

Between 1979 and 1984 seven boreholes (Fig. 1) were completed by Mobil Oil Canada Ltd. and Petro Canada. These boreholes were sampled at selected depths up to 130 m below seabed. Additional short boreholes (not shown) were made for Mobil Oil Canada Ltd. on the northern margin of Grand Bank and between Hibernia and the southern coast of Newfoundland. Reports by Barrie et al. (1983) and Collins and Christian (1984), and Geocon (1980a,b,c) carry logs of the borehole lithologies. Bujak

(1981) and Periera (1984) determined, on the basis of dinoflagellate and foraminiferal evidence respectively, that boreholes in the Hibernia area penetrated sediments of Late Tertiary (Pliocene) age. Clay mineral, lithic and textural information from the borehole samples are reported and interpreted by Segall et al. (1986). Silt and clay strata of probable Tertiary age were also observed beneath surficial sands by submersible investigations at the Hibernia B-08 site and in an iceberg pit (at E on Fig. 1) 11 km to the east (Barrie et al., 1986).

Clay mineral indicators (Segall et al.,1985; Segall et al., 1986; Segall et al., in press) from the Hibernia borehole samples and selected vibrocores (Barrie et al., 1986) document a zone of subaerial weathering of the Tertiary surface beneath Quaternary sediments, indicated by an increase in kaolinite content. This zone is interpreted to be a desiccated crust (Segall et al., 1985), associated with relatively high seismic velocity (Hunter et al., 1981) and high sediment strength, indicated by difficult borehole penetration (Geocon 1980a,b,c).

FIELD INVESTIGATIONS

In July 1986, a total of 760 km of high quality airgun (168 cu cm) sections were obtained on the northeastern Grand Bank shelf-edge area. Data were collected with a 7.6 m single channel streamer, and bandpass-filtered at 80 to 900 Hz before display (Parrott and Lewis, 1986). These data provide a composite regional downdip transect from 70 to 130 m water depth through 7 industry boreholes (Fig. 1 , A to F).

A short 30-cm sample of channel fill was recovered at the 2.8 km position in Fig. 3 using a hollow stem auger coring device (Capps and Ross, 1986). Two short core samples of probable Tertiary sediment (dark grey silty sand) were recovered at the base of the surface Quaternary sands in vibrocores at locations between C and D (Fig. 1).

CHARACTERISTICS OF THE SHELF-EDGE SECTION

Seismostratigraphy

Four distinct types of reflection structure characterize the shallow airgun seismic sections through the Hibernia area. These features are (1) parallel reflections, (2) clinoform reflections, (3) vertically displaced reflections and (4) channel structures.

(1) Parallel reflections. The seismic sections (Figs. 2 and 3) generally exhibit a succession of medium to high amplitude continuous parallel reflections which generally dip eastward at less than 0.5 degrees. Slight divergence to the east characterizes some intervals between reflections. Fader and King (1981) report dips of 1 to 2 degrees, however our calculations

show their reflections (in the airgun profile of their Fig. 9.4) to be dipping at angles similar to reflections in Figs. 2 and 3, between 0.2 and 0.5 degrees to the the east. A seismic velocity of 1.5 km/s was assumed for the calculations.

(2) Clinoform reflections. A relatively thin wedge of strata, from 2 to 16 km along the profile of Fig. 2, constitutes the uppermost Tertiary unit and is characterized by cross-unit (clinoform) reflections. The unit thickens eastward, from 30 m at W1A, 40 m at C1A to 44 m at E1A in Fig. 2. These are minimum thicknesses based on an assumed seismic velocity of 1.5 km/s. The internal reflections are low amplitude s-shaped (sigmoid) at the eastern end of the unit, but become straighter and more oblique towards the western end. The upper surface of this unit is truncated by the Tertiary-Quaternary unconformity.

(3) Vertically displaced reflections. A near-vertical zone of disruption, below 250 m at 2.3 km in Fig. 2, breaks the continuity of continuous, coherent, high-intensity, parallel reflections. The parallel reflections are turned up on the downdip (eastern) side of the disruption zone. The degree to which the relections are turned up tends to decrease higher in the section, suggesting that the disruption was contemporaneous with emplacement of the parallel reflectors. The parallel reflections are slightly bent above the zone of disruption.

(4) Channel structure. A 5.6-km-wide zone disrupts the Tertiary sequence of parallel reflections to about 120 m below seabed at the upper end of the shelf-edge transect (Fig. 3). A network of seismic lines revealed that the zone of disruption trends northwest-southeast. The apparent width on Fig. 3 is 6 km as the seismic section cuts obliquely across the feature. The channel fill exhibits a complex sequence of reflections. A unit, 10 to 30 m thick, of incoherent chaotic and hyperbolic reflections occurs at the base under at least two sequences with conformable, continuous reflections. A phase inversion, evidenced by reflections with a single seismic event, instead of the usual two, occurs within the fill between 4.5 and 5.5 km at about 100 m (150 ms) depth (Fig. 3).

Lithology

Borehole samples (Barrie et al., 1983; Segall et al., 1986) and submersible observations of an iceberg pit and a glory hole at locations E and B-08 on Fig. 1 (Barrie et al., 1986) indicate that the sediments beneath the surficial sands and gravels in the transect area are typically unlithified, composed of semiconsolidated, bedded sandy silt and clay beneath a weathered crust.

Boreholes through the uppermost seismic unit with clinoform reflections (Fig. 2) document a near continuous sequence of sands that are 40 m, 60 m, and 66 m thick at locations W1A, C1A, and E1A respectively (Segall et al., 1986). As this sequence thickens eastward it contains a greater proportion of silt and clay (Barrie et al., 1983). This unit overlies a sequence of silt and clay more typical of sediments in the general transect area.

The upper few metres of sediments filling the channel structure of Figure 3 are dominantly sandy silt and clay beneath a surface veneer of sand (Barrie et al., 1983; G.B. Fader, personal communication, 1986).

Biostratigraphy

Biostratigraphic study in the area is limited to a few determinations of microfaunal assemblages at selected levels in core and borehole samples. A Pliocene age was obtained using dinoflagellate cysts from silt and clay beds within the Hibernia O-35, B-08, and Ben Nevis I-45 boreholes (Bujak, 1981). These Pliocene beds are correlative with the base of the clinoform structure in Fig. 2. A similar but less precise age (Middle to Late Tertiary) is interpreted by Pereira (1984) on the basis of forams for the silt and clay beds beneath the clinoform structure in Fig. 2 (site W1A). The sands of the clinoform structure were sampled sparsely and appeared to be mostly barren of foraminifera. Age determinations for foraminiferal assemblages in the uppermost infilling sediments of the channel structure (Fig. 3) are preliminary and imprecise at present, ranging from Plio-Pleistocene (Pereira, 1984) to Late Quaternary (G. Vilks, personal communication, 1986). A palynological examination suggests a Pleistocene age for the uppermost channel-fill sediments (Bujak, 1986).

Interpretation

Continuous, coherent, gently-dipping parallel reflections are the dominant characteristic of seismic profiles in the transect area, and appear to represent widespread units of bedded marine silt-clay of Tertiary age, deposited offshore on the shelf.

Clinoform reflections indicate that the uppermost wedge-shaped unit, from 2 to 16 km in Fig. 2, was formed by depositional progradation. Considering its position on the shelf and its sandy lithology, it is interpreted as a delta in keeping with criteria discussed in Sheriff (1980), Payton (1977), Sangree and Widmier (1979), and Berg (1982). We propose to informally designate this progradational feature the Hibernia Delta, as it constitutes the foundation for a planned gravity-based oil production facility at the Hibernia oilfield (Long et al., 1986; Thompson et al., 1986). The area of this delta is approximately 750 sq. km. Prodelta sediments grade downdip into shallow marine sediments characterized by parallel reflections. Three stratigraphic units are tentatively defined in the Hibernia region; an upper unit of parallel reflections, a progradational unit with clinoform reflections, and a lower unit of parallel reflections. Additional prograding sequences were identified north of Hibernia, and other probable deltas are known south of Hibernia adjacent to the southeastern margin of Grand Bank (Fader and Miller, 1986b).

Offsets in the parallel reflections shown in Fig. 2 at 2.3 km are interpreted as a near-vertical growth fault, because of the upturned reflections on the downthrown side (eastward). This fault occurs near the western edge of the Hibernia field and appears to be an upward extension (to within 110 m of the seabed) of faults at the margin of the Jeanne d'Arc Basin. This fault has also been identified on multi-channel seismic data collected as part of a site survey through the Hibernia P-15 site (Geomarine Associates Ltd., 1979). It can be traced on these records from depths of about 3 to 4 km, to about 300 m below the seafloor. The single channel seismic data enable detection of this fault to within 110 m of the seafloor. Movement on this fault appears to have slowed in the Late Tertiary as shown by the continuity of the uppermost parallel reflections above the fault zone; a barely perceptible inflection in these reflections over the fault suggests slight subsequent adjustment.

A 5.6-km wide zone of disruption in the characteristic parallel reflections of the Tertiary bedrock is interpreted as a buried erosional channel that trends northwest-southeast at the upper end of the shelf-edge transect. The Late Tertiary bedrock has been eroded to a depth of about 120 m below seabed and infilled with a complex stratified sequence over a non-stratified basal deposit containing point reflectors, possibly a coarse gravel sediment or diamict. The upper fill, as determined by sampling, is a sandy silt-clay. In places the fill probably contains sharp discontinuities in physical properties, such as sand over clay strata, evidenced by a phase inverted reflection. Fader and Miller (1986b) have interpreted this channel to be infilled with glaciomarine sediments based on the presence of continuous coherent reflections with conformable structural style on the seismic reflection profiles. The channeling is probably Pliocene or younger in age; the age of the fill, though probably Pleistocene, is imprecisely known.

DISCUSSION

The large progradational unit located on the shelf at Hibernia, is interpreted to be a delta representing shallow-water deposition. The Hibernia delta is composed of sand and overlies fine-grained deeper-water sediments of Pliocene age. This sequence of coarse, shallow-water sediments over fine-grained deeper-water sediments indicates an episode of relatively low sea level following periods of higher relative sea level in the Late Tertiary. The evidence for a Pliocene lowstand (delta) on Grand

Bank presented here broadly agrees with the Vail and Mitchum (1979) prediction, based on global seismostratigraphic concepts of relative sea level history, of a Late Pliocene-Early Pleistocene lowstand following an Early to Middle Pliocene highstand.

The existence of a Pliocene delta at Hibernia is in broad agreement also with inferences of Pliocene sea levels based on the stratigraphy of continental slope sediments on the eastern Canadian continental margin (Piper et al, in press; Piper and Sparkes, 1986). The onset of valley cutting on the flanks of Flemish Pass, implying fluvial sediment transport across Grand Bank, in early Late Pliocene time may correlate with the Hibernia delta.

The Hibernia Delta, apparently a massive sand body within a sequence of fine-grained sediments, is truncated in part by an unconformity at or near the present seabed. This deposit was probably eroded by glaciers, marine transgression and by iceberg scouring, and may be an important sediment source for sandy bedforms on the present seabottom. Barrie et al (1986) show by mineralogical and lithic analyses that the Late Quaternary-Holocene sands in the Hibernia region are mostly derived from Cretaceous and Tertiary (local) sources.

The relative scarcity of channels on the northeastern portion of Grand Bank, compared to other parts of the Bank (Fader and Miller, 1986b), may signify that this area was protected from erosion in the Late Tertiary and Quaternary. One possibility is that the area supported an ice sheet for parts of Quaternary time. Such a speculation is consistent with the presence of boulders and sediments of presumed glacial origin (Fader and Miller, 1986b) and the evidence of strong semi-consolidated sediments both at Hibernia (Long et al.,1986) and at the large infilled channel west of Hibernia (M.P. Segall, personal communication, 1986). The presence of an ice sheet in the middle Pleistocene would correlate with the onset of till deposition on the upper slope of Flemish Pass, recognized from seismic evidence by Piper and Sparkes (1986).

Long et al (1986) suggest glacial loading, repeated wave loading, weathering during subaerial exposure and removal of overburden as plausible causes of overconsolidation, indicated by high cone-penetrometer point resistance and high undrained shear strengths in the top 20 m of sediments at Hibernia. Segall et al (in press) and Segall (1986) interpret subaerial weathering on the surface of the Tertiary-Quaternary unconformity in the Hibernia region on the basis of clay mineral analysis and suggest that the weathering appears to have developed a relatively strong desiccated crust. The areal limits of weathering, controlled by Quaternary low sea levels and the type of weathering developed within other substrates (e.g. shallow marine Tertiary sediment and channel fills), remain to be evaluated.

The discovery of a growth fault in the shallow subsurface raises scientific questions concerning the roles such faults may play as conduits for gas or liquid migration, or in future seabed settlement, or in response to dynamic loads of wave or earthquake stress. Shallow structural features appear to be related to deeper seated aspects of basin adjustment, a potential relationship that should be investigated more thoroughly.

Our present knowledge of the upper few hundred metres of the Tertiary section indicates several geological features that may influence sediment strength. The distribution of these features could form criteria for a zonation of the potential variability of physical properties affecting stability in the foundation zone of northeastern Grand Bank. Knowledge of regional geological development helps explain spatial variations in physical properties and increases confidence in their areal correlation. The chief elements for such a classification appear to be 1) the stratigraphy and structural features of Tertiary shallow marine sediments, 2) the presence of deltaic and channel fill sediments 3) the presence of unconformities and types of weathered crusts, and 4) the influence of Quaternary history, particularly the effects of relative low sea level and possible ice loading.

CONCLUSIONS

A review of shallow seismic reflection profiles and sample data from northeastern Grand Bank shows the subbottom to be dominated by parallel continuous reflections interpreted as shallow marine mud-rich sediment. This sequence contains progradational clinoform reflections interpreted as deltaic sediments. One such sequence, a major delta of probable Pliocene age, underlies the planned Hibernia production site. It is proposed that this feature be informally designated the Hibernia Delta.

Structural disturbances such as growth faults and flexures are present in the shallow subseabed section and appear to be related to deeper-seated phenomena.

Although channels are generally rare, one major channel, trending northwest-southeast on northeastern Grand Bank, does exist and is interpreted to be infilled with Pleistocene sediments.

The discovery of specific sea-level indicators (deltas) in the sedimentary section facilitates comparison of Late Cenozoic sea levels on the eastern Canadian margin, for example, with those by Piper et al. (in press.) from evidence of valley cutting on the continental slope, and with those predicted by the Vail and Mitchum (1979) concepts of relative sea level change based on global seismostratigraphy. The Pliocene delta at Hibernia broadly agrees with a prediction of a Late Pliocene lowstand.

The Hibernia Delta is partly truncated at the present seabed and may be a significant source of sand for the formation and maintenance of bedforms on the present ocean floor.

A preliminary framework for classifying seabed stability and engineering properties will be based on 1) stratigraphy and structure of Tertiary marine sediment, 2) deltaic and channel fill sediment properties, 3) unconformities and weathered crusts, and 4) the influence of Quaternary glacial and sea level history.

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REFERENCES

Arthur, K.R., Cole, D.R., Henderson, G.G.L., and Kushnir, D.W.
1982: Geology of the Hibernia discovery area; in Halbouty, M.T. (ed.) : The deliberate search for the subtle trap; American Association of Petroleum Geologists, Tulsa Oklahoma, Memoir 32. p. 181-195.

Barrie, J.V., Collins, W.T., Woodworth-Lynas, C.M.T., and Christian, D.
1983: Geological Investigations from the Hibernia Borehole Program; C-CORE, Memorial University of Newfoundland. Contract Report for Geological Survey of Canada.

Barrie, J.V., Lewis,C.F.M., Fader, G.B. and King, L.H.
1984: Seabed processes on the northeastern Grand Banks of Newfoundland; modern reworking of relict sediments; Marine Geology, v. 57, p. 209-227.

Barrie, J.V., Collins, W.T.,Clark, J.I., Lewis, C.F.M., and Parrott D.R.
1986a: Submersible observations and origin of an iceberg pit on the Grand Banks of Newfoundland; in Current Research, Part A, Geological Survey of Canada, Paper 86-1A, p. 251-258.

Barrie, J.V., Collins, W.T., Segall, M.P., and Lewis, C.F.M.
1986b: Holocene development and sediment transport on the northeastern Grand Banks of Newfoundland; Contract Report, C-CORE, Memorial University of Newfoundland, Geological Survey of Canada Open File Report No. 1396. 155 p.

Berg, O.R.
1982: Seismic detection and evaluation of delta and turbidite sequences: their application to the exploration for subtle traps; in Halbouty, M.T. (ed.) : The deliberate search for the subtle trap; American Association of Petroleum Geologists, Tulsa Oklahoma, Memoir 32. p. 57-75.

Bujak, J.P.
1981: Palynological analysis of twelve "soil samples" from the Hibernia B-08, Hibernia O-35 and Ben Nevis I-45 well sites; Geological Survey of Canada, Report No. EPGS-PAL.12-81JPB, May 27, 1981. 3 p.

Bujak, J.P.
1986: Palynological analysis of two samples from the northeastern Grand Banks; Bujak Davies Group, Calgary, Alberta, Report no. 86-091, November, 1986. 3 p.

Capps, J.F. and Ross, D.I.
1986: Development and testing of a subsea electric auger drill (SEADRILL II); Proceedings 3RD. Canadian Conference on Marine Geotechnical Engineering, St. John's, Newfoundland, June 1986, p. 785-802.

Collins, W.T., and Christian, D.
1984: Petro-Canada Borehole Investigation; C-CORE, Memorial University of Newfoundland. Contract Report for Geological Survey of Canada.

d'Apollonia, S.J. and Lewis, C.F.M.
1981: Iceberg scour data maps for the Grand Banks of Newfoundland between 46 N and 48 N.; Geological Survey of Canada Open File Report 819. 13 p.

d'Apollonia, S.J. and Lewis, C.F.M.
1986: Numerical model for calculating spatial distribution and mean frequency of iceberg grounding events; in Lewis, C.F.M., D.R. Parrott, P.G. Simpkin, and J.T. Buckley (eds). 1986. Ice scour and seabed engineering: Environmental Studies Revolving Funds Report No. 049. Ottawa. p. 221-232.

Durling, P.W., Bell, J.S., and Fader, G.B.J.
----: The geological structure and distribution of Paleozoic rocks on the Avalon Platform, Offshore Newfoundland, Canada; Canadian Journal of Earth Sciences. In press.

Fader, G.B.J.
1986: Surficial and bedrock geology on the Grand Banks; Bedford Institute of Oceanography, BIO Review '85, p. 16-20.

Fader, G.B., and King, L.H.
1981: A reconnaissance survey of the surficial geology of the Grand Banks of Newfoundland; in Current Research, Part A, Geological Survey of Canada, Paper 81-1A, p. 45-56.

Fader, G.B., King, L.H., and Josenhans, H.W.
1982: Surficial geology of the Laurentian Channel and western Grand Banks of Newfoundland; Geological Survey of Canada, Paper 81-22. 37 p.

Fader, G.B., Lewis, C.F.M., Barrie, J.V., Parrott, D.R., Collins, W., Miller, R.O., and d'Apollonia, S.J.
1985: Quaternary Geology of the Hibernia Area of Northeast Grand Bank, Map 14968QG. Geological Survey of Canada Open File Report 1222.

Fader, G.B.J., and Miller, R.O.
1986a: Regional geological constraints to resource development - Grand Banks of Newfoundland; Proceedings 3RD. Canadian Conference on Marine Geotechnical Engineering, St. John's, Newfoundland, June 1986, p. 3-40.

Fader, G.B.J., and Miller, R.O.
1986b: A reconnaissance of the surficial and shallow bedrock geology of the southeastern Grand Banks of Newfoundland; in Current Research, Part B, Geological Survey of Canada, Paper 86-1B, p. 591-604.

Geocon Offshore
1980a: Marine geotechnical investigation Hibernia O-35 step out well; Report V8458 A. Confidential report to Mobil Oil Canada Ltd. Nov., 1980.

Geocon Offshore
1980b: Marine geotechnical investigation Hibernia B-08 step out well; Report V8458 B. Confidential report to Mobil Oil Canada Ltd. Nov., 1980.

Geocon Offshore
1980c: Marine geotechnical investigation Ben Nevis I-45 wild cat well; Report V8458 C. Confidential report to Mobil Oil Canada Ltd. Nov., 1980.

Geomarine Associates Ltd.
1979: Well-site survey report, Chevron et al, Hibernia P-15; Contract report by Geomarine Associates Ltd. to Chevron Standard. Oct. 31, 1979. Canada Oil and Gas Lands Administration File No. 8626C4-3E.

Grant, A.C., McAlpine, K.D., and Wade, J.A.
1986: Offshore geology and petroleum potential of eastern Canada; Energy Exploration and Exploitation, v. 4, p. 5-52.

Hunter, J.A.M., Waboso, C., Burns, R., and Good, R.
1981: Seabottom seismic refraction experiment; in Lewis, C.F.M., 1981: Report on Cruise BIO No. 81-012 CSS Baffin, May 22-28, 1981; Bedford Institute of Oceanography, Internal Report. Dartmouth, N.S. 24 p.

Jansa, L.F. and Wade, J.A.
1975: Geology of the continental margin off Nova Scotia and Newfoundland; in van der Linden, W.J.M., and Wade, J.A.(eds.), Offshore Geology of Eastern Canada, Volume 2 - Regional Geology; Geological Survey of Canada Paper 74-30. p. 51-105.

King, L.H., and MacLean, B.
1975: Stratigraphic interpretation of the central Grand Banks from high resolution seismic reflection profiles; in van der Linden, W.J.M., and Wade, J.A. (eds.), Offshore Geology of Eastern Canada, Volume 2 - Regional Geology; Geological Survey of Canada Paper 74-30. p. 175-186.

King, L.H., Fader, G.B., Poole, W.H., and Wanless, R.K.
1985: Geological setting and age of the Flemish Cap granodiorite, east of the Grand Banks of Newfoundland; Canadian Journal of Earth Sciences, v. 22, no. 9, p. 1286-1292.

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

King, L.H., Fader, G.B.J., Jenkins, W.A.M., and King, E.L.
1986: Occurrence and regional geological setting of Paleozoic rocks on the Grand Banks of Newfoundland; Canadian Journal of Earth Sciences, v. 23, no. 4, p. 504-526.

Lewis, C.F.M., and Barrie, J.V.
1981: Geological evidence of iceberg groundings and related seafloor processes in the Hibernia discovery area of Grand Bank, Newfoundland. in Proceedings of the Symposium on Production and Transportation Systems for the Hibernia Discovery, W.E. Russell and D.B. Muggeridge (eds.), Newfoundland Petroleum Directorate, St. John's, Newfoundland, p. 146-177.

Lewis, C.F.M., and Parrott, D.R.
1987: Iceberg scouring rate studies, Grand Banks of Newfoundland; in Current Research, Part A, Geological Survey of Canada, Paper 87-1A. p. 825-833.

Long, L.C., Thompson, G.R., Brown, J.D., and Rivette, C.A.
1986: Hibernia site geotechnical characterization; Proceedings 3RD. Canadian Conference on Marine Geotechnical Engineering, St. John's, Newfoundland, June 1986, p. 99-116.

Parrott, D.R., and Lewis, C.F.M. (eds.).
1986: Cruise Report Hudson 86-018, Grand Banks of Newfoundland and Flemish Pass, July 2-14, 1986; Atlantic Geoscience Centre, Geological Survey of Canada Internal Report. Dartmouth.

Payton, C.E.(ed.)
1977: Seismic stratigraphy - applications to hydrocarbon exploration; American Association of Petroleum Geologists, Memoir 26, Tulsa, Oklahoma, 516 p.

Pereria, C.P.G.
1984: Micropalaeontological analysis of Hibernia and pipeline borehole samples; Contract report by C-CORE, Memorial University of Newfoundland for Geological Survey of Canada. 13 p.

Piper, D.J.W., and Sparkes, R.
1986: Shallow sediment instability in the central part of Flemish Pass, east of the Grand Banks of Newfoundland; Geological Survey of Canada Open File Report No. 1368. 28 p.

Piper, D.J.W., Normark, W.R., and Sparkes, R.
----: Late Cenozoic stratigraphy of the central Scotian Slope, eastern Canada; Bulletin of Canadian Petroleum Geology. In press.

Sangree, J.B., and Widmier, J.M.
1979: Interpretation of depositional facies from seismic data; Geophysics, vol. 44, No. 2, p. 131-160.

Segall, M.P., Barrie, J.V., Lewis, C.F.M., and Maher, M.L.J.
1985: Clay minerals across the Tertiary-Quaternary boundary, northeastern Grand Banks of Newfoundland: preliminary results; in Current Research, Part B, Geological Survey of Canada, Paper, 85-1B, p. 63-68.

Segall, M.P., Lewis, C.F.M., Barrie, J.V., and Maher, M.L.J.
1986: Geological and mineralogical interpretation of shallow sediments from the northeastern Grand Banks of Newfoundland; Contract report by C-CORE, Memorial University of Newfoundland for Geological Survey of Canada Open File Report No. 1439. 102 p.

Segall, M.P., Buckley, D.E., and Lewis, C.F.M.
----: Clay mineral indicators of geological and geochemical subaerial modification of near surface Tertiary sediments on the northeastern Grand Banks of Newfoundland; Canadian Journal of Earth Sciences. in press.

Sheriff, R.E.
1980: Seismic Stratigraphy; International Human Resources Development Corporation, Boston. 227 p.

Thompson, G.R., Foo, S.H.C., and Matlock, H.
1986: Hibernia GBS foundation behaviour; Proceedings 3RD. Canadian Conference on Marine Geotechnical Engineering, St. John's, Newfoundland, June 1986, p. 141-164.

Vail, P.R., and Mitchum Jr., R.M.
1979: Global cycles of relative changes of sea level from seismic stratigraphy; in Watkins, J.S., Montadert, L., and Dickerson, P.W. (eds), Geological and geophysical investigations of continental margins; American Association of Petroleum Geologists, Memoir 29, p. 469-472.

Vilks, G. (ed.)
1984: Report of Cruise No. 83033; Internal Report, Atlantic Geoscience Centre, Geological Survey of Canada, Bedford Institute of Oceanography, Dartmouth, 51p.

FIGURE CAPTIONS

Figure 1. Location of 1986 airgun seismic lines showing position of industry boreholes and shelf-edge transect AF described in text.

Figure 2. Seismic section and line drawing through delta and growth fault, G = ghost reflection, M = seabottom multiple reflection. Not all reflections are interpreted. E1A, C1A, and W1A indicate locations of selected boreholes projected onto seismic transect. Approximate depth scale assumes a seismic velocity of 1500 m/s.

Figure 3. Seismic section and line drawing of buried channel shown in Figure 1, G = ghost reflection, M = seabottom multiple reflection, I = inverted reflection. Not all reflections are interpreted. Approximate depth scale assumes a seismic velocity of 1500 m/s.

HU86-018 TRACK
SEISMOSTRATIGRAPHY

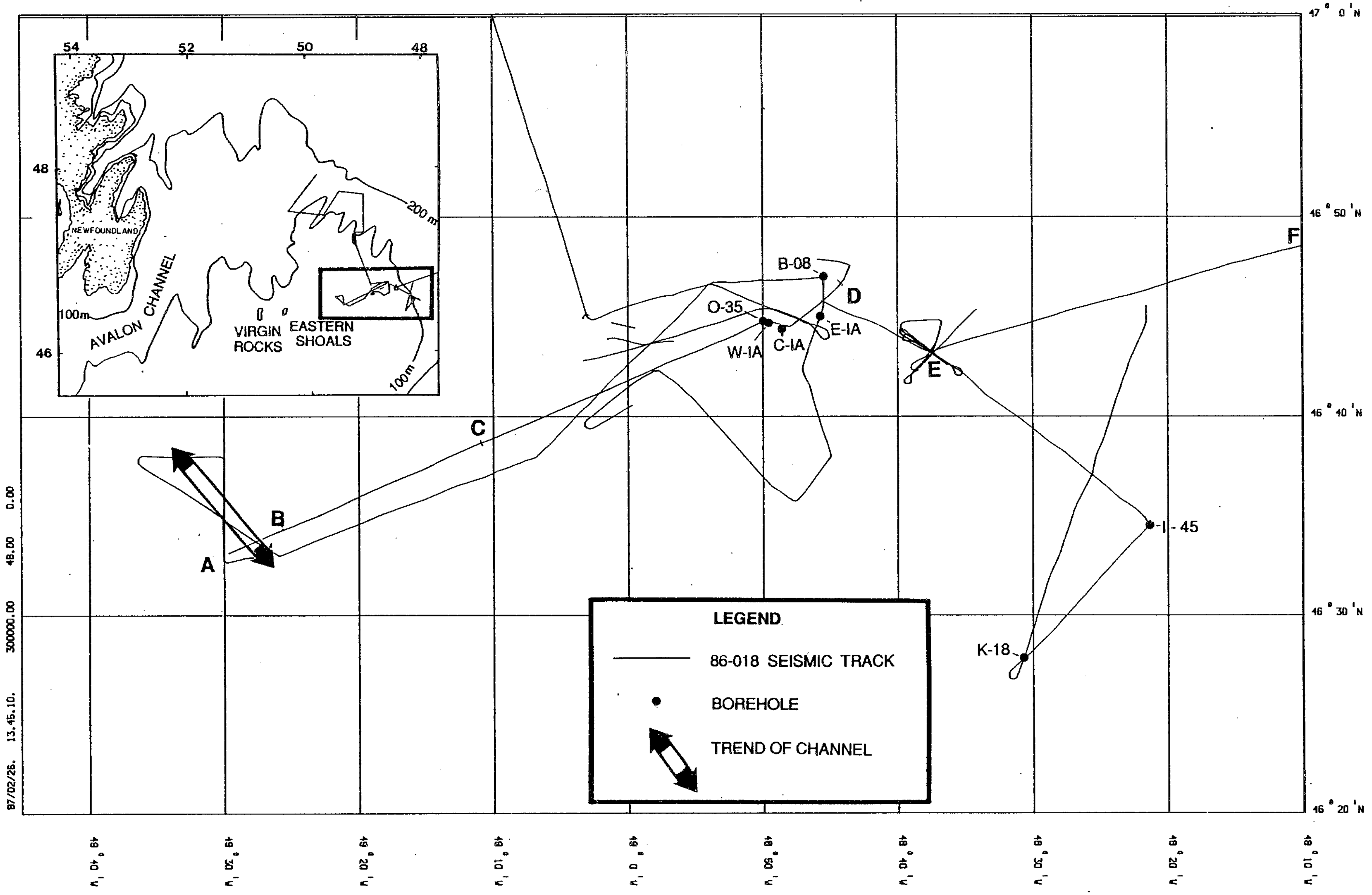

Figure 1

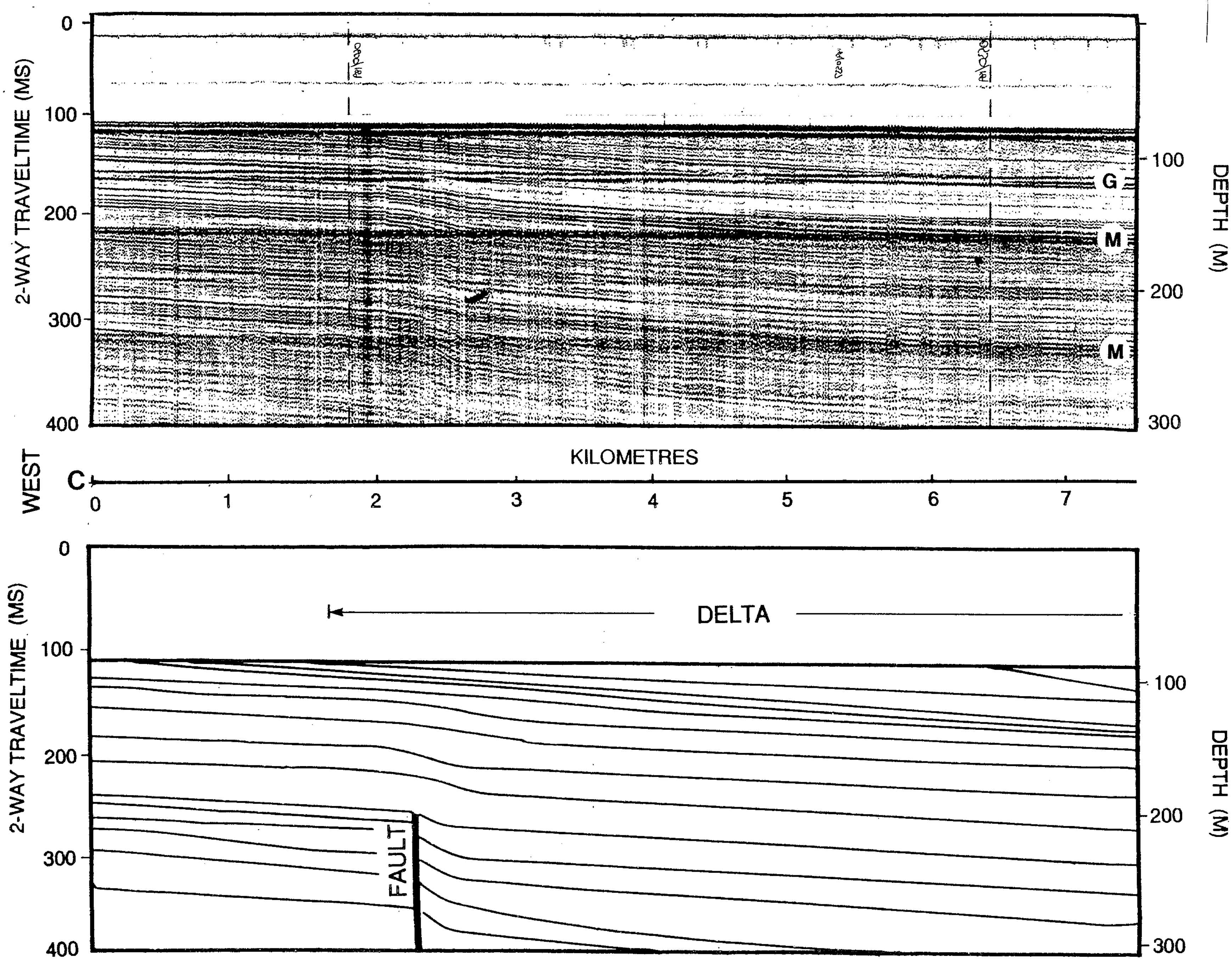
2-WAY TRAVELTIME (MS)
0
100
200
300
400
DEPTH (M)
100
200
300
G
M
M
KILOMETRES
WEST
C
0
1
2
3
4
5
6
7
2-WAY TRAVELTIME (MS)
0
100
200
300
400
DELTA
FAULT
DEPTH (M)
100
200
300

Figure 2

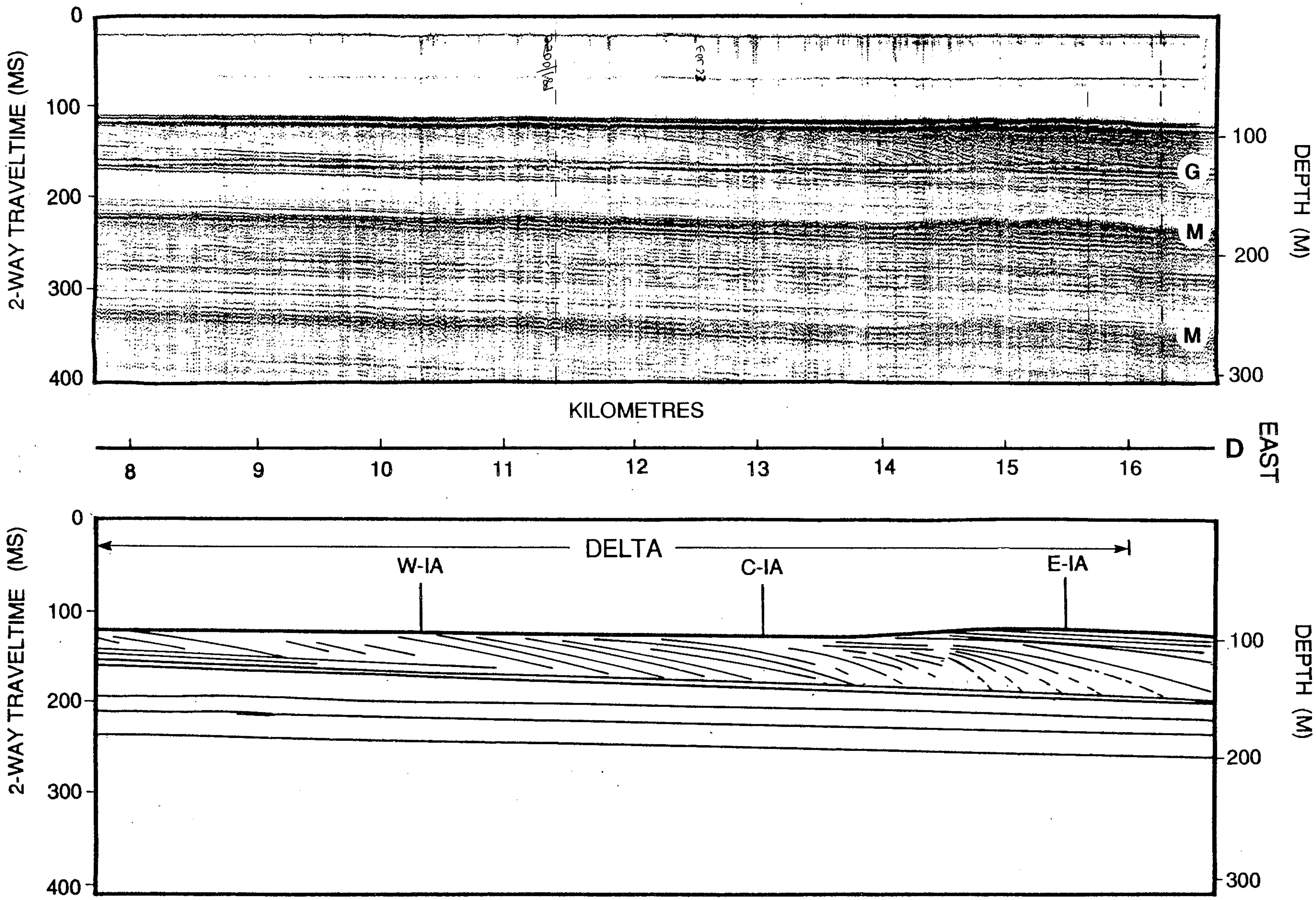

Figure 2 cont'd

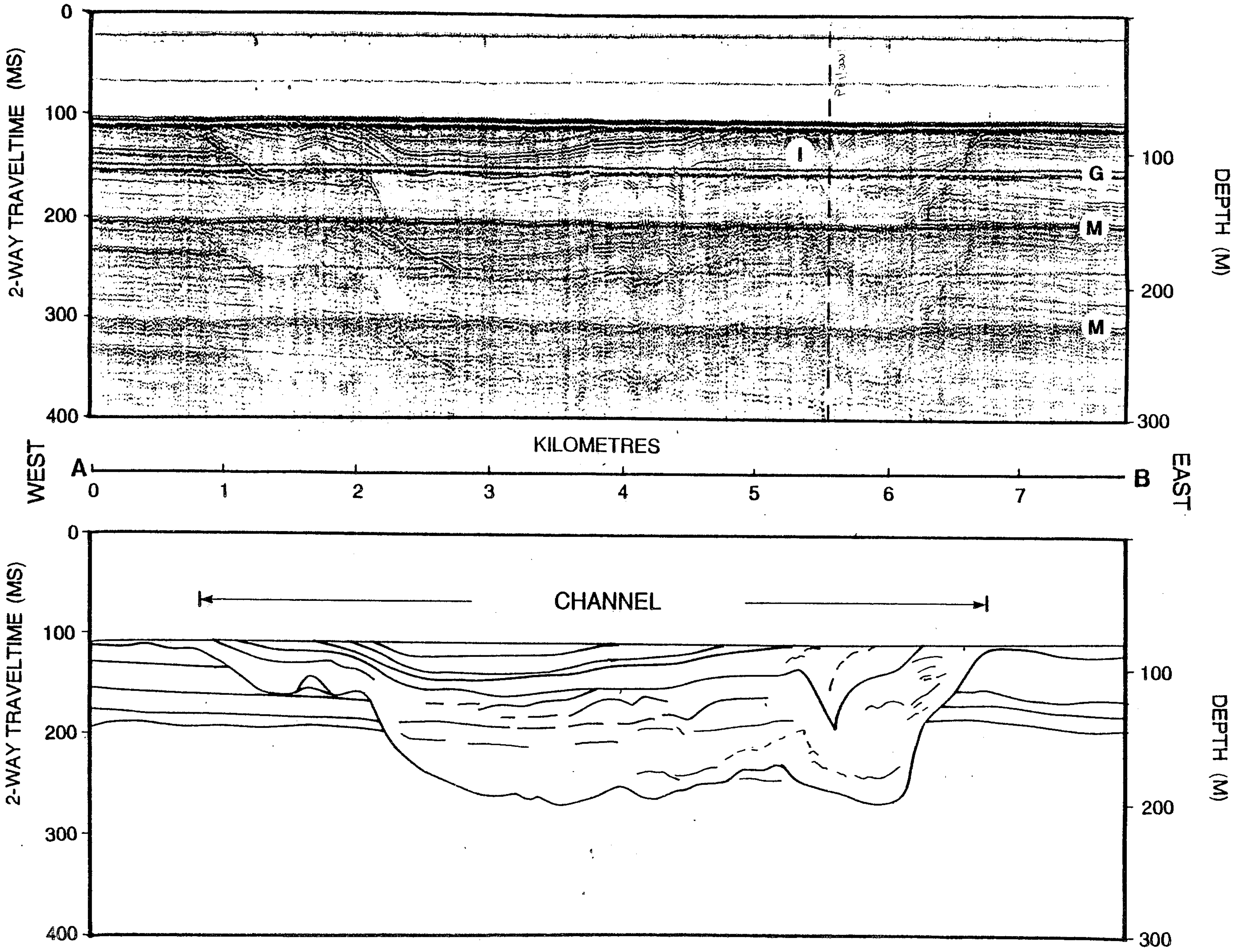
2-WAY TRAVELTIME (MS)
0
100
200
300
400
I
G
M
M
DEPTH (M)
100
200
300
KILOMETRES
WEST
A
0
1
2
3
4
5
6
7
B
EAST
2-WAY TRAVELTIME (MS)
0
100
200
300
400
CHANNEL
DEPTH (M)
100
200
300

Figure 3