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Die Schwere-Signatur einer breiten Quaternär-Ablagerungszone auf offener See in Südostkanada

Robert C. Courtney et David J.W. Piper

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Résumé de l'article

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THE GRAVITY SIGNATURE OF A LARGE QUATERNARY DEPOCENTRE OFF SOUTHEASTERN CANADA*

Robert C. COURTNEY and David J.W. PIPER, Geological Survey of Canada, Atlantic Geoscience Centre, Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, Nova Scotia B2Y 4A2.

ABSTRACT New bathymetry, gravity and Pliocene - Quaternary sediment isopach maps have been compiled and gridded for the Scotian margin. A large positive gravity anomaly exists over the Laurentian Fan, which is the major Pliocene - Quaternary depocentre on the Scotian margin. This gravity anomaly is not related to deep structure but can be largely explained by considering the Pliocene-Quaternary sediments as isostatically uncompensated. This implies that the underlying continental margin lithosphere has had considerable strength for at least 3 Ma. Some residual anomalies not accounted for by Pliocene-Quaternary sediment thickness may represent thicker Miocene depocentres, but improved seismic and stratigraphic data are required to assess this possibility. The technique of gravity identification of major sediment depocentres is a useful reconnaissance tool in certain circumstances, such as where there is a topographic expression and the deposit is thick and of major areal extent.

RÉSUMÉ *L'empreinte gravimétrique d'une zone de grande accumulation quaternaire sur la marge continentale du sud-est du Canada*. On a procédé à la compilation des cartes bathymétrique, de gravité marine et des cartes isopaques des sédiments pliocènes/quaternaires de la marge continentale de Scotian. Il existe une importante anomalie gravimétrique au-dessus du cône Laurentien, principale zone d'accumulation pliocène/quaternaire de la marge continentale de Scotian. L'anomalie gravimétrique n'est pas reliée à la tectonique de fond, mais peut en bonne partie s'expliquer si l'on considère que les sédiments pliocènes/quaternaires n'ont subi aucune compensation isostatique. Ceci implique que la lithosphère de la marge continentale sous-jacente offre une grande résistance depuis au moins 3 Ma. Certaines anomalies résiduelles non imputables à l'épaisseur de la couverture sédimentaire pliocène/quaternaire pourraient être attribuées aux épaisses zones d'accumulation du Miocène; de meilleures connaissances de la sismicité et de la stratigraphie sont nécessaires pour confirmer cette hypothèse. La technique permettant de déterminer la gravité des zones de grande accumulation est un bon outil de reconnaissance en certains cas, c'est-à-dire lorsqu'il y a un relief d'importance et que le dépôt est épais et d'une grande superficie.

ZUSAMMENFASSUNG *Die Schwere-Signatur einer breiten Quaternär-Ablagerungszone auf offener See in Südostkanada*. Neue Karten der Tiefseelotung, der Tiefsee-Schwere und "isopache" Karten der Pliozän/Quaternär-Sedimente wurden für den Kontinentalsaum von Nova Scotia kompiliert. Eine breite, positive Schwereanomalie besteht über dem laurentidischen Fächer, welcher die Hauptablagerungszone im Pliozän-Quaternär am Kontinentalsaum von Nova Scotia ist. Diese Schwereanomalie beruht nicht auf der Tiefenstruktur, sondern kann weitgehend dadurch erklärt werden, daß die Pliozän-Quaternär-Sedimente isostatisch nicht kompensiert waren. Dies bedeutet, daß die Erdkruste des darunterliegenden Kontinentalsaums seit mindestens 3 Ma eine beträchtliche Widerstandsfähigkeit aufweist. Einige Rest-Anomalien, die nicht auf die Dicke des Pliozän-Quaternär-Sediments zurückgeführt werden können, könnten mit dickeren Ablagerungszonen aus dem Miozän erklärt werden; doch um diese Möglichkeit zu bestätigen, sind verbesserte seismische und stratigraphische Messungen nötig. Die Technik, die Schwere von bedeutenden Sedimentablagerungs zonen zu bestimmen, ist unter bestimmten Voraussetzungen ein nützliches Erkennungs instrument, wie z.B. wenn ein wichtiges Relief vorhanden ist, und die Ablagerung dick und von größeren Ausmaßen ist.

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INTRODUCTION

It has long been recognised that the deep sea areas adjacent to the Pleistocene North American ice sheets contain thick sedimentary sequences derived from glacial denudation of the continent (White, 1972; Mathews, 1975). In general, the thick accumulations of sediment on the continental rise lack stratigraphic control from wells and it has proved difficult to trace seismic reflectors to dated Pliocene or Quaternary sections (Piper *et al.*, 1990). For these reasons, it is difficult to make precise estimates of sediment budgets (Piper, 1990).

One of the major Quaternary deep-water depocentres, the Laurentian Fan, has an associated positive gravity anomaly (Fig. 1 and 2). As the Pliocene-Quaternary chronologic control on the Laurentian Fan and Scotian Margin is better than elsewhere on the eastern Canadian margin, this presents an opportunity to evaluate the relationship between sediment accumulation and the gravity anomaly, to see if gravity could provide information on major accumulations of Quaternary sediments on the continental margin.

BATHYMETRIC AND GRAVITY DATA

Over the past thirty years, marine gravity and bathymetry measurements have been made on an ongoing basis by the Atlantic Geoscience Centre of the Geological Survey of Canada (Verhoef *et al.*, 1987). In excess of two million point estimates have been made over the east coast margin of Canada from the Gulf ol Maine to Davis Strait. Much effort has been spent to collate and edit these data, yielding a valuable, fundamental resource for studying geologic features on the northwest Atlantic passive margin.

These gravity and bathymetric data were numerically projected onto a Universal Transverse Mercator map sheet covering the study area and gridded at 10 km intervals using a cubic spline under tension (Smith and Wessel, 1990). The total study area covers 1280 km by 720 km (128x72 grid points). Estimates of gravity have an overall accuracy of ±2.5 mgals while bathymetric estimates are valid within 5%.

PLIOCENE — QUATERNARY SEDIMENTATION ON THE SCOTIAN MARGIN AND LAURENTIAN FAN

An extensive grid of seismic lines on the Scotian Slope and Rise and the Laurentian Fan (Fig. 1) can be used to map the regional distribution of sediments. Figures 3 and 4 show the probable distribution of Pliocene and Quaternary sediments. Sediments north of the salt diapir province on the central Scotian Slope can be dated using stratigraphic picks ranging from middle to latest Pliocene in the Acadia K-62 and Shubenacadie H-100 wells (Piper *et al.*, 1987) but this stratigraphy cannot be traced with confidence through the salt diapir province (Swift, 1987). Seismic markers recognised near the Acadia K-62 well can be correlated on the basis of reflector character to St. Pierre Slope (Piper and Normark, 1989), which in turn can be correlated in a general manner with the Laurentian Fan (Piper and Normark, 1989).

Uchupi and Austin (1979) recognised a regional reflector "L" on the Laurentian Fan (Fig. 4), which they suggested corresponded to the onset of turbidite sedimentation in the Pliocene or Quaternary (Table I). This reflector can be traced beneath the Sohm Abyssal Plain and across the Scotian Rise south of Sable Island (Ebinger and Tucholke, 1988). The onset of turbidite sedimentation occurred on the Sohm Abyssal Plain at the beginning of the Late Pliocene at DSDP site 382 (Tucholke, Vogt *et al.*, 1979). The reflector on the Scotian Rise has been correlated by Ebinger and Tucholke (1988) with the Late Pliocene (≈3-2 Ma) "Horizon Blue" on the United States margin (Mountain and Tucholke, 1985). Although the "L" reflector cannot be correlated far west of the Ebinger and Tucholke (1988) line because of pinchouts, their more easily followed Middle Miocene (MM) reflector provides

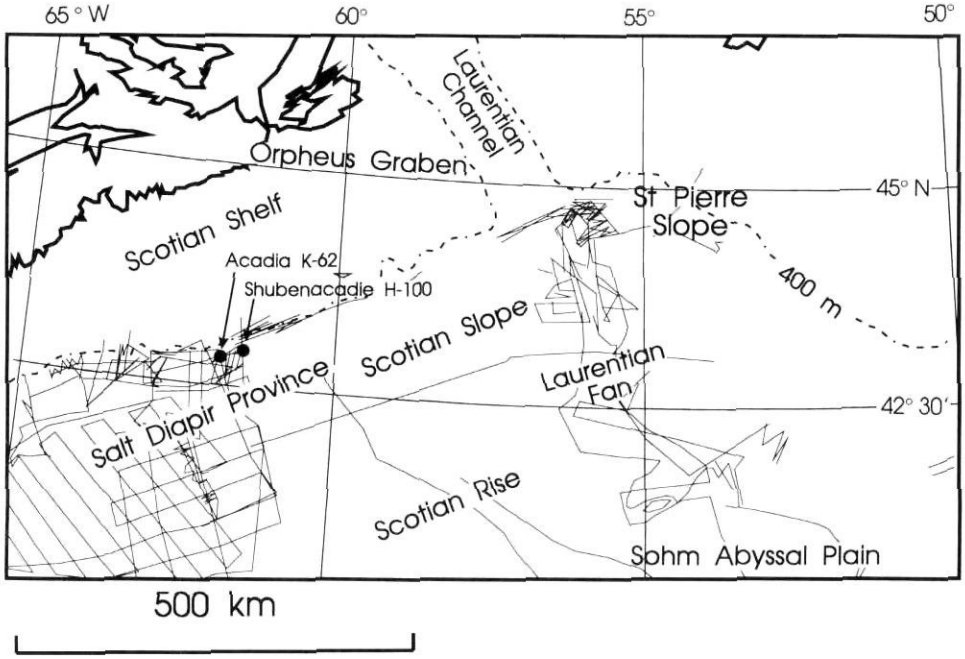

FIGURE 1. Map showing location of the detailed study area measuring 1280 km by 720 km, on the Scotian margin. The dashed line denotes the 400 m bathymetric contour, roughly delineating the shelf edge. Seismic lines used to control Pliocene-Quaternary sediment thicknesses presented in Figure 3 are shown as solid lines,

Carte illustrant la localisation de la région à l'étude de 1280 m sur 720 m sur la marge continentale de Scotian. Le tireté représente la courbe bathymétrique de 400 m, qui délimite grossièrement le rebord du plateau. Les tracés sismiques qui ont servi à déterminer l'épaisseur des sédiments pliocènes/quaternaires (fig. 3) sont représentés par des lignes continues.

some constraints on total Pliocene-Quaternary sediment accumulation.

A second regional reflector on the Laurentian Fan, termed A by Piper and Normark (1982), occurs about half-way between L and the seabed (Table I). Reflector "A" is likely of latest Pliocene age, based on correlation with sediments on the St. Pierre Slope and on a surface outcrop of shale a short distance below A that contains a Late Pliocene foraminiferal fauna (Piper and Normark, 1989).

Pliocene-Quaternary sediment thicknesses are generally less than 50 m on the continental shelf, except on the seaward side of the outer banks (Amos and Knoll, 1987; McLaren, 1988), where Pliocene markers have been encountered in some outer shelf wells (Gradstein and Agterberg, 1982). Glacial erosion features are in general less than 200 m deep; the major exception is the Laurentian Channel leading from the Gulf of St. Lawrence to shelf edge, where there may have been as much as 400 m of net erosion (King and MacLean, 1970). On many parts of the eastern Scotian Slope, continental slope progradation appears to have been approximately balanced by submarine canyon erosion.

Both on the central Scotian Slope and the Laurentian Fan, there is a marked change in sedimentation style within the Quaternary section. On the central Scotian Slope the upper half of the Quaternary section has been interpreted as proglacial from shelf-crossing glaciation, whereas the lower section represents more distal glaciomarine or deltaic sedimentation (Piper *et al.*, 1987; Mosher *et al.*, 1989). During the later

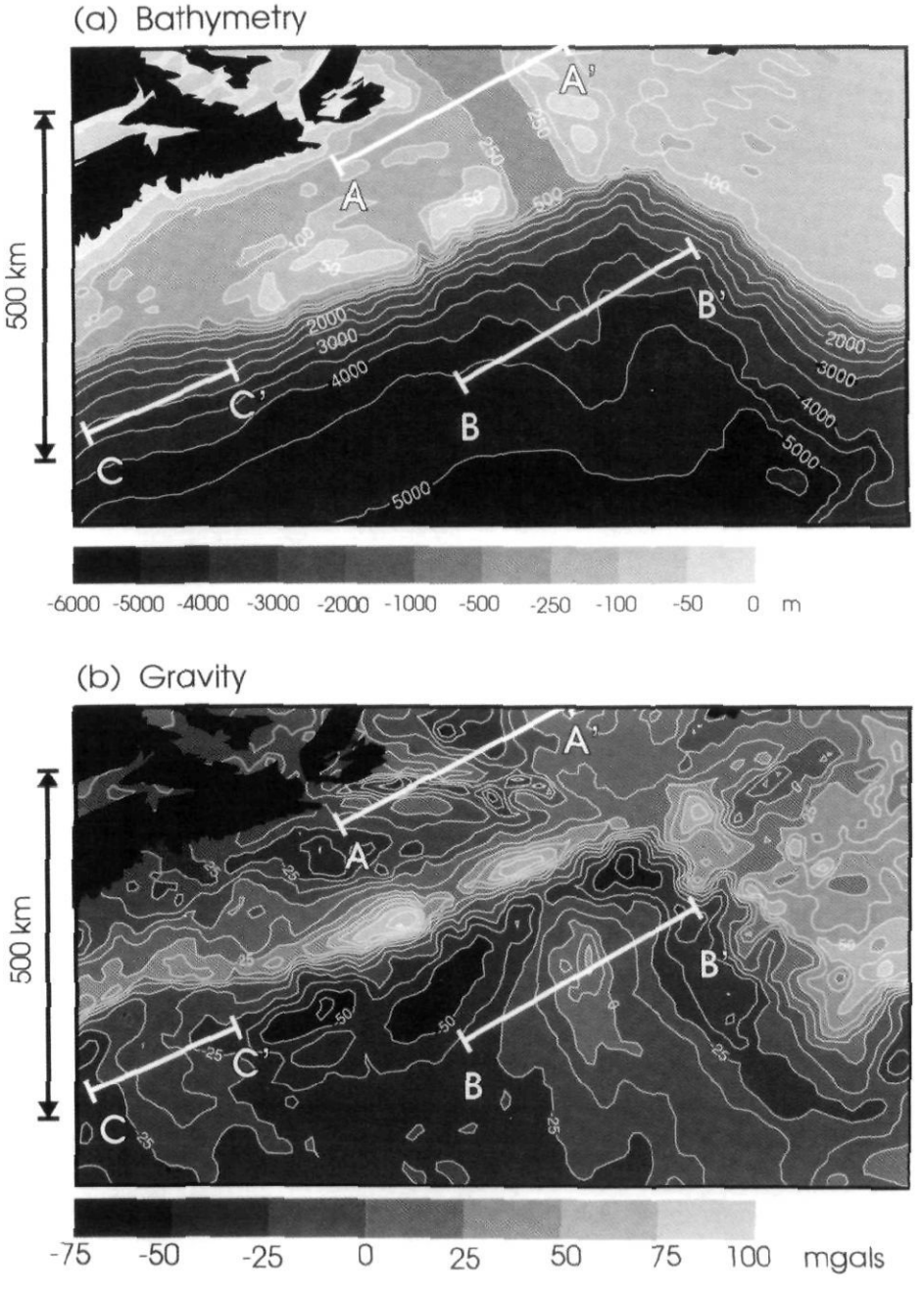

FIGURE 2. a) Bathymetry in metres calculated from the Atlantic Geoscience Centre database. Contour lines are drawn at every transition and midpoint in the grey scale bar. b) Observed free-air gravity anomaly on the Scotian margin deduced from ship measurements. Contour lines are drawn at 12.5 mgal intervals.

a) Bathymétrie (en m) calculée à partir de la banque de données du Centre géoscientifique de l'Atlantique. Les courbes sont tracées à chacun des points de transition et demi-transition de la gamme de gris en contre-bas. b) Anomalie gravitaire observée sur la marge continentale de Scotian à partir des mesures prises du navire. Les courbes sont tracées à intervalle de 12,5 mgal.

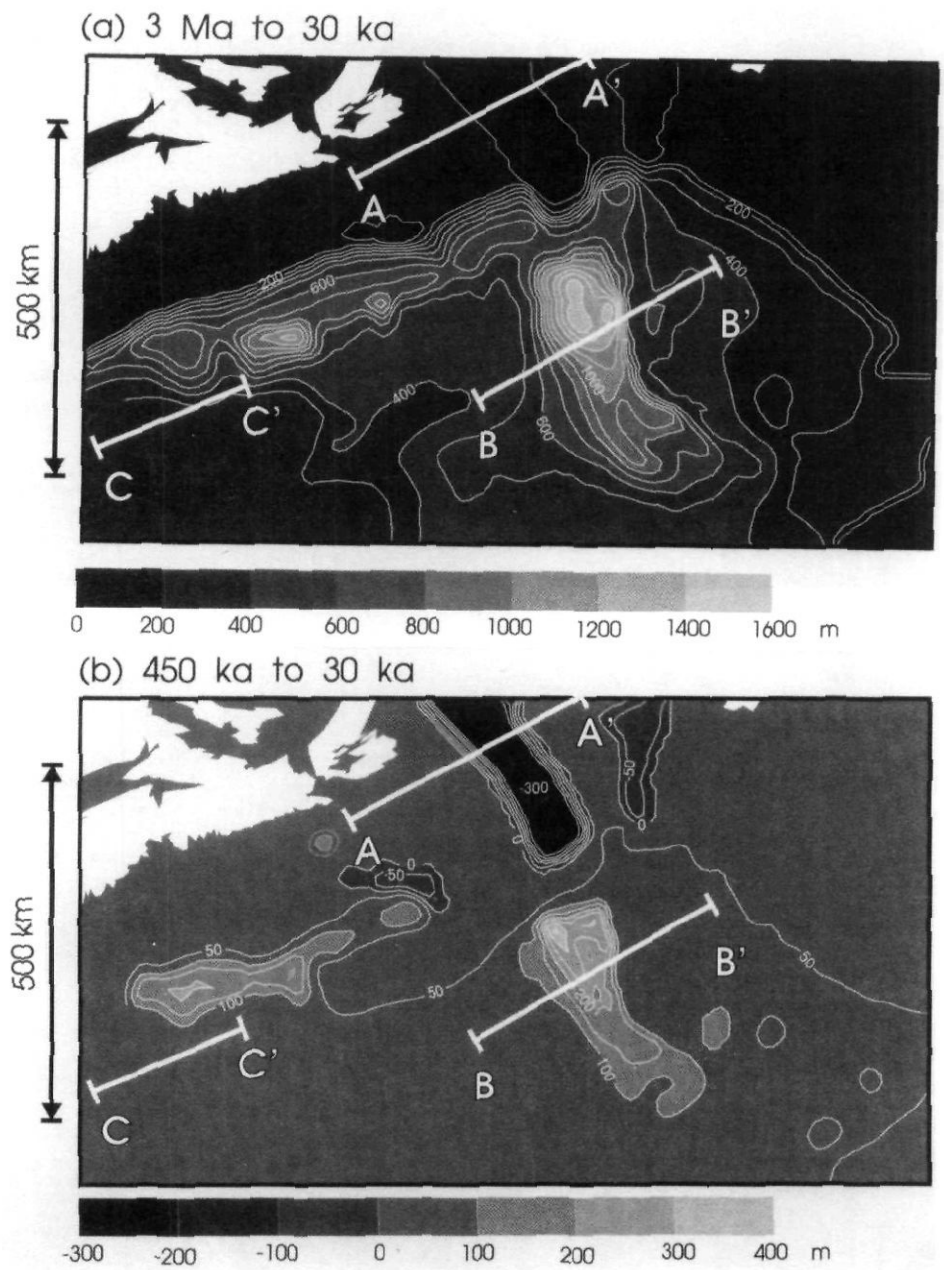

FIGURE 3. Gridded isopach maps of net deposition on the Scotian margin (a) for the period 3 Ma to 30 ka; (b) for the period 450 ka to 30 ka. Contours are at 100 m intervals.

Cartes isopaques de l'accumulation nette sur la marge continentale de Scotian: a) pour la période de 3 Ma à 30 ka: b) pour la période de 450 ka à 30 ka. Les courbes sont à intervalle de 100 m.

Quaternary, much of the Laurentian Fan experienced erosion or sediment bypassing: the onset of this erosion was correlated by Piper and Normark (1982) with the glacial excavation of the Laurentian Channel and the onset of shelf-crossing glaciation. Mosher *et al.* (1989) suggested that the first shelf crossing glaciation, producing the change in sedimentation style, dates from isotopic stage 6 (150 ka), the data of Alam *et al.* (1983) and Skene *et al.* (1991) however indicate that the most extreme glacial event recorded on the continental margin was in isotopic stage 12 (450 ka) and this chronology is adopted in this study (Fig. 3b).

Figure 3a shows gridded isopachs of sediment above the "L" reflector and its correlatives (Table I). Isopachs have been determined using almost all the seismic lines shown in Figure 1. It is difficult to put precise error limits on these isopachs, but a value of ± 40 m seems reasonable. The isopachs for the mid-to-late Quaternary (Fig. 3b) are less reliable, with error limits of ±70 m, because of the difficulty of regionally correlating reflectors and uncertainty as to whether major changes in sedimentation style are synchronous. A map was also prepared of sediment thicknesses for the last 30 ka: these thicknesses are generally substantially less than 100 m and would have little effect on gravity, so this map is not illustrated here.

GRAVITY MODELLING

SIGNIFICANT FEATURES OF THE GRAVITY FIELD

Many features of the gravity field (Fig. 2b) reflect tectonic boundaries and deep sedimentary basins associated with the

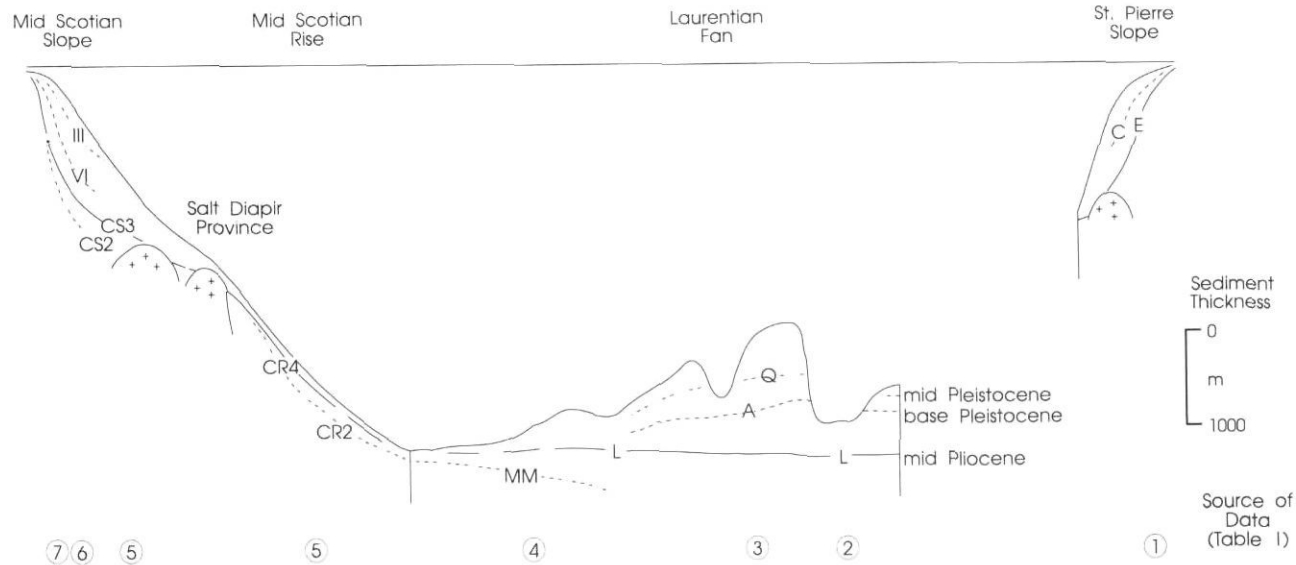

FIGURE 4. Schematic cross section of the continental margin off Nova Scotia showing thicknesses of late Cenozoic sediment and distribution of key reflectors. References to sources of data given in Table I.

Coupe schématique de la marge continentale au large de la Nouvelle-Écosse qui montre l'épaisseur des sédiments du Cénozoïque supérieur et la répartition des réflecteurs de référence. Les sources sont données au tableau I.

spreading of the Atlantic Ocean. For example, at about 45°N, between 55° and 60°W, a gravity anomaly reveals the Orpheus graben (see Fig. 1 for location and orientation), a sedimentary basin more than 6 km in depth (Loncarevic and Ewing, 1967). The shelf break is marked by a long linear positive anomaly of variable amplitude followed seaward by a matching negative anomaly; the magnitude is dependent on the steepness of the slope, the total depth of the sedimentary basin, and the rate of change in crustal thickness from continental to oceanic values (Keen *et al.*, 1990).

The gravity anomaly over the Laurentian Fan is equally pronounced and its relationship to Pliocene - Quaternary depositional patterns will be shown to be direct and causal. The zones of greatest thickness on the SE part of the fan, south of Profile B in Figure 3, correlate well with the gravity field, the maximum thickness being situated close to the maximum in the gravity anomaly. An understanding of this relationship, in conjunction with these regional data sets, could potentially be used to extend the knowledge of Quaternary and older sedimentation patterns over the entire east coast margin of Canada.

The positive correlation between the topographic effects of sedimentation and the gravity field can be seen clearly in profiles illustrated in Figure 5 across the Laurentian Channel (profile A, located on Fig. 2) and the Laurentian Fan (profile B). The Laurentian Channel was formed by the net erosion of up to 400 m of the shelf; its bathymetric anomaly correlates with a gravity low of −30 mgal. The Laurentian Fan rises over 1000 m above the regional depth of the continental rise in profile B. A large gravity anomaly of up to 60 mgals echoes clearly the two depositional levees seen in the peaks of the bathymetric data.

The effects of recent sedimentation are superimposed on a regional gravity field of deeper tectonic origin. For example, the gravity anomaly of the upper crustal Orpheus Graben, which dominates the gravity field on the left hand side of profile A, lacks a corresponding bathymetric signature. The correspondence between gravity and bathymetry is not always direct and a good knowledge of the regional tectonic framework is needed to understand the relationship .

INTERPRETATION OF GRAVITY ANOMALIES

The interpretation of gravity data is predicated on certain physical assumptions as, in the strictest sense, the inversion of gravity data to yield spatial mass distributions is non-unique. Uniqueness may be forced if a model structure is specified; in this case we assume that the Quaternary sediments lie on a pre-existing basin of sediment, underlain by crust and mantle below, each unit with a prescribed thickness and density.

The most important assumption is that of the state of isostasy (Turcotte and Schubert, 1982). If the load of recent sedimentation is locally (or Airy) compensated within the lithosphere (Fig. 6), then the topographic expression, t, of the load is compensated by a deformation, r, of the base of the sedimentary section and, also, of the interface of the crust and underlying mantle. In this mode, the sediments displace their weight in the mantle much as a cork or iceberg would float in water. Generally this assumption is valid for large loads with representative wavelengths of hundreds of kilometres.

The relationship between the height of the topography and the compensating root is determined by the relative density differences between the sediments, ρ_s, and the mantle, ρ_m, with respect to the density of water, ρ_w,:

$$r = \frac{(\rho_s - \rho_w)}{(\rho_m - \rho_w)} 1; 1 = t + r \qquad (1)$$

TABLE I

Summary of assumed ages of seismic reflectors used to compile isopach maps

Area and reference	Reflector assigned to specified age			
	30 ka	450 ka	1.6 Ma	2.5-3.0 Ma
St. Pierre Slope				
(1) Piper and Normark, 1989		?B	C	E
Laurentian Fan				
(2) Uchupi and Austin, 1979				L
(3) Piper and Normark, 1982		?Q	A	R
Sohm Abyssal Plain				
(4) Ebinger and Tucholke, 1988				L
Mid Scotian Rise				
(5) Swift, 1987				CR4
Mid Scotian Slope				
(5) Swift, 1987				CS3
(6) Mosher *et al.*, 1989		III	VI	
(7) Piper and Sparkes, 1989		?"mid-Quat."		"mid-Pliocene"
Sable Island Bank	base seq 1	?Glacial Quat.		
McLaren, 1988	R_1	R_3		
Boyd *et al.*, 1988				
Banquereau		?Total Quat.		
Amos and Knoll, 1987	R_2	R_3		

Note: reflector names are those used in the original publications cited

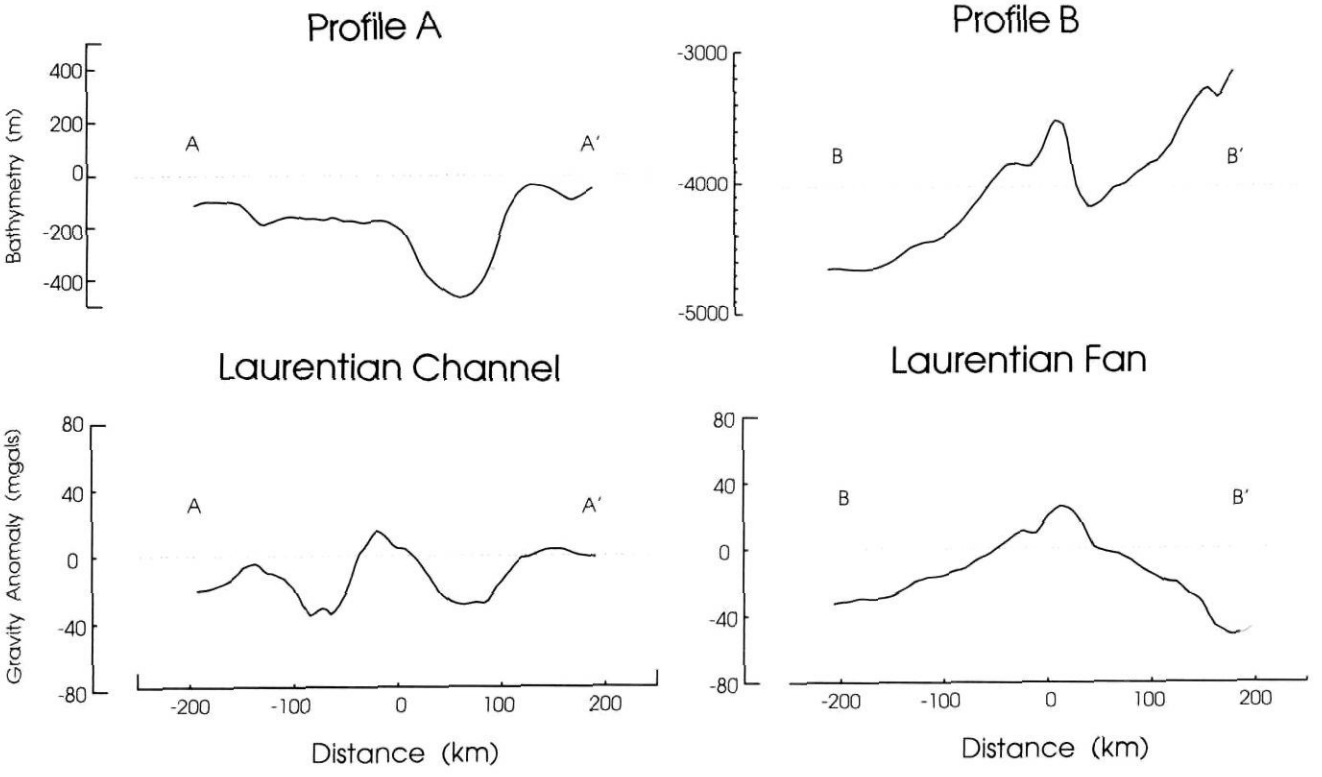

FIGURE 5. Profiles of gravity and bathymetry along lines A and B shown in Figure 2a and b.

Profils de la gravité et de la bathymétrie le long des lignes A et B montrées à la figure 2.

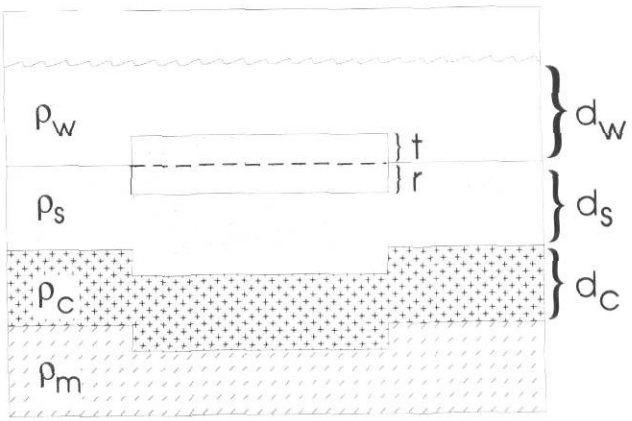

FIGURE 6. The Airy compensation model used to calculate one end member of the predicted gravity over sediment isopachs. Densities of the layers are r_w = 1030 kg/m³ (water), r_c = 2650 kg/m³ (crust), r_m = 3300 kg/m³ (mantle), and r_s = 1800-2300 kg/m³ (sediment). The layer thickness used in the model are d_s = 12 000 km and d_c = 10 000 m.

Le modèle de compensation de Airy qui a servi à calculer un des membres de la gravité prévue au-dessus des isopaques de sédiments. Les densités des couches sont de r_w = 1030 kg/m³ (eau), r_c = 2650 kg/m³ (croûte), r_m = 3300 kg/m³ (manteau) et r_s = 1800-2300 kg/m³ (sédiment). Dans le modèle, les épaisseurs de couches sont de d_s = 12 000 km et de d_c = 10 000 m.

where 1 is the total thickness of the applied load. The observed sediment topography is always less than the total thickness of sediment because of the subsidence of the underlying crust and mantle. For typical values of density, the ratio of topography to total sediment thickness would be 0.5.

The redistribution of mass under the applied load directly affects the magnitude of observed gravity. In the simplest approximation (the Bouguer approximation), the gravity anomaly observed over a laterally infinite sheet of sediment of thickness, h, in water is

$$\Delta g = 2\pi G \delta\rho h \qquad (2)$$

where G is 6.67 × 10⁻¹¹ m³/kg−s² (Telford *et al.*, 1976). A layer of sediment with a thickness of 100 m and a density contrast ($\delta\rho = \rho_s - \rho_w$) of 1000 kg/m³ would change the vertical gravity by about 4 mgals. In the locally compensated case, the positive gravity anomaly of the topographic expression would be greatly reduced by negative contributions from the depression of the sediment/crust density interface and, also, the crust/mantle interface.

If the sediment layers were indeed laterally infinite sheets of material, the total gravity anomaly over the locally compensated structure would be exactly zero. However, accumulations of sediment are never infinite in extent and the Bouguer approximation (Equation 2) forms an upper limit for the contribution of each component to the net gravity anomaly. The contribution of each unit will always be less than the Bouguer maximum, and it will decrease as the distance from the observation point to the sediment package is increased or as the lateral extent of the sediment package decreases. Numerical techniques must be used to calculate the exact quantities.

The other end member to the Airy isostatic compensation model assumes that the load is supported totally by elastic stresses within the underlying crust and lithosphere, and no compensatory root exists. In this case, the observed topography equals the sediment load thickness; the gravity anomaly over this feature is maximal, reflecting only the positive contribution of the extra sediment. This model is generally used for smaller loads with dimensions of tens of kilometres.

Obviously the suitability of either model depends both on the lateral dimensions of the load as well as the structural properties of the underlying lithosphere. The sedimentary packages deposited on the Scotian margin exhibit a wide range ot lateral scales, up to hundreds of kilometres, and it is not clear for these intermediate scales which model is most appropriate.

CALCULATION OF GRAVITY ANOMALIES

The fully three dimensional method of Bhaskara Rao and Babu (1991) was employed to calculate gravity from the digitized Quaternary sediment maps (Fig. 3). This technique permits the calculation of the vertical component of gravity, at a designated observation point, of a rectangular prism of mass located at an arbitrary position in space.

The densities employed for the model calculations are: ρ_w = 1030 kg/m³ (water), ρ_c = 2650 kg/m³ (continental crust), and ρ_m = 3300 kg/m³ (mantle) (*e.g.*, Keen and Beaumont, 1990). Models were generated with sediment densities ranging from 1800 to 2300 kg/m³, but only results for the best fitting models are presented here. A sedimentary basin depth of 12,000 m and a crustal thickness of 10,000 m was used for the local isostatic model, values based on deep seismic profiles of the Scotian margin (Kay *et al.*, 1991).

For the uncompensated model, the gridded values of the sediment isopachs were used to determine the prism heights while the equal lateral dimensions were set to 10 km, the gridding interval for the observations. The vertical position of the tops of the prisms was set by the geographically coregistered values of bathymetry at each grid point. At each observation grid point, the gravity anomaly at the sea surface induced by the sediment distribution was calculated by summing contributions of the prisms at all of the grid points.

The Airy isostatic deflection was calculated separately for each grid point of the sediment load using Equation (1), and the difference between the load thickness and deflection was used to calculate the resultant topographic height. The positive contribution to gravity was calculated in a similar manner as was done for the uncompensated model. Two negative contributions from the sediment/crust interface and the crust/mantle interface were included using the deflection as the prism height and the appropriate density difference across the interface. The offset of these prisms from the surface is augmented by the sedimentary basin depths and the crustal thicknesses as appropriate.

MODEL RESULTS

The strong correlation between the regional pattern of gravity anomalies and the bathymetric expressions of the Laurentian Channel and Laurentian Fan implies that these

latter features are responsible for the gravity anomalies. The gravitational influence of the sediment deficit and sediment excess associated with the Laurentian Channel and Laurentian Fan, respectively, can be calculated and this influence removed from the observed gravity field. This process should leave a residual field that is uncorrelated with bathymetry. The calculated gravity influence of these bathymetric features depends strongly on the assumptions made about their state of isostatic compensation. For this reason, the ability of the bathymetric features to explain correlative features of the gravity field can be used to assess the ability of the lithosphere beneath the shelf and rise to support features out of local isostatic equilibrium.

The offsetting contributions to the gravity field produced by topography and its compensating root are shown in Figure 7 for profile B across the Laurentian Fan. This figure assumes local Airy compensation of the sediment load having a density 2100 kg/m³. The topographic contribution (T) has a maximum value of approximately 30 mgals over the depocentre and decreases to 10 mgal near the ends of the profile. Displacement of each of the sediment crust (SC) and crust-mantle (CM) interfaces makes an approximately equal contribution to the gravity field. Both of these are of opposite sign to the topographic contribution. The net gravity signal associated with the sediment load and its compensating root is small, approximately 5 mgals at the depocentre and negligible elsewhere.

In Figures 8a and b, the calculated gravity for each of the models is plotted along profiles A and B with corresponding plots of the load distribution and the residuals in the observed gravity field after the subtraction of the calculated signals. Note that the "net" curve of Figure 7 is the same as the Airy curve of Figure 8b. In these plots, a sediment density of 2100 kg/m³ has been used. The implications of the choice of this value for density are considered in the discussion following this section. The uncompensated gravity signal is approximately an order of magnitude larger than that locally compensated (Airy); the correction to the observed gravity field for the locally compensated model is almost negligible. In contrast, the gravity calculated for the uncompensated model is a significant portion of the observed gravity field.

Assumption of an uncompensated sediment load across the Laurentian Channel (Fig. 8a) reduces, but does not eliminate the observed gravity anomaly. The calculated correction to the gravity field is approximately 35 % of the local gravity field. A significant signal persists that is apparently not correlatable to the bathymetry. This observation may be in part due to the use of a low sediment density in the model. More probably, it is related to deeper structure of the Orpheus Graben which crosses the channel obliquely and whose gravity signature is unrelated to bathymetry. It is difficult in these profile plots to separate these effects. One must identify two dimensional pattern correlations in the bathymetry and gravity maps, and disregard unrelated features.

The calculated gravity anomaly for Profile B on the Laurentian Fan (Fig. 8b) peaks near 50 mgals over the thickest part of the sediment load for the uncompensated model. When subtracted from the observed gravity field, most of the

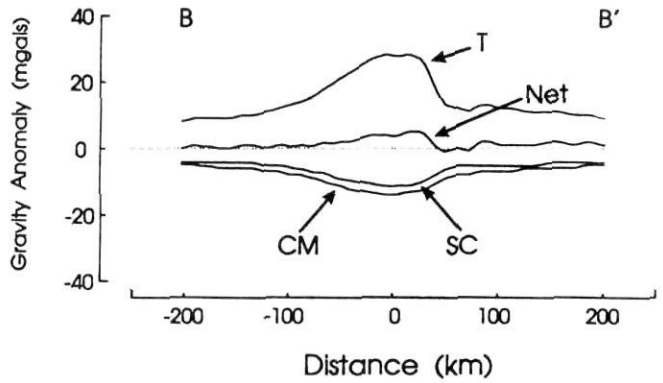

FIGURE 7. Contributions to the total (net) gravity from topography (T) and compensating roots at the sediment/crust interface (SC) and the crust/mantle interface (CM) are plotted along line B for the Airy compensation model.

Les contributions du relief (T) et des racines de compensation, à l'interface sédiments/croûte (SC) et à l'interface croûte/manteau (CM), à la gravité (nette) totale ont été levées le long de la ligne B pour l'établissement du modèle de compensation de Airy.

variation of the gravity field correlatable with bathymetry is removed, suggesting that the entire load of the fan is not compensated. The Airy correction to gravity again induces a minimal change, suggesting that an Airy model is inappropriate.

Residual gravity maps are given in Figures 9a and b for sediment densities of 2100 and 2200 kg/m³ generated using the uncompensated model. A map of the Airy corrected model is not presented as it has been shown that it would not be substantially different from the observed field plotted in Figure 2. A cursory examination of the residual fields shows that in areas covered by significant Pliocene Quaternary sediment thickness, the effect on the observed gravity field is substantial. The positive shelf break anomaly is uniformly reduced, the anomaly under the Laurentian Fan is almost totally removed and the Orpheus Graben signature becomes more continuous as it crosscuts the Laurentian Channel. The higher density model tends to remove more of the Laurentian Fan anomaly. A low amplitude residual anomaly running perpendicular to the strike of the Scotian Shelf to the east of the area covered by the Laurentian Fan (Line B-B') is evident in the residual map. It could be related to an underlying Miocene depositional feature or it might be related to crustal structure of the Newfoundland Transform Margin found to the east (Keen *et al.*, 1990). The residual could not be further reduced by increasing the sediment density, as the sediment load is negligible over much of the area where the residual is observed.

DISCUSSION

It has been shown that the apparent correlation between patterns of Pliocene Quaternary sedimentation and the free air gravity anomaly field can be explained if the load of recent sedimentation remains uncompensated within the lithosphere. The Laurentian Fan lies on top of the Scotian sedimentary basin formed by post Triassic rifting which contains sediments more than 15 km in total thickness (Keen and

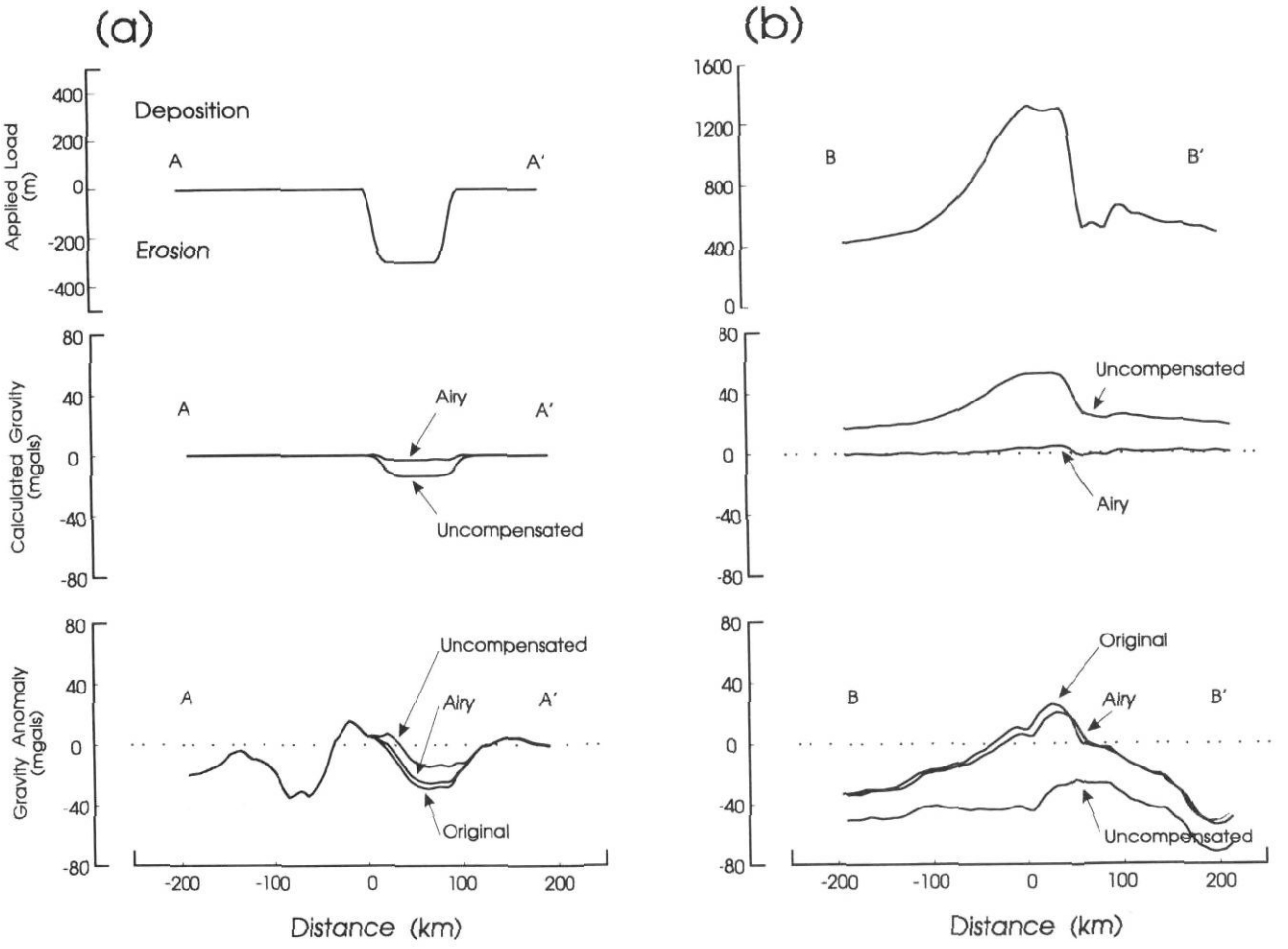

FIGURE 8. Gravity corrections calculated from load distributions assuming both an uncompensated and a locally compensated model. The corrections to the gravity field are removed from the observed gravity field in the lowermost plot: a) for profile A across the Laurentian Channel; b) for profile B across the Laurentian Fan.

Corrections de la gravité calculées à partir de la répartition des charges compte tenu d'un modèle non compensé et d'un modèle de compensation locale. Les corrections aux champs de gravité sont soustraites du champ de gravité observé dans le levé inférieur: a) pour le profil A à travers le chenal Laurentien: b) pour le profil B à travers le cône Laurentien.

Beaumont, 1990), yet a proportional gravity anomaly reflecting the basin depth is not observed.

This apparent discrepancy may be reconciled if the conditions under which the basin developed are considered. The Scotian basin was created during the rifting of the Atlantic margin: the underlying lithosphere at the time of formation and basin infilling was relatively hot and weak. Consequently, the elastic stresses induced by the basin loading were relaxed quickly by viscous flow below the Moho.

The Laurentian Fan and other Quaternary sediments, in contrast, have been deposited on an old, mature and cold lithosphere, which is considerably stronger and more rigid. The lack of deformation under the fan can be used to assess quantitatively the effective strength of the lithosphere; the flexure of the margin under the load is the subject of a subsequent paper in preparation by the authors. Structures that predate or associated with the last rifting cycle would likely be locally compensated in the upper mantle, due to reheating of the lithosphere during rifting. Their gravity signatures would be greatly attenuated by isostatic crustal roots.

The effects of compaction within sediments have not been considered in this preliminary study and mean densities between 2100 and 2200 kg/m³ were needed to generate models that appeared to remove most of the correlation between the load and the gravity field. An exponential decrease in porosity is often used to model the effects of compaction (*e.g.* Keen and Beaumont, 1990):

$$\phi(z) = \phi_o e^{-z/\lambda} \tag{3}$$

where ϕ_o is the surface porosity and λ is the compaction length, then the mean density, ρ', in a layer of thickness, L, is

$$\rho' = \frac{\int_0^L \rho_w \phi(z) + (1 - \phi(z))\, \rho_g \, dz}{L} \tag{4a}$$

or

$$\rho' = \rho_g + \frac{\lambda(\rho_w - \rho_g)(1 - e^{-L/\lambda})}{L} \tag{4b}$$

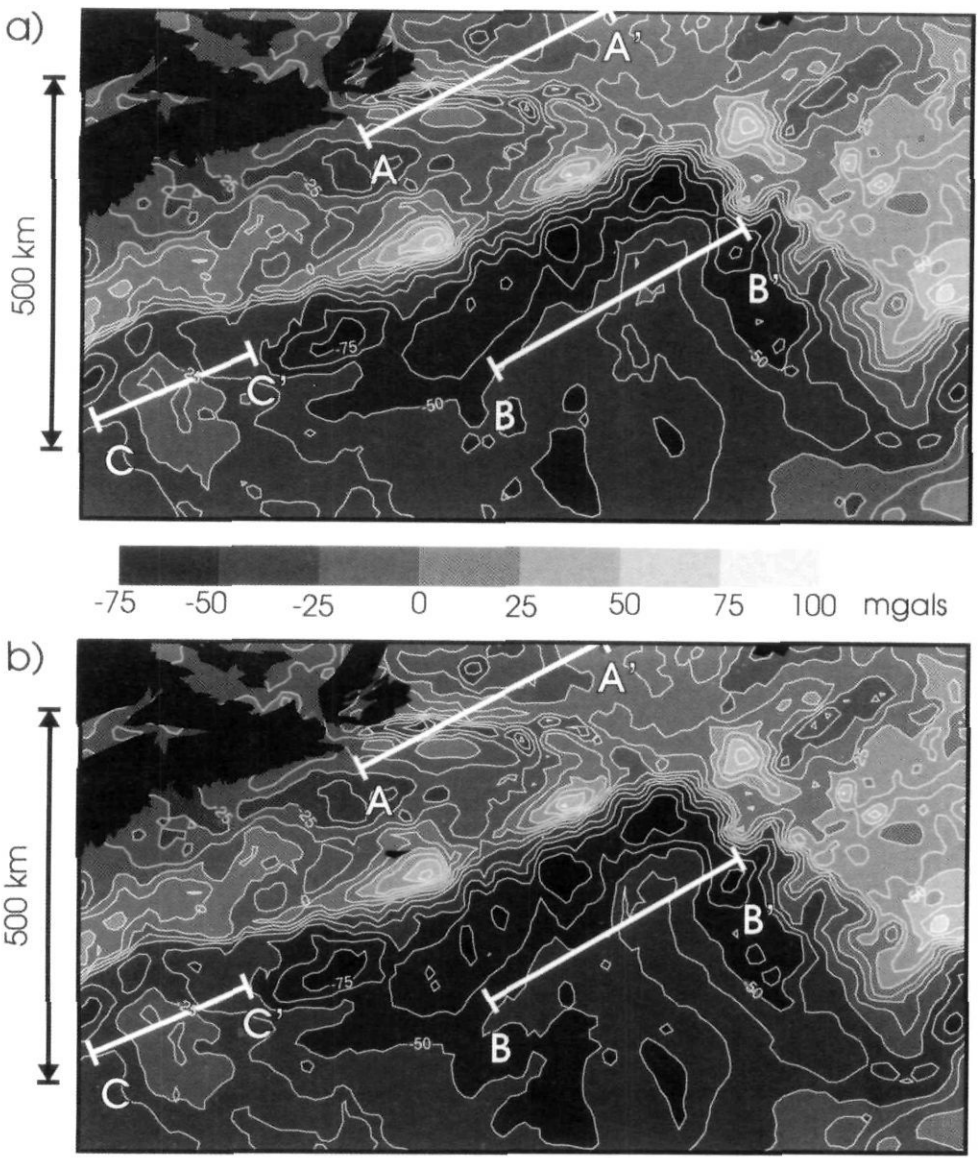

FIGURE 9. Residual gravity anomaly map of the Scotian margin generated by the removal of the uncompensated gravity response of Pliocene-Quaternary sediments deposited between 3 Ma and 50 ka computed: a) with sediment density set to 2100 kg/m³; b) with sediment density set to 2200 kg/m³.

Carte de l'anomalie gravitaire résiduelle de la marge continentale de Scotian produite par la soustraction de la réponse gravitaire non compensée des sédiments pliocènes/quaternaires déposés entre 3 Ma et 50 ka calculée: a) selon une densité établie à 2100 kg/m³; b) selon une densité établie à 2200 kg/m³.

where ρ_g is the matrix density. If ρ_g = 2750 kg/m³ (Keen and Beaumont, 1990), λ = 1000 m, and ϕ_o = 0.60, then the mean density in a 1000 m column of shale would be 2100 kg/m³, as assumed in our model.

Keen and Beaumont (1990) used a larger value of λ equal to 1500 m for shale compaction when modelling sediment compaction during the evolution of the Scotian Basin. This choice of the compaction factor would result in lower mean density of 2000 kg/m³. Issler (pers. comm. 1991), in his study of Beaufort Sea shales, prefers a lower value of 1400 m and a best fit surface porosity of 0.39 yielding a mean density of 2270 kg/m³. So the best fit densities used in the gravity modelling (2100-2200 kg/m³) are not unreasonable for the thicker sequences although they seem somewhat high where the sediment is thin.

If the densities used to fit the observed gravity anomalies remain excessively high, it is possible that the estimated sediment thickness might have been too low, as the product of the two variables combines to produce the gravity signal. Lower estimates on sediment thickness could be attributed to inaccurate velocity profiles used to convert seismic reflection travel times to depth sections. In this roundabout way, gravity measurements may provide an additional constraint on travel time inversion.

Two prominent features in the residual gravity field deserve closer attention. Profile C on the gravity map (Figs. 2, 9a and 9b) crosscuts a feature which resembles closely the character of anomaly found over the Laurentian Fan. There is no known thick deposit of Pliocene or Quaternary sediments that corresponds to this gravity anomaly, although a broad swell, or apron, is detectable in the bathymetry map along the profile. This gravity anomaly probably reveals the depositional configuration of a pre-Pliocene Tertiary fan. Both Swift (1987) and Piper and Sparkes (1989) mapped a small seaward bulge in Miocene isopachs in this region, although there is not a precise correspondence with the gravity anomaly. If this correlation is correct, it suggests that the lithosphere could maintain loads in an uncompen-

sated state over the last 25 Ma. Alternatively, the gravity data may indicate that current seismic correlation across the salt diapir province is incorrect, and unsuspected thicknesses of Pliocene-Quaternary sediment are present in the area.

Two large gravity highs lie superimposed on the shelf break anomaly found midway between profiles A and B in Figure 9. No explanation for these features is offered here, but in light of the results of this study a relationship to recent sediment deposition would be worth further investigation. The amplitude of these gravity features has been related to flexural models of the lithosphere (Keen and Beaumont, 1990) that have not considered detailed distributions of sediment dispersal. It is likely that a gravity map corrected for post-Miocene deposition would change those conclusions, most likely changing their estimates of lithospheric strength and their profiles of crustal thinning across the margin.

Finally, it should be recognized that the resolution of the gravity and bathymetric data sets is limited. Sedimentary units would have to span a number of grid elements in order to be resolved; features less than 40 km in lateral dimension are unlikely to be imaged. Consequently, these data should be used for regional studies and not for detailed local investigations. The accuracy of the gravity data is around 2.5 mgals, corresponding to a sediment thickness of 75 m, placing a limit on the thinnest detectable sedimentary unit.

CONCLUSIONS

Two new maps of Pliocene - Quaternary sediment distribution have been compiled and presented. These maps form a basis for the assessment of the influence of recent sediment deposition on the free air gravity field observed on the Scotian Shelf, Slope and Rise.

There is a strong signature of Pliocene - Quaternary sedimentation contained in the regional free-air gravity anomaly field observed on the Scotian margin. The correlation between bathymetry and gravity may be used as a guide for identifying packages of uncompensated sediment. The magnitude of the field induced by these sediment distributions can exceed 30 % of the total anomaly field in the area studied.

The existence of large anomalies over Quaternary sediments indicates that the weight of the sediments is supported by stresses in the lithosphere, and the use of an Airy compensation model in gravity modelling these structures is not appropriate. Older structures dating back to, or pre-dating, the rift stage of the margin are subdued in the gravity field because of the negative contribution to gravity from compensating relief formed on the Moho when the lithosphere was hot and weak. The gravity signature of these older features reflects primarily crustal thicknesses changes, characterized by paired positive and negative gravity anomalies over the area of transition.

Residual gravity maps, corrected for Pliocene - Quaternary sedimentation, exhibit a reduced shelf edge anomaly. The removal of the gravity effects of Pliocene - Quaternary sediments over the Laurentian Fan clarifies a residual anomaly which may be related to a Miocene depositional structure or it may be related to crustal structure of the Newfoundland transform margin. A second anomaly on the western Scotian margin may also be a consequence of Miocene deposition, or may indicate that current seismic correlation across the salt diapir province is incorrect.

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