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Lithospheric Thickness, Antarctic Deglaciation History, and Ocean Basin Discretization Effects in a Global Model of Postglacial Sea Level Change: A Summary of Some Sources of Nonuniqueness

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The global model of postglacial relative sea level variations that has been developed over the past decade is employed to investigate the constraints that it may be invoked to place on the timing of the deglaciation of West Antarctica. The analyses presented here confirm the suggestion of P. Wu and W. R. Peltier (1983, *Geophysical Journal of the Royal Astronomical Society* 74, 377–450) that the model of this event employed in J. A. Clark and C. S. Lingle (1979, *Quaternary Research* 11, 279–298) may be simply modified to rectify the misfits between theory and observation that are otherwise obtained at Southern Hemisphere sites. A large number of Southern Hemisphere relative sea level data are shown to require that the retreat of Antarctic ice substantially lagged the retreat of Northern Hemisphere ice if the deglaciation of Antarctica was abrupt. The time of onset of Antarctic deglaciation is thereby shown to coincide with the time of most rapid Northern Hemisphere deglaciation. Sensitivity tests are performed which demonstrate that this result is relatively insensitive to the discretization employed to represent the ocean basins; the only exception to this general rule obtains at some coastal sites at which a trade-off is revealed between the delay of West Antarctic melting and the thickness of the lithosphere required to reconcile the observed local variations of relative sea level. At such sites, which are all in the far field of the ice sheets, some attention must be paid to the accuracy of the local finite element representation of the oceans and to the details of the Antarctic deglaciation history.

INTRODUCTION

Over the past decade, beginning with the paper by Peltier (1974), a variety of different geophysical observations have been shown to be intimately related to the earth's dynamical response to the melting of the great continental ice sheets that last achieved their maximum volumes approximately 18,000 yr ago. This last deglaciation event of the current ice age took approximately 10,000 yr to complete and by approximately 7000 yr ago the coverage of the Earth's continental surface by ice had been reduced to that which characterizes the planet at present. Because of the extraordinary amount of water mass that had to be removed from the ocean basins to build these ice sheets, equivalent to a sea level fall of approximately 120 m, the dynamical effects induced by this surface loading event were such as to leave easily discernible evidence in the geological record in the form of relative sea level variations, the timing of which may be accurately constrained using ^{14}C dating methods. In addition to these data from Quaternary geomorphology, the memory of the deglaciation event is also recorded in free air gravity anomalies, that are found today over the continental regions which were once ice-covered, and in two anomalies of earth rotation. The latter consist first of the so-called nontidal acceleration of planetary rotation that was originally inferred on the basis of analyses of ancient eclipse data (e.g., Müller and Stephenson, 1975) and that has recently been reconfirmed through analysis of laser ranging data for the LAGEOS satellite (Yoder *et al.*, 1983; Rubincam, 1984). The second rotational datum that has been shown to be connected unambiguously to the deglacia-

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tion event is the secular drift of the rotation pole with respect to the surface geography that was first revealed by the pzt data of the International Latitude Service (Vincente and Yumi, 1969, 1970) and that has also recently been reconfirmed using Very Long Baseline Interferometry observations (Carter, 1986). The geophysical theory which has been developed to relate all of these observations to the single cause of deglaciation, although based upon the viscoelastic field theory of Peltier (1974), has required the development of special additional ingredients for application to the understanding of each of these different physical signatures of the response.

In the case of the relative sea level data, methods had to be developed to enable an accurate prediction to be made of the time-dependent separation of the surface of the solid earth from the surface of the ocean (the geoid). This required that careful account be taken of the perturbations of the gravitational potential induced by both the ice unloading and ocean loading components of the deglaciation process. Farrell and Clark (1976) showed how the methods of Peltier (1974) and Peltier and Andrews (1976) could be extended to produce a gravitationally self-consistent description of the isostatic adjustment process. This extension of the theory was first applied by Clark *et al.* (1978) and Peltier *et al.* (1978) who employed the deglaciation history tabulated in Peltier and Andrews (1976) called ICE-1 to implement the solution of the integral equation which describes relative sea level change in this extended theory (see Equation (1) of the present paper). These initial calculations demonstrated that, although much of the relative sea level variability over the world's oceans could be explained with this theory, there were large systematic errors between theory and observation in several locations. In particular, predicted sea level variations in the southern oceans were shown to disagree sharply with the predictions of the ICE-1 melting chronology (which neglected any meltwater input from the deglaciation of Antarctica) by predicting the appearance of raised beaches 2000 yr prior to their actual appearance near 6000 yr B.P. There were also large misfits between theory and observation in the regions immediately surrounding the main ice sheets. In Clark *et al.* (1978), the former of these misfits was corrected by delaying the melting of Northern Hemisphere ice by 2000 yr, in marked violation of the ^{14}C-controlled disintegration isochrones. Wu and Peltier (1983) showed that the misfits beyond the ice margins were a simple function of distance away from the ice margin and Peltier (1984, 1986) demonstrated that these misfits could apparently be entirely removed by increasing the thickness of the continental lithosphere to a value somewhat in excess of 200 km. It was also suggested by Wu and Peltier (1983) that a more reasonable explanation of the misfits in the southern oceans (which Clark *et al.* (1978) had corrected by delaying Northern Hemisphere melting) might be simply to delay the melting of Antarctic ice which they tabulated in a model called ICE-2 whose Antarctic component was identical to that previously employed by Clark and Lingle (1979). Although Wu and Peltier suggested that such a delay would provide a simple explanation of sea level misfits in the southern oceans, they did not experiment with such models explicitly. In this paper I will describe a new set of extensive numerical computations which have been performed to demonstrate the much improved fit to the global record of relative sea level change which this modified scenario allows and will comment on its implications with respect to current theories of paleoclimatic change.

MELTING SCENARIOS FOR ANTARCTICA AND A PRIORI CONSTRAINTS ON VISCOELASTIC EARTH STRUCTURE

Figure 1 shows the ice volume history for the separate Northern Hemisphere and

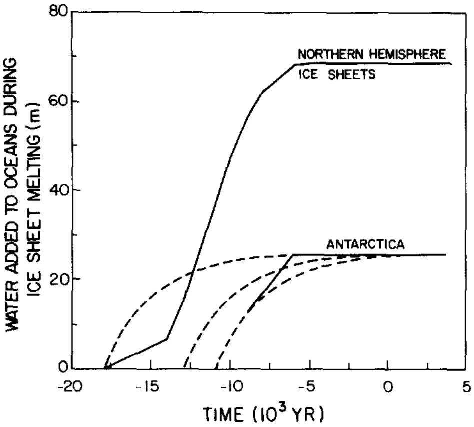


FIG. 1. Contribution to the global eustatic rise of sea level due to the melting of the Northern Hemisphere ice complexes of Laurentia and Fennoscandia (solid line) according to the ICE-2 melting chronology of Wu and Peltier (1983) and the contribution from Antarctica according to four different scenarios (the dashed and dashed-solid lines). The earliest Antarctic melting scenario shown is that from the ICE-2 chronology. The three additional scenarios correspond to delays of the Antarctic component of 5000 and 7000 yr, the latter being the one preferred on the basis of the analyses presented in this paper.

Antarctic portions of the ICE-2 model with four separate versions of the deglaciation history of Antarctica, three of which are shown as dashed and one as dashed-solid lines. The Clark and Lingle (1979) model is the left-most of the dashed lines on the figure and corresponds to the assumption that Antarctic ice melted catastrophically beginning at 18,000 yr B.P. at the same time that Northern Hemisphere ice began slowly to melt back. Also shown are versions of this history in which Antarctic melting is delayed by 5000 and 7000 yr. As I will show in the present paper, the model with 7000-yr delayed Antarctic melting does, in fact, reconcile the misfits in the southern oceans very nicely when the Northern Hemisphere component of the melting chronology is fixed to that of the ICE-2 tabulation. This shift in the melting chronology of West Antarctic ice is also required to conform to the theory of the ice age cycle of glaciation and deglaciation developed in Peltier (1982), Peltier and Hyde (1984), Hyde and Peltier (1985, 1987), and Peltier (1986). In this version of the Milankovitch astronomical theory of paleoclimatic change, the basic 10^5-yr cyclic oscillation of northern hemisphere ice volumes is produced by the nonlinear interaction between the processes of ice sheet accumulation and flow and the process of glacial isostatic adjustment. The synchronmous oscillation of Southern Hemisphere ice is supposed to be induced via coupling of the West Antarctic ice sheet to Northern Hemisphere events through the intermediary of the sea level variations induced by the Northern Hemisphere cryospheric volume fluctuations as discussed in Denton and Hughes (1980). Such strong coupling is expected because the West Antarctic ice sheet is a marine ice sheet the base of which is well below sea level over much of its area. It is therefore highly susceptible to sea level variations.

Although the explicit illustration of the above described ideas will form the basis of the present paper, it is important to keep simultaneously in view the other observational data which have also been successfully explained by the viscoelastic field theory of the isostatic adjustment process that is basic to the accurate prediction of relative sea level histories. For example, analyses of the free air gravity anomalies associated with the isostatic adjustment process have established (Peltier, 1981; Peltier and Wu, 1982; Wu and Peltier, 1983; Peltier, 1985; Peltier *et al.*, 1986) that these data may be fit by the same almost uniform mantle viscosity model required by the sea level data only, apparently, if the mantle density stratification is assumed to be at least partly nonadiabatic. In fact, it has been demonstrated in these articles that the almost isoviscous viscosity profile preferred by the relative sea level (RSL) data is accepted as plausible by the free air gravity observations only if the density jumps associated with the seismic discontinuities at 420 and 650 km depth are assumed to behave in this fashion. As discussed in Peltier (1985), this is not necessarily incompatible with the interpretation of these discontinuities as equilibrium phase transformations since, to the extent that the phase boundaries are sharp (close to univariant), they will behave as chemical boundaries on the timescale of postglacial rebound. These analyses represent the first successful interpretation of the free air gravity data with a model that simultaneously reconciles RSL variability.

The explanations of the previously mentioned anomalies of earth rotation have also been successfully integrated into this same general picture. The interpretation of the LAGEOS observation of $\dot{J}_2$, which is directly related to the nontidal acceleration of the rate of axial rotation, in terms of glacial isostasy, was in fact anticipated by the prediction of this effect in Peltier (1982) prior to the first published reports of the observation by Yoder *et al.* (1983). Detailed analysis of the LAGEOS data were described in Peltier (1983, 1985) and Peltier *et al.* (1986). As pointed out in Peltier (1985), the $\dot{J}_2$ observation is particularly useful because this physical datum is not particularly sensitive to either mantle nonadiabaticity or lithospheric thickness, so that it serves as a particularly useful constraint upon the ratio of upper mantle to lower mantle viscosity. The above-cited analyses also agreed with the RSL and free air gravity data in requiring a weak stratification of mantle viscosity with an asthenospheric value close to 10^{21} Pa sec and a mesospheric value slightly higher, but modestly so, and near 2×10^{21} Pa sec. This is the radial viscoelastic structure that will be employed for the mantle of the earth in all of the relative sea level calculations to be reported in the present article.

The second of the rotational data, the ongoing drift of the rotation pole toward eastern Canada at a rate near 0.95 (± 0.15) degrees per million years, is probably the most interesting phenomenon of all from a fundamental physical point of view. Since publication of the paper by Munk and Revelle (1952), it has generally been believed that no such wander of the rotation pole with respect to the surface geography could occur so long as the planet was not actively subject to changes in its surface load. The Munk and Revelle analysis therefore led its authors to suggest that the observed secular drift of the pole was probably due to present-day continued melting of Greenland and/or Antarctic ice. Their paper has continued to be invoked in favor of such an effect in very recent papers dealing with climatic change (e.g., Barnett, 1983) even though the best present evidence suggests that both of these ice sheets are currently in equilibrium (e.g., Meier, 1984). Reanalysis of this problem by Peltier (1982), Peltier and Wu (1983), Wu and Peltier (1984), and Peltier *et al.* (1986) has demonstrated the existence of a serious flaw in the theoretical analysis of Munk and Revelle, however, which invalidates their conclusion. As demonstrated in these papers, the homogeneous viscoelastic model of the earth employed by Munk and Revelle to compute the polar motion induced by surface loading has the extraordinary characteristic that the separate contributions to the forcing due to glacial isostasy, and to the centrifugal force associated with the changing rotation, exactly annihilate one another at any time when the surface load is steady. In terms of this model, therefore, no polar wander should be observed at a time like the present when this condition apparently holds. The above-cited articles demonstrated, however, that when realistic radial stratification of the planet was taken into account, these two contributions to the forcing no longer cancelled one another and it became possible to explain the observed secular shift of the rotation pole with the same model of the radial viscoelastic structure of the planet as was shown to be required by the previously discussed isostatic adjustment data. The nature of the theoretical prediction is such that the datum is strongly sensitive to all aspects of the radial viscoelastic structure, including lithospheric thickness and internal mantle buoyancy.

All of the analyses cited above are based upon the assumption that the viscoelastic relaxation process could be described in terms of a Maxwell model of viscoelasticity in which the instantaneous response is Hookean elastic and the final response Newtonian viscous. Although some recent work on the inference of mantle viscosity on the basis of isostatic geoid anomalies (Hager, 1984; Richards and Hager, 1984; Forte and Peltier, 1986) suggests that the convection process may be governed by a viscosity which is higher than that inferred through analyses of the glacial isostatic adjustment process, discussion in Peltier (1985, 1986) and Peltier *et al.* (1986) demonstrates that the implied importance of transient relaxation on the timescale of isostatic adjustment may be understood only if the elastic defect associated with the transient component is large. In this limit, the general Burgers body description of the relaxation process degenerates to a Maxwell model governed by an effective viscosity $\nu_{\mathrm{eff}} = \nu_1\nu_2/(\nu_1 + \nu_2)$ in which ν_1 is the steady-state viscosity which governs the convection process and ν_2 is the viscosity which governs the timescale on which the steady-state behavior is approached. The work of Forte and Peltier (1986, 1987) suggests that $\nu_2 \cong \nu_1$ in the upper mantle and, therefore, that the viscosity which governs the isostatic adjustment process could be at most only a factor of about two lower than that which governs convection. In the present paper, all of the analyses will therefore continue to employ the Maxwell representation of the viscoelastic relaxation process but we must keep in mind that the viscosity structure inferred from the sea level data should be interpreted as an effective structure.

THE GLOBAL MODEL OF RELATIVE SEA LEVEL CHANGE

As recently reviewed in detail in Wu and Peltier (1983), the variations of relative sea level, $S(\theta,\phi,t)$, forced by a global deglaciation event may be computed as solutions to the integral equation,

$$S = \rho_I \frac{\phi}{g} * L_I + \rho_w \frac{\phi}{g} * S - \frac{1}{A_0}\left\langle \rho_I L_I \times \frac{\phi}{g} + \rho_w S \times \frac{\phi}{g} \right\rangle_0 - \frac{M_I(t)}{\rho_w A_0}, \tag{1}$$

in which ρ_I and ρ_w are the densities of ice and water, respectively, ϕ is the Green function for the perturbation of the gravitational field at the earth's surface induced by the addition onto the surface of a point load of 1 kg mass, g is the surface gravitational acceleration of the unperturbed spherical equilibrium configuration, A_0 is the assumed constant area of the earth's oceans, the angle brackets $\langle\ \rangle_0$ indicate integration over the surface of the oceans, and $M_I(t)$ is the assumed known mass loss history of the ice sheets, one example of the form of which (expressed in terms of equivalent ocean depth) is shown in Figure 1. In Eq. (1) the space–time convolution operation is represented by *. The sea level Eq. (1) is an integral equation because the unknown field $S(\theta,\phi,t)$ appears both on the left-hand side and under the convolution integrals on the right-hand side. As discussed in Peltier *et al.* (1978), we solve it using an iterative scheme which starts with a eustatic first guess and uses the error to construct an improved solution, continuing until the equation is satisfied to within some prescribed tolerance. The details of this procedure will not be reproduced here but the interested reader can find them in the above-cited references.

NEW RESULTS FROM THE GLOBAL MODEL

In this section I will present results obtained from the global solution of Eq. (1) which are intended to illustrate two different properties of the solutions, the first numerical and the second physical. First I shall discuss the impact on North American RSL predictions of the ocean grid refinement represented by the utilization of the finite element mesh shown in Figure 3 rather than the original grid shown in Figure 2. Second, I shall describe a sequence of calculations using the refined ocean grid to investigate the impact of the different Antarctic melting scenarios described in Figure 1 on the relative sea level predictions for both the Northern and, more importantly, the Southern Hemisphere.

The Influence of Ocean Grid Discretization Error on North American Relative Sea Level Predictions

Figures 4 and 5 together show a collection of 32 observed RSL curves, represented by the solid crosses, compared to the predictions of two models which differ from one another only in the finite element discretization employed for the oceans. The dashed lines are for the original ocean discretization whereas the solid lines are for the improved discretization. On the basis of these comparisons the influence of even rather substantial refinement of the ocean discretization upon the predicted relative sea level variations at sites near major ice masses is rather small and restricted to positions near the ice margin, such as Cape Breton Island, Chezzetcook, Halifax, and the Bay of Fundy in Nova Scotia, and to St. John, New Brunswick. Even at these locations, however, the differences are substantial only for the earliest times. Also modestly effected, and in the opposite sense, are sites in the Gulf of Mexico such as Matagorda Bay, Texas. The ocean discretization has little influence at sites near the major ice sheets in that the response at such locations is strongly dominated by the deformation of the solid earth; direct ocean-loading effects play a relatively minor role.

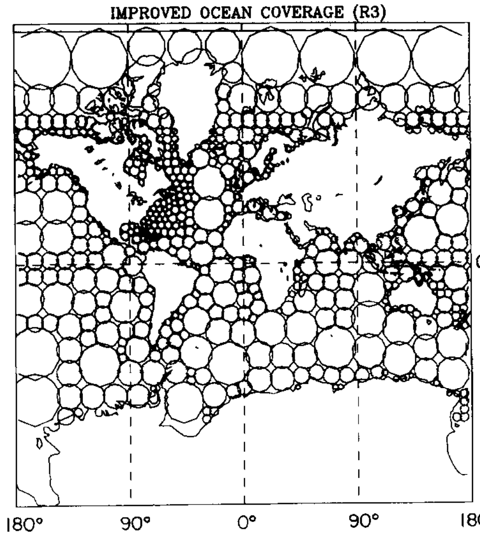


FIG. 3. Refined finite element discretization of the ocean basins employed for the purposes of this paper. Comparison with the earlier model shown in Figure 2 reveals that the refinement is confined to the western North Atlantic and, to a lesser degree, to the western South Atlantic adjacent to the east coast of South America.

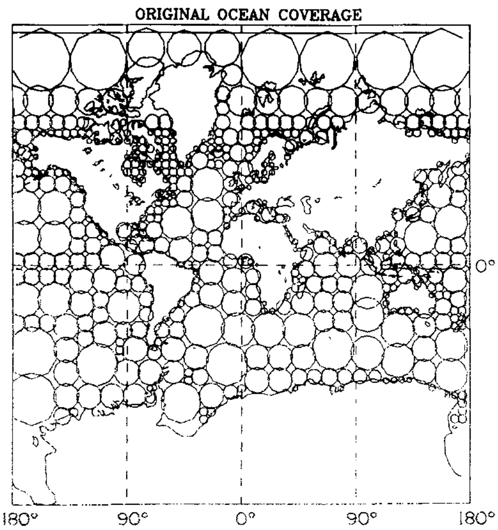


FIG. 2. Finite element coverage of the oceans employed in the calculations of Peltier and Andrews (1976), Clark *et al.* (1978), and Wu and Peltier (1983).

All calculations in this article have been based upon an earth model whose elastic structure is fixed to that of Model 1066B of Gilbert and Dziewonski (1975), whose upper mantle has a viscosity of 10^{21} Pa sec and whose lower mantle has a viscosity of 2×10^{21} Pa sec. This model has been shown to reconcile adequately all of the

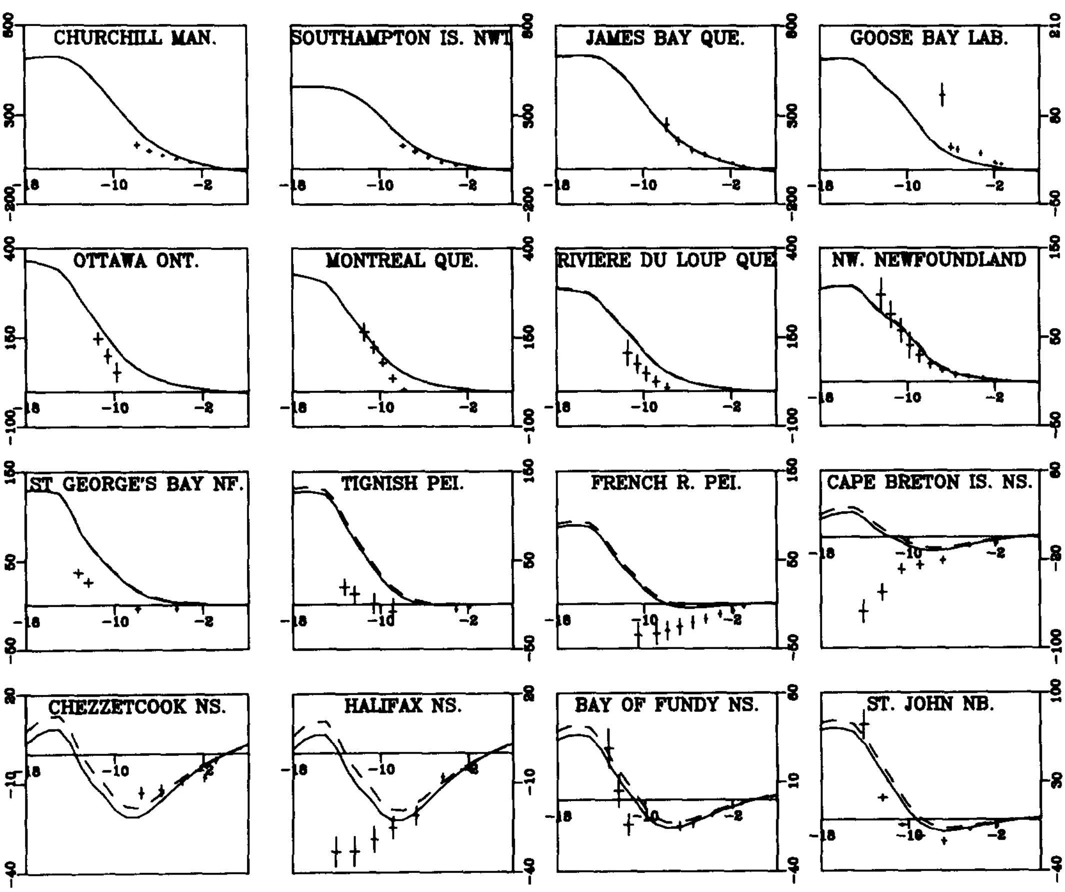


FIG. 4. A comparison between predicted and observed (error bars) relative sea level data at 16 North American sites illustrating the influence of the refinement of the finite element distribution in the western North Atlantic represented by use of the mesh shown in Figure 3 (solid lines) rather than the mesh shown in Figure 2 (dashed lines). The elastic component of the earth model is 1066B, the lithospheric thickness is 196 km, the upper mantle viscosity is 10^{21} Pa sec, and the lower mantle viscosity is 2×10^{21} Pa sec. In this and all subsequent figures of this type relative sea level in meters at each site is shown as a function of age in thousands of years. Neither the height nor the time units are shown on any plate.

observation data discussed in the introduction to this paper. For the purpose of these initial calculations the thickness of the lithosphere has been fixed at 196 km. Effects due to the variation of this parameter on relative sea level data from the Southern Hemisphere will be discussed subsequently.

The Influence of the Timing of Antarctic Deglaciation

Figures 6, 7, and 8 show comparisons between observed and predicted relative sea level histories at 48 locations which are all well removed from the major ice sheets on Canada, Scandinavia, and Antarctica. At many of these sites, including Jonathan Point, Belize; East Panama; Georgetown, Guyana; Paramaribo, Surinam; the Mekong Delta of Vietnam; the Huon Peninsula of Papua New Guinea; Townsville, Queensland, Australia; Maackay, Queensland; Moruya, New South Wales; the Wariu Valley, New Zealand; Christchurch, New

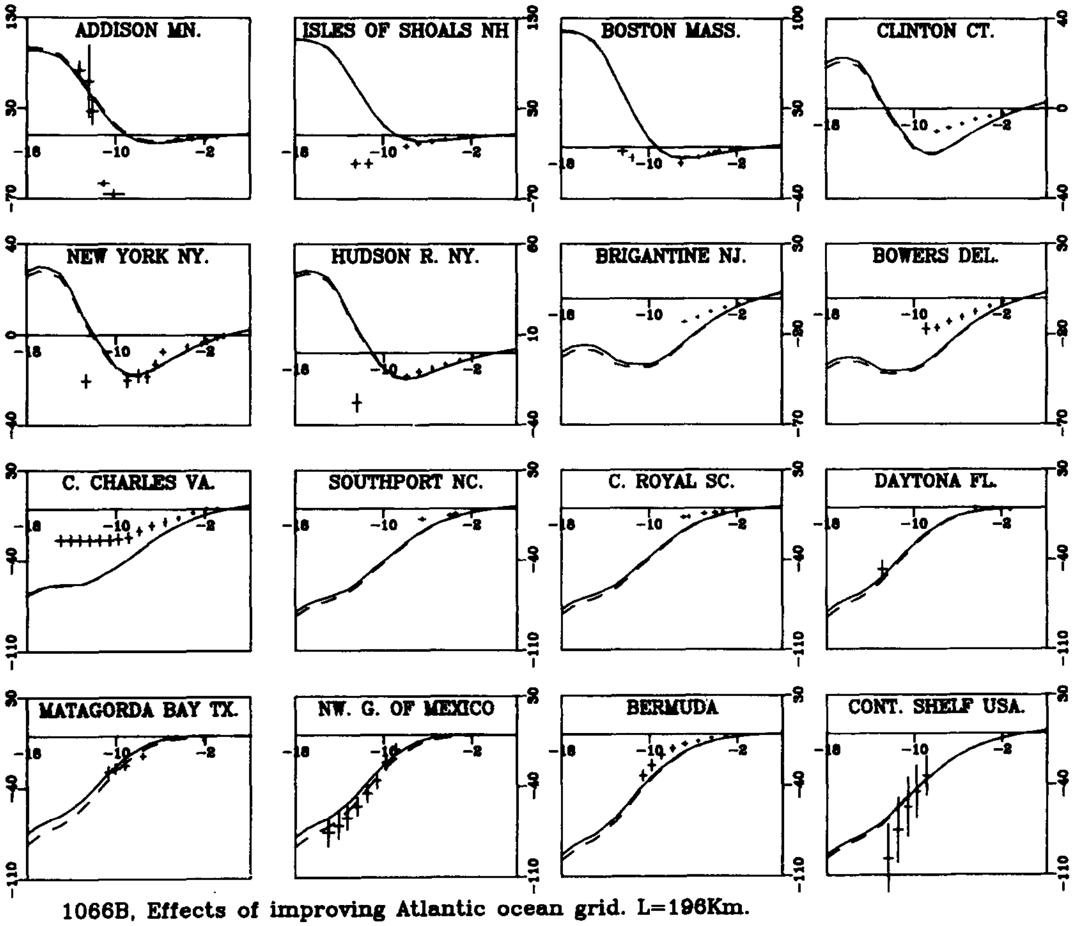
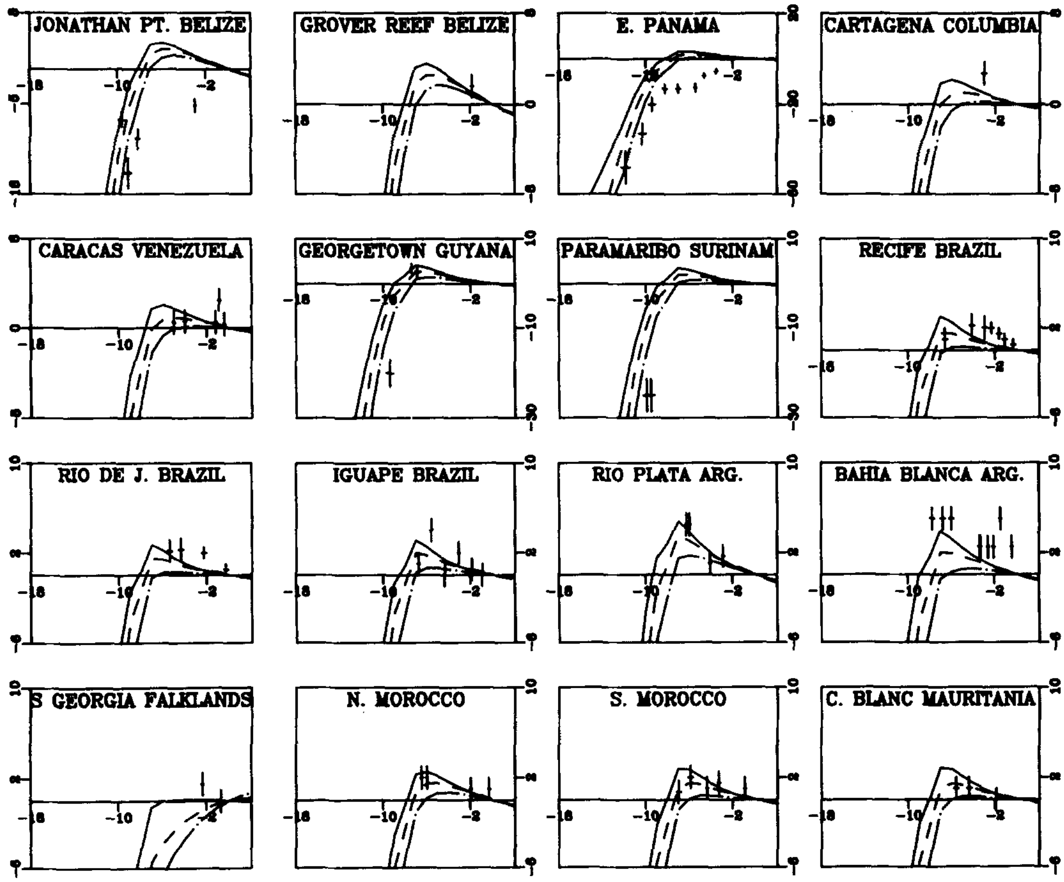


FIG. 5. As in Figure 4, but for 16 additional North American relative sea level sites.

Zealand; the East Caroline Islands; New Caledonia; and Oahu, Hawaii, there are substantial radiocarbon dates from material of age up to 10,000 yr or more. Such information provides extremely important constraints on the nature of the deglaciation history since the data substantially overlap the time in which ice sheet melting is still taking place. At every one of the abovementioned sites a marked improvement in the fit is achieved by delaying the melting of Antarctic ice by the 7000-yr maximum illustrated in Figure 1. In the absence of this alteration of the deglaciation history, every predicted far field relative sea level curve is characterized by the appearance of raised beaches at 8000 yr B.P. rather than at 6000 yr B.P. as is observed, a misfit which was identified by Wu and Peltier (1983) and earlier by Clark *et al.* (1978) and Peltier *et al.* (1978). Many of the sites could tolerate even greater delay of the melting of Antarctic ice than the 7000-yr maximum for which I have shown calculations on these figures. It is only the Antarctic component of the deglaciation history which we are at liberty to adjust in this way since the Northern Hemisphere components of the melting chronology are very well constrained to the ICE-2 pattern by ^{14}C dates on material from terminal moraines.

This 7000-yr delay in the melting of Antarctic ice has disastrous effects on the fit to the relative sea level observations at a large number of other locations (Figs. 6–8). For example, at Recife, Rio De Janeiro, and



1066B, Effects of delaying Antarctic melting 5 or 7 Kyrs. L=196Km.

FIG. 6. Comparison of predicted and observed (error bars) relative sea level histories at 16 sites in the far field of the ice sheets illustrating the influence upon the predicted relative sea level histories of delaying the Antarctic component of the deglaciation chronology from that of the ICE-2 model listed in Wu and Peltier (1983). The solid curves are the predictions using the original melting chronology of ICE-2, the dashed curves are RSL predictions based upon a 5000-yr delay of the Antarctic component of melting, and the dash-dotted curves are predictions employing a 7000-yr delay of Antarctic melting. The elastic structure of the earth model employed for the computations is 1066B, the lithospheric thickness is 196 km, the upper mantle viscosity is 10^{21} Pa sec, and the lower mantle viscosity is 2×10^{21} Pa sec.

Iguape, Brazil; at Rio Plato and Bahia Blanca, Argentina; in North and South Morocco; Cape Blane, Mauritania; and Rota Island, the South Gilbert Islands, New Caledonia, and Jarvis Island, the delay of Antarctic melting completely eliminates the prediction of any raised beaches at all. Yet at every location raised beaches are actually observed. As I will demonstrate in the following subsection, much of the misfit induced at such sites when delayed Antarctic melting is assumed is simply rectifiable either by thinning the lithosphere or by a slight further modification of the Antarctic melting history. These are rather plausible explanations for the discrepancies at the above-mentioned locations as the lithospheric thickness employed in the previously described calculations was near to, but somewhat less than, the value appropriate for the North American continental craton (e.g., Peltier, 1984), and the Antarctic component of the melting history was assumed to possess an infi-

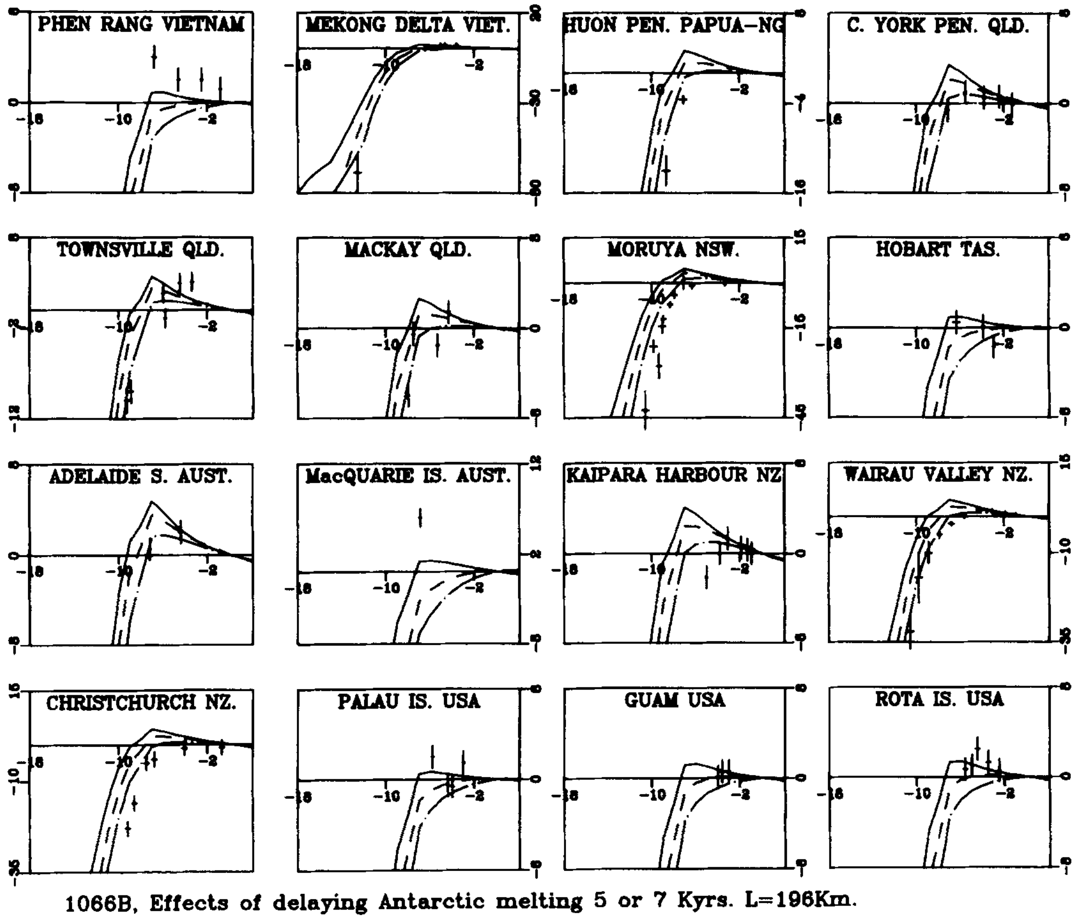


FIG. 7. Same as Figure 6, but for 16 additional sites.

nitely long "tail." A 200-km lithospheric thickness is certainly not appropriate, however, for the near-surface structure of the earth in noncratonic areas such as those whose relative sea level signatures we are concerned with here, nor is it reasonable to assume that the Antarctic ice sheet continued to lose mass long after the North American ice sheet had disappeared.

The Influence of Lithospheric Thickness Variations at Far Field Relative Sea Level Sites

Figures 9, 10, and 11 compare relative sea level predictions and observations at the same 48 sites discussed above in connection with the question of the preference of the data for a significant delay in the melting chronology of Antarctic ice. The effect of thinning the lithosphere to 71 km from 196 km is to increase the amount of emergence predicted for continental coastal sites in the far field of the ice sheets such as all of those along the east coast of South America including Recife, Rio De Janeiro, Iguape, Brazil, and Rio Plato, Argentina, as well as at both North and South Morocco and Cape Blane, Mauritania. This restores the good fit to the data which was lost by delaying the melting of the Antarctic ice sheet in order to remedy the misfits to the submergence curves extending back into the range of times in which deglaciation was still going on. On the basis of these extensive new computations of

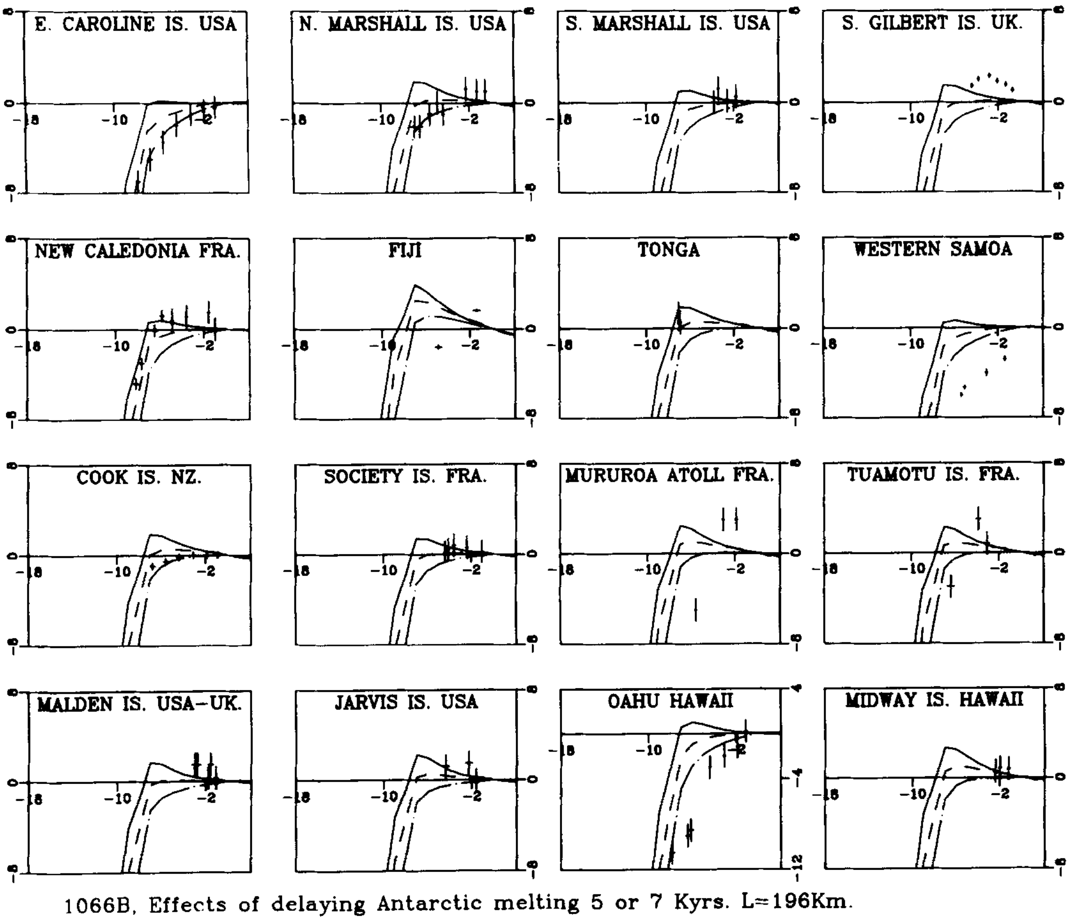


FIG. 8. Same as Figure 6, but for 16 additional sites.

relative sea level variability, this more reasonable scenario for Southern Hemisphere deglaciation is rather easily accommodated within the framework of the global model of relative sea level change if allowance is made for the trade-off between this effect and that due to variations of lithospheric thickness. The far field data do seem to require a much thinner and more conventional oceanic value for this parameter than that required to fit relative sea level data from beyond the margin of the Laurentide ice sheet in North America. However, the large misfits to the amount of emergence for far field beaches in the age range of 3000–6000 yr B.P. is also sensitive to the details of the Antarctic melting chronology.

The Influence of Detailed Characteristics of the Antarctic Melting Chronology at Far Field RSL Sites

Figures 12, 13, and 14 illustrate the influence of the modified Antarctic chronology, shown as the dashed-solid line in Figure 1, upon the relative sea level curves for the same suite of far field relative sea level sites discussed above. The observations at the 48 different geographic locations are compared with the theoretical predictions for three different combinations of earth model and deglaciation history. The deglaciation histories all have the Antarctic component delayed by 7000 years from that employed by Clark and Lingle (1979) and

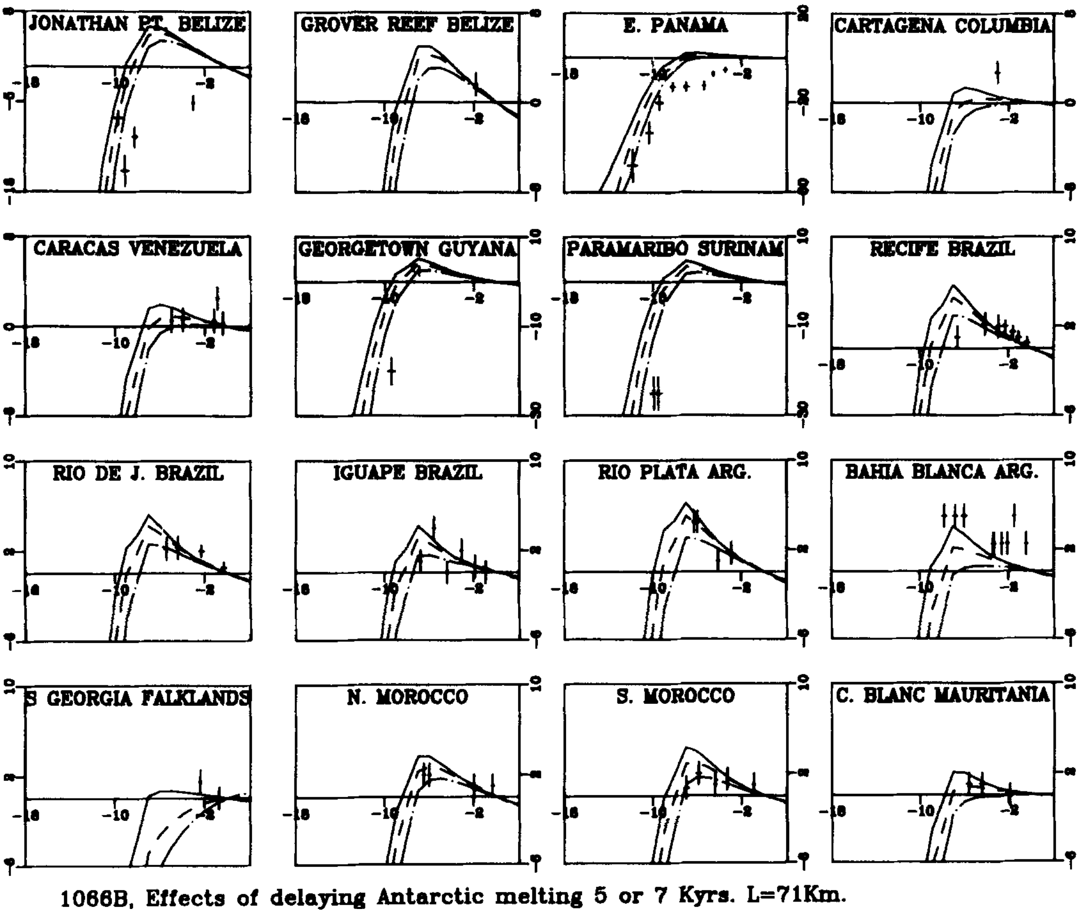
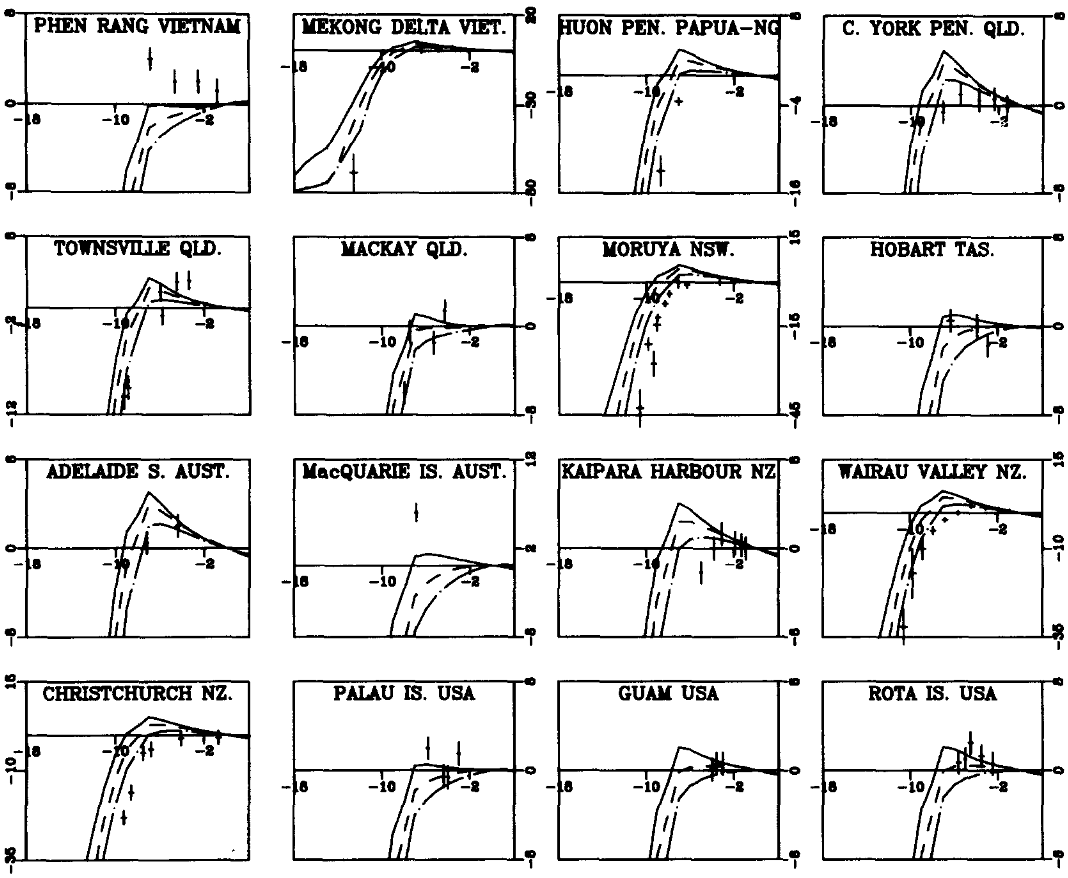


FIG. 9. Comparison of predicted and observed (error bars) relative sea level curves at the same 16 sites shown in Figure 6 but with calculations employing an earth model whose lithospheric thickness is 71 km. As in Figure 6, the solid, dashed, and dash-dotted curves compare the predictions based upon the three scenarios of Antarctic melting illustrated in Figure 1.

previously found necessary to reconcile best the time of first emergence of the land at far field coastal sites. The dashed curves on these figures are results of computation with a model in which the lithospheric thickness is 196 km and the Antarctic melting history is that described by the dashed curve of Figure 1. The solid curves on Figures 12–14 show the results of computation with the same Antarctic melting history, but for an earth model with a lithospheric thickness of 71 km, the same model for which results were discussed above. The dash-dotted curves of Figures 12–14 also show results for the earth model with lithospheric thickness of 196 km, but for these computations the Antarctic melting history is that shown by the dashed-solid curve in Figure 1. The main characteristic of this modified melting scenario is that the long "tail" on the melting curve, which is characteristic of the curves shown as dashed lines, has been "clipped." For this modified melting history it has been assumed that the Southern Hemisphere melting event, like that of the Northern Hemisphere, ended at about 6000 yr B.P.

Inspection of the results shown in Figures 12–14 shows that the influence of this rather minor modification to the melting history of the Antarctic ice sheet is to amplify very strongly the amount of emergence which is recorded at far field



1066B, Effects of delaying Antarctic melting 5 or 7 Kyrs. L=71Km.

FIG. 10. As in Figure 9, but for the same 16 sites as were employed in the thick lithosphere calculations illustrated in Figure 7.

relative sea level sites. This is in the same sense as the effect due to thinning the lithosphere. Therefore, there is a "trade-off" in the solution space of the model between lithospheric thickness and the Antarctic component of the deglaciation history. The only site that seems to reject very strongly the modified (and probably most realistic) version of the Antarctic melting chronology is the Oahu, Hawaii site. At other locations, such as Phen Rang, Vietnam; New Caledonia; and Rota Island the modified melting history is strongly preferred. Of greatest interest perhaps are the sites along the east coast of South America such as Recife, Rio De Janeiro, and Iguape, Brazil, and Rio Plata and Bahia Blanca, Argentina where the modified melting chronology is shown to provide as satisfactory a fit to the data with a lithosphere of 196 km thickness as did the model with the previous melting chronology and lithospheric thickness of 71 km. Clearly, if one is to use far field relative sea level data to constrain lithospheric thickness, then one will need to have much better a priori control on the Antarctic melting chronology than is presently available.

Delayed Antarctic Melting and North American Relative Sea Level Change

Figures 15 and 16 display predicted and observed relative sea level histories for 32 North American sites for the three model scenarios of Antarctic melting that were illustrated in Figure 1 (dashed curves). The

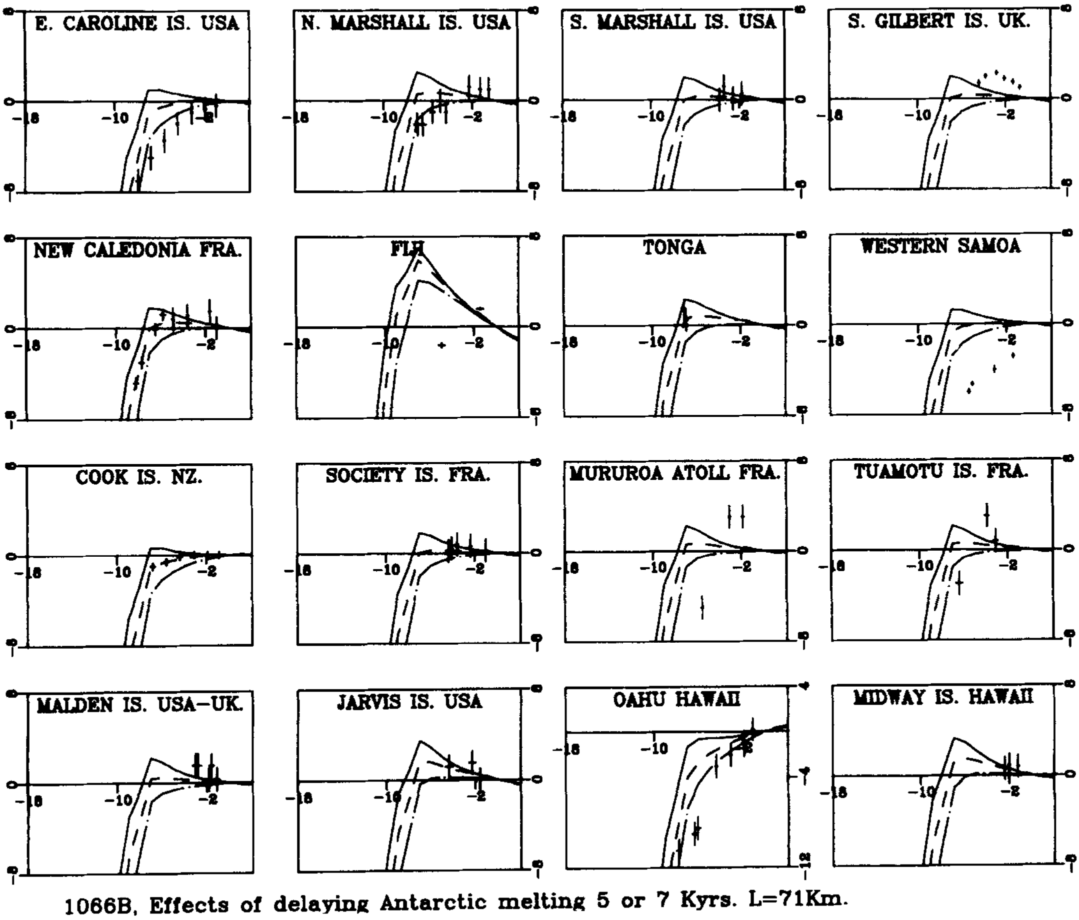


FIG. 11. As in Figure 9, but for the same 16 sites as were employed in the thick lithosphere calculations illustrated in Figure 8.

solid curve on each of these plates represents the prediction for the original scenario employed by Clark and Lingle (1979) and tabulated in Wu and Peltier (1983). The dashed lines are predictions for a new model in which the Antarctic melting event is delayed by 5000 yr and the dash-dotted curve for 7000 yr. Results for the modified Antarctic scenario shown as the dashed-solid curve in Figure 1 will not be discussed here.

Inspection of this suite of comparisons demonstrates a number of interesting aspects of the influence of the delayed Southern Hemisphere melting event on Northern Hemisphere sea level variations. The most apparent is that for sites within the margin of the ancient Laurentide Ice mass like Churchill, Manitoba; James Bay, Montreal, and Riviere du Loup, Quebec; and Southampton Island in the northern Northwest Territories the effect upon the relative sea level prediction is negligible. At such sites, the response is so strongly dominated by the vertical motion of the solid earth that even for times within the period of active deglaciation the Southern Hemisphere variability has no noticeable influence.

This ceases to be the case as one moves progressively further away from the central Laurentide dome and across the location of the margin at ice-age maximum. At these edge locations, the delayed melting of

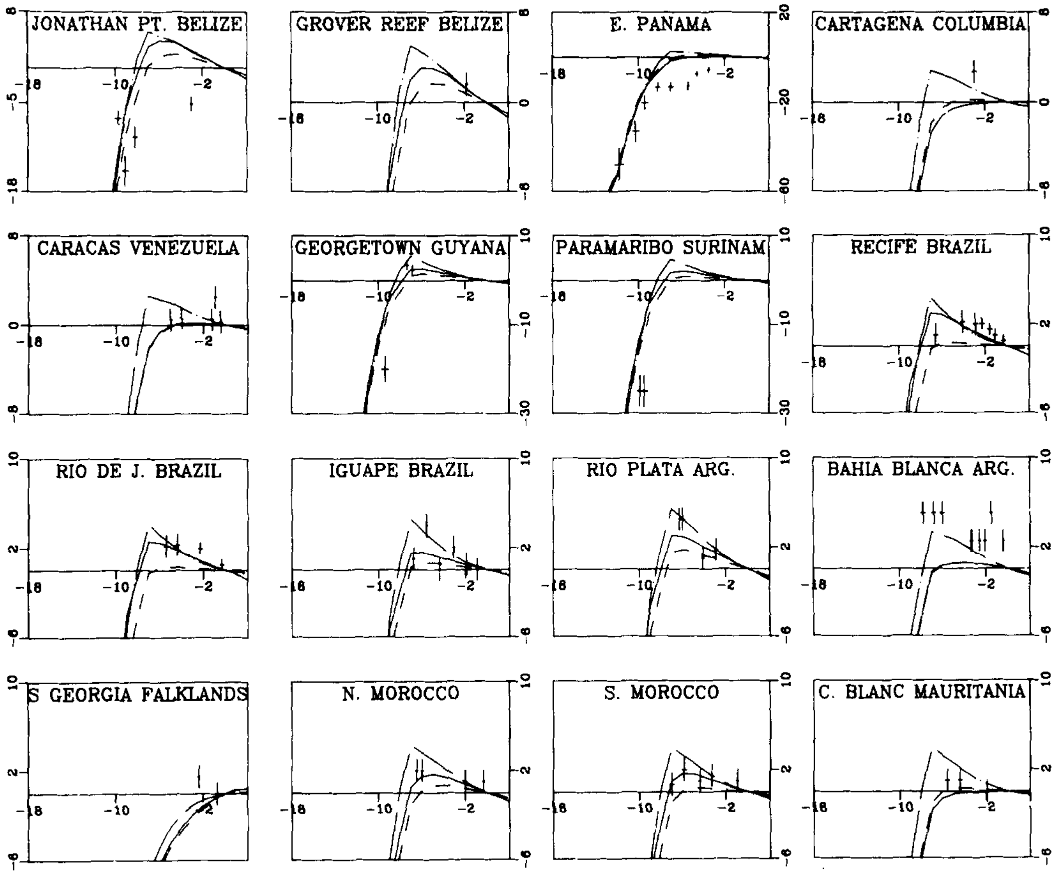


FIG. 12. Comparison of predicted and observed (error bars) relative sea level curves at the same 16 sites shown in Figure 6, but for calculations comparing the effect of lithospheric thickness variations to the effect of the modification of the 7000-yr-delayed Antarctic melting chronology shown in Figure 1. The model predictions denoted by the dashed curves employ the 7000-yr-delayed melting scenario shown as the dashed curve in Figure 1 and a lithospheric thickness of 196 km. The predictions denoted by the solid curves are based upon the same Antarctic melting chronology but employed an earth model with a lithospheric thickness of 71 km. Finally, the predictions denoted by the dash-dotted curves employed an earth model with a lithospheric thickness of 196 km, but in conjunction with the modified Antarctic melting scenario shown as the solid line in Figure 1.

Southern Hemisphere ice diminishes the predicted uplift of the land at sites inside the margin and increases the predicted submergence at sites outside the ice sheet margin, as one would expect on the simplest physical grounds. However, at most locations the effect is significant only for ages in excess of about 7000 yr during the period of active deglaciation. For later times, to which much of the ^{14}C data correspond, the effects are very small. Only at Halifax, Nova Scotia and at New York City and the continental shelf sites off the United States does this influence appear to improve the comparison between the predicted and observed relative sea level data. At some other locations, such as Daytona, Florida, the influence is somewhat adverse. Of greatest importance for our purposes here, however, is that the modification of the relative sea level prediction at sites near the crest of the glacial forebulge,

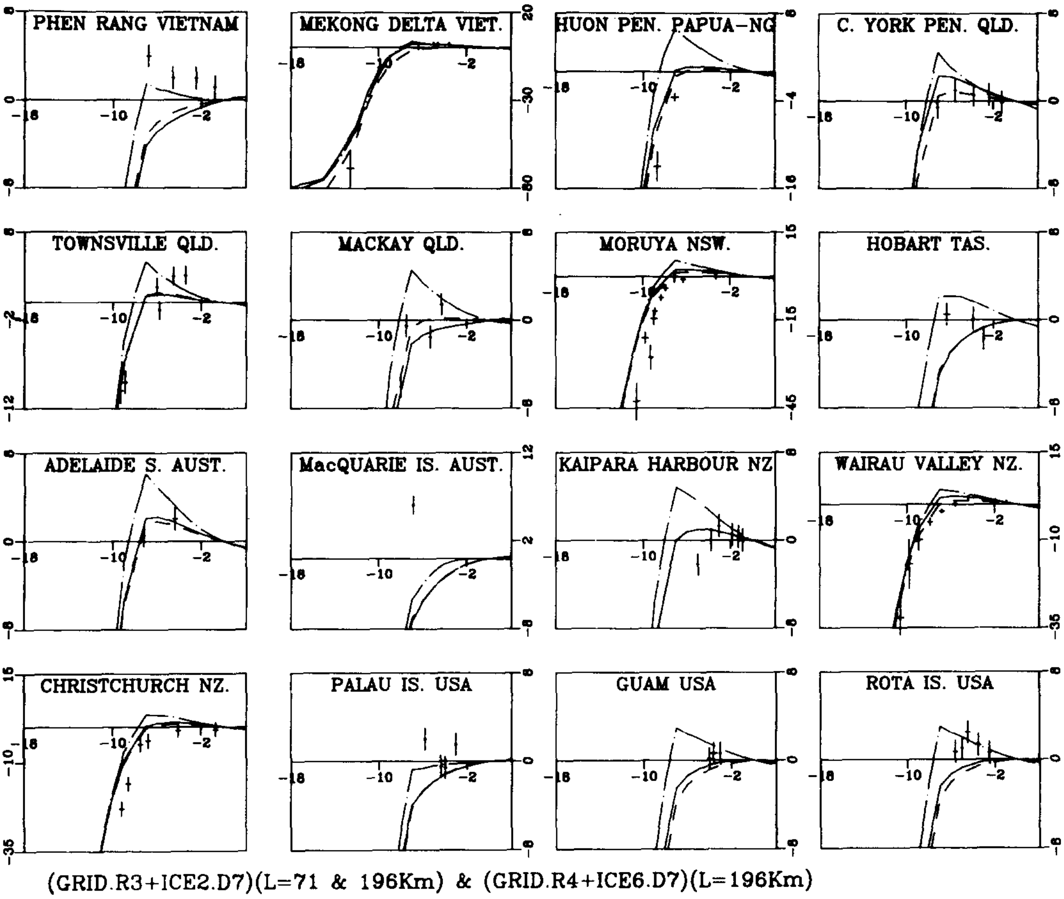


FIG. 13. Same as Figure 12, but for 16 additional sites.

such as Clinton, Connecticut; Brigantine, New Jersey; and Bowers, Delaware, is to amplify further the misfit whose sense would require a further increase of lithospheric thickness from the value of 196 km employed here. As first discussed in Peltier (1984), increasing the thickness of the lithosphere sharply diminishes the predicted submergence at sites near the forebulge crest. Since the model over-predicts the submergence back to 10,000 yr B.P. at such locations, the 196 km thickness which has been employed for these calculations would have to be further increased to rectify the misfits. Peltier (1984) found that a value of about 250 km for this parameter was required to eliminate these characteristic misfits. More recent analyses, which will be published elsewhere, demonstrate that inaccuracies in the specification of the history of melting of the Laurentide ice sheet contribute significantly to these misfits. When these inaccuracies are rectified somewhat thinner lithospheres may then be tolerated by the relative sea level data (thicknesses closer to the 120 km which are characteristic of old oceanic lithosphere).

CONCLUSIONS

The global model of postglacial relative sea level change which has been developed in the past decade of research, based upon

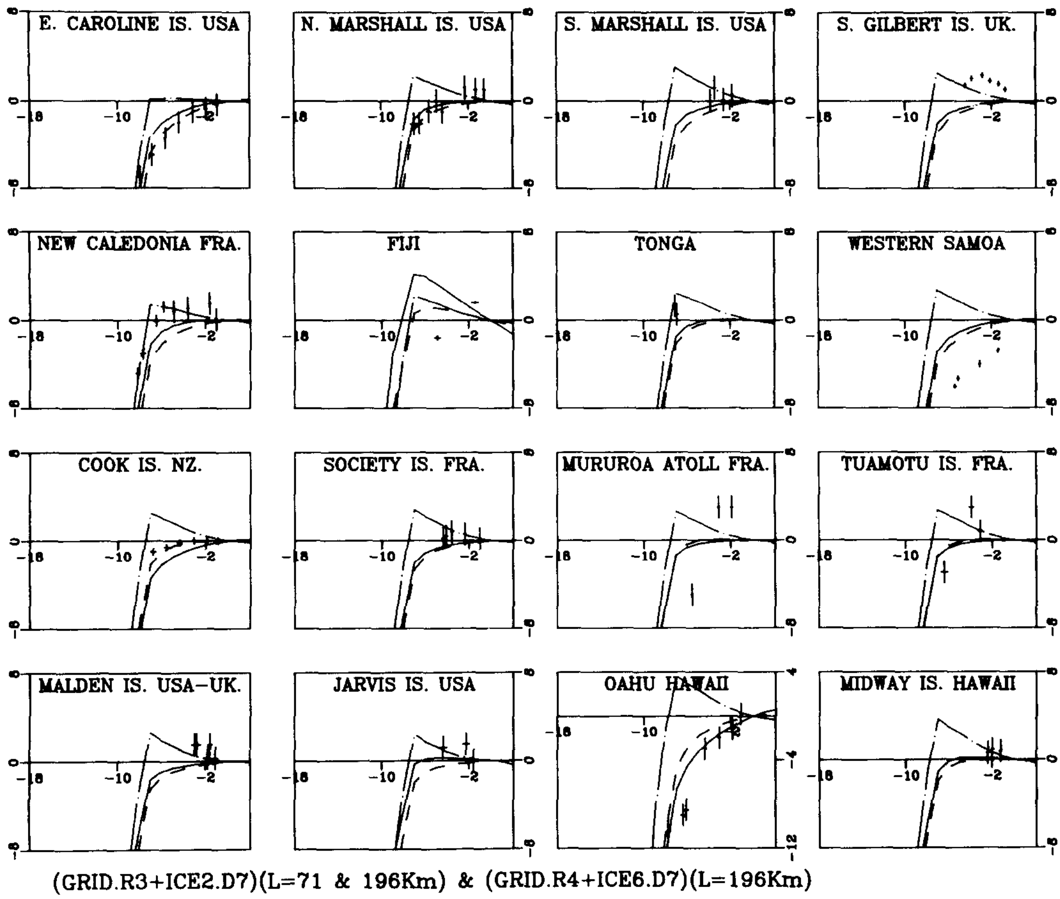


FIG. 14. Same as Figure 12, but for 16 additional sites.

the analysis of the response of a layered viscoelastic planet to surface load forcing in Peltier (1974), has proven to be an extremely useful vehicle in terms of which various elements of the radial viscoelastic structure may be quantitatively inferred. The global data base which we have assembled at the University of Toronto to use in this work now consists of relative sea level data from almost 400 sites on the earth's surface. Many of these data have been presented together here for the first time and employed to demonstrate the strong constraints which they place upon the radial viscoelastic structure of the planet and upon the deglaciation history itself. The analyses have established that the melting history of Antarctica employed by Clark and Lingle (1979) is not in accord with observations of relative sea level change. These data require that the West Antarctic ice mass must have disintegrated in phase with the disintegration of the Northern Hemisphere ice sheets, as assumed in the theory of the ice age cycle developed in Peltier (1982, 1986), Peltier and Hyde (1984), and Hyde and Peltier (1985, 1987). In this context, the phrase "in phase" means that the time of most rapid melting of Antarctic ice must essentially coincide with the time of most rapid disintegration of Northern Hemisphere ice which is near 11,000 yr B.P. (Fig 1). Also demonstrated by the analyses is the fact that the thick-

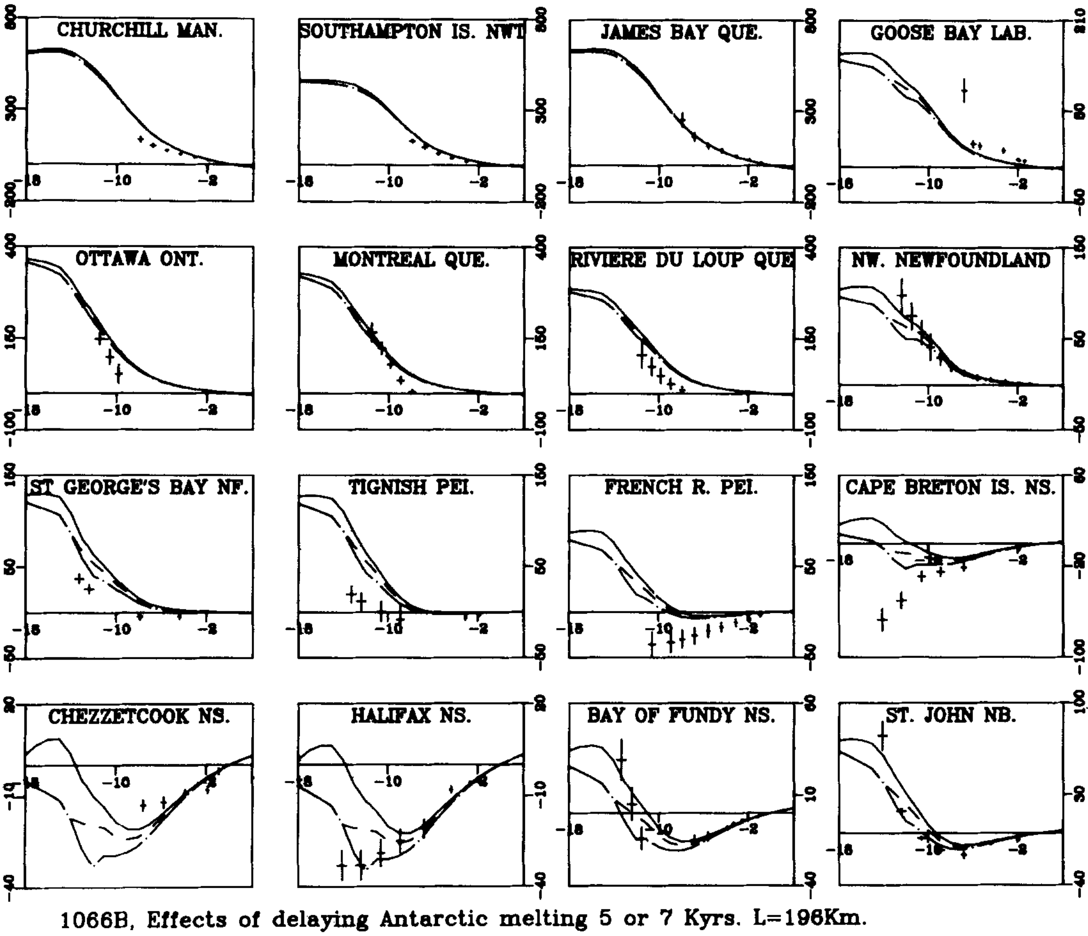


FIG. 15. Comparisons of predicted and observed (error bars) relative sea level histories at 16 North American sites illustrating the influence of the delay of Antarctic melting upon the predictions at such near field locations. As in the previously described analyses, the computational results shown as solid, dashed, and dash-dotted curves are predictions using the Antarctic melting chronology of ICE-2 and those with 5000- and 7000-yr delays, respectively. Note that the influence of this variation is extremely small at sites with the margins of Laurentian Ice and noticeable at most external sites only for times within the actual deglaciation phase which ended at about 7000 yr B.P. Subsequent to this time, within which almost all of the ^{14}C data are found, the influence is small.

ness of the lithosphere is a parameter to which most far field relative sea level data are quite sensitive, but that the signature of lithospheric thickness variations at such sites is identical with that associated with relatively minor modifications of the Antarctic component of the melting history.

This paper reports relative sea level analyses in which finite element models having higher resolution than those previously employed are being applied systematically to the optimum extraction of geophysical information from our very large relative sea level data base. It will prove possible, I believe, to obtain a great deal of valuable new information on the lateral heterogeneity of the near-surface viscoelastic structure of the planet from analyses like those described here, and to constrain much better the history of Quaternary ice sheet decay.

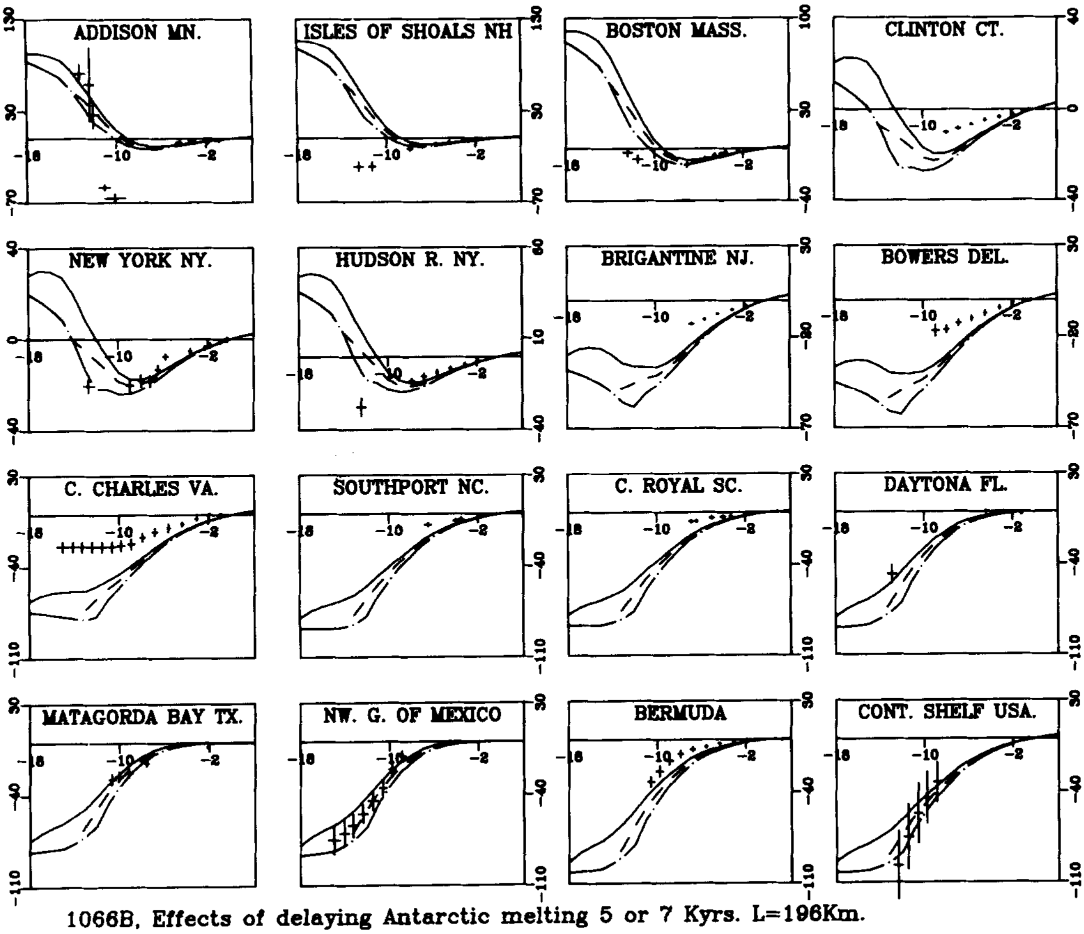


FIG. 16. Same as in Figure 15, but for 16 additional sites.

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