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Late Quaternary Sea Levels along the Atlantic Coast of North America[1]

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ABSTRACT

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The sea level record of the last 16,000 years for the east coast of North America is presented in a novel fashion so that the entire set of 736 sea level indicators can be assessed at one time. The elevation data is presented as a function of latitude and time. The results confirm the well-known processes of post-glacial isostatic rebound, eustatic transgression, and littoral subsidence, and for the first time reveal their spatial relationship. Moreover this presentation suggests that part of the sea level record reflects the collapse of an elastic forebulge, a collapse which may have migrated north following the retreat of the Wisconsinan ice sheet.

ADDITIONAL INDEX WORDS: *Atlantic coast, sea level, eustatic change, marginal ice sheet bulge, Quaternary sea levels.*

INTRODUCTION

The record of sea level change along the east coast of North America reflects a combination of eustatic, isostatic, and elastic components complicated by local, regional, presumably short-term tectonic events and trends. This paper presents a novel approach to the analysis of sea level change along the Atlantic coast for the period 16,000 years BP to the present. We have assembled a data-bank of 736 radiocarbon-dated sea level indicators gleaned from the pages of the journal *Radiocarbon*, published reports, personal communications, and from our own dating program. The data set for the North American Atlantic coast contains samples from the region between 20° and 50° N, and the time interval between 16,000 yBP and the present. (The entire data set, which includes more than 200 of our own dates [CINQUEMANI *et al.*, 1982], is available as a public data set on the City University of New York computer using the facilities of BITNET.)

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Approximately 50% of the data are basal peat samples, collected primarily by coring; 32% are shells collected *in situ* from raised beaches or dredged from the shelf; 18% are samples of various materials such as barnacles, in-place tree stumps, driftwood, and other marine sea level indicators. The location of sample sites is shown in Figure 1. Note that the geographic distribution of sampled locations recognizably defines the Atlantic coastline of North America. The samples were chosen on the basis of their apparently firm relationship to sea level. The maximum elevation of a sample above present sea level was 125 m; the maximum depth of a sample below present sea level was 150 m.

The analysis of past sea level is a 4-dimensional problem. In addition to the 3 dimensions of spatial position, there is the dimension of time (the ^{14}C age). Most previous analyses of sea level change, whether worldwide or local, have consisted almost exclusively of two-dimensional plots of sea level elevation *vs.* age for specific locations (*e.g.*, SHEPARD, 1963; REDFIELD, 1967; NEUMAN, 1971). While these analyses are quite instructive for interpretations of local sea level change, they cannot be readily used to study regional trends. NEWMAN *et al.* (1980, 1981) and PARDI *et al.* (1979) took the approach of plotting three-dimensional (time con-

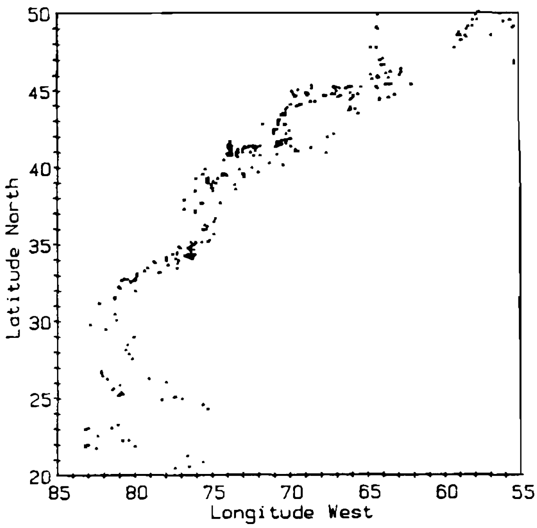

Figure 1. Geographical distribution of the 736 data points.

stant) graphs of elevation *vs.* geographic location. However, such an approach suffers from two fundamental limitations: (1) the data are not uniformly distributed geographically—all the data are coastal, and (2) it is difficult to interpret the results without using a series of such plots.

PROCEDURES

For those coastal reaches which are essentially linear like the Atlantic coast of North America, one dimension of geographic location (here, longitude) becomes superfluous. It is possible, then, to develop a presentation of the data in three dimensions distance (latitude), age, and elevation. Such an analysis defines a surface which is a deck of two-dimensional (*e.g.*, SHEPARD, 1963) sea level curves.

The advantage of this approach is that the surface is generated by calculating regularly spaced elevations over a grid which covers the entire time-distance continuum. The distribution of the original 736 data points in this time-distance space is shown in Figure 2. (Data is relatively sparse in two domains north of 42° N between approximately 6,000 and 8,000 yBP, and south of 32° N prior to 8,000 yBP. The grid values calculated in this region will therefore be less reliable than those calculated for areas with more abundant data.) Each calculated value of the 3D grid (Figures 3 and 4) is a weighted average of the six closest samples (in time-distance). Not only is the effect of erroneous data moderated (by damping the effect of "bad" radiocarbon dates or samples with an erroneous relationship to sea level), but the trend of data for sampled locations is projected into areas where data are sparse or absent. The result is a con-

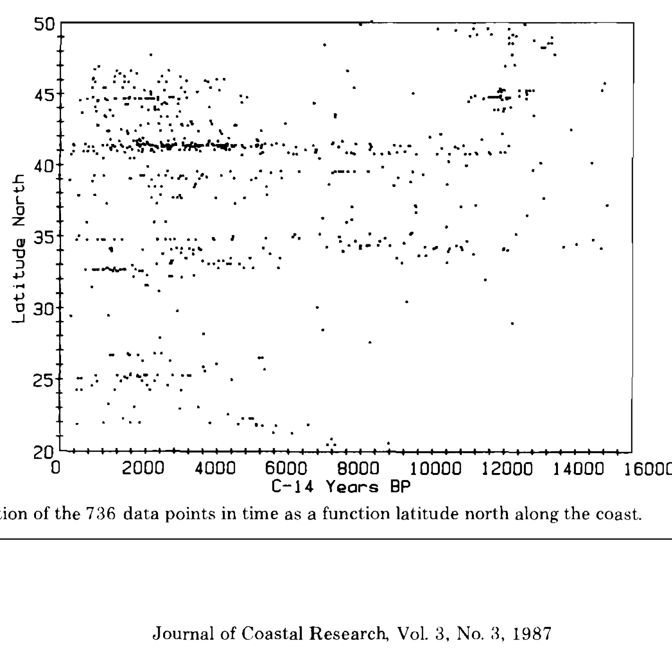

Figure 2. The distribution of the 736 data points in time as a function latitude north along the coast.

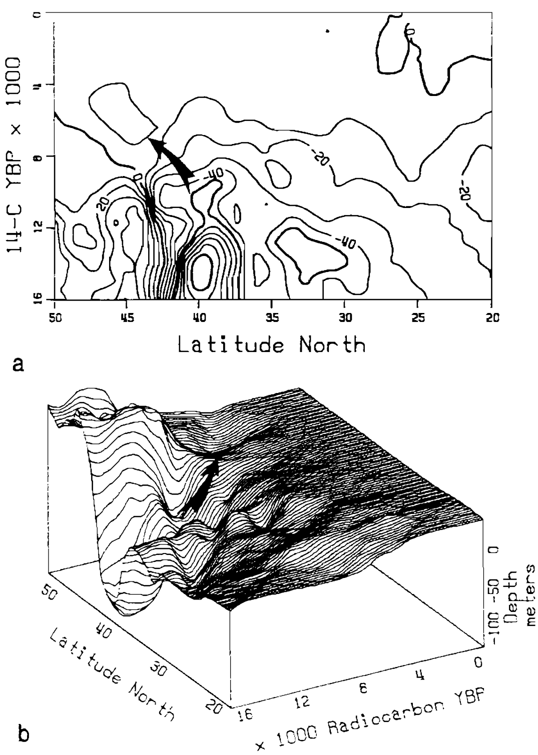

Figure 3. Elevation (metres) of sea level indicators plotted as a function of age and latitude north along the coast. In the 3D plot (b) the corner closest to the observer is 20° N and 16,000 yBP, while that farthest from the observer is 50° N and 0 yBP.

tinuous, relatively smooth surface on which both time- and distance-transgressive features are discernible.

Figures 3a, b and 4a, b present the data in a linear (Figure 3) and logarithmically transformed (Figure 4) manner, both as contour diagrams (a) and three-dimensional surfaces (b). (Values within + or − 1 m of present sea level have been plotted as 0 m in the log normalisation in Figure 4.) Since both eustatic rise in sea level and isostatic rebound are power functions of time, the log transformation helps to emphasize the detail in the sea level record of the last 6,000 years.

DISCUSSION OF RESULTS

The uneven distribution of data as seen in Figure 2 will affect the ultimate presentation of the data in Figures 3 and 4. Among the factors that have controlled that distribution are the accumulation and preservation of suitable samples, concentration of sampling effort in specific areas, and the cost of sampling.

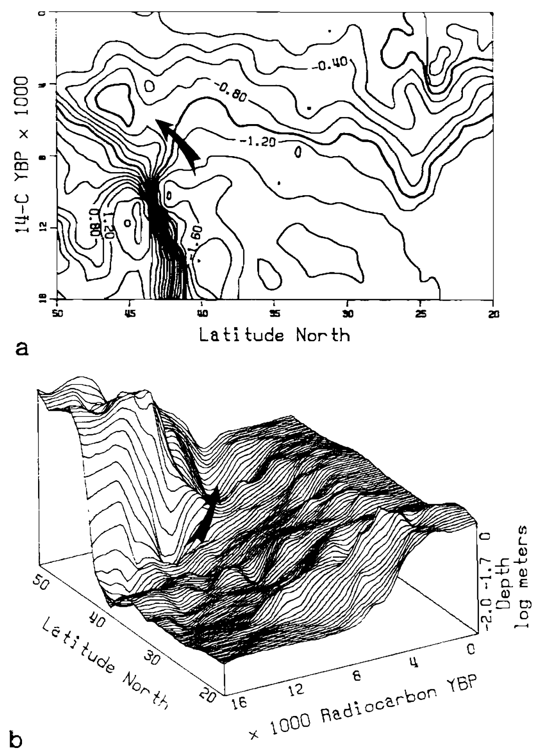

Figure 4. Logarithmically normalized elevation (log metres) of sea level indicators plotted as a function of age and latitude north along the coast. In the 3D plot (a) the corner closest to the observer is 20° N and 16,000 yBP, while that farthest from the observer is 50° N and 0 yBP. Elevations within ± 1 metre of current sea level are plotted as 0 metres.

The general decrease in data with increasing age as shown in Figure 2 is to be expected since the older a peat is, the more likely it will be destroyed by either erosion or decomposition. Since basal peats are the material of first choice as sea level indicators, the data is biased in favor of areas conducive to the accumulation and preservation of peat—namely the region between 32° and 44° N where *Spartina patens* and associated flora thrive in accessible coastal marshes. In addition, both the rate of sea level change and the environment of deposition, each of which may vary considerably along the coast, have some effect on the presence of suitable samples.

Undoubtedly, the primary reason for the uneven distribution of data in Figure 2 is a concentration of effort in limited areas along the coast. For example, the cluster of data at 40±2° derives from work by the authors on sites in the New York City Bight – Hudson River area, while much of the data at the latitude of the Carolinas reflects efforts (*e.g.* COLQUHOUN *et al.*, 1980) on earthquake-related studies in the Charleston area.

The lack of data south of 32° N prior to 8,000 yBP most likely reflects a simple lack of effort—it is probable that appropriate sea level indicators are there to be sampled. On the other hand, the hiatus north of 42° N may be due to a real lack of material. The hiatus corresponds to that period, as described below, when isostatic rebound was approximately balanced by eustatic sea level rise. The stratigraphic interval represented by samples from this period would be appreciably thinner than for periods prior to or subsequent to the hiatus, and this may have affected the course of sampling.

Most of the basal peat samples have been collected from coastal marshes adjacent to dry land, where the cost of sampling has been relatively low. Many (primarily older) basal peats oocur offshore, and the cost of recovering them has been prohibitive. Hence most such samples have been collected fortuitously as a consequence of sampling projects not necessarily related to sea level studies.

The salient features illustrated by Figures 3 and 4 are a general sea level transgression superimposed on a pronounced uplift north of 40° N and a distinctive, localized downwarping along the southern margin of the uplift.

These features were to be expected on such diagrams based on previous detailed discussions. Worldwide post-glacial eustatic rise in sea level is well documented (SHEPARD, 1963; REDFIELD, 1967). Glacio-isostatic rebound of eastern North America was discussed by WALCOTT (1972) among many others. Peripheral subsidence of the New York bight has been attributed to either the collapse of a forebulge (as per DALY, 1920) along the edge of what was a previously ice-covered region (FAIRBRIDGE and NEWMAN, 1968; NEWMAN *et al.*, 1971) or to neotectonic deformation. Modern geodetic measurements in the lower Hudson region reveal both significant vertical crustal movement (PARDI, 1981) and horizontal deformation (ZOBACK *et al.*, 1985; SNAY, 1985).

Figures 3 and 4, especially the logarithmically transformed data in Figure 4b, also illustrate a number of minor features—an increase at about 12,000 yBP in the rate of relative sea level rise for the coastal region between 25° N and 33° N, relative uplift of the region centered about 35±2° N during the period 16,000 to 10,000 yBP, and a suggestion that at least a portion of the subsidence of the New York bight is time- and distance-transgressive, as indicated by a sharp decrease at about 8,000 yBP and younger in the rate rebound north of 40° N.

The possibility that changes in the rate of sea level rise in the coastal region south of 30° N can be attributed to tectonic activity has been discussed by COLQUHOUN *et al.* (1981) and STAPOR and MATHEWS (1983). Uplift of the Chesapeake Bay region (around 37° N) sometime in the last 15,000 years has been documented by HARRISON *et al.*, while the Chesapeake Bay area is known to be subsiding at present much more rapidly than can be explained by eustatic sea level rise alone (WALCOTT, 1972; BROWN and OLIVER, 1976). The possibility that the collapse of a peripheral bulge migrating north (arrows, Figures 3 and 4) as the last ice-sheet retreated has been suggested as an explanation for anomalously transgressive periods in coastal regions north of 40° N where isostatic rebound would be expected to dominate (GRANT, 1975; SCOTT and MEDIOLI, 1982). On theoretical grounds MCGINNIS (1968) had concluded that the magnitude of any forebulge would be too small to be observed in the geologic record; however, the evidence presented here suggests that such a conclusion would have been premature. As discussed in detail be CATHLES (1975), the presence of a relatively minor peripheral bulge (maximum amplitude of 30 to 40 m) which migrates *northward* has important implications for models of the viscosity distribution within the mantle—namely, that the mantle has a rather uniform viscosity distribution overall (about 10^{22} poise) with only a thin upper (about 75 km thick) channel of low viscosity (about 10^{20} poise).

CONCLUSIONS

By eliminating one dimension in the analysis of past sea levels it is possible to display *en masse* regional series of sea level indicator data. This approach would be valid for any coastline, but is especially appropriate for semi-linear coasts such as the eastern margin of North America.

When this approach is taken for an analysis of actual sea level data for the eastern North America the results can be directly evaluated in terms of eustatic, isostatic and elastic components. This presentation supports the concept of a peripheral bulge marginal to the continental ice sheet; a bulge collapse which migrated north and rapidly dissipated with time.

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□ RESUMEN □

Se presenta en este articulo del nivel del mar de los últimos 16.000 años de la coste Este de Norteamérica evaluando al tiempo un grupo de 736 indicadores de nivel del mar. Los datos de nivel se presentan como una función de la latitud y del tiempo. Los resultados confirman el ya conocido proceso post-glacial de isostasia, transgresión eustática y subsidencia litoral, y por primera vez manifiestan una correlación espacial.--*Miguel A. Losada, Universidad de Cantabria, Santander, Spain*

□ ZUSAMMENFASSUNG □

Die Meeresspiegelaufnahmen der letzte 16.000 Jahre wird neuartig dargestellt, um alle 736 Meeresspiegelanzeiger gleichzeitig geschätzt werden. Die Höhendaten wird dann als eine Zeit- und Breitfunktion dargestellt. Die Ergebnisse bestätigen solche wohlbekannte Prozesse als den nach der Eiszeit vorkommenden isostatichen Rückprall, eustatische Überschreitung, und littoralische Senkung; erstmals offenbaren sie ihrer Raumverwandtshaft. Diese Darstellung schlägt auch vor, dass ein Teil der Meeresspiegeldaten das Zusammenbruch einer elastichen Ausbauchung reflektiert; vielleicht zöge diese Ausbauchung nach dem Rückzug des Wisconsingletschers fort. --*Stephen A. Murdock, CERF, Charlottesville, Virginia, USA*

□ RÉSUMÉ □

Les niveaux marins des 16.000 dernières années somt présentés de telle sorte que les 736 indicateurs du niveau soient fixés en une fois. Les données d'élévation sont présentées en fonction de la latitude et du temps. Ces résultats confirment le processus des contre-coups isostatiques post-glaciaires, la transgression eustatique et la subsidence littorale, et pour la première fois, révèlant leurs relations dans l'espace. De plus, cette présentation suggère qu'une partie des données sur les niveaux marins reflète l'effondrement d'un pré-bombement élastique, effondrement qui pourrait avoir migré vers le Nord en suivant le retrait de la calotte Wisconsinienne.--*Catharine Bressolier, EPHE, Montrouge, France*