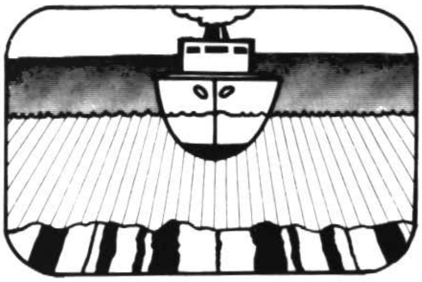

Age of the Ocean Floor: A Digital Data Set for the Labrador Sea and Western North Atlantic[1]

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ABSTRACT

A digital grid of ocean floor ages was constructed from a combination of magnetic anomaly identifications and recent plate kinematic models of the North Atlantic and Labrador Sea. Comparing large gridded geophysical data sets with these gridded age values is a powerful means of studying the variation of geophysical parameters with lithospheric age, and the dynamic processes in the Earth. The data set from the western North Atlantic and Labrador Sea shows the dependence on age of bathymetry, depth-to-basement and gravity.

INTRODUCTION

One of the key observations that led to the acceptance of plate tectonics in the early 1960s was that of magnetic anomalies over mid-ocean ridges. Mike Keen was among the first to observe a pattern of relatively short wavelength magnetic anomalies along profiles crossing the mid-Atlantic Ridge (Keen, 1963) but, at that time, did not observe the rather faint symmetry of the anomalies across the ridge. Using magnetic anomalies along the Carlsberg Ridge (Indian Ocean), Vine and Matthews (1963) subsequently formulated the hypothesis that these marine magnetic anomalies originated at the crest of mid-ocean ridges and that their sources were moved away from the ridge crest by sea-floor spreading. A similar inference was independently made by Morley, whose paper was rejected by *Nature* and by the *Journal of Geophysical Research*, but was partly included in a later publication (Morley and LaRochelle, 1964).

It is now widely accepted that sea-floor spreading magnetic anomalies are caused by a remanent magnetization acquired by oceanic crust after formation along mid-ocean ridges and cooling below the Curie temperature of its magnetic minerals. The reversals in the Earth's magnetic field then give rise to the formation of "stripes" of normally and reversely magnetized crust, and alternating positive and negative magnetic anomalies (Fig. 1). Sequences of anomalies can be recognized from their distinctive patterns, and their age can be calibrated using a geomagnetic polarity time scale (Kent and Gradstein, 1986), which enables mapping of the age of the ocean floor. Knowledge of the age of the ocean floor at each position then allows the study of geophysical and geochemical oceanic data as a function of age.

At present, we are creating a digital world data set with interpreted values for ocean floor ages. This new data set uses directions of sea-floor spreading based on recent plate kinematic models, in addition to identified

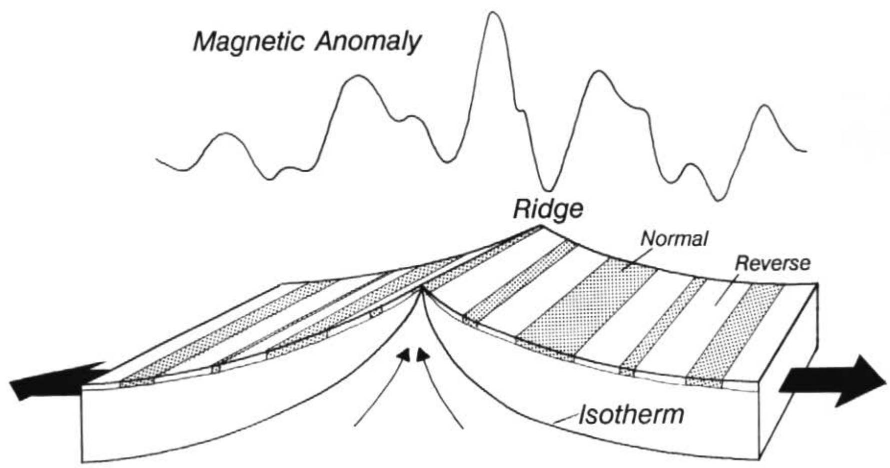

Figure 1 *Oceanic crust is magnetized at the crest of mid-ocean ridges and transported away by sea-floor spreading. Due to polarity changes in the Earth's magnetic field, this process results in stripes parallel to the ridge that are normally (shaded) and reversely magnetized and associated with positive and negative magnetic anomalies. The cooling of the lithosphere as it moves away from the ridge axis is indicated by deepening of the ocean floor and an arbitrary isotherm.*

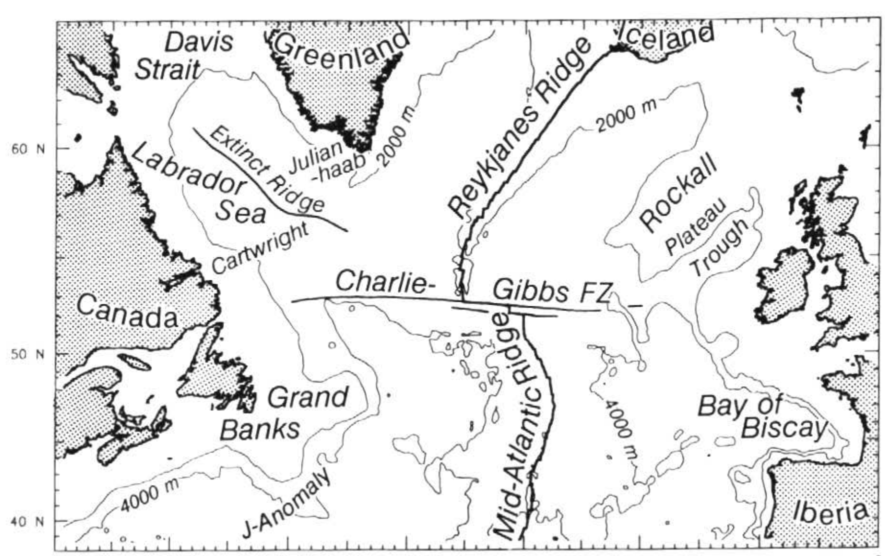

Figure 2 *Tectonic elements of the study area and surroundings. Generalized bathymetric contours show the Mid-Atlantic Ridge, Reykjanes Ridge, the Charlie-Gibbs Fracture Zone, Rockall Plateau and Trough. Neither the J-anomaly ridge nor the extinct spreading ridge and the Julianhaab/Cartwright Fracture zone in the Labrador Sea are visible in the bathymetry.*

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magnetic anomaly locations. In this paper, we present the data set for the Labrador Sea and western North Atlantic (Fig. 2).

MAPPING THE AGE OF THE OCEAN FLOOR

Several analog maps of the age of the ocean floor have been compiled using magnetic anomaly data (*e.g.*, Sclater *et al.*, 1981; Larson *et al.*, 1985). A digital version of the latter map was produced by Cazenave *et al.* (1988), at a grid interval of half a degree (approximately 55 km). There are two reasons for the construction of a more detailed age grid. First, recent improvements in identifications of magnetic anomalies and plate kinematic models permit a more detailed description of the spreading process (*e.g.*, Roest and Srivastava, 1989; Royer and Sandwell, 1989; Shaw and Cande, 1990). Second, worldwide sets of geophysical data (such as bathymetry and gravity) are now available at grid intervals of 5 arc-minutes (NGDC, 1988; Haxby, 1988) or even smaller.

The computation of a grid of the age of the ocean floor is based on identified magnetic anomalies, interpreted as magnetic isochrons. To interpolate their ages onto a regular grid, several assumptions are made. In the first place, we assume that the isochrons are continuous, which is achieved by interpolating between observation points along each isochron (Müller *et al.*, 1990). To ensure the best possible coverage, continuous isochrons are constructed by superimposing conjugate observations, *i.e.*, magnetic anomaly identifications of the same age observed on both sides of a mid-ocean ridge (Fig. 3A). Secondly, we assume that the spreading direction between two adjacent isochrons is given by a constant pole of motion (Fig. 3B), derived from plate kinematic models. Finally, it is assumed that the spreading velocity between two adjacent isochrons is constant and that, consequently, the age varies linearly in the direction of spreading. To simplify the calculations, each pair of adjacent isochrons is transformed to a co-ordinate system where the pole of motion between the two isochrons is the north pole (Fig. 3C). The interpolation can then simply be performed along east-west parallels (Fig. 3D). After the interpolated isochrons are transformed back into the present-day framework, a minimum curvature routine (Smith and Wessel, 1990) is used to obtain age values on a regular grid. The file with digital age values of the world's oceans will ultimately be accompanied by several additional data sets, containing, for example, error estimates, local spreading directions and rates, and the paleolatitude at which the crust is inferred to have formed.

The anomaly identifications for the North Atlantic and Labrador Sea used for constructing the isochrons were compiled and digitized at the Atlantic Geoscience Centre (*cf.* Srivastava *et al.*, 1990). Poles of rotation were derived from various published sources, summarized by Müller and Roest (in press). A preliminary age grid for the oceans off eastern Canada is shown in Figure 4A. It has been suggested that sea-floor spreading propagated northward from the Labrador Sea *via* Davis Strait into Baffin Bay (Roest and Srivastava, 1989). However, due to large shear motions, magnetic anomalies in Davis Strait can not be identified, and the Strait may contain fragments of continental crust as well. Consequently, no age estimates are provided for Davis Strait.

GEOPHYSICAL DATA VERSUS AGE

The theory of sea-floor spreading implies that there are systematic variations in the age of the oceanic crust. When first proposed, the theory triggered the study of various geophysical data sets as a function of the age of the oceanic lithosphere. Water depth increases and heat flow decreases systematically away from mid-ocean ridges, and their variations with age were the first to be successfully explained by thermal models of an oceanic lithosphere that cools as it

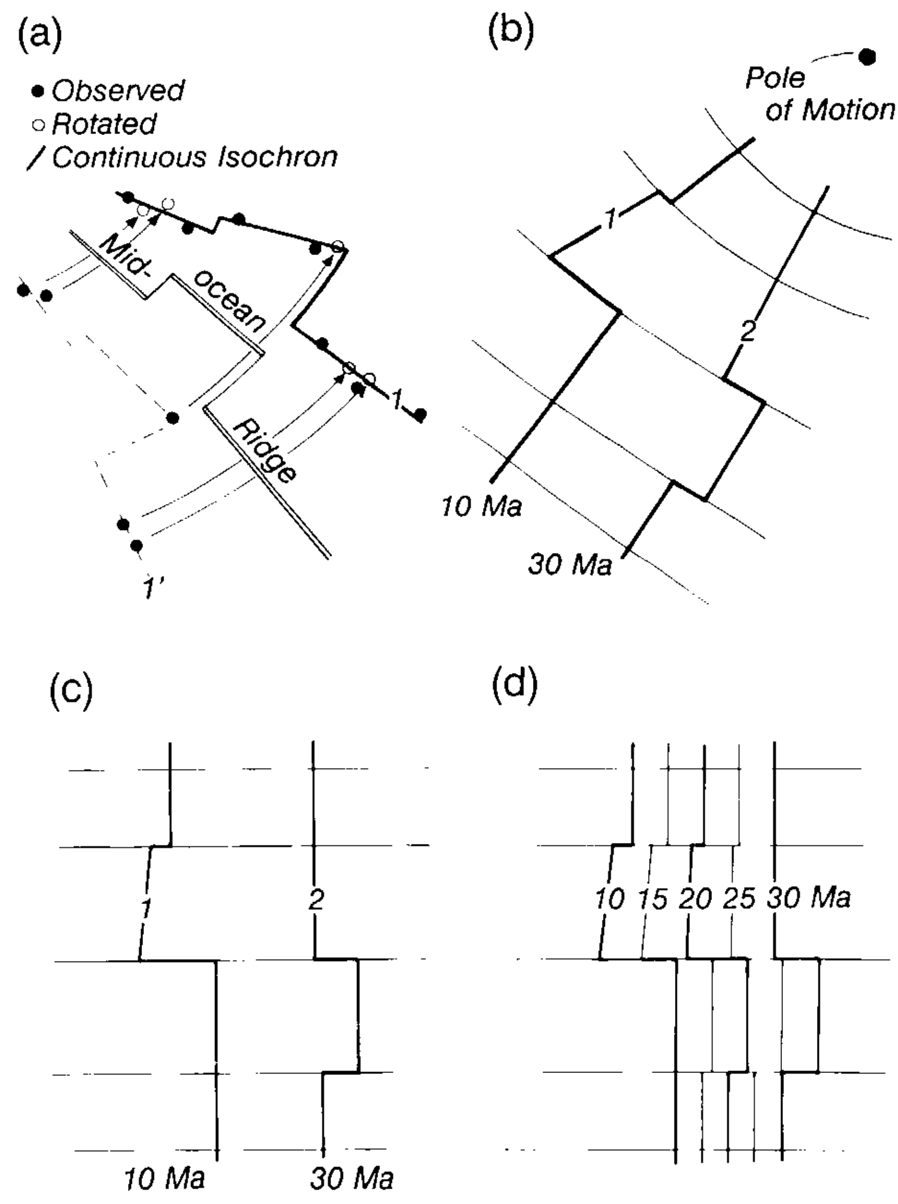

Figure 3 **(A)** *Construction of continuous isochrons using magnetic anomaly identifications along an arbitrary isochron (labelled 1) and its conjugate (1') on the opposite side of a mid-ocean ridge. Filled circles represent magnetic anomaly identifications, observed on individual magnetic profiles. Open circles are rotated observations from isochron 1' on the opposite side of the mid-ocean ridge, using a reconstruction pole of rotation obtained from a plate kinematic model.* **(B)** *The sea-floor spreading direction between adjacent isochrons 1 and 2 located on the same side of a mid-ocean ridge is given by a constant pole of motion.* **(C)** *After transformation to a new co-ordinate system, the direction of spreading becomes east-west.* **(D)** *Intermediate isochrons are calculated by east-west interpolation.*

moves away from the ridge crest (McKenzie, 1967; McKenzie and Sclater, 1969; Sclater *et al.*, 1971; Cochran and Talwani, 1977). More recently, ocean floor ages have been used in studies on age variation of the geoid, on the geochemistry of oceanic crust and on crustal thickness, both on global (Klein and Langmuir, 1987; Cazenave *et al.*, 1988; Klein, 1991) and regional scales (Marquart, 1991; Marks *et al.*, 1991). Those studies indicate that thermal models of a cooling lithosphere are able to predict many important characteristics of the oceans, but that significant deviations exist as well. For example, thermal models do not explain why variations exist in the depth of ocean floor at zero age, *i.e.*, at the crests of mid-ocean ridges (*e.g.*, Le Douaran and Francheteau, 1981). This observation leads to questions such as: is the depth variation along ridge crests constant in time; and is there a relation between measurable parameters of old ocean crust (such as composition and crustal thickness) and the depth at which this crust was originally formed at the ridge? Several of Mike Keen's latest publications dealt with these questions (Keen *et al.*, 1990, in press).

By correcting observations of parameters such as gravity and bathymetry for predicted variations with age, one can obtain the spatial distribution of residual values, which forms a key in understanding the dynamic processes in the earth (*cf.* Phipps Morgan,

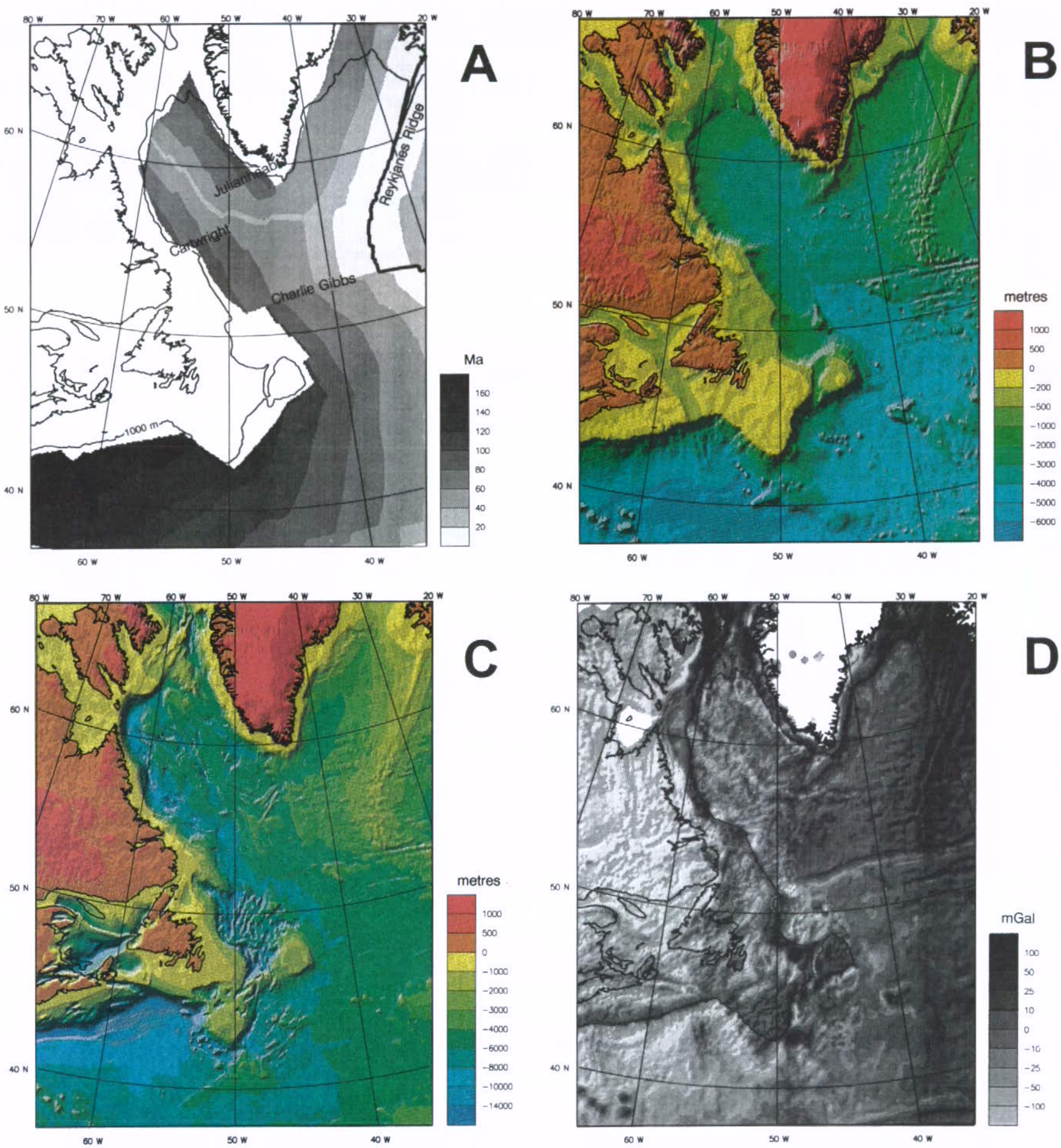

Figure 4 (**A**) *Age for the Labrador Sea and western North Atlantic in millions of years (Ma).* (**B**) *Colour-shaded relief map of bathymetry, illuminated from the northwest.* (**C**) *Shaded relief of depth to basement.* (**D**) *Black-and-white-shaded relief map of gravity anomalies, free-air at sea and Bouger on land.*

1991, which includes an extensive reference list). Significant questions are: what is the relative importance of the different forces that drive plate motions (*cf.* Forsyth and Uyeda, 1975); how are mid-ocean swells such as Iceland and the Azores supported (Courtney and White, 1986); and are hot spots fixed in the mantle or do they show relative motion (Duncan and Richards, 1991)? It is outside the scope of this paper to address these questions, but we would like to stress that the availability of an accurate age grid allows the efficient study of many important scientific problems. Here, we restrict ourselves to a description of the first-order variation of some geophysical parameters with age, as observed in the oceanic regions off eastern Canada.

The Labrador Sea and western North Atlantic have been well surveyed by the Bedford Institute of Oceanography, international institutes and industry, resulting in an excellent coverage of bathymetric, seismic reflection, magnetic and gravity data (*e.g.*, Bell, 1989). The area shown in Figure 2 is complex, with past motion between several plates (Roest and Srivastava, 1989; Srivastava *et al.*, 1990). Sea-floor spreading in the central North Atlantic started with the separation of North America and Africa (about 175 Ma). As can be seen in Figure 4A, by the narrowing of the colour bands, the spreading rate gradually decreased until about 135 Ma, when the breakup between Iberia and the Grand Banks of Newfoundland occurred. After that, sea-floor spreading progressed northward, with a rift first developing in Rockall Trough and then in the Labrador Sea. Simultaneously, Iberia rotated away from Eurasia, thereby opening the Bay of Biscay. At about 60 Ma, spreading started along the Reykjanes Ridge between Greenland and Eurasia. This led to the development of a triple-junction south of Greenland, and a relatively fast northward motion of Greenland. It also led to the unprecedented opening of a large transform fault (Julianhaab/Cartwright Fracture Zone; Fig. 2), which became an oblique spreading centre, clearly visible in the age map (Fig. 4A). Finally, just before chron 13 (36.5 Ma), spreading in the Labrador Sea stopped. The now-extinct mid-ocean ridge is covered by sediments and, as a result, does not show the bathymetry (Fig. 4B). However, it is clearly present in both the depth-to-basement map, compiled by Oakey *et al.* (1989) from several published sources (Fig.4C), and the free-air gravity anomalies (Fig. 4D). Other outstanding features in the geophysical data presented in Figures 4B-D are the high-standing Reykjanes Ridge, the Charlie-Gibbs Fracture Zone that offsets the Mid-Atlantic Ridge, and the deep basins along the North American margins with associated free-air gravity lows.

RESULTS

The age dependency of the geophysical parameters of Figures 4B-D is illustrated by averaging these values over periods of 1 m.y. These averages are shown in Figure 5A, together with their standard deviations and a histogram of the number of gridpoints contributing to each average. The averages were obtained from data covering the different tectonic regimes in the study area, which may be the explanation for the rather large standard deviations. However, due to the geometry of the spreading ridges, the area can be divided quite naturally into different age segments. The central Atlantic forms the part older than about 130 Ma. Between chrons 34 and 25 (84 Ma and 59 Ma, respectively), the North Atlantic and the Labrador Sea formed one single spreading system with only limited rifting taking place

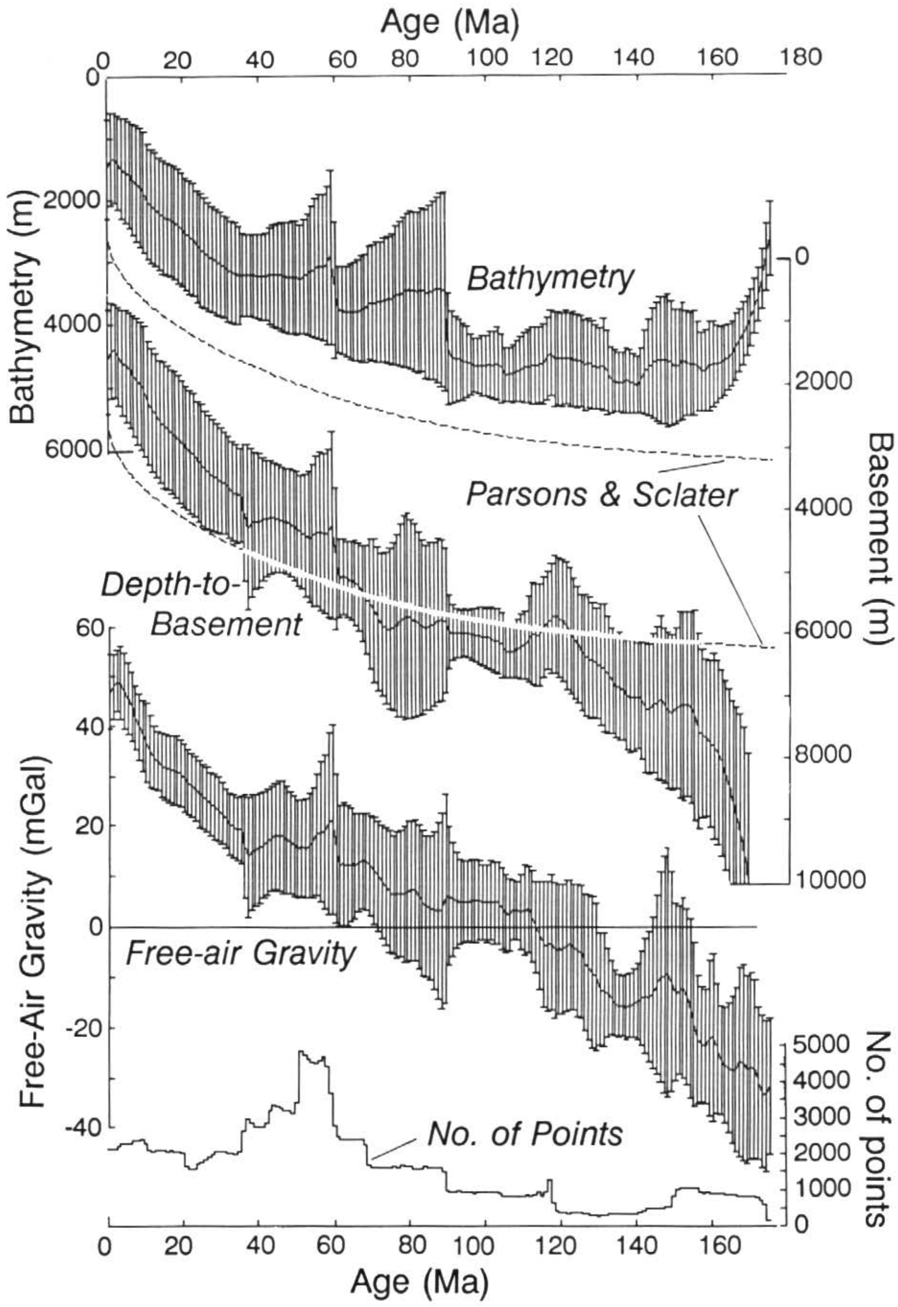

Figure 5 **(A)** *From top to bottom are shown bathymetry, depth-to-basement and free-air gravity, as a function of lithospheric age. Values are averaged over periods of 1 m.y., standard deviations are indicated by vertical lines. The histogram at the bottom shows the number of points in each age band, total number of points being about 250,000.* **(B)** ***(opposite page)*** *Averaged profiles of bathymetry and depth-to-basement. Two different formulas were used to obtain depth-to-basement corrected for sediment loading (curves 1 and 2; see text). The Parsons and Sclater (1977) empirical depth-age curve is shown for comparison. Various tectonic events are visible as disruptions of the general trend.*

between Greenland and Eurasia. Finally, the part of the area younger than chron 24 (56 Ma) is almost entirely formed along Reykjanes Ridge, after sea-floor spreading started between Greenland and Eurasia.

The curves in Figure 5A show disruptions caused by the various breakup events. The breakup between Iberia and the Grand Banks (about 135 Ma), the initial opening of the Labrador Sea (about 90 Ma), the start of spreading along Reykjanes Ridge (60 Ma), and the end of spreading in the Labrador Sea (37 Ma) are clearly visible. The basement high near 120 Ma is caused by the J-Anomaly Ridge (Fig. 2), possibly associated with subaerial spreading, comparable to the present configuration of the Reykjanes Ridge and Iceland. Many of the characteristics seen in the bathymetry and depth-to-basement curves are also reflected in the free-air gravity. The gravity anomalies are generally positive for ocean floor younger than about 120 Ma.

The bathymetry in the study area is about 1500 m shallower than the depth-age curve of Parsons and Sclater (1977). However, their empirical curve is based on depth-to-basement values that were corrected for sediment loading. The accumulation of sediments results in a shallowing of the sea floor and a deepening of basement depth due to isostatic compensation. To investigate the influence of sediments in the study area, Figure 5B shows the bathymetry, depth-to-basement and depth-to-basement corrected for sediment loading. This correction was calculated assuming a local, Airy-type, isostatic compensation. Two models were used to obtain the total mass of the sediment column at each location; for curve 1, we assumed a constant sediment density (2.5 g•cm $^{-3}$) and for curve 2, we used a — perhaps more realistic — sediment density that increases with depth (Cazenave *et al.*, 1988). It appears that the shape of curve 2 is closest to the Parsons and Sclater curve, with values that are still about 1000 m too shallow, except for crust older than about 90 Ma.

Figure 5 shows that the older ocean floor, which is mainly located in the region south of the Charlie Gibbs fracture zone (Fig. 2), is at about the "correct depth", whereas the younger ocean floor is too shallow. If this difference can be ascribed to the thermal anomaly caused by the Iceland hot spot, it would indicate a very large lateral extent of its influence. White and McKenzie (1989) argue that the Iceland hot spot was responsible for the occurrence of flood basalts along the continental margins during the early opening between Greenland and northwest Europe at about 60 Ma. They estimate that the extent of hot-spot influence at that time was about 2000 km in diameter. The convecting mantle in the hot spot caused a dynamic uplift reaching a maximum of 1000-2000 m, which agrees with the present depth anomaly.

A logical next step in mapping the present extent of possible hot-spot activity is the construction of a detailed depth anomaly chart, obtained by subtracting at each gridpoint the predicted ocean depth (derived from the Parsons and Sclater curve) from the sediment-corrected depth-to-basement value. This will allow us to clearly map the area that is too shallow. Since hot-spot activity is generally not symmetric with respect to the ridge axis, comparison of depth anomalies at conjugate locations is a powerful way to study the spatio-temporal distribution of hotspots. Comparison of anomalous depth profiles along isochrons at different lithospheric ages and on both sides of mid-ocean ridges will also resolve the question of whether or not the presently observed axial depth variations existed in the past.

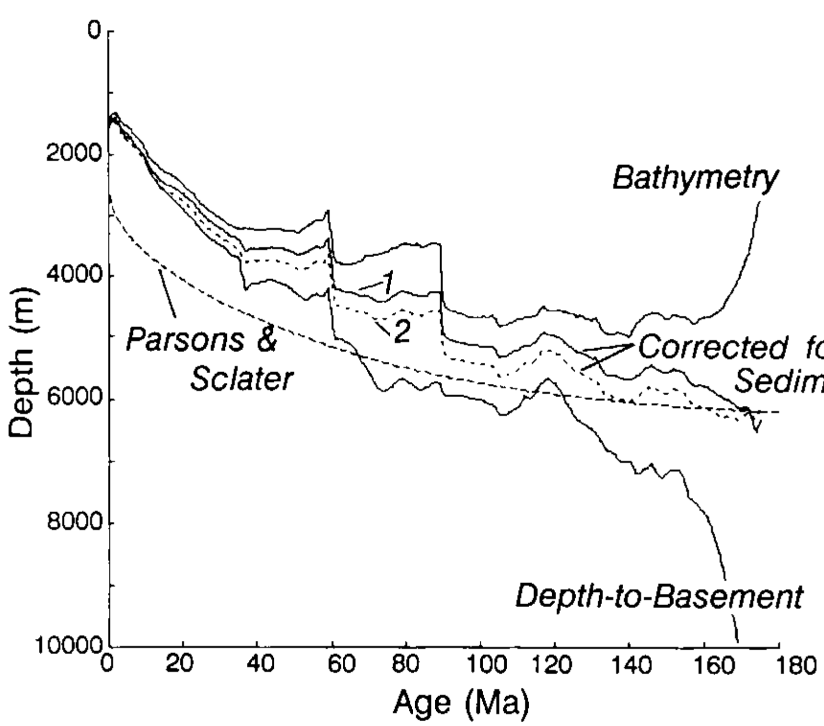

Figure 5 *(continued).*

CONCLUSIONS

A digital age file of the western North Atlantic and Labrador Sea was used to obtain the bathymetry, gravity and depth-to-basement as a function of age. The different periods of continental break-up in this area are clearly visible as disruptions in the geophysical parameters as a function of age. The area north of the Charlie-Gibbs Fracture Zone is characterized by a positive depth anomaly of about 1000 m, related to the Iceland hot spot. Along the eastern margin of North America, the corrected depth, *i.e.*, the depth-to-basement corrected for sediment loading, appears to be in good accordance with predicted values, indicating that this simple correction removes most of the effects of the large sedimentary basins.

With the availability of a digital age file, dynamic processes in the Earth can be studied efficiently. In addition, this digital data set allows several mathematical products to be derived in a straightforward manner. For example, the horizontal derivative of age in the direction of sea-floor spreading yields the reciprocal spreading velocity, and numerical integration can be used to obtain the surface extent of ocean floor of a particular age. Also, revision of a world age grid in case of significant changes in the geomagnetic time scale becomes a simple mathematical operation.

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Mike Keen's enthusiasm in the analysis of crustal thickness data in the world's oceans (*cf.* Keen *et al.*, in press) and discussions on what he called a "dial-an-age" data base initiated our interest in a digital age grid. Shiri Srivastava provided the digitized magnetic anomaly identifications used in the construction of the isochrons. We thank Jean-Yves Royer for his advice and many helpful discussions, Mark Pilkington for constructive comments on an earlier version of the manuscript, and David Piper for a careful review. RDM thanks the sponsors of the Paleo-Oceanographic Mapping Project at the University of Texas at Austin for their financial support for constructing the isochron chart.

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