Gravity Anomalies, Regional Elevation, and the Deep Structure of the North Atlantic

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The pattern of depth and gravity anomalies in the North Atlantic Ocean was examined by using $1^\circ \times 1^\circ$ and $5^\circ \times 5^\circ$ averages. The gravity field is dominated by two features: a broad high in the northern and central portion of the ocean and a large area of very negative anomalies in the western basin. The negative anomaly in the western North Atlantic has no expression in residual depth anomalies and does not appear to be related to surface features. The North Atlantic Gravity High is bounded on the south by an important and distinct boundary near 30°N which is present in both depth and gravity anomalies. North of this latitude, residual gravity anomalies (corrected for the 'ridge anomaly') take the form of a very broad high of about 20 mGal with the values along isochrons nearly constant from 30°N to at least as far north as 75°N . The depths within this region are consistently shallow with $5^\circ \times 5^\circ$ average residual depth anomalies which vary greatly from a few hundred meters near the Charlie Gibbs fracture zone to a few thousand meters near Iceland and the Azores. We used three-dimensional spherical earth models to investigate simple compensated mass distributions which could explain the observed depth and gravity anomalies. The acceptable family of models has the common characteristics that within the anomalous region north of the 30°N boundary a portion of the compensation must be distributed to depths of several hundred kilometers and that this deep mass deficiency must be nearly uniform throughout the area. However, the compensation for more local features within this region must be shallow (within the lithosphere). Thus the topographic highs surrounding Iceland and the Azores are compensated within the lithosphere, but the overall elevation is maintained at some greater depth by a mass deficiency in the asthenosphere. This mass deficiency can be explained by an increase in temperature of about 75°C . Thus the gravity data enable us to establish the presence of a very large upper mantle hot spot that might be associated with the broad overall compensation of the entire North Atlantic north of 30°N . Whether this upper mantle hot spot is associated with a deep mantle plume is uncertain, since the gravity effect of a plume is undetectable. However, its presence suggests that the immediate source of the unusual amount of material erupted at Iceland and the Azores is within the upper mantle.

INTRODUCTION

When it is compared with other oceans, the North Atlantic exhibits an unusual pattern of oceanic depths and gravity anomalies. Cochran and Talwani [1977] examined $5^\circ \times 5^\circ$ average gravity anomalies and residual depth anomalies (the depth expected for ocean floor of a given age minus the observed basement depths corrected for sediment loading) throughout the world's oceans. They found that the $5^\circ \times 5^\circ$ depth anomalies are generally less than about 500 m, with larger positive values found mainly surrounding regions of extensive past or present volcanism away from the midocean ridge, such as the Hawaiian Swell. In these regions the topographic swell is usually about 1000–1500 km across and is found to be associated with a positive gravity anomaly of comparable extent. A large portion of the North Atlantic is also associated with large positive depth anomalies. This is most obvious at Iceland, where the Mid-Atlantic Ridge protrudes above sea level, but the unusually shallow area extends well north of Iceland into the Norwegian-Greenland Sea and south beyond the Azores to a distinct boundary near 30°N .

The same region north of 30°N in the Atlantic is characterized by large positive free air gravity anomalies (see Figures 1 and 2) and is thus one of the few areas in the world's oceans where a large long-wavelength ($\lambda >$ several thousand kilometers) feature of the earth's gravity field is associated with a corresponding area of unusual depths [Cochran and Talwani, 1977]. The other area in which Cochran and Talwani [1977] noted such a correlation is a region in the southwestern Indian Ocean. There, positive regional gravity anomalies of the order of 20 mGal are found over an area of shallow depths. Although the data are sparse, the region appears to be less

extensive than the unusual area in the Atlantic and to have maximum depth anomalies of about 700 m.

Talwani and Le Pichon [1969] noted an apparent strong correlation between regional gravity anomalies and bathymetry in the North Atlantic. They considered the effect on the gravity field of isostatically compensating the $5^\circ \times 5^\circ$ average topography and concluded that shallow compensation results in isostatic anomalies consistently of one sign and in excess of 10 mGal over areas of several million square kilometers. Their conclusion was that the 'isostatic mechanism operates to great depths in the upper mantle' and that there are also 'additional lateral inhomogeneities in the upper mantle which are nonisostatic in character' [Talwani and Le Pichon, 1969, p. 346]. The lateral inhomogeneities were necessary to explain the large negative gravity anomalies along the western margin of the Atlantic which are not related to the regional topography.

Sclater et al. [1975] argue that gravity and depth anomalies in the North Atlantic are directly correlated and result from the response of the lithosphere to convective flow in the asthenosphere. They compared $5^\circ \times 5^\circ$ average free air gravity anomalies and residual depth anomalies between 10° and 50°N to the east of 50°W and noted a good visual correlation and satisfactory statistical correlation with the slope predicted by the numerical models of McKenzie et al. [1974].

Cochran and Talwani [1977], using more gravity data than were available to Sclater et al. [1975], pointed out that there is a correlation between gravity and depth in some areas of the North Atlantic in the sense that both are quite positive over similar areas. However, a direct relationship does not hold over the entire North Atlantic. They suggested that the correlation observed by Sclater et al. [1975] is largely due to two effects. One is the presence of regions of unusual elevation and relatively high gravity surrounding areas of extensive vol-

Fig. 1a. Map of the $1^\circ \times 1^\circ$ average free air gravity anomalies in the North Atlantic, contoured at 20-mGal intervals. Anomalies are referred to the hydrostatic figure of the earth (flattening, $1/299.7$). Data points are indicated by dots. Values north of 60°N are $1^\circ \times 2^\circ$ averages.

canism away from the midocean ridge at the Canary Islands, Madeira, and the Cape Verde Islands, all of which are in the area considered by *Sclater et al.* [1975]. The second is the transition from the anomalous region of the North Atlantic Gravity High to more 'normal' areas. Thus gravity and depth both fall off west of the Azores and at the 30°N boundary. The gravity does not, however, fall off with the depth north of the Azores.

The purpose of this study is to examine the gravity anomalies and depths in the entire North Atlantic to find what patterns exist and quantitatively investigate how they might arise. We will be particularly interested in the area of the Mid-Atlantic Ridge north of 30°N in which positive gravity anomalies and shallow depths are found.

$1^\circ \times 1^\circ$ AND $5^\circ \times 5^\circ$ FREE AIR GRAVITY ANOMALIES

We have compiled $1^\circ \times 1^\circ$ average free air gravity anomalies over the North Atlantic and present these data in Figure 1. The $1^\circ \times 1^\circ$ averages are combined to form $5^\circ \times 5^\circ$ averages which are shown in Figure 2. The $5^\circ \times 5^\circ$ field was sampled at 1° intervals provided that at least 13 $1^\circ \times 1^\circ$ averages were present within a $5^\circ \times 5^\circ$ square. The sources of data and

method of obtaining the averages are discussed in *Cochran and Talwani* [1977], and the values are tabulated there.

The gravity anomalies in Figures 1 and 2 and throughout this study are referred to the hydrostatic figure of the earth (flattening, $1/299.7$). This ellipsoid was chosen because it represents the stress free figure of the earth and departures from it must be supported in some manner. The difference between various ellipsoids appears as a slowly varying level change, and the choice of a particular reference ellipsoid will thus affect only the longest-wavelength anomalies. *Talwani et al.* [1972] present a plot of the difference between the hydrostatic, best fitting, and international reference ellipsoids as a function of latitude.

The most prominent large-scale features of the free air gravity anomaly maps are a gravity high over the Mid-Atlantic Ridge crest and the pronounced asymmetry of the field with respect to the Mid-Atlantic Ridge. The gravity anomalies in the eastern basin tend to be near zero or slightly negative, while large negative values are found in the western basin. Anomalies of the order of -30 mGal are found over much of the Nares, Hatteras, and Demerara Abyssal plains. The most negative $1^\circ \times 1^\circ$ average anomalies are found over the Hat-

Fig. 1b. Map of the $1^\circ \times 2^\circ$ average free air gravity anomalies in the Norwegian-Greenland Sea contoured at 20-mGal intervals. Anomalies are referred to the hydrostatic figure of the earth (flattening, $1/299.7$). Data points are indicated by dots.

ter as Abyssal Plain southeast of Cape Hatteras and reach values of about -60 mGal. The area of negative anomalies is interrupted near 65°W by a north-south trending relative gravity high over the Bermuda Rise.

The crest of the Mid-Atlantic Ridge is also the peak of a gravity high in the $1^\circ \times 1^\circ$ average anomalies. Even at the Azores, where a gravity high is centered just off the ridge crest over the islands (near 27.5°W), there is another distinct maximum over the ridge crest (centered near 32°W). The $1^\circ \times 1^\circ$ average free air anomalies over the ridge crest are close to zero in the southern part of the map. The anomalies over the ridge crest increase to about 20 mGal north of the Kane fracture zone near 24°N and then increase again to about 40 mGal between 30° and 35°N . They generally remain in the range of 40–50 mGal from about 33°N to the northern limit of our data at 80°N (Figure 1). The largest $1^\circ \times 1^\circ$ average free air anomaly over the ridge crest is 63 mGal at 48.5°N . The $1^\circ \times 1^\circ$ average gravity anomalies reach 68 mGal in southeastern Iceland, but this high appears to be associated with the Vatnajökull glacier rather than the ridge crest.

The $5^\circ \times 5^\circ$ average anomalies (Figure 2), as is expected, suppress most of the short-wavelength anomalies in the $1^\circ \times 1^\circ$ anomaly map. The boundary at 30°N is clearly expressed in the $5^\circ \times 5^\circ$ average gravity field. The 0-, 10-, and 20-mGal contours to the east of the ridge crest trend perpendicular to the ridge at that latitude, as do the -10 - and -20 -mGal contours to the west of the ridge crest. The offset of the gravity contours at 30°N on the east side of the ridge crest is also seen in the $5^\circ \times 5^\circ$ average topographic contours (Figure 2). Another important feature of the $5^\circ \times 5^\circ$ average free air gravity anomaly map is intermediate-wavelength (1000–2000 km) gravity highs surrounding areas of unusual elevation. Many of

these, such as Bermuda, the Cape Verde Islands, the Canary Islands, and Madeira, have been locations of extensive volcanic activity away from the midocean ridge system.

RESIDUAL GRAVITY AND DEPTH ANOMALIES

Cochran and Talwani [1977] examined surface ship gravity anomalies over midocean ridges in all of the world's oceans and found that they consistently show midocean crests to be associated with a relative maximum in the free air gravity field which they were able to quantify in terms of an empirical $1^\circ \times 1^\circ$ average gravity-age relationship (Figure 3). They found that the $1^\circ \times 1^\circ$ average free air gravity anomalies resulting from current thermal models of the lithosphere [Sclater and Francheteau, 1970; Lambeck, 1972; Parker and Oldenberg, 1973] are generally compatible with the observed gravity anomalies, although the thermal models predict a greater spreading rate dependence than is observed. Cochran and Talwani [1977] found a second-order spreading rate dependence of the $1^\circ \times 1^\circ$ average gravity anomalies associated with the midocean ridge system such that very fast spreading ridges are associated with a roughly 20-mGal gravity high at the ridge crest, while very slow spreading ridges such as those in the North Atlantic are associated with a 25- to 30-mGal high. The observed difference between fast and slow spreading ridges is much less away from the ridge crest. Cochran and Talwani [1977] concluded that the observed gravity anomalies could be adequately described by a curve in which only the primary dependence on age is considered and that it is more useful to establish a standard relationship for all oceans and discuss second-order variations between oceans than to establish a separate curve for each ocean. In addition to the gravity high over the ridge crest, compensated models of midocean ridges

Fig. 2a. Map of $5^\circ \times 5^\circ$ free air gravity anomalies and depths in the North Atlantic. Gravity anomalies are contoured at 10-mGal intervals, and depths at 1000-m intervals. Gravity anomalies are referred to the hydrostatic figure of the earth (flattening = $1/299.7$). Anomalies north of 60°N are $5^\circ \times 10^\circ$ averages.

Fig. 2b. Map of $5^\circ \times 10^\circ$ free air gravity anomalies and depths in the Norwegian-Greenland Sea. Gravity anomalies are contoured at 10-mGal intervals, and depths at 1000-m intervals. Gravity anomalies are referred to the hydrostatic figure of the earth (flattening = $1/299.7$).

produce broad bands of slightly negative anomalies (see Figure 6). These small negative anomalies are difficult to separate from the background field and are not included in the empirical curve for the sake of simplicity.

The empirical gravity-age relationship determined by Cochran and Talwani [1977] appears to be the result of the ridge and its compensation and is related to the evolution of the oceanic lithosphere. It is therefore reasonable to remove it from the observed $1^\circ \times 1^\circ$ free air gravity anomalies to allow the residual anomalies due to other causes to be examined.

We obtained $1^\circ \times 1^\circ$ average residual gravity anomalies in the North Atlantic Ocean by assigning an age to each $1^\circ \times 1^\circ$ square from the magnetic isochron maps of Pitman and Talwani [1972] using the Cenozoic time scale of Heirtzler *et al.* [1968] and then subtracting the $1^\circ \times 1^\circ$ average gravity anomaly appropriate to that age from the observed $1^\circ \times 1^\circ$ average free air anomalies. For areas older than 40 m.y. the empirical gravity curve for the ridge is zero, and therefore the residual gravity anomaly equals the free air anomaly. The $1^\circ \times 1^\circ$ residual gravity anomalies were summed and averaged to form $5^\circ \times 5^\circ$ average residual anomalies which are shown in Figure 4.

Residual depth anomalies were prepared in the same manner as were the residual gravity anomalies and are referred to the depth-age curve shown in Figure 3b. Ages were determined

for the older portions of the North Atlantic from the magnetic isochron maps of Larson and Pitman [1972] by using the Mesozoic time scale of Larson and Hilde [1975]. The sign convention used is that shallow areas have positive depth anomalies. The observed $1^\circ \times 1^\circ$ average depths were obtained from bathymetric maps of Uchupi [1971]. Corrected basement depths were obtained by adding half of the $1^\circ \times 1^\circ$ average sediment thickness to the water depth to allow for the effect of sediment loading. This is equivalent to assuming local compensation and a density of 2.2 g/cm^3 for the sediment. Sediment thicknesses were determined from the isopach map of Ewing *et al.* [1973].

The nature of the $5^\circ \times 5^\circ$ average residual depth and gravity anomalies in the North Atlantic and their relationship to each other can be seen in Figure 5, which presents a series of west to east profiles at roughly 5° spacings from 25° to 55°N (profiles a-g) and a profile along the Mid-Atlantic Ridge crest (profile h).

The southernmost profile at 24.5°N (profile a) is south of the 30°N boundary and is characterized by depth anomalies that are from a few hundred meters positive to a few hundred meters negative except near the African continental margin at the extreme eastern end of the profile. The residual gravity anomalies are also near zero to the east of the ridge crest but fall off rapidly to the west 45°W , a condition illustrating the

Fig. 3. (a) Empirical $1^\circ \times 1^\circ$ average free air gravity-age relationship after Cochran and Talwani [1977], which was developed through a comparison of gravity-age relationships in all of the oceans. There is some evidence of a small second-order spreading rate dependence with fast spreading ridges slightly below and slow spreading ridges slightly above the curve. An empirical depth-age curve from Sclater *et al.* [1971] is shown for comparison. (b) Depth-age relationship used in calculating depth anomalies. For ages of less than 80 m.y. the curve is an empirical curve determined from data given by Sclater *et al.* [1971]. The older portion of the curve is obtained from the Sclater and Francheteau [1970] theoretical relationship.

Fig. 4a. Map of $5^\circ \times 5^\circ$ residual gravity and depth anomalies in the North Atlantic [after Cochran and Talwani, 1977]. The gravity is contoured at 10-mGal intervals, and the depth at 250-m intervals. Values north of 60° are $5^\circ \times 10^\circ$ averages.

Fig. 4b. Map of $5^\circ \times 10^\circ$ residual gravity and depth anomalies in the Norwegian-Greenland Sea [after Cochran and Talwani, 1977]. The gravity is contoured at 10-mGal intervals, and the depth at 250-m intervals.

pronounced asymmetry in the gravity field. The residual gravity and topographic highs located near 65°W are related to the southern extension of the Bermuda Rise.

The residual gravity anomalies at 30.5°N (profile *b*) show a pattern similar to those at 24.5°N (profile *a*), but the general level of the anomalies to the east of Bermuda is roughly 10 mGal higher. There are, however, some significant differences

between profiles *a* and *b* in the depth anomaly pattern. First, since profile *b* passes just south of Bermuda, the Bermuda Rise is much more prominent in the residual depth profile and is characterized by 5° × 5° average depths nearly 1000 m shallower than those predicted. Second, the eastern flank of the Mid-Atlantic Ridge is unusually high between the ridge crest and the line of seamounts extending south from the Azores. As

Fig. 5. Profiles of 5° × 5° average residual gravity and depth anomalies in the North Atlantic. Profiles *a*–*g* run west to east across the Mid-Atlantic Ridge at roughly 5° spacings. Profile *h* runs along the crest of the Mid-Atlantic Ridge. The points at which profiles cross the ridge crest are marked by 'RC'.

as a result, the depth anomalies increase steadily from about 250 m at the ridge crest to between 1000 and 1500 m near 30°W. Gravity data are somewhat sparse east of the ridge crest, but the available data indicate $5^\circ \times 5^\circ$ average residual anomalies of slightly more than 10 mGal at this latitude over the plateau between the ridge crest and the seamount chain. The gravity anomalies appear to follow the topography in dropping off rapidly east of 30°W before increasing again toward Madeira. The two profiles flanking the Azores (profiles *c* and *d*) are characterized by broad highs in both the residual gravity and the depth anomalies centered to the east of the ridge crest. The depth anomaly high is sharper in profile *c* at 35.5°N and reflects the presence of the Azores Platform. The high is broader in profile *d*, and although it is centered east of the ridge crest, it extends well to the west. Gravity and depth anomalies fall off both east and west of the Azores, so there is a correlation between the two parameters in that region. The depth anomalies level off at a value of about 500 m near 45°W and are relatively constant west of that longitude, while the gravity anomalies continue to decrease to the west. The depth anomaly minimum near 65°W on profile *d* is over an area of thick and variable sediments to the west of the Newfoundland Ridge [Ewing *et al.*, 1973] and may be in part the result of uncertainties in accounting for the sediment loading.

North of about 45°N the $5^\circ \times 5^\circ$ average residual gravity anomalies still take the form of a broad arch centered near the ridge crest, but it is a much flatter high and occupies most of the ocean (profile *e*), which is younger and thus narrower than that to the south of the Azores. The large negative gravity anomalies in the western basin are confined to the older portion of the Atlantic south of the Grand Banks.

The $5^\circ \times 5^\circ$ average depth anomaly contours on the Reykjanes Ridge are nearly perpendicular to the ridge crest (see Figure 4), and the values increase rapidly toward Iceland. Just south of the Charlie Gibbs fracture zone, a prominent depth anomaly minimum is centered near the ridge crest (Figure 4). Neither this feature nor the rapid increase in the depth anomalies toward Iceland on the Reykjanes Ridge is reflected in the residual gravity anomalies which maintain values of about 20 mGal from 40° to 70°N (profile *h*, Figure 5).

The residual gravity anomalies in the North Atlantic are thus dominated by two features. The first is a broad gravity high which occupies the central portion of the ocean from 30°N to the Azores and most of the North Atlantic north of the Azores. South of the Azores it is centered just to the east of the Mid-Atlantic Ridge over a large topographic high. North of the Azores there is generally not a direct correspondence between variations in the gravity and the depth anomalies (as is shown particularly in profiles *f* and *h*, Figure 5), although both are consistently positive over the same regions.

The other feature is a large area of negative anomalies in the western basin, which follows the western margin of the ocean from about 40°N into the South Atlantic. This feature has no relationship to the residual depth anomalies except that it is interrupted by an intermediate-wavelength gravity and topographic high over the Bermuda Rise.

NORTH ATLANTIC GRAVITY FIELD MODELS

In this section we wish to quantitatively investigate the pattern of gravity and depth anomalies in the North Atlantic Ocean. Specifically, we will concentrate on the area north of 30°N in which unusually shallow depths and large positive gravity anomalies are found over the same region. We will begin by determining the gravity anomalies resulting from a

'model' midocean ridge and its compensation on a spherical earth and then will examine how the $1^\circ \times 1^\circ$ residual depth anomalies in the North Atlantic can be compensated in order to minimize the residual gravity anomalies. Finally, the implications and possible origin of the gravity and depth anomalies will be discussed.

It should be noted that our models are all compensated in that we seek to determine a family of mass distributions which can explain the observed gravity anomalies with the assumption that the pressure at some depth is a constant. There are thus two limitations on the model studies which follow. The first is that they are static models concerned with the distribution of mass and do not explicitly include any dynamic effects, although it is possible to invoke dynamic processes to produce and maintain the inferred mass distribution. The second limitation is that our models assume that any processes which are at work are isostatic in the sense that they produce a compensated mass distribution. An uncompensated uplift (or depression) of the lithosphere will produce a gravity effect which can be approximated by that of a Bouguer slab, $\Delta g = 2\pi G \Delta \rho \Delta h$, where Δh is the amount of uplift and $\Delta \rho$ is the density contrast between asthenosphere and water. Thus the gravity effect of simply uplifting the lithosphere by 1 km is about 95 mGal. The residual gravity anomalies of 15–20 mGal observed in the North Atlantic could thus result from only 150 to about 200 m of uncompensated uplift. The observed depth anomalies in the region north of the 30°N boundary are much greater than that, averaging about 1 km. It can thus be concluded that the mass excess associated with the unusually shallow depths in the North Atlantic is at least in part balanced by a mass deficiency somewhere which greatly reduces the gravity effect of the excess elevation. For the purposes of carrying out our calculations we will assume that the compensation is exact, that is, that the excess is exactly balanced by the deficiency.

The input data for the spherical earth model calculations are averages over $1^\circ \times 1^\circ$ squares of depth, sediment thickness, and lithospheric age. As a result, we can describe the structure in terms of $1^\circ \times 1^\circ$ prisms and calculate the gravity effect of each prism by using an expression for the gravity effect of a radial mass line. The details of the gravity model calculations are given in the appendix.

Figure 6 shows the $1^\circ \times 1^\circ$ average free air anomalies calculated for a model Mid-Atlantic Ridge. The depths for the model ridge are given by the depth-age relationship in Figure 3b. Continental areas such as Rockall Plateau are assumed to be at their actual depth. The compensation of the ridge is assumed to occur by a density inversion of constant magnitude in the asthenosphere immediately beneath the lithosphere. For the calculations shown in Figure 6 we assumed that the compensation occurs above a depth of 100 km and has a density contrast of -0.085 g/cm^3 with the lithosphere. The model is illustrated in Figure 7a. This is the method of compensation assumed by Parker and Oldenberg [1973] in calculating their theoretical ridge heights, and the top of the compensating body differs only slightly from their lithosphere-asthenosphere boundary because they chose a slightly different density contrast (-0.082 g/cm^3). Thus the gravity anomaly pattern shown in Figure 6 is that of a midocean ridge with the lithospheric ages and boundaries of the North Atlantic but at the depths predicted by the curve in Figure 3b and where the lithosphere evolves according to a simple Parker-Oldenberg thermal model.

The main feature of Figure 6 is a gravity high of 25–35 mGal

Fig. 6. Calculated $1^\circ \times 1^\circ$ free air gravity anomalies obtained for a three-dimensional spherical earth model of a midocean ridge which has the geometry of the North Atlantic but which has depths predicted by the depth-age curve of Figure 3b rather than the observed depths. Compensation of the ridge is assumed to occur by a density inversion of constant magnitude in the asthenosphere above a depth of 100 km (Figure 7a). The calculated $1^\circ \times 1^\circ$ average anomalies are similar to, but 5–10 mGal higher than, the empirical gravity-age curve shown in Figure 3a.

over the ridge crest, which falls off to zero near the 50-m.y. isochron and is flanked by broad areas of slightly negative anomalies. Beyond these the values return to zero. The calculated ridge crest high is similar to the gravity high of 25–30 mGal observed over slow spreading ridges [Cochran and Talwani, 1977].

Since the gravity anomaly pattern in Figure 6 is quite similar to that observed by Cochran and Talwani [1977], the model of compensation illustrated in Figure 7a was incorporated into all of the models discussed below to compensate the basic subsidence away from the ridge crest.

A simple model for the unusually shallow depths in the North Atlantic is that they are due to increased temperatures in the asthenosphere immediately below the lithosphere, a situation leading to thermal expansion and lowered densities in the upper portion of the asthenosphere. Such a model is shown schematically in Figure 7b. This model is suggested by the presence of large seismic *P* wave arrival time residuals beneath Iceland [Tryggvason, 1964; Long and Mitchell, 1970] and by studies of *ScS* travel time residuals that indicate that shear wave velocities are anomalously low in the mantle directly beneath oceanic islands, including Iceland [Sipkin and Jordan, 1975; Okal and Anderson, 1975]. It is also a model which has been used to approximate a situation in which elevation anomalies are ascribed to convection in the asthenosphere beneath the lithospheric plate (see, for example, Watts [1976]).

Figure 8 shows the $1^\circ \times 1^\circ$ average free air gravity anomalies calculated for the North Atlantic by using a model such as is pictured in Figure 7b. In the calculations we assumed that the elevation anomalies are compensated by a low-density

body in the upper portion of the asthenosphere. The top of the body coincides with the base of the lithosphere and has a density contrast of -0.085 g/cm^3 with normal asthenosphere. This model results in gravity anomalies which closely reflect the depth anomalies. Large $1^\circ \times 1^\circ$ average free air gravity highs are found over the Azores (101 mGal) and Iceland (126 mGal), and the deep compensation of the two topographic highs is seen over wide areas depressing the gravity field in surrounding areas. As a result, the calculated gravity anomalies near the ridge crest just south of the Charlie Gibbs fracture zone are about 15 mGal, which is only half of the anomalies calculated for the model ridge and much less than the 40- to 50-mGal $1^\circ \times 1^\circ$ average gravity anomalies observed in that region.

An entirely different model is illustrated in Figure 7c. Here we have assumed that the depth anomalies are compensated at shallow depths within the lithosphere, in this case by variations in crustal thickness. The free air gravity anomalies resulting from the application of this model to the North Atlantic are shown in Figure 9. Because of the very shallow compensation the depth anomalies make only a very small contribution, and this model results in free air anomalies which are quite similar to those for the model ridge (Figure 6). The main difference is that the ridge crest high broadens out near Iceland and the Azores to include the area of largest depth anomalies. In general, though, the anomalies are within a few milligals of those calculated for the model ridge. As a result, most of the Atlantic from 30° to 60°N is characterized by calculated $1^\circ \times 1^\circ$ average gravity anomalies significantly less than those observed.

These two models illustrate the difficulties encountered in

Fig. 7. Sketches showing the models considered in the text and producing the gravity anomalies shown in Figures 6, 8, 9, and 10. Sketches are not to scale. (a) Compensation of a 'model' midocean ridge by a density inversion in the upper portion of the asthenosphere (Figure 6). We assume that the ridge is compensated above 100 km and that the lithosphere-asthenosphere density contrast is 0.085 g/cm^3 . (b) Compensation of depth anomalies by low-density asthenosphere (Figure 8). (c) Compensation of depth anomalies within the lithosphere (Figure 9). We assume here that the compensation is by variations in crustal thickness, but other mechanisms are possible. (d) Compensation of depth anomalies by a combination of the models sketched in Figures 7b and 7c (Figure 10). Most of the compensation is assumed to occur within the lithosphere, but a portion of it is distributed to depth and occurs within the asthenosphere.

Fig. 8. Map of $1^\circ \times 1^\circ$ average gravity anomalies obtained for a model in which the predicted Mid-Atlantic Ridge is compensated as in Figure 6 and the residual elevation is compensated by a low-density body in the asthenosphere immediately beneath the lithosphere (Figure 7b). The upper map shows the calculated $1^\circ \times 1^\circ$ free air anomalies, and the lower map the difference between calculated and observed anomalies. Areas in which the calculated anomalies are more than 10 mGal too high are stippled; areas in which they are more than 10 mGal too low are ruled. Dots show locations at which anomalies were calculated.

Fig. 9. Map of $1^\circ \times 1^\circ$ average gravity anomalies obtained for a model in which the predicted Mid-Atlantic Ridge is compensated as in Figure 6 and the residual elevation is compensated by varying the crustal thickness (Figure 7c). The upper map shows the calculated $1^\circ \times 1^\circ$ free air anomalies, and the lower map the difference between calculated and observed anomalies. Areas in which the calculated anomalies are more than 10 mGal too high are stippled; areas in which they are more than 10 mGal too low are ruled. Dots show the locations at which anomalies were calculated. Note the similarity of calculated anomalies to those in Figure 6.

attempting to reproduce the observed gravity anomalies by compensation of the depth anomalies with a single simple body. If the compensation is deep, it results in large gravity highs over the Azores and Iceland rather than the nearly flat gravity field which is observed on profiles along isochrons (profile *h*, Figure 5). If the compensation is brought shallow enough that the gravity values are relatively constant along isochrons, then the model does not duplicate the other major characteristic of the North Atlantic gravity field, which is that north of 30°N the general level of the gravity anomalies is 15–20 mGal greater than that observed over other mid-ocean ridges or predicted by ridge models.

A satisfactory model can be obtained by assuming that most of the compensation occurs at shallow depths but that a portion of it is distributed to greater depths. The free air gravity anomaly pattern resulting from one such model is shown in Figure 10. For this particular model, illustrated in Figure 7*d*, we have assumed that in the anomalous portion of the North Atlantic, that is, east of 40°W from 30° to 40°N and in the entire width of the ocean north of 40°N, there is a low-density body in the upper portion of the asthenosphere which is capable of compensating 500 m of excess elevation. The difference between 500 m of excess elevation and the observed depth anomalies were assumed to be compensated at shallow depths through variations in crustal thickness, as were all depth anomalies outside of the unusual area. We assumed a density contrast of -0.006 g/cm^3 for the anomalous asthenosphere, which implies a thickness of 200 km for the compensating body or that compensation is distributed to a depth of about 300 km.

The areas of significant residual gravity anomalies are greatly reduced in Figure 10 in comparison with those in Figures 8 and 9. It should be pointed out that the model illustrated in Figure 10 does not represent an attempt to find a 'best fitting' model or set of parameters. It is rather an example of one of a family of solutions which reproduce the general characteristics of the observed gravity field in which we have adopted convenient values for the various variables. Common characteristics of acceptable solutions are that most of the compensation of the depth anomalies occurs within the lithosphere but that within the anomalous region north of the 30°N boundary a portion of the compensation must extend to a depth of several hundred kilometers. Also, the deep mass deficiency must be of a nearly uniform amount throughout the anomalous area. The mainly shallow compensation is necessary in order that the gravity field be relatively uniform along isochrons and not reflect the large variations in depth. The deep compensation of a portion of the depth anomalies is necessary to elevate the general level of the field by 15–20 mGal above the anomaly due to the midocean ridge. The implication is that the Iceland and Azores topographic highs are for the most part compensated at relatively shallow depths but that the overall elevation of the North Atlantic is maintained at some greater depth.

DISCUSSION

The assumption of a particular mechanism of compensation, such as variations in crustal thickness, and the division of the compensation into a shallow body and a deep body are only mathematical conveniences. What is implied by the model studies is that the compensation of the regional depth anomalies in the North Atlantic must be distributed over several hundred kilometers and involve both the litho-

sphere and the asthenosphere. Also, the deep contribution must be fairly uniform over the entire anomalous region.

We thus agree with *Sclater et al.* [1975] that the asthenosphere must be involved in maintaining the depth anomalies in the North Atlantic. However, we disagree with them in that we have found that the large long-wavelength depth anomalies in the North Atlantic cannot originate entirely within the asthenosphere and in that there is not a simple one to one direct relationship between gravity and depth anomalies passing through the origin such as they hypothesize. A direct relationship between gravity and depth anomalies apparently can exist over single isolated features such as the Hawaiian Swell, as was demonstrated by *Watts* [1976]. Even there though, the gravity anomalies associated with the Hawaiian Swell are superimposed on longer-wavelength gravity anomalies unassociated with the oceanic depth, so that zero depth anomalies are associated with gravity anomalies of -15 to -20 mGal.

If the direct relationship hypothesized by *Sclater et al.* [1975] actually holds in the North Atlantic, then $5^\circ \times 5^\circ$ average gravity anomalies of more than 100 mGal would be expected at Iceland, which is much larger than those observed (see Figure 2). A second example is the western basin of the North Atlantic. Large negative gravity anomalies are found over this region (see Figure 1), which has depths near or slightly shallower than those predicted for crust of that age. The correlation observed by *Sclater et al.* [1975] probably results from the fact that they had a limited data set which included data from the intermediate-wavelength topographic high surrounding Madeira, the Canary Islands, and the Cape Verde Islands as well as the transition from the North Atlantic Gravity High to more normal crust to the south and west of the Azores. They apparently did not use data from the western basin or from north of 50°N.

As was mentioned above, the models which we have considered constitute a limited class of models which are compensated in the sense that we assume that an isobaric surface exists at some depth in the earth. We have not considered nonisostatic models or the stresses that will arise in either case.

In fact, deep compensation is achieved through the presence of lateral inhomogeneities in the asthenosphere, which implies the existence of nonhydrostatic stresses. An order of magnitude calculation of the stresses is given by $\Delta\rho gh$, where $\Delta\rho$ is the density contrast, h the thickness of the anomalous region, and g the gravity. For the model producing the anomalies shown in Figure 10 this gives an order of magnitude estimate of 120 bars. For the low upper asthenospheric viscosities which have been deduced from glacial rebound studies [*Artyushkov*, 1971; *Walcott*, 1973] such stresses will cause creep and must be supported in some manner if the anomalous region is to maintain its identity over a geologically significant time.

A simple model for the pattern of gravity and depth anomalies observed in the North Atlantic is that the mantle is unusually hot and that both lithosphere and asthenosphere are affected to a depth of several hundred kilometers. The temperature increase in the asthenosphere need not be very great. Using a coefficient of thermal expansion of $2 \times 10^{-5} \text{ }^\circ\text{C}^{-1}$ [*McKenzie et al.*, 1974] and the density difference of -0.006 g/cm^3 used in the model of Figure 7*c* to produce the anomalies in Figure 10 gives an increase of temperature of about 75°C.

McKenzie et al. [1974] concluded from the concentration of radioactive elements in oceanic basalts and the measured heat flow that roughly half of the heat released at the surface is

Fig. 10. Gravity anomalies obtained for a model in which the predicted Mid-Atlantic Ridge is compensated as in Figure 6 and the residual elevation is compensated by variations in crustal thickness except in a region north of 30°N and east of 40°N and in the entire ocean north of 40°N. In these areas, 500 m of excess elevation are compensated by a low-density body in the asthenosphere immediately beneath the lithosphere, and the remainder by variations in crustal thickness (Figure 7d). The low-density body is assumed to have a density contrast of -0.006 g/cm^3 with the surrounding mantle and thus has a thickness of 200 km. The upper map shows the calculated $1^\circ \times 1^\circ$ free air gravity anomalies, and the lower map the difference between calculated and observed anomalies. Areas in which the calculated anomalies are more than 10 mGal too high are stippled; areas in which they are more than 10 mGal too low are ruled. Dots show locations at which anomalies were calculated.

from the upper mantle and half from the lower mantle. Recently, *O'Nions et al.* [1978], using revised values for the mean oceanic heat flow [*Williams and Von Herzen*, 1974] and for the concentrations of heat-producing elements, concluded that 'a significant amount of the heat lost by cooling of the oceanic lithosphere is generated in the lower mantle.' They also argued that their isotope data imply that heat transfer from the lower to the upper mantle does not appear to be accompanied by transport of the heat-producing elements to the surface, that is, by a deep mantle plume.

Whether heat transfer from the lower to the upper mantle occurs by conduction across a thermal boundary layer at 700 km as suggested by *McKenzie and Weiss* [1975], by upward migration of volatiles as suggested by the work of *Wyllie* [1971] and *Green* [1971], or by some other mechanism such as plumes, there is no reason to assume that this heat transfer is evenly distributed over the earth. Thus it is possible that the large area of lowered densities which we have deduced to exist beneath the North Atlantic results from an uneven transfer of heat from the lower to the upper mantle.

Langseth and Zielinski [1974] compiled and examined heat flow measurements in the Norwegian-Greenland Sea and on the flanks of the Reykjanes Ridge. They concluded that a large area of abnormally high heat flow extends from at least as far south as the Charlie Gibbs fracture zone to as far north as they had data (roughly 77°N).

Our results also imply that the topographic highs surrounding Iceland and the Azores are compensated at fairly shallow depths, that is, within the lithosphere. Let us examine these results in the context of arguments made concerning the nature of areas such as Iceland and the Azores on the basis of geochemical data.

Schilling [1973] proposed on the basis of variations in rare

earth and minor element concentrations that basalts erupted on Iceland have a distinctly different source than basalts erupted on the Mid-Atlantic Ridge away from the Iceland area. He demonstrated that concentrations of incompatible elements such as K, Ti, P, and the light rare earths (as demonstrated by the ratio La/Sm) and the ratio $\Sigma\text{FeO}/\Sigma\text{FeO} + \text{MgO}$ increase systematically toward Iceland along the Reykjanes Ridge from about 60°N. He interpreted these variations as resulting from the mixture of material from two sources, a 'primordial hot mantle plume' rising from deep beneath Iceland and the 'depleted low-velocity layer' found under the Mid-Atlantic Ridge. Sr and Pb isotope data were also cited as support for the existence of separate sources for the two areas.

The presence of a narrow, deep structure extending to the lower mantle and resembling a plume (Figures 11a and 11b) beneath Iceland cannot be deduced from our data. However, it should be pointed out that such a structure would be difficult to detect from surface measurements in any event. What can be said from our data is that shallow compensation is present in the vicinity of Iceland, and therefore if a plume is present, it must serve as a conduit for bringing a large quantity of low-density material to the surface from deep in the mantle to produce the low-density lithosphere in the vicinity of Iceland.

On the other hand, we have also established the presence of a low-density area within the upper mantle beneath the North Atlantic over an area much larger than that of the geochemical and bathymetric anomalies associated with Iceland. This suggests the possibility that deep plumes may not be involved at all in the production of hot spots but that material from a depth of no more than 200 or 300 km can be invoked as the source of the extraordinary volcanic activity at Iceland and the Azores as sketched in Figure 11c.

Fig. 11. Sketches showing possible simple models for the deep structure associated with areas of unusual volcanic activity. Figure 11a shows the deep mantle plume model developed by *Morgan* [1972] and *Schilling* [1973]. If such a plume is present in the North Atlantic, then the structure must be as is shown in Figure 11b, where the plume is accompanied by, and presumably responsible for, a low-density 'hot spot' in the asthenosphere. Alternatively, the upper mantle hot spot could be the source of the topographic swell and volcanic activity as sketched in Figure 11c. The models shown in Figures 11b and 11c are compatible with our data.

It could be argued that this model may be applicable to Iceland and the Azores but not necessarily to areas such as Hawaii. However, the extraordinary quantity of volcanism which has built the Hawaiian Ridge is not the only manifestation of the Hawaii hot spot. The volcanism at Hawaii is at the crest of a broad topographic swell 1500 km across and 1600 m high [Betz and Hess, 1942; Watts, 1976], which Watts [1976] argues is balanced by a low-density area of comparable extent in the asthenosphere.

Some support for this model comes from recent geochemical arguments presented by O'Nions and co-workers. O'Nions *et al.* [1978] used Sm and Nd isotope ratios as well as Rb and Sr ratios to argue that virtually all basalts erupted in the oceans, including those in Iceland and Hawaii, are derived from source regions which have been depleted to variable extents of Rb and the light rare earths relative to the bulk earth. Thus according to O'Nions *et al.* [1978] there are no magmas from a 'primordial' unmodified mantle source being erupted anywhere in the North Atlantic. The Iceland and midocean ridge basalts are both depleted and differ in the degree of depletion rather than in one case tapping a pristine source and in the other a modified depleted source.

In addition, O'Nions *et al.* [1976] have argued that the geochemical data are incompatible with the binary mixing model proposed by Schilling [1973] and concluded that a better model for the abundance patterns found in the North Atlantic is a single chemically inhomogeneous source region which might be equivalent to our anomalous region in the upper mantle. The model of an inhomogeneous low-velocity zone which serves as the source of both the midocean ridge and Iceland basalts is compatible with the gravity data.

Whatever form the mechanism takes, our results imply that a distinct, well-defined region of lowered densities exists to a depth of several hundred kilometers in the upper mantle beneath the North Atlantic and that this area appears to have maintained its identity for a period of the order of 60 m.y.

If the excess elevation of the North Atlantic is thermal in origin, it will be accompanied by lowered densities in the upper mantle. The density difference in relation to other areas is small but is present over a large area, so it might be discernible by seismic techniques. Published results of studies of seismic velocities in the mantle beneath the anomalous area in the North Atlantic through the use of either *P* wave [Tryggvason, 1964; Long and Mitchell, 1970] or *ScS* [Okal and Anderson, 1975; Sipkin and Jordan, 1975] arrival time residuals are presently only applicable to the area beneath the immediate vicinity of Iceland. Although the direct applicability of these results to the rest of the region is doubtful, they do show lowered velocities extending to a depth of several hundred kilometers under Iceland.

CONCLUSIONS AND SUMMARY

We have examined the gravity field of the North Atlantic Ocean using $1^\circ \times 1^\circ$ and $5^\circ \times 5^\circ$ average free air gravity anomalies. The $1^\circ \times 1^\circ$ averages contain substantial information on relatively short wavelength surface features such as fracture zones and seamounts. These anomalies are, for the most part, averaged out in the $5^\circ \times 5^\circ$ average anomalies which bring out the regional pattern.

The major feature of the regional gravity field in the North Atlantic is a distinct boundary near 30°N which is present in both depth and gravity anomalies (profile *h*, Figure 5). North of this latitude the gravity field is characterized by large positive anomalies which are nearly constant along isochrons.

When the midocean ridge anomaly [Cochran and Talwani, 1977] is removed, the residual gravity field north of the 30°N boundary takes the form of a very broad high centered near or slightly east of the ridge axis. The depths within this area are consistently shallow, but the $5^\circ \times 5^\circ$ average residual depth anomalies vary greatly from a few hundred meters near the Charlie Gibbs fracture zone to a few thousand meters near Iceland and the Azores.

There is therefore a correlation between the residual gravity anomalies and the residual depth anomalies in the sense that they both are consistently positive within a well-defined region. There is not, however, a direct relationship between the two parameters within the area. In particular, the depth anomalies vary by several thousand meters, and these variations are not reflected in the gravity field.

We used three-dimensional spherical earth models to investigate simple compensated mass distributions which could explain the observed patterns of gravity and depth anomalies in the North Atlantic. Common characteristics of the acceptable family of models are that most of the compensation of the depth anomalies occurs at shallow depths but that in the anomalous region north of the 30°N boundary a portion of the compensation must be distributed to depths of several hundred kilometers and that the deep portion of the mass deficiency must be nearly uniform throughout the area. Our results are in agreement with earlier findings that normally the midocean ridges are compensated at a depth less than about a hundred kilometers. However, the abnormally high gravity anomalies over the Mid-Atlantic Ridge suggest a deeper compensation in this region.

The model studies are limited by the facts that they assume a compensated mass distribution and that they are static models concerned with the distribution of mass and thus do not explicitly include any dynamic effects. However, it is possible to infer from our results that a distinct area of lowered densities exists to a depth of several hundred kilometers beneath the North Atlantic.

We suggest that the low densities could result from a modest increase of about 75°C in the temperature of the upper mantle. We speculate that the source of the increased temperatures could be related to an inhomogeneity in the lower mantle resulting in a greater than normal heat transport from the lower to the upper mantle beneath a well-defined area of the North Atlantic Ocean.

APPENDIX: DETAILS OF GRAVITY MODEL CALCULATIONS

The input data for the spherical earth model calculations are averages over $1^\circ \times 1^\circ$ squares of depth, sediment thickness, and lithospheric age. As a result, the shallow structure and its compensation can be described in terms of $1^\circ \times 1^\circ$ prisms. The gravity effect of each prism was computed by using an expression for the gravity effect of a radial mass line on a sphere.

The integral to be solved is

$$\Delta g = k\rho \sin \Theta \, d\Theta \, d\psi \int_{a+h_1}^{a+h_2} \left(\frac{R^2 a}{p^3} - \frac{R^3 \cos \Theta}{p^3} \right) dR$$

where Θ is the angular distance from the point at which the gravity is measured to the location of the mass line, a is the radius of the earth, R is the distance from the center of the earth to the mass element, p is the linear distance from the measurement point to the mass element, h_1 and h_2 are the elevation of the top and bottom of the mass line relative to the

surface of the earth, and $d\theta$ and $d\psi$ are the angular dimensions of the radial mass prism. The solution of this integral for the gravity effect of a radial mass line was first obtained by Kukkamäki [1955] and is given by equation (77) of Talwani [1973]. The derivation of Kukkamäki's expression is very similar to that of the more familiar Cassinis' formula for a spherical cap [Cassinis *et al.*, 1937]. In applying Kukkamäki's expression, allowance must be made for the fact that the mass line is situated below rather than above the earth's surface.

The approximation of a $1^\circ \times 1^\circ$ prism as a radial mass line is not good if the mass line is too near the point at which the computation is made. Figure 12 shows the percentage error in computing the gravity effect of a $1^\circ \times 1^\circ$ square as a radial mass line as a function of the angular distance between the computation point and the center of the $1^\circ \times 1^\circ$ square for two different prisms. The error was calculated by comparing the gravity effect obtained by approximating the $1^\circ \times 1^\circ$ square by a single mass line to that obtained by dividing it into 400 subsquares, approximating each of them as a radial mass line, and summing their gravity effects.

It was necessary therefore to subdivide the $1^\circ \times 1^\circ$ data squares into subsquares when they were near the point at which the computation was made. The gravity effect of each subsquare was then approximated by a radial mass line at its axis. The number of subsquares was chosen to keep the error in calculating the gravity effect below 1%.

The gravity anomalies were calculated at the corners of data squares in order to keep the minimum distance from the point of computation to the center of the data squares as large as possible. Even so, it was found that a prohibitive number of subsquares were required to obtain acceptable accuracy for the four data squares immediately adjacent to the computation point. Therefore the gravity effect of the adjacent $1^\circ \times 1^\circ$ squares was computed by using expressions for the gravity effect of a rectangular parallelepiped given by equations (21) and (24) of Talwani [1973]. The parallelepipeds were 'lowered' according to the method of Takin and Talwani [1966] to allow for the curvature of the earth. The center of gravity of each parallelepiped was used as a reference distance in lowering.

Fig. 12. Percentage error in computing the gravity effect of a $1^\circ \times 1^\circ$ prism as a radial mass line by using an expression of Kukkamäki [1955]. The error is plotted as a function of the angular distance from the center of the $1^\circ \times 1^\circ$ prism. Errors are shown for two prisms located at different depths. The error was calculated by comparing the result obtained by approximating the $1^\circ \times 1^\circ$ square with a single radial mass line to that obtained by dividing it into 400 subsquares and approximating each of them by a radial mass line.

Data squares corresponding to shallow structure above about 20-km depth were subdivided into nine parallelepipeds. A single parallelepiped was used for the deeper structure.

Economy in computing time was obtained by combining $25 \times 1^\circ \times 1^\circ$ squares into a single $5^\circ \times 5^\circ$ square when the angular distance from the computation point to the center of the $5^\circ \times 5^\circ$ square was greater than 10° . This was done only if the $1^\circ \times 1^\circ$ squares within the $5^\circ \times 5^\circ$ square were either all oceanic or all continental so that they all have a similar crustal structure.

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