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Interpretation of the gravity and magnetic anomalies over the Mull Tertiary intrusive complex, NW Scotland

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Abstract: A 50 mGal local positive gravity anomaly over the Mull intrusive complex is interpreted as caused by an underlying dense body of mafic (basic and/or ultrabasic) rocks extending to a depth of between 6.5 and 13 km and occupying a volume of between 2000 and 3600 km^3, depending on density contrast. The granites produce smaller superimposed negative gravity anomalies, which indicate that the granites of the late Loch Bà centre extend to a depth of about 2 km and those of the early Glen More centre occupy a significantly smaller volume. The granites occupy between 5 and 9% of the total volume, consistent with a derivative origin.

The complicated aeromagnetic anomalies have been simplified by applying the pseudogravimetric transformation. The most conspicuous positive pseudogravimetric anomaly occurs over the rocks of centres 1 and 2. This is of much smaller areal extent than the positive gravity anomaly, and it is attributed to highly magnetic rocks extending to a depth of about 2 km beneath centres 1 and 2, including cone sheets. The magnetization of the deeper parts of the complex is much weaker and has not been resolved. A partial ring of linear or arcuate negative magnetic anomalies occurs along the SE, S and W margins of the deep-seated intrusive complex and may mark an unexposed early ring dyke with strong reverse magnetization.

It is estimated that up to a quarter of the volume occupied by the intrusive complex may have been provided by various types of forceful intrusion but that most of the upper crustal space has been made available by ring subsidence and other types of stoping. This is feasible because the magma was demonstrably lower in density than the Moine and Lewisian. The mantle-derived magma probably rose through the more ductile lower crust by diapirism, thereby causing a slight thickening of the underlying crust which may provide isostatic support for the excess mass of the intrusive complex and its associated topography.

The early Tertiary central intrusive complex of Mull occupies most of the central and SE parts of the island. It underwent a complicated history of volcanic evolution which was initially unravelled by Bailey *et al.* (1924) with a more recent summary by Skelhorn *et al.* (1969). New insight into the deep structure underlying the Mull volcanic centre has come from gravity and aeromagnetic surveys. The centre is dominated by a large circular positive gravity anomaly of about 50 mGal amplitude which indicates the presence of a substantial volume of high density rocks occupying the underlying upper part of the crust. Preliminary interpretations were given by Tuson (1959) and by Bott & Tuson (1973). The aeromagnetic map shows a complicated series of large amplitude anomalies, with a central positive anomaly of about 2000 nT amplitude offset towards the SE from the centre of the igneous complex, surrounded by a series of positive and negative anomalies of around 500 nT amplitude. Some further unpublished ground magnetic traverses, showing substantially larger amplitude ground-level anomalies, were made by the British Geological Survey and a qualitative interpretation of the aeromagnetic and ground surveys was given by Bennett (1968). This paper describes the models of the deep structure beneath the intrusive complex based on interpretation of the gravity and aeromagnetic anomalies. The complicated magnetic anomalies have been transformed to pseudogravimetric anomalies prior to interpretation (Tantrigoda 1982) enabling an assessment of the gross deep structure to be made and compared with the gravity models.

The basement beneath most of Mull is probably formed by Moine Assemblage, which crops out in the Gribun and Ross of Mull regions. However, the Great Glen fault is inferred to cross the extreme SE part of Mull and consequently Dalradian, overlain by thin Old Red Sandstone lavas and sediments, is seen in the core of the Loch Don anticline. The Caledonian Ross of Mull granite intrudes the Moine rocks in westernmost Mull and the Moine thrust is believed to occur between Mull and Iona, where Torridonian and Lewisian rocks are found. A thin Mesozoic sequence, observed to be up to about 100 m thick, includes rocks of Triassic to Cretaceous age which are sandwiched between the basement rocks and the basal Tertiary lavas. However, a much greater local thickness of Triassic rocks occurs at Loch Spelve (Rast *et al.* 1968).

The Tertiary igneous activity in Mull commenced with the eruption of nearly 1000 m of mainly olivine-rich plateau basalts which now cover most of N and W Mull and form many of the small islands to the west of Mull. In the region of the intrusive complex, these are overlain by a similar thickness of olivine-poor basalts of the central group which were partly associated with the development of the early caldera and the early period of intrusive activity. Three periods of major intrusive activity formed the central intrusive complex, during which the centre of activity appears to have migrated towards the NW, implanting an approximate bilateral symmetry to the complex.

The *first period* of intrusive activity, centred on Glen More, includes a series of generally earlier granophyres and later olivine gabbros, with associated cone sheets and volcanic vents, intruded round the margins of the early caldera but now truncated on the N side by the later Loch Bà centre. The intrusions include, in order of emplacement, the Glas Bheinn and Derrynaculen granophyres, the Loch Uisg granophyre–gabbro mass, and the Ben Buie gabbro. The intrusions of the *second period* are focused on Beinn Chaisgidle, being dominated by the Glen More ring intrusions, but also including the earlier Corra-bheinn gabbro, augite–diorite masses and associated early and late cone sheets. The activity of the *third period* was centred on Loch Bà along a NW orientated line rather than a focal point (Skelhorn *et al.* 1969). Most of the intrusions associated with this centre are granophyres or felsites, with a few hybrid masses, cone sheets and vent agglomerates. The latest stage was the formation of a late caldera bounded by a ring fault into which the Loch Bà felsite ring dyke was emplaced. This ring dyke truncates the NW parts of the intrusions associated with the two earlier periods of activity. The lavas in a region of about 25 km diameter, including and surrounding the central complex, have been affected by widespread pneumatolysis. Associated with the Mull volcanic centre was the emplacement of the extensive Mull dyke swarm.

Methods of interpretation

Normal two-dimensional methods of interpretation are inadequate for the gravity and magnetic anomalies over the Mull intrusive complex, but a full three-dimensional interpretation seems unnecessarily unwieldy. The approach adopted is to use an approximation of the three-dimensional shape by end corrections (Nettleton 1940; Tanner 1967). A computer programme named GRAVEND was written to calculate the theoretical gravity anomaly over a specific body using this approach.

The specified body is subdivided into a series of rectangular or polygonal prisms, each with its horizontal axis perpendicular to the line of profile. The gravity anomaly of each prism is calculated at each field point using a standard two-dimensional method. An end-correction factor is then computed for each prism at each field point by approximating the prism to a horizontal line mass situated at the centre of gravity of the cross section. The end correction is given by the ratio of the gravity anomaly of the finite length line to that of a coincident horizontal line of infinite length in both directions and the same mass per unit length as the finite length line. The two-dimensional gravity anomaly of the prism at the field point is then multiplied by the end correction to give the estimate of the gravity anomaly of the finite length prism. The contributions from each of the prisms are then summed to give the gravity anomaly at each field point of the whole body. If the area of cross section of the prisms is made sufficiently small, any desired degree of accuracy can be obtained.

The programme GRAVEND was initially written for the forward problem of calculating the gravity anomaly over a body of specified shape as defined by the shape of cross section, density contrast and lateral extent of each of the prisms. With this programme, successive adjustment of the model to obtain a good fit with the observations is carried out manually by repeated use of GRAVEND. This method was used to obtain the gravity anomaly and pseudogravimetric anomaly interpretations in this paper.

Magnetic anomalies are generally more difficult to interpret than gravity anomalies, and this is particularly so over central intrusive complexes such as Mull where large amplitude and short wavelength anomalies produce a highly complicated pattern on the aeromagnetic map. In order to make the interpretation of the aeromagnetic anomalies more tractable, a pseudogravimetric transformation was applied. If the direction of magnetization within the causative body is assumed to be in a fixed direction, and a fictitious density contrast is specified such that the ratio of density contrast to magnetization contrast is constant throughout the body, then the gravity anomaly which would be caused by this fictitious density distribution is called the pseudogravimetric anomaly (Baranov 1957). The pseudogravimetric anomaly can be calculated directly from the observed magnetic anomaly without the need to assume any specific shape for the causative body. We have carried out the pseudogravimetric transformation on the aeromagnetic anomalies of Mull by digitizing the values of magnetic anomaly over the complex and the surrounding regions. The pseudogravimetric transformation can be carried out in the wavenumber domain after applying a double Fourier transform to the data, following the method of Cordell & Taylor (1971). Inverse Fourier transformation then yields the pseudogravimetric anomaly.

The pseudogravimetric anomaly has three advantages over the original aeromagnetic anomaly for interpretation purposes. First, the asymmetry of the anomaly due to the inclination of the magnetization and the magnetic field direction is removed. Second, the pseudogravimetric transformation suppresses the short wavelengths and enhances the longer wavelengths, thus greatly simplifying the anomaly so that the interpretation becomes tractable. Third, the pseudogravimetric anomaly can be interpreted by the normal methods of gravity interpretation in terms of a sub-surface distribution of fictitious density which is proportional to the magnetization contrast. It thus yields a distribution of magnetization which can account for the original magnetic anomaly, with short-wavelength effects to some extent suppressed. The gravity programme GRAVEND has been used to interpret the pseudogravimetric anomalies.

The aeromagnetic anomalies are somewhat distorted because of the varying height of the flight path over the high ground associated with the Mull central intrusive complex and adjacent regions. The pseudogravimetric transformation assumes that the observations are made on a plane surface, and thus some error will carry over because of this problem. However, the long wavelengths which are enhanced are less likely to be badly affected than the short wavelengths which are suppressed. Thus the error is probably not too serious.

Interpretation of the gravity anomalies

The original gravity map of Mull and Ardnamuchan (Bott & Tuson 1973) was based on about 200 gravity stations. Subsequently, a much more detailed gravity survey of Mull and adjacent regions has been carried out by the British Geological Survey. This is referenced to the National Gravity Net 1973, and the Bouguer anomalies have been calculated against the International Gravity Formula of 1967 using a standard density of 2700 kg m^{-3} throughout for the Bouguer correction. Terrain corrections have been applied. These Bouguer anomaly values were kindly supplied to us

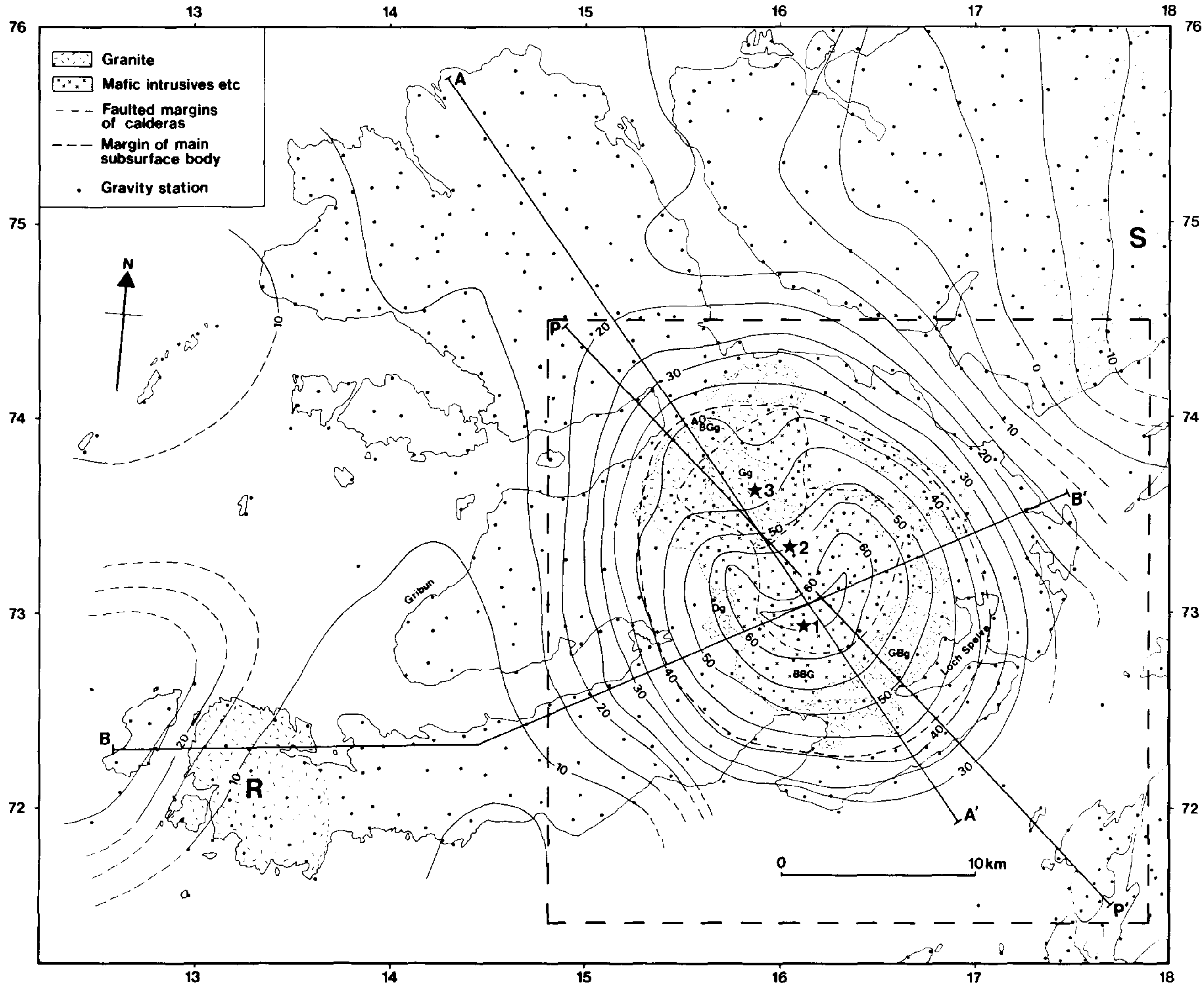

Fig. 1. Bouguer anomaly map of Mull and adjacent regions based on a partly recontoured map supplied by the British Geological Survey. Gravity contours (red) are at 5 mGal interval. The gravity values are connected to the National Gravity Net 1973 and the Bouguer correction has used a density of 2700 kg m^{-3} throughout. Asterisks denote the intrusive centres 1–3 as follows: 1, Glen More; 2, Beinn Chaisgidle; 3, Loch Bà. Other abbreviations are as follows: BBG, Ben Buie gabbro; BGg, Beinn à Ghràig granophyre; Dg, Derrynaculen granophyre; GBg, Glas Bheinn granophyre; Gg, Glencannel granophyre; R, Ross of Mull granite; S, Strontian granite. The area covered by the pseudogravimetric map (Fig. 6) is indicated. Published by permission of the Director, British Geological Survey: Crown Copyright reserved.

by the British Geological Survey and they have been recontoured by hand to produce the Bouguer anomaly map (Fig. 1).

The Bouguer anomaly map shows an approximately circular positive anomaly of about 12 km radius over the central intrusive complex. With a maximum observed anomaly of 67.2 mGal and a regional background level of about 17 mGal, indicated by the values over northern Mull, the local anomaly associated with the complex is about +50 mGal. The anomaly is slightly elongated in a NW-SE direction along the line of intrusive centres, but the nearly radial symmetry of the anomaly is upset by the relatively low values over the outcropping granophyres of the Loch Bà centre. The Bouguer anomalies to the west and east of the complex are lower than the assumed background level because of the negative anomalies caused by the Ross of Mull and Strontian granites.

The positive anomaly is essentially attributed to a large volume of dense basic and/or ultrabasic rocks underlying the complex which may include outcropping gabbros such as Ben Buie. As Mesozoic sediments are thin, the density contrast is essentially between the dense igneous rocks and the metamorphic basement formed by the Moine Assemblage (density 2750 kg m^{-3}). To allow for an increase in upper crustal density with depth, it has been assumed that these are underlain by Lewisian rocks of density 2800 kg m^{-3} at 8 km depth. Specimens of gabbro and eucrite from the Ben Buie intrusion yielded density values of 2930 and 2970 kg m^{-3} respectively (Bailey *et al.* 1924), but ultrabasic rocks may be present at depth suggesting that the true mean density is probably higher. Because of the uncertainty, models have been constructed assuming densities of 3000 and 3100 kg m^{-3} for the main mass although a rather lower density has been used for the basic rocks down to 2 km

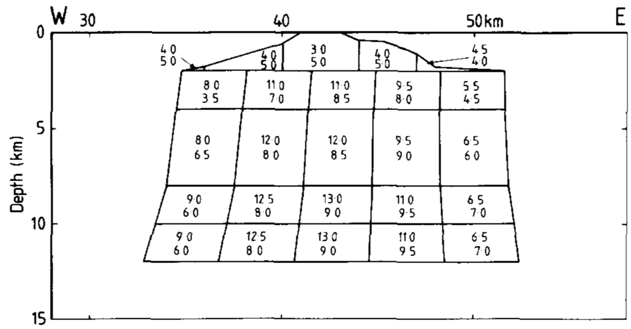

Fig. 2. *The subdivision of the model shown in Fig.* 4(a) *into* horizontal prisms for the application of end corrections. The horizontal widths of the prisms in both directions perpendicular to the vertical section, as used to compute the end corrections, are indicated in kilometres.

depth. Granophyres and other acidic rocks have been assigned a density of 2600 kg m^{-3} based on measurements in Skye and Mull.

Gravity interpretations of the sub-surface structure beneath the Mull intrusive complex along lines AA′ and BB′ (Fig. 1) have made use of the end-correction programme GRAVEND which allows for the three-dimensional shape of the causative body. The subdivision into horizontal prisms for model (a) beneath BB′ is illustrated in Fig. 2; the widths of the prisms perpendicular to the profile were approximately specified using the observed width of the gravity anomaly, and assuming a slight outward slope for the boundary. The interpretations of both profiles (Figs 3 and 4) shows that the depth extent of the dense underlying rocks depends critically on the density contrast with the adjacent basement rocks. If the dense rocks are of olivine tholeiite composition with an assumed density of 3000 kg m^{-3}, then they need to extend to about 13 km deep, about half the crustal thickness, and the volume occupied by the complex is estimated as 3650 km^3. On the other hand, if the dense rocks are predominantly picritic with a density of 3100 kg m^{-3}, then the complex only extends to a depth of 6.5 km with a total volume estimated to be 2000 km^3. The contacts slope steeply outwards at depth, with a steeper outward dip corresponding to the smaller density contrast assumed. Comparison between Figs 3 and 4 shows that the dense body is slightly elongated in the NW–SE direction (profile AA′), with the estimated width at the base of the model being 22–23 km beneath AA′ and 19–20 km beneath BB′. The inferred elongation at depth is approximately along the line of centres, but is not as pronounced as it appears in the surface geology.

Profile AA′ (Fig. 3) lies approximately along the line of centres. Superimposed on the broad positive anomaly is a fairly narrow region where the highest positive values occur which approximately corresponds to the region within the early caldera, comprising the Glen More ring dykes of the Beinn Chaisgidle centre and part of the region of the Glen More centre. As seen on the map (Fig. 1) and the profile (Fig. 3), a region of distinctly lowered gravity anomalies corresponds with the granophyric rocks of the Loch Bà centre. In order to fit the observations, the granophyres need to extend to a depth of the order of 1.5–2.2 km where they appear to be underlain by the dense mafic rocks which form the bulk of the complex at depth. The drop of over 20 mGal between the Glen More and Loch Bà centres is thus mainly accounted for by the density contrast at shallow depth between the dense rocks beneath the Glen More and Beinn Chaisgidle centres and the much lower density granophyres of the Loch Bà centre. The contact is interpreted as coinciding with the boundary between the Glencannel granophyre and the Beinn Chaisgidle complex and with the Loch Bà ring dyke. It slopes steeply away from the Loch Bà centre as might be expected and the granophyre appears to extend SW beneath the Glen More ring dykes. Within the Loch Bà centre, the base of the Beinn à Ghràig granophyre at the NE edge is noticeably shallower than the Glencannel granophyre in the interpreted model.

Near the SE end of profile AA′, the anomaly values are somewhat lowered over the outcrop of the Glas Bheinn granophyre, and a corresponding low density region extending to about 1 km depth has been incorporated in the models. The thick Triassic sediments beneath Loch Spelve (Rast *et al.* 1968) have not been included in the model, and

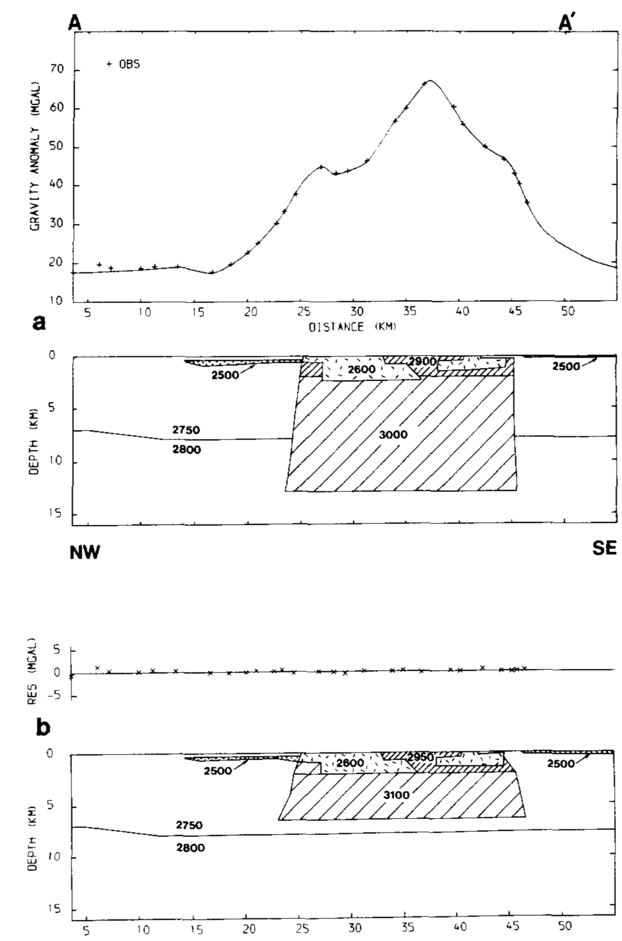

Fig. 3. Interpretation of gravity profile AA′ (Fig. 1) in terms of two possible subsurface density distributions (a & b), using end corrections to model the intrusive complex, with densities shown in kg m^{-3}. Stippling denotes sediments, diagonal shading denotes mafic igneous rocks and randomly orientated dashes denote granite. OBS denotes observed anomaly, the continuous curve is the computed anomaly for model (a), and RES is residual anomaly (observed minus computed) for model (b).

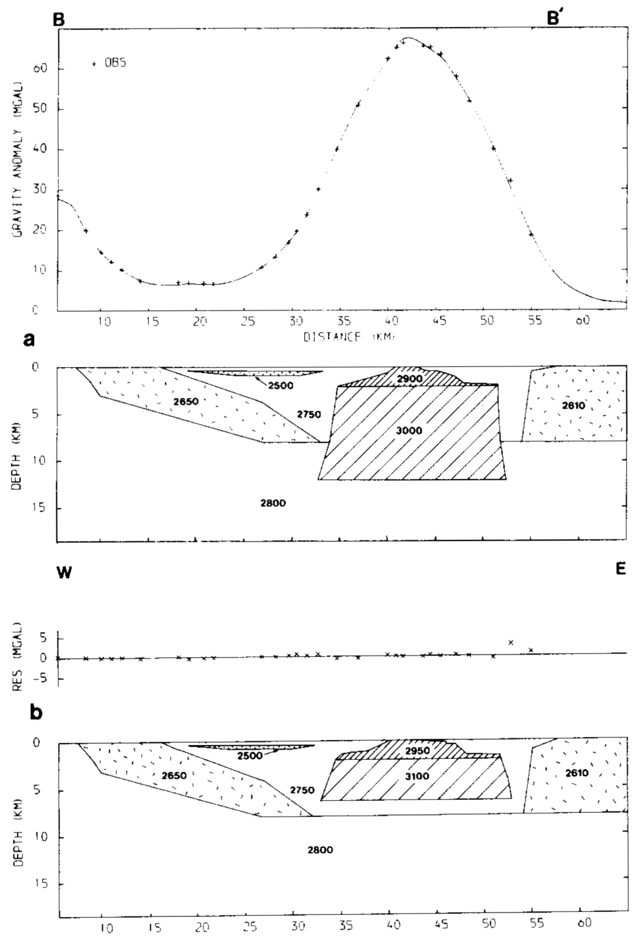

Fig. 4. Interpretation of gravity profile BB′ (Fig. 1) in terms of two possible subsurface density distributions (a & b), using end corrections to model the intrusive complex, with densities shown in kg m^{-3}. Ornamentation and abbreviations are as in Fig. 3.

their presence means that the SE contact of the main body may be slightly less steep than shown in the models. A small pocket of low density Mesozoic sedimentary rocks underlying the lavas near the NW end of line AA′ has been included in the model to improve the fit, but further evidence would be needed to establish the existence of this trough.

The models for profile BB′ (Fig. 4) incorporate low density bodies to the east and west of the complex representing the sub-surface extensions of the Caledonian Strontian and Ross of Mull granites. These explain the relatively low background levels along this profile and enable approximate consistency of interpretation with the models shown in Fig. 3 along profile AA′. The local variations of gravity over the complex have been attributed in the models to varying depth to the roof of the dense mafic rocks, but they could equally well be attributed to lateral density variation within the uppermost part of the complex. The estimated depth to the base of the complex is marginally shallower beneath profile BB′ due to extraneous factors.

The gravity anomalies thus indicate that dense mafic (basic and/or ultrabasic) rocks predominate beneath the Mull intrusive centre. The granitic rocks, although nearly as abundant as the basic rocks in surface outcrop, are estimated to form only 5–9% of the total volume of the complex. There is also a remarkable resemblance to the deep structure of the Skye intrusive complex as interpreted from gravity anomalies (Bott & Tuson 1973). Both complexes extend to about the same depth and are of closely similar width. The relationships of the granitic to mafic rocks are similar in geometry and volume. These similarities do not extend to other early Tertiary intrusive complexes of the region. However, the Mull and Skye complexes have distinctly differing surface geological characteristics and magnetic properties.

Interpretation of the magnetic and pseudogravimetric anomalies

The aeromagnetic map (Fig. 5) displays complicated and large amplitude magnetic anomalies over the Mull intrusive complex and adjacent regions. Bennett (1968) presented a qualitative interpretation after follow-up measurements at ground level. Some of his main conclusions are as follows. (1) The magnetic anomalies have an approximate bilateral symmetry along the line of centres. (2) The most prominent feature is the large positive anomaly of over 2000 nT over the SE part of the complex, covering the intrusives of the Glen More centre and the outer ring dykes of the Beinn Chaisgidle centre. (3) The anomalies drop steeply by 3000 nT NW across the ring dykes to a minimum in the vicinity of Beinn Chaisgidle, and then rise gently towards a region of depressed and subdued anomalies over the granophyres of the Loch Bà centre. (4) The main positive anomaly was attributed to strongly magnetized rocks of normal polarity at depth below in contrast to the much weaker magnetization of the Loch Bà granophyres. (5) A belt of positive anomalies lies just outside the Loch Bà ring dyke on its W and N sides; a local positive at Gruline was attributed to shallow basic rocks beneath the Knock granophyre (as seen in Fig. 3) and a large positive anomaly over the peripheral Killbeg ring dyke probably arises from underlying buried basic intrusives. (6) Outside the intrusive complex, the anomalies over the basaltic lavas are mainly negative reflecting their reversed magnetization. (7) A series of more intense peripheral linear or arcuate magnetic anomalies of short wavelength extend round the complex except on its N side, and Bennett attributed these to mainly linear near-vertical bodies possessing reversed magnetization.

In order to carry out a quantitative interpretation of the major features, the aeromagnetic map was digitized at 1 km intervals at the national grid intersections over an area of 32×32 km^2 for transformation to pseudogravimetric anomalies. This transformation requires the direction of magnetization to be specified. Mussett *et al.* (1980) summarized available palaeomagnetic results on Mull lavas and intrusive rocks. The rocks of the three intrusive centres are normally magnetized apart from some early representatives from centre 1 (Glen More). The plateau lavas and most of the central group are reversely magnetized, and so are the late regional dykes which post-dated the complex. Mussett *et al.* suggested two possible polarity time-scale sequences during the Mull activity. The simpler model 2 has reverse polarity during the extrusion of the lavas and the early activity of centre 1, normal polarity during the

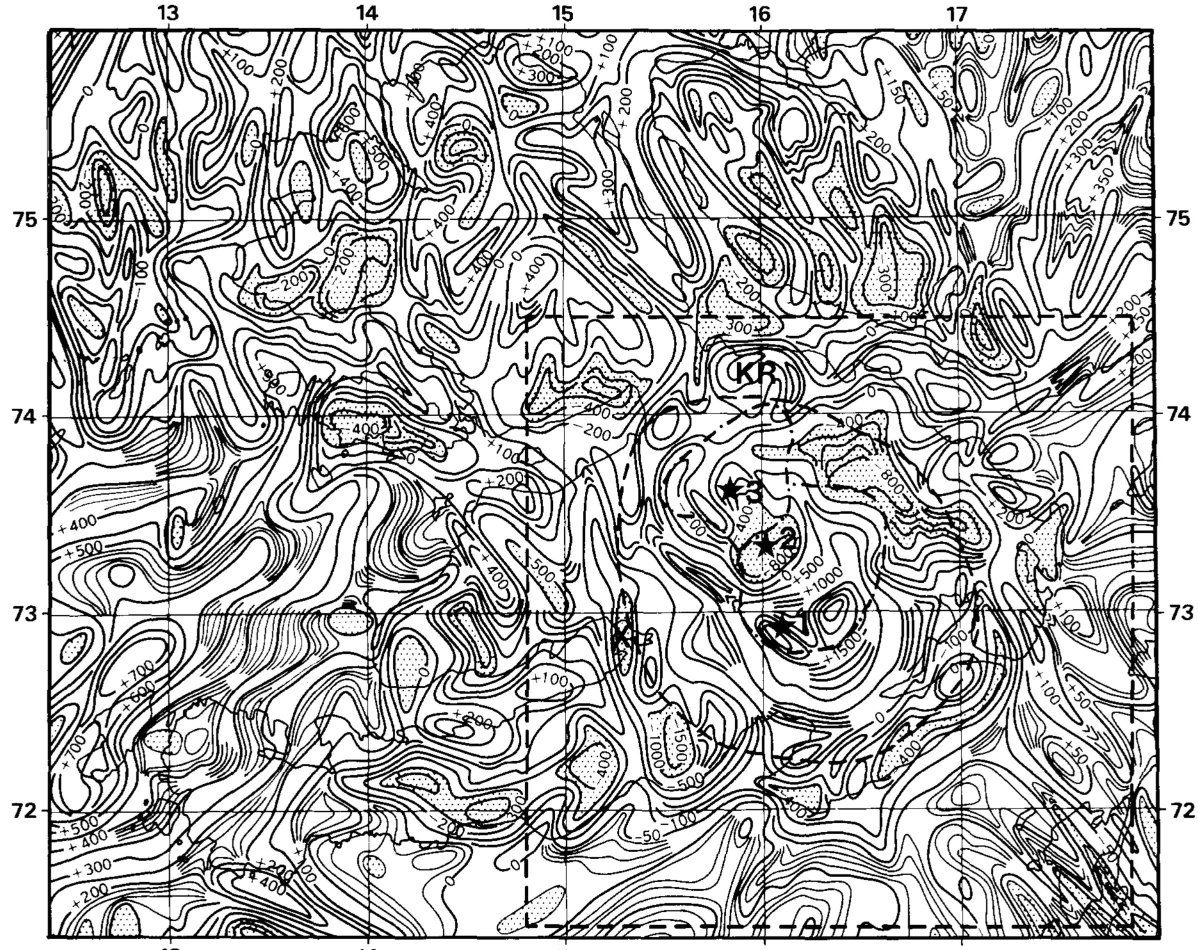

Fig. 5. Aeromagnetic map of the Mull intrusive complex and adjacent areas, with contour values in nT. The map covers the same area as Fig. 1 except that the western edge is 2 km further east. The faulted margins of the main calderas, the intrusive centres, the edge of the main subsurface body and the area covered by the pseudogravimetric map are shown as in Fig. 1. KR denotes Killbeg ring dyke. Published by permission of the Director, British Geological Survey: Crown Copyright reserved.

emplacement of the rest of the central complex, followed by reverse polarity during late dyke emplacement. Model 1 additionally includes a normal polarity epoch during the later part of the central lavas. The remanent magnetization is approximately along the present direction of the Earth's magnetic field or along the opposite direction. We have therefore assumed that the magnetization, which includes remanent and induced components, is along the present field direction.

The pseudogravimetric anomalies (Fig. 6) are contoured in mGal, but their amplitude depends directly on the assumed constant of proportionality between intensity of magnetization J and density ρ. In constructing the pseudogravimetric map, it has been assumed that the fictitious density is related to the intensity of magnetization by

$$\rho = \frac{\mu_0 J}{40\pi G}$$

where G is the gravitational constant. According to this relationship, a fictitious density of 150 kg m^{-3} corresponds to a magnetization of 1 A m^{-1}. In reality we are dealing with the contrast in magnetization beween the igneous rocks and the basement, but as the igneous rocks are much more strongly magnetized than metamorphic basement rocks, we can use actual magnetization without serious error. The background level of the pseudogravimetric map is purely arbitrary, and thus we are interested in the lateral variations of anomaly rather than the absolute level. Pseudogravimetric highs appear over normally magnetized rocks and lows over reversely magnetized rocks. The pseudogravimetric map can be interpreted in terms of an underlying distribution of 'fictitious' density by gravity interpretation methods, and knowing the relationship between fictitious density and magnetization, the distribution of magnetization can be determined.

The pseudogravimetric anomaly map of the Mull complex (Fig. 6) is dominated by a central positive anomaly of about 50 mGal amplitude which is almost coincident with the extent of the intrusions of the Glen More and Beinn Chaisgidle centres. The anomalies are slightly positive and featureless over the Loch Bà centre. The central positive anomaly is flanked on its W, S and NE sides by smaller amplitude negative anomalies with their minimum regions approximately coinciding with the intense linear or arcuate negative magnetic anomalies of the original aeromagnetic map. A conspicuous flanking positive anomaly is centred on the north edge over the Killbeg ring dyke. In general, the

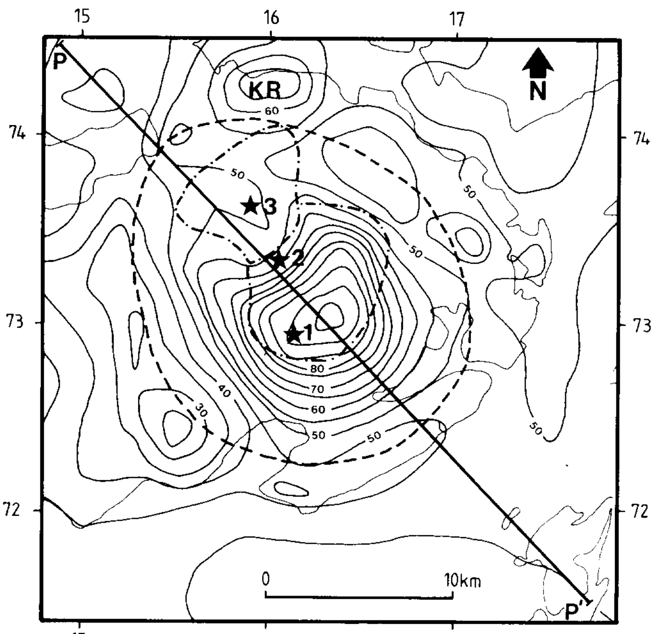

Fig. 6. Pseudogravimetric map of the Mull intrusive complex based on an assumed ratio of magnetization in A m^{-1} to density in kg m^{-3} of 150.0, and magnetization in the direction of the present geomagnetic field. The contour interval is 5 mGal. The faulted margins of the main calderas, the intrusive centres and the edge of the main subsurface body are shown as in Fig. 1. KR denotes Killbeg ring dyke.

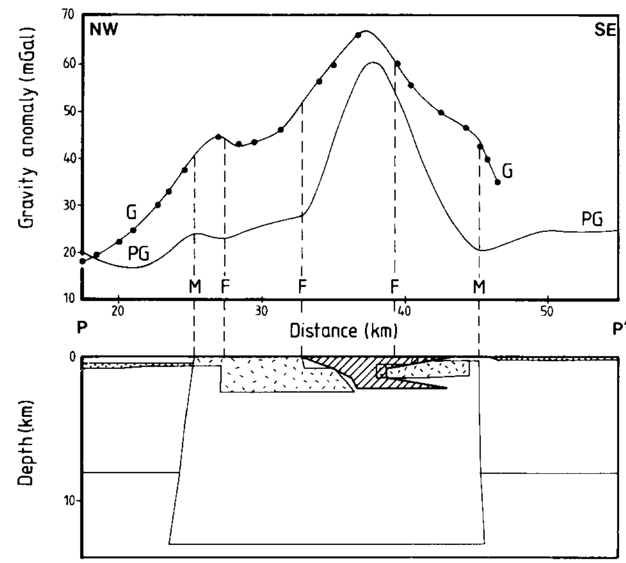

Fig. 7. Comparison of the pseudogravimetric anomaly profile PP′ (Figs 1 and 6) marked PG with the nearby Bouguer anomaly profile along part of AA′ (Fig. 1) marked G, and of the corresponding gravity and pesudogravimetric models of Figs 3(a) and 8(c). M denotes the edge of the main complex and F denotes ring faults.

pseudogravimetric map is much simpler than the original aeromagnetic map as a result of suppression of the shorter wavelengths, and the anomalies are also more directly related to the underlying distribution of magnetization.

The pseudogravimetric map (Fig. 6) shows that the dominant magnetic feature of the Mull complex is a region of strongly magnetized rocks of normal polarity underlying the SE part of the complex. This approximately coincides with the intrusive rocks of the Glen More and Beinn Chaisgidle centres. A simple preliminary interpretation can be made by assuming the causative body is a sphere. The ratio of maximum gradient to maximum anomaly yields an estimated depth of 3 km for the centre of the sphere. However, the anomaly is about 40% wider than would be expected for such a sphere, indicating that it is caused by a shallower and wider body. A further indication of the source of the anomaly comes from comparison with the geological map. The radial symmetry of the pseudogravimetric anomaly is broken by an embayment of the contours on the NW side of the anomaly. The contours here run approximately parallel with the Loch Bà ring dyke, in the same sense as the late cone sheets crossing Beinn Chaisgidle which relate to the Loch Bà centre. The embayment is thus most simply explained by truncation of the highly magnetic rocks of the two earlier centres by the much more weakly magnetized granophyres associated with the Loch Bà centre. The pseudogravimetric map gives no indication of the occurrence of highly magnetized rocks at depth beneath the granophyres of the Loch Bà centre which according to the gravity interpretation extend about 2 km down. The highly magnetic rocks causing the main positive pseudogravimetric anomaly are thus probably restricted to the uppermost 2–3 km (or thereabouts) beneath the two earlier centres and probably extend up to the surface.

A lower limit on the magnetization of the body underlying the central positive pseudogravimetric anomaly can be obtained by treating the body as a vertical cylinder of infinite depth which reaches up to the surface. To fit the observed width of the anomaly, such a cylinder would have a radius of about 3.5 km In order to account for the observed pseudogravimetric amplitude of 50 mGal, the cylinder would need to have a density of 341 kg m^{-3} corresponding to a magnetization of 2.27 A m^{-1}. As the causative body in reality is of smaller volume, the actual average magnetization is likely to be higher by a factor of two or more.

It is of interest to compare the pseudogravimetric anomaly with the actual gravity anomaly on the maps (Figs 1 and 6) and on nearby profiles along the line of centres (Fig. 7). In the vicinity of the earlier two centres, the pseudogravimetric and gravity anomalies are closely similar, but the similarity does not extend to the whole anomaly. The gravity anomaly has a half-width (the distance from the centre to the point where the anomaly is equal to $A_{max}/2$) of 10 km in a NW–SE direction and of 7.5 km in a NE–SW direction. In contrast, the pseudogravimetric anomaly has a half width of 3.3–3.6 km. The gravity anomaly is thus of much wider extent than the pseudogravimetric anomaly, and as the two types of anomaly are directly comparable, we can say that the magnetic body causing the central positive is much smaller in width and depth extent than the bodies accounting for the gravity anomalies.

Three models of the distribution of magnetization which can account for the main pseudogravimetric positive anomaly along line PP′ of Fig. 6 are shown in Fig. 8. These have been constructed by trial and error using the end correction programme GRAVEND. The contacts of model (a) slope inwards, those of model (b) slope outwards and

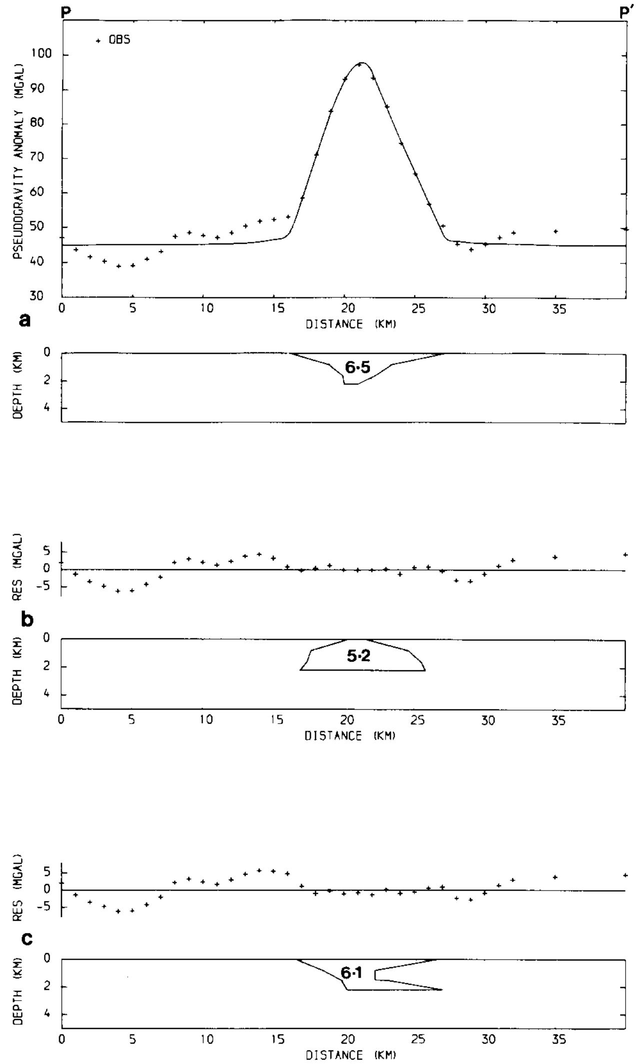

Fig. 8. Interpretation of the pseudogravimetric anomaly profile PP′ (Fig. 6) in terms of possible subsurface distributions of magnetization (a, b & c) which fit the main central positive anomaly, with magnetization shown in A m^{-1} in the direction of the present geomagnetic field. OBS denotes observed pseudogravity, the continuous curve is the computed anomaly for model (a) and RES denotes residual anomaly (observed minus computed).

the more complex model (c) takes into account the gravity models (Fig. 3). The observed profile is not sufficiently smooth to distinguish between the models, all of which give a good fit to the central positive anomaly and show comparable residuals over the peripheral regions. However, the inward dipping models (a) and (c) agree better with the observation of Bennett (1968) that very strongly magnetized rocks occur near the surface in the region of the Glen More ring dykes and also with the close correlation between the contours and the south-eastern part of the Loch Bà ring dyke (Fig. 6). They would also fit an explanation in terms of highly magnetic cone sheets. Model (c) is in particularly good agreement with the gravity model (Fig. 7). Nevertheless, the anomaly is likely to be caused by a more complicated and variable distribution of magnetization. Because of the sharpness of the anomaly, the magnetization must be essentially restricted to the uppermost few kilometres as in the models, and the total magnetic moment of cross section would need to be similar to that of the models. The modelled magnetization value of about 6 A m^{-1} indicates strongly magnetized igneous rocks. The strongly magnetic rocks forming the surface topography must contribute to the anomaly. However, the lack of strong correlation of the anomaly with the topography indicates that the bulk of the strongly magnetized rocks occurs below sea level, as in Fig. 8. The total three-dimensional volume of the strongly magnetized rocks is estimated to be between 70 and 105 km^3, which is between 2% and 5% of the total volume of the intrusive complex as estimated from the gravity anomalies.

The pseudogravimetric model (c) along PP′ is compared with the gravity model along AA′ in Fig. 7. These two profiles are not identical, but are sufficiently close for realistic comparison. The comparison reinforces the conclusion that the strongly magnetized rocks are contained within the shallow rocks of intrusive centres 1 and 2. The northern side of the magnetic body is almost coincident with the density interface between the northern granites and the central mafic body. The lack of strong magnetization of the granites of the Loch Bà centre is conspicuous although they appear to possess some positive magnetization. The Glas Bheinn granite in model (c) is also relatively weakly magnetized.

The main volume of the Mull intrusive complex lying beneath 2–3 km depth is much less magnetic than the upper regions associated with the two earlier centres. On the present interpretation, it has not been possible to resolve any significant magnetization for these deeper regions, but a weaker normal or reverse magnetization of the order of 0.1–0.5 A m^{-1} cannot be excluded. Pseudogravimetric interpretation of the magnetic anomalies over the Blackstones centre indicates a reverse magnetization of 0.95 A m^{-1} extending to a depth of about 15 km, and a normal magnetization of 1.1 A m^{-1} extends to a similar depth beneath the Skye intrusion (Tantrigoda 1982). It is possible that the deeper parts of the Mull intrusive complex are reversely magnetized, with induced and remanent components of comparable magnitude leaving a net magnetization of less than 0.5 A m^{-1} and producing only a small amplitude anomaly in relation to the other strong magnetic effects at shallow depth, including the lavas.

Alternatively, the magnetization of the deep parts of the complex may be weaker than that of the shallow mafic rocks for compositional reasons. A possible explanation is as follows (C. H. Emeleus, pers. comm.). The strongly magnetized rocks at shallow depth are the basaltic cone sheets, gabbros, quartz gabbros and possibly diorites of centres 1 and 2, which are characterized by abundant titano-magnetite (especially the quartz gabbros and dolerites). In contrast, the dense mafic rocks at greater depth beneath the whole complex may be more ultrabasic in composition, with the main oxide mineral being weakly magnetic chromium-rich spinel to which magnetite is subordinate.

Interpretation of the peripheral magnetic anomalies

As pointed out by Bennett (1968), the central positive magnetic anomaly is surrounded by a series of narrow peripheral anomalies of large amplitude. These are apparent on Fig. 5 in the vicinity of the outer margin of the main

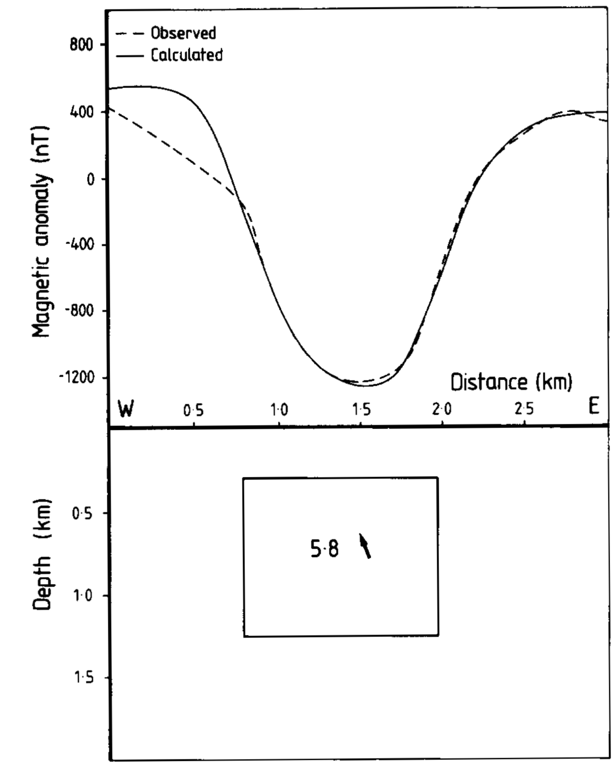

Fig. 9. Interpretation of the magnetic anomaly profile across anomaly X (Fig. 5) in terms of a reversely magnetized tabular body of strong magnetization (shown in A m^{-1}), reproduced from Tantrigoda (1982).

intrusive complex as outlined by gravity. These peripheral anomalies are dominantly negative around the SE, S and W margins and dominantly positive around the N and NE margins. They are visible but much less prominent on the pseudogravimetric map (Fig. 6) because of their relatively short dominant wavelengths.

Two-dimensional quantitative interpretations across seven of these peripheral magnetic anomalies have been carried out by Tantrigoda (1982) using non-linear optimization to obtain the fits to the observed profiles. At first an attempt was made to interpret the profiles in terms of structure in the lavas, but good fits could not be obtained and it was therefore assumed that the anomalies are probably caused dominantly by underlying intrusive bodies. One of the interpreted profiles is shown in Fig. 9. This crosses a conspicuous negative anomaly on the SW side. It can be satisfactorily interpreted in terms of a strongly magnetized tabular or dyke like body with reverse magnetization. Closely similar interpretations were obtained for the other six profiles examined.

The marginal positive anomalies along the northern margin can be related to shallow mafic rocks underlying the Beinn à Ghràig granite (as modelled at the northern edge of the complex in Fig. 3) and to the Killbeg ring dyke. In contrast, there is no apparent corroboration from the exposed geology or from the gravity anomalies for the reversely magnetized dyke-like bodies which are inferred to occur along the SE, S and W margins of the main deep-seated intrusive body. These are tentatively interpreted as a discontinuous ring dyke or dykes averaging an overall width of about 0.5 km and marking the approximate edge of the whole intrusive complex. Such a feature would only cause a small and unresolvable gravity anomaly, and might have been emplaced at a period of reverse magnetization either before or after the main normally magnetized intrusive activity in Mull.

Discussion

The geophysical evidence yields quantitative information on the deep structure and relationships of major rock types which is inaccessible to surface geology and which is relevant to hypotheses of origin and emplacement of the intrusive complex. The most important result is the inference from the gravity anomalies that anomalously dense rocks shaped like an inverted flower pot, squashed into a slightly elliptical plan, underlie the Mull intrusive complex to a depth of 7–13 km depending on the actual density. The only obvious explanation is that the dense rocks consist of crystalline mafic rocks which occupy a volume considerably in excess of that of the surface lavas of Mull and Morvern. Because of their large volume, the deep-seated dense rocks beneath the complex probably approximate in composition to the parent magma of the central complex and the associated non-porphyritic lavas.

Thompson (1982) suggested that the parent magma for the central complex of Mull may resemble the Preshal Mhor magma type of Skye, which is a magnesium-rich olivine tholeiite similar to ocean ridge basalts (Table 1). The density of a crystalline rock of this composition has been estimated by computing the CIPW norm and using the densities of the constituent minerals. Assuming 1% porosity and making a small allowance for increase in temperature with depth outweighing the compression, this magnesium-rich olivine tholeiite yields a density of 3030 kg m^{-3}. This is marginally denser than the deep-seated rocks of the lower density model of Figs 3 and 4. Thus if the parent magma was of this type, the intrusive complex must extend to a depth approaching 12 km.

Alternatively, the parent magma may be of picrite composition (Table 1). Evidence that picrite magmas may have been important in certain of the neighbouring early Tertiary intrusive complexes comes from the prominent

Table 1. *Possible compositions (%) of the Mull parent magma*

	(1)	(2)
SiO_2	46.99	48.14
TiO_2	1.21	1.49
Al_2O_3	15.54	10.46
Fe_2O_3	1.50	1.91
FeO	9.35	9.20
MnO	0.22	—
MgO	9.13	18.00
CaO	12.69	8.22
Na_2O	1.83	1.68
K_2O	0.10	0.75
H_2O	1.34	—

(1) Magnesium-rich olivine tholeiite from Preshall Mhor, Skye (Thompson 1982); (2) Model picrite, derived by fractional addition of olivine to a model basalt (Cox 1980).

occurrence of layered ultrabasic rocks in certain complexes such as Rhum, and from the exceptionally large positive gravity anomalies over complexes such as Blackstones (McQuillin *et al.* 1975) and St Kilda (Bott *et al.* 1979) which require densities around $3100\,kg\,m^{-3}$ or more. The computed density of the model picrite of Cox (1980) shown in Table 1, assuming 1% porosity and making the same allowance as above for temperature and pressure at depth of a few kilometres, is $3090\,kg\,m^{-3}$. This closely resembles the higher density models of Figs 3 and 4. If the parent magma is picritic, then the complex extends to a depth of about 7 km. More generally, the models of Figs 3 and 4 provide approximate upper and lower limits on the true depth of the complex.

Mechanism of emplacement

How was this large, nearly cylindrical plug of dense igneous rocks emplaced within the upper crust, and how did the magma migrate through the lower crust? The two main processes which may be relevant are forceful emplacement and stoping.

Richey (1932) proposed that the Tertiary centres formed as follows. The first stage was the development of an elongated basaltic magma reservoir at unspecified depth beneath the line of Scottish centres. This reservoir fed the dyke swarms and some of the magma segregated to form cupola-shaped local reservoirs above which the central intrusive complexes developed. Space for the local cupola-shaped magma reservoirs was provided by subsidence of the country rock which allowed the reservoirs to reach within about 5 km of the surface (as suggested by the dips of the cone sheets). The local magma chambers gave rise to cone sheets when magma pressure was high and ring dykes when the pressure was low, according to the mechanisms suggested by Anderson (Bailey *et al.* 1924, pp. 11–12). According to Richey, some space for the intrusions was provided by explosive activity and by updoming associated with cone-sheet emplacement, but the major factor was probably cauldron subsidence of country rock and other forms of stoping. Most subsequent discussions have followed similar lines (e.g. Walsh *et al.* 1979) but Walker (1975) suggested a controversial variant in which the diapiric rise of granite magma paved the way for the later emplacement of the more mafic intrusives and exerted considerable influence on the emplacement of cone sheets. Recently some doubt has been thrown on the efficacy of stoping in emplacing tholeiitic magma into the 'granitic layer' of the upper crust because tholeiite magma in particular is demonstrably denser than granite (Kushiro 1982), but it needs also to be recognized that upper crustal basement rocks such as the Moines and Lewisian have much higher average densities than granite (see below).

The mechanism of emplacement is here reassessed to take account of the quantitative inferences from the geophysical data, particularly gravity. New insight into the contrasting intrusive processes at different crustal levels also comes from the recognition that the lower crust was probably ductile and the upper crust was brittle and strong at the time of emplacement.

Some forceful emplacement took place in the early Glen More centre as witnessed by the concentric marginal folding which affected the basalts and underlying rocks. This is believed to be related to the forceful emplacement of the Glas Bheinn and Derrynaculen granophyres (Bailey *et al.* 1924) and other eroded early granitic material (Walker 1975). Walker estimated that the folding provided space of about $20\,km^3$, which is about half the volume of the Glas Bheinn granophyre as estimated from the gravity results. Early doming, preceding the formation of the early caldera, may have provided space of about $80\,km^3$. A similar amount of space may have been provided by uplift associated with cone sheet emplacement, and a further small contribution may have come from explosive activity. The total volume of space provided by all these processes is about 10% or less of the volume of the whole intrusive complex. It is unlikely that diapirism can have been effective at depths within the range 4–12 km because of the strength and brittle nature of the relatively cool upper crust. The processes of diapirism and doming therefore appears to be inadequate to explain the bulk of the emplacement, these being only effective in granite emplacement at high level during the early stages, and in cone sheet emplacement.

The mechanism of emplacement must therefore dominantly take place by processes associated with fracture rather than flow, this being the mechanism of failure appropriate to the cool and strong upper crust. The mechanism must also be compatible with contemporaneous strain in the adjacent regions. One possibility which meets these requirements is extension fracture in a NW–SE direction compatible with contemporaneous dyke emplacement in the upper crust in the adjacent regions. Movement on the Great Glen fault may have taken some part in accommodating such extension. The slight elongation of the Mull intrusive complex in a NW–SE direction is consistent with some space being provided in this way, although the gross thickness of the visible dykes implies that this could provide about 15% of the space and is thus probably not the major factor in the emplacement mechanism. The other possibility is stoping, which also operates by fracture followed by sinking of the country rock to the base of the magma chamber.

Stoping can only take place if the stoped rocks are denser than the rising magma. The density of anhydrous silicate melts of specified composition can be determined with considerable accuracy from the partial molar volumes of the oxide components. The method of Bottinga *et al.* (1982) allows for the composition dependence of the molar volume of aluminium oxide in the melt whereas the method of Mo *et al.* (1982) assumes independence of all the constituent molar volumes. An approximate allowance for water content can be made from experimental data on the partial molar volume of water in albite melts (Burnham & Davis 1969) and allowance for pressure is based on experimental results of Kushiro (1982). Computations have been carried out for the model parent magmas for anhydrous melts and for melts with an assumed water content of 0.5% by weight. The olivine tholeiite is assumed to be at 1300 °C and the picrite at 1400 °C. The results (in $kg\,m^{-3}$) are given in Table 2, with the method of Bottinga yielding the lower estimate and the method of Mo yielding the higher estimate throughout.

The actual density of the magma may have been slightly higher because of the presence of a small crystal fraction. Even with this factor taken into account, the actual density of the magma is unlikely to exceed $2720\,kg\,m^{-3}$ at the surface or $2750\,kg\,m^{-3}$ at a depth of 11 km and is probably significantly lower because of the water content. The upper

Table 2. *Densities in kg m^{-3} of model parent magmas for anhydrous melts and melts with an assumed water content of 0.5% by weight*

	Surface	11 km depth (3 kb)
Mg-rich olivine tholeiite		
(a) anhydrous	2670–2727	2700–2750
(b) 0.5% water	2630–2670	2690–2700
Model picrite		
(a) anhydrous	2690–2725	2730–2755
(b) 0.5% water	2645–2680	2685–2720

crustal basement rocks penetrated by the Mull complex have a well determined density of 2750 kg m^{-3} at shallow depth rising to at least 2800 kg m^{-3} a few kilometres down. Thus the magma almost certainly had a lower density than the country rocks and therefore stoping could readily have taken place. The geophysical evidence guides us back towards the classical views of Richey (1932) supported by Tuson (1959) that ring dyke emplacement or other forms of stoping were the dominant process by which the bulk of the intrusive complex invaded the upper crust.

The above mechanism does not solve the space problem in the lower crust. The parent magma certainly originated in the underlying mantle. During the overall process of emplacement, a volume of 1500–3000 km^3 of lower crustal material must have been forced sideways and downwards to make room for this magma, the space thus created being now filled with the stoped material removed from the upper crust. The lower crust was almost certainly ductile rather than brittle, and emplacement from the mantle into the lower crust may therefore have occurred by diapirism and other types of forceful emplacement such as dyke and sill injection. The crustal emplacement of the Mull complex thus took place in two stages, dependent on the rheological subdivision of the crust into a ductile lower layer into which diapiric emplacement can take place and a strong and brittle upper layer where stoping and extension fracture allow the upward passage of the low density magma.

The postulated forceful emplacement of the magma into the lower crust has an interesting implication in that it would produce a small thickening of the crust. Assuming a volume of 2500 km^3 of lower crust has been forced sideways and downwards, an average resultant crustal thickening of 1 km would be required over an area of 50×50 km^2. This may be partly counterbalanced by thinning of the lower crust if major dykes are restricted to the upper crust. Crustal thickening on this small scale is probably hard to detect in the gravity anomalies, but nevertheless it may provide a regional isostatic compensation for the excess upper crustal load associated with the dense intrusive complex, including the locally high topography.

The granites

One of the most important results from the gravity interpretation is the clear demonstration that the granites are distinctly subordinate to the mafic rocks of the complex, being estimated to form between 5 and 9% of the total volume. The volumetric relationship between granite and the rest of the complex is almost identical to that of the Skye complex (Bott & Tuson 1973). This proportion is just what would be expected if the granites originated from mafic magma by the combined effects of magmatic differentiation and partial fusion of crustal material, in accordance with present petrogenetic and geochemical evidence (Walsh *et al.* 1979; Thompson 1982).

The geophysical results indicate that the main volume of granite in the Mull complex underlies the Loch Bà centre, occupying the uppermost 2 km beneath the outcropping granites, particularly the Glencannel intrusion. According to geochemical evidence, these granites are predominantly formed by fractional crystallization of basaltic magma with a small proportion from crustal contamination (Walsh *et al.* 1979), with the acid magma possibly being repeatedly recycled during the evolution of the complex (Thompson 1982). The volume of the centre 3 granites appears to be consistent with these suggestions.

The granites of centre 1 appear to occupy a significantly smaller volume than those of centre 3, consistent with an origin from early partial melting of Lewisian or other lower crustal material with some differentiation of basaltic magma (Walsh *et al.* 1979). This raises the problem of whether the volume of such an acid diapir would be large enough to pave the way for the main intrusion as suggested by Walker (1975), even if erosion has removed some of it. The granites of the Glen More ring dykes of centre 2 appear to be volumetrically unimportant, although the Glencannel granite extends some way beneath this region.

Conclusions

The main conclusions are as follows:

(1) A local positive gravity anomaly of 50 mGal amplitude occurs over the Mull intrusive complex and is attributed to underlying dense mafic (basic and/or ultrabasic) rocks. The dense body of rocks extends from near the surface to a depth of about 13 km for a density of 3000 kg m^{-3} appropriate to an olivine tholeiite composition, or to about 6.5 km for a density of 3100 kg m^{-3} appropriate to model picrite. The dense body is elongated by about 10% in a NW–SE direction along the line of centres, but otherwise has the shape of an inverted flower pot with the mean diameter increasing from about 19 km at shallow depth to 21 km at the base. The total volume occupied is estimated to be between 2000 and 3600 km^3.

(2) Smaller superimposed negative gravity anomalies occur over the granites of centres 1 and 3, destroying the simple near radial symmetry of the main positive anomaly. The granites of centre 3 (Loch Bà) are interpreted as extending to a depth of about 2 km where they are underlain by mafic rocks of the main body. The earlier granites of centre 1 occupy a significantly smaller volume than the centre 3 granites, and the granites of centre 2 have an insignificant effect on the gravity field. It is estimated that the granites form between 5% and 9% of the total volume of the complex, consistent with secondary derivation from basaltic magma by differentiation and/or fusion of crustal rocks.

(3) A highly disturbed magnetic anomaly field is associated with the Mull complex and the adjacent lava fields and dyke swarm. The complicated field has been simplified by pseudogravimetric transformation. The most conspicuous feature of the pseudogravimetric map is a large positive anomaly over the rocks of centres 1 and 2. The pseudogravimetric anomaly is of much smaller areal extent than the positive gravity anomaly, and is mainly attributable to highly magnetic rocks (magnetization about 6 A m^{-1})

occupying the uppermost 2 km or thereabouts beneath centres 1 and 2. Cone sheets may be an important factor in producing this anomaly. The magnetization of the main part of the complex below a depth of 2 km cannot be resolved on present evidence, but a relatively weak magnetization of less than 0.5 A m^{-1} cannot be ruled out.

(4) A partial ring of strong negative magnetic anomalies surrounds the central magnetic anomaly on the S and W sides, corresponding approximately with the upper edge of the intrusive complex as defined by the gravity anomaly. This is attributed to arcuate or linear dyke-like or tabular bodies which have very strong reverse magnetization. This may represent an early ring dyke not visible in the surface geology.

(5) Up to 25% of the volume occupied by the complex might be accounted for by the combined effects of diapirism, doming including uplift caused by cone sheet emplacement, explosive activity, and crustal extension associated with upper crustal dyke swarm intrusion. It is inferred that most of the upper crustal space occupied by the complex was made available by ring subsidence and other forms of stoping. It is demonstrated that parent magmas of either magnesian-rich olivine tholeiite or model picrite composition would be less dense than the upper crustal basement rocks (Moine and Lewisian) even if anhydrous, indicating that stoping could readily have taken place.

(6) It is suggested that the mantle-derived parent magma rose through the ductile lower crust by diapirism to form a magma pool at mid-crustal depths beneath the brittle and strong upper crust, through which it rose by processes involving fracture as indicated in (5) above.

(7) The net addition of intrusive (and extrusive) material to the crust may have caused a slight underlying thickening of the crust sufficient to give isostatic support to the excess mass, including the associated high topography.

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