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A gravity investigation of the Middleton Granite, near Inverurie, Aberdeenshire

Department of Trade and Industry

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Mineral Reconnaissance Programme Report 120

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SUMMARY

This report describes the results of a gravity survey in the Inverurie area of Aberdeenshire. The primary target was the Middleton Granite, which is associated with molybdenum and tungsten mineralisation. An 8 km^2 detailed survey area around this granite was covered at a station density of 30 per square kilometre, while a surrounding area of approximately 120 km^2 was surveyed at a station density of about 2 per square kilometre.

A distinct residual Bouguer anomaly low is evident over the Middleton Granite. The results indicate a granite subcrop centred slightly to the north-west of its previously mapped location and a shallow granite ridge extending about 1.5 km to the south-south-west. This structure considerably enlarges the target area suitable for further mineral exploration. Modelling indicates that the Middleton Granite is a cupola projecting from the buried roof of the Bennachie component of the Eastern Highlands batholith. It also delineates a north-east–south-west trending feature which is interpreted as the concealed margin between the Bennachie Granite and the more dense and/or thinner granite components to the south-east.

A limited magnetic survey located a (Permo-Carboniferous?) basic dyke cross-cutting the Middleton Granite. Trial electrical soundings indicated little contrast in electrical properties between the granite and surrounding Middle Dalradian rocks.

INTRODUCTION

The Middleton Granite is a small granite stock or cupola which lies about 2 km south-south-east of Chapel of Garioch and 4.5 km west-north-west of Inverurie, in Aberdeenshire (Figure 1). Molybdenum and tungsten mineralisation are found in quartz veins spatially associated with this granite (Colman et al., 1989). A gravity survey was undertaken with the aim of providing information on the form of the intrusion, and its relationship with the Eastern Highlands granite batholith. The gravity survey would not provide a direct indication of economic mineralisation, but it was hoped that it could assist in defining the most suitable areas for further exploration. A brief qualitative description of the results of this survey has been provided by Colman et al. (1989) and this is expanded in this report to include a more thorough quantitative treatment.

National Grid references are given in kilometres throughout this report. The study area covered parts of Ordnance Survey 1:25 000 sheets NJ 61, 62, 71 and 72.

REGIONAL SETTING

The gravity survey was conducted over an area of Dalradian (Argyll Group) metasediments flanked by granites to the west (Bennachie) and south, and by basic and ultrabasic rocks of the Insch intrusion to the north (Figure 1). The Middleton Granite is exposed in a small quarry at [372.96 822.02]. Rb-Sr dating indicates that the age of the Bennachie Granite is approximately 400 Ma (Lower Devonian), while
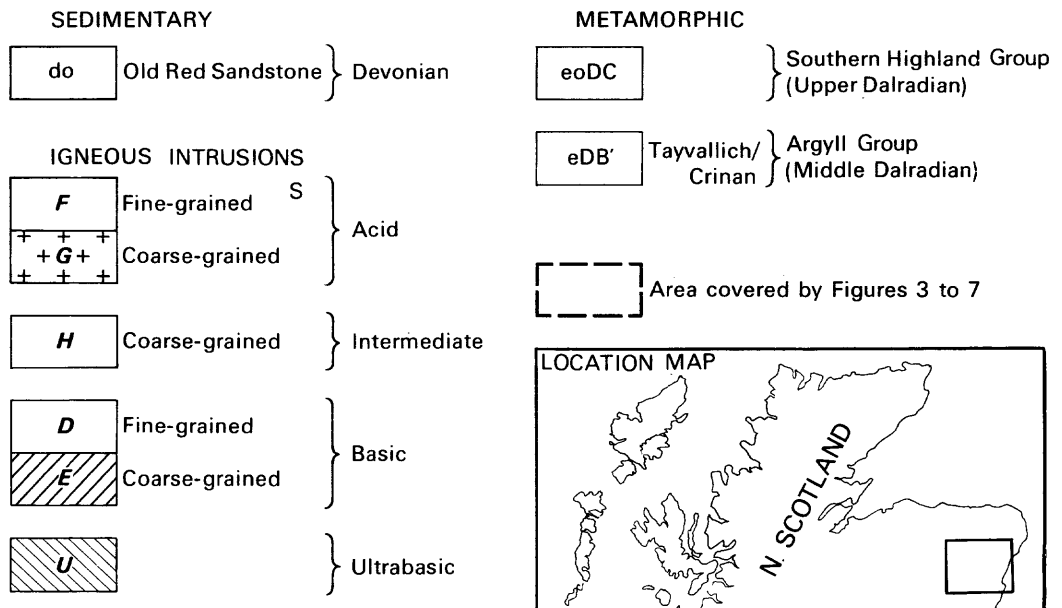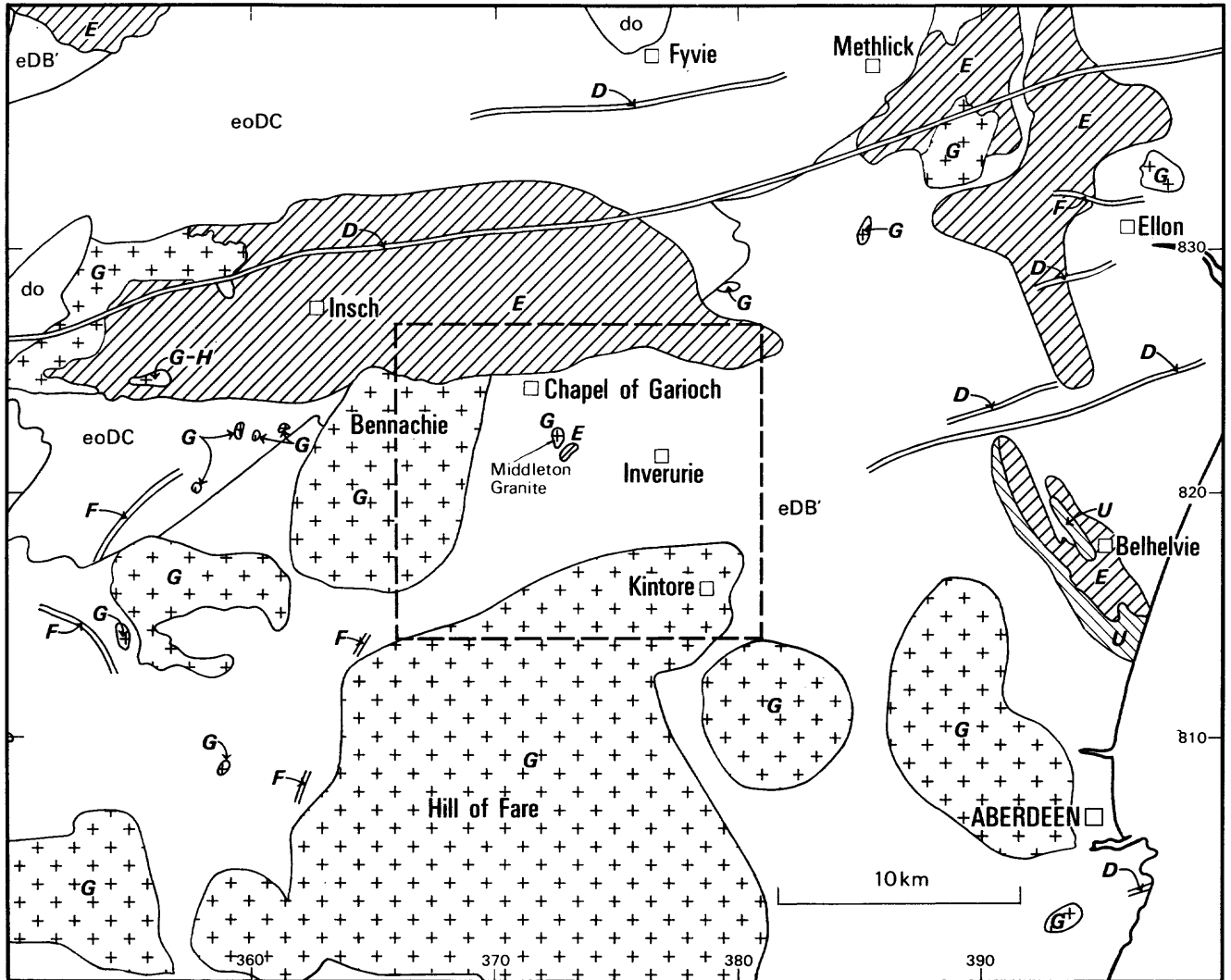
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Figure 1 Geological map (after BGS Moray-Buchan 1:250 000 sheet and Colman et al., 1989)

2

the Middleton Granite is inferred to be of similar age and possibly derived from the same magmatic source (Darbyshire and Beer, 1988). Recent studies (Harrison, 1987; D Gould, personal communication) have revealed that the large area of granite to the south of the survey area, which was previously all referred to as the Hill of Fare Granite, in fact comprises a number of intrusions ranging in age between Lower Ordovician and Upper Silurian, and in composition between intermediate and acid; the most northerly intrusions (the Tillyfourie Tonalite and Kemnay Granite) are of probable Lower Ordovician age.

The Bouguer gravity anomaly map of the region (Figure 2) reveals a conspicuous low extending southwards and westwards from Bennachie. This is the eastern part of a major Bouguer anomaly low associated with the belt of voluminous, low density granites of the Eastern Highlands. Three-dimensional gravity modelling (Rollin, 1984) indicates continuity at depth between the various granites, which form a major composite batholith. A depth to the base of the batholith of 13 km is required if a granite/Dalradian density contrast of -0.1 Mg/m^3 is assumed. The model of Rollin (1984) cannot provide detailed information, as it is based on a relatively coarse (2 km) grid, but it does imply that the top of the granite extends eastwards from Bennachie at shallow depth as far as the Middleton Granite, then descends steeply to the north-east of the latter.

Bouguer gravity anomaly highs centred at [372 831] and [389 838] are associated with the Insch and Haddo basic intrusions respectively (Figures 1 and 2). These bodies are members of the 'Younger' (c. 500 Ma) basic suite of intrusions in the Grampian region. Models produced by McGregor and Wilson (1967) and Rollin (1984, fig. 5.4) suggest that the Insch body is approximately 3 km thick to the north of the Bennachie Granite.

DATA ACQUISITION AND REDUCTION

Gravity measurements were made at 522 stations in an area extending from National Grid line 368E to 380E and 815N to 826N. An 8 km^2 detailed survey area around the Middleton Granite was surveyed at a station density of approximately 30 per square kilometre, while the station density over the remainder of the survey area averages approximately 2 per square kilometre (Figure 3). All the gravity measurements were made with LaCoste and Romberg gravity meter G456. They have been corrected for tides and meter drift, and referred to the National Gravity Reference Net 1973 (NGRN 73) via ties to the Fundamental Bench Mark at Elgin.

Primary elevation control was provided by Ordnance Survey benchmarks. Within the detailed survey area, stations were located along field boundaries and tracks; their elevations were measured using a Wild RDS tacheotheodolite. The survey loops were tied at each end to benchmarks, with elevation misclosures averaging 0.15 m. In the surrounding area most stations were at benchmarks, although some were at spot heights and a few were surveyed using a theodolite. A number of stations were established at electricity pylons, making use of the setting levels provided by the North of Scotland Hydro-electric Board.
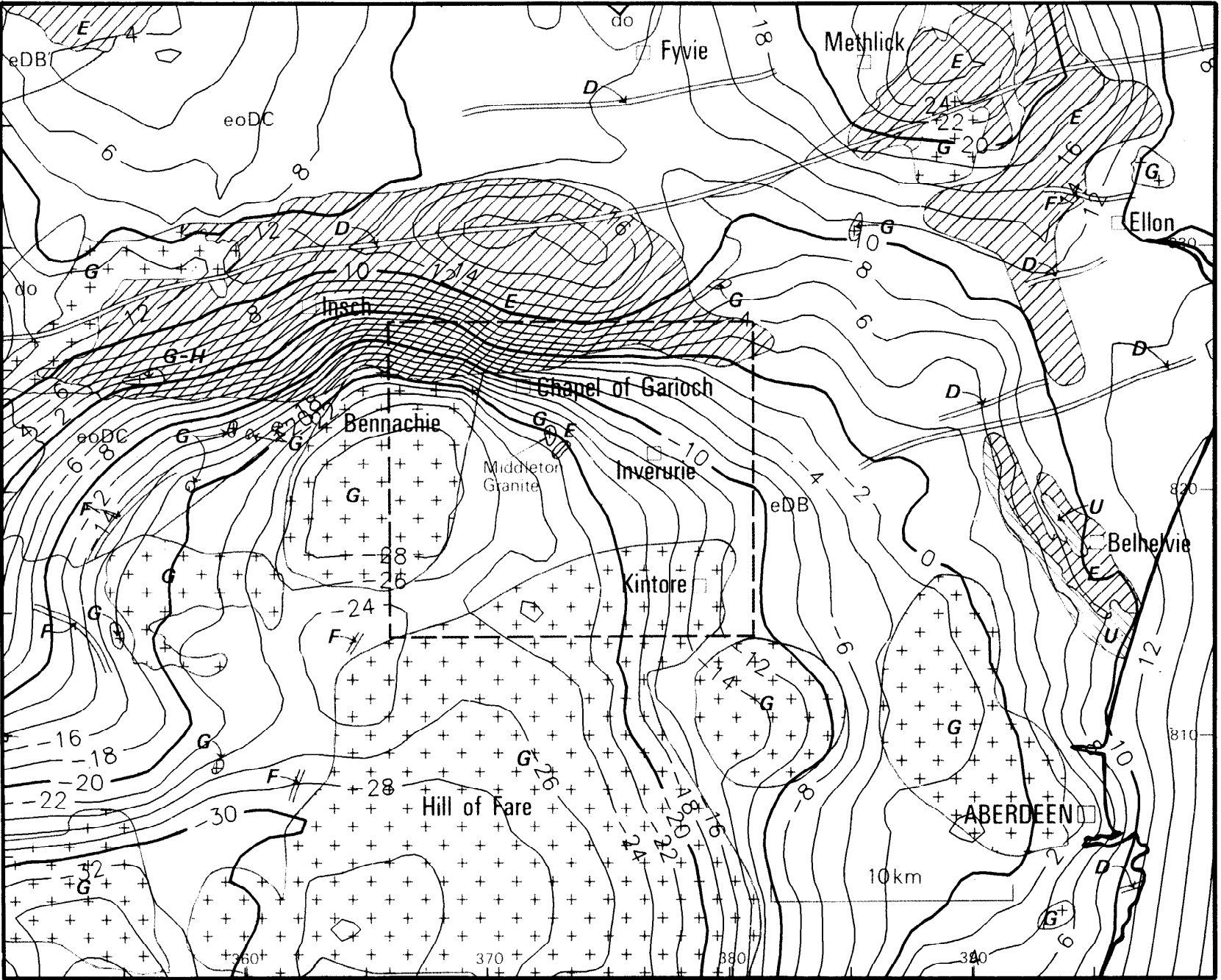
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Figure 2 Bouguer gravity anomalies superimposed on geological map (Figure 1). Contour interval = 2 mGal

The data are presented in the form of terrain-corrected Bouguer gravity anomalies. Theoretical gravity values have been calculated using the 1967 International Gravity Formula, and a density of 2.75 Mg m^{-3} has been assumed for the elevation corrections. Terrain corrections out to Hammer zone G (1.53 km) were estimated by the zone chart method (with some interpolation where stations were closely spaced). Outer zone terrain corrections (out to 48.6 km) were estimated using a matrix of mean elevations in 1 km squares.

Three magnetic traverses were conducted using an Elsec model 770 proton precession magnetometer. Diurnal corrections were estimated from repeat readings at a local base. Trial resistivity/IP soundings were conducted using Huntec Mk III time domain equipment; an expanding Schlumberger array was used, with current electrode separations of between 2 m and 400 m.

ROCK DENSITIES

Density determinations were made on 19 samples from the boreholes drilled at Middleton (Entwisle, 1988). The mean saturated bulk density of 14 samples of the Middleton Granite, from boreholes CG5 and CG7, is 2.59 Mg/m^3 (see Colman et al. (1989) for borehole locations). Although the density of these samples is likely to have been influenced by alteration, their mean is similar to published values for the Bennachie Granite: 11 samples from a borehole drilled into this granite at [366.9 821.0] have an average density of 2.60 Mg/m^3, decreasing from 2.61 Mg/m^3 at 95-98 m to 2.59 Mg/m^3 at 293-294 m (Rollin, 1984).

The densities of 5 samples of Dalradian metasediments from boreholes CG1 and CG3 vary widely, ranging between 2.65 and 2.94 Mg/m^3. McGregor and Wilson (1967) estimated an average density of 2.74 Mg/m^3 for the Dalradian rocks of this region from a sample of 80 specimens; the range of densities was 2.65-2.95 Mg/m^3.

The density of 49 specimens of basic rocks from the Insch mass averaged 2.91±0.03 Mg/m^3 (McGregor and Wilson, 1967).

THE BOUGUER ANOMALY MAP

The Bouguer gravity anomaly map in Figure 3 is based on all the stations from the new survey plus approximately 40 stations around the perimeter which were obtained from the BGS regional gravity data bank. Routines from the Interactive Surface Modeling (ISM) package (Dynamic Graphics Inc., 1988) were used to grid (at 0.2 km intervals) and contour the data. The geological boundaries shown on this and subsequent figures, and referred to in the following discussion, are based on recent BGS remapping of the Inverurie (76E) sheet (D Gould, personal communication), and supercede those used on the published 1:250 000 sheet (Figure 1).

The map is dominated by strong regional gradients with minimum Bouguer anomaly values in the south-west, associated with the Eastern Highlands granite batholith, and maximum values in the north, associated with the Insch basic intrusion. A contour

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Figure 3 Bouguer gravity anomaly map of Chapel of Garioch area (contour interval 1 mGal)
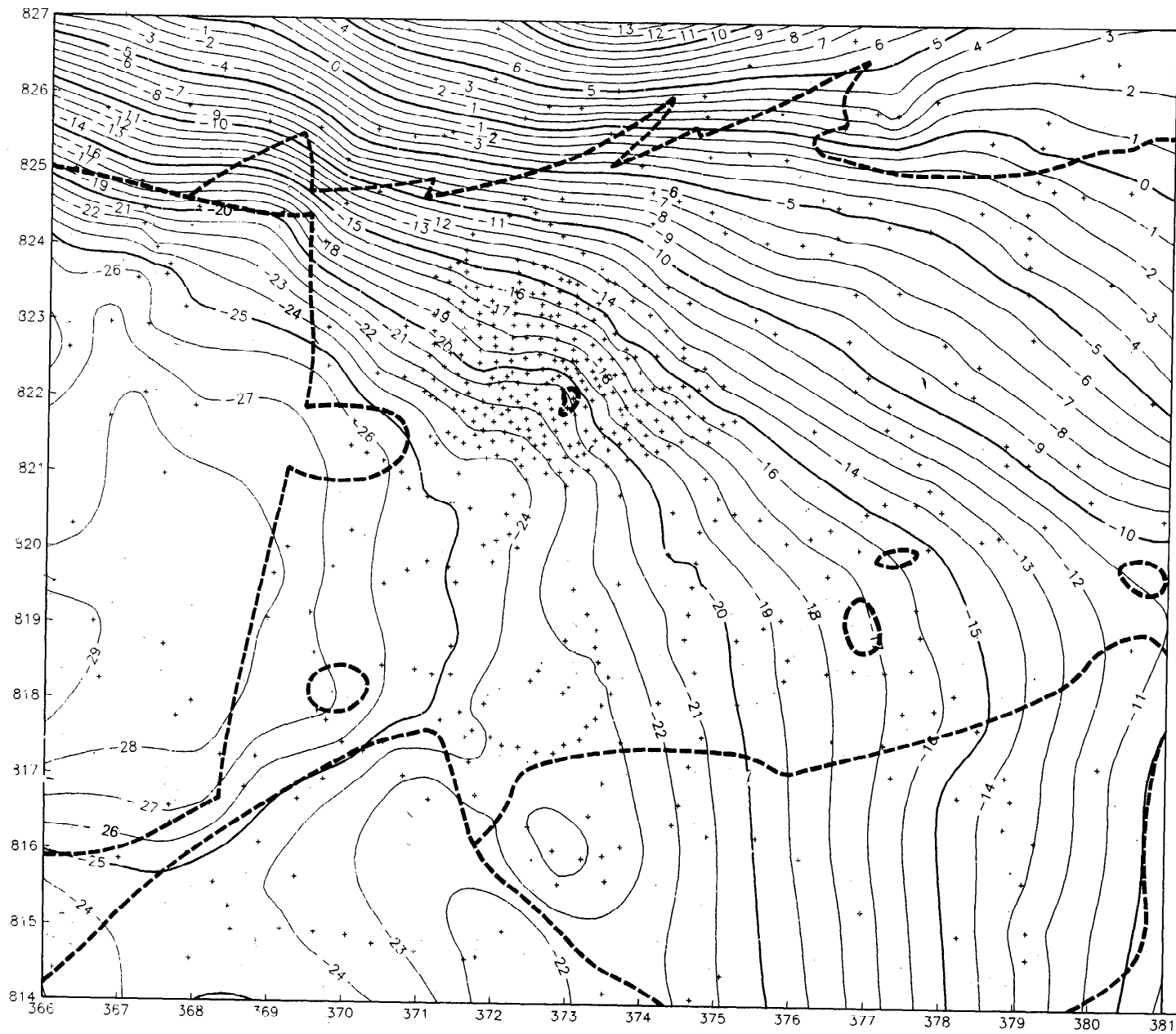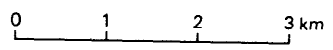
KEY

+ Gravity Station
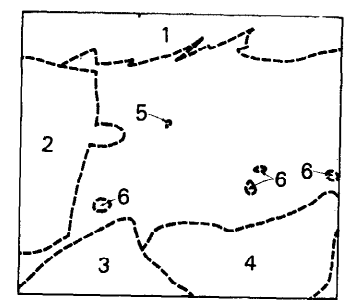
Pecked lines indicate mapped geological boundaries

1 Insch basic/ultrabasic intrusion

2 Bennachie Granite

3 Tillyfourie Tonalite

4 Kemnay Granite

5 Middleton Granite

6 Other granite outcrops

Remainder = Dalradian (Argyll Group), with quartz-dolerite dykes (Permo-Carboniferous) and metamorphosed igneous rocks

0   1   2   3 km

inflection is evident over the Middleton Granite [373 822], but it is very difficult to resolve such local effects clearly when they are superimposed on strong gradients. To enhance local effects it is necessary to separate the Bouguer anomaly field into 'regional' and 'residual' components. One way of doing this is to approximate the regional field by a best-fit polynomial surface, which is subtracted from the original field to produce the corresponding residuals. This process is illustrated in Figures 4 to 7 for third and tenth order non-orthogonal polynomials. The 0.2 km data grid and the REGRES2D program (author: C A Green, BGS) were used. The higher order residuals accentuate near-surface features, but caution is necessary in their interpretation since the resulting anomaly pattern is very sensitive to data inaccuracies and terrain related effects (due to differences between the terrain density and the density assumed in the Bouguer reduction). Variations in the the thickness of glacial drift may also have a significant influence; a 10 m change in drift thickness, for example, will produce a gravity change of approximately 0.3 mGal, assuming a drift/bedrock density contrast of 0.7 Mg/m^3.

Both residual maps (Figures 5 and 7) show a clear minimum over the Middleton Granite. From these maps it appears likely that that the granite subcrop* is centred slightly to the north-west of the mapped position, and that shallow granite extends for about 1.5 km in a south-south-west direction from this location. The gravity data are relatively sparse over the southern end of the postulated granite ridge, but there is the suggestion in the tenth order residuals of a secondary granite culmination here and possibly also a second granite ridge extending eastwards from this location (Figure 7). There is also evidence of a residual low extending eastwards from the Bennachie Granite towards the Middleton Granite, and the recent geological mapping has suggested an eastward projection of the subcrop of the Bennachie Granite in this area. The mapping also indicates that elsewhere the eastern margin of the Bennachie subcrop is controlled by a north–south fault; there are only minor indications of this fault in the gravity data, suggesting that its throw is small.

Residual Bouguer anomaly highs flank the Middleton low to the north-west and south-east, over the Hill of Whitecross [371.7 822.5] and Knockinglews Hill [373.3 821.8] respectively. There is no obvious geological explanation for the Hill of Whitecross feature, although it is possible that it is due to relatively dense rocks underlying the hill and/or topographically related variations in drift thickness. At Knockinglews meta-basic igneous rocks (amphibolites) are the probable cause of the positive anomaly. Previously it was assumed that these rocks capped the hill, but the revised mapping shows amphibolite slightly further to the south, on the southern flank of the hill, where it is exposed in a small quarry. There is good agreement between the axis of the residual Bouguer anomaly high and this remapped position.

The residual maps indicate a broad high to the north-east of the Middleton Granite. With the tenth order residuals this is a closed feature centred at about [374.5 823], while the equivalent third order feature extends westwards to the edge of the map. Commercial airborne survey data (collected for Exploration Ventures Ltd.) indicate a coincident zone of magnetic anomalies, which shows the best correlation with the third order residual high. Amphibolites are the most likely cause, since they have been observed in this area and the south-western corner of the zone of magnetic disturbance extends over such rocks at Knockinglews.
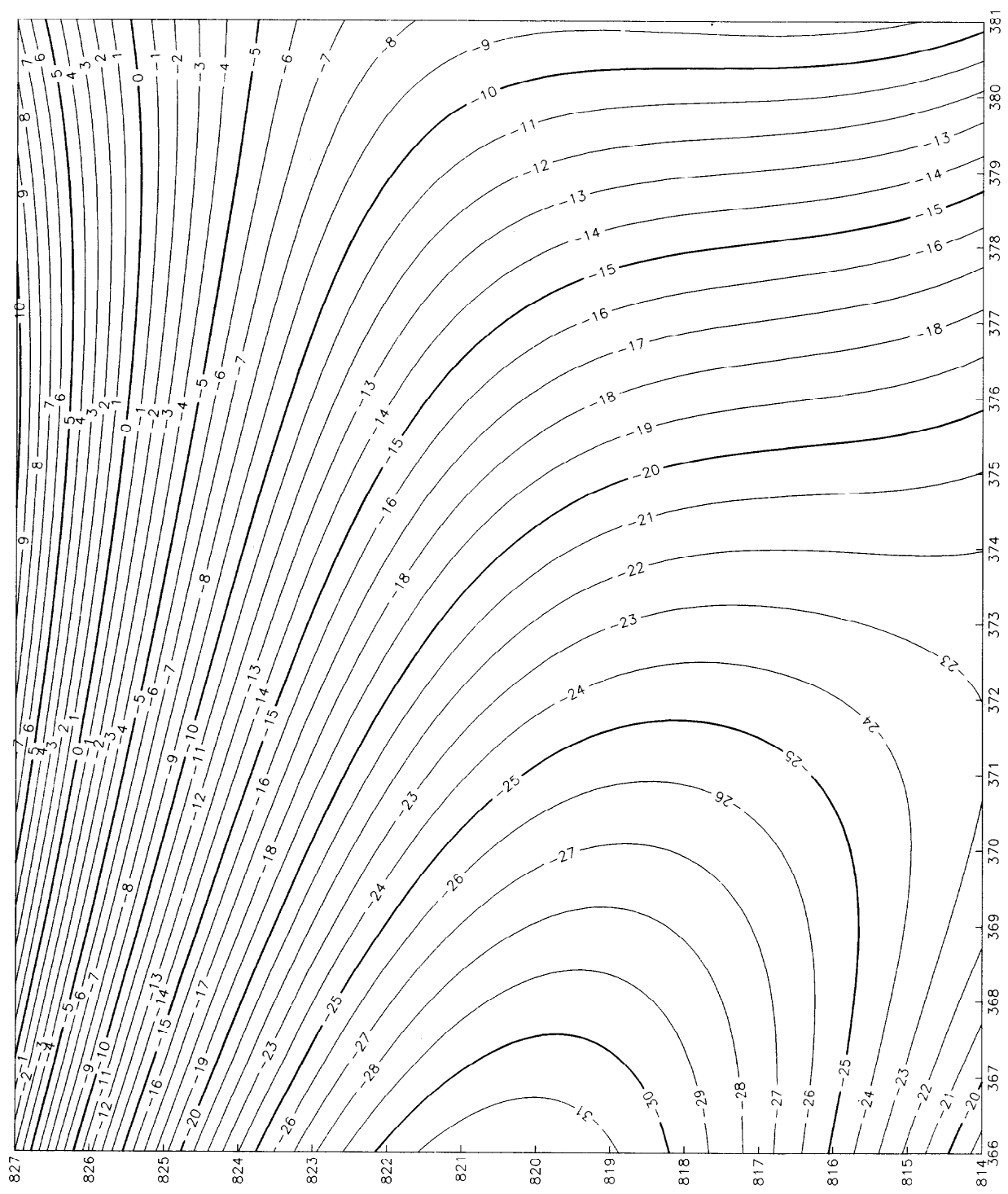
Figure 4 Third order regional Bouguer anomalies (contour interval 1 mGal)

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Figure 5 Third order residual Bouguer anomalies (contour interval 0.5 mGal)

KEY

+ Gravity Station

Pecked lines indicate mapped geological boundaries

1 Insch basic/ultrabasic intrusion

2 Bennachie Granite

3 Tillyfourie Tonalite

4 Kemnay Granite

5 Middleton Granite

6 Other granite outcrops

Remainder = Dalradian (Argyll Group), with quartz-dolerite dykes (Permo-Carboniferous) and metamorphosed igneous rocks
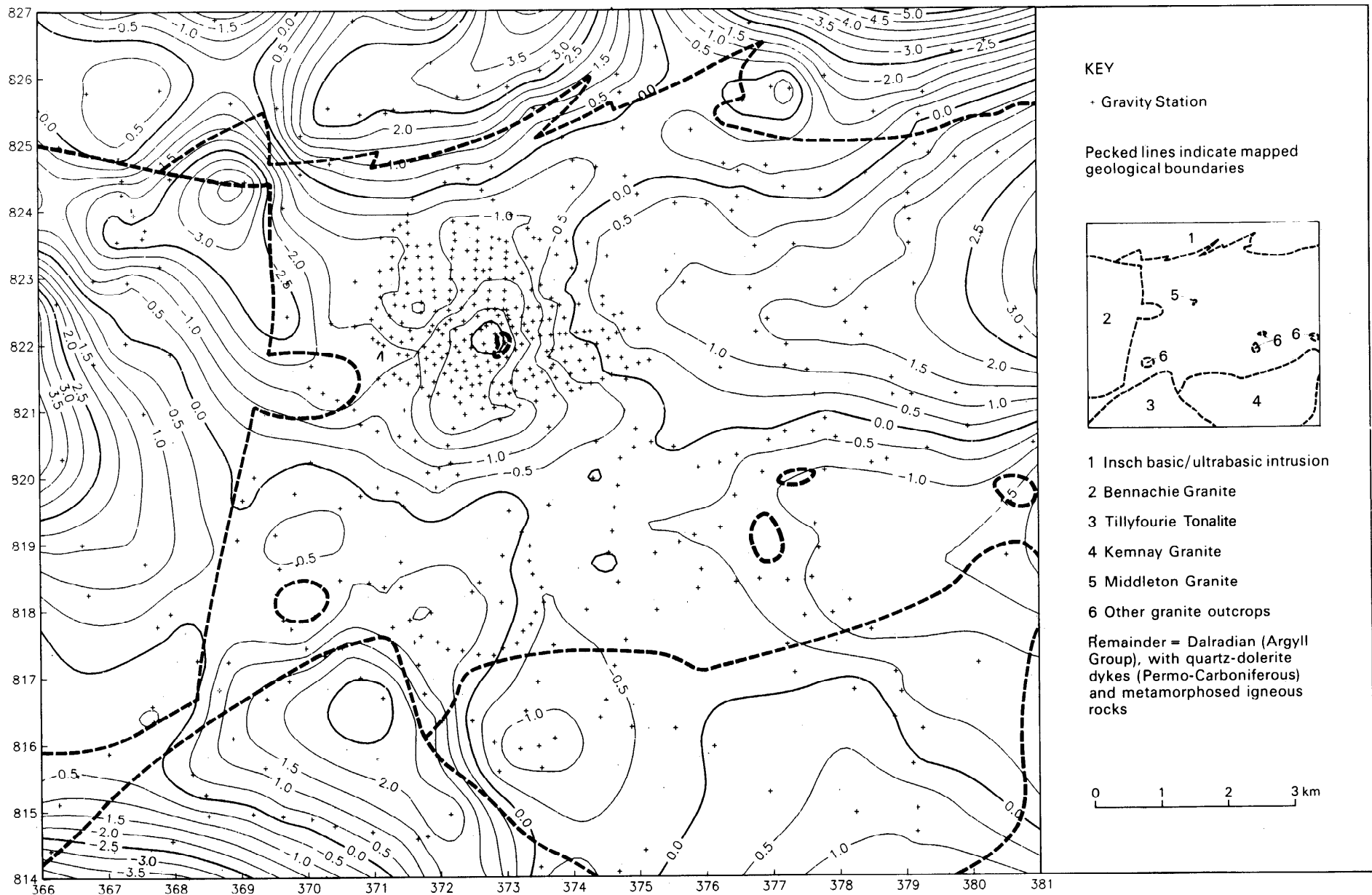
0   1   2   3 km

9

Figure 6 Tenth order regional Bouguer anomalies (contour interval 1mGal)
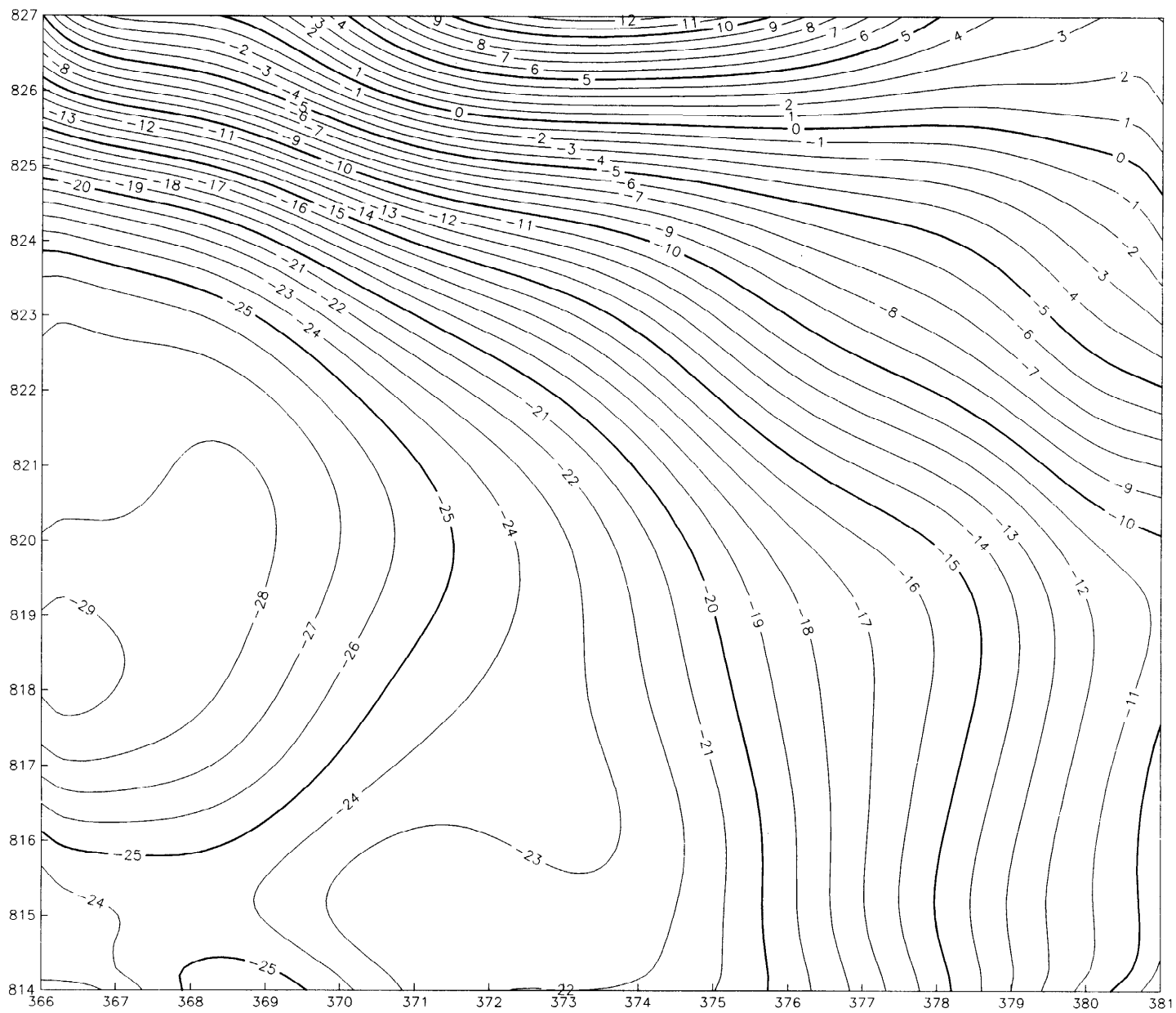
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Figure 7 Tenth order residual Bouguer anomalies (contour interval 0.2 mGal)
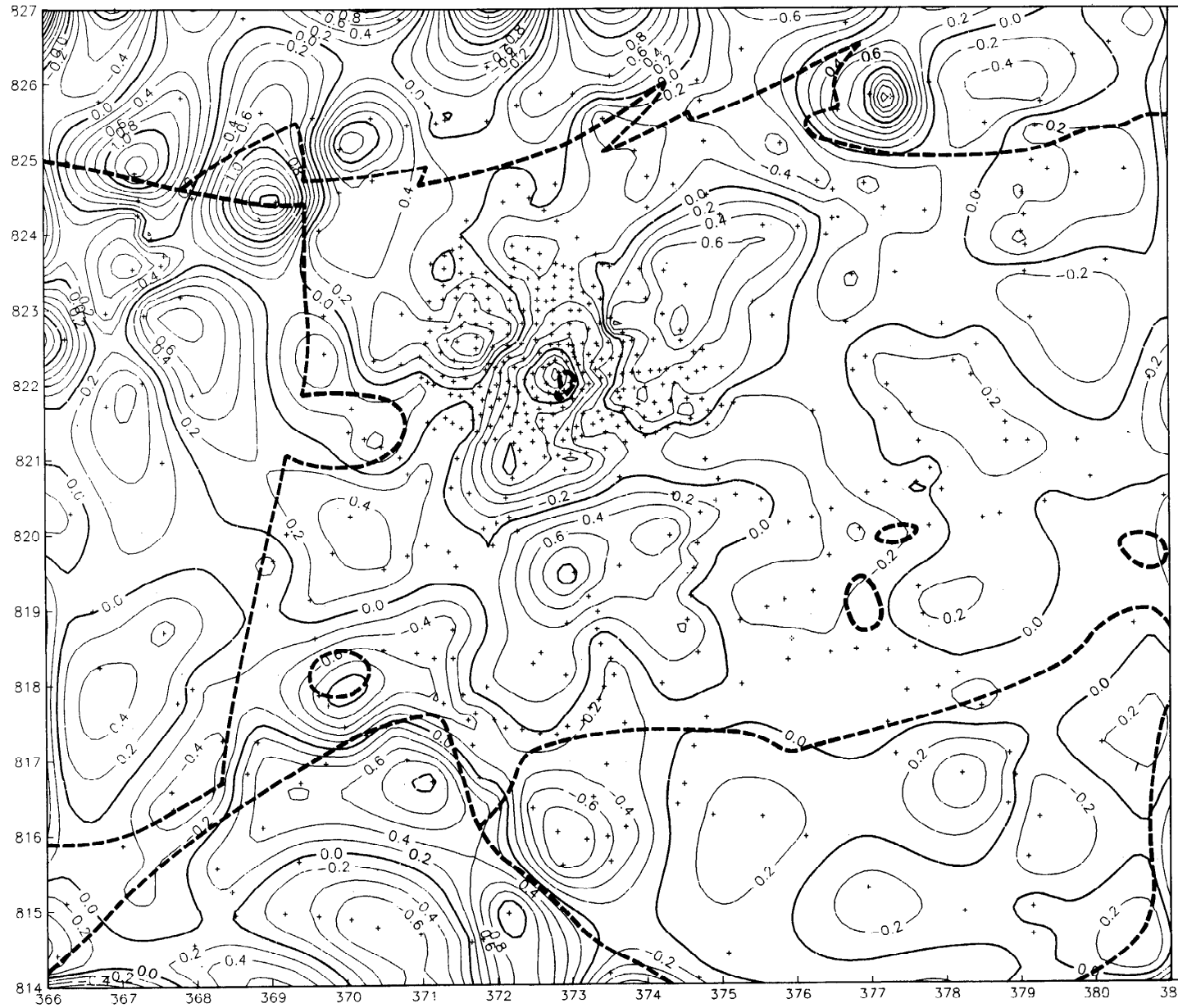
KEY

+ Gravity Station
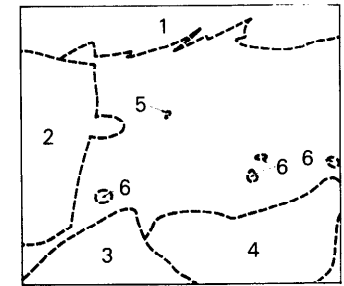
Pecked lines indicate mapped
geological boundaries

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Remainder = Dalradian (Argyll
Group), with quartz-dolerite
dykes (Permo-Carboniferous)
and metamorphosed igneous
rocks

0   1   2   3 km

11

A feature which is accentuated by the tenth order residual map (Figure 7) is a local minimum at [370 818], and this may be due to a minor granite culmination. This is evident as a slight contour inflection in the Bouguer anomaly map (Figure 3), but it is not substantially enhanced by the third order regional/residual separation (Figure 5). Recent geological mapping suggests that granite may be present at subcrop at this location.

THREE-DIMENSIONAL MODELLING

An attempt has been made to model the form of the buried granite contact to the east of Bennachie. The complicated geometry under consideration necessitates three-dimensional modelling, and it is also important that the models extend a considerable distance from the area of interest in order to minimise edge effects. An iterative procedure was used, in which the form of a modelled body is approximated by a set of vertical prisms with square cross section; one surface of the prisms is constrained and the other varied by an iterative process in order to achieve the best fit with the observed gravity anomalies. The program GM3D (Rollin, 1988) was used for this modelling.

For the model to be suitably representative of local geological structure, a relatively small prism cross-section is necessary. However, such detail is not required in estimating structure distant from the area of interest, and would be extremely slow in terms of computer time. The approach adopted was initially to construct a coarse model (1 km prism side length) of the structure within a 30 x 30 km area and then to use this to estimate distant effects while remodelling the region of interest using smaller (0.2 km) prisms. The detailed modelling area measured 15 x 11 km. On the basis of the rock density data and modelling trials it was assumed that the granite is 0.15 Mg/m^3 less dense than its Dalradian host while the basic igneous rocks are 0.20 Mg/m^3 more dense than the Dalradian. The basic rocks were only modelled north of 825.5 N, and the simplifying assumption was made that granite did not extend to the north of this line. A base level of 8 km was assumed for the granite (this differs from Rollin's (1984) model primarily because of different density assumptions).

Initially, granite was extended up to ground level over all the area to the south of 825.5 N, the gravity effect calculated, and this subtracted from the observed Bouguer anomalies. The tops of all the prisms were then set at ground level and appropriate positive density contrasts (Dalradian-granite or basic-Dalradian) assigned according to prism location. The form of the lower surfaces of the basic rocks and upper surfaces of the granite were then simultaneously modelled by iterative adjustment of the prism bases. The regional Bouguer anomaly field was set at 0 mGal throughout the area.

Figure 8 shows part of the final, detailed model of the top surface of the granite. The root mean squared difference between observed and calculated Bouguer anomalies over the 1681 prisms within this area is 0.19 mGal. The largest residual errors (about -1 mGal) are in the extreme northwestern corner of the area shown, and probably occur because the model does not replicate the likely extension of the Bennachie Granite beneath the Insch intrusion (McGregor and Wilson, 1967, p. 109).
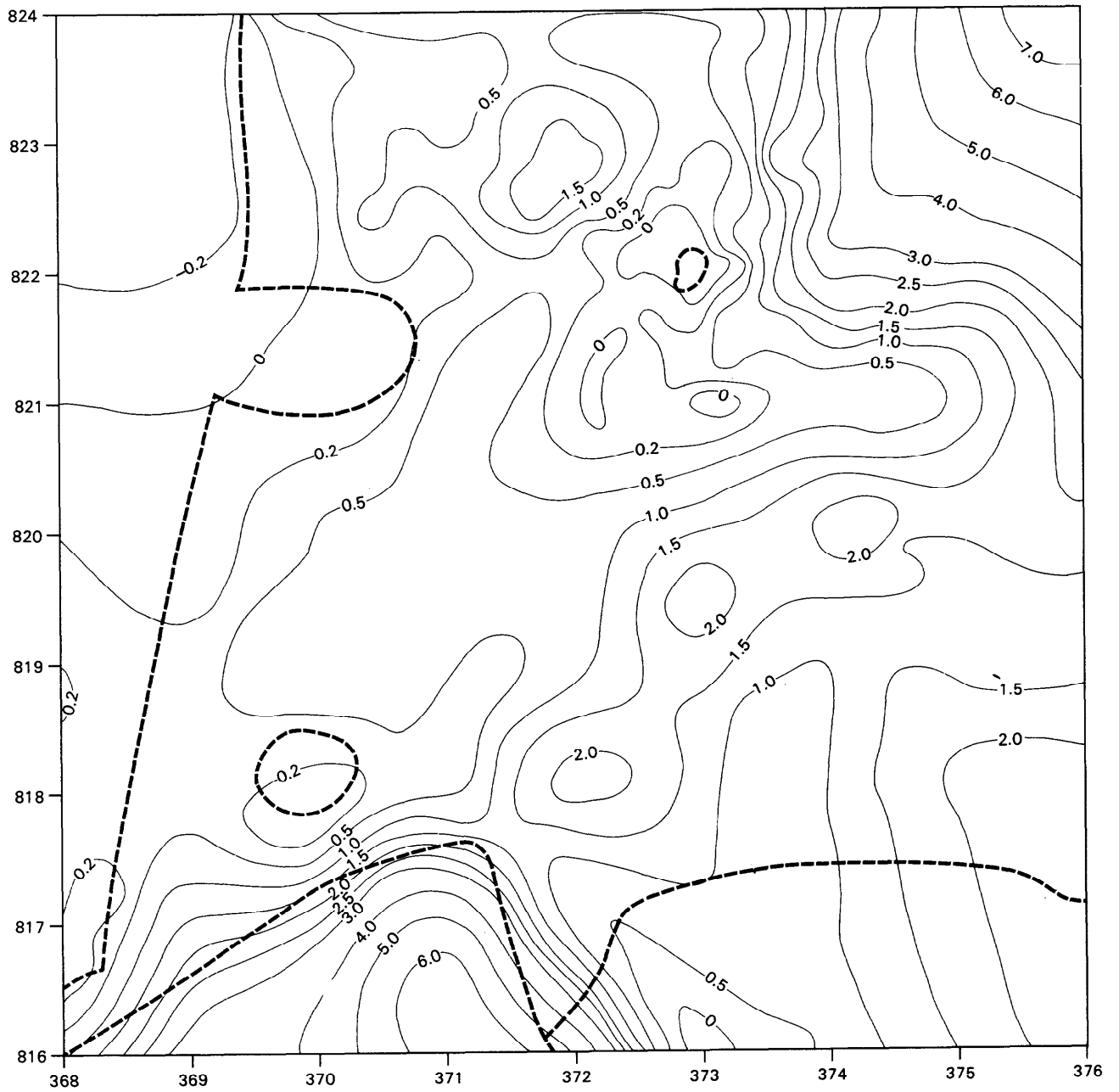
Figure 8 Three-dimensional granite model. Contours show modelled depth to granite in km below Ordnance Datum. Dotted lines are mapped geological boundaries as in Figures 3, 5 and 7.

Errors may also arise in the granite model because of variations in its density and/or depth to base; density variations in the overlying Dalradian rocks; inadequacies in modelling the gravity effect of the Insch basic mass and failure to account for other basic rocks in the region (e.g. amphibolites); variations in drift thickness; unaccounted for regional field variations; and the geometrical limitations of the prism approach.

The limitations of the model are evident when it is compared with the outcrop pattern. The outcrop of the Bennachie Granite is only well replicated towards the north (where there may in any case be distortion, as discussed above), while in the south the modelled granite surface lies several hundred metres too deep. It is clear that the Tillyfourie Tonalite must be significantly more dense than its neighbours, as would be expected from compositional differences, because there is an apparent 'low' in the modelled surface which correlates well with its mapped position. There is a poor correlation between the modelled surface and the Kemnay Granite, presumably because of incorrect assumptions of density and/or depth to base; this granite is similar in composition and probably also in age to the Aberdeen Granite [390 810], which also has a relatively minor gravity effect. There is a a slight overestimate in the depth to the Middleton Granite: the modelled top of the granite lies at a depth of around 50 m in the vicinity of the observed outcrop. The model attempts to account for the Hill of Whitecross positive feature by locally increasing the depth to granite to more than 1.5 km, but it is perhaps more likely that this feature is due to density contrasts within the rocks overlying the granite.

Further refinement of the model would be possible, for example by incorporating variations in the granite density and regional field, but the present version does provide valuable insights which are unlikely to be modified by more sophisticated modelling. In particular it demonstrates that the Middleton Granite is a cupola rising from the concealed eastern flank of the Eastern Highlands batholith, rather than an isolated body, and confirms the inference made from residual maps that shallow granite probably extends for about 1.5 km south-south-west from the Middleton subcrop. The depth to this granite ridge is not quantified accurately but, as the model tends to overestimate depths elsewhere, it certainly appears likely that it extends above Ordnance Datum and within 200 m of surface in its shallowest parts. While this ridge can be identified with some confidence, a second apparent granite ridge which extends eastwards from its southern end is more equivocal. The strike of the latter feature and its correlation with a belt of more psammitic Dalradian rocks (D Gould, personal communication) suggest the possible influence of intra-Dalradian density variations, perhaps enhanced by the gravity effect of the Knockinglews amphibolite.

There is an apparent extension of relatively shallow (<0.5 km below OD) granite northwards from the Middleton subcrop. This feature may be artificially enhanced towards the northern edge of Figure 8 because of distortion close to the density boundary at 825.5 N. Such distortion does not appear to be serious in the immediate vicinity and to the south of the Middleton Granite.

There is a distinct deepening of the modelled granite surface across a north-east–south-west line extending from [368 816] to [375 821], which is more clearly defined by the model than by residual plots. It seems likely that this marks the concealed boundary between 'Bennachie-type' granite to the north-west and the
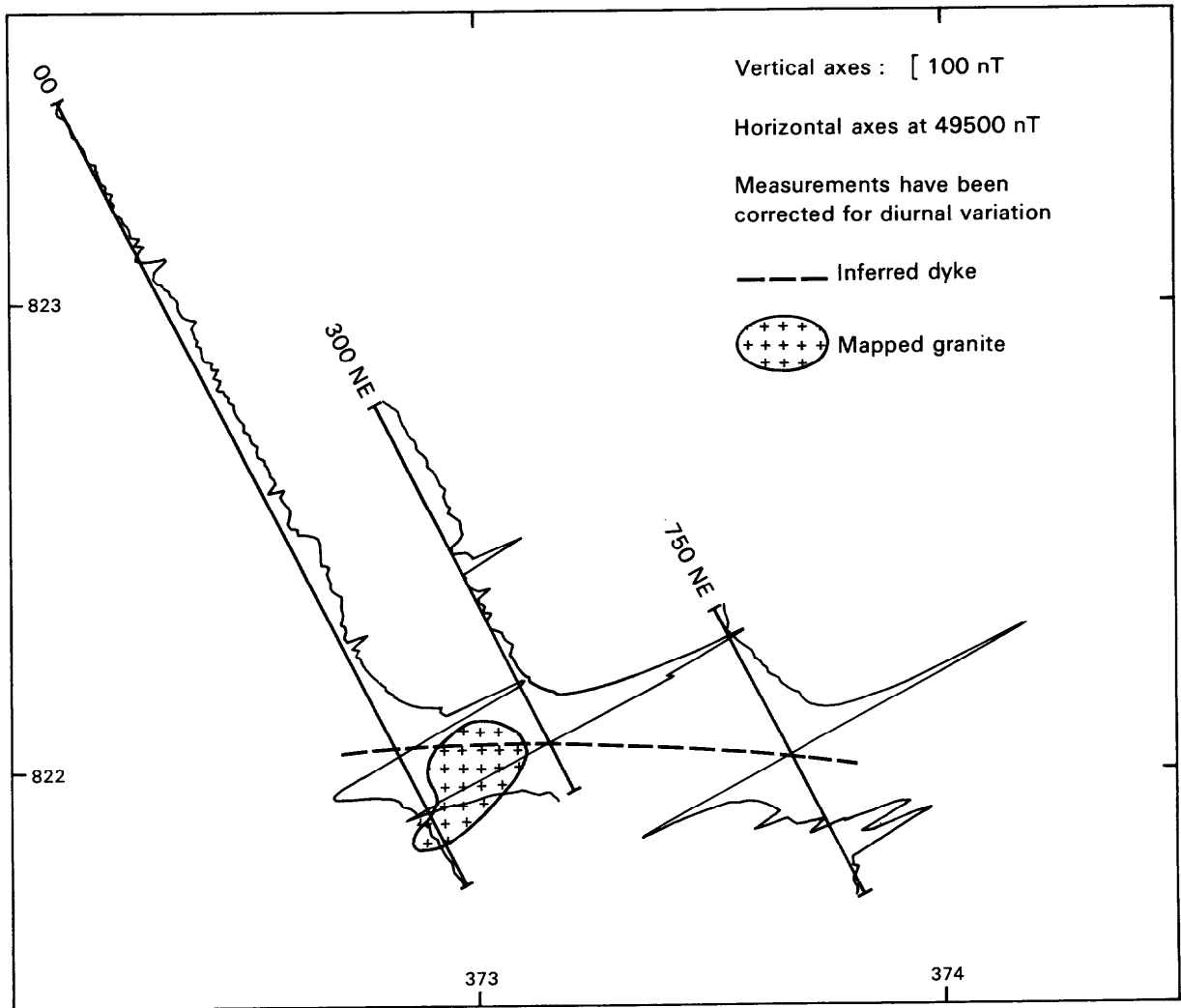
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Figure 9 Magnetic traverses in the vicinity of the Middleton Granite

more dense and/or thinner granite and tonalite to the south-east. Thus the model tends to support the inference by Darbyshire and Beer (1988) that the Middleton and Bennachie granites are related. The geophysical and geological evidence indicates that local granite exposures to the south-east the projection of this line are of Kemnay Granite type. Contour alignments suggest the possibility of further north-east—south-west structures in the region of shallow granite between Bennachie and Middleton.

OTHER GEOPHYSICAL SURVEYS

Magnetic measurements were undertaken to confirm the location of a linear magnetic feature detected by the commercial aeromagnetic survey. The results are presented in Figure 9. A conspicuous east-west trending anomaly is revealed, which cross-cuts the Middleton Granite. This is interpreted to be caused by a reversely magnetised basic dyke of probable Permo-Carboniferous age. Magnetic disturbances toward the south end of line 750 NE are probably due to amphibolites.

Trial electrical soundings conducted on the granite stock and on neighbouring Middle Dalradian metasediments indicated that these two rock types are unlikely to be geophysically distinguishable, at least by surface surveys, on the basis of their electrical properties.

CONCLUSIONS

Interpretation of detailed gravity survey data has provided valuable insights into the form of the Middleton Granite. Standard Bouguer anomaly maps do not clearly resolve this relatively small structure, because its effects are swamped by the strong gradients due to nearby major intrusions, but its signature has been identified by regional/residual separations and its approximate form inferred by three-dimensional gravity modelling. The modelling reveals that it is a cupola rising from the buried eastern flank of the Bennachie Granite (part of the major Eastern Highlands batholith) and that it appears to lie at the north-east end of a local granite ridge. The new survey provides a basic data set for studies of granite related mineralisation in the region, and the granite model enlarges the prospective area for molybdenum and tungsten mineralisation associated with the Middleton Granite.

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