Natural Environment Research Council

Institute of Geological Sciences

# Mineral Reconnaissance Programme Report

*A report prepared for the Department of Industry*

S. H. U. Bowie
Programme Manager
Institute of Geological Sciences
64-78 Gray's Inn Road
London WC1X 8NG

# No. 11
# A study of the space form of the Cornubian granite batholith and its application to detailed gravity surveys in Cornwall

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J.M.C. Tombs, BSc

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# A study of the space form of the Cornubian granite batholith and its application to detailed gravity surveys in Cornwall

J.M.C. Tombs

Summary

A three-dimensional computer model of the Cornubian granite batholith, defined by polygonal contours, was created so that its calculated gravity field matched the observed Bouguer Anomaly field, both onshore and off-shore. The model was used to define a background (="regional") field in three areas where detailed gravity surveys had been undertaken in the search for shallow granite. From the residual field maps of depth to granite were produced by an iterative technique. Geological interpretations of the batholith model and of the depth maps are included.

INTRODUCTION

This report, prepared as part of the Department of Industry's Mineral Reconnaissance Programme, is an expansion of the geophysical section of a previous report (Beer, Burley and Tombs, 1975) in the same series. Bouguer anomaly data relating to detailed surveys, which were presented in the former report, together with a separate compilation of regional Bouguer anomaly data, have been processed by computer to give contour maps of depth to the shallowly-concealed roof of the Cornubian granite batholith. As a necessary step in the data processing new information on the possible space form of the granite body has been obtained. It is hoped that the results of this investigation will provide not only significant new evidence in the search for a direct relationship between granite plutons and mineralisation, but also a geophysical interpretation technique of general applicability in similar geological settings.

A more detailed knowledge of the relationship between high-temperature mineralisation and the boundary between batholithic granite and metamorphosed slate cover (known in south-west England as killas) is of importance in the continued search for economic mineral deposits of the tin-tungsten-copper type. The object of the geophysical surveys was to produce a detailed picture of depth to granite in three areas (Fig. 1) where the killas cover was believed to be shallow. The principal method used was gravity: previous work in south-west England (Bott, Day and Masson Smith, 1958) and elsewhere had clearly demonstrated the negative gravity anomalies of granite plutons. It was hoped that refinement of both the quality of the raw gravity data and interpretation techniques would permit an accurate quantitative interpretation.

In the Bosworgy area seismic reflection techniques have also been used: the results will be presented as a separate report.

THE GRAVITY SURVEYS

Outline of the procedure for obtaining depth to granite

It is first assumed that the Bouguer anomaly variations are due entirely to the granite having a lower density than the rocks surrounding it.

Let one of the areas within which the thickness of killas was to be determined be called A. The technique used was to extract from the observed Bouguer anomaly field a contribution, GRES, which was proportional to the attraction of the killas within A. (GRES is defined more rigorously below). If GRES were known precisely, then the thickness of killas could in principle be uniquely determined everywhere within A. In practice an approximation was obtained to the values of GRES at points on a square grid within A, and the killas thickness was then derived therefrom, at the same points, by an automatic omputer technique.

GRES is the difference between the observed Bouguer anomaly field and the field which would be observed if the killas within A were replaced by granite. If a computer model (M1) could be created which was an exact representation of the (anomalous) density distribution everywhere (this is obviously impracticable), its computed gravitational attraction (G1) would be identical to the observed Bouguer anomaly (GOBS) at all points. A second model M2, differing from M1 only in that granite reaches surface everywhere within A, would have an attraction G2 differing from G1, and hence from GOBS, by GRES.

In the present work a model M1a had been set up to approximate M1. To avoid excessive computing it was necessary to limit both the complexity of the model and the amount of Bouguer anomaly data used to control its shape. M1a was designed to reproduce the anomaly at the intersections of a 5 km square grid covering the whole region of influence of the batholith; it therefore represents a very smoothed version of the actual granite surface beneath the killas. From M1a a model M2a, approximating M2, was obtained directly. The difference between the attractions G2 and G2a should be small within A except near its periphery. G2a was computed and subtracted from GOBS over a grid within A of much closer spacing than was used to derive M1a. Hence an approximation to GRES was obtained which made full use of detailed Bouguer anomaly data within A while also allowing for the broader background effect of the batholith as a whole.

It is evident that to carry out this work the following data were required:

(a) detailed gravity measurements over the areas of interest, together with less detailed cover over a large surrounding area;

(b) estimates of the densities of granite and killas so that their relative gravity effects could be determined;

(c) borehole information, where available, to provide control on the interpretation.

The collection and use of the above data are discussed in the following sections.

Gravity measurements

In 1973 IGS completed its onshore regional gravity survey in south-west England, stations having been established at bench marks and spot heights at a density of 70-80 per 100 $km^2$, using vehicle-borne Worden or LaCoste and Romberg gravity meters. The regional survey was supplemented in 1972 and 1973 by detailed gravity and levelling traverses along roads, tracks and fields in the three areas of interest, the density of cover in these areas being thereby increased some tenfold. In 1974 the punched cards on which these observations had been recorded were reprocessed by computer to derive consistent Bouguer anomalies over the whole area. The steps in the data reduction were:

(a) correction for gravity meter drift and earth tides;

(b) calculations of observed gravity based on NGRN 73 gravity reference stations and claibrations (Masson Smith, Howell and Abernethy-Clark, 1974);

(c) combined elevation correction to sea level and terrain correction to 50 km radius (Hammer zones A to M) for an average density of 2.7 g $cm^{-3}$ (shortage of time prevented allowance being made for minor departures of actual density from the average; the resulting error, normally less than 0.5 mGal, might approach 2 mGal over extreme topographic highs but would be partially compensated in subsequent processing);

(d) calculation of Bouguer anomaly by subtraction of the 1967 International Gravity Formula.

Continous marine profiles of gravity collected by IGS on an 8 km grid were processed similarly.

Onshore Bouguer anomaly maps have been placed on open file at IGS (Beer, Burley and Tombs, 1975).

Onshore and offshore data have been published by IGS and are included in this report as Fig. 6. The actual data used in this present work included unpublished offshore data extending to the south and west of Fig. 6.

To create machine-readable observed fields for comparison with computed fields, the regional data were interpolated to the intersections of a square grid defined by 5 km National Grid intersection points where they were digitised manually. For the detailed survey areas the grid size used was 0.25 km.

Density estimates

Two sources of borehole and surface density measurements have been considered:

(a) table 1 of Bott, Day and Masson Smith (1985);

(b) density measurements by IGS on selected samples from Cornwall (McCann, 1973, and Gibbs, 1973).

These measurements show granite densities (g $cm^{-3}$) in the range 2.58 (Hensbarrow) to 2.67 (Bosworgy borehole). Non-granite densities range from 2.49 (Culm sandstone) to 2.99 (Lizard hornblende schist). Intrinsic to the measurements are the following possible sources of error:

(a) Samples of slaty killas taken from depth may open out slightly along their cleavage planes leading to a low measured density. This effect can usually be detected at the time of measurement and is not thought to be a significant source of error (McCann, 1973).

(b) Weathering of samples taken from the surface would lead to the low measured densities but, again, can normally be recognised.

(c) Any small sample may have a density untypical of its formation as a whole.

(d) There are obvious dangers in extrapolating near-surface granite density measurements down to great depth. Gravitational separation of heavy minerals might have occurred during solidification of the magma, leading to an increase in density with depth.

Consideration of these measurements shows the granite density to be less than the density of the surrounding rock by around 0.1 g $cm^{-3}$ with a large scatter. This was taken as a starting value in the modelling, and subsequently modified area by area to achieve the nest fit to observed Bouguer anomaly data compatible with a geologically acceptable model.

Borehole information

Figs 3, 4, 5(c) show the depths below sea level of borehole determined granite contacts. Only major discrepancies between depths derived from the Bouguer anomaly and borehole depths have been considered valid reasons for changing model parameters as large but local changes in depth to the granite roof would not be reflected in the Bouguer anomaly.

Other controls on the modelling

Correspondence between computed and observed granite outcrops has been an important check on the model, bearing in mind possible errors in the mapped positions of surface contacts and in extrapolation of a granite contact at surface down to sea level, for which the assumed value of slope must be rather subjective.

It was necessary to define a datum or background anomaly value over the whole area. The value chosen was +30 mGal, comparing with previous estimates of 25 mGal over Dartmoor, 30 mGal over the other granites (Bott and others, 1958), 35-45 mGal in the English Channel (Bott and Scott, 1964), and 40 mGal in the North Celtic Sea (Davey, 1970). Obviously there will be some interdependence between the value chosen and the computed depths to the deeper parts of the batholith, although depths to its upper surface will be unaffected.

In general no attempt was made to remove anomalies obviously not caused by granite. A greater discrepancy between calculated and observed values has been allowed in areas where such anomalies occur.

## Construction of the batholith model

A computer program was written to calculate the effect of a model using the method of Talwani and Ewing (1960), but with their formulae modified for faster execution. Computation of the effect of the model of Fig. 2 over 1363 output points took 21 seconds on an IBM 360/195 computer. The input to the program consists of the depths, densities and vertex coördinates of polygons approximating contours of the body. The program first computes the attraction of laminae bounded by each such polygon and having a surface density equal to the volume density of the model at the depth of the polygon; for each defined depth this gives the attraction per unit thickness of the body. For a model whose shape changes gradually from polygon to polygon this would be a smoothly varying function of depth. By integrating numerically with respect to depth the program derives the attraction of the whole body.

A model was set up and manually adjusted until its computed gravitational attraction was in reasonable agreement with the observed field. The form of the model as finally used, after some 40 runs of the program, is shown in Figs 2(a), 2(b) and 2(c). This has been compared with observed data over the 5 km grid mentioned previously. Over the whole area (between National Grid Eastings $^{0}70$ and $^{3}00$, Northings $-^{0}20$ to $^{1}20$) the RMS error is 5.9 mGal. On land west of $^{2}90$E and south of $^{1}00$N, where the granite effect is dominant, the error is 2.9 mGal. This reduces to 2.1 mGal in the vicinity of the detailed survey areas, which is thought to be sufficiently accurate for the purpose described in the following section. No attempt was made to model non-granite structure, which is the dominant influence on the Bouguer anomaly field well away from the batholith. The extension of the batholith to the Scilly Isles has been modelled very roughly only, and for convenience the model has been truncated just to the west of the Scillies.

## The detailed survey areas

For each area the above program was re-run to give an output over the 0.25 km grid of detailed survey data, minor changes to the model then being made if necessary to improve the fit, particularly around the edges of the area for reasons explained above. The RMS error of the final model was normally near 1 mGal. The model was then temporarily further modified to give granite reaching up to sea level everywhere within the detailed survey area, and the program run again. The difference between observed and calculated values for this model was, as explained above, due to the excess mass of a body of killas lying within this area and extending from sea level down to a depth which was to be determined, plus a small error component due to inadequacies of the polygon model just outside the survey area. The depth to the base of the mass excess (i. e. the granite roof) was computed at each mesh point by a program using the iteration method of Cordell and Henderson (1968). This program is restricted to a single density value; an average value over the expected range of depths was used. On the 360/195 computer each iteration for an area of 2553 mesh points took 2.5 minutes.

The results of the computation are presented in contour form in Figs 3, 4 and 5. Figs 3(a), 4(a) and 5(a) show the regional fields, which when subtracted from the observed fields give the residual fields of Figs 3(b), 4(b) and 5(b). These when processed lead to depths to granite shown in Figs 3(c), 4(c) and 5(c) in contour form and in Figs 3(d), 4(d) and 5(d) as representative cross-sections. The accuracy is least near the edges of each area; contouring has been terminated where values are doubtful.

# INTERPRETATION OF THE MODELS

## The batholith model

### The problem of indeterminacy

In general the same gravity anomaly can be caused by an infinite number of different bodies, differing from each other in shape and density. The degree of confidence with which one can say that a particular model is an approximation to reality depends on the complexity of the situation and the availability of other information (geological surveys, other geophysical methods) providing constraints on the model. Features of the batholith model which are open to question because of indeterminacy are discussed in the description below; in general the form of the "roof region" of the batholith, including the dips of its edges, is better defined than the deeper features.

### Description of the model

In studying Fig. 2(a), three points should be borne in mind:

(a) The contour spacing is not uniform.
(b) The shape and density assigned to a particular contour refer to the body at that depth. These parameters are assumed by the program to vary smoothly between the defined values.
(c) Above the uppermost, and below the lowermost, defined depths, no body is assumed to exist; i. e. the top and bottom of the body are plane polygons.

The model shows a depth to the base of the batholith beneath Dartmoor of 20 km, decreasing to about 15 km near Lands End and about 10 km at the Scillies. This is for a constant density deficiency below about 3 km of 0.1 g cm$^{-3}$; the magnitude of the Bouguer anomaly could, however, equivalently be accounted for by an increase in density deficiency towards the east with a constant base level, or by a change in the background level from the +30 mGal which has been assumed. The near-surface density deficiency shown by the model is near 0.12 g cm$^{-3}$ except for central and southern Dartmoor where it is nearer 0.16 g cm$^{-3}$. In general, the edges of the major exposed granites dip steeply outwards to depths of at least 2 km. Exceptions are the northern margin of the St Austell (Hensbarrow) granite and the southern and eastern margins of the Lands End granite, where the outward dip is more gentle. A northward-trending ridge extends from the Carnmenellis granite to and beyond the St Agnes/Cligga exposures, and an east-west ridge at somewhat greater depth along the Hingston Down/Kit Hill axis connects the Dartmoor and Bodmin Moor granites. Shallow ridge structures are otherwise notably absent; however, it is possible that minor linear features may have remained undetected due to the relatively coarse 5 km grid used. Deep southward-facing troughs separate the Scillies from the mainland and the Carnmenellis from the St Austell granites; with the exception of the "saddle" to the west of Dartmoor such structures appear to be absent from the northern margin of the batholith, suggesting some degree of asymmetry.

Discussion

Previous two and three-dimensional studies of the Bouguer anomaly field (Bott and others, 1958; Bott and Scott, 1964; Bott and Smithson, 1967) supported by seismic evidence (Bott, Holder, Long and Lucas, 1970; Holder and Bott, 1971) have been interpreted to show a diffuse but level base to the batholith at around 12 km depth, below which the lower crust extends to a level Moho at 27 km. The differing features of the present model are considered to be at least equally valid because:

(a) it is the result of more sophisticated interpretation of more complete gravity data;
(b) the seismic refraction profile of Bott and others was only reversed between Carnmenellis and a point to the west of the Scillies, where the present model indicates a depth of 10-15 km to the base. No seismic arrivals were received directly from the base, thereby indicating its diffuseness; it was merely deduced that a base at 12 km was consistent with the required velocity distribution.

The westward thinning of the batholith shown by the present model is though to be more likely than a reduction in the density contrast because radioactivity studies of exposed granites (Tammemagi and Smith, 1975) have shown an apparent high degree of compositional uniformity along the length of the batholith. It is unlikely therefore, that there is significant lateral density change at depth. A change in the mean density of the surrounding sediments would be reflected in a change in the background Bouguer anomaly value; inspection of Fig. 6 shows this to be unlikely (follow, for example, the course of the +30 mGal contour on each side of the batholith). The presumed westward thinning matches a westward decrease in elevation of the topographic highs forming the major granites, supporting ideas of a high-level isostatic compensation mechanism (Bott and others, 1958).

In considering the present-day shape of the batholith it should be remembered that the combinded effect of many north-west trending Tertiary wrench faults has been to displace its eastern end by some 34 km south-eastwards from its original position. Restoration brings the southern margins of the Bodmin and Dartmoor granites to the same latitude (Dearman, 1963). The displacement due to any individual fault zone would be too small to be apparent in the model.

The conclusions of Beer and others (1975) relating to areas not covered by detailed survey are not modified by the present work.

Finally it must be pointed out that the need to minimise computer time has led to a considerable degree of approximation in the representation of relatively minor features. Without further refinement and elaboration of the model too much reliance should not be placed on it as an accurate picture of the near-surface form of the granite in any particular area.

The detailed survey areas

In considering Figs 3(c), 4(c) and 5(c) it should be noted that trends are more accurately represented than absolute values; and that depths greater than 1 km, which have not always been shown, are liable to considerable error because they are very sensitive to small changes in density contrast. Fig.2(a) is probably a better representation of the deeper features.

a. Hayle-Leedstown area

As already mentioned, the Bosworgy part of this area will be treated in a separate report, to include consideration of seismic results and near gravity data. Preliminary results do not indicate any major discrepancy with the following:

The postulated shallow ridge connection from north of the Godolphin granite to Carn Brea is clearly indicated: Fig. 3(d) shows dips of up to 45° on the flanks. A second localised rise in the roof occurs near (590 365). Agreement with boreholes is reasonable; the Parbola borehole which failed to intersect granite at -583m OD is seen to lie probably on the north flank of the ridge. (Sample measurements (Gibb, 1973) do not support the idea that the unexpected arenaceous succession found in this borehole has lower density than the average for killas; however, this may be a partial explanation for the discrepancy here).

b. St Agnes area

Fig. 4(c) suggests the presence of a ridge connecting the Carn Marth and St Agnes granites; a shallow northward extension of the former is indicated but the depth of the ridge then increases to more than 1.5 km. The dip of the eastern flank is steep, but because of the lack of gravity data from just offshore combined with computation errors due to edge effects the western flank is not well defined.

Whilst the distribution of known mineral lodes in this area (Dines, 1956) closely matches the areas of thinnest slate cover, the strike direction of individual lodes retains the west-south-west/east-north-east trend widely observed in the Camborne area and elsewhere. For this reason and because of the greater depth of burial of the ridge, the situation here appears to be different from the Carn Brea-Godolphin ridge, and possibly less favourable in a mineral prospecting context.

c. St Austell area

The granite roof lies less than 500 m below sea level over a large area extending northwards from the St Austell outcrop to encompass Belowda (968 625) and

Castle-an-Dinas (944 624). Within this area a few apparent depressions in the roof (938 590, 980 595) correspond in position to mapped calc-flintas bands. These may well have a higher density than the average for killas in which case such apparent depressions would be spurious. Most of the major known mineral deposits lie within the "roof region"; it is particularly striking that the Prosper lode (029 642), which strikes east-west, lies on a local rise in the roof. A smaller local rise, at (003 642), appears to have no known mineralisation associated with it and could be a target for future exploration. The north-south Mulberry stockwork lies outside the roof region and seems to be unrelated to shallow granite. Linear features are notably absent from this area.

## CONCLUSIONS

This work has achieved its major objective in providing a detailed picture of the depth to granite in the three selected areas. The maps and sections presented here provide general information on the relationship between granite and mineralisation together with one specific recommendation for future mineral exploration in the St Austell area. Valuable incidentals to the main objective have been:

(a) The setting up of a model of the granite batholith which everywhere matches the observed gravity field to a reasonable accuracy considering its relative simplicity.

(b) The introduction of new techniques in gravity interpretation which have become a matter of routine and have already been applied to other areas.

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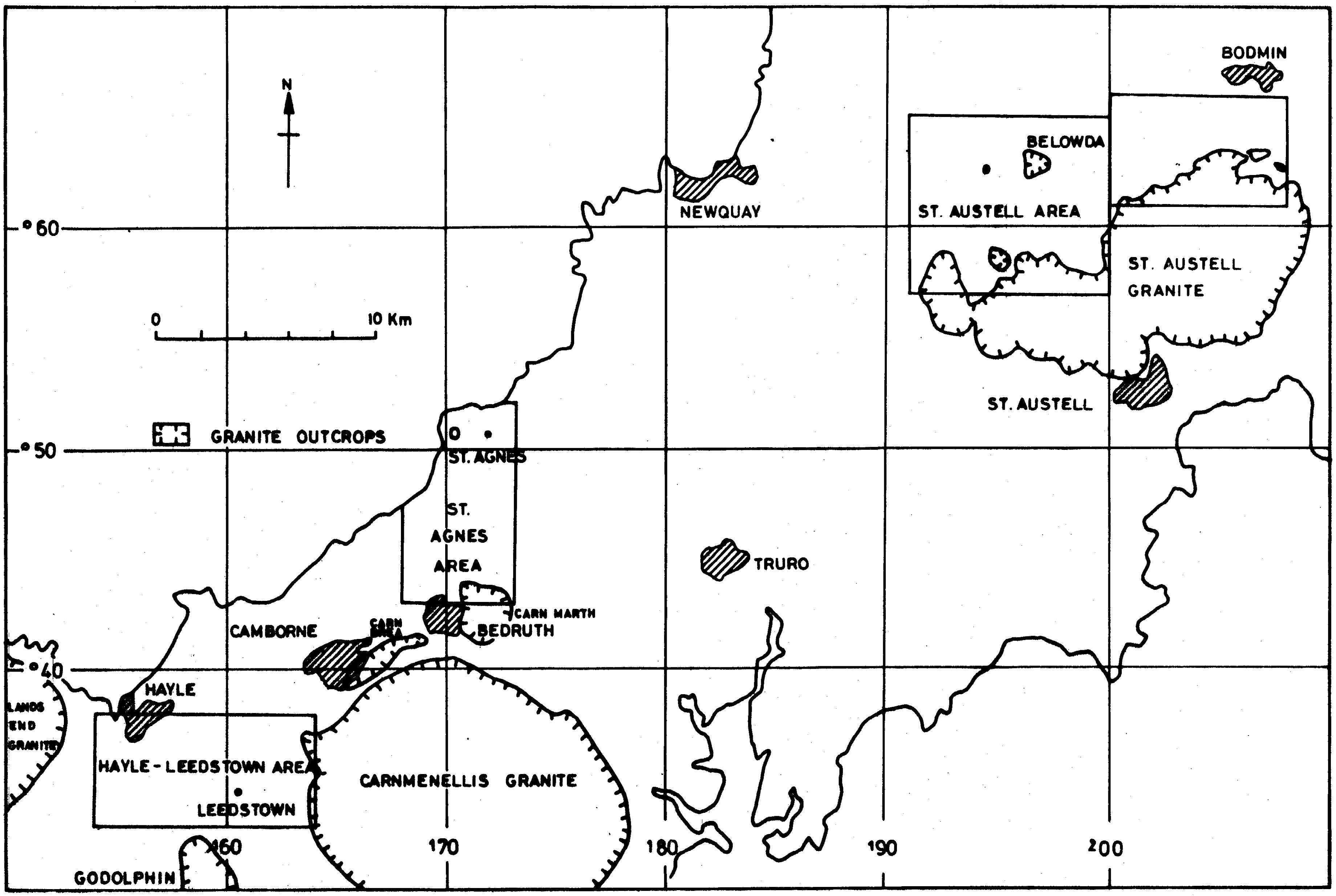



FIG. 1 LOCATION MAP

AREAS OF DETAILED SURVEY ARE OUTLINED

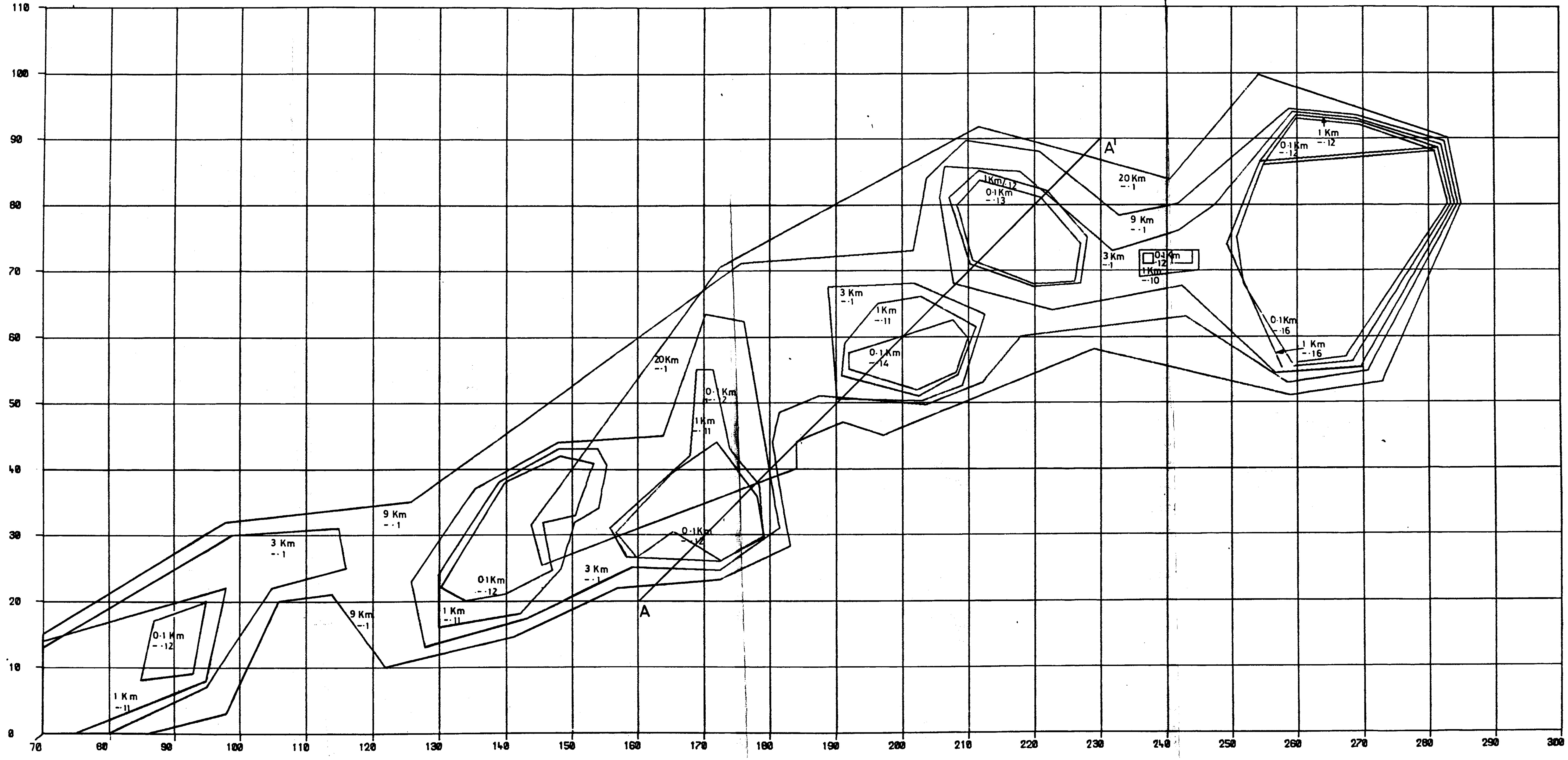



FIG 2 (A) THE BATHOLITH MODEL - POLYGON APPROXIMATION SCALE 1 IN 500 000

ANNOTATIONS SHOW DEPTH AND DENSITY DIFFERENCE ASSIGNED TO EACH POLYGON

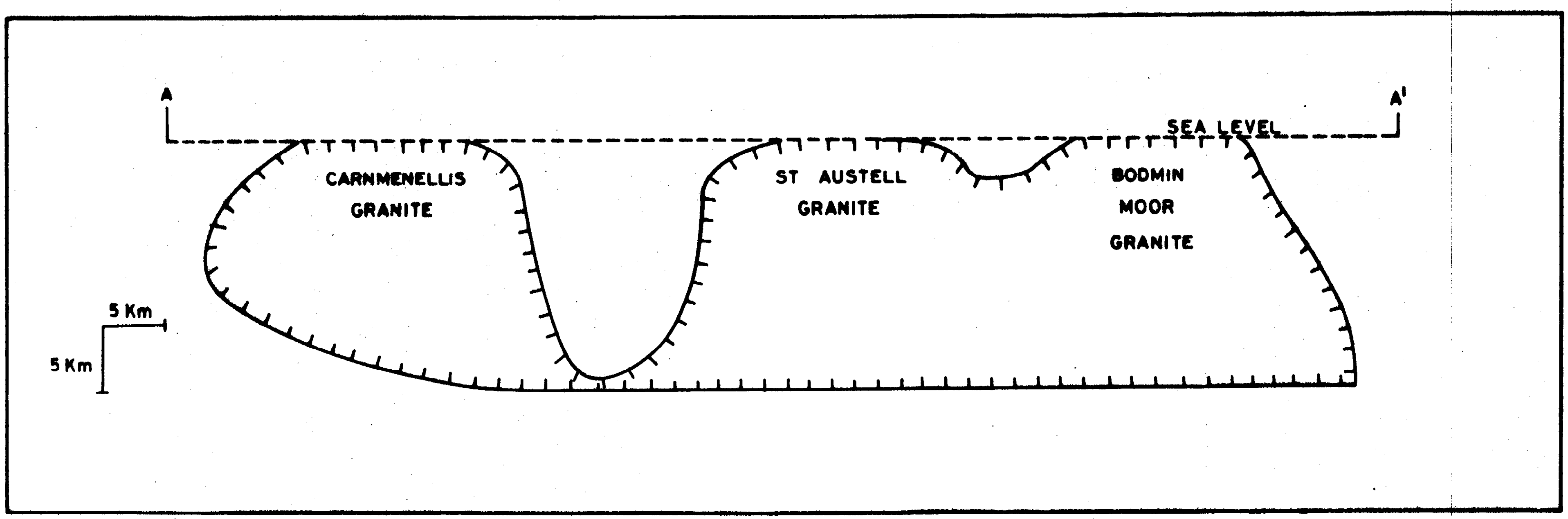



FIG. 2(b) THE BATHOLITH MODEL-SECTION ALONG LINE A-A'

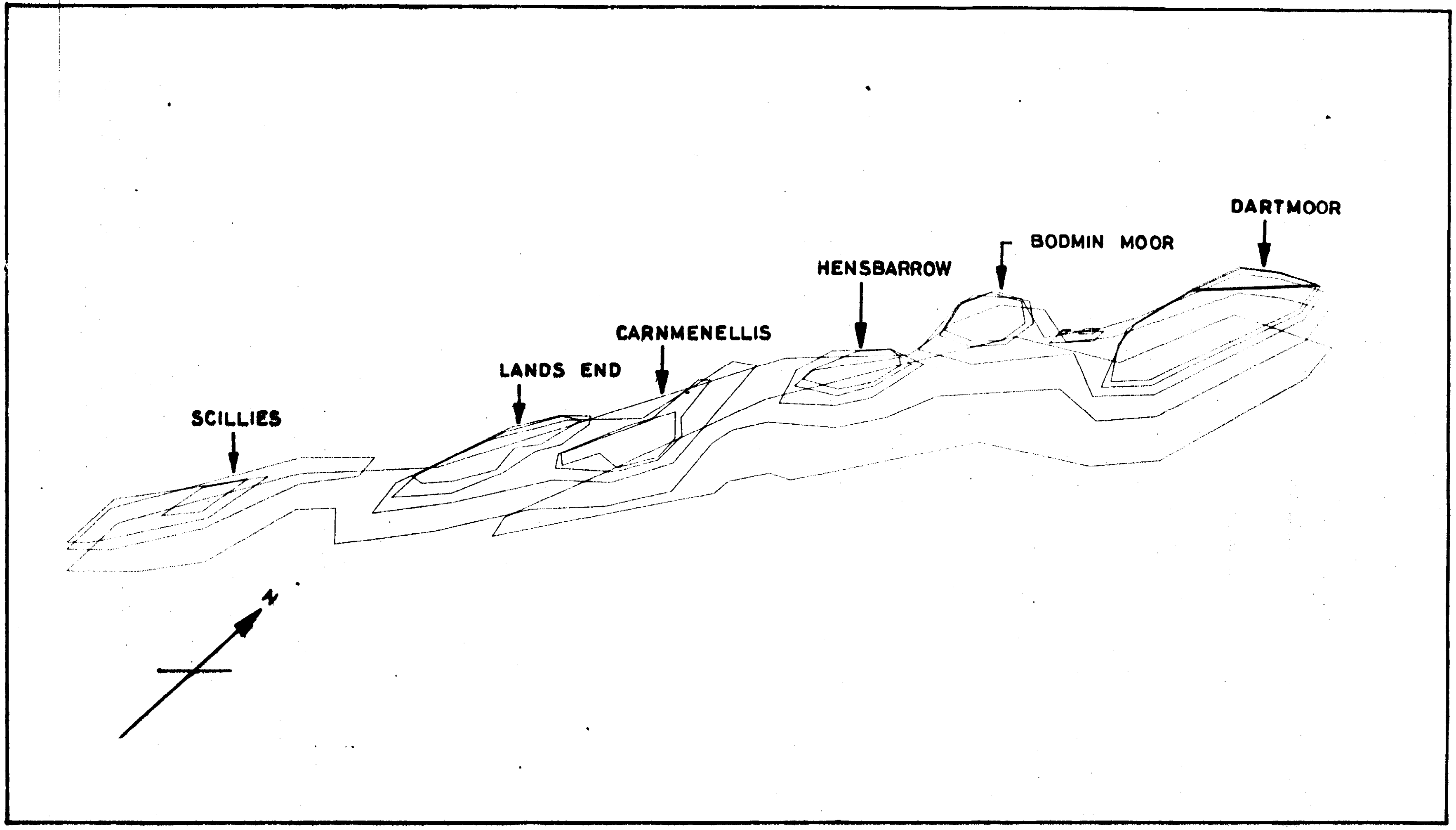



FIG. 2 (c) THE BATHOLITH MODEL - PSEUDO - PERSPECTIVE VIEW

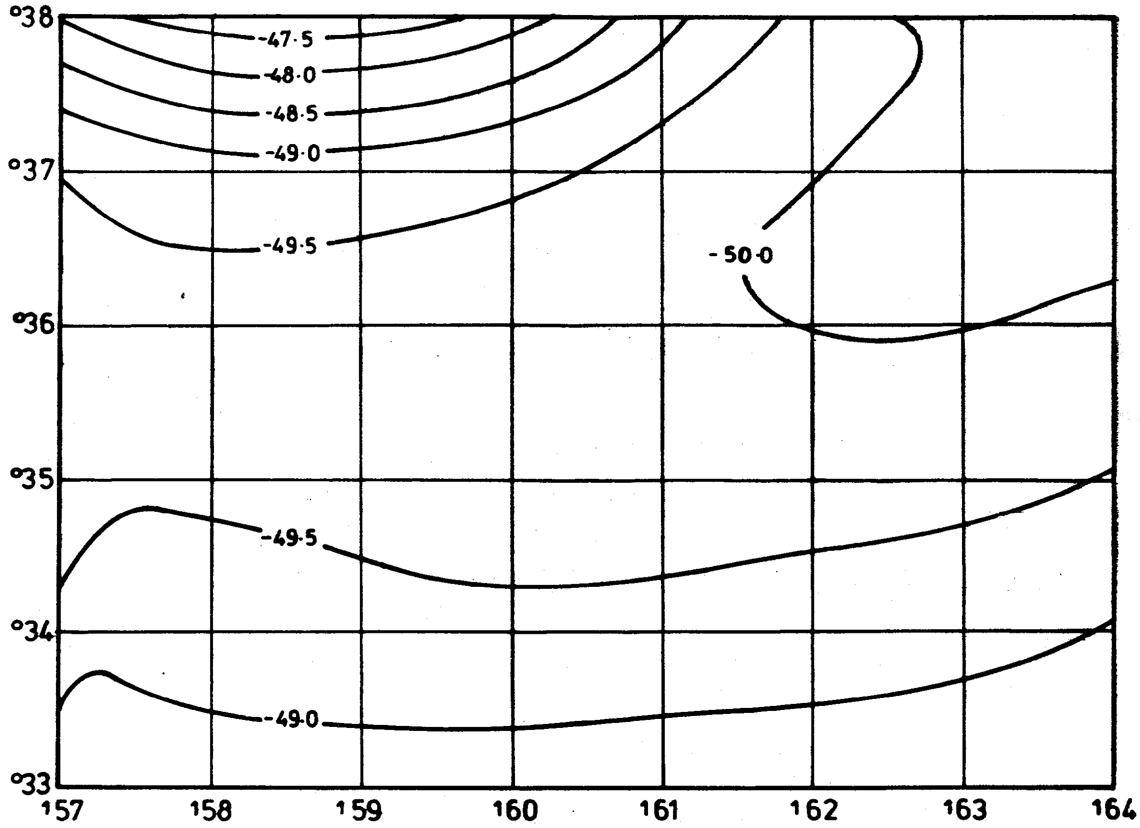



FIG. 3(a) HAYLE-LEEDSTOWN AREA REGIONAL FIELD IN MGAL

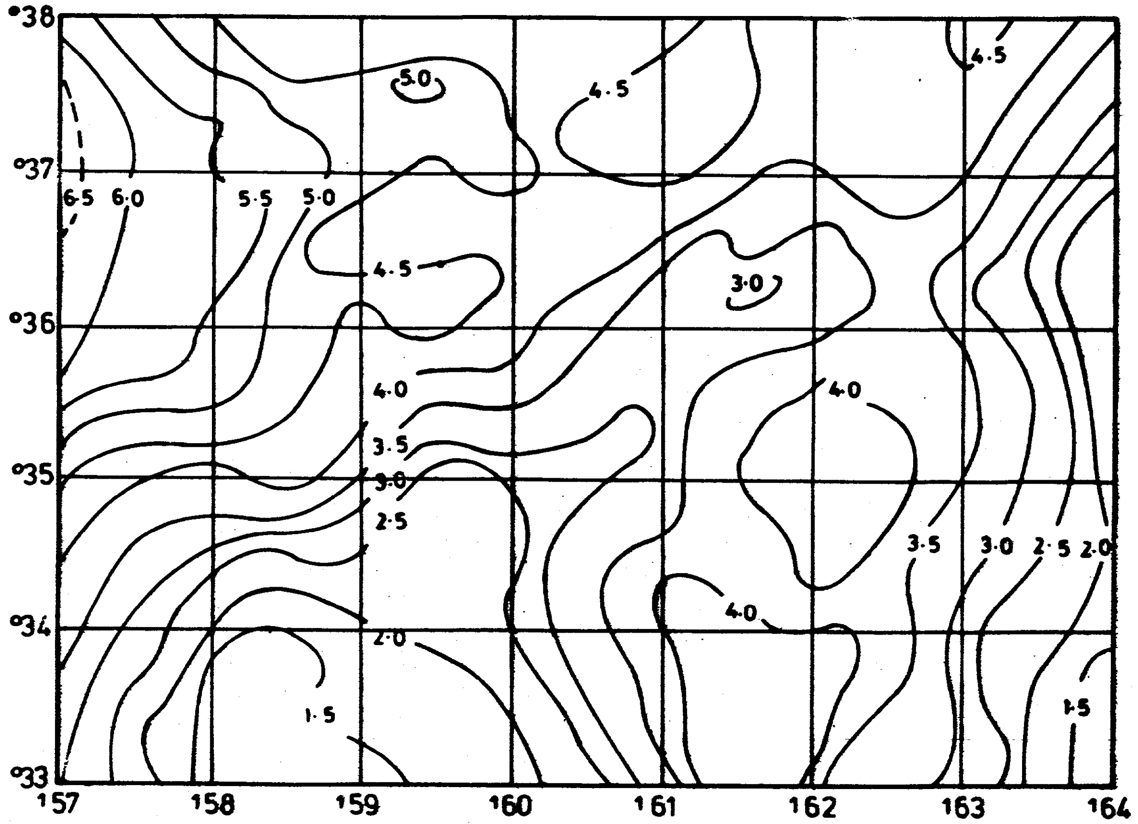



FIG. 3(b) HAYLE - LEEDSTOWN AREA - RESIDUAL FIELD IN MGAL

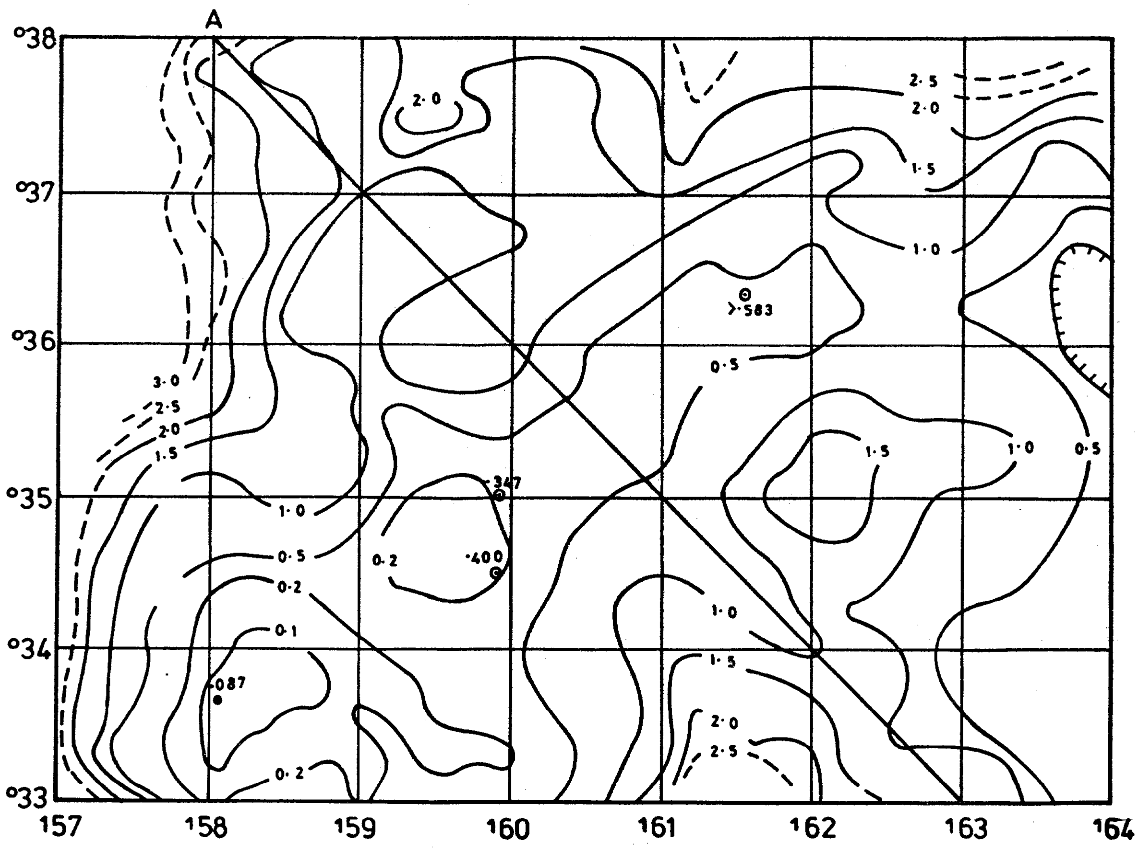



FIG. 3(c) HAYLE-LEEDSTOWN AREA - DEPTH OF GRANITE BELOW SEA LEVEL IN Km.

GRANITE OUTCROP

BOREHOLE WITH DEPTH TO GRANITE BELOW SEA LEVEL IN Km.

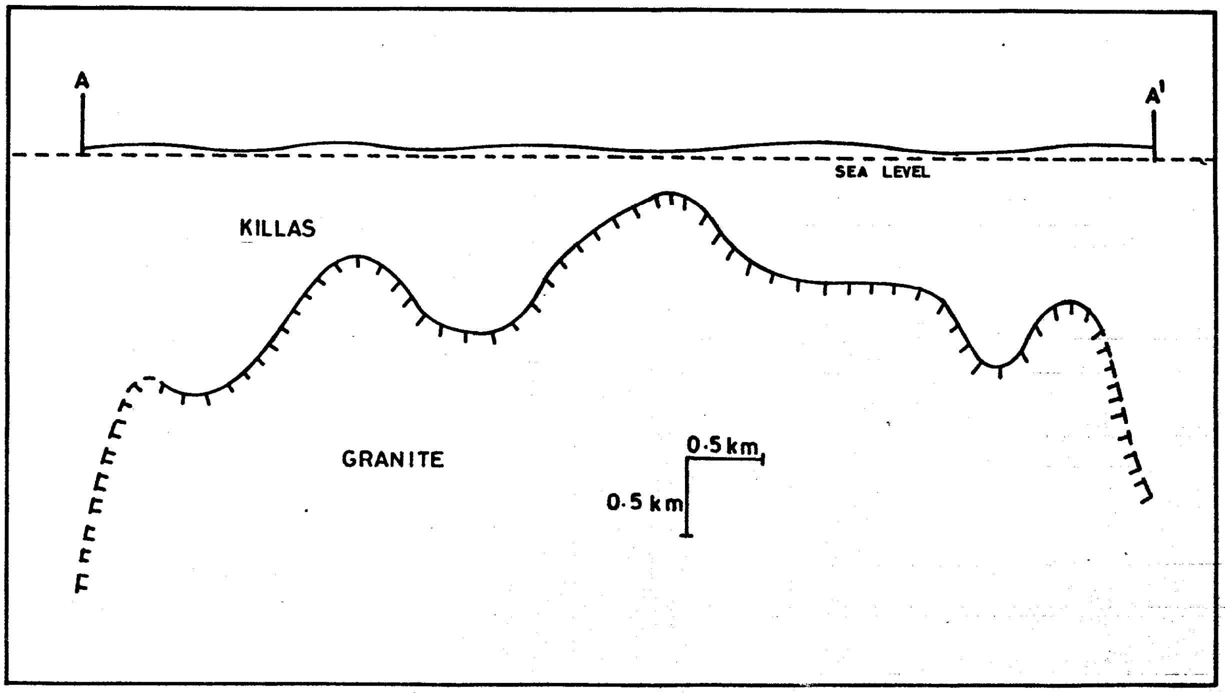



FIG. 3(d) HAYLE - LEEDSTOWN AREA - SECTION ALONG LINE A-A'

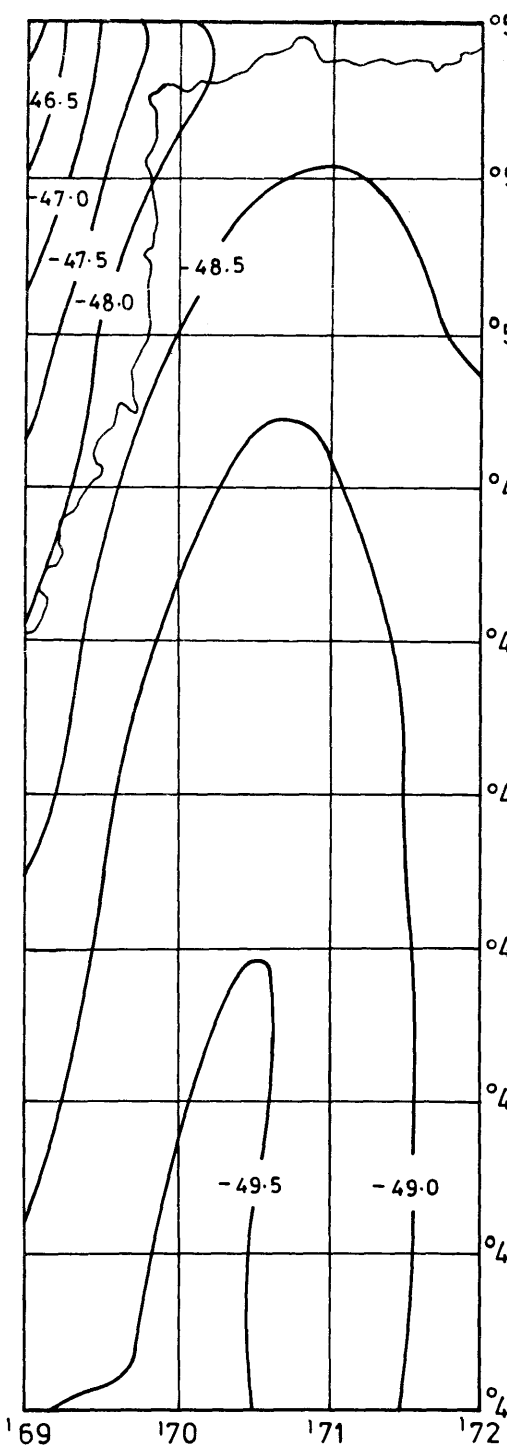



FIG. 4(a) ST. AGNES AREA-
REGIONAL FIELD IN MGAL

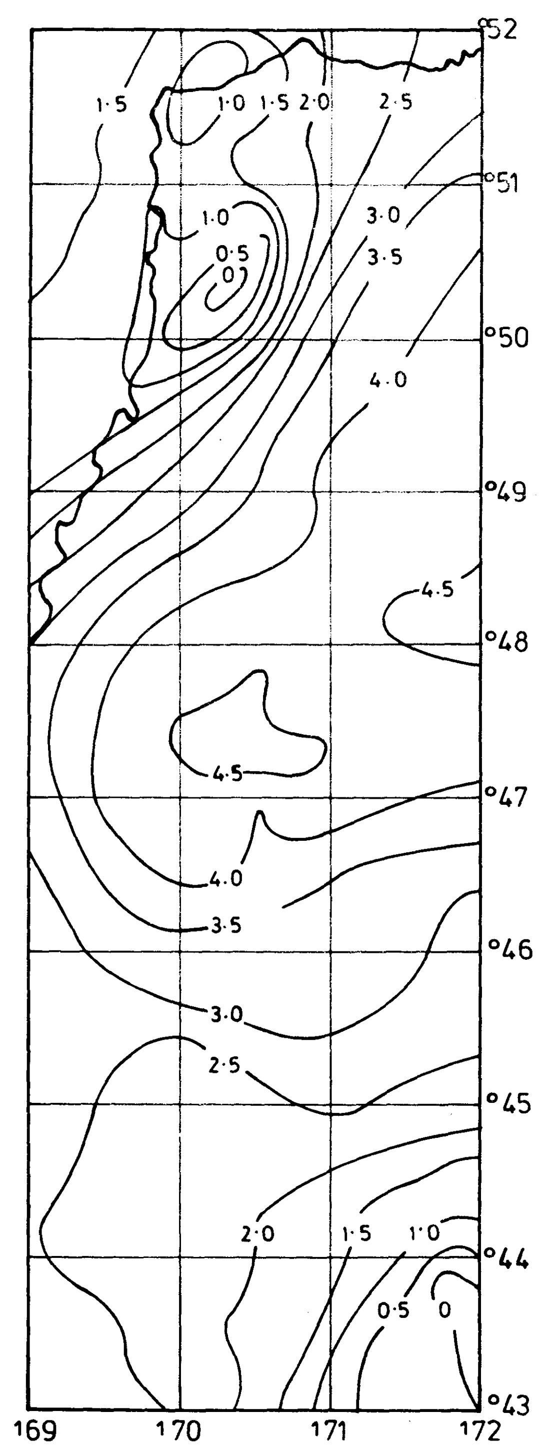



FIG. 4(b) ST. AGNES AREA-
RESIDUAL FIELD IN MGAL.

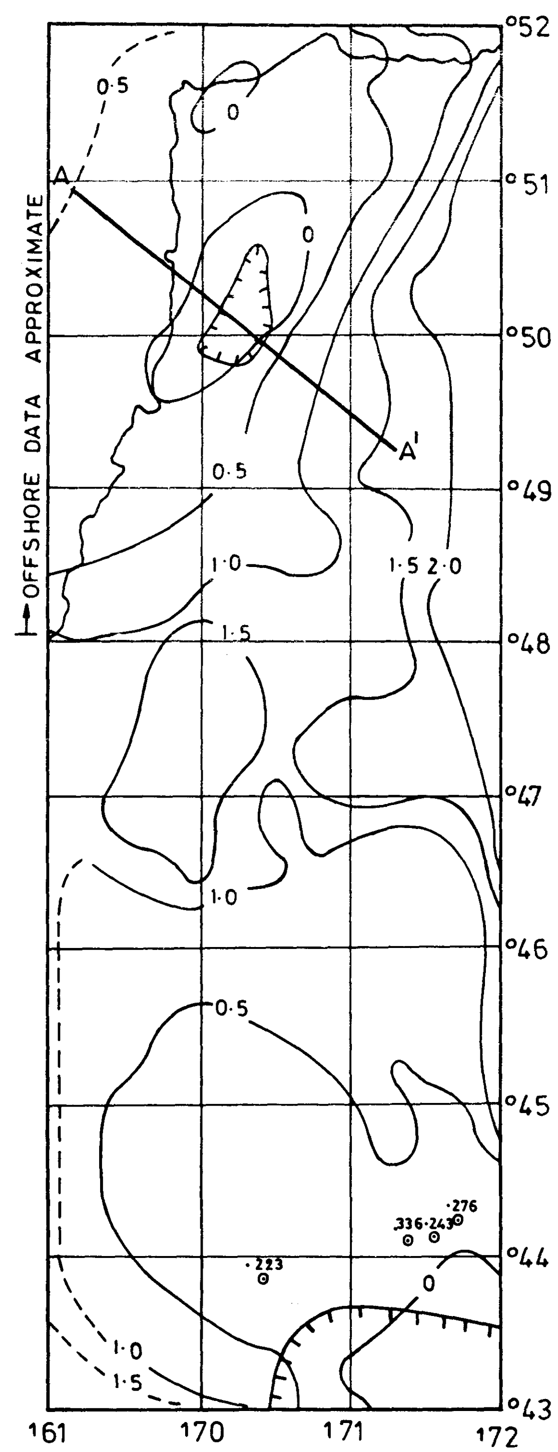



FIG 4(c) ST. AGNES AREA -
DEPTH OF GRANITE BELOW
SEA LEVEL IN Km.

GRANITE OUTCROP

BOREHOLE WITH DEPTH TO
GRANITE BELOW SEA LEVEL IN Km

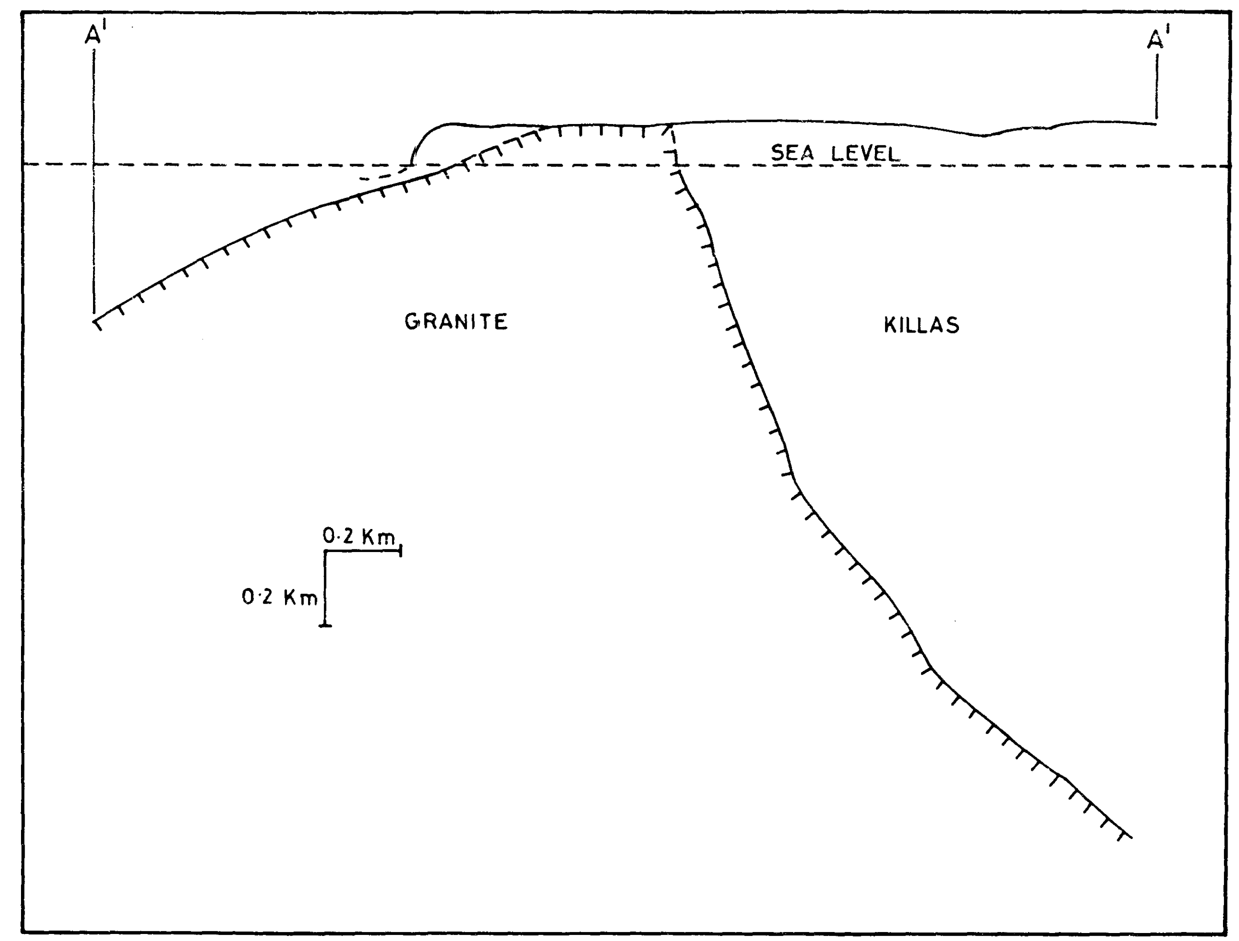



FIG. 4(d) ST. AGNES AREA - SECTION ALONG LINE A - A'

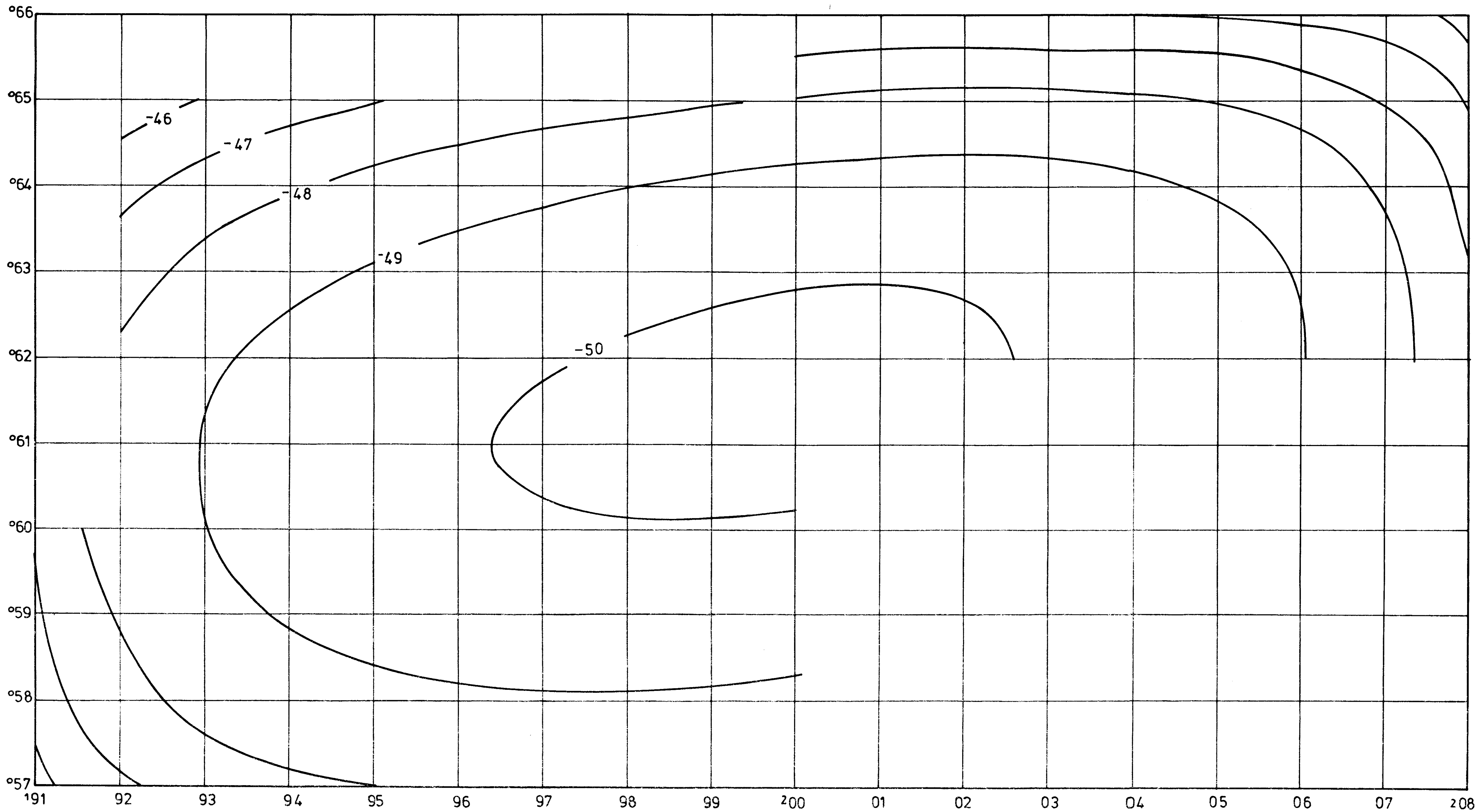



FIG 5(a) ST. AUSTELL AREA - REGIONAL FIELD IN MGAL

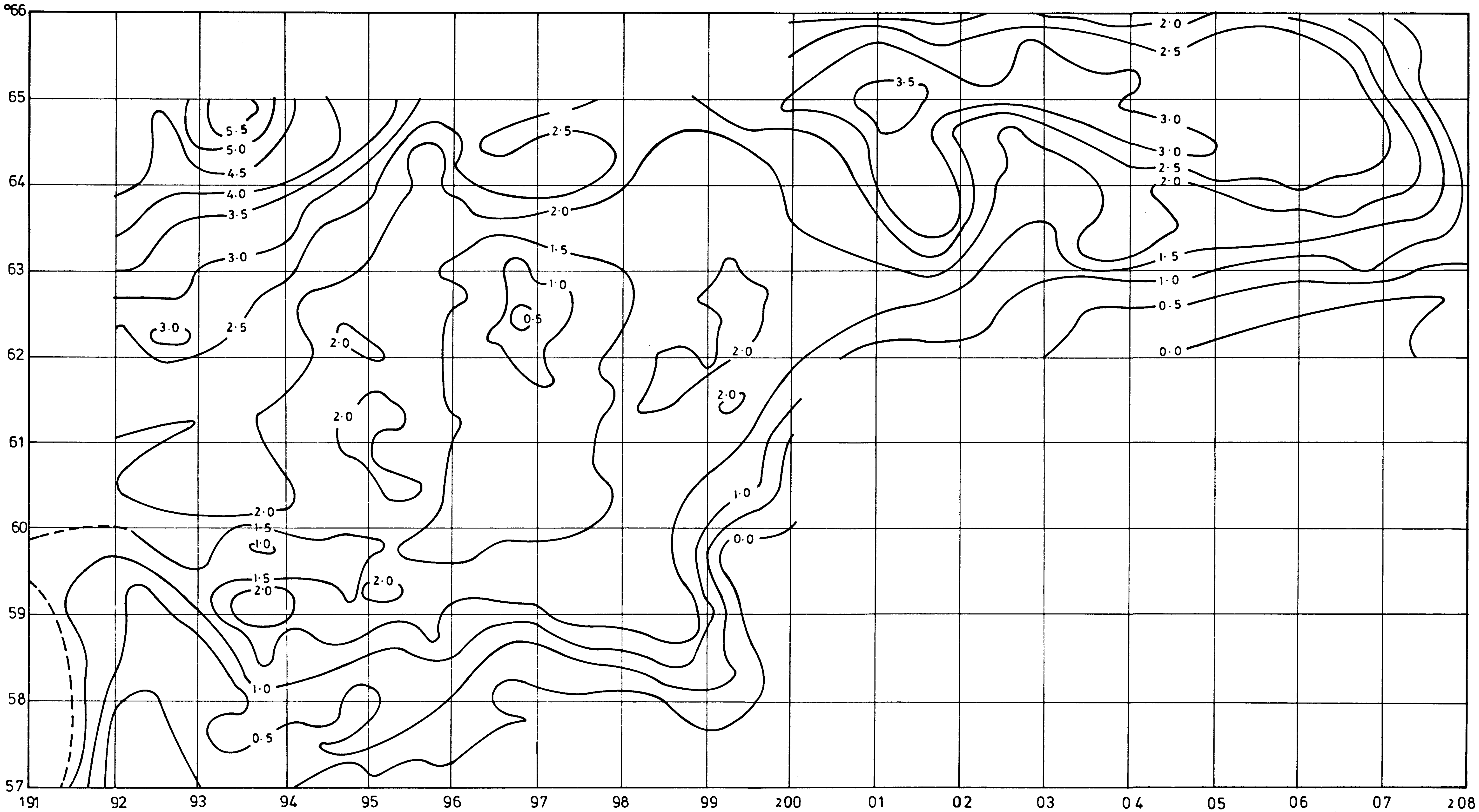



FIG. 5(b) ST. AUSTELL AREA – RESIDUAL FIELD IN MGAL

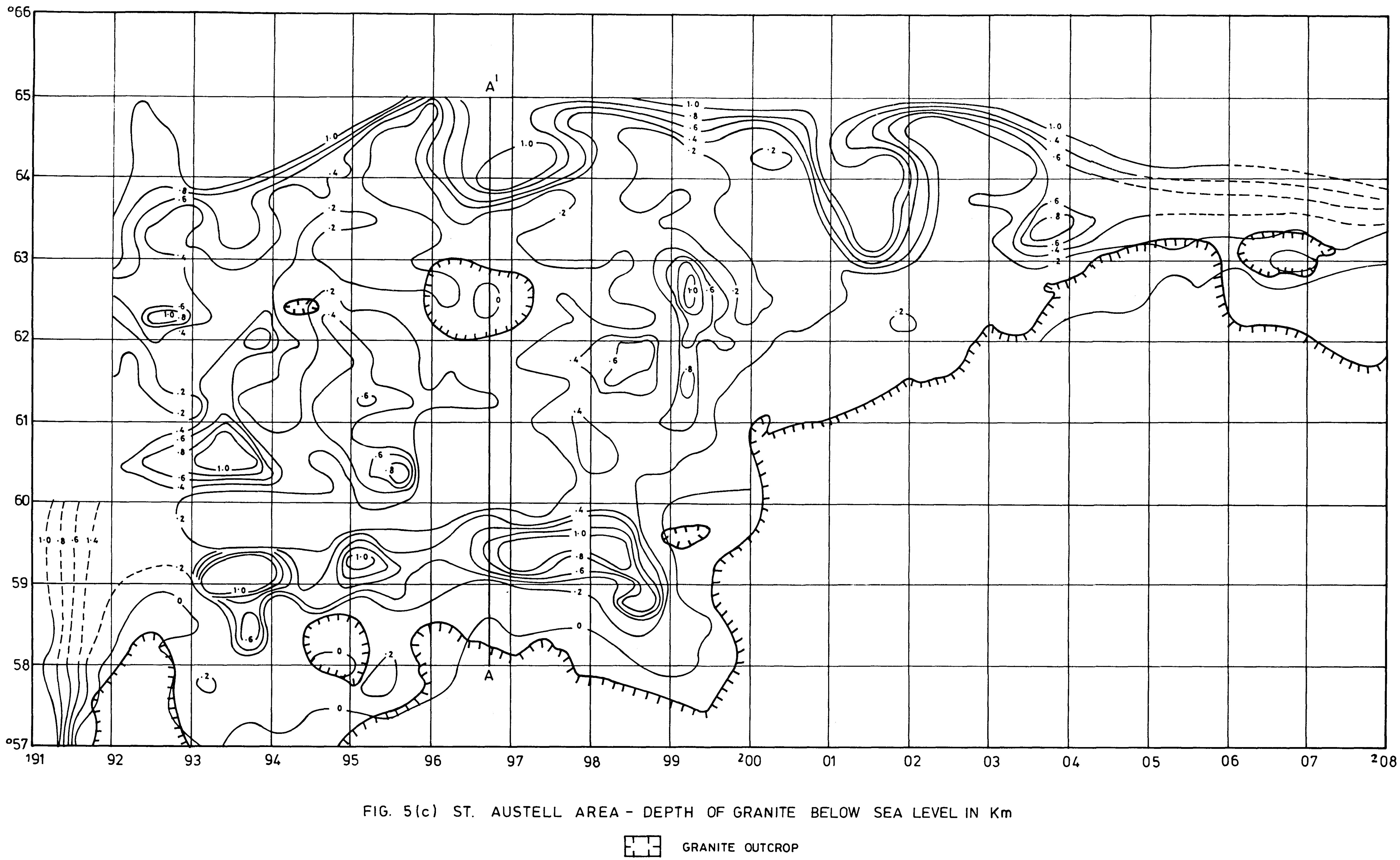



FIG. 5(c) ST. AUSTELL AREA - DEPTH OF GRANITE BELOW SEA LEVEL IN Km

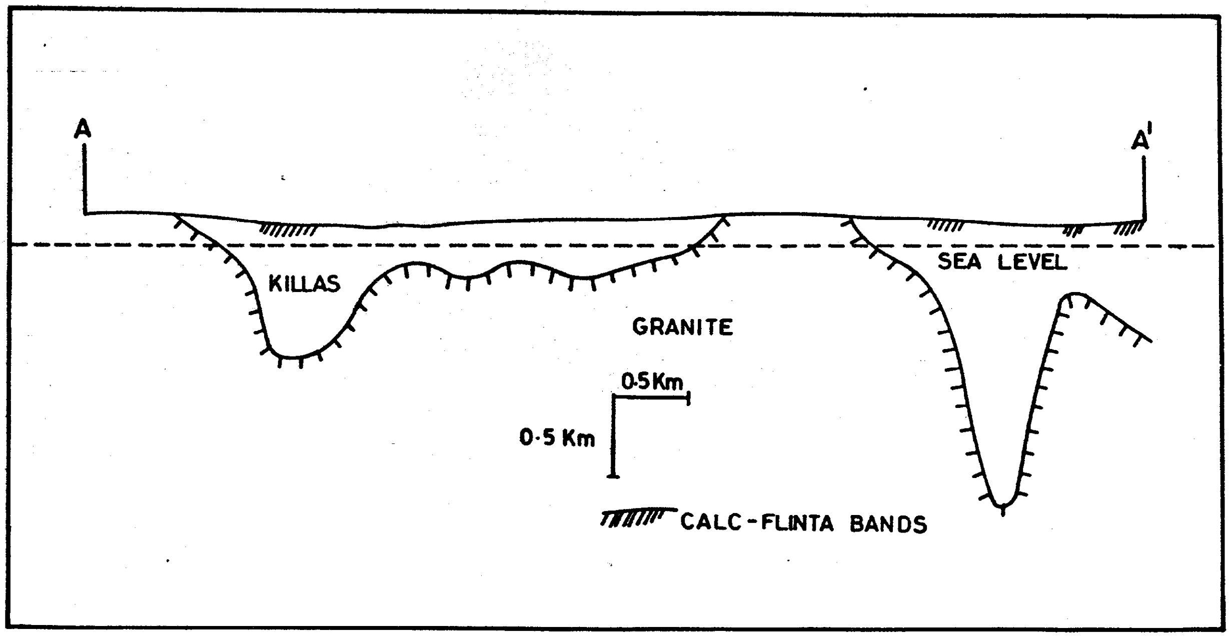



FIG. 5(d) ST. AUSTELL AREA - SECTION ALONG LINE A-A'

# LANDS END

## Sheet 50°N-06°W

Institute of Geological Sciences
1:250 000 Series

## BOUGUER GRAVITY ANOMALY MAP
## (PROVISIONAL EDITION)

### EXPLANATION

ISOGAL VALUES IN MILLIGALS

15 — THICK LINES AT 5 MGAL INTERVAL (BROKEN IN AREAS NOT COVERED BY MARINE SURVEY)

THIN LINES NORMALLY AT 1 MGAL INTERVAL

25 — ANOMALY "HIGH"

5 — ANOMALY "LOW"

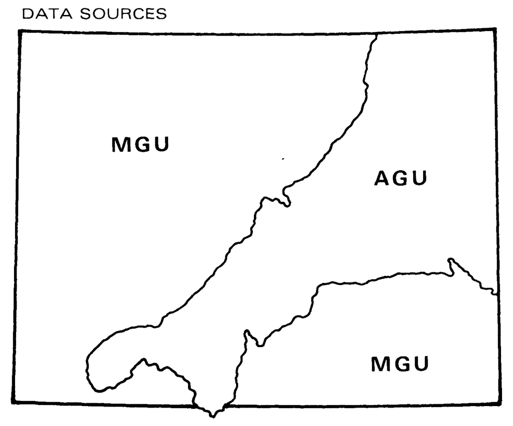
DIRECTION OF HACHURES INDICATES NATURE OF LOCAL CLOSURES

BOUGUER ANOMALIES CALCULATED AGAINST THE INTERNATIONAL GRAVITY FORMULA, 1967, AND REFERRED TO THE NATIONAL GRAVITY REFERENCE NET, 1973.

DENSITIES ($g/cm^3$) FOR BOUGUER CORRECTIONS: 2.70 ON LAND
1.64 AT SEA (SEA WATER 1.03)

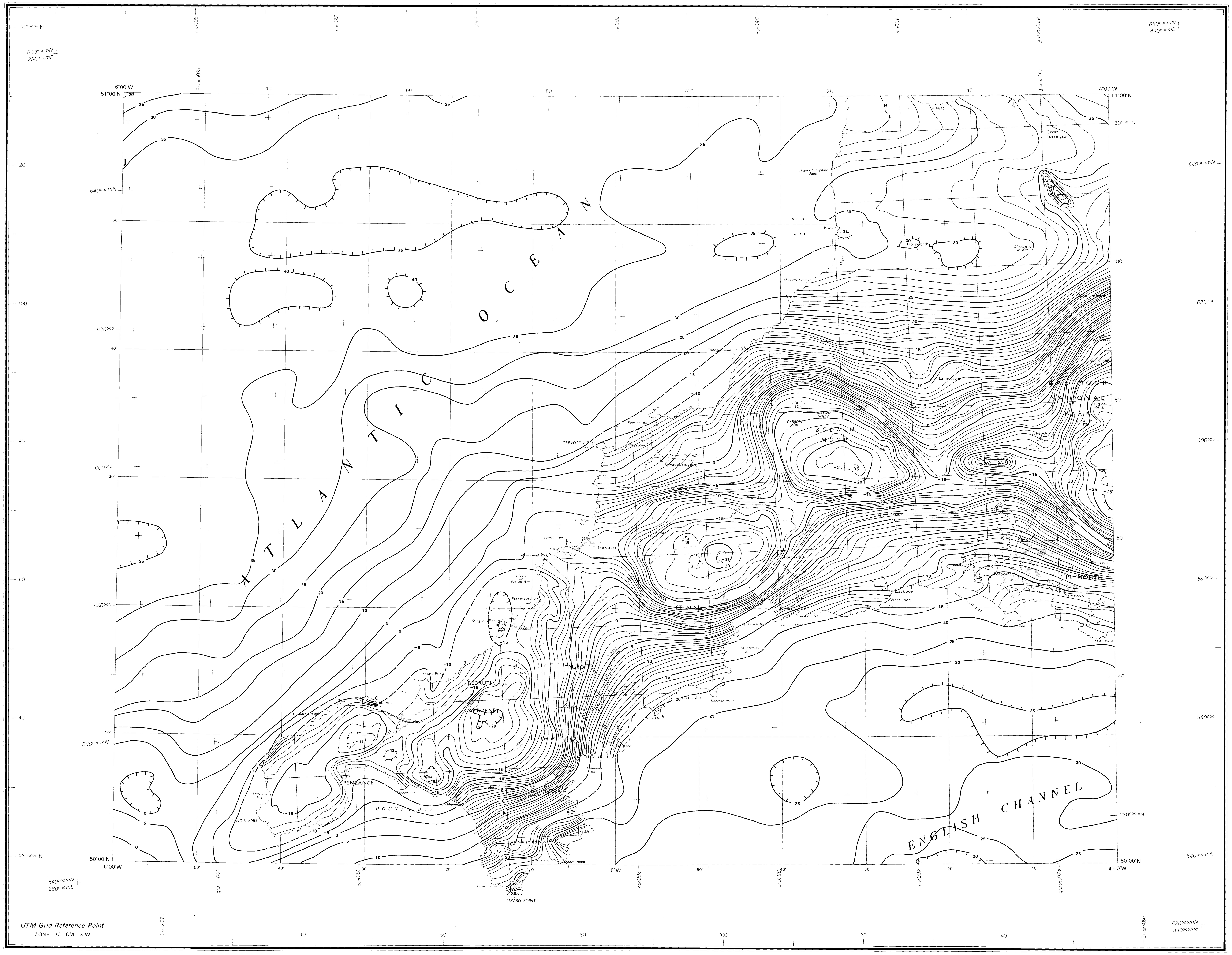
TERRAIN CORRECTIONS APPLIED TO LAND OBSERVATIONS FOR TOPOGRAPHY WITHIN A RADIUS OF 50km OF THE STATIONS

DATA SOURCES

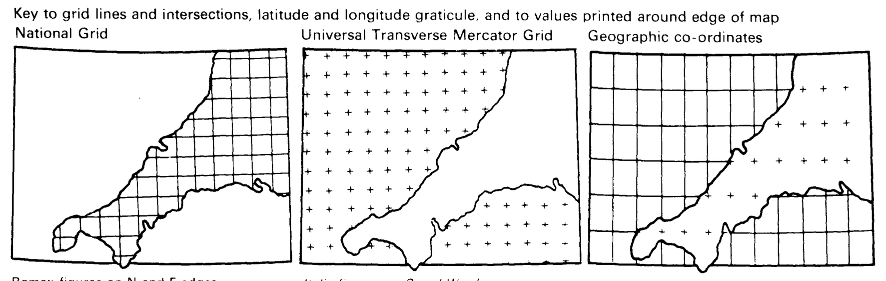



AGU – APPLIED GEOPHYSICS UNIT, IGS
MGU – MARINE GEOPHYSICS UNIT, IGS

DISTRIBUTION OF OBSERVATIONS
ON LAND: 70–80 PER $100km^2$
AT SEA: CONTINUOUS PROFILES ON 8km GRID

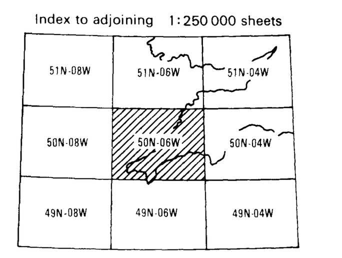



Key to grid lines and intersections, latitude and longitude graticule, and to values printed around edge of map

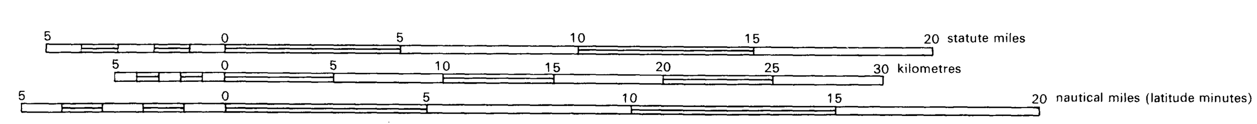


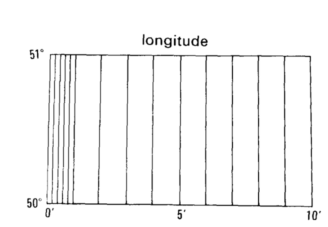

Roman figures on N and E edges | *Italic figures on S and W edges* | Roman figures on S and W edges

Index to adjoining 1:250 000 sheets




Projection: Universal Transverse Mercator Zone 30 Central Meridian 3°W





Compiled from surveys by the Applied and Marine Geophysics Units of the Institute of Geological Sciences.

Based on the Ordnance Survey 1:250 000 map with the permission of the Controller of Her Majesty's Stationery Office.

Published 1975. Sir Kingsley Dunham, D.Sc., F.R.S., Director, Institute of Geological Sciences.