PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Geophysical Studies Relating to the Tertiary Volcanic Structure of the British Isles

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Geophysical studies relating to the Tertiary volcanic structure of the British Isles

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Gravity and magnetic survey results over the Scottish Tertiary districts are characterized by step, linear and circular anomalies relating to faulted basalts, dykes and intrusive centres. A few circular anomalies in areas offshore can be interpreted to define additional intrusive centres. Step anomalies observed in Northern Ireland indicate that normal faulting occurred after the period of igneous activity. Deep crustal structure is ill-determined; observations of anomalous magnetic time variations and enhanced heat flow appear to warrant continuation of these studies.

Introduction

Most of the surface exposures of Tertiary igneous rocks in the British Isles lie along the north-western seaboard and form part of the North Atlantic or Thulean province which stretches from Baffin Land through Greenland, Jan Mayen, Iceland and the Faeroes to northwest Scotland and northeast Ireland. The British part of this province has long been explored geologically, systematic survey beginning at the start of the nineteenth century, and though this is already probably the best studied igneous province in the world (Tomkeieff 1964), the region remains the scene of intensive geological research. Much recent activity has arisen from improved speedier methods of chemical analysis and isotope work, and recognition that the widespread volcanism was probably contemporaneous with intense tectonic activity along this part of the North Atlantic continental margin, especially in relation to initiation of the split between the Faeroe rise and Greenland.

The main igneous forms can be subdivided briefly as:

(1) Plateau lavas accompanied by minor intrusions of sills and plugs, exemplified by the Antrim lavas, vents, cones and plugs of northeastern Ireland.

(2) Plutonic complexes, such as those of St Kilda, Skye, Rum, Ardnamurchan, Mull, Arran, Slieve Gullion, Carlingford and Mourne. Both basic and acid types occur; in some cases the geological evidence indicates close association of acid and basic material in space and time. Concentric intrusions, ring-dykes and cone-sheets vary in composition and texture.

(3) Dyke swarms, both radial and tangential, centred on the major plutonic complexes, notably those of Skye, Mull and Arran.

Away from the northwestern province, Tertiary dykes occur in southern Scotland, northern England, central England and North Wales: most of these converge on the plutonic centres of Mull, Arran or Northern Ireland.

Apparently isolated from the main Hebridean group of complexes is the granite complex of Lundy Island, Bristol Channel, radiometrically dated as Eocene by Miller & Fitch (1962) and Dodson & Long (1962). Earlier, Blundell (1957), from palaeomagnetic measurements which revealed magnetization directions similar to those of Antrim and Mull lavas, had concluded that the rocks of the Lundy dyke swarm are Tertiary, and probably Eocene in age.

Outline of geophysical studies

To date, the most extensively applied geophysical techniques (excluding radiometric dating) have been palaeomagnetic studies, magnetic force and gravity surveys. These kinds of investigation of British Tertiary igneous material started with field studies by McLintock & Phemister (1931) and field and laboratory studies by Hallimond & Herroun (1933) over two tholeiite dykes. Recognition, from the laboratory tests, of a significant permanent magnetization directed anomalously in relation to the terrestrial field was confirmed and extended from an examination of the Cleveland dyke by Bruckshaw & Robertson (1949) which led, during the next twenty years to much palaeomagnetic research into Tertiary rocks from Scotland and Northern Ireland. A very high proportion of the rocks examined have proved to be reversely magnetized; this has led Wilson (1970) to suggest that the whole of the British Tertiary province was extruded in an extremely short time, equivalent to not much more than one reversed epoch.

Perhaps unexpectedly, the first important gravity results were obtained offshore in 1946 from the submarine H.M.S. *Tudor* by Browne & Cooper (1950). In the St Kilda area they recorded a strong positive anomaly and suggested that during the Tertiary period an upward convection current might have existed below this region. From measurements made during 1950 in the Carlingford–Mourne area which revealed a strong positive gravity anomaly over the centres of Slieve Gullion and Carlingford but no detectable anomaly related to the Mourne granite, Cook & Murphy (1952) concluded that both the Slieve Gullion–Carlingford area and the Mourne Mountains are underlain by heavy basic igneous rocks with centres of gravity about $6\frac{1}{2}$ km beneath the surface. Since then, mainly through the measurements of Tuson & McQuillin (1963) and by the Institute of Geological Sciences (1965) it has been demonstrated that all the Scottish Tertiary complexes are associated with positive Bouguer anomalies, intense over the basic centres and with only partial reduction over the outcrops of associated acid rocks. An average diameter for the anomaly feature is about 10 km. Offshore, gravity coverage is growing rapidly from the areas north and west of Scotland. Roberts (1970) figures a free-air gravity anomaly map for the northwestern approaches which reveals in the area between Scotland and Rockall at least four gravity highs which simulate those recorded over the land Tertiary centres.

Magnetic force observations over the plateau basalts of the Tertiary province were first undertaken in Northern Ireland (Bullerwell 1954), but the most comprehensive magnetic field data have been obtained from aeromagnetic surveys undertaken for the Geological Survey over the period 1955–65. These extended over Northern Ireland in 1959 and progressively northwards through Scotland between 1961 and 1965. Results for the whole area have been published as line isogam maps at the 1:250000 scale (Bullerwell 1964, 1968). For southern England and Wales a colour map at the 1:625000 scale has also been published (Bullerwell 1965); the corresponding sheet for Scotland and northern England is in an advanced stage of preparation.

Scottish area

(*a*) *Magnetic anomaly patterns*

The published results reveal intense magnetic anomalies in all areas of known Tertiary complexes and plateau basalts, with repetitions of three anomaly forms:

(*a*) Narrow, mainly negative, linear or arcuate, unipolar patterns associated with dykes.

Some of these extend for several kilometres and a few wider features of this type (up to 2 km anomaly half-width as recorded at the aircraft) can be traced for 80 or more kilometres.

(*b*) Laterally persistent gradient changes or positive–negative excursions associated with faulting, e.g. the Southern Upland Fault.

(*c*) Circular patterns in which an outer ring of positive anomaly may surround a negative, or vice versa, associated with the major complexes. The amplitude of the anomalies vary from intense, 4000 nT over the Mull centre, to weak, about 25 nT over the Mourne granite. In areas of plateau basalts or dyke swarms, any weak features of this type are obliterated. An average diameter for the outer anomaly is about 10 km.

An attempt was made to examine the geological associations of the circular-type anomaly and dyke-swarm patterns by detailed ground magnetic surveys on the Isle of Mull, the main aims being to locate the anomalies more precisely in relation to surface structures and to obtain additional information about deeper structure. Some of the results have been described by Bennett (1968). The first objective of the investigation was achieved and in many places short wavelength anomalies could be interpreted in terms of shallow structure. However, some very intense surface anomalies were encountered and this kind of background noise complicated the problem of deep structural interpretation. Both normally and reversely polarized rocks were located; some of the initial interpretations are being reviewed in the light of recent palaeomagnetic results by Ade-Hall *et al.* (1970) revealing an asymmetry between normal and reverse dykes of the Mull swarm.

Over a considerable part of the Tertiary province the regional anomaly pattern is greatly confused by local anomalies due to dyke systems and strongly magnetic lavas. Removal of these effects might clarify the deeper structure associated with the complexes or reveal details of the environment in which the centres were emplaced. Hall & Dagley (1970) have digitally filtered the Geological Survey aeromagnetic data to produce a smoothed aeromagnetic map. The cut-off wavelength of the filter system, about 13 km, effectively suppressed all dyke anomalies and makes apparent a strong Caledonoid trend in the structural framework. Most of the Tertiary complexes remain apparent as circular anomalies, confirming that they represent emplacements of considerable depth extent. Indeed some of the transformed magnetic patterns over the centres seem more readily interpretable than the raw data. For example, the binary pattern over the Isle of Skye, where the Cuillins are marked by a negative anomaly and a positive anomaly lies over the Eastern Red Hills centre, seems to be repeated in the area of St Kilda, where a negative anomaly centres north of Soay and a positive to the east of St Kilda. In addition two centres offshore, one northwest of Lewis and the other west of Dubh Artach, become more evident.

(*b*) *Tertiary intrusive centres*

One of the significant contributions which geophysics has so far been able to make so the study of the British Tertiary province has been to extend information offshore and, specifically, to locate probable sites of additional intrusion complexes. Some of these have been named directly from associated sea-bottom features, but this does not prove possible for the two occurrences mentioned at the end of the preceding paragraph. For the postulated intrusion complex situation off northwest Lewis the name Outer Roag is proposed, as it lies about 10 km offshore of the entry to East Loch Roag. The prominent magnetic anomaly centre west of Dubh Artach was first revealed during the Geological Survey's aeromagnetic survey in 1962 as the possible location of an igneous complex related to dykes crossing Islay and Jura. The name

Blackstones is proposed, and I am grateful to Mr D. G. Roberts of the National Institute of Oceanography for suggesting this name during personal discussion. According to Donovan (1968, p. 9), Close's Fishing Chart notes bottom of 'black stones' in this area. Combining these proposals with features identified by Roberts (1970), the postulated offshore centres are as set out in table 1.

On a qualitative basis the basic centres are associated with high gravity and intense magnetic anomaly, usually negative, e.g. Rum. On the other hand, the acid centres appear to display two forms, those associated with intermediate gravity and strong magnetic anomaly, e.g. Arran, and those which show little effect in gravity and only weak magnetics, e.g. Mourne. On this simple

TABLE 1. TERTIARY IGNEOUS CENTRES POSTULATED FROM GEOPHYSICAL DATA

Rockall	57° 36′ N, 13° 41′ W
Anton-Dohrn seamount	57° 25′ N, 11° 03′ W
Hebrides Terrace seamount	56° 28′ N, 10° 20′ W
Blackstones	56° 07′ N, 7° 09′ W
Outer Roag	58° 26′ N, 6° 54′ W

TABLE 2. SIGN OF MAGNETIC ANOMALY OVER TERTIARY CENTRES

negative anomaly	positive anomaly
Mull (Centre 1)	late stages in Mull
Skye (Cuillins)	Skye (eastern Red Hills)
Rum	Slieve-Gullion–Carlingford
Ardnamurchan	Arran
Blackstones	—
Outer Roag	—

scheme, of the offshore centres, Anton-Dohrn, Hebrides Terrace, Rockall and Blackstones appear dominantly basic in character. In the case of Outer Roag, gravity data are not yet available, and both the gravity and magnetic data are incomplete for a gravity high north of St Kilda noted by Roberts (1970). Quantitatively, the acid rocks associated with the complexes do not appear to exceed 1000 m in thickness, while the basic masses seem to average at about 15 km. The signs of the residual magnetic anomalies over the main centres, listed in table 2, are not related directly to petrology or chemistry but in two cases, Mull and Skye, the associations in a multiple centre suggest a similar age relationship.

(*c*) *Dykes*

From the aeromagnetic survey results the plateau lavas uniformly exhibit reversed magnetization. Most of the dyke anomalies are negative and also symmetrical, indicating a near-vertical attitude. For this kind of structure, models are not very sensitive to variations in depth extent, but good fits can be obtained for a base level of 8 to 10 km. Anomaly patterns related to several of the dyke swarms show clear swings in direction in the neighbourhood of adjacent centres. Thus the dykes from Skye appear to pull in towards Mull and the dykes of the Mull swarm appear to pull in towards Arran. The wider dyke-like features, such as the North Minch anomaly which extends from Loch Ewe to north of the Butt of Lewis, deviate from the norm in other respects. They trend slightly obliquely in respect of adjacent dyke features and show no connexions with presently known igneous centres. Some of them traverse areas of low gravity and it is possible that they were intruded into a different type of basement and without the vertical component of stress prevalent near intrusive centres. Speculatively, they may represent

wedge-like infillings of tension cracks affording adjustment between blocks defined during development of the split between the Faeroe rise and Greenland. It is possible, however, that the key to these problematic features lies outside the surveyed area.

Northern Ireland

Some features concerning the emplacement and subsequent history of the basalts can be studied best in Northern Ireland for which gravity and magnetic anomaly maps at the 1:253440 scale have been published (Bullerwell 1967, 1971). The gravity anomalies over Northern Ireland show a relatively high mean value against which a series of SE to NW-trending fault disturbances register clearly as zones of steeper gravity gradient. It is striking that the gravity values maintain a lower average value across the high-density basalts than in the adjacent areas. The general pattern suggests that the basalts were extruded into sedimentary basins defined by rift-like faulted boundaries. Several of the fault disturbances register clearly on the magnetic anomaly map, in some cases indicating post-emplacement faulting within the basalts. In these cases the fault disturbance is indicated by a change in the level of the magnetic field without displacement of axial features, and in general the post-emplacement faulting appears to have been restricted to vertical disturbance without lateral movement. Similar characteristics extend to the northeasterly extensions of these faults, and also to a disturbance which forms the northwestern boundary of a sedimentary basin situated in the Sea of the Hebrides where sparker profiles penetrating the shallow succession also indicate normal faulting.

The general run of negative magnetic anomalies over the basalt area in Northern Ireland is interrupted by a positive anomaly which trends from Dundrum Bay, County Down to Crumlin, County Antrim. The geological cause is uncertain, but the feature runs close to the Hillsborough dyke swarm and the possibilities of a direct association merit consideration. Within the general negative area, a few kilometres northeast from Antrim, a weak, positive, arcuate magnetic anomaly centres over the rhyolite outcrop near Tardree Mountain. In the southwestern part of Northern Ireland and passing from Donegal through Fermanagh, Monaghan and on across the Irish Sea to Anglesey occurs a series of dyke-like magnetic features of which the most southerly example, a wide, continuous feature, relates to a notable member of the Donegal–Kingscourt swarm, described by Preston (1965). Changes in magnetic field across this anomaly suggest that it is intruded along a fault. As in the northeastern part of Ireland, the continuity of axial trends across the disturbance suggest vertical displacement; one perpendicular magnetic anomaly changes level abruptly across this disturbance in the Irish Sea area between Ireland and Anglesey.

Lundy Island

Geophysical results for the Lundy Complex have been well summarized by Bott & Scott (1964). Its gravity anomaly is comparable to that observed over the Mourne granite and it is associated with a weak arcuate magnetic anomaly ring-pattern. These features are in marked contrast to those associated with the Armorican granites of southwest England. However, the gravity and magnetic data throw no light on possible connexions between the Lundy complex and other Tertiary igneous centres.

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Conclusion

Seismic crustal information adjacent to the British Isles has been summarized by Blundell & Parks (1969), Bott & Watts (1971) and Bamford & Blundell (1971). In relation to the British Tertiary province, the crustal models for the most critical areas are incomplete due to insufficient penetration and more elaborate explosion experiments are very desirable. Limited offshore extensions of Tertiary igneous rocks have been established from reflexion seismic, sparker and sonar surveys.

A shallow column of sea water provides the equivalent of a mathematical filtering effect on magnetic and gravity measurements. Around the Hebrides, effects due to topography at the sea-bed should cause less difficulty than those from the vigorous terrain of the land Tertiary centres, which greatly complicated the detailed ground survey in Mull. Therefore, a detailed and accurately positioned marine survey of one of the offshore centres, employing simultaneously seismic, sonar, gravity and magnetic techniques, and followed by geological sampling, might well prove the most effective way of investigating the deeper form and structure of central intrusions.

A promising line for further experiment appears to be the study of anomalous time variations in the magnetic field, possibly combined with magneto-telluric work. Time-variation studies of Osemeikhian & Everett (1968) suggest the existence of a temperature anomaly in the Upper Mantle below Eskdalemuir, Southern Uplands. Other work in France by Fontaine, Le Borgne, Le Mouel & Rossignol (1965*a*, *b*) suggests the existence of a deep electrical conductor extending northeastwards across the western English Channel from Ouessant towards Start Point. The associated temperature anomalies might result in measurable variations in heat flow. It is encouraging, therefore, in connexion with the southern Scotland conductivity anomaly, that measurements in the Geological Survey of Northern Ireland deep borehole at Portmore, County Antrim, by Mr J. Wheildon (personal communication) revealed a heat flow of 80 mW m^{-2} (1.9 μcal cm^{-2} s^{-1}), above the average observed in the British Isles. I am grateful to Mr Wheildon for permission to quote this result. If the association between conductivity anomalies and heat flow could be confirmed and extended to adjacent districts the question might then be to determine whether the phenomena signify a relict of Tertiary processes or some new engine brought into action by recent movements close to the continental margin.

References (Bullerwell)

Ade Hall, J. M., Dagley, P., Wilson, R. L., Smith, P. J., Evans, A. & Riding, A. 1970 In *Palaeogeophysics* (ed. S. K. Runcorn), pp. 139–143. London: Academic Press.

Bamford, S. A. D. & Blundell, D. J. 1971 *Rep. no.* 70/14, *Inst. geol. Sci.* pp. 143–156.

Bennett, J. R. P. 1968 *Proc. geol. Soc. Lond.* no. 1647, 61–65.

Blundell, D. J. 1957 *Geol. Mag.* **94**, 187–193.

Blundell, D. J. & Parks, R. 1969 *Geophys. J. R. astr. Soc.* **17**, 45–62.

Bott, M. H. P. & Scott, P. 1964 *R. geol. Soc. Cornwall* 150th Anniversary volume, pp. 25–44.

Bott, M. H. P. & Watts, A. B. 1971 *Rep. no.* 70/14, *Inst. geol. Sci.* pp. 77–88.

Browne, B. C. & Cooper, R. I. B. 1950 *Phil. Trans. R. Soc. Lond.* A **242**, 243–310.

Bruckshaw, J. McG. & Robertson, E. I. 1949 *Mon. Not. R. astr. Soc.* (*geophys. suppl.*) **5**, 308–314.

Bullerwell, W. 1954 *Bull. geol. Surv. Gt. Br.* no. 6, 21–32.

Bullerwell, W. 1964 Aeromagnetic map of part of Great Britain and Northern Ireland. Sheets 1–9. *Geol. Surv. Gt. Br.*

Bullerwell, W. 1965 Aeromagnetic map of Great Britain, Scale 1:625 000. Sheet 2. *Geol. Surv. Gt. Br.*

Bullerwell, W. 1967 Gravity anomaly map of Northern Ireland. *Geol. Surv. Northern Ireland.*

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Bullerwell, W. 1968 Aeromagnetic map of part of Great Britain and Northern Ireland. Sheets 10–16, *Geol. Surv. Gt. Br.*

Bullerwell, W. 1971 Magnetic anomaly map of Northern Ireland. *Geol. Surv. Northern Ireland.*

Cook, A. H. & Murphy, T. 1952 *Geophys. Mem.* no. 2, part 4, *Dubl. Inst. Adv. Studies.*

Dodson, M. H. & Long, L. E. 1962 *Nature, Lond.* **195**, 975–976.

Donovan, D. T. (ed.) 1968 *Geology of shelf seas.* Edinburgh: Oliver and Boyd.

Fontaine, M., Le Borgne, E., Le Mouel, J. & Rossignol, J-C. 1965*a* *C. r. hebd. Séanc., Paris* **260**, 261–264.

Fontaine, M., Le Borgne, E., Le Mouel, J. & Rossignol, J-C. 1965*b* *C. r. hebd. Séanc., Paris* **261**, 1887–1890.

Hall, D. H. & Dagley, P. 1970 *Rep. no.* 70/10, *Inst. geol. Sci.*

Hallimond, A. F. & Herroun, E. F. 1933 *Proc. R. Soc. Lond.* A **141**, 302–314.

Institute of Geological Sciences 1965 *Annual Report for* 1964. London: H.M.S.O.

McLintock, W. F. P. & Phemister, J. 1931 Summary of Progress for 1930, Part III. *Mem. geol. Surv. Gt. Br.*

Miller, J. A. & Fitch, F. J. 1962 *Nature, Lond.* **195**, 159–160.

Osemeikhian, J. E. A. & Everett, J. E. 1968 *Geophys. J. R. astr. Soc.* **15**, 361–366.

Preston, J. 1965 *Proc. geol. Soc. Lond.* no. 1626, 149–150.

Roberts, D. G. 1970 *Proc. geol. Soc. Lond.* no. 1662, 87–93.

Tomkeieff, S. I. 1964 In *Advancing frontiers in geology and geophysics*, pp. 327–350. Hyderabad: Osmania University Press.

Tuson, J. & McQuillin, R. 1963 *Nature, Lond.* **199**, 1276–1277.

Wilson, R. L. 1970 *Geophys. J. R. astr. Soc.* **20**, 1–10.

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