Read at the Annual Conference of the Ussher Society, January 1990

Magnetic evidence for the nature and extent of the Exeter lavas

J.D. CORNWELL, R.A. EDWARDS, C.P. ROYLES and S.J. SELF

Cornwell, J.D., Edwards, R.A., Royles, C.P. and Self, S.J. 1990. Magnetic evidence for the nature and extent of the Exeter lavas. *Proceedings of the Ussher Society, 7, 242-245.*

Scattered outcrops of volcanic rocks (the `Exeter lavas') occur at the base of, or within, the New Red Sandstone sequence in the Exeter-Crediton area. The lavas retain stable remanent magnetisations consistent in direction with their formation in a near-equatorial position at a time when a reversed geomagnetic field existed. Tropical weathering conditions and possible hydrothermal alteration processes resulted in much of the magnetite being oxidised to haematite. Most of the lavas are therefore only detectable from aeromagnetic survey results as low amplitude features, and the form of these anomalies is characteristic of reversed magnetisation. One notable exception is the minette of Killerton which produces a large magnetic anomaly due to the preservation of magnetite. The form and nature of this and the adjacent lavas have been investigated by more detailed ground measurements; a complex anomaly pattern is revealed, and it is suggested that the lower surface of the minette is near- horizontal. The aeromagnetic survey also revealed other anomalies which indicate extensions to known lavas and, just south of Exeter, a possible extensive but completely concealed flow.

J.D. Cornwell. C.P. Royles and S.J. Self, British Geological Survey, Keyworth, Nottingham NG12 5GG. R.A. Edwards, British Geological Survey, St Just, 30 Pennsylvania Road, Exeter, Devon EX4 6BX.

Introduction

Scattered outcrops of igneous rocks (informally termed `Exeter lavas' in this paper) occur in association with the Permo-Triassic New Red Sandstone (NRS) red-bed sequence in the vicinity of Exeter, and within the partly fault-bounded Crediton Trough (Fig. 1a). Most of these rocks are clearly lava flows; other occurrences, for example in the Broadclyst area (Bristow 1983), have the appearance of volcanic necks. Cosgrove (1972, p.155) considered that the form of the outcrop of the igneous rocks at Killerton Park was "suggestive of a volcanic plug".

Some of the lavas rest directly on folded Carboniferous rocks (Culm), as in the Exeter City area, while others are intercalated in higher parts of the NRS sedimentary sequence (as at Raddon, near Thorverton, in the Crediton Trough). The lavas at the base of the NRS sequence at Exeter may be the remnants of more extensive flows that were partly removed by erosion prior to the deposition of the NRS (Scrivener 1984). This explains the discontinuous nature of the outcrops in this and possibly other areas.

Basaltic lavas from Dunchideock have been radiometrically dated by Miller and Mohr (1964) at 281±1Ma. Potassium-argon age determinations on biotite samples from minettes at Killerton Park gave ages of 279±6Ma (Miller *et al.* 1961), recalculated to 291±6Ma by Thorpe e*t al.* (1986). These ages are close to the date of 290±5Ma proposed by Forster and Warrington (1985) for the beginning of the Permian period.

The most comprehensive account of the petrography of the Exeter lavas is that of Knill (1969), who divided them into an earlier basaltic group and a later group of highly potassic lavas.

Little is known, however, of the extent at depth of the lavas, their form and interrelationship. Geophysical methods were therefore considered as a means of examining these problems, and also of determining if any completely concealed lava flows existed. Magnetic surveys were considered most appropriate as the lavas should have a significant contrast in magnetisation with the adjacent sedimentary rocks. This paper briefly describes the results obtained from an examination of existing aeromagnetic data (Fig. 1b) and from some ground magnetic surveys of selected sites, notably the Killerton lavas. The results are described in greater detail by Cornwell *et al.* (In prep).

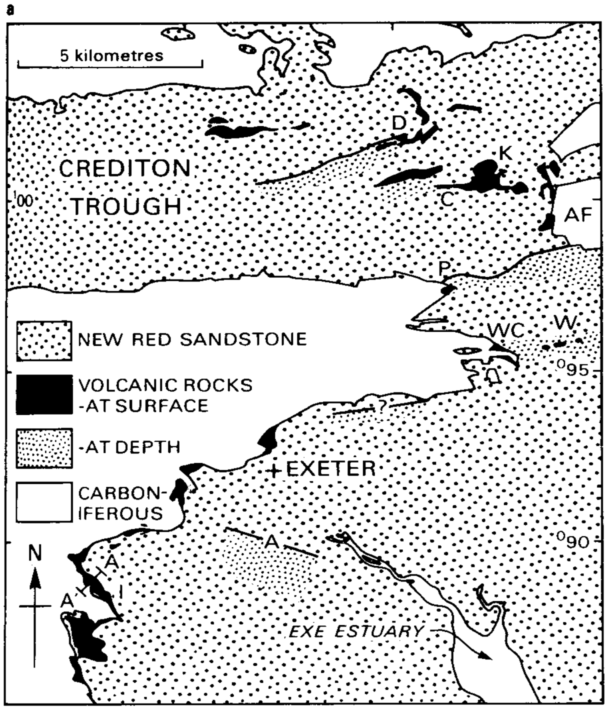
Magnetic properties

The Exeter lavas were included by freer (1957) in an early study of the palaeomagnetic significance of a variety of rock groups of different ages from the British Isles. In his study, the directions of magnetisation of the Lavas were shown to have a mean direction of 190° (declination), 10° upwards (inclination), consistent with their formation in a near-equatorial position. The pole position calculated from these data contributed to one of the first examples of a polar-wandering curve (freer *et al.* 1957), which provided the basis at that time for the renewed interest in the concept of continental drift. It was assumed that the directions of magnetisation for the Exeter lavas - were acquired when the lavas cooled below their Curie temperature, that is, a thermo-remanent magnetisation, but subsequent studies by Cornwell (1967) suggested that the original magnetite of these rocks had been largely destroyed by tropical weathering or alteration due to hydrothermal processes, and had been partly replaced by haematite. A chemical remanent magnetisation was thus acquired, but the process occurred so soon after extrusion of the Lavas that the difference in direction of magnetisation was not significant This was suggested by the stability of the magnetisation during magnetic `cleaning' to temperatures in excess of the Curie temperature of magnetite but below that of haematite.

Other consequences of the introduction of haematite as the main magnetic mineral were the reduction of the magnetic susceptibility of the rocks, compared with that for magnetite-bearing rocks, and the increase in the ratio of the remanent to the induced magnetisations (the `Q-values' of the rocks). The average Q-value of the Exeter lavas is about 10 (Fig. 2), suggesting that the forms of any associated magnetic anomalies will be dominated by the remanence component. Theoretical anomaly profiles calculated for models representing near-horizontal Lavas with a direction of magnetisation similar to the observed *in situ* mean are characterised by positive anomalies over the northern edge and negative anomalies over the southern edge. One exception to this is the lava at Killerton (Fig. 2), which has a Q-value and intensity suggestive of the preservation of magnetite. Isolated occurrences of rhyolite lavas in south Devon at Withnoe and Cawsand were regarded as part of the Exeter Lavas by Tidmarsh (1932), a suggestion subsequently supported by the similarity in directions of magnetisation. These rhyolite Lavas have particularly low intensity values. On average, however, the intensity values are much less than those for typical basic igneous rocks, typified in Fig. 2 by that for the Whin Sill, an intrusion similar in age to the Exeter lavas.

General significance of the aeromagnetic data

The main source of evidence for the extent of the Exeter lavas is provided by the national aeromagnetic survey coverage for the area. Although the survey was one of the first to be carried out in the UK, the 0.4km line spacing and 0.15km (500ft) flying height produced good quality, high resolution data. The original analogue data have recently been made available in a digital form (Smith and Royles 1989) suitable for processing using modern techniques.



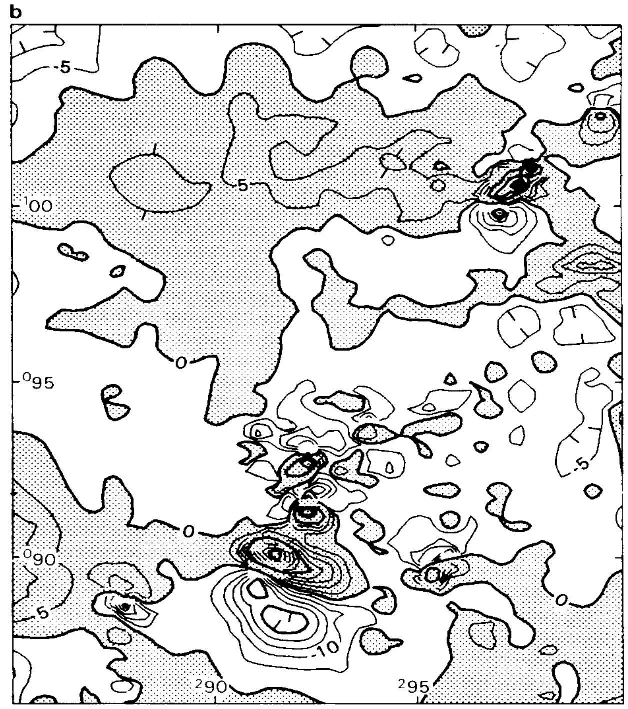


Figure 1.a. Simplified geological map. Key to abbreviations: A - Alphington; G Columbjohn; D - Dunsmoor; K - Killerton: I - Idestone; P - Poltimore; W -Wishford Farm; WC - West Clyst: AF - Ashclyst Forest.

b. Residual aeromagnetic anomaly map of the Exeter area derived by removing a background field defined by a second-order polynomial. Contour interval 5nT. Based on total field aeromagnetic survey data in the BGS data bank.

The aeromagnetic map shown in Fig. 1b was derived from the digital data set by removing a second-order polynomial component representing anomalies due to a deep-seated source. The anomalies remaining therefore are due largely to magnetic bodies located at, or near, the surface, including in some cases those of man-made origin.

A comparison of the aeromagnetic data with the geology of the area (Fig. la) indicates that many of the mapped lavas are associated with low amplitude `reversed' anomalies, as would be predicted from the magnetic property data. The form and distribution of the anomalies provide information on some of the exposed lavas and on possible concealed flows.

Magnetic evidence for exposed lavas

Ground magnetic traverses have been carried out over several of the known lavas to examine their detailed form and to assess the use of the geophysical method. The results are typified by a profile (Fig. 3) over the Idestone lava, one of the basaltic group of Knill (1969), which occurs at the base of the NRS sequence near Dunchideock. This profile is similar to that recorded by the airborne survey, with the dominant negative anomaly indicating that the lava dips gently to the north. The amplitude of the ground anomaly is, as expected, much greater (more than 300 nanotesla (nT) compared with 40nT in the air) and also far more irregular, due to the dominating effect of nearsurface irregularities of the magnetic properties and the bedrock surface. The upper part of the lava appears to be particularly strongly magnetised, with a calculated value greater than the observed magnetisations shown in Fig. 2.

The largest amplitude anomaly in Fig. 1b is associated with the Killerton lavas, and these were examined in some detail on the ground. There is an apparent considerable difference in age between the Killerton minette and the NRS strata that surround it, the minette being possibly 30 million or more years older than the NRS strata. These strata belong to the Brampford Speke Sandstone, a member of the Dawlish Sandstone Formation (Edwards 1987); the position of the Brampford Speke Sandstone in the New Red Sand-stone sequence around and north of Killerton is shown in Table 1.

Table 1. NRS succession in the Killerton area (Edwards 1987), with thicknesses in metres (m).

Bussell's Member	90m)	) Dawlish Sandstone Fm.
Brampford Speke Sandstone	100m)	
Yellowford Formation	200m	
Thorverton Sandstone	100m	
Cadbury Breccia	270m	

The Thorverton Sandstone was correlated by Edwards (1984, figure 3) with the Whipton Formation of the Exeter area, which has yielded late Permian palynomorphs indicating an age of around 260Ma (Warrington and Scrivener 1988). The strata around Killerton lie at a higher stratigraphical level than the Thorverton Sandstone (Table 1). The Killerton minette, dated around 290Ma, is therefore associated with strata less than about 260Ma old. An explanation might be that the Killerton minette rests directly on Carboniferous `basement' at relatively shallow depth, and that the NRS strata have gradually been banked up around the minette. In support of this is the presence of breccia consisting of angular clasts of minette in a red sandstone matrix in poor exposures [9692 0073] on the west side of the minette. There is some evidence from gravity data which indicate that Killerton occurs on a concealed ridge of Culm rocks extending to the WNW from the Ashclyst Forest Culm inlier.

However, other localities provide evidence for the existence of NRS rocks older than the minette. A small quarry [9765 0075] on the east side of Killerton Park, for example, shows in the north face large irregular blocks of grey minette apparently overlying and projecting downwards into rubbly reddish brown sand containing rotted pieces of minette. By the adjacent road (B3185) Ussher (1902, figure 6) figured a section [?9769 0069], no longer visible, showing irregular blocks of minette resting on 'gravelly loam'. There is also a record (Tidmarsh 1932, p. 724) of lava overlying `marls and conglomerates, the disturbance of which shows that the direction of flow was from the west at this point', in the cutting to a new quarry [9749 0049] on the east side of the mass, near the chapel.

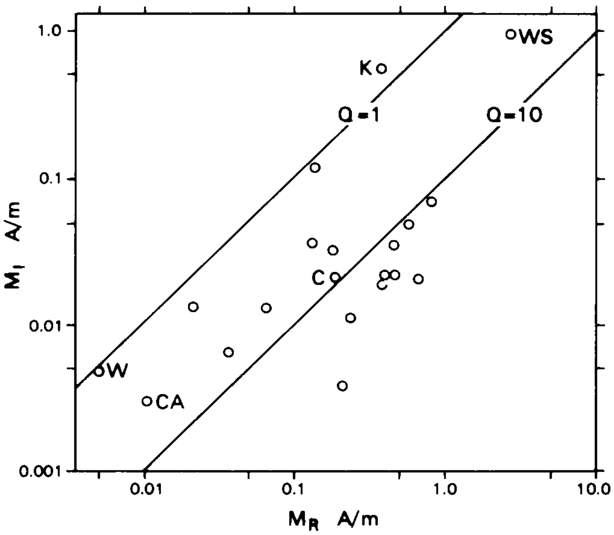


Figure 2. Cross-plot of mean induced (M_I) and remanent magnetisation (M_R) intensities for Exeter lavas sites and for the Whin Sill (WS). C - Columbjohn; K - Killerton; CA - Cawsand; W - Withnoe. Intensity in amps per metre (A/ m).

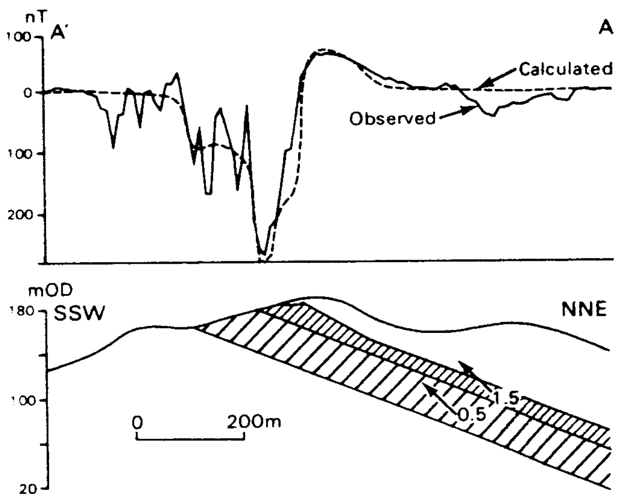


Figure 3. Observed ground magnetic profile (AA') and calculated profile for the lava at Idestone (Sec Fig. 1a for location). Directions of magnetisation indicated, with intensities in A/m.

The stratigraphical relationships of the Columbjohn lava (apparently basalt in hand specimen, but termed 'syenitic lamprophyre' by Knill (1969)) are clearer than those of the minette; the Columbjohn lava is interbedded with NRS (Brampford Speke Sandstone), which, as noted above, is probably younger than 260Ma. It seems possible, therefore, that the Columbjohn lava is considerably younger than the minette. There is no clear field evidence showing the relationship between the Killerton minette and the Columbjohn `basalt'.

Ground magnetic surveying along traverses and at isolated points reveal a complex anomaly pattern for the Killerton lavas (Fig. 4). In broad terms, there is a contrast between the southern, more intensely magnetised component probably represented by the rocks which provided the property values shown in Fig. 2. North of a probable sandstone-filled col, a more weakly magnetised rock type exists which could have a magnetisation more typical of the Exeter lavas. This magnetic susceptibility distinction, however, is not shown by petrological studies, as Knill (1969) referred to both areas as being occupied by minette. To the west of the main outcrop of minette, magnetic anomalies follow the linear outcrop of lava in Columbjohn Wood, and their form is consistent with the southward dips measured in sandstones immediately overlying the lava. The broad anomaly at the eastern end of the Columbjohn lava, adjacent to the minette (Fig. 4), could be due to a deeper magnetic source.

The distinction between the northern and southern components of the Killerton minette is also apparent from the magnetic profile shown in Fig. 5a. This profile has been interpreted to provide cross-sections through the lavas, such as that shown in Fig. 5b. The magnetisation vectors indicated were derived from magnetic data (Cornwell 1967) which suggest that the minette, with its low Q-value, probably has an almost vertically downward direction of total magnetisation. An exact interpretation has not been produced, but various attempts were made to model the well-defined negative anomaly at the southern

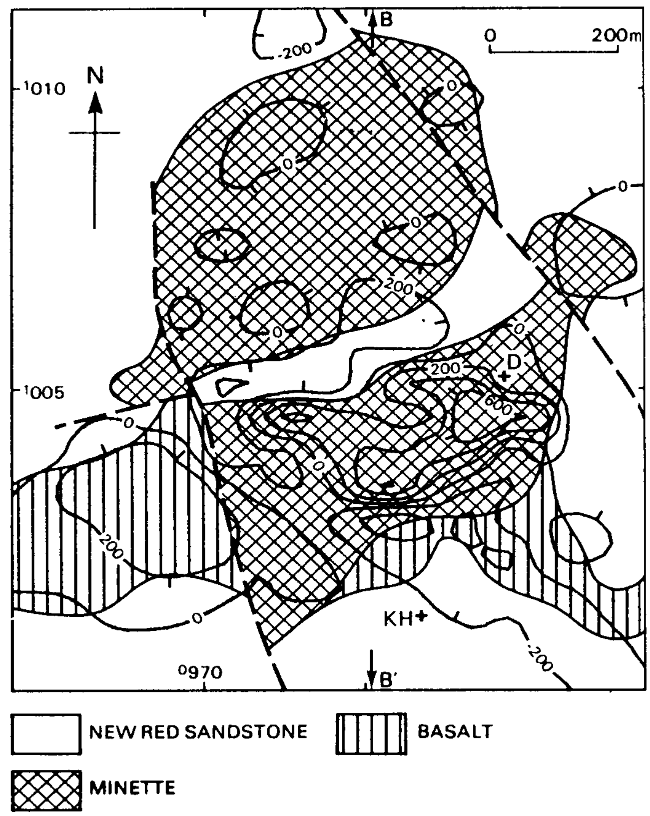


Figure 4. Simplified magnetic map of the Killerton area based on ground measurements and outcrops of lavas. Contours at 200nT intervals. D= Dolbury KH = Killerton House.

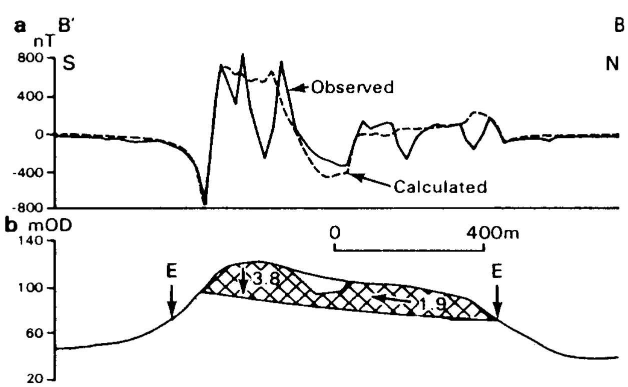


Figure 5.a. Ground magnetic profile (BB') across the Killerton lavas (see Fig. 4 for location of profile).
b. Model for the lavas producing the calculated profile shown in Fig. 5a. The model has limited strike extents and directions of magnetisation indicated, with intensities in A/m. E - mapped margin of lavas.

margin of the main highly magnetic zone. It was found to be difficult to reproduce this feature without making the base of this zone nearly horizontal; that is, suggesting that a sub-vertical intrusive contact was unlikely. The `basalt' of Columbjohn type on the south side of the minette mass is not considered to contribute significantly to the form of the magnetic anomaly.

Magnetic evidence for concealed lavas

Several of the aeromagnetic anomalies in Fig. 1b suggest the existence of concealed extensions of known lava flows or, in some cases, flows which do not come to crop. The positions of these concealed lavas are shown in Fig. la, together with an indication of the uppermost margin of the igneous rocks, based on interpretation of the forms of the anomalies. Some of these interpretations are, however, very tentative due to the low amplitude of the airborne survey anomalies or to the absence of ground magnetic data.

One of the largest anomalies occurs over Alphington, south of Exeter, and its broad form, recorded on seven flight lines, together with its reversed polarity (positive anomaly to the north) provide good evidence that a concealed lava, covering an area of about 3km^2, is responsible. Much of the area occupied by the anomaly has, unfortunately, been built on since the time of the original survey, but two ground magnetic profiles, totalling 2km, validated at least one part of the airborne anomaly. Accurate interpretation of profiles is not feasible owing to the limited strike extent of the anomaly, but interpretation models suggest that the source must lie at depths of several hundred metres. The depths appear to increase towards the south-east away from the margin of the NRS sequence; if it is assumed that the lava lies at the base of the NRS sequence; then the thickness of overlying sedimentary rocks at Alphington is already significantly greater than that predicted on seismic evidence east of the River Exe (Henson 1972). Gravity survey results also support these increased thickness estimates. The amplitude of the Alphington anomaly suggests that the source rocks are likely to contain magnetite, and are therefore perhaps comparable with the Killerton minette lava. The concealed lava could be partly defined by downward extension of faults mapped by Bristow *et al.* (1985) at the surface. The south-eastward elongation of the flow is clear (Fig. 1b), but it is not known whether this is due to the direction of the flow, or to a possible feeder dyke.

Anomalies occurring over the built-up area of Exeter are likely to have non-geological origins. An anomaly 4km to the east of Alphington has a more uncertain origin.

In the north of the area shown in Fig. 1b, low amplitude aeromagnetic anomalies suggest the existence of westward extensions of the Columbjohn and Dunsmoor lavas. To the south-east of these, two zones of anomalies cross the narrow basin of NRS rocks between the main Culm outcrop and the Ashclyst Forest inlier. Evidence from gravity surveys (Davey 1981) suggests that the NRS thickens rapidly to 400m away from the south-east margin of the inlier. The more northerly of these zones indicates a possible extension eastwards of the small lava outcrop at Poltimore, but the anomalies become more pronounced at the margin of the Ashclyst Forest inlier, probably due to the decreased thickness of NRS there. The more southerly zone is less well defined, but appears to indicate a connection between the West Clyst lava and the small isolated occurrence of lava at Wishford Farm.

Conclusions

The magnetic properties of the Exeter lavas are characterised by the widespread occurrence of haematite which was probably formed by rapid weathering of the lavas on the Permian land surface. The directions of magnetisation are consistent with the palaeomagnetic field at that time, and the intensity of magnetisation is usually greater than that of the induced magnetisation. The Exeter lavas are therefore characterised by low amplitude magnetic anomalies with forms determined by the reversed magnetisation. Detailed ground magnetic measurements at Killerton revealed a complex anomaly pattern with rapidly varying magnetic properties for the igneous rocks, but suggest that their lower surface is probably near-horizontal. Aeromagnetic survey results indicate the existence, south of Exeter, of a concealed magnetite-bearing lava flow at a depth of several hundred metres. Other concealed extensions of lavas in the Crediton Trough are suggested, and two zones of largely concealed lavas are indicated between the main Culm outcrop and that forming the Ashclyst Forest inlier.

Acknowledgements. This work was undertaken as part of the British Geological Survey Lyme Bay - Bristol Channel Project. The authors wish to thank G.S. Kimbell, Dr R.C. Scrivener and Dr R.W. Gallois for their comments on the paper, which is published with the approval of the Director, British Geological Survey (NERC).

References

Bristow, C.R. 1983. Geology of Sheet SX 99 NE (Broadclyst, Devon). *Geological Report for DoE: Land use planning.* (Exeter: Institute of Geological Sciences.)

Bristow, C.R., Edwards, R.A. Scrivener, R.C. and Williams, B.J. 1985. Geology of Exeter and its environs. *Geological Report for DoE.* (Exeter: British Geological Survey.)

Cornwell, J.D. 1967. Palaeomagnetism of the Exeter lavas, Devonshire. *Geophysical Journal of the Royal Astronomical Society, 12,* l81-196.

Cornwell, J.D., Edwards, R.A., Royles, C.P. and Self, S.J. In prep. Magnetic evidence for the nature and extent of the Exeter lavas. *British Geological Survey Technical Report.*

Cosgrove, M.E. 1972. The geochemistry of the potassium-rich Permian volcanic rocks of Devon. *Contributions to Mineralogy and Petrology, 36,* 155-170.

Creer, K.M. 1957. Palaeomagnetic investigation in Great Britain. IV. The natural remanent magnetisation of certain stable rocks from Great Britain. *Philosophical Transactions of the Royal Society of London, A, 250, 111* - 129.

Creer, K.M., Irving, E. and Runcorn, S.K. 1957. Palaeomagnetic investigations in Great Britain. VI. Geophysical interpretation of palaeomagnetic directions from Great Britain. *Philosophical Transactions of the Royal Society of London, A, 250,* 144-156.

Davey, LC. 1981. Geophysical studies across the Permian outcrop in central and east Devonshire. *Proceedings of the Ussher Society, 5,* 194-199.

Edwards, R.A. 1984. *Geological notes and details for 1:10 000 sheets.* Parts of Sheets SS 80 SE and SS 90 SW (Thorverton, Devon). (Exeter: British Geological Survey.)

Edwards, R.A. 1987. *Geological notes and details for 1:10 000 sheets.* Sheet SS 90 SE (Silverton and Bradninch, Devon). (Exeter: British Geological Survey.)

Forster, S.C. and Warrington, G. 1985. Geochronology of the Carboniferous, Permian and Triassic. *In:* Snelling, N.J. (ed) The Chronology of the Geological Record. *Geological Society of London, Memoir No. 10,* 99-113.

Henson, M.R. 1972. The form of the Permo-Triassic basin in south-east Devon. *Proceedings of the Ussher Society, 3,* 447-457.

Knill, D. 1969. The Permian igneous rocks of Devon. *Bulletin of the Geological Survey, No. 29,* 115-138.

Miller, J.A. and Mohr, P.A. 1964. Potassium-argon measurements on the granites and some associated rocks from south-west England. *Geological Journal, 4,* 105-126.

Miller, LA., Shibata, K. and Munro, M. 1961. The potassium-argon age of the lava of Killerton Park near Exeter. *Geophysical Journal of the Royal Astronomical Society, 6,* 394-396.

Scrivener, R.C. 1984. *Geological notes and details for 1:10 000 sheets.* Sheet SX 99 SW (Exeter, Devon). (Exeter: British Geological Survey.)

Smith, I.F. and Royles, C.P. 1989. The Digital Aeromagnetic Survey of the United Kingdom. *British Geological Survey Technical Report WK/89/5.*

Thorpe, R.S., Cosgrove, M.E. and Van Calsteren, P.W.C. 1986. Rare earth element, Sr- and Nd- isotope evidence for petrogenesis of Permian basaltic and K-rich volcanic rocks from south-west England. *Mineralogical Magazine, 50,* 481-490.

Tidmarsh, W.G. 1932. Permian lavas of Devon. *Quarterly Journal of the Geological Society, London, 88,* 712-775.

Ussher, W.A.E. 1902. The geology of the country around Exeter. *Memoir of the Geological Survey of Great Britain,* Sheet 325.

Warrington, G. and Scrivener, R.C. 1988. Late Permian fossils from Devon: regional geological implications. *Proceedings of the Ussher Society, 7,* 95.