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# Proposed Mesozoic dykes in the Celtic Sea

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A swarm of dykes 56km long and 2.5km broad cutting the Haig Fras granite batholith and the surrounding country rock is proposed from interpretations of magnetic, bathymetric and seismic surveys. A model of the magnetic anomaly consists of six vertical bodies, three of which have reversed magnetisation and three weaker, normal magnetisation. Each body may consist of many dykes. Only a Mesozoic age is consistent with the structural setting, strike and magnetic properties of the proposed dykes, and they may be part of a phase of intrusion dated elsewhere between 200Ma and 110Ma.

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## Regional geology

A shoal of granite in the Celtic Sea was discovered in 1962 by Smith *et al.* (1965) who named it Haig Fras. A gravity interpretation by Edwards (1984a,b) showed that the shoal was the outcrop of the top of a batholith which is considerably larger than the shoal. The batholith is separate, and parallel to the Cornubian batholith to the south (Bolt and Scott 1966; Cheadle *et al.* 1986). Jones (1988) describes a detailed survey, which included radiometric measurements, on which Fig. 2 is based. Both batholiths were intruded into Devonian and Carboniferous rocks, which were deformed during the Hercynian Orogeny (Dunning 1985), and which now form the Cornubian Platform. The Haig Fras granite has been dated at 277Ma (Smith *et al.* 1965), and is approximately contemporaneous with the Cornubian batholith, which is dated 280 to 290Ma (Darbyshire and Shepherd 1984), and also magmatic activity in the region (Sutherland 1982). The Cornubian Platform is bounded to the NNW by the South Celtic Sea Basin, and to the SSE by the Western Approaches Basin. A shallow basin, the Haig Fras Basin, lies on the Cornubian Platform between the two batholiths.

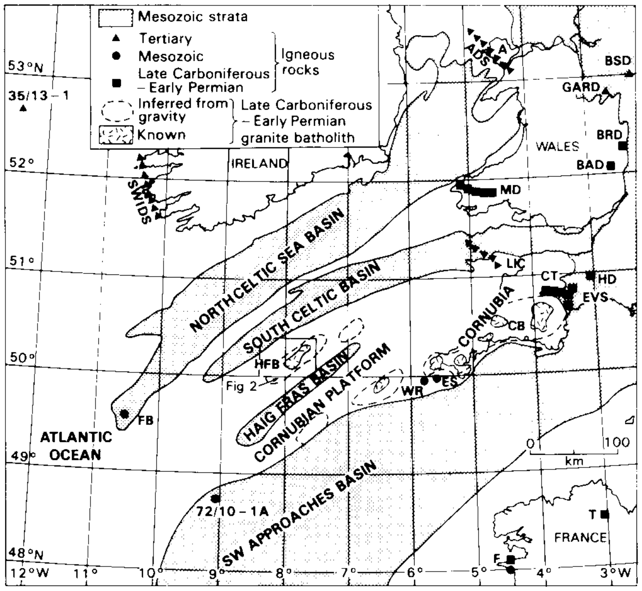


Figure 1. Regional setting of the Haig Fras region. After Dunning (1985). A=Anglesey; ADS=Anglesey Dyke Swarm; BAD=Bartestree Dyke; BRD=Brockhill Dyke; BSD=Butterton-Swynnerton Dyke; CB=Cornubian Batholith; CT=Crediton Trough; ES=Epson Shoal; EVS=Exeter Volcanic Series, F=Finistère; FB=Fastnet Basin; GARD=Grinshill and Acton Reynald Dyke; HD=Hestercombe Dyke; HFB=Haig Fras Batholith; LIC=Lundy Igneous Complex; MD=Mathry Dyke; SWIDS=South West Ireland Dyke System; T=Trègorrois; WR=Wolf Rock.

## Geophysical survey

Geophysical surveys were carried out in the Celtic Sea in 1973, 1978 and 1979 by the Marine Geophysics Unit of the Institute of Geological Sciences, which included depth, gravity and magnetic measurements, and high resolution seismic recordings. The location of all survey lines in the area is shown in the inset to Fig. 2, while the main part of the figure shows the detailed positions of the lines considered here. Line 32 of project 78/04 (Armstrong 1978) showed a strong magnetic anomaly (which was briefly mentioned by Edwards (1984b). The anomaly can be traced on other lines with confidence, though with a reduced amplitude, for 30km, and with less confidence for a further 10 and 15km (Fig. 2), where it branches into a number of smaller anomalies. The depth profiles show that the strongest part of the anomaly is associated with an area of rough sea-bed. A high-resolution seismic record is reproduced in Fig. 4, and shows that the roughness of the sea bed near the anomaly (marked D) is caused by the bed-rock, and not a sand-wave, an example of which can be seen between fixes 20 and 25. During the gravity modelling of the Haig Fras batholith, Edwards (1984b) found it necessary to postulate a small dense body on the NNW side of the batholith, but the resolution of the method did not allow the shape or depth of the body to be determined.

## Magnetic interpretation

Fig. 3 shows the magnetic and depth profiles for four lines over the anomaly. Line 32 was selected for modelling, as the magnetic anomaly is developed strongest on this line. A linear regional magnetic field was subtracted from the total magnetic field to leave the residual field. The regional field was chosen so that the residual field was zero away from the anomaly of interest.

The forward modelling method was used, in which geologically plausible magnetic properties were created and their magnetic field compared with the residual field. The shape and magnetic properties of the bodies were changed until a close fit was obtained between the calculated magnetic field and the residual field. As the anomaly was about 2km wide, and over 30km long, a two-dimensional model was used which assumes that the bodies are infinitely long, and have the same cross-section along their entire length (Walker 1981). The best match consisted of six, vertical outcropping bodies with individual widths of between 0.13 and 0.42km, spread over a distance of 2.47km (Fig. 5). Details are on open file in Briant (1987), which also gives additional models which were considered, but rejected. The intensity of magnetisation is similar to that measured on laboratory samples of magnetised rocks and that found during modelling of other anomalies. Details are given in Table 1. In particular, the intensity of magnetisation is closest to that found in dolerites, rather than phonolites, or lamprophyres. The base of the bodies in the model was 2km, but little difference in the calculated magnetic profile was seen when

Table 1. Late Carboniferous to Tertiary magmatism and magnetism, SW Britain area.

| LOCATION | AGE (Ma) | PERIOD | PETROLOGY | FORM | WIDTH (dykes, plugs), or THICKNESS (m) | TREND | MAGNETISATION | | | | REFERENCES * |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | TYPE | DECLINATION (°) | INCLINATION (°) | INTENSITY (Am⁻¹) | |
| 35/13-1 Borehole | 26 | U Oligocene | Dolerite | Sills | 30 & 145 | AW NW-SE dyke swarm | — | — | — | — | Seeman (1984) |
| SW Ireland | 25-42 | Oligocene | Olivine-dolerite | Dyke | 0.5-5.0 | NNW-SSE | NRM<br>I | 164 (C)<br>349 | -63 (C)<br>68 | 3.38<br>0.84 | Morris (1974); Horne & Macintyre (1975) |
| Grinshill & Acton Rey-nald/Clive | — | Tertiary | Dolerite | Dyke | 0.5-2.5 | NW-SE | NRM<br>Total (I) | 200<br>350 | -39<br>68 | ~ 1.68 | Pocock & Wray (1925); Dagley (1969); Cornwell et al. (1971) |
| Anglesey | — | | Olivine-dolerite | Dykes | ~ 100 | NNW-SSE | NRM<br>Total | 175<br>~ 170 | -65<br>~ -75 | ~ 0.1 | Dagley (1969)<br>Kirton & Donato (1985) |
| Butterton-Swynnerton | 52 | L Tertiary | Olivine-dolerite | Dyke | 1-2 | | NRM<br>NRM<br>Total (-I) | 127<br>~ 170<br>350 | -43<br>~ -60<br>+60 | small<br>8-20 | Dagley (1969)<br>Sowerbutts (1987) |
| Lundy | 50-55 | | G & BIC<br>Olivine-dolerite | Plug<br>Dykes | ~ 30,000<br>1-2 | AW NW-SE FZs<br>NW-SE | NRM & I | 175 (NRM,G)<br>~184 (NRM) | -9 (NRM,G)<br>~ -63 (NRM) | small (G)<br>~ 2(I) | Dollar (1941); Blundell (1957); Dodson & Long (1962); Miller & Fitch (1962); Mussett et al. (1976); Burley (1979); Edmonds et al. (1979); Arthur (1989) |
| 72/10-1A Borehole | 110 | L Cretaceous | Basalt lavas & tuffs | Stratified | 36 | NA (near NE-SW basin margin) | — | — | — | — | Bennet et al. (1985) |
| Wolf Rock | 131 | | Phonolite | Plug | ~ 2000 | | NRM<br>NRM (C) | 7<br>11 | 27<br>79 | 0.02<br>0.07 | Mitchell et al. (1975); Harrison et al. (1977) |
| Epson Shoal | 131 | | Phonolite | Plug | ~ 2000 | | — | — | — | — | |
| Fastnet Basin | 170 | M Jurassic-L Tertiary | Olivine-dolerite | Sills<br>Plugs | 0.5-180<br>900-1300 | AW NW-SE FZs | — | — | — | — | Caston et al. (1981); Robinson et al. (1981) |
| Finistère | 200 | U Triassic-L Jurassic | Dolerite | Dykes | 0.3-30 | | — | — | — | — | Leutwein et al. (1972) |
| Trégorrois | 265 | U Carbon-iferous - L Permian | Dolerite | Dykes | 0.3-30 | unstated | — | — | — | — | |
| Finistère & Trégorrois | 254-285 | | Lamprophyre | Dykes | 0.3-30 | | — | — | — | — | |
| Hestercombe | 264 | | Lamprophyre | Dykes | 10-20 | WNW-ESE | — | — | — | — | Edmonds & Williams (1985) |
| Exeter Volcanic Series | ~ 280 | | Basalt & Lamprophyre | Lavas & agglom-erates | 1-20 | NA (part AW E-W FZs) | I<br>NRM | 352<br>188-198 | 68<br>-9-(-25) | 0.003-0.03<br>~ 0.03-0.65 | Creer (1957); Miller et al. (1962); Miller & Mohr (1964); Cornwell (1967a); Zijderveld (1967); Edmonds et al. (1968); Hawkes (1982); Laming (1982); Cornwell et al. (1990) |
| Bartestree | ~ 295 | L - U Carbon-iferous | Olivine-dolerite | Dyke | 11 | ENE-WSW | Total | 1 or 301 | +5-(+10) | 0.65-2.00 | Reynolds (1908); Arthur (1982). |
| Mathry | ⪢ (238-297) | | Quartz-dolerite | Dyke | 2-15 | WNW-ESE | Total (I) | 353 | 68 | ~ 3.0 | Cave et al. (1989) |
| Brockhill | 295(306) | | Dolerite | Dyke | ~ 9 | ~ E-W | I | ~ 350 | 68 | ~ 1.49 | Hallimond (1939); Taylor (1940) |

* See also: Fitch & Miller (1964); Fitch et al. (1970); Harrison et al. (1979); Harrison (1982); Edmonds et al. (1985).

Total magnetisation = vector sum of NRM and I.

AW = Associated with; BIC = Basic igneous complex; C = Cleaned; FZs = Fault zones; G = Granite; I = Induced; L = Lower; M = Middle; NA = Not applicable; NRM = Natural Remanent Magnetisation; U = Upper

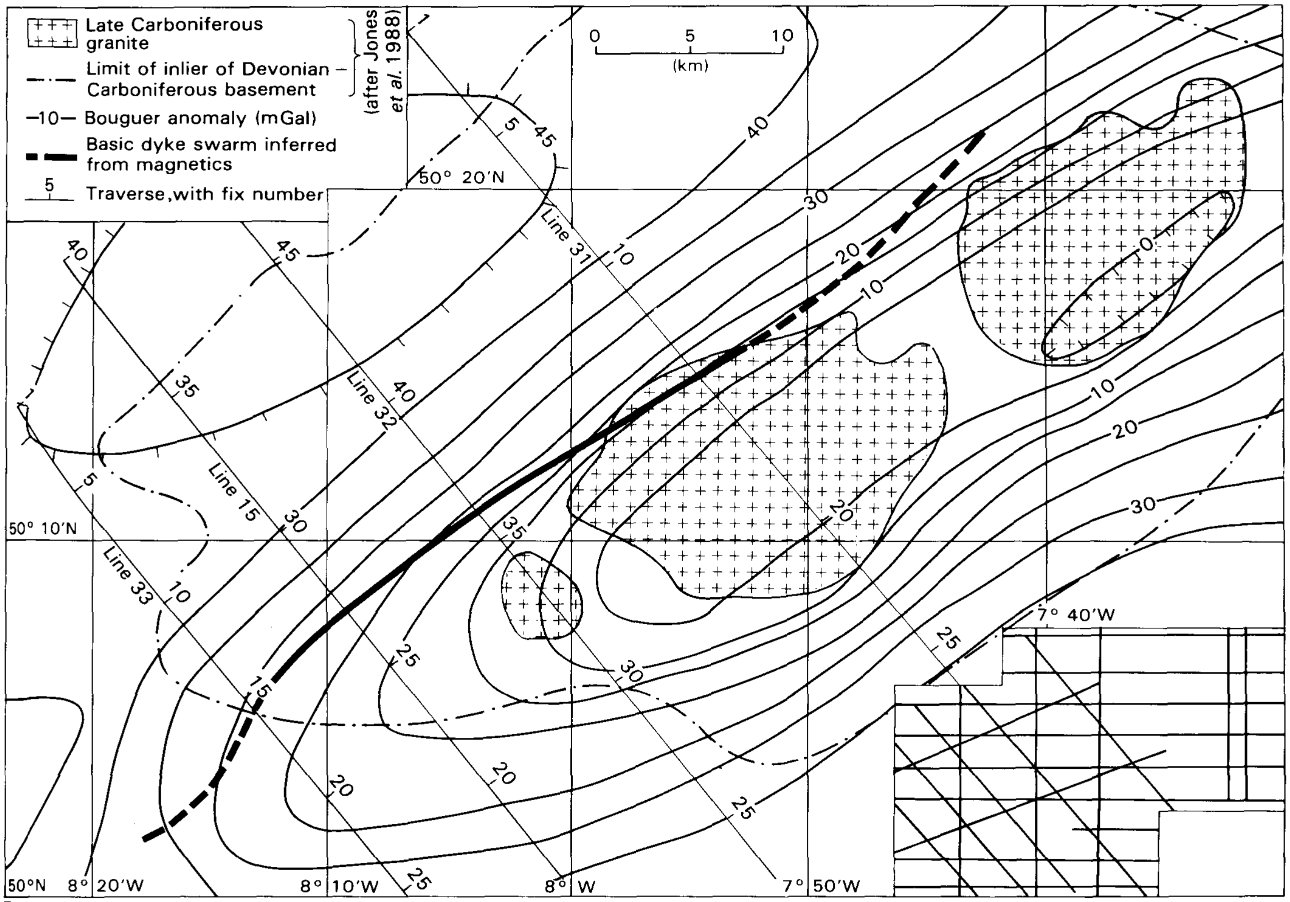


Figure 2. Bouguer anomaly map, geophysical traverses reproduced in Fig. 3 and inferred path of basic dyke set, Haig Fras Granite area. The inset in the bottom right-hand corner shows all geophysical traverses in the area.

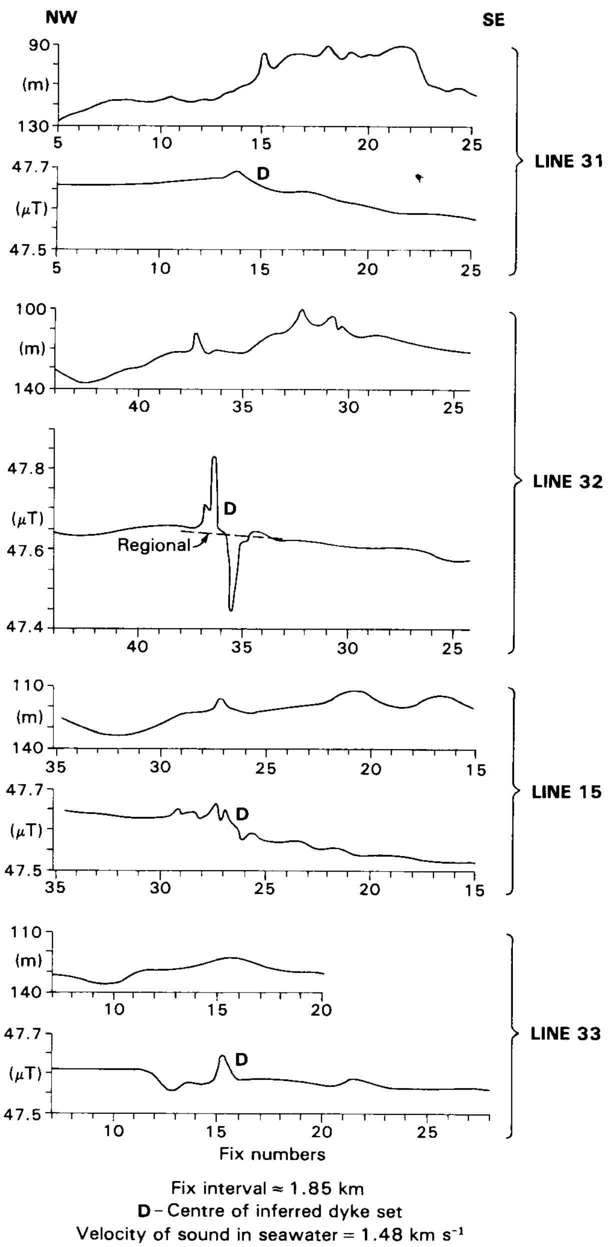


Figure 3. Total magnetic field and seabed depth profiles, Haig Fras Granite area.

the depth was made 20km, so no firm depth for the base of the bodies can be derived.

The length of anomalies is similar to dykes described elsewhere in the British Isles, but the widths of the bodies in the model are much greater than the widths of dykes, which seldom exceed a few tens of metres (Table 1). Dykes often consist of several near parallel or *en echelon* leaves: for example, leaves of the Grinshill and Acton Reynald dykes occur over a distance of about 50m (Pocock and Wray 1925), and the Anglesey Dyke Swarm is about 40km broad (Kirton and Donato 1985). Thus each body in the model may consist of a number of near parallel and intersecting intrusive dykes.

There is a broad correlation between the rough sea-bed and the magnetic bodies in the model, but a close correlation could not be achieved, and would not be expected. Dykes may erode more readily than the country rock, as happens with the Tertiary dolerite dykes in SW Ireland (Morris 1974). In addition, the metamorphosed country rock at the margin of the dykes may be more magnetic than the centre of the dyke, as is found with the Brockhill Dyke (Hallimond 1939). The bodies could be regions of sulphide mineralisation, though this is unlikely. Pyrrhotite mineralisation is thought responsible for magnetic anomalies north of the Dartmoor and Bodmin Moor cupolas of the Cornubian batholith, but the intensity of magnetisation is about a tenth of that found for the bodies here (Cornwell 1967b; Tombs 1985), and mineralisation would not account for the roughness of the sea-bed.

It is concluded from the modelling that the anomalies are caused by vertical bodies, and from geological considerations that the bodies are regions of basic dykes.

## Age of the dykes

The proposed dykes intrude Devonian and Carboniferous rocks for most of their length, and the Haig Fras granite near its margin for 7km. The samples of the Haig Fras granite which have been collected include a number trawled between the dykes proposed here and the northern margin of the granite (location Di4852, Smith *et al.* 1965). This trawl included samples of migmatite in addition to granite, to which Sabine (in Smith *et al.* 1965) gave the descriptive terms permeation gneiss and injection gneiss. The relationship between the migmatites and the granite is unclear, and the former may be a pre-Devonian basement (Exley 1966). As the proposed dykes are younger than late Carboniferous they must belong to one of three distinct phases of magmatism and intrusion which have been recognised in Britain and Ireland: late Carboniferous and early Permian, Mesozoic, and Tertiary. Dykes which have been described in the region of the Celtic Sea are summarised in Table 1.

Late Carboniferous and early Permian activity is influenced by Hercynian structures and caused by a phase of N-S regional tension late in the Hercynian orogeny (Edmonds *et al.* 1985). The best studied example is the lavas of the Exeter Volcanic Series in the Crediton Trough, which developed by the tensional reactivation of a Hercynian thrust (Durrance 1985). Like contemporaneous rocks in France, they are lamprophyres. They have low magnetisation, possibly due to weathering, as shown by measurements of hand specimens, and the absence of an aeromagnetic anomaly over them (Geological Survey 1965). The natural remanent magnetisation of intrusive and extrusive rocks of this age in SW Britain is reversed with a low inclination of between 15° and -15°, which is consistent with the region being in the tropics at the time (Everitt 1960; Everitt and Belshé 1960; Briden and Mullan 1984).

The period of igneous activity referred to as Mesozoic in this discussion occurred during the late Triassic, Jurassic and early Cretaceous (aged 200 to 110Ma) and is associated with the rifted margin of Mesozoic basins (Harrison 1982), which are in turn controlled by Hercynian structures (Gardiner and Sheridan 1981, Fig. 9). The dykes proposed here are parallel to the axis of the South

Table 2. Induced magnetic inclinations for SW Britain calculated from Permian to Recent latitudes. Ages and latitude after Smith et al. (1981).

| AGE | SERIES/STAGE | SYSTEM | | LATITUDE | INCLINATION* |
|---|---|---|---|---|---|
| (Ma) | | | | (°) | (°) |
| 0 | Recent | latest | Quarternary | 50N | 67 |
| 10 | Miocene (late) | late | | 46N | 64 |
| 20 | Miocene (early) | mid | } Tertiary | 43N | 62 |
| 40 | Eocene (late) | mid | | 43N | 62 |
| 60 | Palaeocene | early | | 41N | 60 |
| 80 | Santonian | late | | 39N | 58 |
| 100 | Cenomanian (earliest) | mid | } Cretaceous | 39N | 58 |
| 120 | Hauterivian | early | | 38N | 57 |
| 140 | 'Tithonian' | late | | 36N | 55 |
| 160 | Callovian | mid | } Jurassic | 36N | 55 |
| 180 | Pliensbachian | early | | 36N | 55 |
| 200 | - Rhaetian | latest | } Triassic | 33N | 52 |
| 220 | - Anisian | mid | | 24N | 42 |
| 240 | - Tatarian | late | } Permian | 10N | 19 |
| 280 | - Sakmarian | very early | | 1N | 2 |
| 320 | - Namurian | mid | Carboniferous | 6S | -12 |

* For normal Earths field, signs reversed for reversed field.
Inclination - tan 1(2 tan latitude).

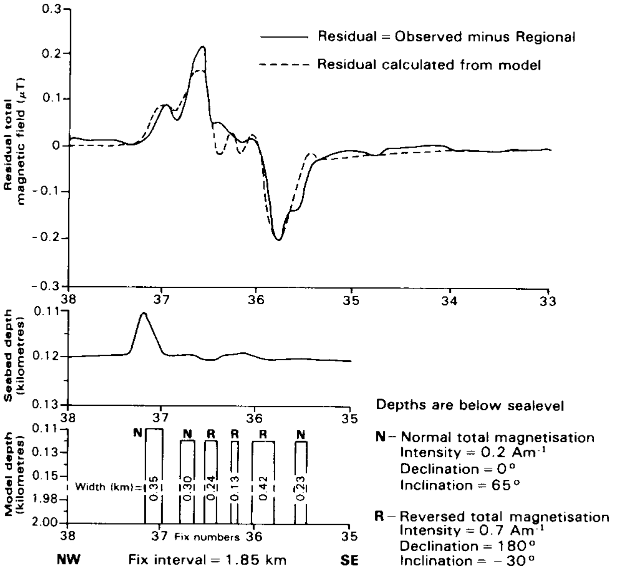


Figure 5. Residual total magnetic field, seabed depth profile and dyke models, Line 32, Haig Fras Granite area.

Celtic Sea Basin and could therefore be of this age. The magnetic properties of Mesozoic igneous rocks are less well known than the properties of rocks of the other two phases considered here. The basic rocks of the Fastnet Basin (Caston et al.1981) produced weak anomalies at sea-level, but no discernible anomalies at the height of an aeromagnetic survey, which was probably 100m. No aeromagnetic anomaly can be seen over Wolf Rock and Epson Shoal (Geological Survey 1965), which are Mesozoic in age (Harrison *et al.* 1977).

Dykes of Tertiary age in the British Isles (Emeleus 1982; Kirton and Donato 1985) often produce a strong magnetic anomaly (Musset et al. 1976). The Lundy Tertiary dykes (Cornwell 1971; Hains *et al.* 1983) are in a similar structural position to Haig Fras and have a NW-SE strike, as do most Tertiary dykes in the British Isles (Emeleus 1982). As the strike of the known Tertiary dykes is perpendicular to that of the proposed Haig Fras dykes it is unlikely that the two sets are of the same age.

In the next paragraph it is argued that the directions of magnetisation of the bodies in the model could have been acquired only in a certain band of latitudes. The region was within this band during the Mesozoic and Tertiary phases of intrusion, and outside it during the Permian phase. The rest of this paragraph summarises nomenclature for readers unfamiliar with geomagnetism. The total

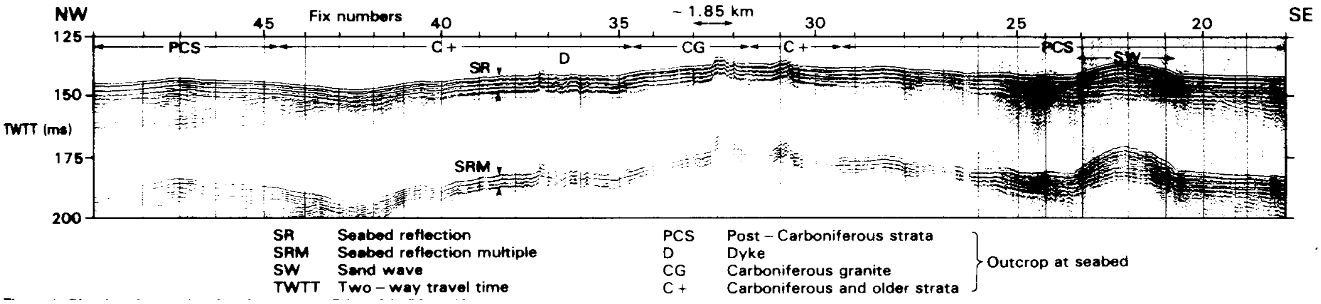
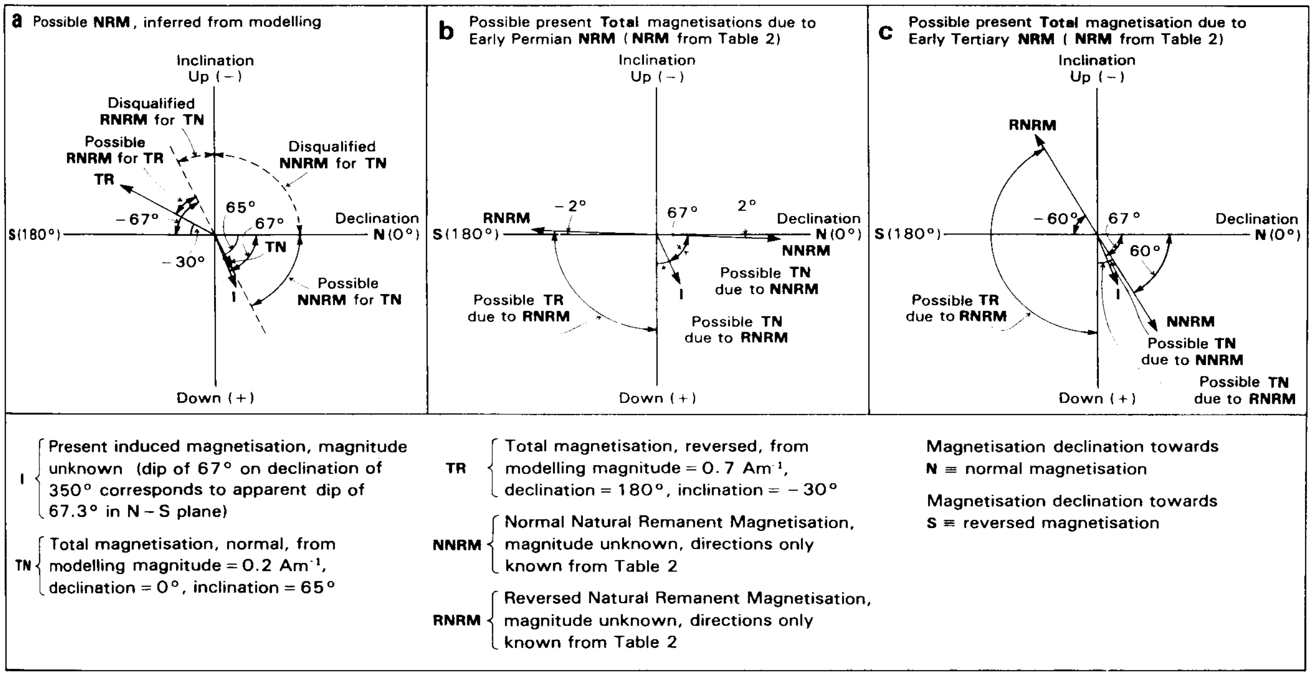


Figure 4. Single-channel seismic record, Line 32, Haig Fras Granite area.



I Present induced magnetisation, magnitude unknown (dip of 67° on declination of 350° corresponds to apparent dip of 67.3° in N – S plane)

TN Total magnetisation, normal, from modelling magnitude = 0.2 Am⁻¹, declination = 0°, inclination = 65°

TR Total magnetisation, reversed, from modelling magnitude = 0.7 Am⁻¹, declination = 180°, inclination = −30°

NNRM Normal Natural Remanent Magnetisation, magnitude unknown, directions only known from Table 2

RNRM Reversed Natural Remanent Magnetisation, magnitude unknown, directions only known from Table 2

Magnetisation declination towards N ≡ normal magnetisation

Magnetisation declination towards S ≡ reversed magnetisation

Figure 6. Known and possible induced, total and remanent magnetisations, Haig Fras dykes.

magnetisation of a rock is the vector sum of the magnetisation induced by the Earth's present field, and the natural remanent magnetisation (NRM) formed when the rock cooled through the Curie temperature. The ratio of the sizes of the magnetisations can vary considerably, and can change with very small changes in mineralogy. Magnetisation vectors are defined by their magnitude, declination (the angle in a horizontal plane between true north and the vector), and inclination (the angle between the vector and the horizontal plane, with downwards taken as positive). During normal polarity of the Earth's magnetic field, its inclination is positive in the northern hemisphere, and negative in the southern hemisphere, and declination is close to zero in both hemispheres. During reversed polarity, inclination is negative in the northern hemisphere, positive in the southern, and declination is close to 180° in both hemispheres. For a rock to have reversed total magnetisation, it must have reversed NRM greater than the induced magnetisation. A rock with normal total magnetisation can have either normal NRM, or reversed NRM with a magnitude smaller than the magnitude of the induced magnetisation. From vector addition, if follows that the total magnetisation must lie in the acute angle between the induced magnetisation and the NRM.

Fig. 6 shows vectors drawn in a vertical plane along true north. In Fig. 6a, TN and TR are the total magnetisation vectors of the bodies of normal and reversed magnetisation respectively, and I is the direction of the Earth's present field, and hence the induced magnetisation. Consider first the case of bodies with reversed total magnetisation. The NRM must be reversed with inclination between I and TR, that is, between -67°, and -30° (Fig. 6a). The latitude of the region since the Carboniferous is well established from palaeomagnetic studies, and is summarised in Table 2. Fig. 6b shows the directions of the NRM vectors expected at the latitude of the region during the early Permian, and the possible angles of the total magnetisation vectors. It shows that the total magnetisation of the reversed bodies could not have been acquired during the early Permian. Fig. 6c shows the vectors for the Early Tertiary, and shows the total magnetisation of the reversed bodies is consistent with them cooling at this time. The angles of the vectors for the Mesozoic phase of intrusion are similar to those for the Early Tertiary, and the bodies could be of this age also.

The bodies in the model with normal magnetisation have much weaker total magnetisation than the bodies with reversed magnetisation, and within the accuracy of the modelling the inclination could be slightly greater or slightly smaller than the present inclination of the Earth's magnetic field. Figs. 6b and 6c show that no limitations can be put on the age of the bodies with normal magnetisation from their magnetic properties.

## Conclusion

In conclusion, only a Mesozoic age to the proposed dykes is consistent with their strike, structural setting, and magnetic properties.

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