BRITISH ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE AT KEELE 1993
SECTION C (GEOLOGY) EXCURSION W1 WEDNESDAY 1ST SEPTEMBER AT 17.30 HRS.

Murchison's and Darwin's dykes in North Staffordshire

Excursion leader: David B Thompson (Senior Lecturer Science Education, Keele University; Hon. Local Secretary Section C).

The purpose of this field excursion is to savour the delights of the area where Charles Darwin visited his cousins the Wedgwoods and where, as a budding geologist of the first rank, he is alleged to have been the first to discover the dolerite dykes of the area. The fact that he had been prompted to do this as a result of Roderick Impey Murchison being keen for him and others to apply a then-new but woefully inadequate predictive theory, illustrates aspects of the history of science which are often neglected. The results of recent geochemical work and fission-track dating on the Late Cretaceous/Palaeocene dykes of North Shropshire and North Staffordshire will be introduced and discussed against the overall picture of the evolution of the British Tertiary Igneous Province.

Our general route is marked on the accompanying map (Fig.1) upon which the localities which will be visited are set down.

1. **Meet at Keele University, Horwood car park F** at 17.15 hrs. Note that the most northerly two localities where the dykes are known to exist are at depth in NCB Springpool borehole No.10 by the western side of the tip of the top lake extending southwards from Keele Hall (**Locality 1**) and in the grounds of the former sewage works in the woods immediately south of the fifth and lowest lake (Cope 1966) (**Loc.2**). The Sneyds of Keele Hall were friends of the Wedgwoods at Maer Hall and Charles Darwin is likely to have visited Keele at some time.

2. Travel westwards to Keele Village, turning south down the length of Three Mile Lane to Whitmore. Turning right, follow the A53 through Baldwin's Gate, cross the **Grand Junction Railway** and **"Whitmore" Station** of 1837 (**Loc.3**) from which Charles Darwin and his wife Emma took the train to London in order to honeymoon in late January 1839. Continue through Baldwin's Gate before turning left down Sandy Lane to meet the A51 (the former Chester-Nantwich-Stone-London coach road). Turn right before taking the road left to **Maer Village, Maer Church and Maer Hall (Loc.4)**, the home of Josiah Wedgwood II, a distinguished but reluctant potter of few words (see photo A).

   It was here between 1817 and 1842 that Charles Darwin (see photo A) and his sisters frequently visited, particularly after the death of their mother in 1817, in order to socialise and hunt, shoot and fish. The background to Charles Darwin's interest and accomplishments in geology, and igneous geology particularly, will be discussed in relation to: old Mr Cotton of Shrewsbury; his two years at Edinburgh University as a medical student (John Walker, Robert Jamieson, James Hutton, Thomas Hope, Joseph Black, James Hall); his three years at Cambridge as a

theology student (Rev. John Henslow, Rev. Adam Sedgwick); his tour of North Wales in 1831 on horseback with the last mentioned; the third choice offer of a trip on HMS surveying ship Beagle (1831-6) as the second naturalist and gentleman companion to Capt. Robert Fitzroy. Dr Robert Wareing Darwin FRS at first refused permission to take the appointment but had his mind changed by letters from Uncle Josiah Wedgwood II whom Charles was visiting in order to plead his case (the exchange of letters is in the University Library: Wedgwood archives). It was at Maer Hall and at Shrewsbury that the first pencil sketch of Darwin's Species theory was written (35pp.) in 1842.

The story will be told of how in 1834 at Acton Reynald Hall, North Shropshire, Roderick Impey Murchison was introduced to a dark rock (greenstone porphyry - now tholeiitic dolerite) cutting pebbly red sandstones (now the Chester Pebble Beds Formation, Lowest Triassic in age). Having recently worked in the Breidden Hills where igneous rocks, lavas and dykes were common, Murchison was keen to link the origins of these rocks with the new dykes at Acton Reynald and the topography of the perceived double line of hill masses extending to the ENE: Moel-y-Golfa - Rodney's Pillar; Clive Hill - Grinshill, Hawkstone-Bury Walls; the hills around Ashley and Loggerheads ...(Fig.2). To do this he was keen to be the first to use the newest theory - "The Theory of Elevation" of the frenchman Elie de Beaumont (1829-1830) - in the British Isles. In so doing, and using a theory which did not have great credence even in its own time, he predicted the presence of dykes in the hilly areas of North Staffordshire (Fig.2).

Thus he came to write to Robert Garner, physician of the North Staffs Infirmary at Etruria and personal doctor to Josiah Wedgwood II of the Etruria pottery, in order to ask him to look out for dykes. Garner did not find any dykes but Charles Darwin did. Kirkby (1894) writing c.50 years after the event notes that "the dyke was discovered some time afterwards by Darwin, who was on a visit to Josiah Wedgwood at Maer and told him of it. Mr Wedgwood told Mr Garner and the latter has it marked in (sic) the map illustrating his History of Staffordshire" (Garner 1844). The date of this discovery could be anywhere between 1836 and 1844 but circumstantial evidence will be used to tie down the date to 1842. The exact location of Darwin's discovery is not known but two places have been suggested, both of which will be visited later. The dyke(s) in Hanchurch Woods were discovered independently by James Kirkby, a true amateur, in the early 1840s (Kirkby 1894).

The point made here is that an important new discovery in science was made by a person not engaged in this particular scientific research programme. It was made by a gifted individual who had probably been briefed by Murchison himself, for Darwin was at that time in the swim of things whilst acting as secretary to the Geological Society between 1838 and 1841. He had been briefed on the basis of an inadequate theory which had been badly applied to the geological evidence of the area. Being the first person in the British Isles to use the theory appeared to be the driving force for Murchison, for he was ever aware of the need to polish his emergent reputation, even after the publication of The Silurian System (1839). Notice that the amateur's discovery is largely unknown.

3. **Drive along the likely route of one of Charles Darwin's long walks from Maer to the Hanchurch Hills**, i.e. *via* Hill Chorlton, Chapel Chorlton (**Loc.5**) (the former the building stone quarry for Maer Church - in the Bromsgrove Sandstone Formation - formerly the Lower Keuper Sandstone - on the east of the lane), *via* Stableford and Pennyleasow to where, in the Hanchurch Hills, a dark rock would have been seen in the early 1840s crossing the bright red pebbly sandstone exposed on the surface and flanks of the road from Hanchurch to Stableford (**Loc.6**). This rock is now the Kidderminster Conglomerate Formation (once the Bunter Pebble Beds) of Lower Triassic, ?Scythian age, c.245 million years ago (see Fig.4).

   Conduct a "search and find" operation for two outcrops of the dyke rock hereabouts, one adjacent to the road, a second in an old quarry south of the road, where Molyneux (1861) once claimed to have seen copper mineralisation (malachite).

4. Drive northwards taking the A519 briefly before turning left and northwestwards through Hanchurch village in order to take the twisting lane past Butterton Hall to **Butterton Lodge Gates (Loc.7)**. It is near here that Walcot Gibson, the Geological Survey Officer who came from mapping South Wales in 1897 to start work mapping the geology of the North Staffs Coalfield, made field notes and sketches of a dyke crossing the lane. He stated, without documentary or circumstantial evidence, that Charles Darwin had been the first person to discover a dyke at this location (Gibson 1902, 1905) - the second "Darwinian" locality.

   More recently the area has been mapped geologically by Cope (1947, 1966 and in Exley 1970) who depicted one dyke and Exley (1970) who contemplated two dykes. The area has been the object of a vertical field magnetic gradiometer survey by Sowerbutts (1988) whose data give good reason to recognise the presence of two dykes across the corner of the two lanes. This interpretation has been adopted in the new 1:50000 Stoke geological sheet. Members of the party are invited to search for loose fragments of dolerite in the lanesides hereabouts.

   The trend of the dykes, 350° and parallel with the Apedale Fault 1.25 kms away to the east, is suggestive of an upper crustal Malvernoid structural influence which controls both the dykes and the fault. The trend is toward the dykes of the Bowland Fells (where six dyke localities are known) (Fortey 1992) but there they are aligned more north westerly (320°). A general prolongation towards Arran and Mull is obvious. There is no hint of a connection with the dykes of North Shropshire, Anglesey and the Mourne Mountains-Antrim area of Northern Ireland.

5. Drive southwards before turning left (eastwards) and parking in front of Butterton Church (built probably of Lower Triassic Sandstones of the Bromsgrove Sandstone Formation, Scythian in age, possibly from Chapel Chorlton Quarry rather than the Hollington Quarries near Cheadle, Staffs.). Walk down Butterton Church Wood southwards for 400 m to the former roadstone quarry: **Butterton Church Wood Quarry (Loc.8)**. We visit by kind permission of Mr C J Matthews

of Lymes Farm (Butterton)

The dykes were first noticed by Edward Binney FRS of Manchester and W Warington Smythe in 1851 (see Ward 1894), but they were not recognised or plotted on the first geological survey maps or sections of Hull (1857) and Hull and Green (1859). The quarry was most carefully described by Molyneux (1861) without igneous rock being mentioned! By 1890 the outcrop was well known enough for the GA of London to visit it (Hind 1890) (Fig.7). Dyke rocks were described by Ward (1894) and Kirkby (1894) and specimens from here were sent by Sir Archibald Geikie (1897) for measurement in the early days of geomagnetic studies by Rūcker and White (1898). Two dyke rocks were described and diagramatised by Wilcot Gibsom (1898 published 1905) (Fig.8) whose drawings (but not his text) suggest that multiple intrusions may be present. The outcrop was visited by the Geologists Association again in 1903. The petrography of alkali olivine dolerites/basalts was described by Flett (1905) who soon (1910) recognised the best nepheline bearing rocks in the British Isles. Later Alexander Scott (1920, 1925, 1926) deputy principal of Stoke-on-Trent Technical College (but formerly a lecturer in petrology at both Oxford and Glasgow Universities) took petrographic description of the rocks of this general area to new heights and produced a petrogenetic history of the area (Fig.9). In postwar years the dykes have been described by Cope (1966), Exley (1970) and Thompson (1975). Recently the presence of two dykes has been investigated by a vertical field magnetic gradiometer in the area immediately south of the quarry (Sowerbutts 1987) and the presence of minor offsets (?faulting) has been noted (Fig.10). The development of three dykes *en echelon*, with rising and falling tongue-shaped upper surfaces, is equally a possibility.

K-Ar age dating has been achieved by Miller (in Cope 1966) and Evans (1969) on the western freshest dyke, the date of c.52 my suggesting an Eocene Ypresian age. Subsequent zircon fission track dates suggest an age of 59-62 my (Palaeocene Danian) (Lewis et al. 1992) whilst apatite fission track dates suggest a cooling of the sandstones adjacent to the dykes below 90-110° at 54 my (ibid.). The oldest dates suggest correlation with the first phases of intrusion-extrusion associated with the opening of the North Atlantic (Dewey and Windley 1988) (Figs.11 and 12); the youngest dates with the late phase of intrusion-extrusion and /or the mineralisation of the dykes and adjacent sandstones.

Reverse magnetisation was reported by Dagley (1969) – a not uncommon feature of Tertiary times.

Recent geochemical trace element studies (Thompson and Winchester in preparation) show that these alkali olivine dolerites/basalts of Butterton-Hanchurch are of a quite distinct kind compared with their counterparts at Yarnfield-Norton Bridge (Fig.13). Both these suites are totally different from the two tholeiitic dolerite suites of North Shropshire, which in turn best relate to the dykes of Anglesey and Northern Ireland. Geochemically the Staffordshire dyke suites are quite close, however, to the rocks at Grindleton and Caton in the Bowland Fells.

6. Drive northwards through Butterton Village towards the A53. View the positions of the former exposure of the dykes **alongside Lymes Farm** (Butterton) (Cope 1966) (**Loc.9**) which were difficult to map geologically (Cope 1947, 1966; Exley 1970) but which have been subjected to geophysical study (Sowerbutts 1988) (Fig.6). View the position of the outcrop of a dyke in 1962 alongside the **northwestern end of the motorway bridge** (Cope 1966) (**Loc.10**). Continue across the A53 along the lane past Lymes Farm (Keele) and try to locate the position of the **Lymes Farm (Keele) (= Seabridge) borehole (Loc.11)**. The rocks in this hole (Anon 1920) showed up to 10 dykes (Fig. 6) and were subject to considerable petrographic study (Scott 1920, 1925, 1926) which revealed rather basic affinities for these alkali olivine-nepheline basalts which were assigned to the crinanite family and were compared with rocks in the Tertiary Igneous province of Scotland (amongst others).

   Consider geologists' attempts to map the rocks of this small area and the implications of the faulting which they employ (Cope 1966, 1970; Exley 1970), British Geological Survey (Wilson and Rees 1993) here and elsewhere. Is there a case for post Eocene sinistral wrench faulting? All the evidence of slickensides and the dips and the downthrows of the faults suggest normal extrusional faulting has prevailed. All this must be seen against the stressfields associated with the dykes and relationships of these to the opening of the North Atlantic (England 1988) (Fig.14) and the push of the African plate against the Eurasian Plate to give the Alpine orogeny (Dewey and Windley 1988).

7. Return to Keele University via the A53, the ring road through the Westlands and the A525, passing the **old quarry** on the left (south) **in Rosemary Wood (Loc.12)** where Cope (in Millot, Cope and Berry 1946) and in personal conversations to the author (1992) reported that a Spirorbis limestone bed in the Newcastle Sandstone Formation was "marmorised" i.e. metamorphosed, presumably by the still undected presence of igneous rocks.

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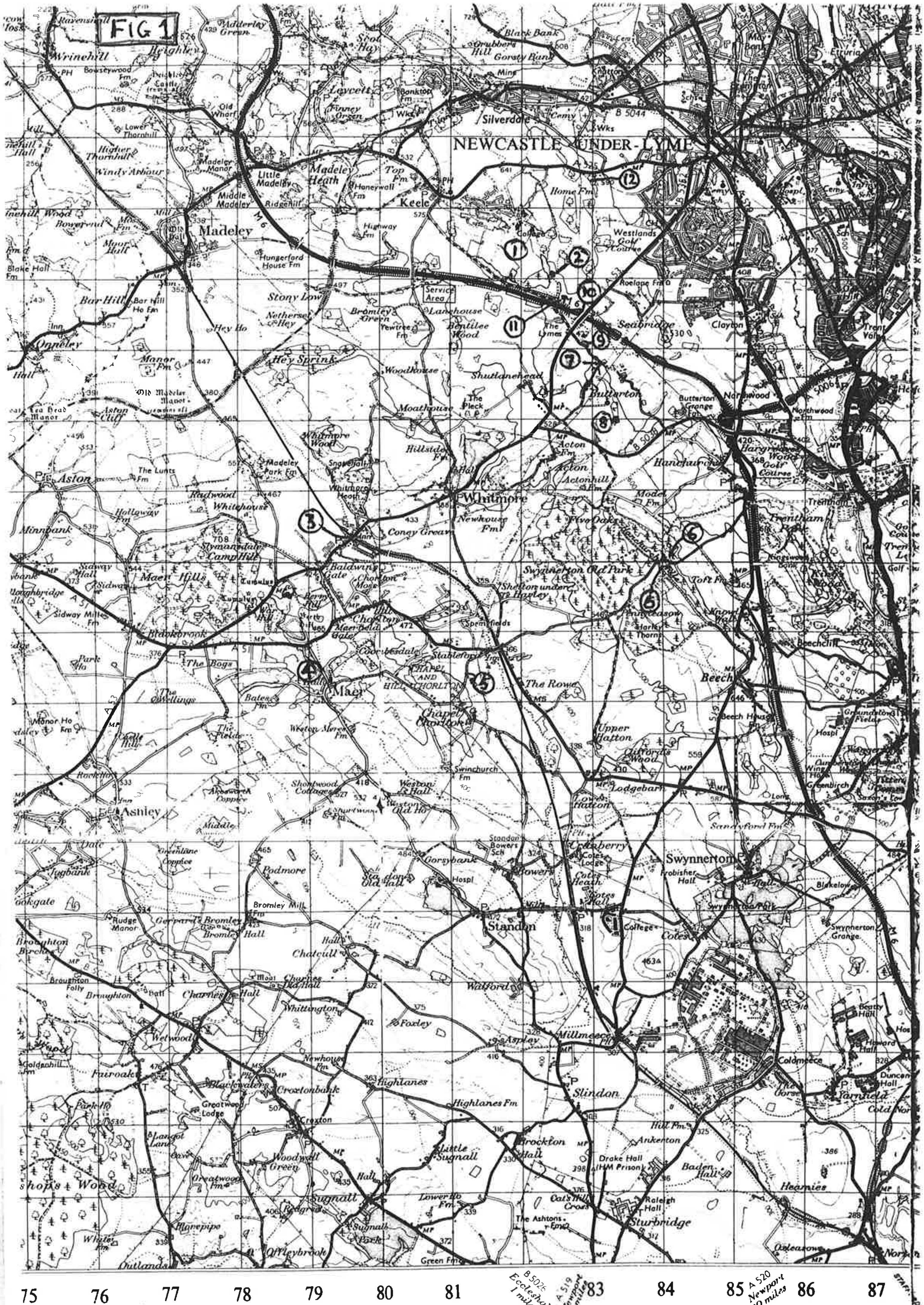
PHOTOS (A)

Charles Darwin, 1840.

Josiah Wedgwood II. Portrait by William Owen.

Courtesy of the Trustees of the Wedgwood Museum, Barlaston

FIG 1



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Beech
Butterton
Seabridge
Westlands Golf Course
Madeley Heath
Little Madeley
Leycett
Wrinehill
Onneley
Aston
Ashley
Baldwins Gate
Chorlton
Chapel Chorlton
Hill Chorlton
Stableford
Shelton under Harley
Swynnerton Old Park
Acton
Millmeece
Croxton
Sugnall
Chatcull
Charnes Hall
Wetwood
Fairoak
Podmore
Mill Meece
Cotes Heath
Walford
Aspley
Highlanes
Offleybrook
Outlands
Drake Hall HM Prison
Raleigh Hall
Baden Hall
Hall Fm
Ankerton
Brockton Hall
Cat's Hill Cross
Little Sugnall
Madeley Park Fm
Hey Sprink
Woodhouse
Moathouse
Shutlanehead
Newhouse Fm
Coney Greave
Five Oaks
Model Fm
Hargreaves Wood Golf Course
Northwood
Trent Vale
Swynnerton Grange
Blakelow
Beech House
Upper Hatton
Lower Hatton
Lodgebank
Cranberry
Frobisher Hall
Stony Low
Service Area
Lanehouse
Bentilee Wood
Bromley Green
Yewtree Fm
Nethersett Hey
Hey Ho
Manor Fm
Old Madeley Manor
Bar Hill
Aston Cliff
Tea Head Manor
Radwood
Whitehouse
Maer Hills
Camp Hill
Blakebrook
The Bogs
Bates Fm
Weston Meres Fm
Weston Hall
Gorsybank
Standon Old Hall
Standon Bowers Sch
The Rowe
Broughton
Gerrard's Bromley
Bromley Mill Fm
Bromley Hall
Rudge Manor
Whittington
Foxley
Newhouse Fm
Highlanes Fm
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Woodwall Green
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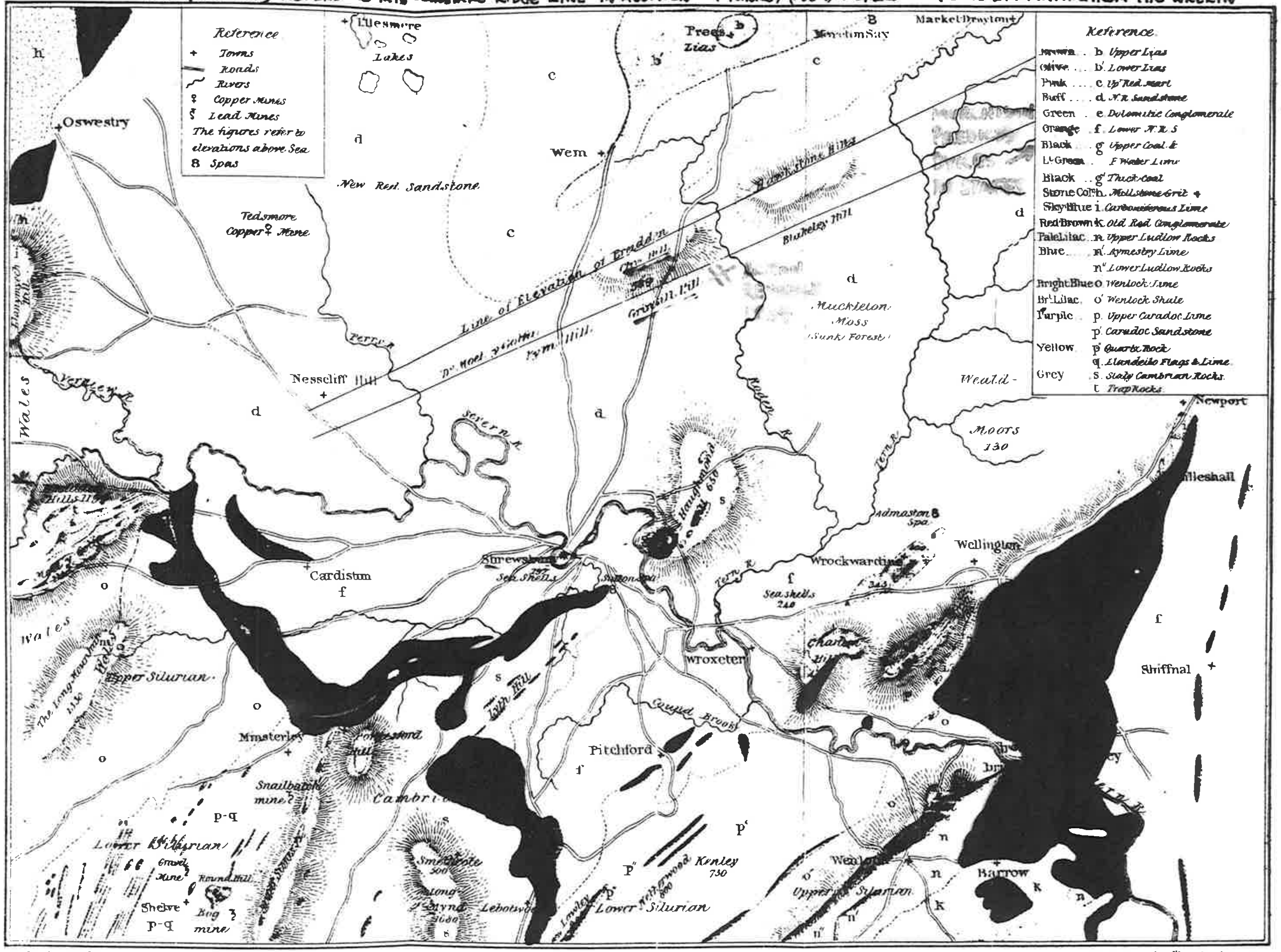

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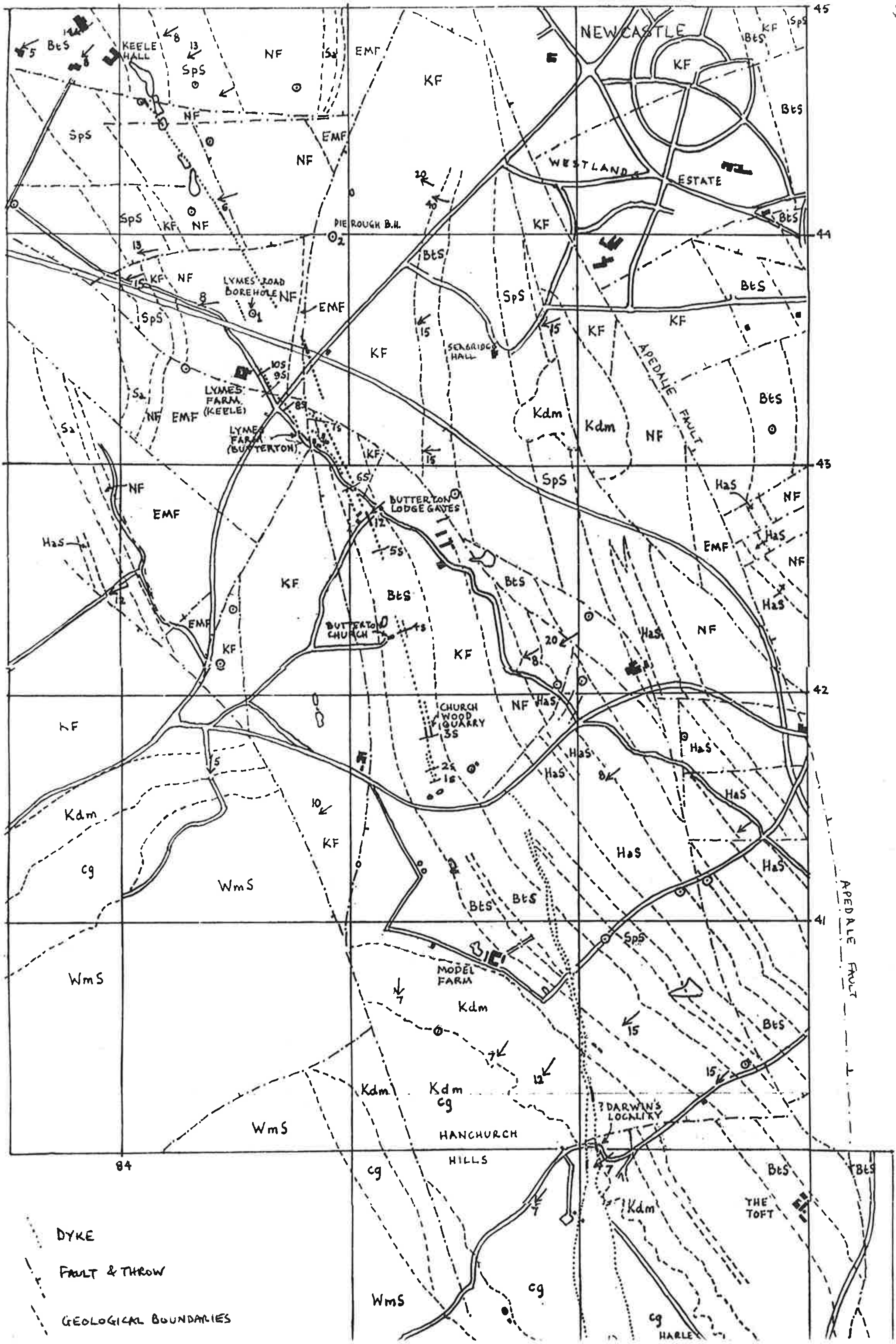
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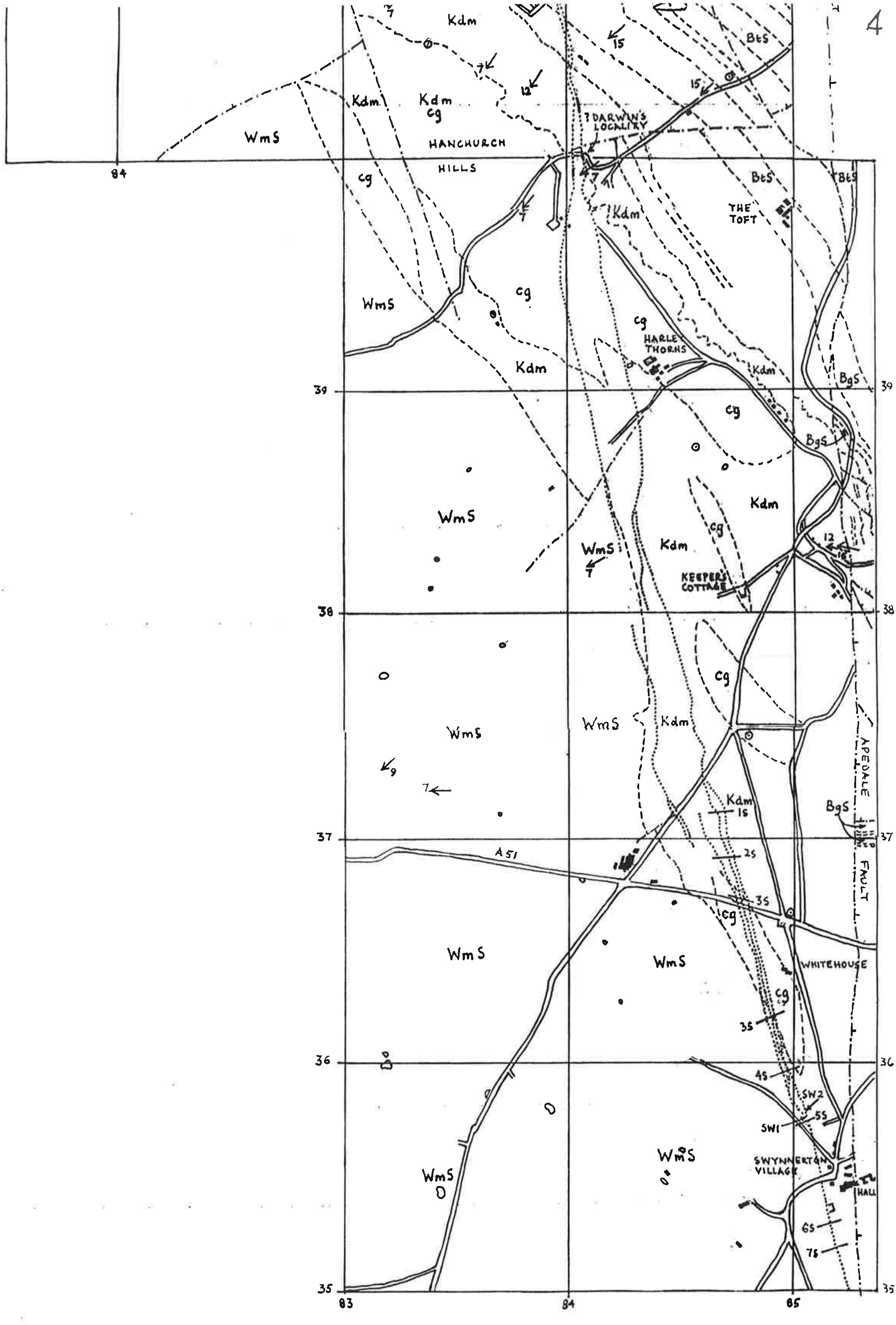
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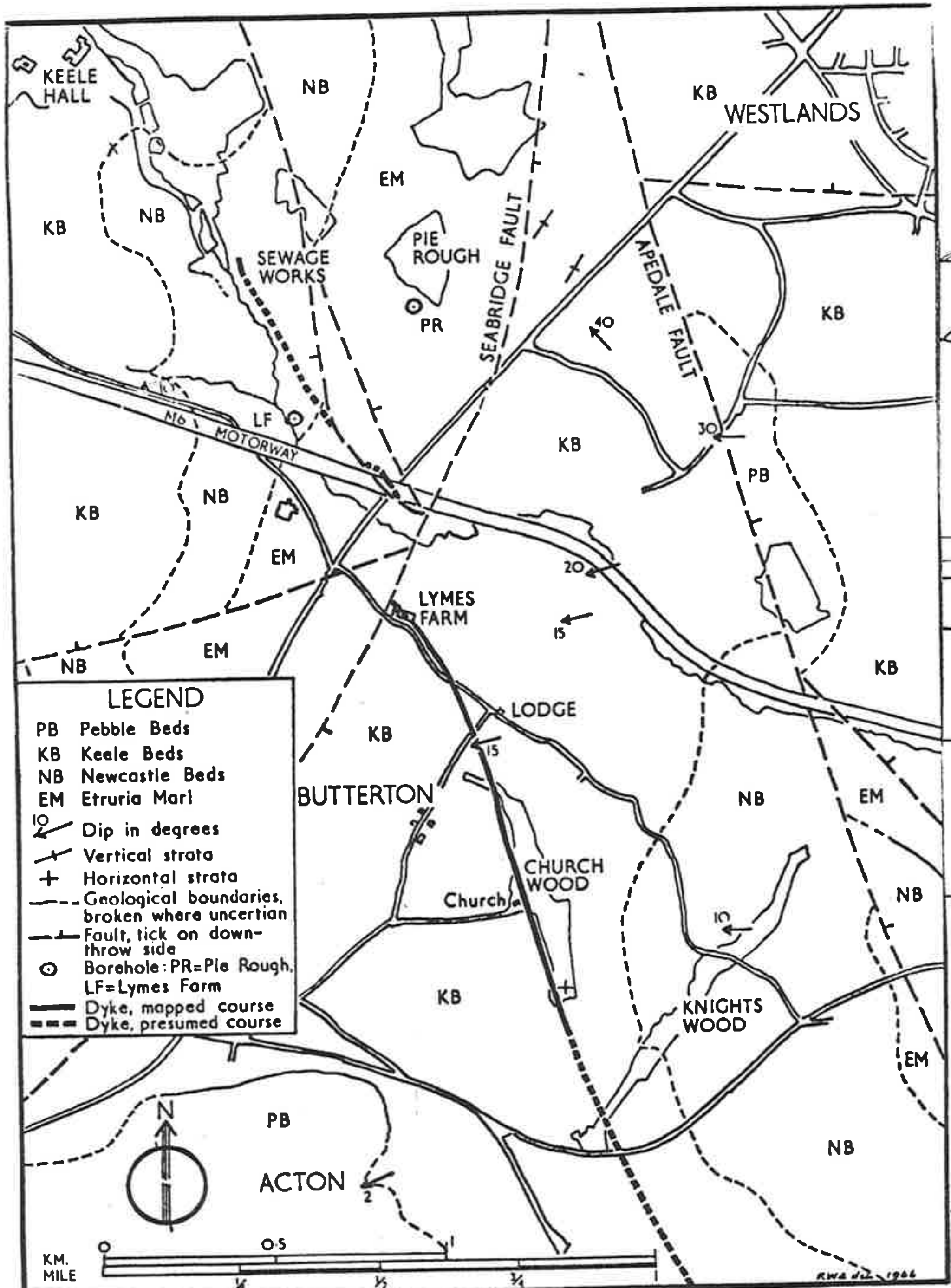
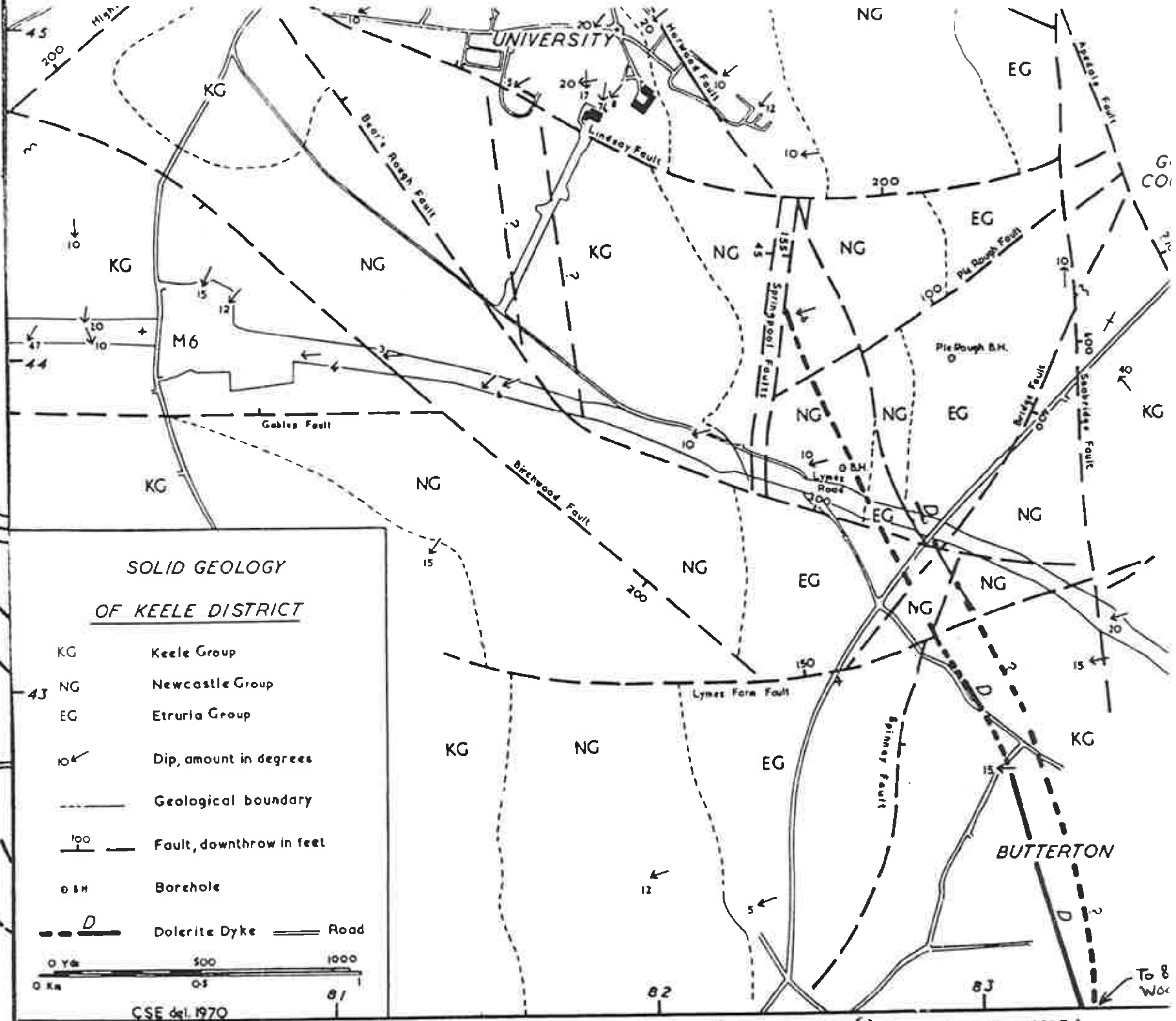


Figure 1 - Geological sketch-map of the area between Keele, Newcastle, and Butterton, Staffordshire, to show the course pursued by the Butterton Dyke. (F.W. COPE. 1966)



GEOLOGICAL MAP OF THE AREA OF THE BUTTERTON DYKE (C S EXLEY 1970)

6A

SOWERBUTTS 1988

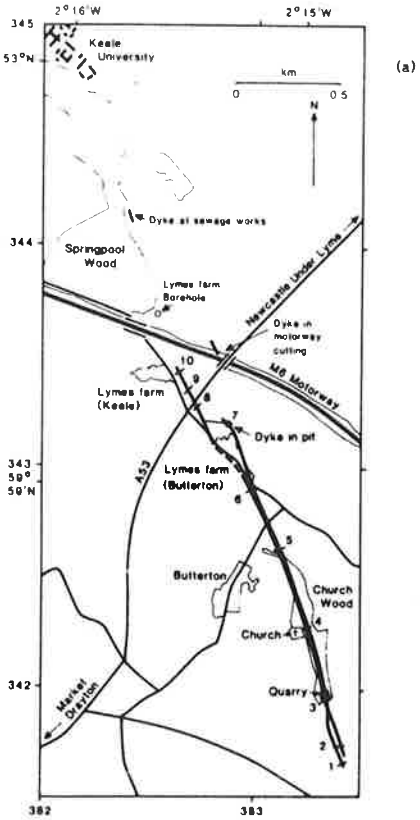
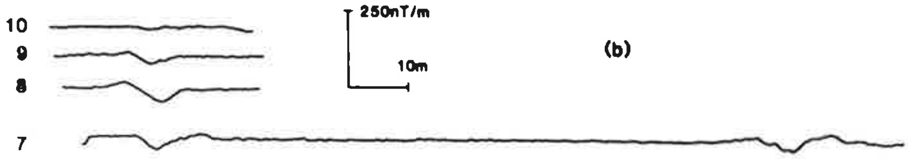
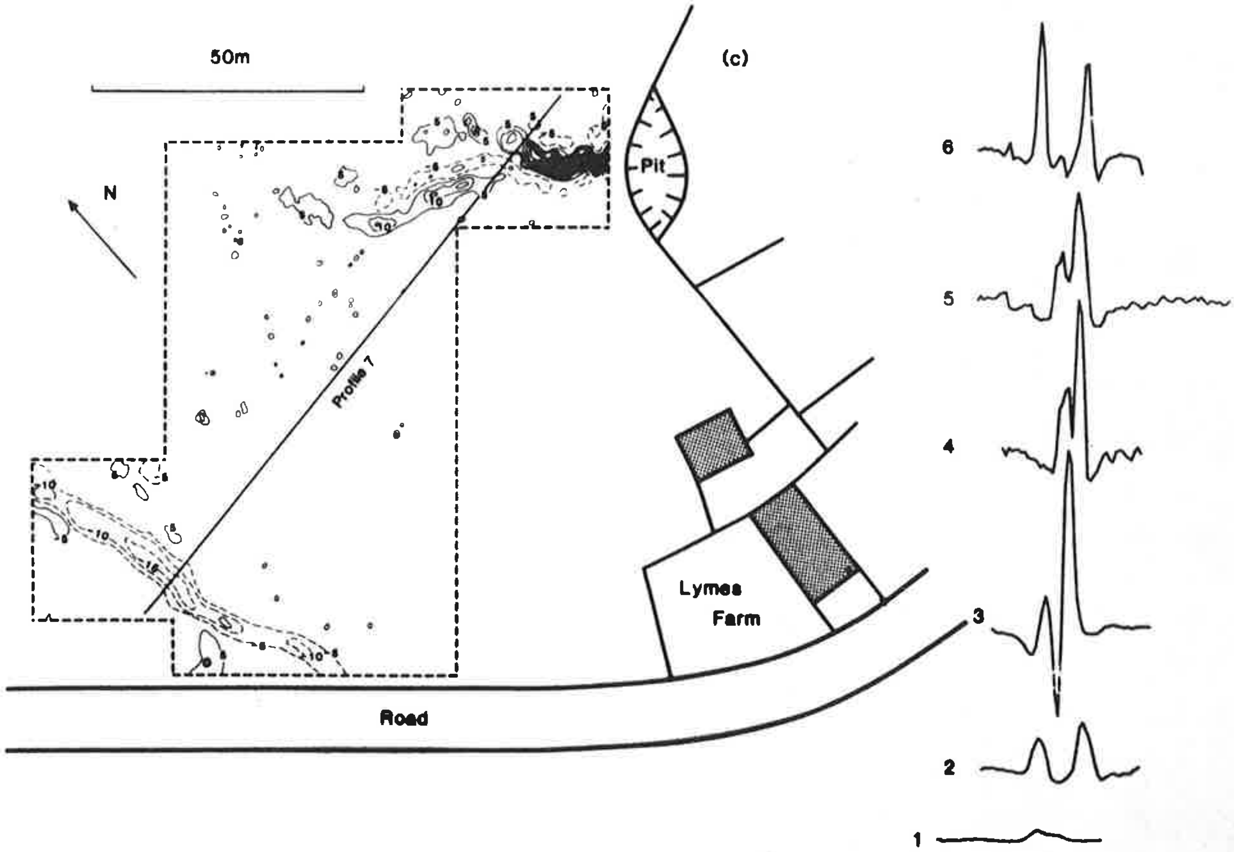
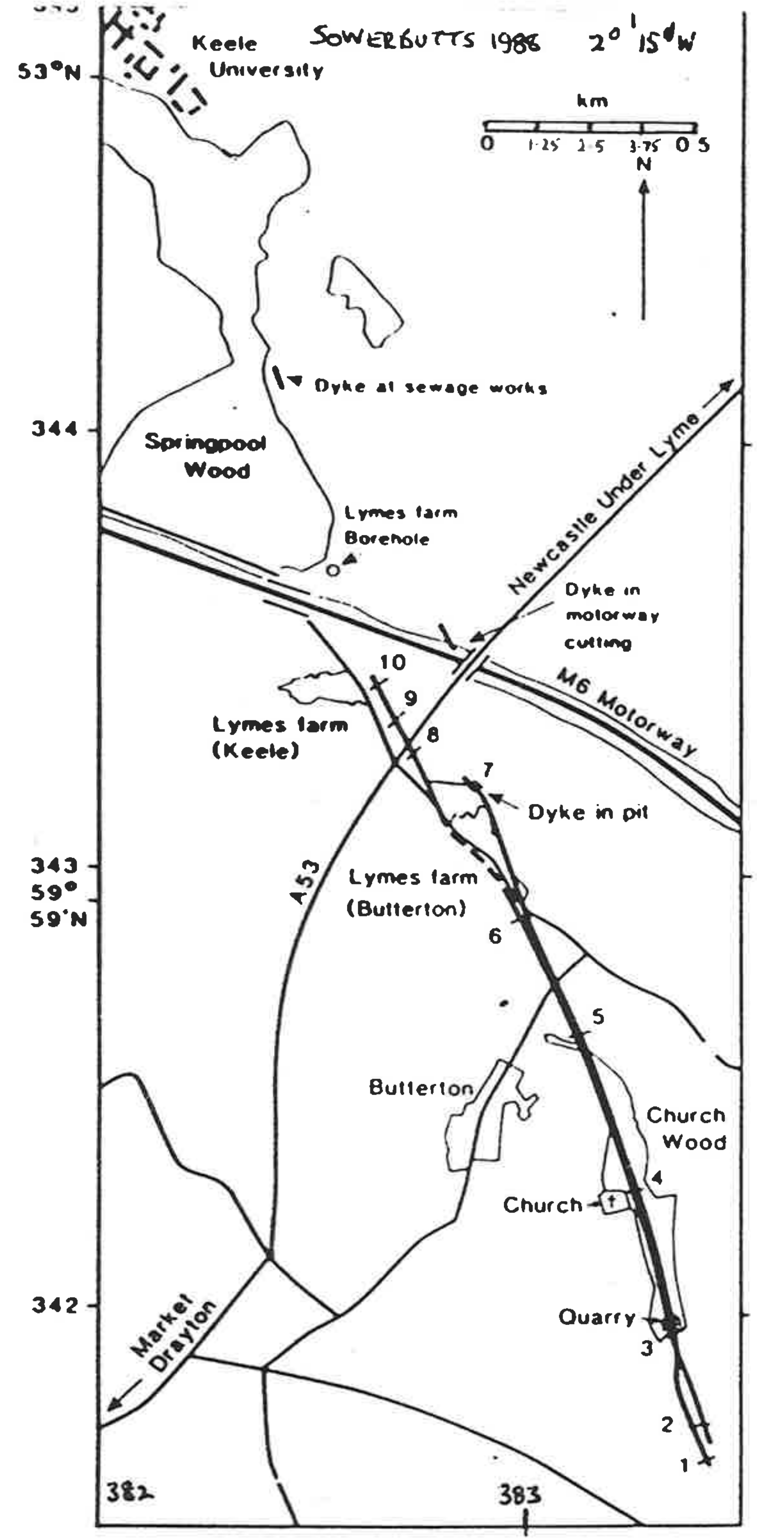


Fig. 2. The northern end of the Butterton–Swynnerton Dykes. **(a)** Map showing the course of dykes as determined using the magnetic scanning method and location of magnetic profiles. **(b)** Profiles of vertical magnetic gradient showing the form of magnetic anomalies produced by the dykes. **(c)** Contour map showing the results of a vertical magnetic gradient survey immediately northwest of Lymes Farm (Butterton). The contour interval used is 5 nT m^{-1}, positive values are contoured as solid lines, negative values as dashed lines.







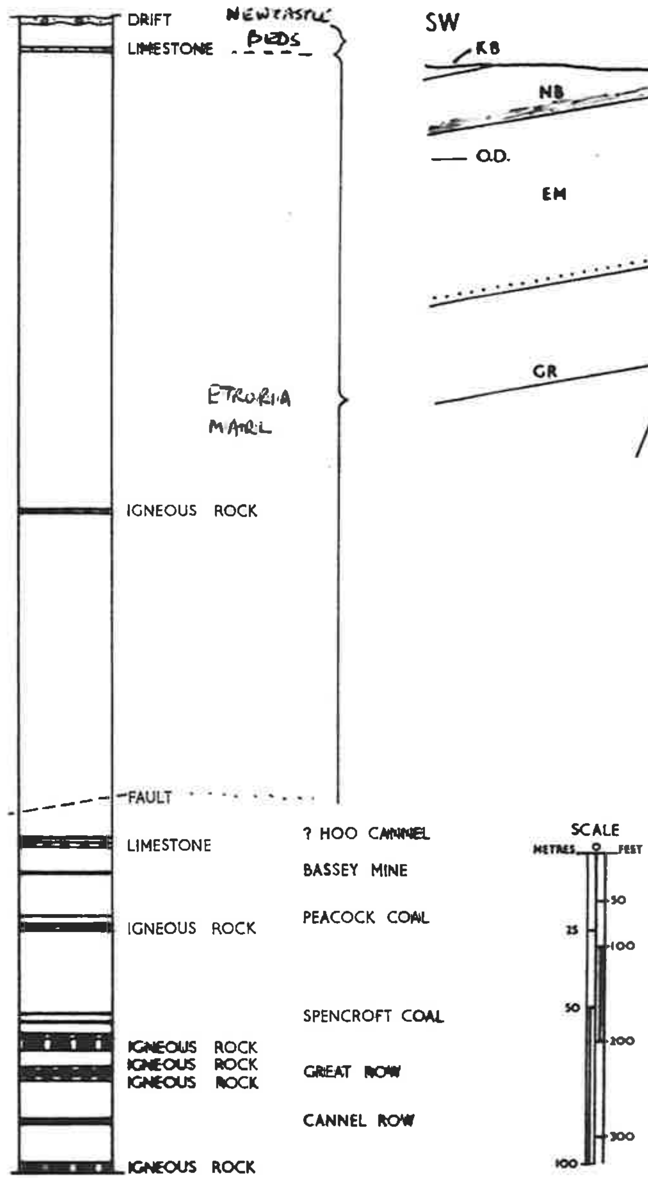


FIGURE 2 - Section of the Lymes Farm borehole, Lymes Road near Keele, Staffordshire, showing the main coals and igneous intrusions intercepted.

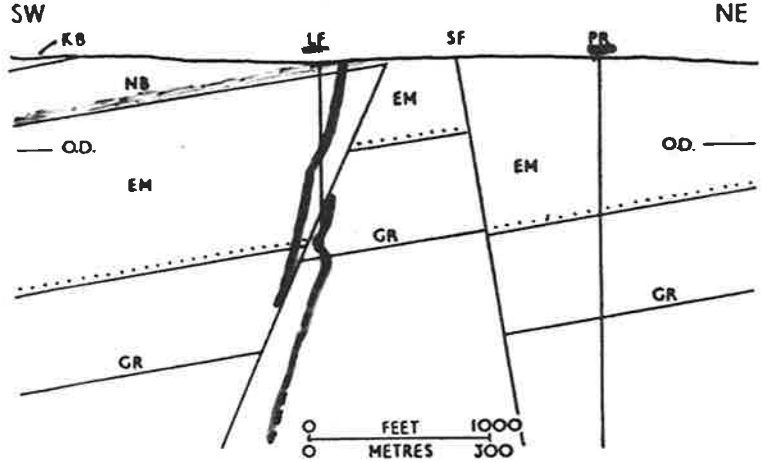


FIGURE 4 - Section along a line through the Lymes Farm borehole (LF) and Pie Rough borehole (PR), showing a possible interpretation of the structure, and behaviour of the Butterton Dyke (thick broken line).
Key to lettering: KB, Keele Beds; NB, Newcastle Beds; EM, Etruria Marl; GR, Great Row; SF, Seabridge Fault.

LYMES FARM BOREHOLE 1920
Scott in Gibson & Wedd 1925
Original record in BGS and NCB Chatterley Whitfield

SCOTTS DESCRIPTION & DEPTHS (IN FEET)

ORIGINAL BOREHOLE RECORD

M
①
②

DEPTH	TRUE THICKNESS
MINERALISATION at 525	
DYKE 1 2'6" 530 - 532'6	1'9"
DYKE 2 1'6" 533'6" - 535'	1.0"

600 FEET

p 94 534' three specimens described
(i) basic crinanite (basic subalkalic)
(ii) augitite (ultrabasic)
(iii) limburgite (ultrabasic)

700

ORIGINAL CORES EXAMINED BY T. A. ROBERTSON (OF BGS) AND ALSO BY J.T. STOBBS

800

p 94 1093 = 5a basic crinanite sub alkalic basic
1097 = 5a similar rock; larger phenocrysts
1100 = 5b still coarsely porphyritic – same rock type
1107 = 5c same rock type olivine > augite
1112 = 5c same rock: small porphyritic crystals in fine matrix

DYKE 3 1-0"
844-845

900

1130 = 7 basic crinanite
porphyritic olivine scarce : replaced by calcite often

DYKE 4 4'0"
972-976

1000 FEET

COMPOSITE DYKE 5
5a – 7'0" 1092-99
5b 12'0" 1101-1113 } 1100 calcite
5c

DYKE 6 4'0"
1020-1024

DYKE 7 1-0" calcite
1129-1130

DYKE 8 4'0"
1232 - 1236
black shale + igneous rock

1200

FIELD VISIT OF GEOLOGISTS ASS'N TO BUTTERTON HALL QUARRY

c. 1893?

PHOTO (B)

CAN YOU DATE THE EXCURSION ON THE STYLE OF THE LADY'S COSTUME?

CAN YOU IDENTIFY FURTHER NAMES OF PARTICIPANTS?

See Hind et al 1903 p. 181

'Butterton Hall Quarry' c. 1890?
with W. Whitaker (bearded?)
+ Walcott Gibson (2nd from right?)
Copy of original in the possession of Ted Watkin (NSGGA)
(Information on back of original in ? John Ward's handwriting)

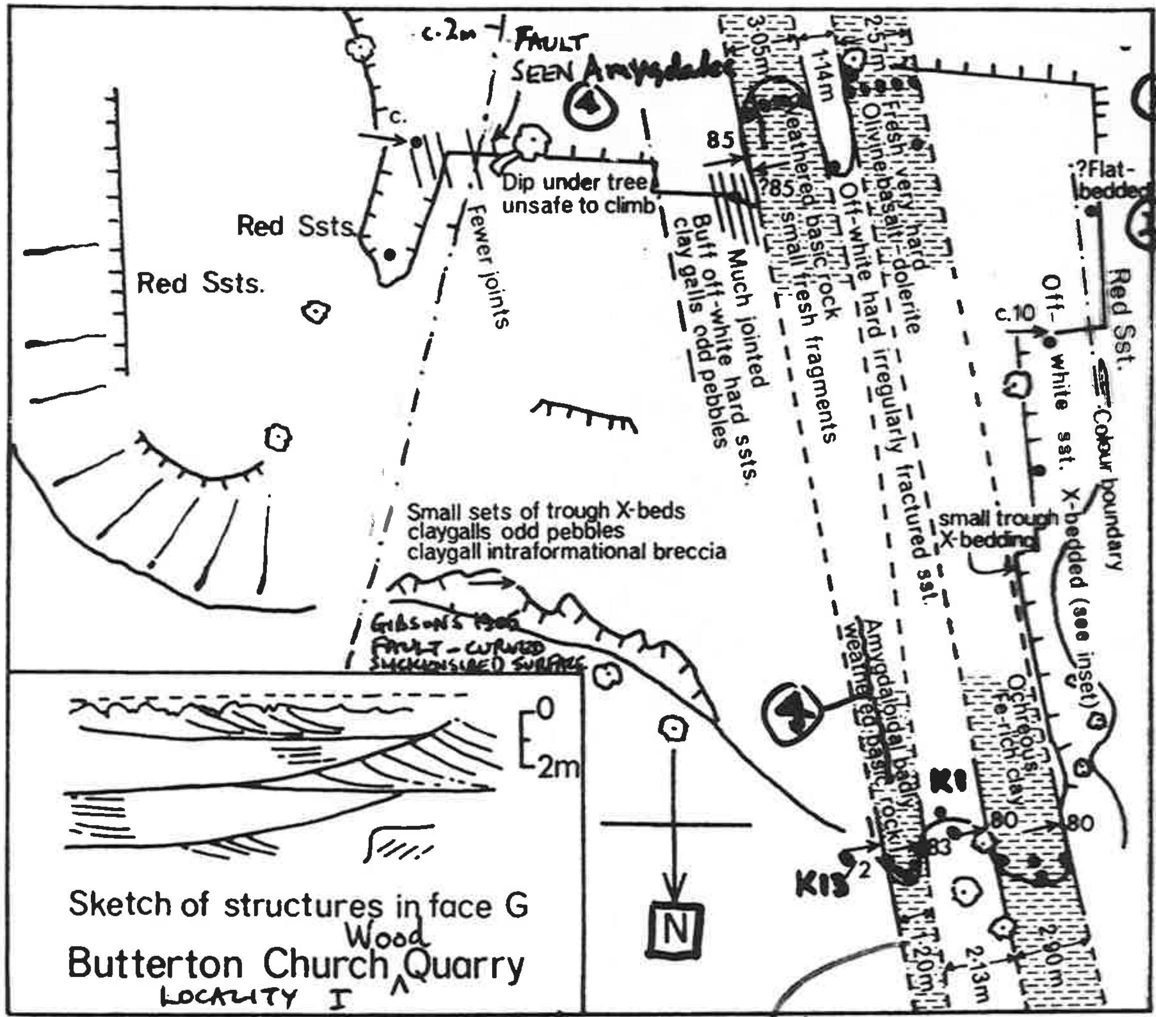


Fig. 3. Outline geological map of Butterton Church Wood Quarry. LOCALITY I. (Thompson 1970)

EXTRA DESCRIPTION FROM GIBSON 1905 p 193

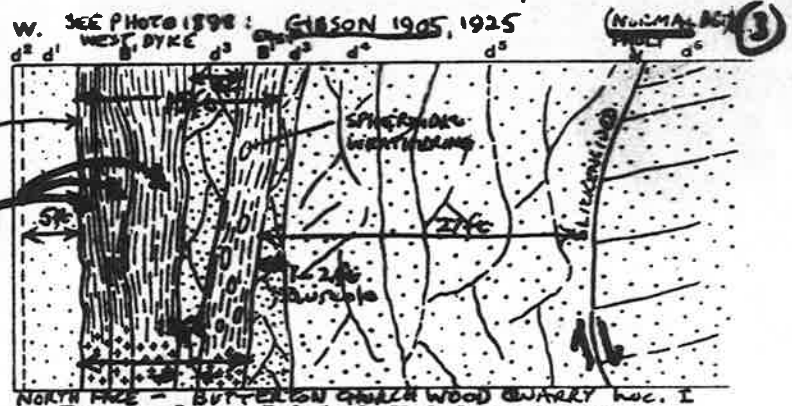


FIG. 15.—*Igneous Dyke in the Keele Group, Butterton Park.*

d² Unaltered sandstone.	d³ Altered grit, 3 to 4 ft. wide.
d¹ Altered do., 3 ft. wide.	d⁴ Soft white sandstone, 10 ft. wide.
B¹ Dyke, 8 ft. and 3 ft. wide.	d⁵ Olive coloured sandstone.
	d⁶ Red sandstone.

NORTH SIDE

32 F. WOLVERSON COPE 1966 p. 32

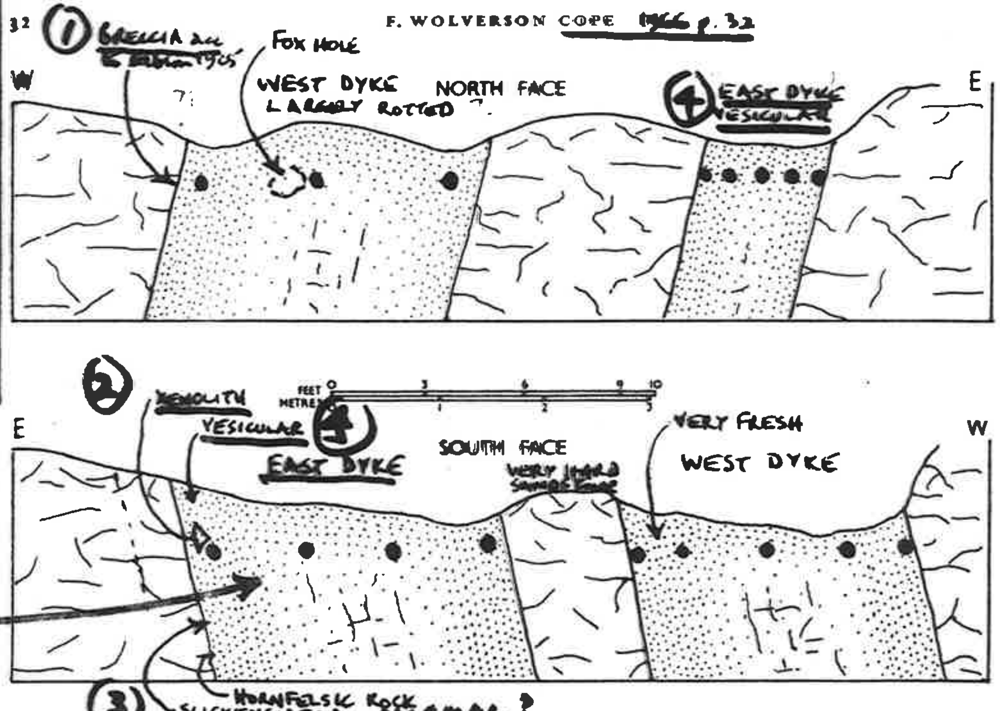
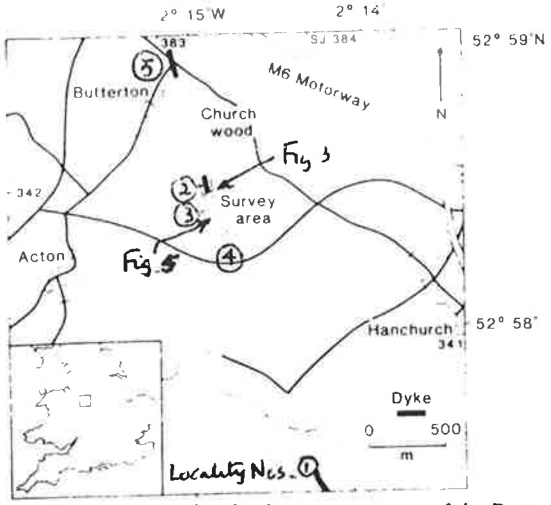
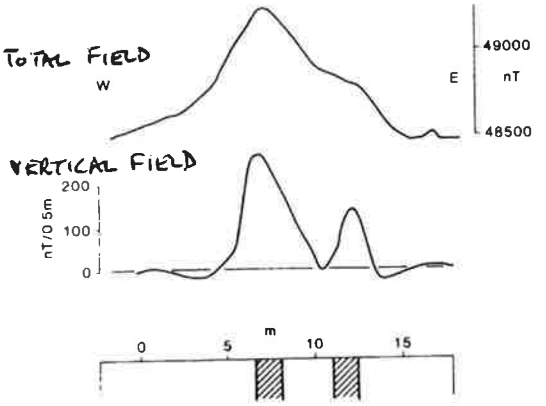


FIGURE 3 Diagrammatic representations of the Butterton Dyke as exposed in the faces of the disused quarry at the south end of Church Wood, Butterton. Sandstone is indicated by unshaded areas with markings of strong irregular jointing. Decomposed dolerite is represented by the dotted areas; fresher dolerite appears as cores marked with sub-parallel joints.

MAGNETIC MAPPING OF THE BUTTERTON DYKE – W.T.C SOWERBUTTS (Jl. geol. Soc. Lond. 144 1987 pp29–33.)



ıg. 1. Location map showing known exposures of the Butterton yke and the area where the magnetic survey was made.



g. 3. Magnetic profiles obtained above the northern end of hurch Wood Quarry (Grid Ref. SJ84; 834420) and section showing e position of two dykes (hatched) observed in the quarry face. ıe total magnetic field measurements show one broad anomaly hereas the profile of vertical magnetic gradient shows separate ıomalies over each dyke.

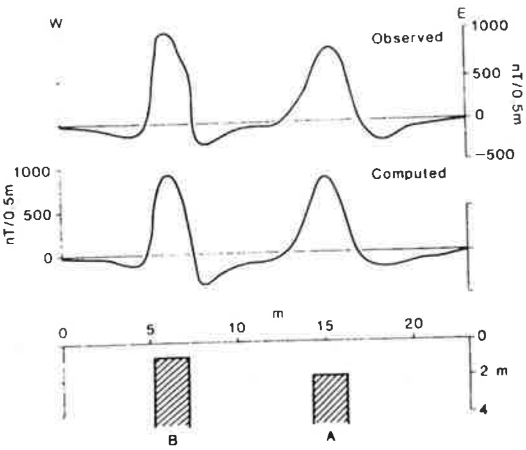
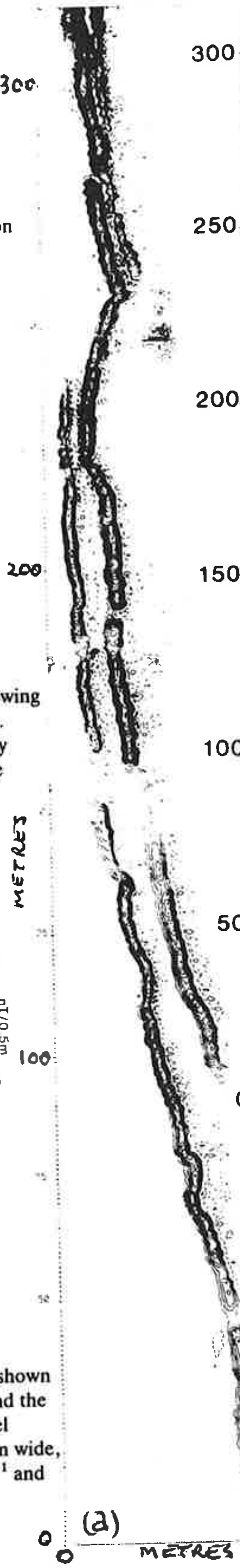
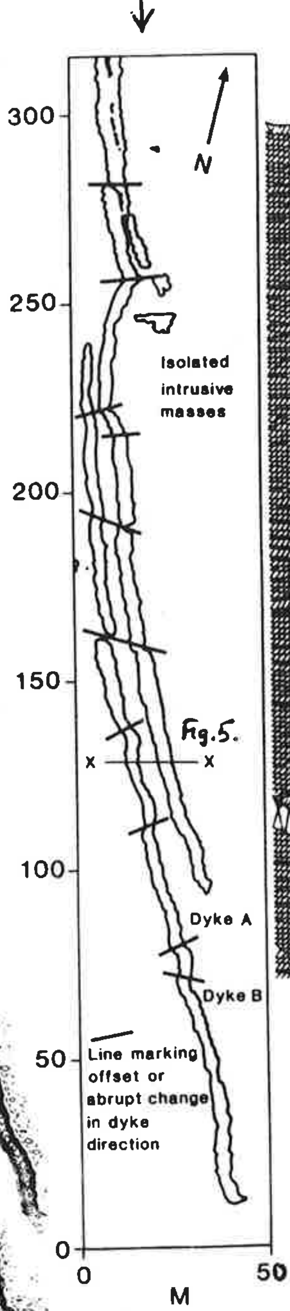


Fig. 5. Vertical magnetic gradient profiles for the line X–X shown in Fig. 4. The top profile is the measured vertical gradient and the bottom profile gives values computed for the two-dyke model shown in section below. In the model Dykes A and B are 2 m wide, 2 and 1 m below the surface, with magnetizations of 20 $\mathrm{Am^{-1}}$ and 8 $\mathrm{Am^{-1}}$ respectively.

Fig. 4. Map showing the +10 nT/0.5 m (+20 $\mathrm{nT\,m^{-1}}$) magnetic contour to illustrate the detailed nature of the igneous intrusions. Places are marked where the orientation of the dykes appears to change. X–X marks the line of the magnetic profile shown in Fig. 5.





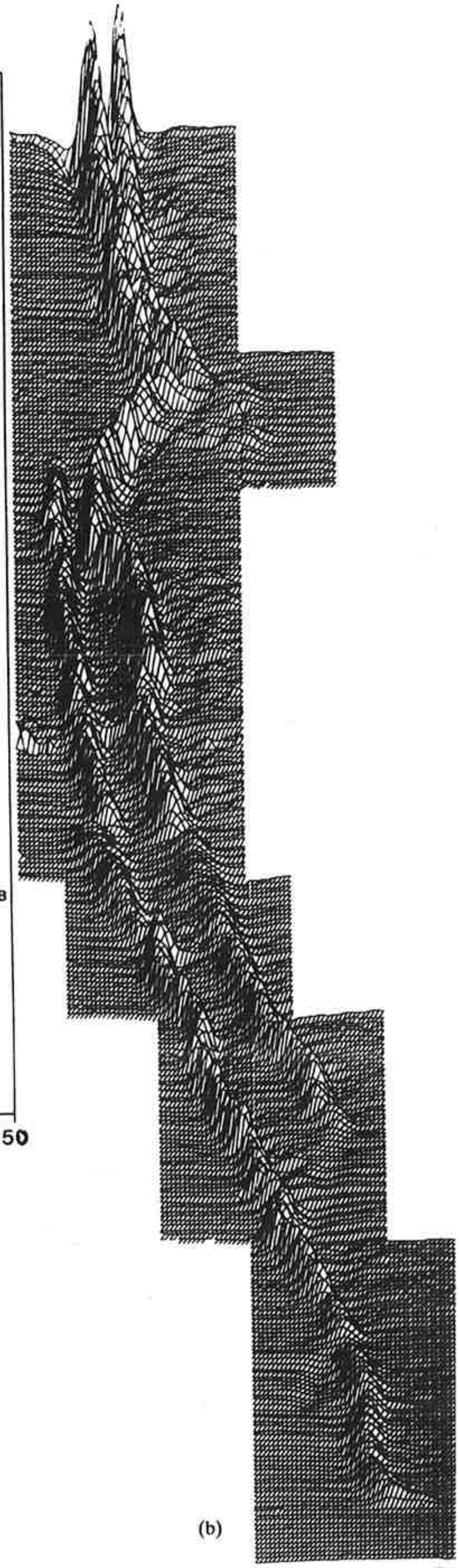


Fig. 2. Contour map and isometric plot showing the results of a vertical magnetic gradient survey made over part the Butterton Dyke. The contour interval used is 10 nT/0.5 m (20 $\mathrm{nT\,m^{-1}}$), positive values are contoured as solid lines and negative values as dashed lines.

PETROGENETIC HISTORY OF THE BUTTERTON-SWINNERTON MAGMA(S).

1. PARTIAL MELTING DEEP IN THE MANTLE > km BENEATH AREA OR TERTIARY CENTRE (? MULL – ARRAN). MATERIAL AGGREGATES TO FORM A DIAPIRIC MUSH AS IT RISES
2. RISE TO UPPER LEVEL MAGMA CHAMBER IN UPPER MANTLE OR CRUST; FEW NUCLEI; CRYSTALLIZATION OF AGGREGATES OF LARGE CRYSTALS > 2 mm (PHENOCRYSTS) SOMETIMES UNDER FLUCTUATING CONDITIONS. CRYSTALS OF:
   (a) OLIVINE ($(FeMg)SiO_3$: density 3.22–4.39) + MAGNETITE ($FeO.Fe_2O_3$: density 5.18)
   (b) PLAGIOCLASE FELDSPAR (LABRADORITE or BYTOWNITE ($(Ca>Na)Al_2Si_2O_8$ density 2.70) SOMETIMES ZONED.
   TITANIFEROUS AUGITE [$Ca(Mg,Fe,Al)AlSi_2O_6$: density 3.25 to 3.55] SOMETIMES ZONED.
   (c) ACCESSORY Apatite, Spinel, Chrome Spinel.
   SLIGHT DIFFERENTIATION IN EARLY STAGES DUE TO DENSITY-GRAVITY SETTLING.
3. INTRUSION: UPRISING VERTICALLY or LATERALLY-VERTICALLY (SUDDENLY OVERNIGHT?) TAKING ADVANTAGE OF TENSIONAL AND/OR WRENCH FRACTURE SYSTEMS IN THE EARLY EOCENE PERIOD, USE OF INHERITED DEEP-SEATED LINEAMENTS (APEDALE), FOCUSSING ON CENTRES (? PILSEN'S WOOD). SOME BRECCIATION (CHURCH WOOD)
4. RATE OF COOLING INCREASES ABRUPTLY: MANY MORE SPONTANEOUS NUCLEI AS TEMP FALLS FROM c. 1200°C – c. 1100°C AND ROCK IS CRYSTALLISED IN A FEW HOURS IN THIN DYKES. FINE-GRAINED < 0.1 mm GROUNDMASS OF:
   OLIVINE, AUGITE, PLAGIOCLASE FELDSPAR (BASIC LABRADORITE).
5. RESIDUAL MAGMATIC LIQUIDS, ENRICHED IN SODA (Na_2O) and WATER (H_2O) + K_2O ATTACK FERROMAGNESIAN MINERALS AND CORRODE THEM, RETURNING CaO, MgO, FeO, Al_2O_3, SiO_2 TO MAGMA TO BE RECRYSTALLIZED OR CHANGING MARGINS OF CRYSTALS AS FOLLOWS:
   MAGNETITE → BIOTITE $K(MgFe)_3(OH)_2(AlSi_3O_{10})$
   OLIVINE → SERPENTINE $Mg_6(OH)_8Si_4O_{10}$
   → CHLORITE $(MgFeAl)_6(OH)_8(AlSi)_4O_{10}$
   AUGITE → TI-MAGNETITE, ILMENITE ($FeTiO_3$)
6. IN SOME CASES DUE TO LOWERING OF CONFINING PRESSURE (DUE TO ESCAPE TO SURFACE?), GASES COME OUT OF SOLUTION FORMING CAVITIES OF SPHERICAL SHAPE.
7. DUE TO SLIGHT VARIATIONS OF SiO_2 and Al_2O_3 ratio and AMOUNT OF MAGMATIC WATER; CRYSTALLIZATION OF FELSPATHOID MINERALS (SiO_2 deficient) AS MATRIX AND ANALCITIZATION OF ROCK. CRYSTALS OF THE FOLLOWING FORMED IN CAVITIES: STELLATE TEXTURE.
   Na RICH-FELDSPAR,
   NEPHELINE $(Na,K)(AlSiO_4)$
   ANALCITE $Na(AlSi_2O_6).H_2O$ – A ZEOLITE MINERAL
   NATROLITE $Na_2(Al_2Si_3O_{10}).2H_2O$ – A ZEOLITE MINERAL
8. MINERALISATION. FILLING OF SPHERICAL CAVITIES BY HYDROTHERMAL-MAGMATIC SOLUTIONS. Calcite replaces augite and olivine (Seabridge borehole)
   CALCITE $CaCO_3$; DOLOMITE $CaMg(CO_3)_2$; BARITE $BaSO_4$;
   CHALCOPYRITE $CuFeS_2$; AZURITE $Cu_3(OH)_2(CO_3)_2$
9. WRENCH-TEAR FAULTING? SINISTRAL ON SWYNNERTON FAULT;

FINAL ROCK COMPOSITIONS (after Scott 1926 p. 146)

	1	2	3	4	
PLAGIOCLASE	17.4	14.4	22.4	15.0	FELSIC
NEPHELINE/ANALCITE	9.8	9.9	10.3	17.8	
AUGITE	39.7	42.8	35.6	35.4	FEMIC
OLIVINE	30.4	30.0	28.6	28.9	
ILMENITE	1.7	1.7	1.8	1.6	
APATITE/BIOTITE	1.0	1.2	0.9	1.3	

1. = BUTTERTON CHURCH WOOD LOC. I : CRINANITE
2. = HANCHURCH WOOD LOC. O : CRINANITE
3. = HANCHURCH WOOD LOC. O : CRINANITE
4. YARNFIELD CLAY PITS LOC f : CRINANITE

BASIC ROCKS
- Alkaline: OLIVINE BASALT → TACHYLITE GLASS; OLIVINE DOLERITE
- Sub-Alkalic: CRINANITE; NEPHELINE-BASANITE } where Nepheline % high

ULTRA BASIC ROCKS (Seabridge = Lymes B.H.)
- AUGITITE (Augite > Olivine) + Magnetite
- LIMBURGITE (Olivine > Augite) + Magnetite

COMPARISONS
VOLCANIC, HYPABYSSAL ROCKS OF TERTIARY PRO[VINCE]
CRINANITES OF ARRAN, JURA BUT STAFFS ROCKS ARE MORE BASIC, LESS ALKALIC (due to less SiO_2 + H_2O) (Scott 1925, 1926)

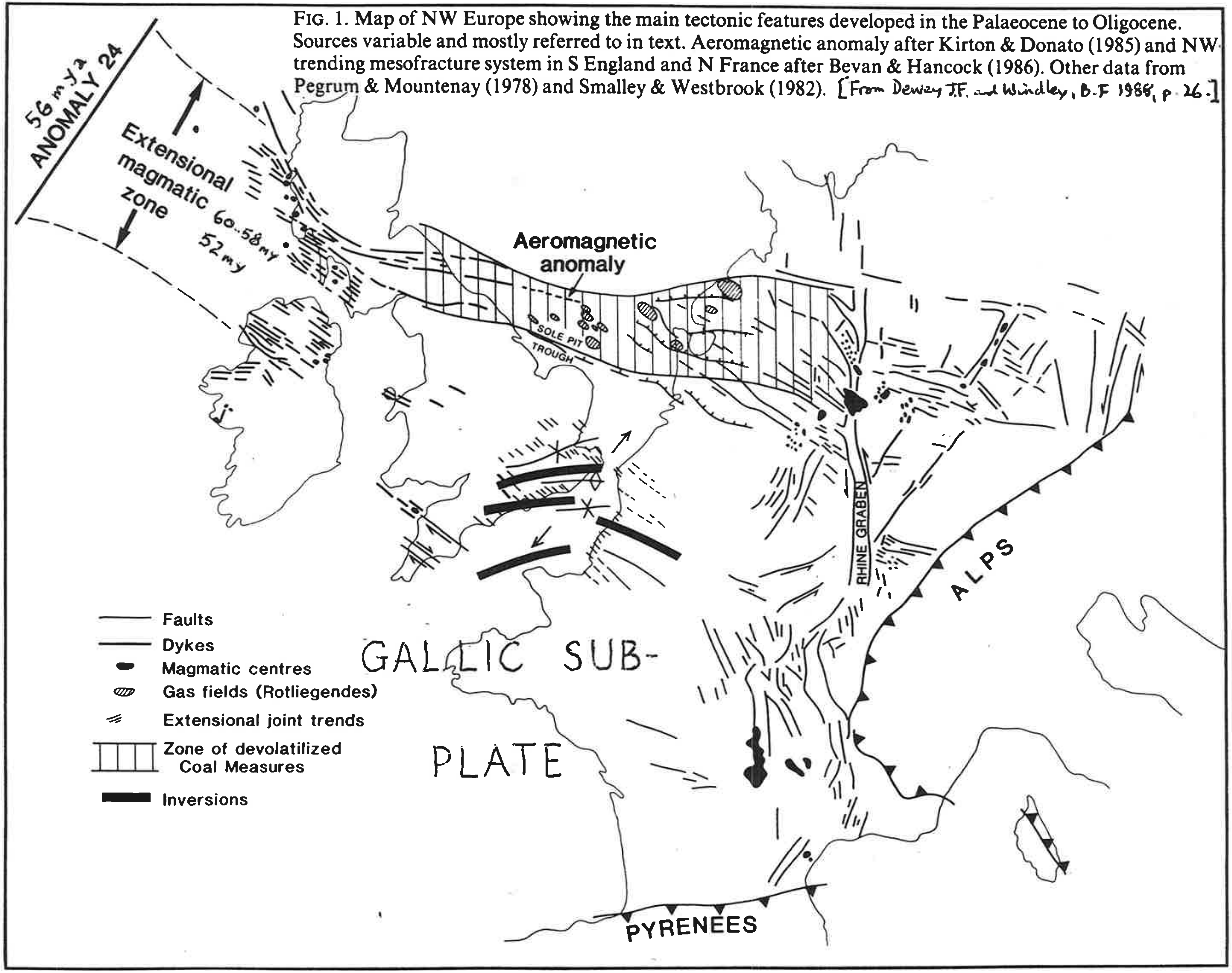


FIG. 1. Map of NW Europe showing the main tectonic features developed in the Palaeocene to Oligocene. Sources variable and mostly referred to in text. Aeromagnetic anomaly after Kirton & Donato (1985) and NW trending mesofracture system in S England and N France after Bevan & Hancock (1986). Other data from Pegrum & Mounteney (1978) and Smalley & Westbrook (1982). [From Dewey J.F. and Windley, B.F 1988, p. 26.]

11

From Dewey J.F. and Windley B 1988
p. 28

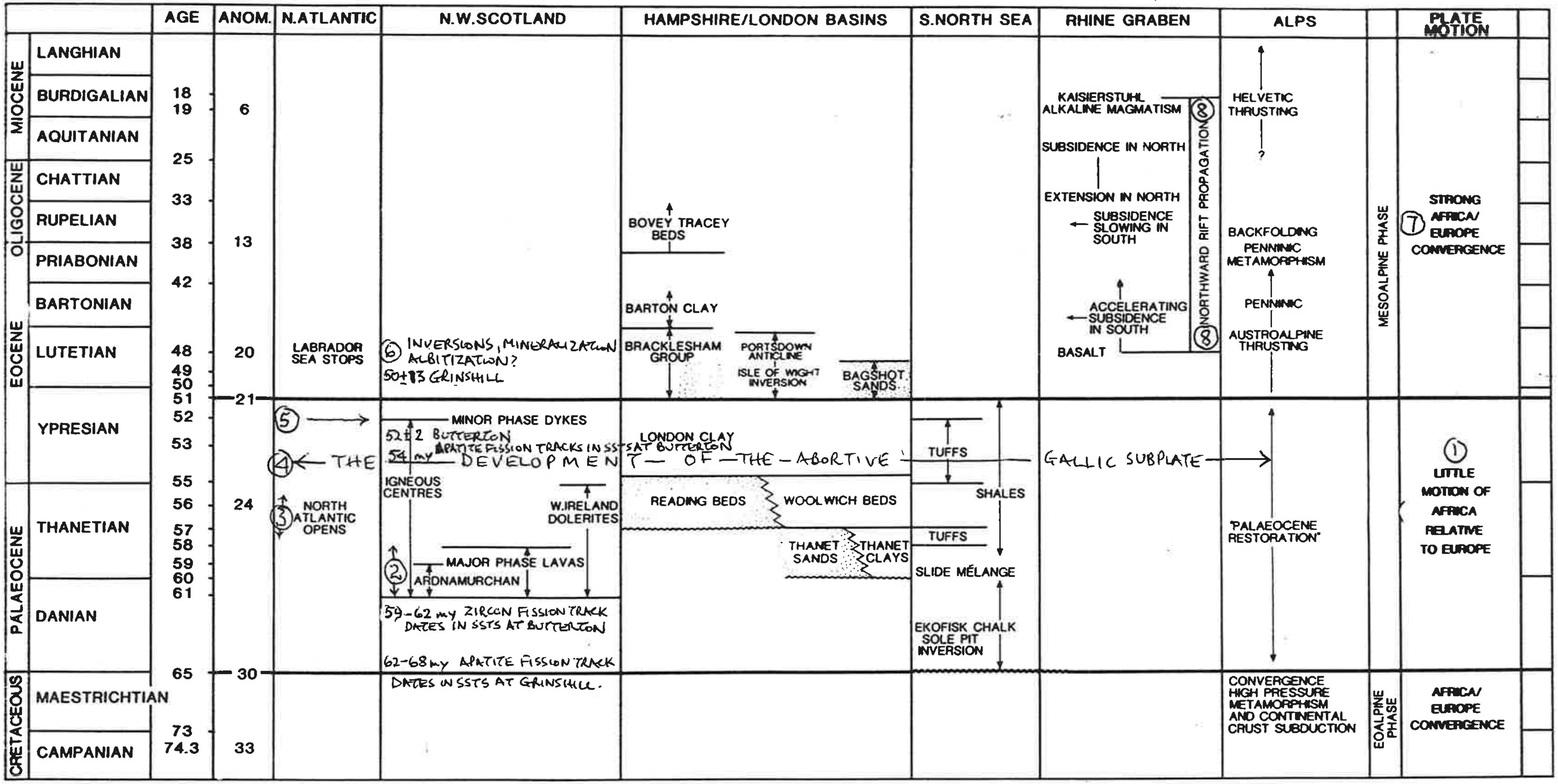
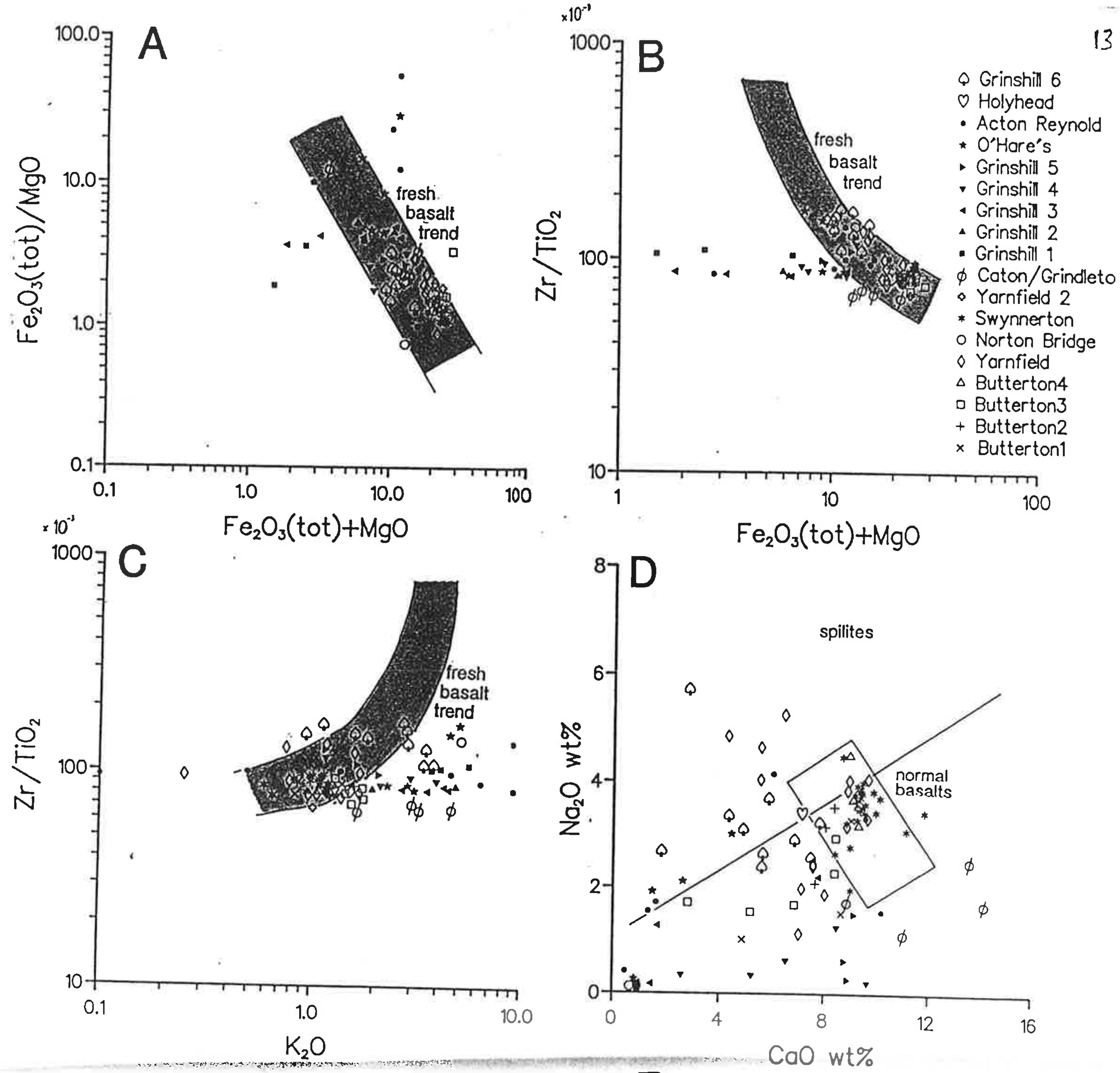


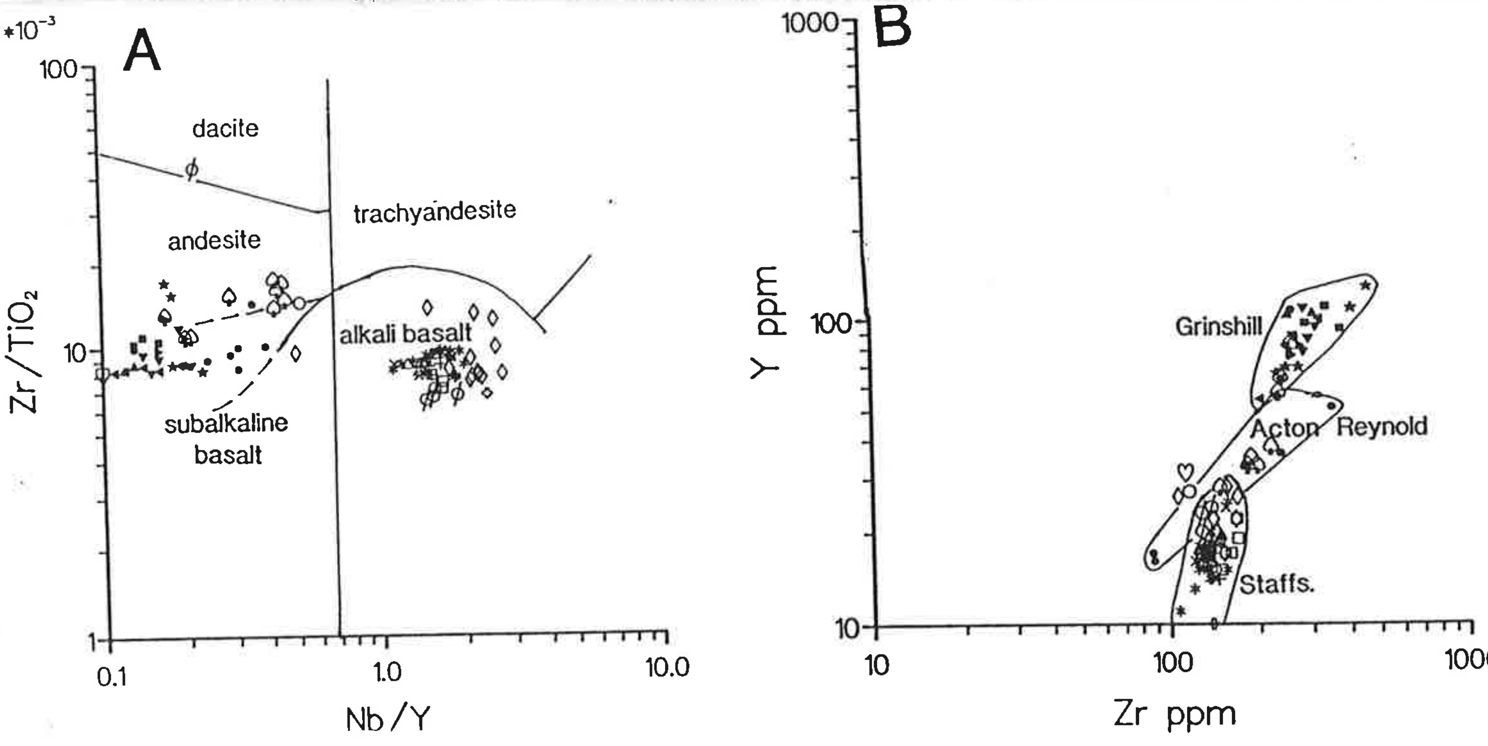
Fig. 2. Time chart of principal events in the evolution of NW Europe from the late Cretaceous to the Miocene. Data from Knox & Harland (1979), Knox (1984), Odin & Curry (1985), Aubry *et al.* (1986) and Mussett (1986).

Order of events are given by the numbered circles 1—8

12



A
B
C
D
Fe_2O_3(tot)/MgO
Fe_2O_3(tot)+MgO
Zr/TiO_2
K_2O
Na_2O wt%
CaO wt%
fresh basalt trend
spilites
normal basalts
Grinshill 6
Holyhead
Acton Reynold
O'Hare's
Grinshill 5
Grinshill 4
Grinshill 3
Grinshill 2
Grinshill 1
Caton/Grindleto
Yarnfield 2
Swynnerton
Norton Bridge
Yarnfield
Butterton4
Butterton3
Butterton2
Butterton1



A
B
Zr/TiO_2
Nb/Y
dacite
andesite
trachyandesite
alkali basalt
subalkaline basalt
Y ppm
Zr ppm
Grinshill
Acton Reynold
Staffs.

14

From
R. W. England 1988 p. 382

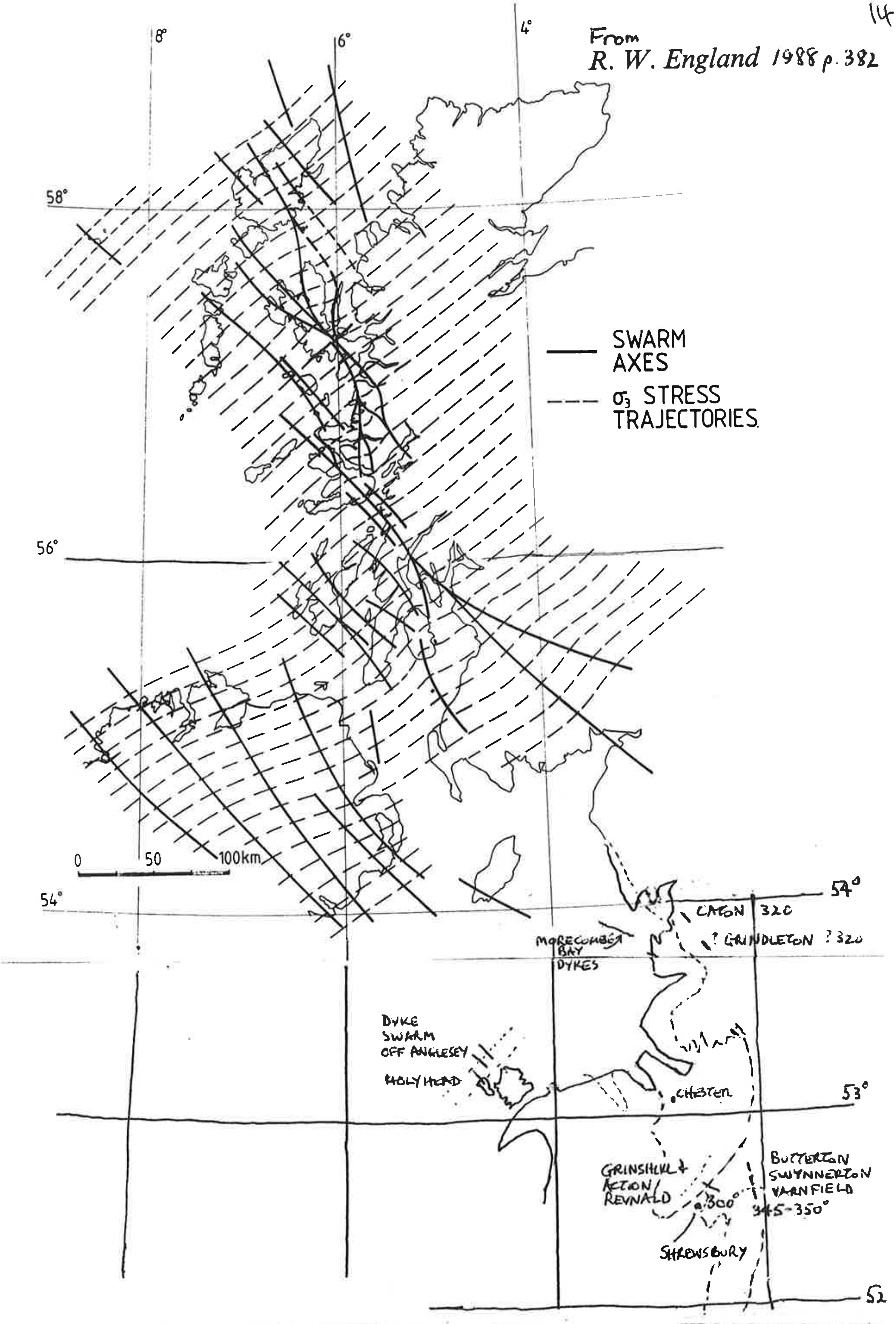


FIG. 1. Map showing the spatial orientation of the minimum principal stress trajectories across the BTVP as derived from local extension directions indicated by the major, secondary and subswarms of dykes. (Pattern of swarm axes taken from Speight *et al.* 1982.)