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EARLY PALAEOZOIC ARC-RELATED VOLCANISM IN THE CONCEALED CALEDONIDES OF SOUTHERN BRITAIN

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(18 figures and 3 tables)

ABSTRACT. – Deep boreholes in a NW-SE trending belt running from the south Pennines to The Wash, to NE of the Midlands Microcraton, proved pre-Carboniferous intermediate to felsic tuffs and lavas. Associated mafic volcanic rocks are rare. A cluster of boreholes near the edge of the microcraton also proved felsic tuffs. This concealed volcanic suite is petrographically and geochemically distinct from the exposed Precambrian basement in eastern England, but the age of the individual provings is poorly constrained, and they may not be coeval. Isotopic studies suggest a probable mid to late Ordovician age, comparable to that of calc-alkaline plutonic magmatism in the East Midlands. It is proposed that a subaerial calc-alkaline volcanic arc extended from the Brabant Massif in Belgium, beneath eastern England to the Lake District in the Ordovician, developing in response to closure of the Tornquist Sea convergence zone.

In the southern part of the Midlands Microcraton, mafic lavas and intermediate tuffs of Llandovery (or earlier) age encountered in a few deep boreholes are geochemically comparable with exposed early Silurian volcanic sequences at Skomer in south Wales, the Mendips and the Tortworth Inlier. These rocks form a seismic marker horizon which can be traced over an extensive area, and are believed to represent an eastward continuation of the early Silurian volcanic suite along the northern edge of the concealed Variscan Front.

INTRODUCTION

Volcanic rocks have been proved in 30 boreholes penetrating Upper Palaeozoic and/or Mesozoic sedimentary cover in southern Britain. Their ages are not well constrained biostratigraphically, or by unequivocal isotopic dating. Some volcanic rocks, in boreholes located close to Precambrian outcrops, and principally in central England, can be reliably correlated with Uriconian, Charnian and Malvernian igneous suites using petrographical and geochemical data (Pharaoh & Gibbons, in prep.). Other, more widespread, concealed volcanic rocks are probably unrelated; this account reviews the petrological, geochemical and isotopic evidence for their lower Palaeozoic age and discusses their geotectonic setting in terms of Caledonide plate tectonic reconstructions.

PREVIOUS WORK

Petrological studies of concealed volcanic rocks in the area began over 100 years ago. The felsic tuffs in the Orton borehole (Fig. 1, Table 1) were originally assigned an 'Archean' age by Eunson (1884, 1886) and likened to similar rocks in a borehole at Oxendon Hall by Poole *et al.* (1968). Felsic tuffs in North Creake 1 were matched with Charnian (Precambrian) tuffs by Phemister (in Kent, 1947). The petrographical similarities of these rocks and their inferred Precambrian age were subsequently extended to the tuffs proven by Sproxton 1 (Falcon & Kent, 1960) and Glinton 1 (Kent, 1962). Based on these conclusions, Kent (1968) and Wills (1978)

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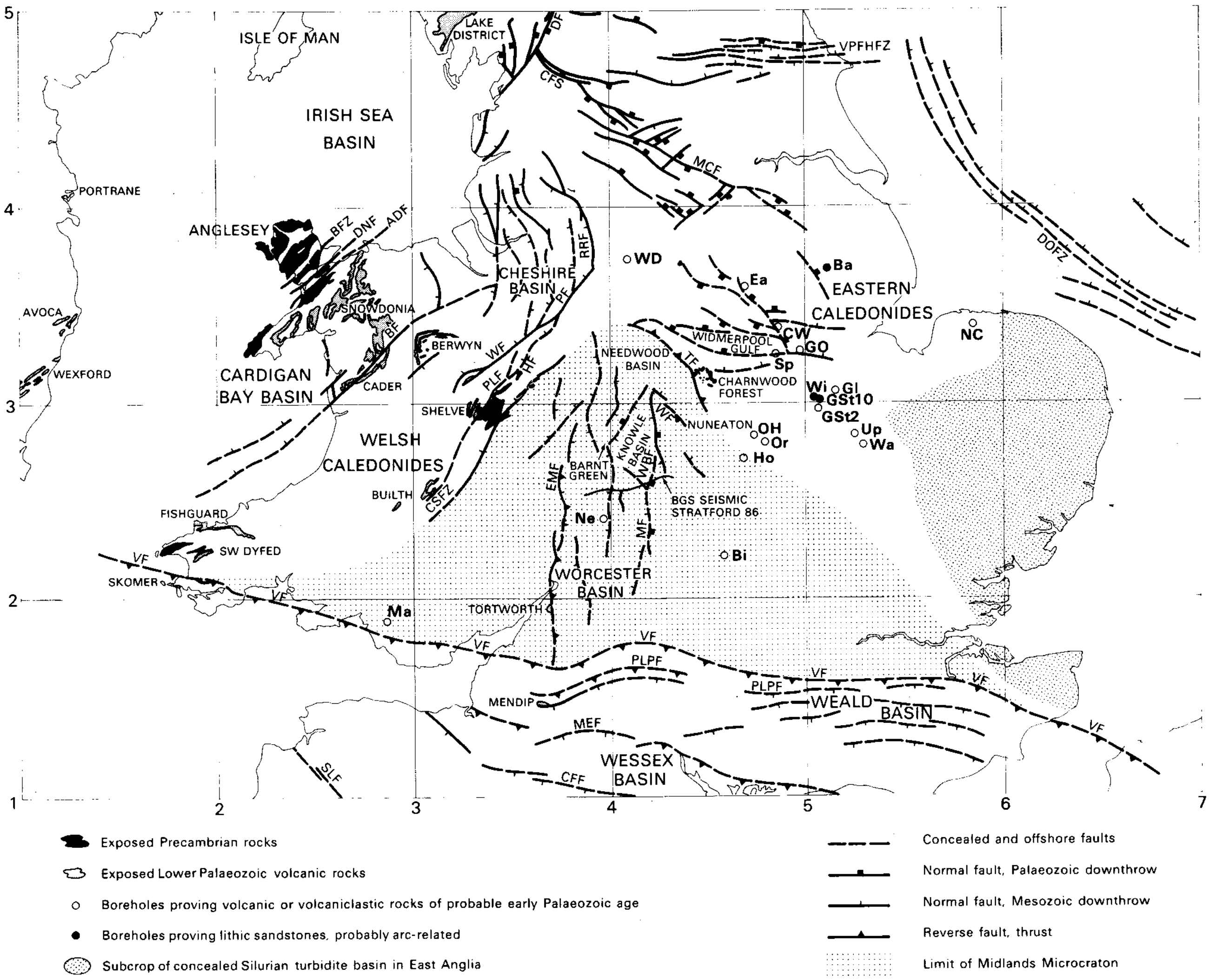

Fig. 1.- Borehole location map. Fault pattern after Smith (1985), Whittaker (1985) and Lee et al. (1990). Key to faults: ADF, Aber-Dinlle Fault; BF, Bala Fault; BFZ, Berw Fault Zone; CFF, Cranborne-Fordingbridge Fault; CFS, Craven Fault System; CSFZ, Church Stretton Fault Zone; DF, Dent Fault; DFZ, Dowsing Fault Zone; EMF, East Malverns Fault; DNF, Dinorwic Fault; HF, Hodnet Fault; MCF, Morley-Campsall Fault Zone; MEF, Mere Fault; MF, Moreton Fault; PF, Prees Fault; PLF, Pontesford-Linley Fault; PLPF, Pewsey-London Platform Faults; RRF, Red Rock Fault; SLF, Sticklepath-Lustleigh Fault; TF, Thringstone Fault; VF, Variscan Front; VPFHFZ, Vale of Pickering-Flamborough Head Fault Zone; WBF, Warwickshire Coalfield Western Boundary Fault; WEF, Wem Fault; WF, Warton Fault.

Key to boreholes: Bi, Bicester 1; Ba, Bardney1;CW, Coxs Walk 1; Ea, Eakring 146; Gl, Glinton 1; GO, Great Osgrove Wood 1; GSt2, Gas Stamford 2; GSt10, Gas Stamford 10; Ho, Hollowell 1; Ma, Maesteg 2; Ne, Netherton 1; NC, North Creake 1; Or, Orton 1; OH, Oxendon Hall 1; Sp, Sproxton 1; Up Upwood 1; Wa, Warboys 1; Wi, Wittering; WD, Woo Dale 1.

inferred the presence of a belt of Precambrian rocks (the 'Midland Barrier') from north of Charnwood to The Wash. A possible ignimbritic origin for the tuffs at Glinton, Oxendon and Orton was inferred by Evans (1965) and Dearnley (1966).

Boreholes at Upwood and Warboys in Huntingdonshire (Fig. 1) proved mafic volcanic and hypabyssal rocks of uncertain age (Institute of Geological Sciences, 1966). Further north-west, volcanic rocks interbedded with supposed early Palaeozoic shales and sandstones proved by Eakring 146 were described by Phemister (in Edwards, 1967). The lavas and tuffs proved by the Woo Dale 1 borehole (Cope, 1949) have been assigned ages ranging from Precambrian to pre-Carboniferous (Cope, 1979) or possibly early Carboniferous (Le Bas, 1972). However, an Ordovician age is indicated by biostratigraphical evidence (Downie, in Evans, 1979). Volcaniclastic sedimentary rocks in Hollowell 1 borehole were attributed a Precambrian age, mainly because of their petrographical similarities with rocks of the Maplewell Group of Charnwood (Harrison, Le Bas pers. comms. in Allsop *et al.*, 1987), but are reinvestigated here because of their spatial proximity to the boreholes at Orton and Oxendon Hall.

Table 1.- Borehole location and geological data for the concealed volcanic suite. Brief bibliography gives key references describing the basement lithology. Published radiometric ages in Ma (see text for sources): SW, Rb-Sr whole-rock age; KW, K-Ar whole-rock age. New data reported here for Cox's Walk and Woo Dale are also included.

BOREHOLE (BGS register)	LITHOLOGY	AGE DATA (Ma)	DEPTH (m sub MSL datum)	OVERLY. FM	COUNTY	UK GRID REFERENCE	BRIEF BIBLIOGRAPHY
Bicester 1	Altered basalt, tuff	?Early Sil	297.9/426.2	L Sil.	Oxon	SP 5872 2081	Shell composite log (unpubd.)
Coxs Walk 1	Intermediate lavas	466±11 RW	510.2/744.6	L Carb.	Lincs	SK 8412 380	Pharaoh et al.(1987a)
Eakring 146	Andesite, phyllite	?Lwr Pal.	2090.3/2174.5	L Carb.	Notts	SK 6808 5948	Edwards (1967)
Gas Stamford 2	Tuff or greywacke	?Lwr Pal./PC	233.5/249.3	Trias	Nhants	TL 0674 9673	Gas Council composite log (unpubd.)
Glinton 1	Felsic crystal tuff	448±32 RW	347.2/378.0	Trias	Nhants	TF 1500 0528	Kent (1962), Pharaoh et al. (1987a)
Gt Osgrove Wood	Rhyolite lava	?Lwr Pal./PC	752.0/753.4	U Carb.	Lincs	SK 9652 2460	Webb & Brown (1989)
Hollowell 1	Agglomerate, tuff	?Lwr Pal./PC	336.4/359.8	Trias	Nhants	SK 6833 7183	Allsop & al. (1987)
Maesteg 2	Tuff	?Early Sil	2411.6/2416.1	L Sil.	Glams	SS 8528 9245	
Netherton 1	Andesitic tuff	424±8 KW	1707.5/2268.6	Perm.	Worcs	SO 9982 4138	Harrison (1974), Wills (1978)
North Creake 1	Felsic tuff	?Lwr Pal./PC	720.6/780.6	Trias	Norfolk	TF 8567 3864	Kent (1947), Wills (1978)
Orton 1	Felsic ash-flow tuff	?Lwr Pal./PC	103.7/126.6	Trias	Nhants	SP 7942 7916	Evans (1965), Dearnley (1966)
Oxendon Hall 1	Felsic ash-flow tuff	?Lwr Pal./PC	114.3/129.6	Trias	Nhants	SP 7343 8275	Dearnley (1966), Poole & al. (1968)
Sproxton 1	Slate with tuff beds	?Lwr Pal./PC	644.7/787.6	U Carb.	Leics	SK 8451 2394	Kent (1968), Dunning (1975)
Upwood 1	Agglomerate, tuff	?Lwr Pal./PC	184.4/207.7	Trias	Hunts	TL 2493 8304	Horton & al. (1973), Webb & Brown (1989)
Warboys 1	Altd. diorite intrus.	311±10 KW	149.3/196.0	Trias	Hunts	TL 2903 7839	Horton & al. (1973), Webb & Brown (1989)
Woo Dale 1	Int. tuff, felsic lava	399±9 RW	35.1/73.7	L Carb.	Derbys	SK 0985 7284	Cope (1973; 1979), Webb & Brown (1989)

Boreholes proving lithic sandstones spatially associated with the concealed volcanic rocks.

Bardney 1	Lithic sandstone	?Lwr Pal./PC	1851.0/1892.2	L Carb.	Lincs	TF 1192 6862	Kent (1968)
Gas Stamford 10	Lithic sandstone	?Lwr Pal./PC	251.7/254.8	Trias	Nhants	TF 0658 0096	Sanderson, IGS Pet. Rep. (unpubd.)
Wittering 1	Lithic sandstone	?Lwr Pal./PC	232.0/246.6	Trias	Lincs	TF 0492 0185	Kent (1968), Wills (1978)

Volcanic rocks of latest Ordovician or early Silurian age have been encountered by the Bicester 1, Netherton 1 and Maesteg 2 hydrocarbon exploration boreholes in the southern part of the Midlands Microcraton. Little published information is available on these provings however.

Geochemical data of the volcanic rocks in the Woo Dale 1, Glinton 1, Cox's Walk 1 and Upwood 1 boreholes were presented by Pharaoh *et al.* (1987a) and Webb & Brown (1989) and were the basis for reinterpretation of the genetic and age relationships of the concealed volcanic suites. Isotopic data are sparse (Table 1); the tuffs at Netherton yielded a K-Ar whole rock age of 424±8 Ma (unpublished IGS report cited in Wills (1978)), the lavas and tuffs at Woo Dale yielded K-Ar whole rock ages in the range 383 to 208 Ma (Cope, 1979), and the Warboys sill a K-Ar whole rock (minimum) age of 311q10 Ma (Fitch *et al.*, 1970). More recently felsic tuff at Glinton yielded an Rb-Sr whole rock age of 448±32 (Sri=0.7162±0.0021) (Pharaoh *et al.* 1987a). All of these radiometric dates should be regarded as minimum estimates for the age of crystallisation.

STRUCTURAL AND STRATIGRAPHIC POSITION OF THE CONCEALED VOLCANIC ROCKS

The Caledonides of southern Britain comprise thick basinal successions (in Wales and East Anglia) of early Palaeozoic age separated by a wedge-shaped area referred to as the Midlands Microcraton in Fig. 1. This is spatially comparable to the 'Midlands Platform' of some authors e.g. Woodcock (1990), defined on the basis of Silurian sedimentary facies. The latter term is however inappropriate for describing this area in a pre-Silurian context, and the term 'microcraton' introduced by Wills (1978), by analogy with the syndepositional and tectonic behaviour of cratons in Archaean shield areas, is preferred here. The boundaries of these terrain elements were defined by Smith (1985), Pharaoh *et al.* (1987) and Lee *et al.* (1990) and are in good agreement with the subsurface structure of northern and central England inferred by Turner (1949). Deep boreholes and seismic reflection data within the microcraton indicate that the Precambrian basement is overlain by up to 3 km of Cambrian to Tremadoc strata (Wills, 1978; Smith, 1987). Except around the margins of the microcraton, Ordovician (excluding Tremadoc) strata are absent, having been eroded (or never deposited) before the deposition of the thin onlapping Silurian platform sedimentary sequence. Seismic reflection profiles across the microcraton, e.g. the BGS Stratford 1986 line (Chadwick & Smith, 1988), indicate the presence of a laterally extensive bright reflector near the base of the Silurian sequence. The reflector is interpreted here as the top of a volcanic unit of probable early Silurian age, which has been proved in the borehole at Bicester, and possibly also in the boreholes at Netherton (Wills, 1978) and Maesteg.

Most of the boreholes lie northeast of the microcraton in a terrain referred to as the concealed Caledonide fold/thrust belt of East Anglia or eastern England (Smith, 1985, 1987; Pharaoh *et al.* 1987a and Chadwick *et al.*, 1989). Eight of these boreholes (Woo Dale 1, Eakring 146, Cox's Walk 1, Great Osgrove Wood 1, Sproxton 1, Glinton 1, Gas Council Stamford (GSt) 2 and Upwood 1) lie in a northwest-southeast trending belt (Fig. 1) about 150 km long between the south Pennines (Woo Dale 1) and Cambridgeshire (Upwood 1). A diorite sill proved by Warboys 1 is spatially associated with this belt, as are provings of volcaniclastic sedimentary rocks (Wittering 1, Stamford (GSt) 10 and Bardney 1). North Creake 1 lies isolated from the main volcanic belt to east of The Wash, while Oxendon Hall 1, Orton 1 and Hollowell 1 lie in a separate group close to the northeast margin of the microcraton.

According to the map of Smith (1985), the volcanic rocks of the main belt are replaced in the subcrop to the southeast (Fig. 1) by turbiditic sediments of early Silurian to Pridoli age (Bullard *et al.*, 1940; Molyneux, 1990). Computer-generated images of digital aeromagnetic data (Lee *et al.* 1990) indicate that in East Anglia (as in North Wales) the Silurian turbidite basin progressively blankets out the high-frequency signature from the underlying basement, of which the concealed volcanic rocks are part.

PETROGRAPHY

The volcanic rock types from the boreholes which have been re-examined are illustrated schematically in Fig. 2. The amount of cored material available has diminished over the years, particularly from the older boreholes such as Orton 1 and Oxendon Hall 1. Many of the boreholes are hydrocarbon exploration wells from which only small rock chipping samples remain. A representative collection of material is held by the National Geoscience Data Centre of the British Geological Survey at Keyworth. The following petrographical information was derived from a full examination of the cored material and thin-sections in the collection.

Felsic tuffs

The most common lithology is felsic (rhyolitic-rhyodacitic) tuff proved by 4 boreholes (Fig. 2). Glinton 1 penetrated 35 m of light brownish- grey and cream coloured vitric-crystal tuff (Kent, 1962), comprising abundant large whole and fragmented phenocrysts of pinkish feldspar (oligoclase with a little orthoclase) and corroded quartz in a devitrified vitroclastic matrix (Wells, in Kent, 1962). The 60 m of brown crystal-lithic tuff proved by North Creake 1 (Kent, 1947; Dunning, 1975) is strongly deformed. Corroded quartz crystals and fragments of epidotised and sericitised oligoclase are contained in a sheared sericite- and chlorite-rich matrix. Orton 1 proved 23 m of pale grey coloured lithic-vitric tuff containing partially resorbed quartz phenocrysts and glomerocrystic aggregates of feldspar up to 4 mm across (Evans, 1965; Dearnley, 1966). Devitrified pumice fragments are deformed by the cleavage. The matrix exhibits a relict non-welded shardic texture. The 15 m proving of felsic tuff at Oxendon Hall (Poole *et al.*, 1968) is devitrified and recrystallised. Quartz crystals occur in a matrix in which Dearnley (1966) recognised original finely banded eutaxitic texture. The petrographical evidence favours an ash-flow genesis for all four provings, with little evidence for sedimentary reworking.

Felsic lavas

At Woo Dale 1, the lowest lavas are flowage-banded, pink and green rhyodacites containing flow-aligned microphenocrysts of alkali feldspars in a devitrified hyalocrystalline groundmass of quartz and orthoclase. Chloritic pseudomorphs after ferro-

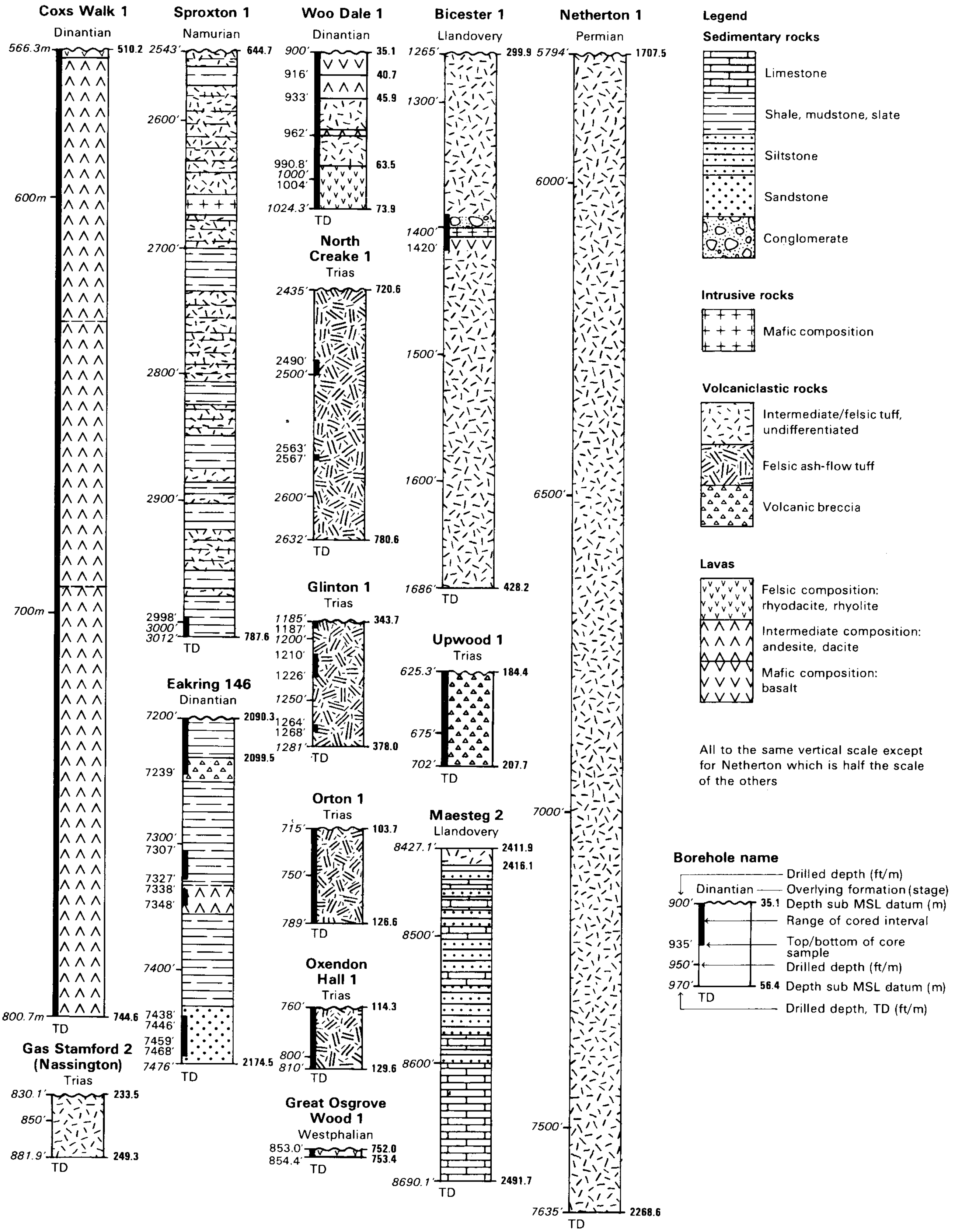

Fig. 2.- Lithology of volcanic rocks of supposed early Palaeozoic age proven by boreholes in the concealed Caledonides of eastern England and on the Midlands Microcraton. Solid bars on the left hand side of each stratigraphic column indicate the depth range sampled by conventional coring. To scale, except for Netherton, drawn at half the scale of the others.
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magnesian minerals, possibly orthopyroxene, also occur. The uppermost few metres of the volcanic sequence at Cox's Walk comprises highly altered rhyodacitic or rhyolitic lavas. They consist of scattered microphenocrysts of zoned plagioclase, now albite (<0.4 mm) and acicular hematitic pseudomorphs after plagioclase laths and/or ferromagnesian minerals, in a devitrified groundmass now comprising anhedral quartz-feldspar mosaics and white mica. Strongly altered mafic (chloritic) autoliths (cognate volcanic material) are occasionally seen and are possibly derived from the underlying andesitic lavas. Brecciated lava at 568.2 m depth consists of rhyodacitic clasts (<6 mm) in an iron-stained matrix of comminuted lava fragments, partially cemented by calcite.

The Great Osgrove Wood Borehole proved 1.4 m of felsic lava exhibiting cream and pale green-coloured flowage-banding, and containing fragments of banded lava up to 4 cm in size. In thin-section, the rocks consist largely of devitrified felsitic glass showing subspherulitic and snowflake textures of intergrown quartz and feldspar. Rare phenocrysts of feldspar, up to 3 mm in size, are mostly sericitic pseudomorphs. Quartz phenocrysts are absent. The flowage bands are up to 1 mm thick. The dark bands are very fine-grained, <0.01 mm, and poorly birefringent; they contain much disseminated opaque dust and commonly show a crude flow-alignment of quenched feldspar microlites. Pale bands are quartz-feldspar mosaics lacking flow-alignment. In places the banding is folded, but elsewhere it is disrupted. These features are typical of flowage disruption of the chilled carapace of a viscous lava. The intense alteration is probably a consequence of sub-unconformity weathering.

Intermediate lavas and tuffs

A thin (<10 m thick) flow of intermediate lava is intercalated with clastic and argillaceous sediments of supposed Lower Palaeozoic age (Edwards, 1967) in Eakring 146. The lowest lavas proved in Cox's Walk 1 (at 800-690 m depth, Fig. 2) are micro-porphyritic, amygdaloidal, calcite- veined and highly altered. Aphyric andesites at 741 m and 800 m depth consist of scattered microphenocrysts (<1.0 mm) of zoned plagioclase (now albite) in a groundmass of crudely aligned plagioclase laths, opaque oxide granules and interstitial chlorite, the latter probably representing an original glassy mesostasis. Porphyritic andesites contain phenocrysts of plagioclase (now albite and calcite) up to 7 mm long, in a trachytoid groundmass of plagioclase laths, Fe-(Ti) oxide granules and interstitial chlorite. Chlorite pseudomorphs after ferromagnesian minerals form approximately 3% of the lavas and include pseudomorphs after orthopyroxene. The andesites are overlain by about 50 m of dacite lavas from 640 to 690 m depth, which typically consist of microphenocrysts (<2 mm) of zoned plagioclase (now albite) in a groundmass of plagioclase laths, quartz-feldspar mosaics, opaque dust and chlorite-white mica (secondary) intergrowths. Trachytoid alignment of groundmass plagioclase is preserved in several dacite samples. Autoliths comprising microdioritic intergrowths of plagioclase, Fe-Ti oxide and chloritic pseudomorphs are also present in the dacites, and probably represent earlier crystallised volcanic components. The dacites are overlain by more andesite lavas from 640 to 570 m. These are more coarsely porphyritic and amgdaloidal, containing a distinct flowage fabric dipping at 50°.

The geological logs of the hydrocarbon boreholes at Bicester, Netherton, Sproxton and Stamford (GSt2) record intermediate tuffs from rock-cuttings samples. Intermediate tuffs were cored between 45.9 m and 63.5 m in Woo Dale 1 (Fig. 2). The mottled purple and green lapilli tuffs contain felsic, intermediate and mafic lava clasts in a devitrified crystal-vitric matrix. Mafic clasts are more abundant upwards. Vitroclastic fragments include pumice and possible hyaloclastic debris. Flowage-banded plagioclase-microphyric lavas of intermediate, and less commonly, mafic composition are interbedded with, and overlie, the tuffs. The lavas commonly contain pseudomorphs after orthopyroxene and rare β-quartz paramorphs (possibly xenocrysts). Vesicles are variously filled by celadonite, silica and calcite. Hollowell 1 borehole (Allsop *et al.*, 1987), not shown in Fig. 2, proved 3 units of coarse heterolithic volcanic agglomerate 2-7 m thick containing sub-angular blocks of pale green, grey and purplish colour, interbedded with finer-grained, graded and laminated pale purplish grey and green tuffs of intermediate and felsic composition. Volcaniclastic sandstones geochemically similar to intermediate volcanic rocks were proved in boreholes at Bardney, Wittering and Stamford (GSt10), which lie in close spatial proximity to the volcanic provings.

Mafic lavas, tuffs and intrusions

Igneous rocks of mafic composition are uncommon. About 23 m of coarse volcanic agglomerate was penetrated by the Upwood 1 borehole. Clasts comprise variably altered plagioclase-phyric basic amygdaloidal lavas, in a chloritised mafic fragmental matrix with carbonate veining. Amygdales are filled with quartz and zeolites (Webb & Brown, 1989). The nearby Warboys 1 borehole penetrated nearly 50 m of coarse-grained altered basic diorite (Institute of Geological Sciences, 1966). Pyroxene and amphibole phenocrysts are mainly chloritised, while zoned plagioclase phenocrysts are less altered. White mica and epidote are common alteration products and some samples exhibit carbonate alteration and silicification (Webb & Brown, 1989). The cored interval in Bicester 1 was largely of altered amygdaloidal basalt composed of chloritic pseudomorphs after ferromagnesian minerals and highly altered feldspars together with a medium-grained lithology which may represent an intrusive unit.

GEOCHEMICAL DATA

Preliminary accounts of the geochemistry of some of the concealed volcanic rocks (including samples from Glinton, Great Osgrove Wood, Upwood, Warboys and Woo Dale) have been presented by Pharaoh *et al.* (1987a) and Webb & Brown (1989). New data are presented for core samples from Bicester, Cox's Walk, Eakring 146, Hollowell, North Creake, Orton, Oxendon Hall and Woo Dale and cuttings samples from Bicester, Netherton, North Creake and Sproxton. Also considered here are data for volcaniclastic sandstones from Bardney 1 and Wittering 1 which are spatially associated with the volcanic rocks. Representative data are listed in Table 2 and a full set of data are held by the National Geoscience Data Centre.

Sample preparation and analysis

Core material was cleaned, jaw-crushed and ground to a fine powder in an agate mill. Rock cuttings samples were carefully selected from the >2mm sieve fraction to remove obvious caved material prior to crushing. The majority of the samples were analysed by X-ray fluorescence (XRF) spectrometry using the Philips PW1400 instruments at Nottingham University and Midland Earth Science Associates. Major elements were determined on fusion beads, except for samples from Warboys, Upwood, Great Osgrove Wood and Glinton which were analysed as pressed pellets checked against fusion beads (Jones & Webb, 1989). Trace elements were determined on pressed powder pellets prepared with a PVP/methyl cellulose binder. The typical limit of detection using this method is 1-2 ppm for most trace elements, but slightly higher for Ba (10 ppm). Where only a very small amount of material was available for analysis the powders were analysed by inductively coupled plasma atomic emission spectrometry (ICPS) at Royal Holloway Bedford New College, Egham. Typical limit of detection is 1-2 ppm for most trace elements. The rare earth elements (REE) were determined either at the Open University using instrumental neutron activation analysis (INAA), or at RHBC, Egham using ICPS following cation-exchange separation. Limit of detection using the latter procedure ranges from 1 ppm (for Ce, Nd, Tb and Tm), to 0.5 ppm (for Dy, Er, Gd, Ho and Sm) and 0.1 ppm (for Lu and Yb).

Alteration effects

All the volcanic rocks exhibit petrographic evidence of alteration which may have occurred at various times: during synvolcanic hydrothermal alteration and mineralisation; during low grade metamorphism associated with the Caledonian Orogeny; subsequent Hercynian mineralisation (e.g. see Le Bas, 1972); or as a result of intense sub-unconformity weathering, particularly during the Carboniferous and Triassic. Chloritised ferromagnesian minerals and sericitised feldspars are ubiquitous, and secondary carbonate and silica are commonly present. Further evidence for alteration is provided by variation diagrams based on major elements such as SiO_2, MgO, CaO, Na_2O and K_2O, which show a wide scatter. For brevity, these are not shown here however. Using petrographical and geochemical criteria, the most altered samples appear to be the intermediate lavas from Cox's Walk, intermediate tuffs from Woo Dale and the mafic lavas from Bicester. Most of the latter fail the screen for unaltered mafic rocks (MgO+CaO>12 wt %) of Pearce & Cann (1973). Most of the samples from Great Osgrove Wood and shallower samples from Glinton and Woo Dale are affected to some extent by silicification and alkali-mobility, probably a sub-unconformity weathering effect. The uppermost samples from Cox's Walk are strongly silicified probably as a result of syn-volcanic hydrothermal alteration. Zeolite-facies alteration has been recognised at Upwood (Webb & Brown, 1989) and Woo Dale. A summary of element mobility and alteration styles exhibited by many of the volcanic rocks is presented in Webb & Brown (1989, Section 7.6 and Table 7.7).

Most sample suites show good covariation of high field strength (HFS) trace elements such as Nb, Y and Zr (Figs. 3 and 4), suggesting that these elements were relatively immobile during alteration processes.

Greater reliance is therefore placed on geochemical diagrams based on the less mobile HFS elements and REE in the interpretation of the geochemical data which follows. The restricted range of Y/Zr and Nb/Zr values suggest relative homogeneity of the magmatic source region.

Primary composition

The volcanic rocks are classified in terms of their primary petrochemical composition on the Nb/Y-Zr/TiO_2 diagram (Winchester & Floyd, 1977), Fig. 5. Interpretation of this diagram must be made with care because many of the rocks plotted on it are fragmental rocks (Fig. 2) which may have suffered considerable modification from primary, igneous compositions. The rocks plot in fields ranging from

Table 2.- Geochemical data for representative samples of the concealed volcanic suite. Sample depths in metres sub Mean Sea Level. Major elements in weight%, total Fe as Fe_2O_3. Analyses shown with LOI marked * were determined on pressed powder pellets and calculated on an equivalent anhydrous basis (Webb & Brown, 1989). Analytical procedures: XN, XRF at Nottingham; PE, rare earth elements by ICP at Egham; NA, rare earth and other trace elements by INAA at the Open University; Cuts, Cuttings sample. Trace elements in ppm; -, not determined.

Sample number	BDZ0066	BLF8513	EAK7348	BDB4343	BDT8050	BDT8051
Borehole	Bicester 1	Cox's Walk	Eakring146	Glinton 1	Glinton 1	Glinton 1
Lithology	Basalt (altered)	Andesite lava	Andesite lava	Felsic tuff	Felsic tuff	Felsic tuff
Depth (m)	429.8	662.1	2239.7	369.7	385.9	386.2
Analytical proc.	XN+PE	XN+PE	XN+PE	XN+NA	XN+NA	XN+PE
SiO2	49.80	55.14	57.82	70.42	67.89	76.84
TiO2	1.71	1.35	1.58	.46	.30	.23
Al2O3	18.81	16.06	14.85	14.88	18.92	11.67
Fe2O3	11.86	7.74	8.25	2.29	1.97	1.00
MnO	.06	.17	.18	.11	.04	.10
MgO	4.04	4.14	2.14	.63	.44	.26
CaO	3.56	4.45	4.82	2.27	.87	2.52
Na2O	2.48	2.80	4.39	2.01	4.62	3.00
K2O	2.68	1.02	.82	4.84	4.65	3.58
P2O	5 .25	.20	.35	.09	.05	.05
LOI	5.21	6.95	5.29	*	*	*
Rest	.20	.15	.18	.26	.26	.20
Total	100.66	100.17	100.67	98.20	100.01	99.45
C.I.P.W. normative values						
Diff. Index	45.21	49.14	58.27	80.73	86.63	87.68
PI	39.49	47.99	58.81	28.64	43.58	33.49
Norm Plag (%An)	43.60	47.02	33.13	39.28	9.91	23.55
Ba	385	116	184	1056	952	787
Cr	302	154	7	3	0.8	1
Cu	22	76	287	5	8	6
Hf	-	-	-	9.67	9.66	-
Nb	5	8	11	16	21	16
Ni	100	29	5	3	3	-
Pb	12	8	2	20	22	22
Rb	64	25	32	185	197	138
Sc	-	24	-	11.3	9.5	6
Sr	222	115	154	146	151	132
Ta	-	-	-	1.72	2.36	-
Th	3	5	7	14.1	23.5	16
V	135	213	133	17	10	7
Y	36	23	49	45	67	42
Zn	32	76	80	60	59	34
Zr	133	150	261	374	334	239
La	14.40	13.31	29.21	42.30	63.70	43.21
Ce	33.05	28.46	64.43	93.10	140.00	91.08
Pr	4.49	3.73	8.03	-	-	10.70
Nd	18.98	14.95	36.68	46.80	65.60	39.91
Sm	4.81	3.40	8.18	9.58	13.10	7.89
Eu	1.67	0.88	2.32	2.21	2.11	1.19
Gd	5.50	3.55	8.33	-	-	6.96
Dy	5.59	3.51	8.07	-	-	6.38
Ho	1.12	0.72	1.74	-	-	1.24
Er	3.29	2.24	4.48	-	-	3.74
Yb	3.01	2.10	4.25	4.30	6.00	3.49
Lu	0.49	0.35	0.64	0.69	1.00	0.55

Sample number	GO853.4	GO853.9	GO854.0	HOL7	NETH7335	NC2494.5
Borehole	Gt Osgrove Wood 1	Gt Osgrove Wood 1	Gt Osgrove Wood 1	Hollowell 1	Netherton 1	N Creake 1
Lithology	Felsic lava	Felsic lava	Felsic lava	Intermed tuff	Intermed tuff	Felsic tuff
Depth (m)	853.4	853.9	854.0	350.8	2235.7	760.3
Analytical proc.	XN+NA	XN+PE	XN+NA	XN+PE	XN+PE Cut	XN+PE
SiO2	74.39	75.40	73.75	54.85	55.57	68.43
TiO2	.18	.18	.17	.34	.68	.58
Al2O3	15.65	12.93	16.22	17.17	16.85	14.10
Fe2O3	.86	.98	.31	5.94	8.34	4.64
MnO	-	.01	-	.14	.13	.08
MgO	.33	.18	.26	4.16	3.11	1.87
CaO	.06	.15	.04	3.55	4.67	2.16
Na2O	.61	.26	.24	1.60	4.33	2.37
K2O	7.40	8.44	7.54	4.72	2.64	3.71
P2O5	.13	.11	.12	.08	.13	.13
LOI	*	1.38	*	7.86	3.24	1.90
Rest	.21	.24	.22	.22	.30	.16
Total	99.82	100.26	98.87	100.63	99.99	100.13
C.I.P.W. normative values						
Diff. Index	90.95	94.14	90.90	56.07	56.43	74.47
PI	5.19	2.60	2.06	33.57	57.96	30.82
Norm Plag (% An)	-	14.28	-	56.18	33.95	33.38
Ba	682	886	704	841	1379	482
Cr	0.7	1	0.8	89	65	23
Cu	7	6	6	41	21	12
Hf	5.45	-	5.50	-	-	-
Nb	12	12	12	21	6	12
Ni	10	20	11	7	17	9
Pb	8	-	12	9	20	7
Rb	180	204	195	148	65	94
Sc	5.8	8	6.4	-	-	-
Sr	438	409	442	47	442	134
Ta	1.50	-	1.39	-	-	-
Th	15.5	17	16.3	31	7	14
V	10	12	15	69	141	59
Y	36	25	28	44	22	38
Zn	10	21	9	55	81	42
Zr	178	166	171	201	87	196
La	49.60	50.23	60.60	54.02	29.07	34.19
Ce	117.00	104.90	131.50	106.70	56.54	69.46
Pr	-	11.28	-	10.36	7.23	7.62
Nd	51.60	39.71	48.50	43.33	28.42	33.07
Sm	8.72	6.46	8.29	8.12	5.40	6.51
Eu	1.29	0.98	1.18	1.39	1.41	1.30
Gd	-	4.37	-	7.20	5.01	6.23
Dy	-	4.02	-	6.42	4.38	5.78
Ho	-	0.92	-	1.37	0.96	1.25
Er	-	2.84	-	3.58	2.56	3.25
Yb	3.80	2.96	3.30	3.59	2.55	3.28
Lu	0.65	0.49	0.60	0.55	0.41	0.51

Sample number	OR718	OH236	BX9327C	BX9329M	BX7351	BX7374
Borehole	Orton 1	Oxendon Hl	Upwood 1	Upwood 1	Warboys 1	Warboys 1
Lithology	Felsic tuff	Felsic tuff	Basalt clast	Tuff matrix	Basic diorite	Diorite
Depth (m)	218.8	236.0	208.2	212.8	205.2	213.8
Analytical proc.	XN+PE	XN+PE	XN+PE	XN+NA	XN+NA	XN+NA
SiO2	72.34	69.54	48.97	48.89	51.07	52.71
TiO2	.41	.43	.76	.77	.86	1.18
Al2O3	14.59	13.79	20.73	15.34	13.54	13.52
Fe2O3	1.66	1.61	7.22	12.09	10.54	10.48
MnO	.02	.06	.20	.17	.16	.17
MgO	.57	.64	5.98	6.40	10.69	7.29
CaO	.80	1.81	10.71	12.31	9.60	5.79
Na2O	4.12	3.23	1.78	1.19	2.09	3.73
K2O	3.36	4.18	1.22	.76	1.11	2.33
P2O5	.11	.12	.10	.10	.16	.53
LOI	1.79	3.65	*	*	*	*
Rest	.22	.24	.15	.13	.22	.22
Total	99.99	99.30	97.82	98.15	99.04	97.95
C.I.P.W. normative values						
Diff. Index	89.06	85.48	22.96	16.85	24.52	46.85
Pl	39.22	37.65	61.89	45.75	42.44	46.32
Norm Plag (% An)	9.17	23.80	74.92	77.29	57.87	29.60
Ba	741	1046	222	148	234	298
Cr	24	3	100	70	333	49
Cu	5	3	117	73	125	275
Hf	-	-	-	2.06	2.67	4.52
Nb	16	13	5	6	7	10
Ni	7	3	23	37	124	33
Pb	56	28	9	2	9	10
Rb	139	148	26	14	26	46
Sc	9	-	31	26.6	36.3	22.9
Sr	196	139	197	128	187	122
Ta	-	-	-	0.46	1.12	1.57
Th	12	11	1	1.9	4.1	6.5
V	26	37	205	223	264	353
Y	41	40	16	19	21	33
Zn	60	45	56	87	86	75
Zr	296	322	85	82	100	157
La	42.94	40.19	7.59	9.34	15.60	28.90
Ce	94.40	78.34	16.25	19.00	32.00	61.60
Pr	11.07	9.48	2.18	-	-	-
Nd	42.03	42.23	7.86	10.50	16.30	32.60
Sm	8.30	7.72	1.81	2.35	3.79	6.88
Eu	1.83	1.66	0.77	0.76	1.07	1.74
Gd	7.09	6.63	2.01	-	-	-
Dy	6.09	5.83	2.29	-	-	-
Ho	1.22	1.25	0.52	-	-	-
Er	3.55	3.26	1.52	-	-	-
Yb	3.33	3.20	1.56	1.80	2.00	2.70
Lu	0.54	0.50	0.27	0.32	0.34	0.49

Sample number	BX7383	W3	WD1020	BA6188	SP2851	BZ459
Locality	Warboys 1	Woo Dale 1	Woo Dale 1	Bardney 1	Sproxton 1	Wittering 1
Lithology	Diorite	Intermed tuff	Felsic lava	Lithic sandstone	Lithic sandstone	Lithic sandstone
Depth (m)	217.0	291.7	310.9	1886.1	869.0	294.3
Analytical proc.	XN+PE	XN+NA	XN+PE	XN	XN Cut	XN+PE
SiO2	50.76	56.82	68.83	62.84	53.38	60.25
TiO2	1.22	1.46	.66	.94	1.49	1.00
Al2O3	14.61	17.37	14.63	15.32	15.88	19.67
Fe2O3	10.95	10.33	4.08	7.36	11.71	9.40
MnO	.16	.08	.05	.12	.17	.19
MgO	8.50	4.66	.55	2.44	3.85	3.31
CaO	7.02	2.35	.97	2.52	4.27	.74
Na2O3	.08	3.22	4.33	2.44	2.93	2.06
K2O	1.80	3.28	3.85	2.74	.65	3.41
P2O	5 .15	.22	.15	.11	.22	.08
LOI	*	*	2.11	3.41	5.08	*
Rest	.26	.19	.22	.18	.14	.19
Total	98.51	99.98	100.43	100.42	99.77	100.30
C.I.P.W. normative values						
Diff. Index	37.74	55.82	85.51	64.65	44.60	61.49
Pl	48.11	38.00	41.65	-	-	20.90
Norm Plag (% An)	44.32	27.66	10.04	36.33	44.33	16.00
Ba	378	309	735	714	142	502
Cr	173	27	26	49	77	72
Cu	224	16	6	26	97	14
Hf	-	5.63	-	-	-	-
Nb	10	11	15	9	11	14
Ni	97	13	11	21	23	44
Pb	9	8	9	11	22	14
Rb	44	85	105	82	27	127
Sc	26	22.3	10	-	-	17
Sr	435	251	170	133	200	114
Ta	-	0.74	-	-	-	-
Th	7	7.30	13	9	6	12
V	294	190	41	126	185	107
Y	21	51	57	32	35	24
Zn	80	79	66	-	-	100
Zr	117	231	390	168	-	181
La	16.09	30.80	32.41	-	-	29.11
Ce	33.23	69.60	72.04	-	-	62.03
Pr	4.21	-	8.69	-	-	7.36
Nd	16.01	36.00	34.37	-	-	26.75
Sm	3.59	8.18	7.59	-	-	5.08
Eu	1.05	2.30	1.68	-	-	1.10
Gd	3.56	-	7.63	-	-	4.30
Dy	3.43	-	8.30	-	-	4.44
Ho	0.73	-	1.70	-	-	0.90
Er	2.01	-	5.23	-	-	2.77
Yb	1.85	4.20	5.31	-	-	2.76
Lu	0.30	0.70	0.84	-	-	0.45

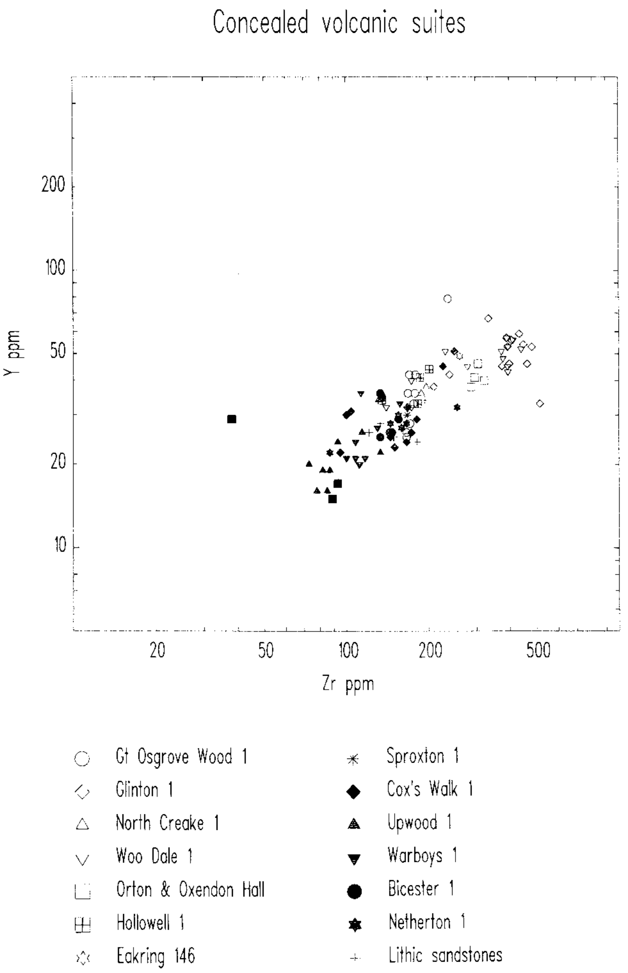

Fig. 3.- Y-Zr covariation diagram, for components of the concealed volcanic suite encountered in 14 boreholes (see key) together with lithic sandstones from 3 boreholes (crosses). Filled squares are clasts in Triassic basal breccia overlying the volcaniclastic basement at Hollowell.

sub-alkaline basalt and basaltic-andesite (Bicester, Upwood, Warboys and a few samples from Woo Dale and Cox's Walk), to andesite (Netherton, Eakring 146, most Woo Dale tuffs, some Hollowell samples and volcaniclastic sandstones from Bardney and Wittering), dacite (North Creake tuffs and many Cox's Walk lavas) and rhyodacite (most lavas from Woo Dale and Great Osgrove Wood, and the majority of felsic tuffs from Orton, Oxendon Hall and Glinton). A few samples from Great Osgrove Wood and Glinton are of rhyolitic composition. In terms of the Nb/Y ratio (an index of original alkalinity), the rocks are clearly subalkaline. Similar classifications are obtained using the other diagrams presented by Winchester & Floyd (op. cit.) and are in good agreement with the petrographical classification outlined in an earlier section. The data cluster into broadly mafic to intermediate (basaltic-andesite/ andesite/dacite) and felsic (rhyodacite/ rhyolite) compositional groupings (Fig. 5).

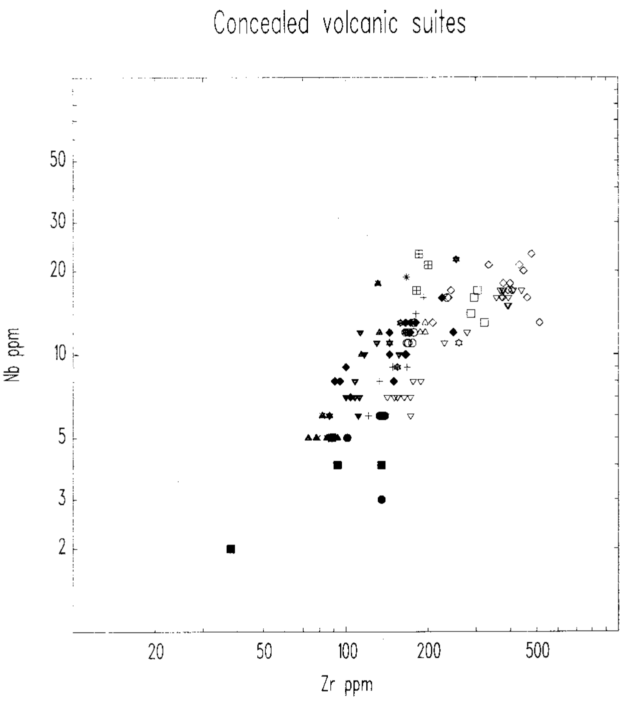

Fig. 4.- Nb-Zr covariation diagram for the concealed volcanic suite.
Symbols as in key to Fig. 3.

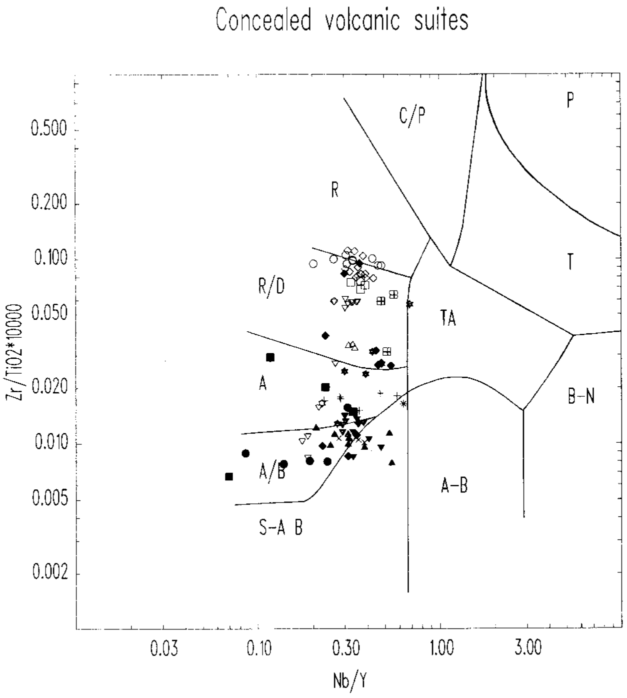

Fig. 5.- Zr/TiO2-Nb/Y covariation diagram. Field boundaries after Winchester & Floyd (1977): S-AB, sub-alkaline basalt; A/B, basaltic-andesite; A, andesite; D/R, dacite/rhyodacite; R, rhyolite; A-B, alkali-basalt; TA, trachyandesite; T, trachyte; B/N, basanite/ nephelinite; P, phonolite; C/P, comendite/ pantellerite. Symbols as in Fig. 3.

The distribution of certain immobile elements e.g. Zr, Y and Nb was investigated to test for the presence of a compositional gap, as suggested by Fig. 5. Histograms of SiO2 content are frequently used to demonstrate bimodality in little altered volcanic suites, but are of uncertain reliability in the light of the widespread silicification described above. The data for Zr (Fig. 6a) show a bimodal tendency with a distinct, separate peak for Zr at high concentrations, while it is less evident in the data for Y (Fig. 6b), which do however show a distinct skew toward higher values. The felsic ash-flow tuffs from Glinton, Orton etc (black ornament) make a substantial contribution to the high Zr values, rhyodacite lavas from Woo Dale comprising most of the remainder. A significant proportion of the mafic samples come from Bicester and Netherton (diagonal ornament), which are probably not coeval with the remainder of the samples.

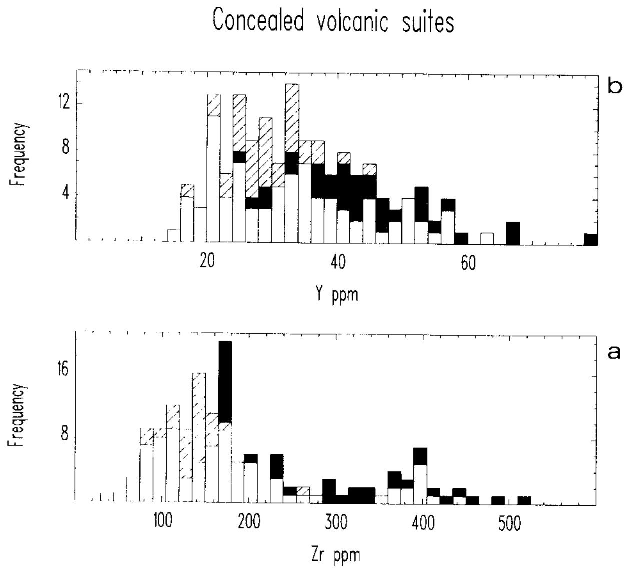

Fig. 6.- Histograms of Zr (n=125) and Y (n=149) content in the concealed volcanic suite. Samples of rhyolite and rhyodacitic composition from Glinton, Orton, Oxendon Hall and Great Osgrove Wood shown in black (nZr=34, nY=35); samples of mafic and intermediate composition from Bicester and Netherton shown with a diagonal rule (nZr=29, nY=35).

The AFM plot (Fig. 7) is based on major elements susceptible to mobility during alteration and cannot be interpreted with the same degree of confidence as diagrams based on immobile trace elements. Few of the samples plot in the tholeiitic field of the diagram, the majority forming a well defined (although scattered) calc-alkaline fractionation trend, as previously recognised by Webb & Brown (1989). The heterolithic samples of tuff from Hollowell contain anomalously high levels of MgO for intermediate and felsic rocks, probably reflecting the incorporation of mafic clastic material.

Volcanotectonic setting

Data for concealed volcanic rocks of mafic composition satisfying the alteration screen (MgO+CaO>12 wt.%) are plotted (Fig. 8) on the Ti-Zr-Y triangular diagram of Pearce & Cann (1973). The majority of the samples from Upwood and Warboys plot in the volcanic arc basalt field (C). The few mafic samples from Bicester which pass the

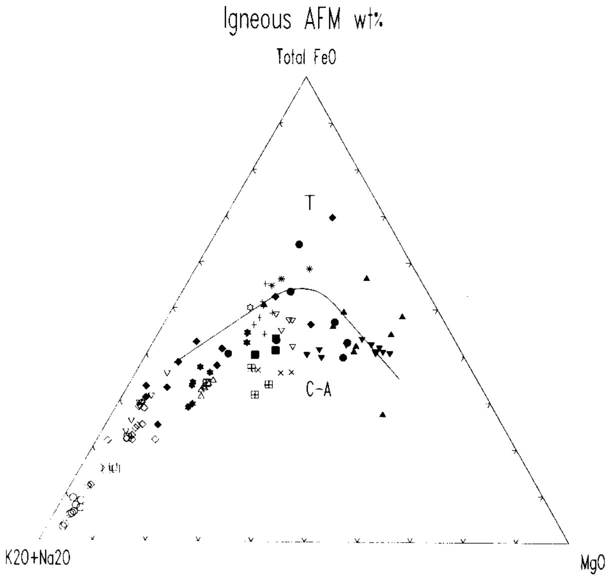

Fig. 7.- Igneous AFM diagram for all samples. Field boundary between tholeiitic (T) and calc-alkaline (C-A) fields after Irvine & Baragar (1971). Symbols as in Fig. 3.

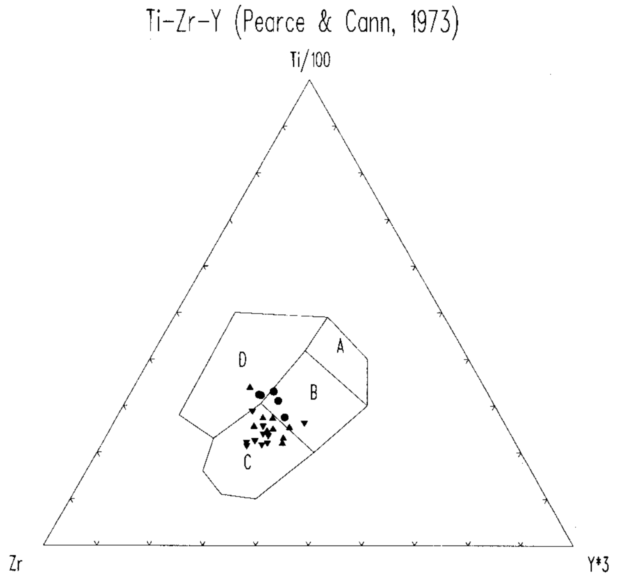

Fig. 8.- Ti-Zr-Y covariation diagram for mafic (MgO+CaO>12 wt %) compositions. Field boundaries after Pearce & Cann (1973): A, island arc tholeiites; B, MORB overlap field; C, calc-alkaline arc basalts; D, within-plate basalts. Symbols as in Fig. 3.

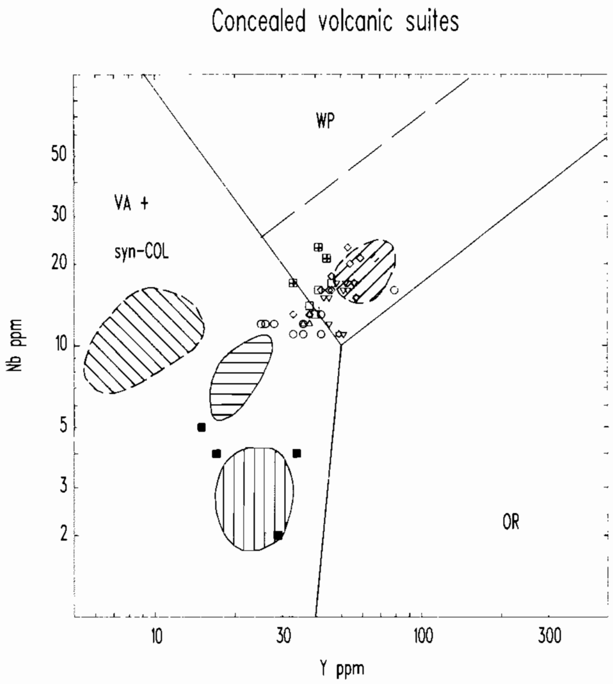

Fig. 9.- Nb-Y covariation diagram for felsic and intermediate volcanic compositions. Field boundaries for plutonic equivalents derived by Pearce *et al.* (1984): VA + syn-COL, volcanic arc and syn-collision felsic magmas; WP, within-plate felsic magmas; OR, ocean-ridge felsic magmas. The fields occupied by data from volcanic rocks of the Precambrian Charnian Supergroup (vertical rule), granitoid rocks of the Caledonian Mountsorrel-South Leicestershire Diorite Suite (horizontal rule), and from the Caledonian plutons of Weardale (diagonal rule sloping down to right) and Wensleydale (rule sloping down to left) are from Webb & Brown (1989). Symbols as in Fig. 3.

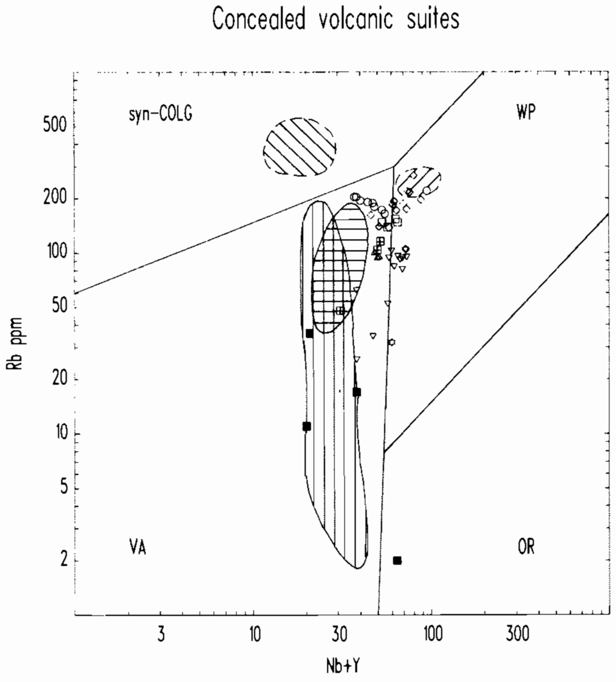

Fig. 10.- Rb-(Nb+Y) covariation diagram. Boundaries after Pearce *et al.* (1984). Field labels and data sources as in Fig. 9. Symbols as in Fig. 3.

above criterion plot in the within-plate field (D), or in the adjacent part of the MORB overlap field (B). These characteristics suggest that the arc component is less significant in the Bicester samples.

The data for the felsic volcanic rocks are plotted on the discrimination diagrams for granitic rocks developed by Pearce *et al.* (1984). Usage of these diagrams is here extended to felsic volcanic rocks, and some of the data relate to fragmental rocks, as noted above. On the Nb-Y diagram (Fig. 9), data plot in the volcanic arc (samples from Great Osgrove Wood, North Creake) to within-plate (samples from Glinton, Orton, Woo Dale) fields, data from some boreholes occupying both fields. A similar spread of data is featured on the Rb-Nb+Y diagram (Fig. 10) even though Rb is likely to be mobile during alteration processes (e.g. Merriman *et al.*, 1987). Data from the calc-alkaline granitoid intrusions of Leicestershire e.g. Mountsorrel, Croft and Enderby (Webb & Brown, 1989) which are attributed a Caledonian age (Le Bas, 1968, 1982; Pidgeon & Aftalion, 1978) plot adjacent to those of the concealed volcanic rocks in the volcanic arc field, whereas data from the Wensleydale pluton (Webb & Brown, 1989) of the central Pennines lie in the within-plate field. The three samples of the heterolithic tuff proven in the basement at Hollowell also plot close to these, however the volcanic clasts from the Triassic breccia overlying the basement at Hollowell have far lower contents of Nb (2-5 ppm) and plot in the lower part of the volcanic arc field, adjacent to the lavas of the Charnian Supergroup (Pharaoh *et al.*, 1987a). Together, Figs. 9 and 10 could suggest that the concealed felsic volcanics were erupted in a mature volcanic arc located on continental crust. Some components, particularly the felsic tuffs from Glinton, exhibit a within-plate signature and may have been erupted in a more transitional environment, possibly an ensialic back-arc basin (Bevins *et al.*, 1984; Kokelaar *et al.*, 1984).

Data for REE for a limited number of samples are presented in Fig.11. The mafic samples from Upwood, Warboys and a basaltic-andesite from Cox's Walk are plotted in Fig. 11a, and intermediate-felsic samples from Eakring, North Creake, Warboys and Woo Dale are plotted in Fig. 11b. The chondrite-normalised profiles of these groups show strong enrichment of the light REE (LREE) from La to Sm, with flatter profiles across the heavy REE (HREE). The Eu anomaly (Eu/Eu*, where Eu* is the extrapolated value between Sm and Gd) ranges from 0.89-1.19 in mafic rocks to 0.65-0.89 in intermediate-felsic compositions. The general parallelism of the profiles suggest that all the samples depicted in Fig. 11a and b could be related by crystal- fractionation, and the increasing size of the negative Eu anomaly suggests fractionation of plagioclase may have played a part in this. The evolved felsic rocks from Glinton, Orton, Oxendon Hall and Great Osgrove Wood are plotted in Fig. 11c. The profiles are similar in shape to the suites shown in Fig. 11a and b, indeed the profiles for the HREE are indistinguishable. The LREE are strongly enriched in the evolved felsic rocks however (c.f. the envelope of data from Fig. 11a and b). The Eu anomaly is also significantly larger and more negative (0.53-0.58) suggesting significant plagioclase fractionation in these samples. REE profiles for the samples from Bicester and Netherton (Fig. 11d) have similar slopes to those shown in Fig. 11a and b.

Data for a limited but representative suite of samples are plotted in the form of geochemical patterns (Pearce, 1982) in Fig. 12. The groups of samples plotted are the same as in Fig. 11. 'Spidergrams' of the mafic rocks from Warboys, Upwood and Cox's Walk (Fig. 12a) exhibit a gentle slope from P to Yb, with a slight enrichment of Ce with respect to neighbouring elements Nb and P, and a moderate enrichment of large ion lithophile (LIL) elements, Sr to Ba. It should be noted that in all the MORB- normalised diagrams, the most incompatible element that can be regarded as relatively immobile during secondary alteration processes, and thus indicative of magmatic evolution, is Th (Pharaoh & Pearce, 1984; Merriman *et al.*, 1987). Andesite lavas from Eakring 146, diorite from Warboys, intermediate tuffs and felsic lavas from Woo Dale and felsic tuffs from North Creake exhibit further enrichment, both in HFS elements, light REE (e.g. Ce) and Th, with respect to Nb (Fig. 12b). Slight depletion of P and Ti is evident in some samples. The strong enrichment of Th and light REE is typical of arc-related volcanic suites, particularly mature calc-alkaline arcs (Pearce, 1982). The most evolved felsic compositions (rhyodacitic and rhyolitic tuffs from Glinton, Orton, Oxendon Hall and Great Osgrove Wood) exhibit the strongest enrichment in Th, in Ce (with respect to Nb and Ta) and strong depletion of Ti and P with respect to other HFS elements (Fig. 12c). Their geochemical patterns are typical of evolved volcanic rocks erupted in mature volcanic arcs.

The data for the spatially distinct volcanics from the south of the microcraton (Bicester 1, Netherton 1) have been plotted separately in Fig. 12d. The geochemical patterns are rather similar in shape (with enrichment of Th and Ce, relative depletion of Nb) to other mafic and intermediate components of the concealed volcanic suite. Although the strong enrichment of LIL elements observed in Fig. 12 is possibly an artefact of alteration, the progressive enrichment of LIL elements with increasing silica content, in conjunction with increasing Th, suggests these enrichments also reflect magmatic evolution. The more evolved compositions exhibit depletion of Ti and P, presumably due to removal of these elements in fractionating phases such as ilmenite and apatite. The content of HFS elements such as Nb, Zr and Hf is generally greater than that of MORB.

ISOTOPIC DATA

Very few isotopic age data are available in the published literature to help constrain the age of eruption of the concealed volcanic rocks. Although some data are held in unpublished Geological Survey reports, these are mostly Rb-Sr or K-Ar analyses of uncertain reliability. New isotope age data detailed below were obtained from 25 samples of the concealed volcanic rocks using the Rb-Sr and Sm-Nd techniques.

Analytical techniques

The $^{87}Sr/^{86}Sr$ isotopic composition of samples was determined using a V.G. 354 multicollector mass spectrometer. During the period of analyses a value of 0.710240±39 ppm (average of 21 analyses) was obtained for the NBS 987 international $^{87}Sr/^{86}Sr$ isotopic standard. The Rb/Sr ratios were determined by XRF using a Philips automated 1450 spectrometer, following the procedure of Pankhurst & O'Nions (1973) and the quoted ratios are the average analyses of both sides of a powder pellet. The Rb and Sr concentrations (which are not required for the age calculation) were estimated using the molybdenum Compton scatter peak matrix correction procedure and are probably accurate to about ±5% (1-sigma). The best fit lines on the isochron diagrams were determined using a York-Williamson least-squares fit regression with errors on both axes. The errors assigned to the strontium ratio are 0.01% (1-sigma) and the errors on the Rb/Sr ratio are 0.5% (1-sigma). The decay constant used for ^{87}Rb is $1.42*10^{-11}a^{-1}$ (Steiger and Jäger, 1977). Where the MSWD is greater than 3, the errors on the age and initial ratio have been multiplied by the square root of the MSWD. This artificially reduces the MSWD to unity and expresses the uncertainty on the regression in terms of error due to the excess geological scatter.

Concentrations of Sm and Nd, determined by isotope dilution using ^{149}Sm and ^{150}Nd enriched isotopic tracers, and the $^{143}Nd/^{144}Nd$ isotope ratios were measured on a V.G. 354 mass spectrometer which gave a value of 0.511843±0.000016 ppm (2-sigma) for the La Jolla international $^{143}Nd/^{144}Nd$ standard during analysis of the samples. The decay

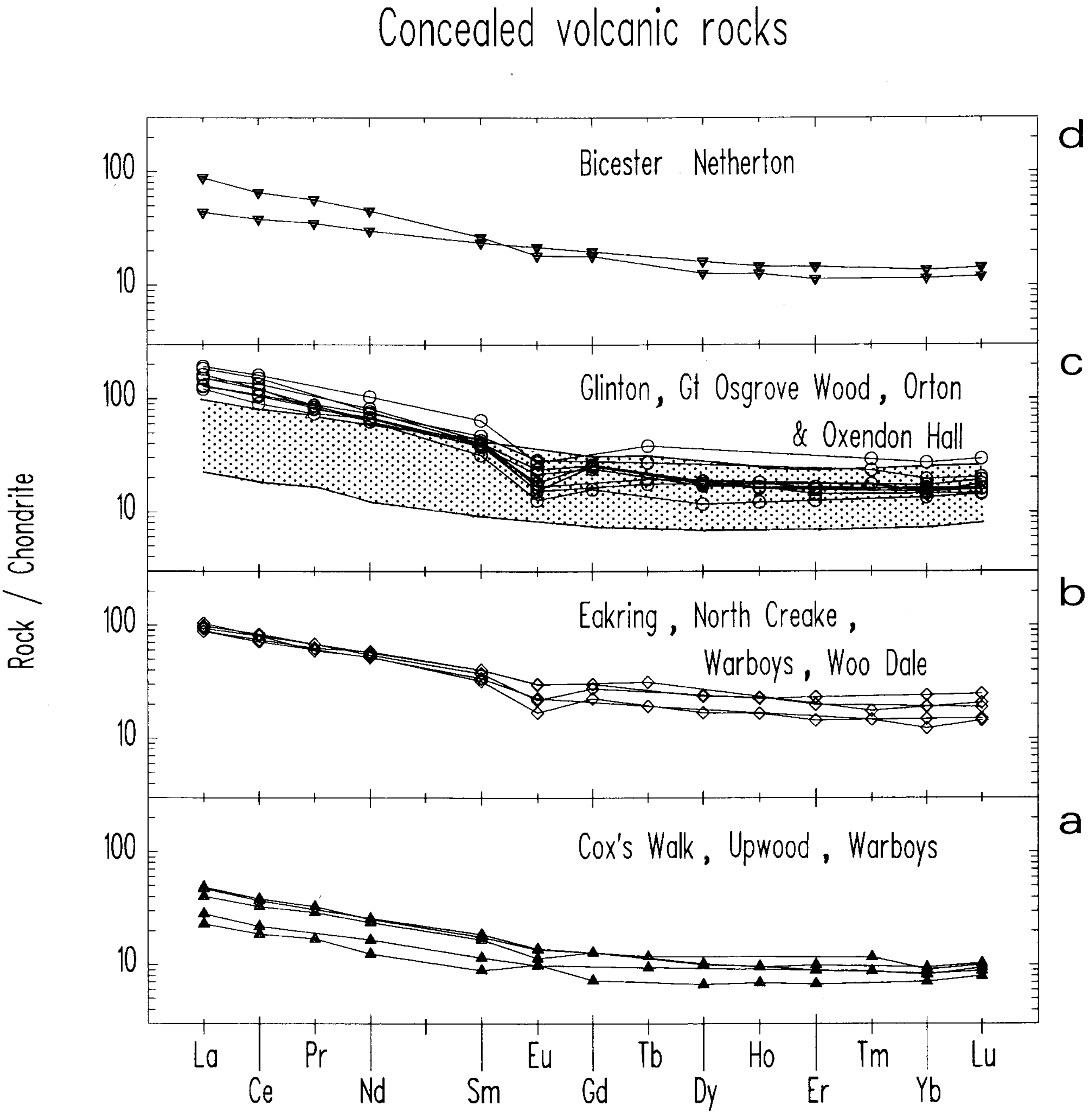

Fig. 11.- Chondrite-normalised rare earth element data for the concealed volcanic suite. Chondrite-normalisation values from Nakamura (1974). N.B. the symbols used here are not the same as those in Figs. 3 to 10.

a. Mafic samples from Warboys (basic diorite), Upwood and Cox's Walk (basaltic-andesite lavas).

b. Intermediate-felsic compositions from Eakring 146 (andesite), North Creake (felsic tuff), Woo Dale (andesitic tuff and rhyodacite lava) and Warboys (diorite).

c. Rhyodacitic-rhyolitic volcanic rocks from Glinton, Orton and Oxendon Hall (ash-flow tuffs) and Great Osgrove Wood (flowage-banded lava). Shaded area is range of data depicted in Figs. 11a and b.

d. Patterns for (early Silurian) volcanic provings in the southern part of the Midlands Microcraton (Bicester and Netherton).

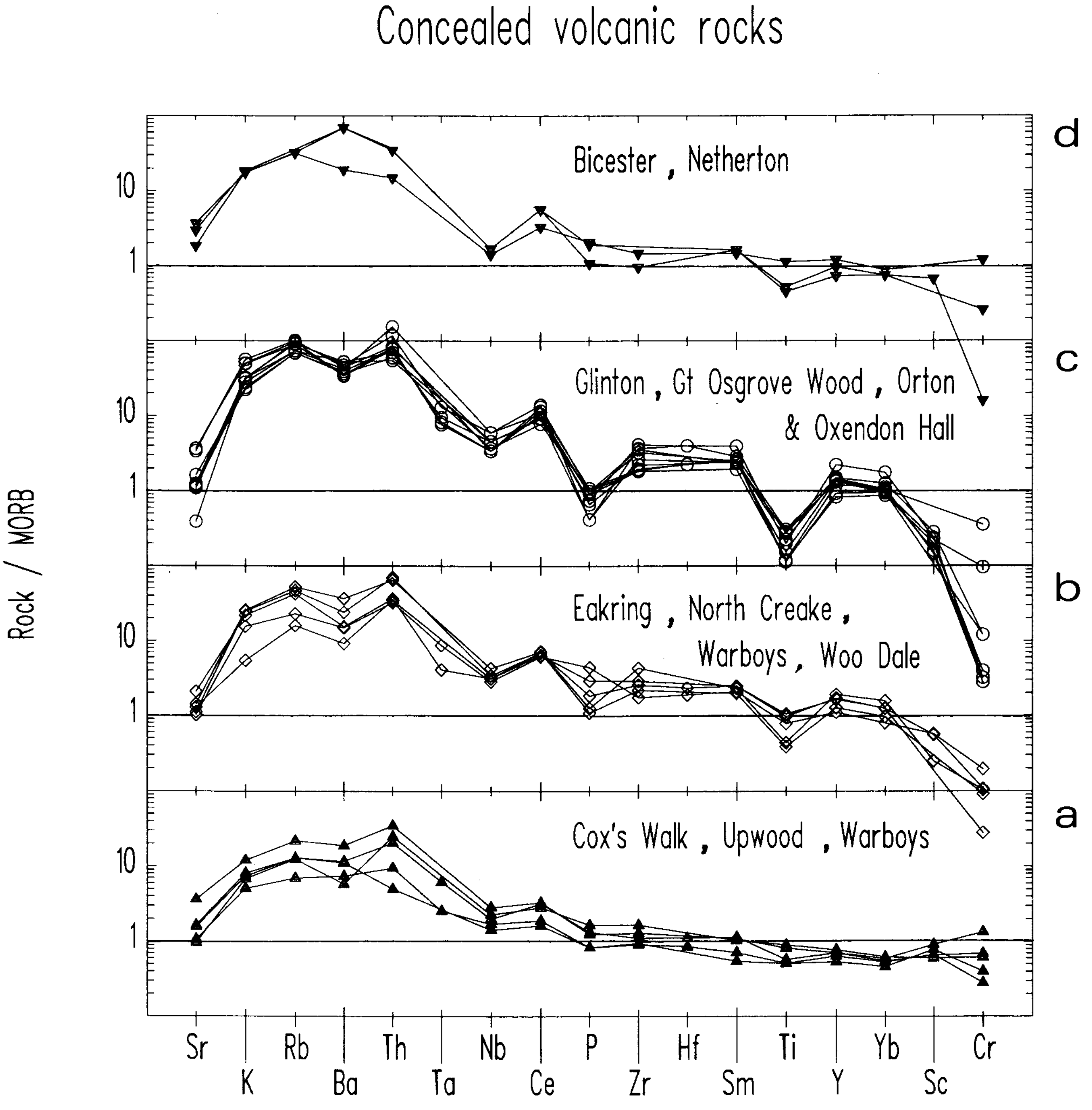

Fig. 12.- MORB-normalised geochemical patterns for the concealed volcanic suite. MORB-normalisation values from Pearce (1982). Sample groups as in Fig. 11.

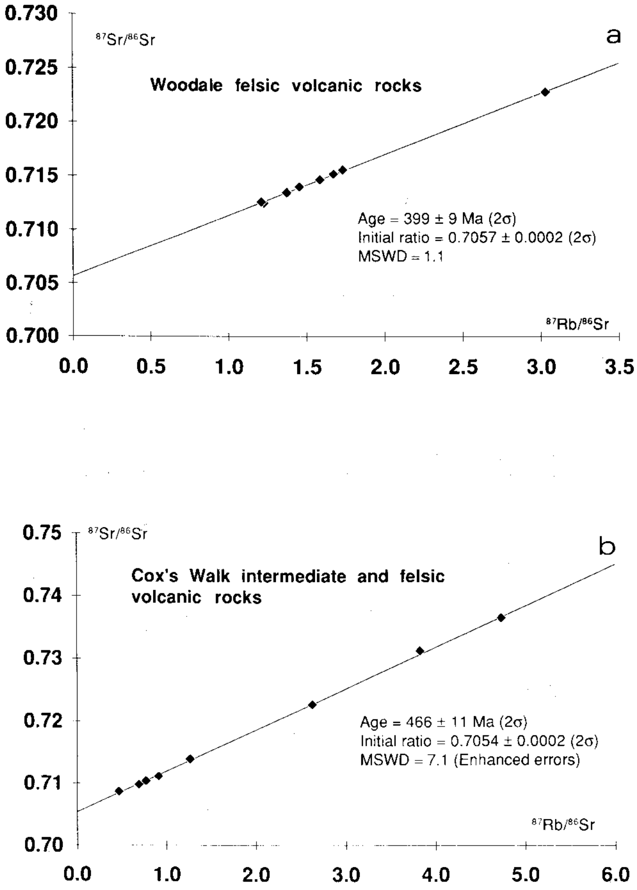

Fig. 13.- Rb-Sr isochron diagrams for samples from two provings of the concealed volcanic suite.

a. Rhyodacitic lavas, Woo Dale borehole.

b. Basaltic-andesite and dacite lavas, Cox's Walk borehole.

constant taken for ^{147}Sm = 6.54*10^{-12} a^{-1}. The following values were used in the calculation of depleted mantle (TDM) model ages and Nd epsilon values; $(^{143}\mathrm{Nd}/^{144}\mathrm{Nd})_{CHUR}$ = 0.512638, $(^{143}\mathrm{Nd}/^{144}\mathrm{Nd})_{DM}$ = 0.5131, $(^{147}\mathrm{Sm}/^{144}\mathrm{Nd})_{CHUR}$ = 0.1967 and $(^{147}\mathrm{Sm}/^{144}\mathrm{Nd})_{DM}$ = 0.225 (DePaolo & Wasserburg, 1976).

Results

New isotopic data for the volcanic rocks at Woo Dale and Cox's Walk are presented in Table 3 and shown graphically in Figs. 13 and 14. Nine samples from the Woo Dale borehole give an Rb-Sr whole rock isochron age of 399±9 Ma (MSWD=1.1) and an initial ^{87}Sr/^{86}Sr ratio of 0.7057±0.0002 (Fig. 13a). Nine samples from Cox's Walk borehole give an Rb-Sr whole rock age of 466±11 Ma (MSWD=7.1) and an initial Sr ratio of 0.7054±0.0002 (Fig. 13b). Within the errors the latter result agrees with the less precise age of 448±32 Ma obtained from the felsic tuffs at Glinton (Pharaoh *et al.*, 1987a), although there is a large difference in the initial ratios of the two suites, Glinton having the higher initial ratio of 0.7162±0.0021.

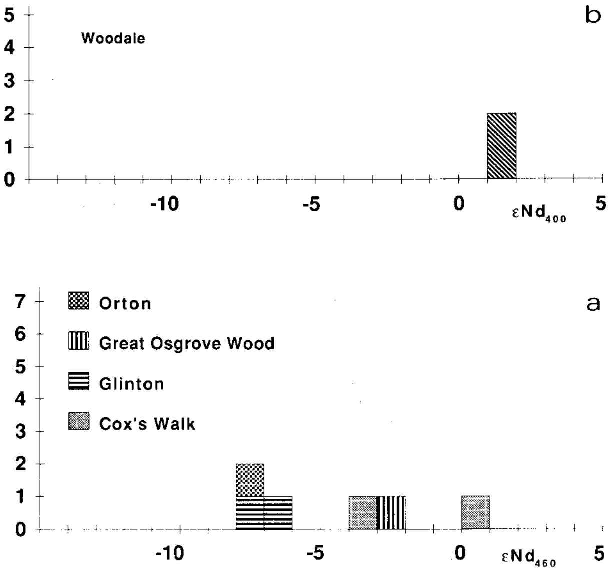

Fig. 14.- εNdt for concealed volcanic suites at model ages of: a. 400 Ma; b. 460 Ma.

Two samples from Woo Dale have positive εNd400 values between +1 and +2 within the lower range of modern-day mantle values (Fig. 14a). The majority of calc-alkaline and OIB basalts have values between -2 and +8 (White & Hofmann, 1982) so the Woo Dale felsic lavas could be derived from either of these sources by fractionation and crustal contamination. The parent magma to these rhyodacites could also be formed by greater degrees of crustal contamination of a more depleted mantle such as MORB, which has modern day Nd epsilon values between +8 and +12 (White & Hofmann, 1982). The Nd epsilon values of the volcanic rocks at Orton, Great Osgrove Wood, Glinton and Cox's Walk are calculated from an early Ordovician age (timescale of McKerrow *et al.*, 1985) of 460 Ma.

The two samples from Cox's Walk have significantly different εNd_{460} values of 3.3 and 0.7 (Fig. 14b). This difference could mean that the two samples were derived from different sources, but a more likely interpretation is that they represent different amounts of crustal contamination of a common parent magma. The more evolved sample (SiO_2=65 wt.% as opposed to SiO_2=55 wt.%) has the lower εNd_{460}, supporting the latter interpretation. Samples from the Orton and Glinton boreholes have the least radiogenic ^{143}Nd/^{144}Nd signatures (Fig. 14b). They have low εNd_{460} values between -6.3 and -7.4 and Proterozoic TDM ages between 1.47 and 1.6 Ga (Table 3). These epsilon values are the lowest yet recorded in Palaeozoic volcanic rocks of southern Britain and could be a result of melting of Proterozoic crust.

Table 3.- Sr and Nd isotopic data for rocks of the concealed volcanic suite. εNdt calculated at 400 Ma for Woo Dale data and 460 Ma for the rest of the samples.

Sample	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
WD 980	84	80	3.030	0.722789
WD 998.5	96	226	1.228	0.712482
WD 1002	96	202	1.377	0.713467
WD 1006	92	219	1.213	0.712574
WD 1010	97	193	1.455	0.713999
WD 1011.7	101	185	1.587	0.714674
WD 1017	97	168	1.674	0.715200
WD 1020	101	168	1.739	0.715633
WD 1023	91	152	1.731	0.715589
Cox's Walk				
BLF 8507	97	59	4.735	0.736535
BLF 8508	91	68	3.831	0.731243
BLF 8509	77	81	2.632	0.722683
BLF 8510	2	82	0.683	0.709971
BLF 8512	61	139	1.262	0.713925
BLF 8513	19	122	0.468	0.708706
BLF 8515	39	149	0.771	0.710405
BLF 8521	49	207	0.693	0.709815
BLF 8522	69	219	0.915	0.711144

Sample	Sm ppm	Nd ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	T_{DM}	εNd_t
Woodale						
WD 980	9.226	44.90	0.1242	0.512521	0.90	+1.4
WD 1006	7.173	33.49	0.1295	0.512529	0.91	+1.3
Cox's Walk						
BLF 8507	2.402	12.19	0.1191	0.512239	1.24	-3.3
BLF 8513	3.591	15.85	0.1370	0.512459	1.05	+0.7
Glinton						
BDT 8047	12.328	62.27	0.1197	0.512084	1.47	-6.3
BDT 8049	8.012	38.26	0.1266	0.512068	1.6	-7.1
Great Osgrove Wood						
GO 854.10	4.453	26.74	0.1007	0.512230	0.98	-2.4
Orton						
OR 719	8.005	40.48	0.1195	0.512028	1.55	-7.4

DISCUSSION

Relationship to exposed sequences

The petrographical and geochemical evidence reviewed here suggests that the volcanic rocks of the concealed Caledonides in eastern England are a suite (or suites) with dominantly calc-alkaline affinities. They appear to have been erupted in a mature, ensialic volcanic arc. A slight bimodal tendency is apparent in the distribution of some elements (e.g. Zr, Fig. 6a). The significance of this is not clear, with the presently available data. It may reflect a sampling bias, bimodality within one coeval suite or the combination of two (or more) non-coeval suites. The majority of the concealed volcanic rocks are massive lavas or tuffaceous rocks with primary pyroclastic textures (e.g. welding) and showing little evidence for subaequeous reworking. Pillow textures are lacking, and, in the absence of sedimentary textures indicating submarine deposition, it is presumed that the volcanic rocks were erupted sub-aerially. Lithic sandstones with a volcanic source of similar chemical composition may be associated with the volcanic rocks. By contrast, lavas form a very subordinate component of the Charnian Supergroup (Late Precambrian) in the East Midlands, the closest exposed volcanic terrain to the concealed volcanic belt. The Charnian Supergroup is a thick (>3 km) well exposed sequence of predominantly well-bedded, sub-aequeously reworked volcaniclastic rocks. Lavas (porphyritic andesite and dacite flows and domes) form a volumetrically minor part of the sequence while ash-flow tuffs, with or without welding, have not been recognised.

There are considerable geochemical differences too, for the Charnian volcanic rocks were erupted in a more primitive volcanic arc setting (Thorpe *et al.* 1984, Pharaoh *et al.* 1987b). In Fig. 15, MORB-normalised geochemical patterns are presented for four Precambrian arc-related igneous suites of southern Britain. These suites are highly variable in character, reflecting a diversity of late Proterozoic volcanic arc environments (Thorpe *et al.*, 1984; Pharaoh *et al.*, 1987b). The most distinctive feature of the Charnian volcanic and intrusive rocks (Fig. 15d) is the strong depletion of Nb (and Ta) with respect to Th and Ce, so that abundances of the former (and most other HFS elements) are MORB. By contrast, all components of the concealed volcanic suite have a content of Nb (and Ta) >MORB, as shown in Fig. 12. The patterns of the Warren House Formation (Fig. 15c) are flatter across the spectrum of HFS elements than the sloping profiles of the concealed volcanic suite. Evolved, felsic components of the latter show stronger enrichment of LREE (eg. Ce) than the Charnian suite, or any of the other Precambrian suites shown here.

Comparable early Palaeozoic volcanic rocks occur in three regions adjacent to the concealed Caledonides of eastern England, in Wales, northern England and Belgium (Fig. 17). In the Welsh Basin, volcanic rocks are predominantly mafic and felsic, with relatively few intermediate rocks, and range in age from Tremadoc to Caradoc (Bevins *et al.*, 1984; Kokelaar *et al.*, 1984). Geochemically, the rocks indicate a transition from an early Ordovician calc-alkaline magmatic arc i.e. the Rhobell Volcanic Group (Kokelaar, 1986) to a Caradoc ensialic extensional basin, particularly in North Wales e.g. the Llewelyn and Snowdon Volcanic Groups (Campbell *et al.,* 1988; Howells *et al.,* 1991). Data for the Rhobell Volcanic Group (Fig. 16a) exhibit strong depletion of Ta and Nb, to values <MORB, and enrichment of LIL elements, typical of calc-alkaline arc volcanic rocks (Pearce, 1982). These geochemical patterns resemble those of the calc-alkaline Charnian igneous rocks (Fig. 15d). Geochemical patterns of the later Llewelyn Volcanic Group rocks (Fig. 15b) exhibit gentle downward slopes from Ta to Yb which are typical of within-plate volcanic rocks, with depletion of P and Ti in more evolved felsic compositions. The group shows a

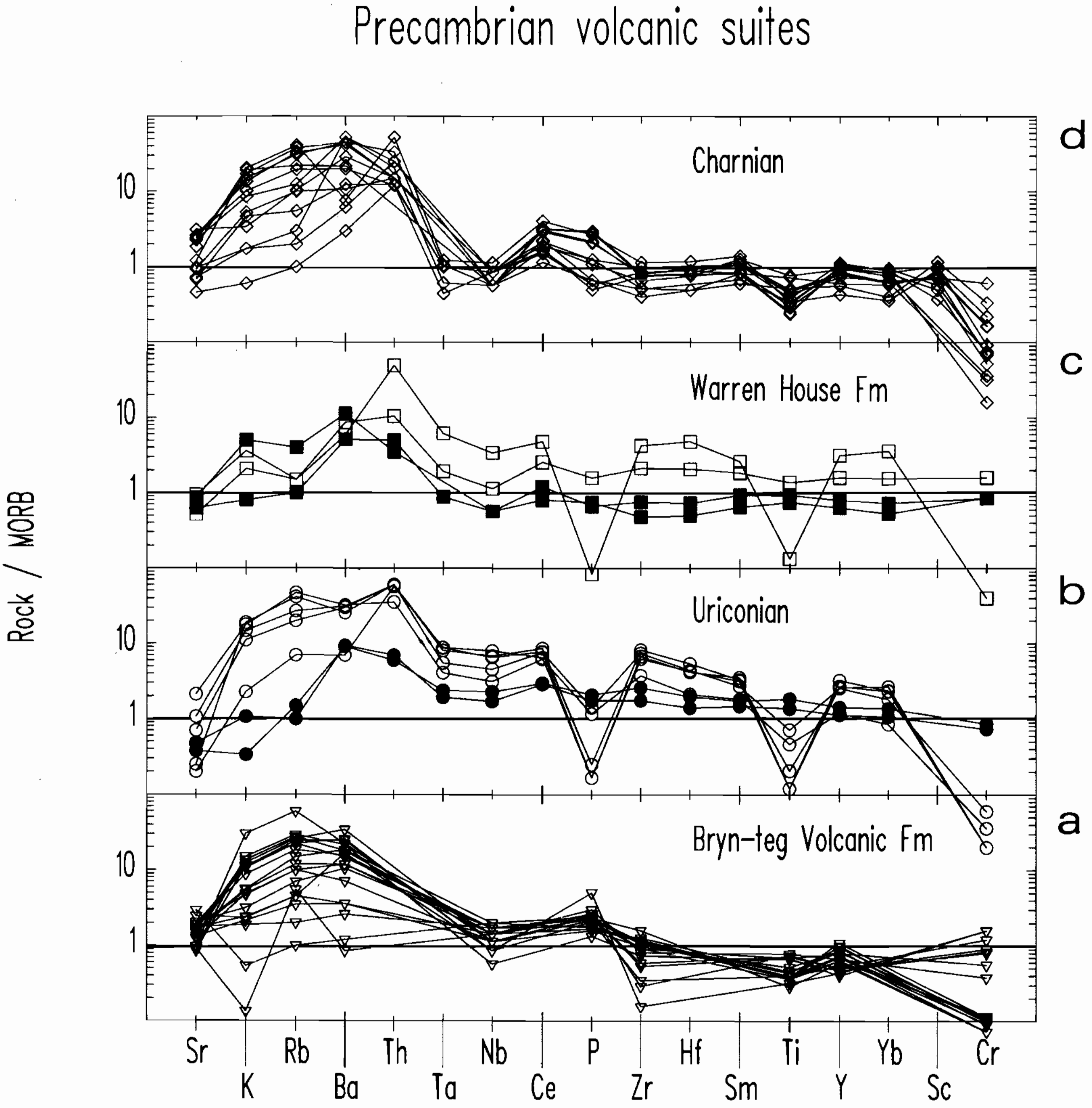

Fig. 15.- MORB-normalised geochemical patterns for exposed Precambrian volcanic and intrusive suites of southern Britain.

a. Basalts, andesites and rhyolites of Bryn-teg Volcanic Formation, N. Wales. Data from Allen & Jackson (1978).

b. Mafic (filled symbols) and felsic (open symbols) rocks of the Uriconian volcanic group, Shropshire. Data from Pharaoh et al. (1987b).

c. Mafic (filled symbols) and intermediate/felsic (open symbols) volcanic rocks of the Warren House Formation, Malvern Hills. Data from Pharaoh et al. (1987b).

d. Intermediate/felsic 'porphyroids' and mafic/intermediate intrusions, Charnwood, E. Midlands. Data from Pharaoh et al. (1987b).

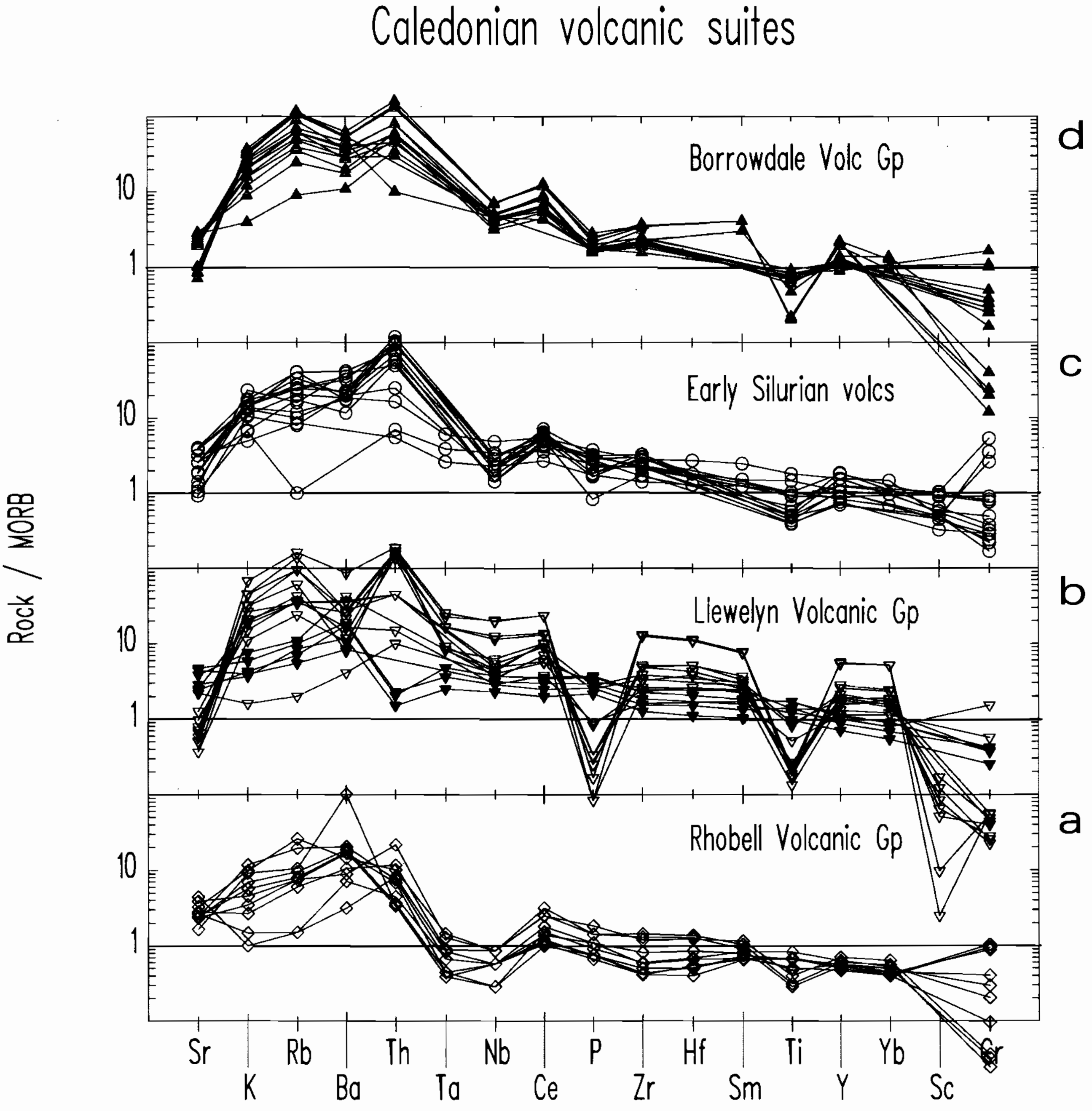

Fig. 16.- MORB-normalised geochemical patterns for exposed early Palaeozoic volcanic suites of southern Britain.

a. Andesites and microdiorites of the Rhobell Volcanic Group (Tremadoc), N. Wales. Data from Kokelaar (1986).

b. Data for rocks of the Llewelyn Volcanic Group (Caradoc), N. Wales; dolerites of Tal y Fan intrusion (filled symbols), from Merriman et al. (1987) and felsic tuffs and rhyolite lavas (open symbols), from Howells et al. (1990).

c. Early Silurian (Llandovery) volcanic rocks of Skomer Island, S.W. Wales, Tortworth and the Mendips. Data from Van de Kamp (1969) and Thorpe et al. (1989).

d. Andesite and rhyolite lavas of the Borrowdale Volcanic Group (Llanvirn-Caradoc). Data from Allen et al. (1988) and Fitton (1971) cited in Millward (1978).

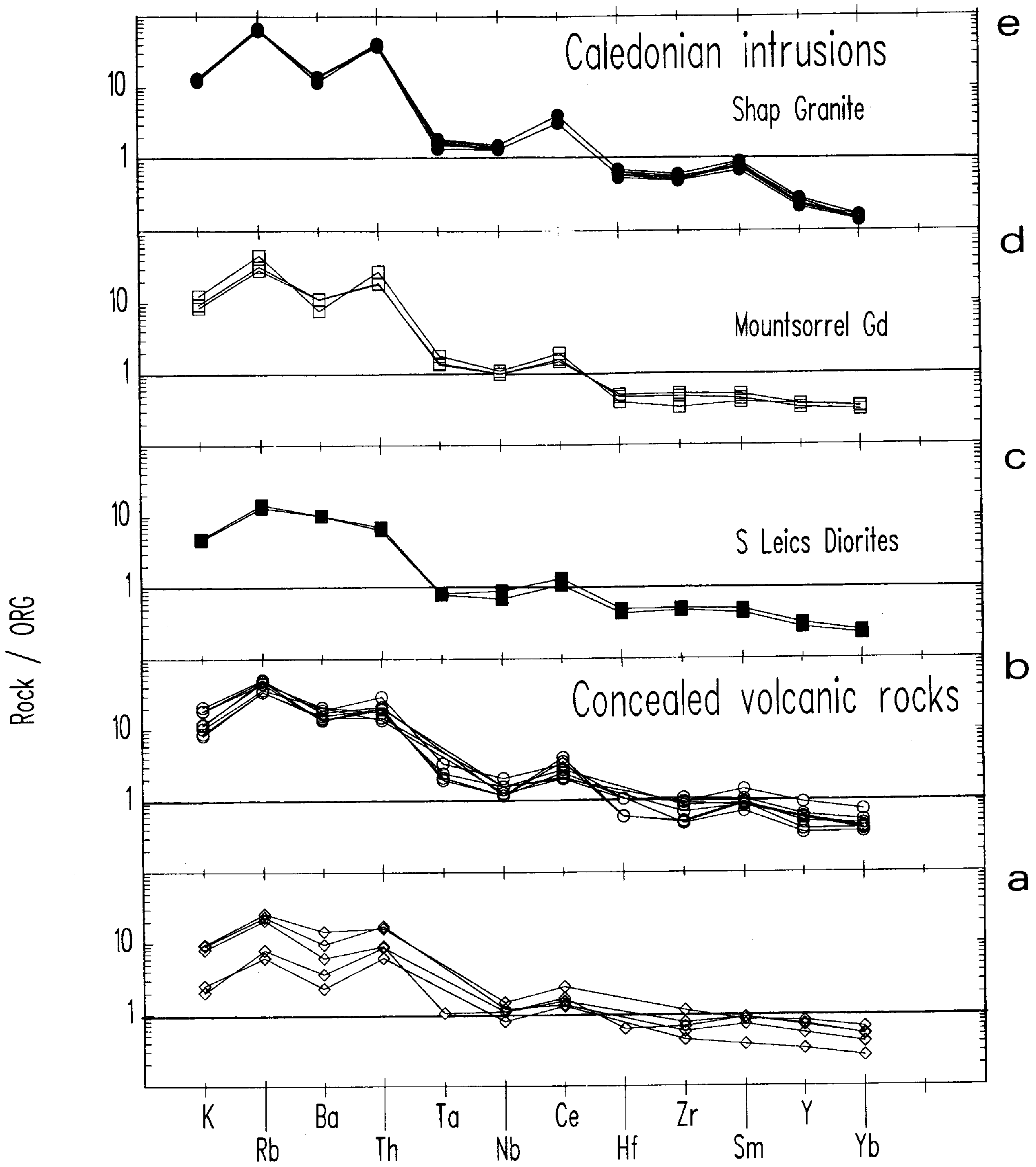

Fig. 17.- ORG-normalised geochemical patterns for intermediate and felsic components of the concealed volcanic suite, and exposed Caledonian 'granitoid' plutonic suites of southern Britain.

ORG-normalisation values from Pearce et al. (1984).

a. Intermediate-felsic compositions from Eakring 146 (andesite), North Creake (felsic tuff), Woo Dale (andesitic tuff and rhyodacite lava) and Warboys (diorite).

b. Rhyodacitic-rhyolitic volcanic rocks from Glinton, Orton and Oxendon Hall (ash-flow tuffs) and Great Osgrove Wood (flowage-banded lava).

c. Diorites of the South Leicestershire Suite, Croft and Enderby quarries. Data from Webb & Brown (1989).

d. Granodiorite of the Mountsorrel intrusion, Buddon Wood quarry.

Data from Webb & Brown (1989).

e. Shap Granite. Data from Webb & Brown (1984).

distinct bimodality, with a compositional gap between the mafic (e.g. the Tal y Fan dolerites) and felsic (e.g. Conwy Rhyolite Formation and Snowdon Centre Rhyolites) members of the group (Howells *et al.*, 1991). Felsic volcanic rocks in the Welsh Basin are predominantly subalkaline and peralkaline rhyolitic ash-flow tuffs and lavas which evolved mainly in a within-plate setting (Leat *et al.*, 1986; Howells *et al.*, 1991). Late Caradoc ocean island basalt (OIB)-type magmas have also been identified in the Snowdon Volcanic Group and, according to Leat & Thorpe (1989), their presence marks the end of southerly-directed subduction beneath the Welsh Basin. Data for the early Silurian volcanic suites of south-west Wales, Tortworth and the Mendips are shown in Fig. 16c. These patterns exhibit enrichment of LIL, Ce and Th, and resemble the patterns from Bicester and Netherton shown in Fig. 12d.

The volcanic rocks of the Lake District range in age from early Llanvirn to late-Caradoc or Ashgill, and comprise mafic, intermediate and felsic lavas, pyroclastic deposits and minor intrusions. They probably represent the eroded remnants of a series of sub-aerial calc-alkaline stratovolcanos developed in a volcanic arc, possibly on a continental margin (Moseley & Millward, 1982; Branney, 1988). Geochemical patterns for intermediate and felsic components of the Borrowdale Volcanic Group are shown in Fig. 16d. These patterns closely resemble those of the intermediate components of the concealed volcanic suite (Fig. 12b). Unfortunately high-precision data (including REE, Hf, Ta and Th) are not presently available for either the Eycott or Borrowdale Volcanic Groups, so it is not possible to make a more detailed comparison at present.

Early Palaeozoic volcanic rocks in Belgium have been described by André (1986), who distinguished an earlier, Ordovician 'calc-alkaline series', largely comprising pyroclastic rocks of dacitic and rhyolitic composition (with subordinate lavas) and a later, Silurian 'tholeiitic series', mainly represented by hypabyssal intrusions of gabbro and dolerite. Data for these suites were presented by André (1983) but do not include Nb and Ta which are needed to establish the magnitude of any arc magmatic component. Comparison with the Caledonide arc-related volcanic rocks of southern Britain reviewed above is therefore not attempted here.

Since there is no way of knowing if sampling to date is representative of the range of compositions and relative abundances of the concealed volcanic rocks, comparisons with volcanic rocks in the Welsh Basin and Lake District have obvious shortcomings. However a number of similarities and differences stand out. Firstly concealed mafic rocks are less common than the relatively abundant mafic rocks of the Welsh Basin, and they appear to be less diverse in terms of magma types; no OIB-types have so far been identified in the concealed volcanic suite. Secondly, concealed intermediate rocks appear to be relatively more abundant than in the Welsh Basin and in this respect resemble the Ordovician volcanic rocks of the Lake District. Thirdly, concealed felsic volcanic rocks are largely subalkaline types ($Nb/Y<0.7$) that evolved in a volcanic arc transitional to a within-plate setting, whereas comparable rocks in the Welsh Basin are subalkaline and peralkaline types (Leat *et al.*, 1986), that evolved predominantly in a within-plate setting. Finally, plutonic granitoid intrusive rocks are uncommon in the Welsh Basin (Howells *et al.*, 1990) whereas several plutonic intrusions in the Midlands and eastern England (e.g. the South Leicester Diorites, the Mountsorrel Granodiorite and its concealed continuation) appear to be coeval with the concealed volcanic rocks (Figs. 8 and 9) and there is additional evidence of probable granitoids concealed beneath The Wash (Allsop, 1987). A number of early granitoid intrusions are associated with Ordovician volcanism of the Lake District including the Threlkeld, Eskdale and Ennerdale-Buttermere intrusions. These intrusions are thought to form part of a concealed plutonic complex, the Lake District batholith, which probably developed in the late Ordovician.

In Fig. 17, geochemical patterns normalised to ocean-ridge granite (ORG) values are presented for the concealed volcanic rocks (Figs. 17a and b), the South Leicestershire and Mountsorrel plutonic suites (Figs. 17c and d) of late Ordovician age (Pidgeon & Aftalion, 1978; Le Bas, 1972, 1982) and the Shap Granite (Fig. 17e) of early Devonian age (Wadge *et al.*, 1978). The geochemical patterns of the concealed volcanic rocks are very similar to those of South Leicestershire and Mountsorrel, supporting the interpretation that the volcanic and plutonic suites are coeval, as already inferred from Figs. 9 and 10. By contrast, the Shap granite exhibits relative depletion of Y and Yb, and is more strongly enriched in LIL (e.g. Rb) and Th.

Age and isotopic characteristics

Two new Rb-Sr whole-rock ages support an early Palaeozoic, and probable Ordovician age of volcanism in the concealed Caledonides of eastern England as previously inferred by Evans (1979) and Pharaoh *et al.* (1987a). The Llanvirn age (timescale of McKerrow *et al.*, 1985) from Cox's Walk (466±11 Ma) agrees within error with the less precise Caradoc age from the Glinton volcanic rocks (448±32 Ma). Because of the alteration of the volcanic rocks, further isotopic studies, preferably using high precision radiometric techniques such as the U-Pb zircon procedure, are required to confirm the Ordovician age and constrain the duration of this magmatic episode. The geochemical data reported here show that geochemical correlation is not possible between the volcanic rocks of the concealed suite and those of the late Precambrian Charnian Supergroup exposed in the East Midlands, although it may not be possible to make this distinction for all of the Precambrian volcanic rocks in southern Britain.

The significance of the early Devonian radiometric age for the Woo Dale volcanic sequence (399±9 Ma) is unclear, and cannot be reconciled easily with the biostratigraphical evidence of an Ordovician age (Downie, pers. comm., cited in Evans, 1979) unless the acritarchs are reworked from older sedimentary rocks. The Woo Dale sequence is possibly the least altered of the volcanic rocks examined. Devonian volcanic rocks are well represented on the northern side of the Iapetus suture, in northern England and Scotland (Thirlwall, 1988) but, with the exception of the Townsend Tuff horizon, have not been reported previously from southern Britain. The presence in the vicinity of The Wash of concealed granites has been inferred from gravity data by Allsop (1987). It is conceivable that these could be of Devonian age by analogy with the granites of northern England (Stephens, 1988). Krogh *et al.* (1988) reported a precise zircon age of 394^{+6}_{-4} Ma for the 'Grand Beach Porphyry' which outcrops near the northern edge of the Avalon Terrane in Newfoundland. It is notable that Ordovician (Caradocian) felsic volcanic rocks in North Wales had their Rb/Sr whole-rock systems reset to an age of about 400 Ma during Acadian low grade metamorphism (Evans, 1989). This is a possible explanation for the Woo Dale age despite the very low grade (zeolite facies) alteration of the sequence.

The εNd_{400} values of the Woo Dale felsic volcanic rocks (+1.3 to +1.4) are within the range of Caradoc rhyolitic ash-flow tuffs and lavas of the Snowdon Volcanic Group. The latter have εNd_{445} values between -1.0 and +2.6 (J. Evans, unpublished data), and were probably derived from mafic magmas by fractional crystallisation during a period of extension in the Welsh Basin (Campbell *et al.,* 1988). The volcanic rocks from Cox's Walk and Great Osgrove Wood have εNd_{460} values in the range -3.3 to +0.7, comparable to those of the 'calc-alkaline series' in Belgium (André *et al.,* 1986).

As noted above, two of the felsic tuffs (from Orton and Glinton) have rather unradiogenic $^{143}Nd/^{144}Nd$ signatures, while Glinton has a high Sr initial ratio of 0.7162±0.0021 (Pharaoh *et al.*, 1987a). The Nd epsilon values of these samples (-6.3 and -7.4 at 460 Ma) are the lowest yet recorded in Palaeozoic volcanic rocks in southern Britain, and cannot be explained solely by sedimentary or igneous reworking of the majority of available late Precambrian crust which, as represented by the Mona and Sarn Complexes of Wales, is too radiogenic. Rocks of the Mona Complex of Anglesey yield εNd_{600} between -3.6 and -3.2 (recalculated from Davies *et al.,* 1985) and a diorite from the late Precambrian-early Cambrian Sarn Igneous Complex in North Wales gives an εNd_{550} value of -5.4 (Evans, unpublished data). The Rushton Schists of the Welsh Borders, an isolated occurrence of almandine-amphibolite grade metasedimentary schists with a metamorphic age of 667±20 Ma (Thorpe *et al.,* 1984) and εNd_{600} values of -8.5 and -8.0 (recalculated from Davies *et al.*, 1985) are the only Precambrian suite in southern Britain with a Nd-isotope signature comparable to that in the Orton and Glinton samples, and more typical of Proterozoic crust. If the volcanic rocks evolved above a subduction zone, as indicated by the geochemical evidence, assimilation of sediments with a Proterozoic signature could provide the unradiogenic Nd. Alternatively the low Nd epsilon values could be acquired during ascent and emplacement of the magma through the crust, by contamination from older Proterozoic basement underlying the concealed Caledonide foldbelt, or melting of that same crust. The strong enrichment in LREE visible in the REE patterns for Glinton, Orton, Oxendon Hall and Great Osgrove Wood may also reflect this contamination. More detailed isotopic studies of Nd and Pb isotope systematics are required to constrain the various possibilities.

Tectonic setting

Given our present limited knowledge of the volcanic terrain concealed beneath eastern England, it is tentatively suggested that there are more similarities between the volcanic arc terrain of the Lake District than there are with the Welsh back-arc basin. It is possible that the Lake District arc terrane is contiguous with the northwest-trending volcanic belt beneath eastern England and extends into the calc-alkaline Ordovician volcanic belt of the Brabant Massif (Fig. 17) described by André *et al.* (1986). This essentially Ordovician volcanic arc would appear to be related to the closure of the Tornquist Sea convergent zone (Cocks & Fortey, 1982; Soper *et al.*, 1987), and implies southerly or southwesterly directed subduction beneath the Midlands Microcraton and the Welsh Basin.

Additional evidence suggests that by the end of the Ordovician or early in the Silurian, parts of the Lake District-Brabant arc had been breached, eroded and/or submerged. In East Anglia, the volcanic terrain terminates abruptly and is replaced along strike in the basement subcrop to the southeast by cleaved sedimentary rocks exhibiting graded bedding and slumping (Bullard *et al.*, 1940) and ranging in age from early to latest Silurian (Pridoli) age (Molyneux, 1990). The Silurian sedimentary rocks are here interpreted as turbidites infilling a deep water marine basin, the latter overstepping across the older volcanic arc.

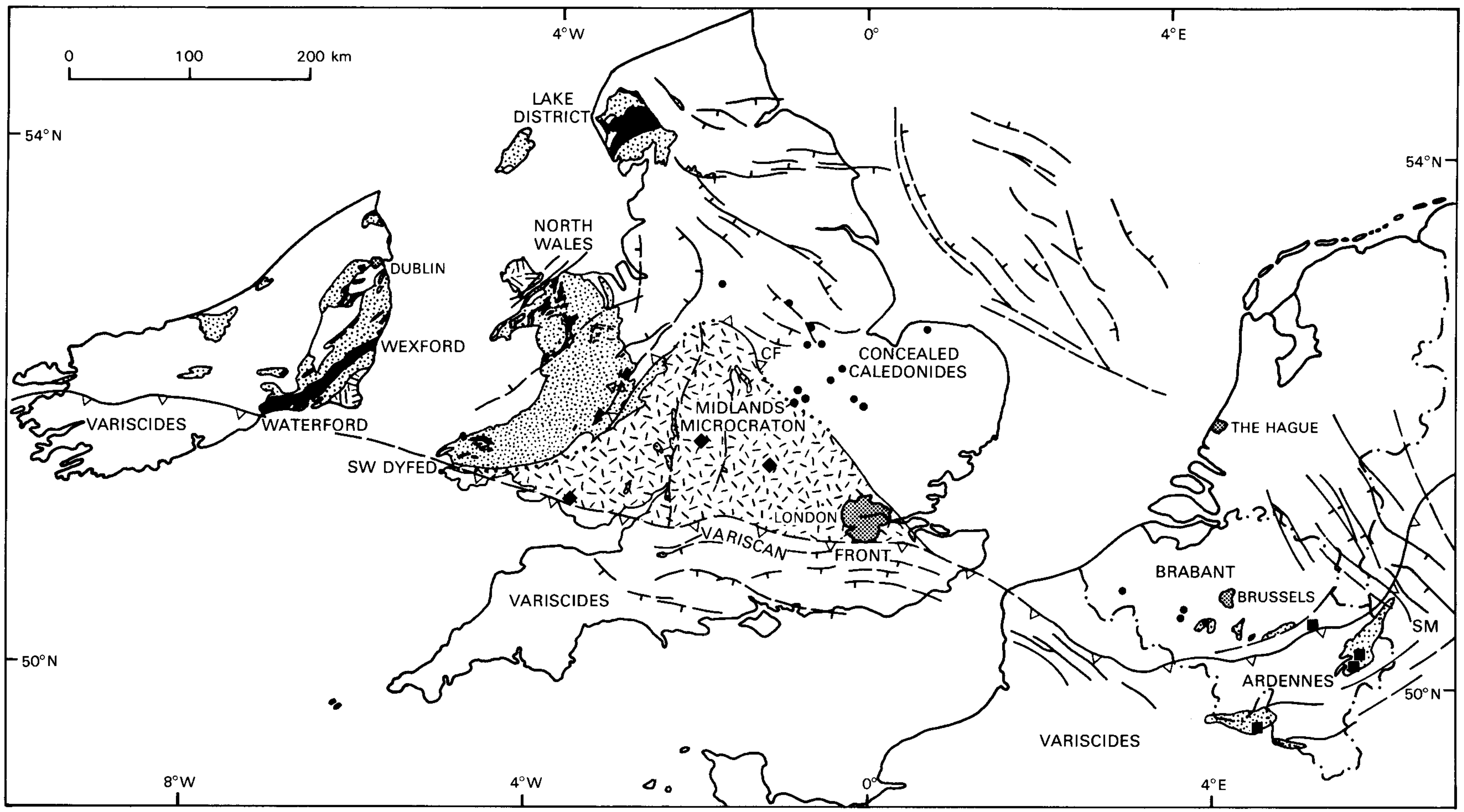

Fig. 18.- The concealed volcanic arc of eastern England - relationship to early Palaeozoic volcanic suites in Wales, the Lake District and Belgium (after André, 1986). Key:

■, Approximate location of dykes and sills of the 'tholeiitic series' in the Ardennes Massif;

●, Occurrence of calc-alkaline series (borehole in UK, borehole and outcrop in Belgium);

◆, Proving of early Silurian volcanic rocks within the Midlands Microcraton.

Three boreholes (at Orton, Oxendon Hall and Hollowell) lie in a cluster removed from the main volcanic belt and adjacent to the boundary of the Midlands Microcraton. All samples from Orton and Oxendon Hall, and some from Hollowell, exhibit the 'enriched' HFS element signature displayed by the volcanic rocks of the main belt e.g. Glinton, and an early Palaeozoic age for these provings is inferred by analogy (although not yet confirmed by isotopic evidence). By contrast, clasts from the basal Triassic breccia overlying the basement at Hollowell have a chemical composition which reflects a source more depleted in HFS trace elements, akin to that of Charnian lavas. These locations are reminiscent of the occurrence of volcanics in the Shelve and Builth inliers of the Welsh Basin, which were discrete volcanic centres whose location adjacent to the microcraton was structurally controlled by major crustal lineaments (Kokelaar, 1988).

The volcanic sequences proven at Bicester (pre-Upper Llandovery), Netherton and Maesteg are geographically distinct from the concealed volcanic belt of eastern England, and may be genetically distinct too, although they cannot easily be distinguished on petrographical or geochemical criteria. Radiometric data are not available at present. Seismic reflection data and the overall stratigraphic framework of the microcraton, suggest that these volcanic rocks are of early Silurian age. They may be equivalents of the early Silurian Skomer-Mendip-Tortworth suite (Van de Kamp, 1969; Thorpe *et al.*, 1989; Leat & Thorpe, 1989) which exhibits similar compositional variety and geochemical characteristics transitional between those of within-plate and arc volcanic signatures.

According to Leat & Thorpe (1989), the eruption of ocean island basalt in North Wales in Caradoc times marks the cessation of Caledonian subduction. Cessation of the volcanism in the Caledonides of eastern England is reflected in the superposition of a turbidite-filled deep water sedimentary basin upon the arc in the early Silurian. However, volcanism continued in a younger belt, extending east-west along what was soon to become the foreland of the developing Variscan Orogen. This early Silurian phase of volcanism on the southern edge of the Midland Microcraton, which shows a combination of within-plate plus ?inherited arc magmatism (Thorpe *et al.,* 1988), continuous into southern Belgium (André *et al.,* 1986) and may mark a phase of rifting of the Rheic Ocean of Fortey & Cocks (1988).

CONCLUSIONS

Concealed calc-alkaline volcanic rocks are located in a northwest-southeast trending belt extending from The Wash to the south Pennines. This volcanic terrain is of probable late Ordovician age, although the possible presence of older volcanic rocks cannot be excluded with the available isotopic evidence. Geochemical data indicate that the concealed volcanic rocks are chemically distinct from the exposed Precambrian suite in closest proximity i.e. the Charnian Supergroup and related intrusions.

The volcanic terrain may be contiguous with the Lake District volcanic rocks to the northwest and continue southeastwards beneath a Silurian turbidite-filled basin to link up with the Ordovician calc-alkaline volcanic belt in Belgium (Fig. 18). Together these outcrop and subcrop sequences define a sub-aerial volcanic arc which may have formed in response to closure of the Tornquist Sea involving southerly or south-westerly directed subduction beneath the Midlands Microcraton and the Welsh back-arc basin in the Ordovician.

Spatially distinct from the above belt, and probably of younger (early Silurian) age, is a belt of volcanic rocks of diverse chemical composition which runs east-west along the northern edge of the Variscan fold belt. These volcanic rocks are believed to postdate the main phase of Caledonian oceanic subduction, but may be related to the opening of the Rheic ocean basin to the south of Britain.

The εNdt values from the concealed volcanic rocks in this study display a wide range from -7.4 to +1.5, with the Glinton and Orton volcanic rocks giving the most unradiogenic εNdt values of -6.3 and -7.4. These are the lowest values recorded from Palaeozoic volcanic rocks in southern Britain and demonstrate the involvement of Proterozoic crust in the genesis of the concealed volcanic rocks, either by contamination or crustal melting. Further detailed radiometric studies using high precision techniques such as Ar-Ar step reheating and U-Pb zircon analysis are required to determine the duration of this magmatic activity.

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REFERENCES

ALEXANDRE, J., 1976. Les surfaces de transgression exhumées et les surfaces d'aplanissement. *In* : «Géomorphologie de la Belgique», coord. par A. Pissart, Liège: 75-92.

ALLEN, P.M. & JACKSON, A.A. 1978. Bryn-teg Borehole, North Wales. Bulletin of the Geological Survey of Great Britain 61, 52 pp.

ALLEN, P.M., COOPER, D.C. & FORTEY, N.J. 1988. Composite lava flows of Ordovician age in the English Lake District. Journal of the Geological Society of London 144, 945-960.

ALLSOP, J.M. 1987. Patterns of late Caledonian intrusive activity in eastern and northern England from geophysics, radiometric dating and basement geology. Proceedings of the Yorkshire Geological Society, 46, 335-353.

AMBROSE, K. & ELSON, R.J. 1987. New data on the stratigraphy and geophysics in the area around Hollowell, Northamptonshire, provided by a coal exploration borehole. Proceedings of the Geologists' Association, London 98, 157-170.

ANDRÉ, L., 1983. Origine et évolution des roches éruptives du massif du Brabant (Belgique). Ph. D. Thesis, Université Libre de Bruxelles, Belgium, 422 pp.

ANDRÉ, L., HERTOGEN, J. & DEUTSCH, S. 1986. Ordovician-Silurian magmatic provinces in Belgium and the Caledonian orogeny in middle Europe. Geology 14, 879-882.

BEVINS, R.E., KOKELAAR, B.P. & DUNKLEY, P.N. 1984. Petrology and geochemistry of early to mid-Ordovician igneous rocks in Wales: a volcanic arc to marginal basin transition. Proceedings of the Geologists' Association, 95, 337-347.

BRANNEY, M.J. 1988. The subaerial setting of the Ordovician Borrowdale Volcanic Group, English Lake District. Journal of the Geological Society of London 145, 887-890.

BULLARD, E.C., GASKELL, T.F., HARLAND, W.B. & KERR-GRANT, C. 1940.
Seismic investigations on the Palaeozoic floor of East England. Philosophical Transactions of the Royal Society of London, Series A, Vol. 239, 29-95.

BURGESS, I.C. 1982. The stratigraphical distribution of Westphalian volcanic rocks in the area east and south of Nottingham, England. Proceedings of the Yorkshire Geological Society, 44, 29-44.

CAMPBELL, S.D.G., HOWELLS, M.F., SMITH, M. & REEDMAN, A.J. 1988. A Caradoc failed-rift within the Ordovician marginal basin of Wales. Geological Magazine, 125, 257-266.

CHADWICK, R.A., PHARAOH, T.C. & SMITH, N.J.P. 1989. Lower crustal heterogeneity beneath Britain from deep seismic reflection data. Journal of the Geological Society, London, 146, 617-630.

CHADWICK, R.A., & SMITH, N.J.P. 1988. Evidence of negative structural inversion beneath central England from new seismic reflection data. Journal of the Geological Society, London, 145, 519-522.

COCKS, L.R.M & FORTEY, R.A. 1982. Faunal evidence for oceanic separations in the Palaeozoic of Britain. Journal of the Geological Society, London, 139, 465-478.

COPE, F.W. 1949. Proceedings of the Geological Society, London 1446, 24. (Woo Dale Borehole).

COPE, F.W., 1973. Woo Dale borehole near Buxton, Derbyshire. Nature, Physical Science 243, 29-30.

COPE, F.W., 1979. The age of the volcanic rocks in the Woo Dale borehole, Derbyshire. Geological Magazine 116, 319-320.

DAVIES, G., GLEDHILL, A. & HAWKSWORTH, C. 1985. Upper crustal recycling in southern Britain:evidence from Nd and Sr isotopes. Earth and Planetary Science Letters 75, 1-12.

DEARNLEY, R. 1966. Ignimbrites from the Uriconian and Arvonian.
Bulletin of the Geological Survey of Great Britain 24, 1-6.

DEPAOLO, D.J. & WASSERBURG, G.J. 1976. Nd isotopic variations and petrogenetic models. Geophysical Research Letters 3, 249-252.

DUNNING, F.W. 1975. Precambrian craton of central England and the Welsh Borders. In; HARRIS, A.L., SHACKLETON, R.M., WATSON, J., DOWNIE, C., HARLAND, W.B. & MOORBATH, S. A correlation of the Precambrian rocks in the British Isles. Geological Society, London, Special Report 6, pp83-96.

EDWARDS, W.N. 1967. Geology of the Country around Ollerton (Sheet 113).
Memoir of the Geological Survey of Great Britain.

EUNSON, H.J. 1884. The range of the Palaeozoic rocks beneath Northampton. Quarterly Journal of the Geological Society, London 40, 482-96.

EUNSON, H.J., 1886. Notes on the deep boring at Orton, near Kettering, Northamptonshire. Journal of the Northamptonshire Natural History Society, 4, 57-68.

EVANS, A.M. 1965. Note on the Orton boring, Northamptonshire. Journal of the Northamptonshire Natural History and Archaeological Society 34, 281-284.

EVANS, A.M. 1979. The East Midlands Aulacogen. Mercian Geologist 7, 31-42.

EVANS, J.A. 1989. Resetting of the Rb-Sr whole-rock isotope system of an Ordovician microgranite during Devonian low-grade metamorphism.
Geological Magazine, 126, 675-679.

FALCON, N.L. & KENT, P.E. 1960. The Geological results of petroleum exploration in Britain. 1945-1957. Memoir 2, Geological Society, London 56 pp.

FITTON, J.G. 1971. The petrogenesis of the calc-alkaline Borrowdale Volcanic Group, Northern England. Unpublished Ph.D. Thesis, University of Durham.

FORTEY, R.A. & COCKS, L.R.M. 1988. Arenig to Llandovery faunal distributions in the Caledonides. in: HARRIS, A.L. & FETTES, D.J. (eds) The Caledonian-Appalachian Orogen. Special publication 38, Geological Society, London.

HARRISON, R.K. 1974. Sidewall slices from Ultramar Well, Netherton.
Unpubd. Pet. Dept. Report, Geological Survey of Great Britain.

HORTON, A., LAKE, R.D., BISSON, G. & COPPACK, B.C. 1973. The geology of Peterborough. Rep. 73/12 Institute of Geological Sciences.

HOWELLS, M.F., REEDMAN, A.J. & CAMPBELL, S.D.G., 1991. Ordovician (Caradoc) Marginal Basin volcanism in Snowdonia (N.W. Wales). Book Series, British Geological Survey.

INSTITUTE OF GEOLOGICAL SCIENCES, 1966. Annual Report for 1965.

IRVINE, T.N. & BARAGAR, W.R.A. 1971. A guide to the chemical classification of the common volcanic rocks. Canadian Journal of Earth Sciences, 8, 523-548.

JONES, D.G. & WEBB, P.C. 1989. In: PLANT, J. & JONES, D.G. Appendix 3. Geochemical sampling and analysis. In: PLANT, J.A. & JONES, D.G. (eds). Metallogenetic models and exploration criteria for buried carbonate-hosted ore deposits- a multi-disciplinary study in eastern England. The Institution of Mining and Metallurgy, London and British Geological Survey, Keyworth. p 161.

KENT, P.E., 1947. A deep boring at North Creake, Norfolk. Geological Magazine 84, 2-18.

KENT, P.E., 1962. A borehole to basement rocks at Glinton, near Peterborough, Northants. Proceedings of the Geologists' Association, London. 1595, 40-42.

KENT, P.E., 1968. The Buried Floor of Eastern England. In: FORD, T. D. & SYLVESTER-BRADLEY, P. C. (eds). Geology of the East Midlands.
Leicester University Press. 400 pp.

KOKELAAR, B.P. 1986. Petrology and geochemistry of the Rhobell Volcanic Complex: amphibole dominated fractionation at an early Ordovician arc volcano in North Wales. Journal of Petrology 27, 887-914.

KOKELAAR, B.P., 1988. Tectonic controls of Ordovician arc and marginal basin volcanism in Wales. Journal of the Geological Society, London, 145, 759-775.

KOKELAAR, B.P., HOWELLS, M.F., BEVINS, R.E., ROACH, R.A. & DUNKLEY, P.N. 1984. The Ordovician marginal basin of Wales. In: KOKELAAR, B.P. & HOWELLS, M.F. Marginal Basin Geology: volcanic and associated sedimentary and tectonic processes in modern and ancient marginal basins. Geological Society, London. Special Publication 16, 322 pp. Blackwell Scientific Publications, Oxford.

KROGH, T.E., STRONG, D.F., O'BRIEN, S.J. & PAPEZIK, V.S. 1988. Precise U-Pb zircon dates from the Avalon Terrane in Newfoundland. Canadian Journal of Earth Sciences, 25, 442-453.

LEAT, P.T. & THORPE, R.S. 1989. Snowdon basalts and the cessation of Caledonian subduction by the Longvillian. Journal of the Geological Society, London, 146 , 965-970.

LEAT, P.T., JACKSON, S.E., THORPE, R.S. & STILLMAN, C.J. 1986. Geochemistry of bimodal basalt-subalkaline/peralkaline rhyolite provinces within the southern British Caledonides. Journal of the Geological Society, London. 143, 259-273.

LE BAS, M.J. 1968. Caledonian Igneous Rocks. In: FORD, T.D. & SYLVESTER-BRADLEY, P.C. (eds). Geology of the East Midlands. Leicester University Press. 400 pp.

LE BAS, M.J., 1972. Caledonian igneous rocks beneath central and eastern England. Proceedings of the Yorkshire Geological Society, 39, 71-86.

LE BAS, M.J., 1982. Geological evidence from Leicestershire on the crust of southern Britain. Transactions of the Leicester Literary and Philosophical Society, 76, 54-67.

LEE, M.K., PHARAOH, T.C. and SOPER, N.J. 1990. Structural trends in central Britain from images of gravity and aeromagnetic fields. Journal of the Geological Society, London, 147, 241-258.

McKERROW, W.S., LAMBERT, R.J. & COCKS, L.R.M. 1985. The Ordovician, Silurian and Devonian periods. In: SNELLING, N.J. (ed). Geochronology and the Geological Record. Geological Society of London Memoir 10, pp 73-80.

MERRIMAN, R.J., BEVINS, R.E. & BALL, T.K. 1987. Petrological and geochemical variations within the Tal y Fan intrusion: a study of element mobility during low grade metamorphism with implications for petrotectonic modelling. Journal of Petrology, 27, 1409-1436.

MILLWARD, D., MOSELEY, F. & SOPER, N.J. 1978. The Eycott and Borrowdale Volcanic Rocks. In: MOSELEY, F. (ed). The Geology of the Lake District. Yorkshire Geological Society Occasional Publication, 3, 99-120.

MOLYNEUX, S.G., 1991. The contribution of palaeontological data to an understanding of the Early Palaeozoic framework of eastern England. *In:* L. André, A. Herbosch, M. Vanguestaine and J. Verniers (eds), Proceedings of the International Meeting on the Caledonides of the Midlands and the Brabant Massif, Brussels, 20 to 23 september 1989. Ann. Soc. géol. Belg., 114 (1): 93-105.

MOSELEY, F. & MILLWARD, D. 1982. Ordovician volcanicity in the English Lake District. In: SUTHERLAND, D.S. (ed.) Igneous rocks of the British Isles. John Wiley & Sons., pp 19-35.

NAKAMURA, N. 1974. Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. Geochimica cosmochimica Acta., 38, 757-775.

PANKHURST, R.J. & O'NIONS, R.K., 1973. Determination of Rb/Sr and $^{87}Sr/^{86}Sr$ ratios of some standard rocks and evaluation of X-Ray fluorescence spectrometry in Rb-Sr geochemistry. Chemical Geology, 12, 127-136.

PEARCE, J.A. 1982. Trace element characteristics of lavas from destructive plate boundaries. In: THORPE, R.S. (ed.) Orogenic Andesites, J. Wiley & Sons, Chichester, 525-548.

PEARCE, J.A., & CANN, J.R. 1973. Tectonic setting of basic volcanic rocks determined using trace element analysis. Earth & Planetary Science Letters, 19, 290-300.

PEARCE, J.A., HARRIS, N.B.W. & TINDLE, A.G. 1984. Trace Element Discrimination Diagrams for the Tectonic Interpretation of Granitic Rocks. Journal of Petrology 25, 956-983.

PHARAOH, T.C. & PEARCE, J.A. 1984. Geochemical evidence for the geotectonic setting of Early Proterozoic metavolcanic sequences in Lapland. Precambrian Research, 10, 283-309.

PHARAOH, T.C., MERRIMAN, R.J., WEBB, P.C. & BECKINSALE, R.D. 1987a. The concealed Caledonides of eastern England: preliminary results of a multidisciplinary study. Proceedings of the Yorkshire Geological Society, 46, 355-369.

PHARAOH, T.C., WEBB, P.C., THORPE, R.S. & BECKINSALE, R.D. 1987b. Geochemical evidence for the tectonic setting of late Proterozoic volcanic suites in central England. In: PHARAOH, T.C. BECKINSALE, R.D. & RICKARD, D. (eds), 1987. Geochemistry and Mineralization of Proterozoic volcanic suites. Special Publication of the Geological Society, London, 33, 541-552.

PLANT, J.A. & JONES, D.G., 1989. (eds). Metallogenic models and exploration criteria for buried carbonate-hosted ore deposits-a multidisciplinary study in eastern England. The Institution of Mining and Metallurgy, London and British Geological Survey, Keyworth.

PIDGEON, R.T. & AFTALION, M. 1978. Cogenetic and inherited zircon U-Pb systems in Palaeozoic granites from Scotland and England. In: BOWES, D.R. & LEAKE, B.E. (eds.). Crustal evolution in northwest Britain and adjacent regions. Geological Journal Special Issue 10. Seal House Press, Liverpool, 183-220.

POOLE, E.G., WILLIAMS, B. J. & HAINS, B.A. 1968. The Market Harborough District (Sheet 170). Memoir of the Geological Survey of Great Britain

SMITH, B. 1936. On a boring at Oxendon, Northamptonshire. Memoir of the Geological Survey of Great Britain. Summary of Progress (for 1934), 2, 28-30.

SMITH, N.J.P. (Compiler) 1985. Map 1. Pre-Permian geology of the United Kingdom (South). British Geological Survey.

SMITH, N.P.J. 1987. The deep geology of central England : the prospectivity of the Palaeozoic rocks. In: BROOKS, J. & GLENNIE, K. (eds), Petroleum Geology of North West Europe. Graham & Trotman, London.

SOPER, N.J., WEBB, B.C. & WOODCOCK, N.J. 1987. Late Caledonian (Acadian) transpression in North West England: timings, geometry and geotectonic significance. Proceedings of the Yorkshire Geological Society 46, 175-192.

STEIGER, R.H. & JÄGER, E., 1977. Subcommission on Geochronology: Convention on the use of decay contents in geo- & cosmochronology. Earth and Planetary Science Letter, 36, 359-362.

STEPHENS, W.E. 1988. Granitoid plutonism in the Caledonian Orogen of Europe. In: HARRIS, A.L. & FETTES, D.J. The Caledonian-Appalachian Orogen. Geological Society of London Special Publication 38, 389-404.

THIRLWALL, M.F. 1988. Wenlock to mid-Devonian volcanism of the Caledonian-Appalachian Orogen. In: HARRIS, A.L. & FETTES, D.J. (eds.) The Caledonian-Appalachian Orogen. Geological Society of London Special Publication 38, 415-428.

THORPE, R.S., BECKINSALE, R.D., PATCHETT, P. J., PIPER, A., DAVIES, G. R. & EVANS, J.A. 1984. Crustal growth and late Precambrian-early Palaeozoic plate tectonic evolution of England and Wales. Journal of the Geological Society, London 141, 521-536.

THORPE, R.S., LEAT, P.T., BEVINS, R.E. & HUGHES, D.J. 1989. Late orogenic alkaline/subalkaline Silurian volcanism of the Skomer Volcanic Group in the Caledonides of south wales. Journal of the Geological Society, London 146, 125-132.

TURNER, S. 1949. The deeper structure of central and northern England.

Proceedings of the Yorkshire Geological Society 27, 280-297.

VAN DE KAMP, P.C. 1969. Silurian volcanic rocks of the Mendip Hills, Somerset and Tortworth, Gloucestershire, England. Geological Magazine, 106, 542-555.

WADGE, A.J., GALE, N.H., BECKINSALE, R.D. & RUNDLE, C.C. 1978. A Rb-Sr isochron for the Shap Granite. Proc. Yorks. Geol. Soc., 42, 297-305.

WEBB, P.C. & BROWN, G.C. 1984. Lake District granites: heat production and related geochemistry. Investigation of the geothermal potential of the UK. British Geological Survey.

WEBB, P.C. & BROWN, G.C. 1989. Geochemistry of pre-Mesozoic igneous rocks. In: PLANT, J.A. & JONES, D.G. (eds). Metallogenic models and exploration criteria for buried carbonate-hosted ore deposits-a multidisciplinary study in eastern England. The Institution of Mining and Metallurgy, London and British Geological Survey, Keyworth, p 95-121.

WHITE, W.M. & HOFMANN, A.W. 1982. Sr and Nd isotope geochemistry of oceanic basalts and mantle evolution. Nature 296, 821-825.

WHITTAKER, A. 1985 (ed). Atlas of onshore sedimentary basins in England and Wales. Post-Carboniferous tectonics and stratigraphy. Blackie, Glasgow.

WILLS, L.J. 1978. A palaeogeological map of the Lower Palaeozoic Floor below the cover of Upper Devonian, Carboniferous and later formations. Memoir of the Geological Society, London 8, 36 pp.

WINCHESTER, J.A. & FLOYD, P.A. 1977. Geochemical discrimination of different magma series and their differentiation products using immobile trace elements. Chemical Geology 20, 325-343.

WOODCOCK, N.H., 1991. The Welsh, Anglian and Belgian Caledonides compared. *In:* L. André, A. Herbosch, M. Vanguestaine and J. Verniers (eds), Proceedings of the International Meeting on the Caledonides of the Midlands and the Brabant Massif, Brussels, 20 to 23 september 1989. Ann. Soc. géol. Belg., 114 (1) : 5-17.