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Mineral Reconnaissance Programme

# The potential for diamonds in Britain

Department of Trade and Industry

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Technical Report WF/95/1

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*Authors*

R C Leake, BSc, PhD
J D Cornwell, BSc, PhD
K E Rollin, BSc
M T Styles, BSc, PhD
*BGS Keyworth*

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Keyworth, Nottingham NG12 5GG
☎ 0115-936 3100 Telex 378173 BGSKEY G
Fax 0115-936 3200

Murchison House, West Mains Road, Edinburgh, EH9 3LA
☎ 0131-667 1000 Telex 727343 SEISED G
Fax 0131-668 2683

London Information Office at the Natural History Museum, Earth Galleries, Exhibition Road, South Kensington, London, SW7 2DE
☎ 0171-589 4090 Fax 0171-584 8270
☎ 0171-938 9056/57

19 Grange Terrace, Edinburgh EH9 2LF
☎ 0131-667 1000 Telex 727343 SEISED G

St Just, 30 Pennsylvania Road, Exeter EX4 6BX
☎ 01392-78312 Fax 01392-437505

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS
☎ 01232-666595 Fax 01232-662835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ 01491-838800 Telex 849365 HYDROL G
Fax 01491-25338

*Parent Body*

Natural Environment Research Council
Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ 01793-411500 Telex 444293 ENVRE G
Fax 01793-411501


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Dr D C Cooper
Minerals Group
British Geological Survey
Keyworth
Nottingham NG12 5GG



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**SUMMARY**

Most diamonds at the earth's surface occur there because of the combination of two unusual processes, the lowering of the geothermal gradient deep in the mantle, which allows the diamond stability field to be entered, and the formation of a magma at or below these great depths within which diamond-bearing xenoliths can be transported very rapidly to the earth's surface. As most diamonds seem to have formed in sub-cratonic roots during the early history of the earth, the Lewisian terrane of the north-west Highlands of Scotland and the Hebrides, a fragment of the ancient Laurentian craton, represents the most favourable environment in Britain. No kimberlites are known in this terrane but, although it is probably the most intensely mapped cratonic segment in the world, exposure is very poor over large sectors of the Hebrides and existing aeromagnetic data is too widely spaced to give an adequate indication of whether any diatremes are present.

The nature of the basement of the rest of the Scottish Highlands is less clear, but it could partly be of early Proterozoic age so that some potential for the occurrence of diamonds in lamproitic rocks exists. The centres of alkaline igneous activity in northern Scotland and major structures, such as the Great Glen Fault, which is rooted deep in the mantle, are possible environments of interest. Elsewhere in Britain the basement is uncertain but is probably mostly late Proterozoic in age and therefore too young to have sub-cratonic mantle roots, though in south-west England, in particular, there could be segments of Archaean basement. The only British rock which fits clearly into the lamproite class occurs in south-west England, but there are several others in the same region and elsewhere, generally of Permian age, which approach lamproite in chemistry. Furthermore the aeromagnetic data from south-west England, which is more closely spaced than for the rest of the country, suggests the presence of several unexposed pipe-like intrusions. In northern Britain the most potassic and alkaline rocks of similar age occur in Orkney.

Other igneous rocks are capable of carrying diamonds to the surface from shallower depths in the mantle if the geothermal gradient had been depressed sufficiently to allow these shallower rocks to enter the diamond stability field. Recent thinking, emanating particularly from Australia, suggests that diamond could crystallise within a cold subducted slab which caused local depression of the geothermal gradient. Such a remnant cold slab could be left behind at the cessation of subduction and form a transient source of diamonds which could possibly be tapped by lamprophyres, alkali basalts and nephelinites. Recognition of such an environment is highly speculative but it could have been present in the Southern Uplands of Scotland at the end of the Silurian and early Devonian. The regional swarm of potassic minettes are a medium in which diamonds derived from such a source could have reached the surface. A subducted slab could also have been stagnant beneath south-west England and tapped by the Permian lamprophyric and lamproitic intrusions or alkaline lavas.

Diamonds could occur in palaeoplacer deposits, particularly in the Proterozoic Torridonian sequence of north-west Scotland, since the source of these fluviatile rocks could have been an Archaean craton to the west of the Lewisian and the sequence has suffered little deformation and metamorphism.

Further work is recommended, particularly in south-west England and north-west Scotland, to determine whether potentially favourable deep-seated intrusions and palaeoplacers are diamondiferous and to investigate the source of aeromagnetic anomalies of potential interest.

## INTRODUCTION

The occurrence of diamonds at the earth's surface requires two unusual geological phenomena to have taken place. Firstly, there must be a suitable source region for the diamonds to form, usually in the mantle. Secondly, diamonds must be transported quickly to the surface in a suitable magma which then crystallises rapidly so that the diamond persists as a metastable phase and does not recrystallise as graphite. Subsequently the primary hosts may be eroded and diamonds redistributed into placer deposits.

The stability field of diamond has been determined experimentally and the results show that diamond would only crystallise in areas where the geothermal gradient was anomalously low. Areas of anomalously low gradient occur either where lithosphere is particularly thick, in sub-cratonic mantle roots, or where a subducted slab of cold material has caused a short-term depression of the geotherm. The second environment could occur at a higher level in the lithosphere than the first on cessation of subduction when the cold slab of subducted material could become stagnant and then sink into the mantle. Such a slab could cause depression of the local geothermal gradient and entry into the diamond stability field. The anomalous low temperature of the slab is likely to be transient due to heating by surrounding mantle, but could form a source of diamond to be transported in a magma generated under more normal conditions in the mantle below and rapidly transported to a high crustal level. A shallow angle of subduction could favour the formation of such a slab.

Diamond is known from a number of source rocks, but by far the commonest hosts are mantle xenoliths of harzburgite, lherzolite and eclogite brought to the surface in kimberlite pipes. Diamonds have also been found in garnet peridotites from alpine-type massifs, and octahedral graphite aggregates after diamond occur abundantly in garnet-pyroxenite layers in lherzolites in the Sierra Ronda in southern Spain (Davies et al., 1993) and in the nearby similar massif of Beni Bousera in Morocco. This environment is thought to account for several sites where alluvial diamonds occur in Phanerozoic mobile belts apparently remote from areas of kimberlitic magmatism, since diamond inclusions within garnet may be protected from recrystallisation. Diamond also occurs in ultra-high-pressure metamorphic rocks in Kazakhstan (Dobrzhinetskya et al., 1994), in Dabie Shan, China (Shutong et al., 1992) and the Western Gneiss Region of Norway (Dobrzhinetskya et al., 1993). In the Kazakhstan rocks microdiamonds occur in a range of metasedimentary gneisses and calc-silicate rocks, in China the diamond is present as inclusions in garnet within eclogite and garnet pyroxenite and in Norway it occurs in eclogite gneiss. The mode of origin of all these occurrences is not yet clear. A Russian occurrence of microscopic diamond, locally in abundance, is thought to have originated from graphite as a result of shock metamorphism due to meteoritic impact. It is clear that diamonds are increasingly being found in areas remote from the stable Archaean cratonic regions which, until recently, were regarded as the only prospective environments.

Potential diamond host rocks of igneous origin must have originated at sufficient depths in the mantle to tap the diamond source regions. By far the most important igneous hosts are intrusive kimberlites and intrusive and extrusive lamproites in which diamonds occur as xenocrysts or within xenoliths. However, recently diamonds have been reported from a variety of other igneous rocks, thought not apparently in economic amounts. There are reports of diamonds within certain types of ultramafic lamprophyre, especially alnöite (Atkinson et al., 1990), and also in alkaline-type lamprophyres like monchiquite (Rock and Groves, 1988; Atkinson et al., 1990). Particularly puzzling is the source of the diamond recovered from a heavy concentrate taken from the side of a maar (tuff ring) in Queensland, since none of the typical diamond indicator minerals are present (Robertson and Robertson, 1994).

Recent thinking about the source of the widespread alluvial diamonds in New South Wales suggests that diamonds could form within a subducting slab and subsequently be brought to the surface in alkali basalts and nephelinites (Barron et al., 1994). These discoveries have been made following extensive exploration in Australia and elsewhere as a result of a change in exploration strategy following the unexpected discovery of diamonds in lamproite within a Proterozoic mobile belt in northern Australia. The drastic change in thinking was a consequence of the occurrence of the diamondiferous lamproite within a geological environment thought to have no potential, on the basis of previous understanding of the controls of diamond formation. Thus, while exploration is still focused on the search for kimberlites in Archaean cratons, a much wider range of possible diamond host rocks emplaced in a variety of geological environments are now being considered as possibly diamondiferous. For this reason it is opportune to review the potential of Britain for diamonds.

The only igneous rocks with potential for carrying diamond to the surface, apart from kimberlites and lamproites, are (1) rapidly extruded alkali basalts and related rocks and (2) alkali mafic and lamprophyric intrusive rocks that have been emplaced and cooled rapidly. Transport of the magma would have to be in one stage, as residence of magma in a chamber at intermediate depths would cause recrystallisation. Though diamonds can exist as a metastable phase at the earth's surface indefinitely, an increase in temperature of the host rock due to metamorphism or intense hydrothermal alteration would be expected to destroy any diamond that may be present unless it is protected as an inclusion within a resistant mineral like garnet. An increase in temperature within the source environment of diamond in the mantle is likely to move the region into the stability field of graphite. Several geological process can adversely affect sub-cratonic mantle roots and destroy diamond source regions. These include mantle plumes, extensive rifting, and collision. The presence of thick and widespread mafic igneous activity in the upper crust indicates the probability of an enhanced geothermal gradient stretching down well into the mantle. However, it is possible that suitable igneous rocks associated with the onset of a major phase of igneous activity could be diamondiferous if they tapped a suitable source before it was destroyed or if the igneous activity was peripheral to the main centre of activity. The lateral and vertical extent of thermal perturbations in the mantle which give rise to extensive volcanic fields is not known. The enormous outpouring of Karoo volcanic rocks during the early Mesozoic in South Africa and neighbouring countries did not prevent the subsequent formation of diamondiferous kimberlites.

The geology of various parts of Great Britain is discussed below, firstly in terms of the nature of the basement and possible source regions for diamond formation and secondly in terms of possible host rocks within which diamonds could have been transported to the surface. In addition, potential sedimentary hosts for diamonds are considered.

That there is some potential for the occurrence of diamond in Britain can be deduced from the record of the discovery of a diamond in 1816 in a stream bed in Co. Fermanagh, Northern Ireland (Ball, 1887). Since this is the way the first South African diamonds were found, the report of this discovery has to be taken seriously. The Colbrooke river, from which it is claimed the diamond was found, drains an area with thick drift deposits underlain by Carboniferous strata including basal conglomerates rich in fragments of metamorphic rock. There are also reports of diamonds in Scotland but these are either doubtful or vague. Microscopic diamond was reported to occur near New Cumnock in Ayrshire within graphite derived from coal at the contact with dolerite (Smith, 1895). Very close to the contact the graphite contains small crystals of a mineral which scratches quartz and shows an optical fire similar to that of diamond. The identification of this material with diamond is circumstantial and a proper mineralogical identification is required before the record can be taken seriously. It is also recorded (McCallien, 1937) that the famous Scottish mineralogist Heddle believed that small diamonds occurred three miles north-east of Ben Hope in the extreme north of Scotland underlain by Moine rocks close to the Moine Thrust.

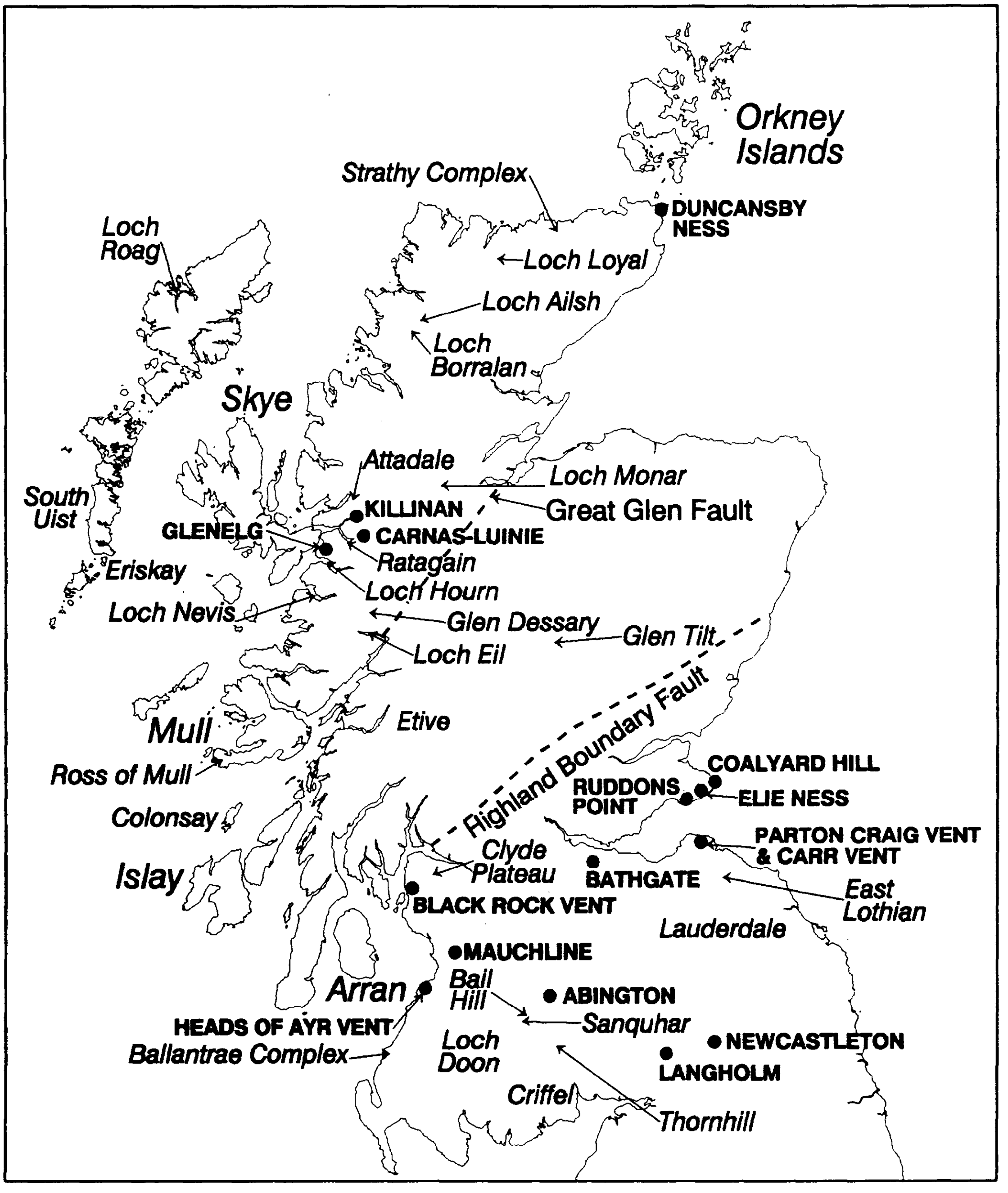


**Figure 1** Location map for northern Britain

Sites and areas mentioned in the text are shown on Figures 1 and 2. The major faults cutting northern Britain are shown in Figure 3, together with the locations of outcrops of vent agglomerate and lamprophyre samples held in the BGS registered collection. However, this map does not give a fully representative indication of the incidence of these rocks, as the collection is biased strongly towards those areas that have been geologically surveyed by BGS recently.

## THE NATURE OF THE DEEP BASEMENT WITHIN BRITAIN

As part of an assessment of diamond potential it is necessary to consider the origin and age of the deep basement, because there is evidence that diamond formation within mantle roots has been confined mostly to the older Precambrian. Thus diamonds associated with garnet harzburgites in kimberlite from South Africa are thought to have crystallised in the mantle only during the early Archaean (Richardson et al., 1993). However, the diamonds associated with garnet lherzolites in the same environment have a Lower Proterozoic age and the eclogitic diamonds have a much younger Middle Proterozoic age (Richardson et al., 1993). These age criteria may not apply to all diamond crystallisation, especially if it occurred at a higher level in the lithosphere than the typical mantle root. The present crust in Britain is of normal thickness and the Moho is at depths of between 25 and 35 km. In northern Britain seismic reflection data suggest that transcurrent structures cut the entire crust and may therefore be important controls of magmatism.

### The Lewisian terrane of north-west Scotland and the Hebrides

The Lewisian terrane is a fragment of the ancient North Atlantic or Laurentian craton and contains the oldest known rocks in Britain, which appear to be a sequence of metasedimentary and metavolcanic rocks. The outcrops in north-west Scotland and the Hebrides formed the north-west foreland to the Caledonian orogenic belt, while those to the east of the Moine Thrust are inliers, incorporated into the orogen. On the basis of similarity to rocks in the Ammassalike area of Greenland (Kalsbeek et al., 1993), the original Lewisian rocks are dated at about 2900 Ma (Fettes et al., 1992). These rocks were deformed, metamorphosed and intruded by large volumes of granodioritic material during the Scourian event which occurred about 2700 Ma. After this there were at least eight episodes of deformation or igneous intrusion (Fettes et al., 1992). There is evidence that the Flannan structure, observed on BIRPS seismic lines west of the Outer Hebrides, can be traced to depths of 80 km which is evidence of a coherence between the crust and mantle in the area and may indicate a cratonic root beneath the Lewisian foreland. The age of these rocks is comparable to those of regions elsewhere in the world which contain later diamondiferous intrusions.

### The basement of the Scottish Highlands to the east of the Moine Thrust

Several inliers of Lewisian rocks occur within the Moine sequence to the east of the Moine Thrust, the largest of which is the 30 km long Glenelg-Attadale inlier. The Lewisian inliers are divided into two, a western type which is similar to the rocks of the foreland to the west and an eastern type which contains rocks otherwise rare in the Lewisian. The rocks forming the inliers were deformed during the Caledonian Orogeny, but records of pre-Moine igneous and metamorphic events can be seen at least as far as the granulite-facies metamorphism which predated the intrusion of the Scourie dykes in the western Lewisian (May et al., 1993). The more easterly Lewisian contains eclogites of probable Grenville age, discussed separately below, but no record of earlier metamorphic episodes. Elsewhere in the Scottish Highlands there are no comparable inliers of Lewisian rocks. In the north of Sutherland there is a group of rocks, the Strathy Complex, which differs markedly in chemistry from the surrounding Moine sequence and it has been suggested that these rocks could represent Proterozoic basement (Moorhouse and Moorhouse, 1983). On the islands of Islay and Colonsay there are outcrops of gneissic rocks which originally were thought to be equivalent to the Lewisian rocks further north (Johnstone, 1966) but have recently been established as early Proterozoic juvenile mantle-derived material (Marcantonio et al., 1988). Gneissic rocks from north-west Mayo in Ireland

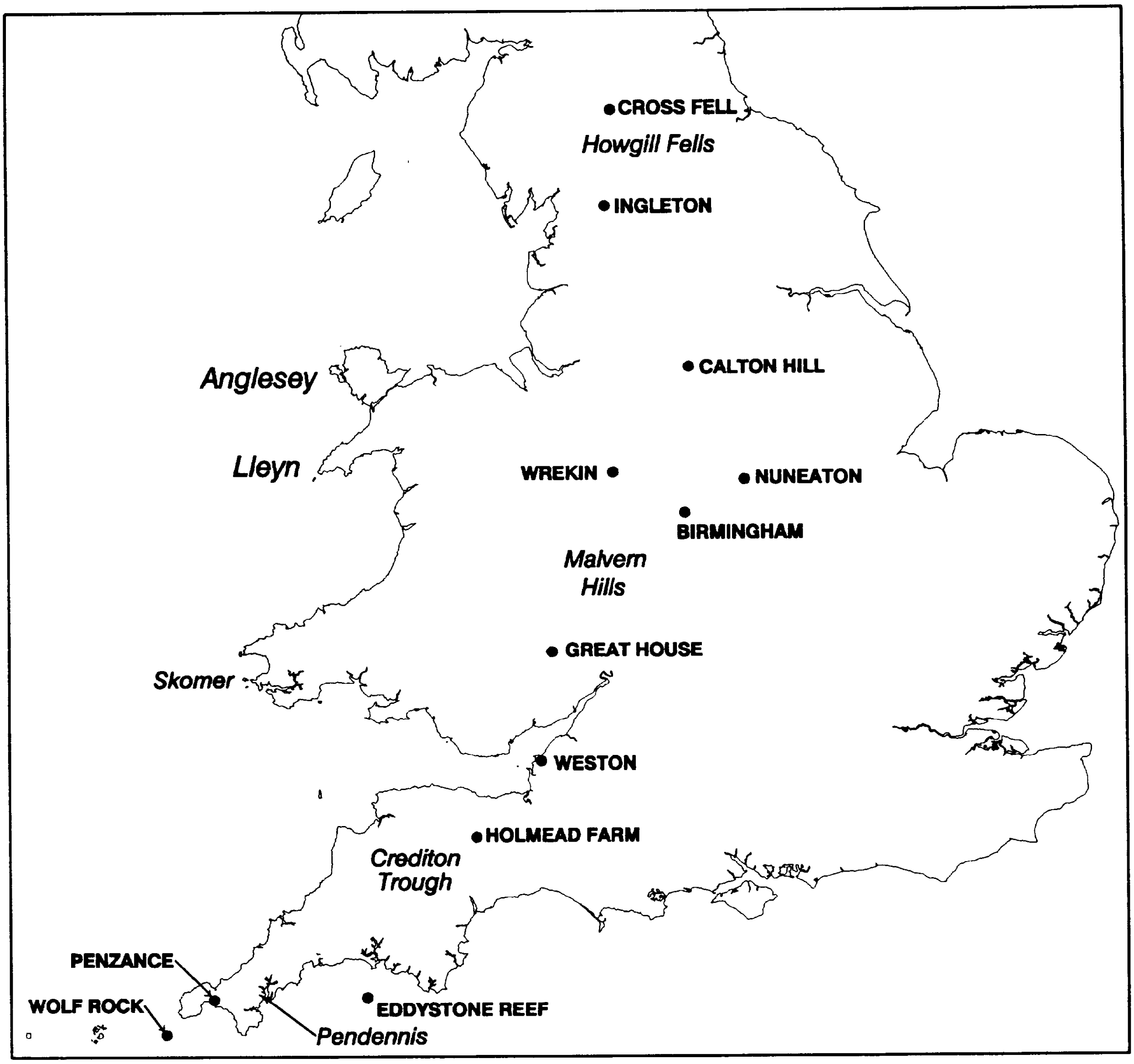


**Figure 2** Location map for southern Britain

have given a similar age (Dickin and Bowes, 1991). Furthermore, evidence from the dating of inherited zircons in granitoid rocks suggests that an early Proterozoic gneiss terrane extends from the west Ireland to north-east Scotland (Dickin and Bowes, 1991), forming the basement to the Dalradian Supergroup between the Great Glen Fault and the Mid-Grampian Line. It is therefore probable that most of the Highlands of Scotland is underlain by basement of sufficient age to fit within the known window of diamond formation. Since this segment of the crust represents a mobile belt rather than a craton, lamproitic rocks would be the most likely diamond carriers.

**The basement of the Midland Valley of Scotland**

The Midland Valley and Southern Uplands terranes are composed largely of allochthonous sequences of Lower Palaeozoic age, so that only post-docking igneous activity has any relationship to the basement now underlying them. Direct evidence of the nature of the basement of the Midland Valley terrane comes from studies of xenoliths in several post-docking late-Palaeozoic alkali-basaltic vents (Upton et al., 1984). Dating of the majority of the xenoliths suggests that a basement of Grenvillian age underlies the Midland Valley. In addition, there are chemical differences between the basic granulite xenoliths and typical Lewisian mafic granulitic rocks, which suggests that basement in the Midland valley terrane is different from the Lewisian terrane (Hunter et al., 1984). The age of the basement would appear to be too young to fit within the known window of diamond formation in mantle roots.

**The basement of the Southern Uplands of Scotland.**

Basement is not exposed in the Southern Uplands, but xenoliths have been obtained from three sites within the Southern Uplands terrane. Granulite xenoliths, apparently similar to those from igneous rocks in the Midland Valley, have been obtained from two localities relatively close to the Southern Uplands Fault but not from the vent rocks in the Newcastleton area, close to its southern margin (Upton et al., 1984). Indirect evidence of the nature of the basement in the Southern Uplands is provided by the ages of zircons within the granite intrusions. No evidence of older inherited zircons were found in the Southern Uplands granites or indeed in the Distinkhorn granite, which is within the southern part of the Midland Valley (Pidgeon and Aftalion, 1978). This evidence would suggest that old basement is absent beneath the Southern Uplands and the basement is too young to be favourable for diamonds in mantle roots.

**The basement of northern England**

There is no direct evidence of the nature of the basement in northern England. On the basis of similarity of seismic velocity with upper crustal velocities in Brittany it has been suggested (Dunning, 1992) that the northern England basement consists of Cadomian (late Proterozoic) metamorphic rocks. No xenolithic igneous rocks are known from the region to provide direct evidence of the nature of the lower crust. There is no evidence of older inherited zircons in the Lake District granites (Pidgeon and Aftalion, 1978) which suggests absence of old basement and thus absence of diamond potential in mantle roots.

**The basement of Wales and central England**

The rocks exposed in Anglesey and Lleyn are of late Proterozoic age and there is no evidence to suggest that the gneisses within these areas are significantly older (Harris, 1992). Similarly, in the Welsh Borders there are no exposures of rocks older than the late Proterozoic. Much of central England is underlain by late Proterozoic rocks of the Charnian type. No gneissic xenoliths have been found in the Calton Hill pipe in Derbyshire (Donaldson, 1978) which could give an indication of the nature of the deep crust in the area. Xenoliths of tectonised quartz-plagioclase rocks occur in the Great House vent near Usk in south-east Wales (Upton et al., 1984) but the age and significance of these is not clear. In south-east Ireland the Rosslare complex contains rocks that have been dated as early Proterozoic (Davies et al., 1985). The Rosslare Complex is bounded by shears (Murphy, 1990) of the type that is typical of the Avalon Terrane in North America and its equivalent in northern France (Gibbons, 1990). The Rosslare complex could be a remnant of more ancient crust which formed the basement upon which the late Proterozoic rocks were deposited and which was caught up with the younger rocks during the Cadomian orogeny (Gibbons, 1990). The present complexities within the zone result from the transcurrent dismemberment of the late Precambrian magmatic arc and associated rocks during the later part of the Cadomian orogeny. If remnants of old crust of the Rosslare type occur beneath Wales, then these could be of sufficient age to fit within the diamond crystallisation window in mantle roots.

**The basement of south-west England**

There is no available direct evidence as to the nature of the basement in south-west England. Garnetiferous gneiss occurs to the south of Plymouth in the Eddystone reef but the age of the protolith is not known. It is possible that the basement in the region is made up of Cadomian rocks similar to those found in the Channel Isles and northern France and which contain segments of Archaean crust, the Icart gneisses (Calvez and Vidal, 1978). Alternatively, the basement could be of the Uriconian type, of later Proterozoic age and rich in calc-alkaline volcanic rocks. The Pb isotopic compositions of feldspars from the south-west England granites (Hampton and Taylor, 1983) suggest that they were derived from crust of late Proterozoic and/or earliest Palaeozoic age, which would suggest a Uriconian-type basement. Direct geophysical evidence of the nature of the basement is sparse, the main indication possibly being the existence of long-wavelength aeromagnetic anomalies trending west-north-west and extending over much of the south-west peninsula and nearby offshore areas. The nature of the anomalies is consistent with source rocks lying at depths in excess of 3 to 4 km. In the English Channel to the south of this anomalous belt there are very low magnetic anomaly values, followed further south by pronounced highs associated with a postulated ophiolite belt. Evidence is insufficient to give a clear indication of the nature of the basement in this region but if remnants of Archaean rocks occur, as in the basement of northern France, then these would be old enough to fit within the mantle-root diamond-crystallisation window.

**Fertility of mantle below areas of old basement**

There is evidence that the extreme compositions of kimberlite and lamproite can only originate from mantle material that has been depleted by removal of a melt fraction and then enriched by a metasomatic melt fraction (Tainton and McKenzie, 1994). Evidence for the existence of metasomatised mantle material both in xenoliths in deep intrusions and in the composition of subsequently erupted basalts could therefore be of interest in assessing the potential of an area for diamondiferous intrusions.

A source of information about the mantle in the north-west Highlands is the composition of the Tertiary volcanic rocks. The Tertiary Hebridean basalts seem to be depleted in incompatible elements relative to other similar basalts (Morrison et al., 1980). Furthermore, the Mull lavas and Arran crinanite are more depleted than the Skye lavas (Morrison et al., 1980), which may reflect differences in the mantle between the Lewisian foreland and the terrane to the south. In contrast, the Karoo basalts of Jurassic age, which were erupted through the Capvaal craton in southern Africa, the environment of subsequent diamond-bearing kimberlites, were derived from mantle enriched in the elements Rb, Ba, Th, U, K and La (Marsh and Eales, 1984). If a prerequisite of diamond formation is mantle enriched in volatile elements, then the mantle underlying the Highlands of Scotland would seem not to be favourable, at least from the Tertiary onwards. The depletion of the Scottish mainland mantle could be in part the consequence of previous mafic magmatism e.g. that occurring during the late Palaeozoic (Morrison et al., 1980). On the other hand, isotopic work on xenoliths within the monchiquite dyke at Loch Roag in Lewis suggests that the mantle beneath the Outer Hebrides is highly fertile (Menzies et al., 1987).

## DEEP-ROOTED IGNEOUS ACTIVITY WITH POTENTIAL TO TRANSPORT DIAMONDS TO EARTH'S SURFACE

The various episodes of basic and alkaline igneous activity in Britain which had the potential to bring diamond up to the earth's surface are described below, from oldest to youngest.

### Precambrian igneous activity

Diamonds are only likely to have survived in areas where possible diamond host rocks have not been subjected to high-grade metamorphism. Thus the basic rocks within the Moine sequences, which have undergone sufficient deformation and metamorphism to completely recrystallise the original igneous rock, are unlikely to contain diamonds (Brown, 1991). Within the Dalradian succession there are relicts of igneous texture in the thicker basic lavas and sills, but the composition of these rocks is similar to tholeiites of accreting plate margins, an environment with little potential for diamonds. There is no evidence of basaltic or alkaline igneous activity between the end of the Laxfordian deformation and metamorphism and the Caledonian orogeny, although in Norway there are many ultramafic dykes with carbonatitic affinities and some alkaline dykes which are coeval with the late Proterozoic Fen Central Complex (Dahlgren, 1994).

Evidence of late Proterozoic igneous activity is widespread in the scattered outcrops of Precambrian rocks in England and Wales. Albitised basalts occur within the Uriconian sequence of the Welsh Borders, along with intermediate to acid volcanic rocks. These rocks are thought to have erupted in an ensialic marginal basin (Pharaoh et al., 1987). Altered or highly altered intrusions of olivine-dolerite and, in places, quartz-dolerite cut the Uriconian rocks and are thought to be of similar age. The Warren House formation in the Malverns contains abundant basalt which has suffered low-grade metamorphism or intense alteration (Worssam et al., 1989). Chemically these rocks resemble tholeitic basalts erupted in primitive oceanic island arcs and back-arc basins (Pharoah et al., 1987). On the basis of their compositions and degree of alteration the volcanic and intrusive mafic rocks of late Proterozoic age in the Welsh Borders are not likely to carry diamonds.

### Cambrian and Ordovician igneous activity

The Highland Border Complex, mostly of Ordovician age, is a dismembered ophiolitic complex but contains local bodies of alkalic within-plate basalt. The mafic rocks have been highly altered and metamorphosed (Walton and Oliver, 1991) and are not therefore considered to have any potential for diamonds. The Ballantrae ophiolitic complex of Ordovician age is exposed to the north of the Southern Uplands Fault. The composition of basic lavas associated with the complex is variable and suggests that they were erupted in a variety of environments before tectonic juxtaposition (Brown, 1991). The general interpretation by Smellie and Stone (1992) suggests an early oceanic island arc setting followed by extension and ocean-island type tholeiite extrusion with final accretion during arc-continent collision, environments in which rocks with potential to carry diamonds are unlikely.

Minor amounts of Ordovician basalt occur in the Northern Belt of the Southern Uplands. Both mildly alkaline and tholeiitic basalts occur, the former predating the later and suggesting eruption within a rift environment (Lambert et al., 1981). A larger mass of Ordovician volcanic rocks occurs within the Southern Uplands at Bail Hill, near Sanquar, comprising mildly alkaline lavas and a volcanic neck, thought originally to have been a seamount (Hepworth et al., 1982). The diamond-bearing potential of these rocks is low.

Mafic volcanic rocks of Lower Palaeozoic age occur widely in the Lake District and Wales but they are mostly island arc tholeiites or calc-alkaline basalts (Francis, 1992) which are unlikely to have originated at sufficient depth to have picked up diamondiferous xenoliths. Basic intrusions of presumed Ordovician age cut the Cambrian rocks in the Wrekin, Malverns and Nuneaton areas. They are albite-rich and altered but some could originally have been alkaline. In Wales there are several dolerite sheet intrusions of presumed Ordovician age but the chemistry of these is similar to the volcanic rocks, and alkali basaltic rocks seem to be absent. None of the volcanic rocks of this age in these areas are likely to have been generated at sufficient depths or in crustal regimes with low geothermal gradient, so they and are unlikely to contain diamonds.

**Mafic igneous activity of Silurian age**

Alkali basalts are the most abundant component of the Silurian Skomer Volcanic Group of south-west Wales (Ziegler et al., 1969) but they are also associated with intermediate and trachytic rocks. There is no record of xenoliths of deep origin within the basalts. Some at least of the alkaline intrusions in the north-west Highlands of Scotland are also Silurian in age. The Loch Borralan and Loch Ailsh intrusions consist mostly of several varieties of syenite, nepheline syenite and pyroxenite together with some highly potassic rocks and carbonatite at Loch Borralan (Brown, 1991: Young et al., 1994). Dyke rocks associated with these complexes could potentially be diamondiferous, especially if highly potassic. The Loch Loyal intrusions are quartz syenites without associated ultramafic rocks and the Glen Dessary syenite also lacks associated ultramafic rocks.

**Late Caledonian mafic igneous activity**

*Lamprophyres*

Lamprophyre dykes of late Caledonian age occur to the north of the Great Glen and especially around the Ratagain complex and the Ross of Mull pluton. Many lamprophyres, mostly pyroxene minettes, have been located around the Ratagain complex and elsewhere in the Kintail region in the course of recent detailed geological mapping (May et al., 1993). Spessartites, kersantites and minor minettes occur in close association with the Ross of Mull pluton (Rock and Hunter, 1987). Some of the most primitive lamprophyre compositions are thought essentially to be primary mantle-derived compositions (Rock and Hunter, op. cit.). All four varieties of calc-alkali lamprophyre occur as components of dyke swarms adjacent to some of the plutons in the Grampian Highlands e.g. Etive and Glen Tilt (Richey, 1939). Around the Glen Tilt pluton most of the lamprophyres are kersantites, vogesites and spessartites (Richey, op. cit.). In addition, there are a few ultrabasic dykes in the same area which need to be characterised further.

A more recent and comprehensive study has been made of lamprophyres and other dykes in the Southern Uplands of Scotland (Rock et al., 1988). Hornblende lamprophyres occur most abundantly adjacent to the Loch Doon and Criffel plutonic complexes while mica lamprophyres are dominant within a 10 km wide swarm stretching over 300 km from Northern Ireland right across the southern part of the Southern Uplands belt in areas remote from plutonic rocks (Rock et al., op. cit.). Compositionally they are relatively primitive and enriched in K, Sr and Ba (Rock et al., 1986).

Lamprophyres cut Lower Palaeozoic rocks in the southern and eastern parts of the Lake District and the adjacent Howgill Fells and in the Cross Fell and Ingleton inliers (Macdonald et al., 1985). Both kersantites and mica lamprophyres of relatively primitive composition occur but they appear to differ chemically in some elements from the Southern Uplands lamprophyres (Rock et al., 1988). Lamprophyres of late Caledonian age seem to be absent from Wales, the Welsh Borders and Charnwood Forest. However the highly altered intrusions in the Nuneaton inlier are thought to be spessartites of Caledonian age (Worssam and Old, 1988).

The most primitive mica lamprophyres are the most likely to be diamondiferous but only if there is evidence for a low geothermal gradient such as could result from a sinking slab of subducted material prior to their intrusion. The regional swarm of minettes in the Southern Uplands is possibly the most favourable, though the controls of late Caledonian igneous activity in the region are unclear and the postulated episode of low geothermal gradient speculative.

*Appinites*

Some appinites are thought to be the plutonic equivalents of the hornblende lamprophyres; they occur in pipes, mostly closely associated with granitoid plutons in the Highlands and, to a much lesser extent, in the Southern Uplands of Scotland. These rocks are widespread in the Dalradian segment of the Highlands but also occur in parts of the northern Highlands and in isolated examples on Lewis (Fettes et al., 1992), with a phase of intrusion at 425 Ma related to transcurrent faulting. Ultramafic varieties occur in minor amounts usually marginal to biotite-pyroxenite and hornblendite (Wright and Bowes, 1979). Chemically, the rocks are marked by enrichment in potassium compared with most basic rocks and a general enrichment in volatiles. There is a notable concentration of pyroxene-bearing appinites together with some ultrabasic types in one area in the northern Highlands, to the west of Invergarry (Smith, 1979). Though appinites are not known to carry diamonds, the most highly potassic varieties and the ultramafic types merit further consideration.

*Fenites*

Fenites and other evidence of alkali metasomatism are associated with parts of the Great Glen, and their presence has led to the suggestion that carbonatites may be associated with the Great Glen Fault (Garson et al., 1984). A zone of alkaline metasomatism between Loch Hourn and Loch Nevis may represent evidence of deeper alkaline magmatism and could have some diamond potential. The Great Glen Fault has been a major structure rooted in the mantle since the Caledonian and could be the locus of other types of alkali igneous activity including kimberlite.

**Late Palaeozoic igneous activity**

*Carboniferous basic volcanism and associated intrusions*

A considerable part of the Carboniferous sequence in the Midland Valley of Scotland is made up of basic volcanic rocks, most of which are alkaline. Visean volcanic rocks are the predominant rock type at the western end of the Midland Valley on both sides of the Clyde and form the Clyde Plateau Volcanic Formation. South of the Clyde the rocks are mostly mildly alkaline lavas varying in composition from ankaramitic basalt to trachyte (Macdonald, 1975). Rocks of similar age occur further east in the Midland valley, especially in East Lothian. Chemical data suggest that the volcanic rocks became progressively more undersaturated with time and it has been suggested (Macdonald, 1975) that this reflects magma production at increasing depths within the mantle. Nodules and xenocrysts are virtually absent in the volcanic rocks of Visean age but increase in importance in later volcanic rocks (Macdonald, op. cit.). The lack of high-pressure phenocrysts in the Visean lavas is thought to indicate accumulation and reequilibration in a shallow crustal magma reservoir which would have destroyed any diamond in the magma (Macdonald, op. cit.).

Ultramafic inclusions are conspicuous in some Carboniferous vents exposed along the Ayrshire coast. The Black Rock vent (Alexander et al., 1986) is thought to be late Carboniferous in age and consists of basanite within which there are a wide range of ultramafic xenoliths including lherzolite, websterite and metasomatised types, as well as xenocrysts of Cr-diopside, garnet and other minerals, though their identification is often difficult because of alteration. Carbonated peridotite and serpentinite occur as conspicuous xenoliths in pyroclastic and intrusive rocks associated with the Heads of Ayr vent further south along the coast (Whyte, 1968). These rocks probably originated at insufficient depth to be potentially diamondiferous.

The East Lothian lavas differ from the Clyde Plateau lavas in being mildly potassic. This characteristic may reflect mantle heterogeneity since the later volcanic rocks in the area are also potassic. A basanitic suite of plugs, dykes and sills of uncertain age, some of which contain xenoliths of ultrabasic rocks, occurs in East Lothian. Leucite basanite occurs in dykes cutting the Carr vent (Davies et al., 1986). Of particular interest are inclusions of biotite-rich ultramafic rocks (mica peridotite and glimmerite) in the Parton Craig vent. These potassium-rich rocks indicate significant metasomatism of the mantle whether derived from deep mantle or subduction sources. Thus they may have some potential for diamonds which originated in a subducted slab.

Volcanism in the Midland Valley was more local and on a smaller scale during the Namurian and Westphalian, and tuffs form a much greater proportion of its products. In the Bathgate area some of the lavas at the base of the Namurian are basanites (Macdonald et al., 1977). A complete change in the type of magmatism produced sills and dykes of quartz dolerite prior to the re-establishment of alkali basic igneous activity in the Permian.

There are also minor occurrences of volcanic rocks in the Southern Uplands which are similar in composition to the lavas from the Midland Valley, though they are mostly Tournaisian in age. There are numerous volcanic necks in the Langholm area which are thought to be vents from which the local sequences of Carboniferous basalt lavas issued (Lumsden et al., 1967). These vents may have some potential for diamonds as they could have sampled mantle affected by past subduction and lowering of the geothermal gradient.

In the Derbyshire dome there are minor amounts of basic volcanic rocks of Visean age comprising both lavas and tuffs, now highly altered. Compositionally they vary from tholeiite to alkaline basalt. The Derbyshire igneous activity is not thought to be associated with a major tensional stress field, in contrast to the Midland Valley of Scotland (Macdonald et al., 1985). Some of the rocks are rich in potassium, but this could be a consequence of alteration rather than a primary feature (Aitkenhead et al., 1985). The Calton Hill pipe intrusion of similar age contains inclusions of spinel-bearing lherzolites and harzburgites which are considered to have originated at a depth of between 45 and 48 km (Donaldson, 1978). As there are no other types of inclusion possibly derived from deeper levels, it is unlikely that diamonds would be present in the pipe. Minor mafic volcanic rocks comprising both lava and tuff occur at and around Weston-super-Mare (Whittaker and Green, 1983) and other localities to the south-west of Bristol. The rocks are alkaline olivine basalts rich in potassium, which is probably due to alteration. They probably originated at shallower depths than that at which diamonds might be expected.

*End Carboniferous and Permian volcanic rocks and associated subvolcanic intrusions*

In the eastern part of the Midland Valley on both sides of the Forth there are a series of vents and other intrusions of alkali basaltic rocks of Stephanian and Permian ages. There are over 100 necks in east Fife (Forsyth and Chisholm, 1977) and many occur on the Fife coast between Ruddons Point and Coalyard Hill. Inclusions of spinel lherzolite are known from two localities but pyroxenite inclusions are more widespread. The host rocks vary from mildly under-saturated alkali basalts to basanites and to strongly undersaturated monchiquites. The tuff at Elie Ness contains pyrope garnet xenocrysts, but these are chemically dissimilar to garnets from garnet peridotites and eclogites (Chapman, 1976). These garnets are thought to have crystallised as phenocrysts from a primitive alkali basaltic liquid at depths of over 70 km which then rapidly reached the earth's surface. As this depth is not great enough to intersect the diamond stability field in cratonic roots the potential for diamond is low. Furthermore the widespread earlier Carboniferous volcanicity in the Midland Valley would have tended to destroy any diamond that may have formed previously due to a subduction-related low geothermal gradient. McCallien (1937) mentions that Heddle and others, stimulated by the finds of diamonds around Kimberly in South Africa, searched the necks of Fife extensively for diamonds but failed to find any.

The locations of Permian volcanic rocks in Scotland are controlled by north–south to north-west–south-east rifting (Francis, 1992). The main outcrops occur in the Mauchline basin in Ayrshire and further south-east in the Southern Uplands around Sanquhar and Thornhill. At Mauchline the volcanic rocks comprise alkali basalts with some basanites with intercalated tuffs and sediments together with many volcanic necks. They are restricted in composition compared with the Visean lavas and more silica-undersaturated, which suggests that they originated deeper in the mantle. They were also extruded more rapidly than the Visean lavas and thus would be more favourable to the preservation of diamond. Xenoliths of peridotite are found in subvolcanic intrusions of monchiquite in the area around the lava outcrop (Mykura, 1967). However, the high geothermal gradient implied by the Carboniferous igneous activity in the region would have tended to destroy any diamond that could have formed in association with a remnant cold subducted slab before the Permian igneous activity.

There are only isolated examples of alkali mafic rocks in the Southern Uplands most of which are probably late Carboniferous or Permian in age. A monchiquite dyke similar in appearance to rocks from Ayrshire is recorded from Lauderdale (Walker, 1925). A plug of nepheline basanite occurs at Southdean to the south of Jedburgh (Tomkeieff, 1952). Further west in the Southern Uplands, a dyke of monchiquite occurs near Abington in association with essexite (Scott, 1915). In the Sanquhar coalfield there are thin decomposed sills of dolerite and five vents filled largely with olivine basalt. Monchiquite and camptonite dykes of probable Permian age also occur, including one monchiquite rich in inclusions of peridotite, which was cut within a coal mine. These rocks could have more potential than similar intrusions further north, as they were emplaced away from the main centres of previous Carboniferous volcanism.

Volcanic rocks and associated subvolcanic intrusions occur in the Crediton Trough and elsewhere in Devon, within the Permian red-bed sequence. They comprise a basaltic group and a potassic or lamprophyric group, but due to extensive alteration their original mineralogy is difficult to identify. The basaltic group is enriched in Rb, Ba, Th and K (Thorpe et al., 1986), similar to shoshonites, and has recently been found to be variably enriched in gold (Cameron et al., 1994). The mode of occurrence of the potassic group is highly variable, comprising lavas, pyroclastic rocks and pipe and dyke intrusions. They are also highly variable in composition. Some of the rocks are extremely potassic (maximum 13% $K_2O$; Knill, 1969) and highly enriched in P, Ba, Sr and light rare earths (Cosgrove, 1972). Of particular interest are volcanic rock fragments within agglomerate at Holmead farm near Tiverton, which are described in detail by Thorpe (1986) and to which the name analcite-bearing lamproite had previously been given. There is no mention of xenocrysts or xenoliths in any of the descriptions, but all these rocks merit much more detailed study. As exposure is poor in the area, other bodies of igneous may be present which have so far escaped detection.

Away from the outcrops of Permian rocks in south-west England there are sporadic occurrences of lamprophyre, generally minette. They occur right across the region from Penzance eastwards and are of similar age to the volcanic rocks and associated rocks further east in Devon. They are commonly highly altered, but apatite is often conspicuous. The dyke at Pendennis near Falmouth is classified as a lamproite *sensu stricto* on the basis of both mineralogy and chemistry (Bergman, 1987). The lamproitic and lamprophytic rocks have some diamond potential and should be studied in more detail.

*Carboniferous and Permian minor intrusions remote from exposed volcanic rocks of similar age*

There are very many dykes and pipes of alkali lamprophyre and related rocks in northern Scotland. Both camptonites, compositionally equivalent to alkali basalt and basanite, and monchiquite, compositionally equivalent to basanite and nephelinite, are present (Baxter, 1986). Monchiquites are thought to be more primitive than camptonites and to have risen rapidly into the upper crust from mantle levels (Baxter, 1986). Though typical monchiquites are not thought to have originated at sufficient depth to tap diamond in cratonic mantle roots, there are some types of dyke and pipe intrusion with more extreme compositions which have some potential to be diamondiferous.

The various post-Caledonian dyke swarms in the Highlands of Scotland have given a range of dates from Visean to late Permian (Baxter and Mitchell, 1984). Dykes occur in the Outer Hebrides on Eriskay and South Uist, with a few on North Uist, Benbecula and South Harris (Fettes et al., 1992). Most of the intrusions are camptonite or basaltic camptonite but one monchiquite occurs at Loch Roag in Lewis and is of particular interest because it contains the richest suite of xenocrysts and xenoliths found in this type of rock in Scotland (Fettes et al., 1992). Included in the xenocrysts are hexagonal corundum crystals. Eight additional swarms of similar alkali lamprophyres have been recognised to the north-west of the Great Glen (Rock, 1983). In Orkney, dykes of camptonite and monchiquite occur, together with a few more felsic dykes including one (Swona dyke) extremely rich in potassium (Rock, 1983). The Orkney dykes are generally richer in nepheline than similar dykes from further south. In southern Orkney there are also several monchiquite-agglomerate vents. A monchiquite vent on the Caithness coast at Duncansby Head is rich in xenoliths of chrome-spinel clinopyroxenites, wehrlites and lherzolites; they are thought to have been derived from a depth of around 50 km

(Chapman, 1975) which is too shallow for diamond to be present. Although the chemistry of the dykes suggests a deeper source for the monchiquite, by a small degree of partial melting of garnet lherzolite (Baxter, 1987), it would still be too shallow to carry diamond up from a cratonic root.

Only a few dykes have been recognised in Sutherland and Wester Ross, but further south there are two adjacent swarms, the Monar and Killilan swarms. Most of the Monar swarm are camptonites, but among the monchiquites is a pyroxene-rich ultramafic variety to which the term yamaskite has been applied (Peacock et al., 1992) and which could merit further study. Camptonite is also the predominant rock in the Killilan swarm. A monchiquite vent or exploded dyke occurs at Camas Luinie and contains xenoliths of spinel lherzolite and xenocrysts of clinopyroxene and magnetite and apatite aggregates, but no inclusions typically associated with diamond-bearing rocks. Further south, the Eil-Arkaig swarm has been dated as Visean rather than Permian (Baxter and Mitchell, 1984), and is similar to the Monar swarm. To the east-south-east there are several monchiquite vents, some rich in xenoliths and xenocrysts (Hartley and Leedal, 1951; Walker and Ross, 1955), associated loosely with the Eil-Arkaig swarm, but no inclusions which would indicate derivation from a depth sufficient to represent a cratonic root have been found. Of the other three swarms further south (Ardgour, Coll and Tiree and Iona and Ross of Mull) only the Ross of Mull swarm is relatively rich in monchiquite dykes (Rock, 1983).

Typical monchiquites are not thought to have originated at sufficient depth to incorporate potentially diamondiferous material from cratonic roots. Perhaps of greater interest are intrusions which depart significantly from this composition, particularly when highly potassic. Thus the Orkney dyke swarm and cluster of pipe intrusions seem to be the most likely to contain additional types of rock which could have been derived from deeper levels and therefore to be more prospective for diamonds.

Monchiquite occurs in association with a vent at Great House near Usk in Gwent (Eyles and Blundell, 1957) and as a dyke some two miles further to the north-west. Associated with the monchiquite are xenoliths of spinel lherzolite. The intrusion is probably either Lower Carboniferous or Permian in age and is remarkable for its isolation. However the inclusions are not derived from sufficient depth to suggest the likely presence of diamonds.

**Tertiary igneous activity**

Though volcanic rocks of Triassic, Jurassic and Cretaceous age are known from the North Sea, they are absent on land in England and Wales except for horizons of bentonite and dykes cutting the Triassic rocks in Staffordshire. In contrast, there were major centres of Tertiary igneous activity in western Scotland and Northern Ireland. Magmatism was bimodal, producing mostly basic and acid igneous rocks. The earlier basic lavas found in Skye are alkali and transitional basalts, with more fractionated lavas becoming important in the higher part of the succession. The youngest flows are of low-alkali tholeiites (Emeleus, 1991). In Mull the earlier lavas were also alkali and transitional basalts and these were followed by tholeiites now preserved only close to the central complex. There are also several central complexes which represent the roots of volcanoes and some separate granitic intrusions. Dykes are abundant and occur as linear swarms loosely associated with the central complexes. Individual dykes can be traced for over 400 km from Mull across northern England. A wide range of compositions from alkali olivine dolerite to quartz dolerite are present within the dyke swarms. There has been considerable debate as to the origin of the basic magmatism (Emeleus, 1991). One hypothesis suggests that original magma was picritic and dense and was ponded periodically at the base of the crust and at higher levels before eruption, allowing differentiation to more evolved compositions and contamination with crustal material. This model accounts for the lack of xenoliths of mantle or deep-crustal origin in the Tertiary basic lavas and associated minor intrusions and means that they have little potential for diamonds.

## THE POTENTIAL FOR DIAMONDS WITHIN ECLOGITES

Diamonds have been found as inclusions up to 0.7 mm in size in garnet within eclogite and similar rocks of ultra-high-pressure type in China and Norway (Shutong et al., 1992; Dobrzhinetskya et al., 1993). The diamonds have been protected from the effects of later retrograde metamorphism by the surrounding garnet. There are a variety of eclogites in which increased pressure is reflected by changes in mineralogy. The highest pressure eclogites that have been located at the earth's surface contain coesite instead of quartz and pressure/temperature estimates of their formation, based on mineral equilibria, approach and possibly cross into the diamond stability field (Smith, 1988). Assuming that all pressure is lithostatic, then diamond-bearing eclogites would have had to be tectonically emplaced from depths greater than 100 km to the upper crust. Tectonic overpressures have also been invoked to account for these rocks as an alternative hypothesis, which would allow their formation at shallower depths (Smith, 1988), but this hypothesis for formation is controversial.

Eclogites occur as lenticular masses and bands up to several metres in thickness among hornblende and biotite gneisses in the Glenelg region of the western Highlands, near to the Moine thrust (Peacock et al., 1992). An age of about 1,100 Ma has been obtained for eclogitic metamorphism from Sm-Nd isotopes (Sanders et al., 1984). This is interpreted as indicating Grenville age metamorphism of the basement. However it is not clear to what extent the occurrence of eclogite is related to a zone of shearing within which tectonic over-pressures could have developed. Though retrogressive alteration is widespread, relics of the original mineralogy suggests temperature around 700° C and relatively iow pressures compared with the coesite eclogites in western Norway (Smith, 1988). Thus the eclogites of the western Highlands seem to have formed at pressures too low to have any potential for diamonds.

## THE POTENTIAL FOR DIAMONDS WITHIN PALAEOPLACERS

Since diamond is the hardest substance known and highly resistant to abrasion it tends to be preserved in the sedimentary rocks derived from primary igneous source rocks. In some places e.g. Brazil, diamonds in sedimentary rocks were found and worked long before the primary igneous sources of the mineral. The proportion of gem-quality diamonds is much higher in secondary deposits than in the primary igneous sources because only the flawless stones will survive significant transport. The 8 km thick arenaceous late Proterozoic Torridonian sequence resting on the Lewisian in parts of the north-west Highlands of Scotland is a potential source of diamonds in palaeoplacer deposits. The sediments are predominantly fluvial and lacustrine and have suffered little deformation or metamorphism. The source of some of these rocks was clearly west of the Outer Isles Fault but not from the presently exposed Lewisian in the Outer Hebrides. A possible source from a Scourian supracrustal sequence similar to those found in typical Archaean greenstone belts has been suggested (Stewart, 1987). If such a sequence contained diamondiferous intrusions then diamonds derived from such a source could be preserved within the Torridonian sequence.

Another possible palaeoplacer is the Stornoway Formation of north-east Lewis. This undeformed conglomerate sequence of Permo-Triassic age lies unconformably on the Lewisian and consists predominantly of clasts of Lewisian gneiss and vein quartz (Fettes et al., 1992). It is thought to consist mostly of alluvial fan deposits and thinner fluvial deposits and therefore to have some potential as a diamond palaeoplacer if contemporary or older sources of diamondiferous rocks existed in the Lewisian terrain to the west and north-west. Other possible palaeoplacers are coarse fluviatile and fan deposits of Devonian, Lower Carboniferous and Permian ages at several localities in Scotland and of Permian age in south-west England. As all of these sediment sequences are of local derivation they would only have some potential if their catchments contained diamond-bearing intrusions. The diamond from Northern Ireland, if the source attributed to it is genuine, would seem most likely to have been derived from this type of sediment sequence.

## DIAMOND-DESTROYING PROCESSES

Destruction of diamond in upper crustal rocks can occur by elevation of the temperature of the rock due to metamorphism or hydrothermal activity. Recrystallisation of diamond as graphite can also occur in the deep lithospheric environment of primary crysallisation, due also to an elevation of temperature but this deep environment is not accessible for direct study. Any direct correlation between an increase in thermal gradient in the upper crust which leads to metamorphism and an increase in thermal gradient in the mantle at the depths at which diamond crystallises is difficult to establish. North of the Highland Boundary Fault, the basement appears to be early Proterozoic or older in age and therefore within the age span of most dated diamond source rocks. The Lewisian has undergone several phases of deformation, metamorphism and igneous activity since the deposition of the Archaean protoliths, as revealed by recent detailed mapping (Fettes et al., 1992). Few other areas of Archaean gneisses have been studied in as much detail as the north-west Highlands and Islands of Scotland. Comparable studies of Archaean cratons in which there are diamondiferous intrusions are necessary to establish whether the amount of post-Scourian tectonism and igneous activity in the Lewisian was sufficient to destroy a pre-existing diamondiferous root but such comparisons have not yet been published. However, evidence is accumulating (Kjarsgaard and Wyllie, 1994) that the diamondiferous kimberlites in the Lac de Gras area of the North-west Territories in Canada are confined to a part of the Archaean Slave Province that has escaped the older Slave Province volcanic rocks and associated plutonic rocks (2695-2650 Ma) though not the younger Slave province granitoid intrusions (2625-2580 Ma). Further work of this sort in different cratons is required before it will be possible to predict from the nature and history of the metamorphic and igneous rocks in basement regions whether any diamonds in cratonic roots would have survived.

The presence of substantial amounts of basic volcanic rocks implies an elevation of the geothermal gradient stretching down into the mantle at the time of extrusion. However it is not clear to what extent such an increase in temperature is mirrored at deeper levels in the mantle within the environment of cratonic roots. North-west Scotland was the locus of extensive basic volcanicity of Tertiary age but most of the rest of the Highlands has escaped significant Phanerozoic volcanicity and thus any diamondiferous cratonic roots could have survived. Volcanicity between the Lower Devonian and early Permian in south-west England is relatively minor and local, particularly in the northern part of the region prior to the Stephanian. Thus any diamondiferous source rocks could have survived to be tapped by Permian lamproites. The Carboniferous and Permian volcanic activity in the Midland Valley of Scotland would seem to have been more intense than in south-west England and therefore the potential for destruction of any pre-existing diamond greater.

## AREAS WITH MOST POTENTIAL FOR DIAMONDS

### Diamond in a kimberlite or lamproite host

The Lewisian terrain is the most likely area to have kimberlite intrusions, though none have been identified so far. Diamonds have been located in kimberlite in Finland within the Archaean rocks of the Baltic shield (Anon, 1994). There are also lamproites of mid-Proterozoic age and kimberlites of end-Proterozoic age in the Nagssugtoquidian mobile belt in Greenland, which has been correlated with the Lewisian of Scotland (Bergman, 1987). Furthermore, diamonds have been recovered from drainage sediment and from kimberlite in south Greenland. However, there is no evidence of igneous activity in the Lewisian terrain comparable with that of mid-Proterozoic age in West Greenland and end-Proterozoic age in Norway and Greenland. Isotopic work on xenoliths from the Loch Roag monchiquite suggest that the mantle beneath the Outer Hebrides was fertile and has similarities with lamproites and even the composition of garnet inclusions found within diamond (Menzies et al., 1987).

The possibility of kimberlite or lamproite intrusions associated with the alkali igneous centres of northern Scotland cannot be ruled out. The Loch Borralan and Loch Ailsh intrusive centres have received exploration attention in recent years (Shaw et al., 1992, 1994) but for precious metals rather than diamonds. The source of these alkali intrusions may be to the east of their present location since they could have been detached from their roots by movement on the Moine Thrust. Kimberlites or lamproites could be associated with the Great Glen Fault which has been a major structure rooted in the mantle since the Caledonian.

Though there is good coastal exposure over most of north and west Scotland, there are inland areas of poor exposure, especially in the Outer Hebrides. The existing aeromagnetic data are far too widely spaced for adequate detection of unexposed kimberlite. The Outer Hebrides has the best potential for diamondiferous intrusions, given the evidence for fertile mantle. The most likely sites for these intrusions would be along Proterozoic extensional faults cutting through the Lewisian terrane, which may have been reactivated in more recent times.

Lamproite occurs in south-west England and it is likely that other bodies of similar rock may be present but undetected beneath the agricultural landscape of the region. The aeromagnetic survey of the region provides several anomalies of the right type, the sources of which are as yet unknown. As it is possible that old basement may underlie the region the lamproitic intrusions could have tapped diamondiferous mantle as they rose through the lithosphere.

**Diamond in primitive minette of lamproitic affinity**

Recognition of a geological environment which could have had a transient remnant cold subducted slab is very difficult and speculative. Such environments could have been marked by collision tectonics of a relatively mild type and the formation of granite batholiths remote from a suture. These geological features are present in south-west England where several aspects of the plate tectonic evolution are still unclear. Most of the lamprophyres in the area seem to be minettes, some with lamproitic affinity. Thus a higher level in the mantle than a typical cratonic root is also a possible source of diamonds in Permian lamprophyres and related intrusions in south-west England.

The geological environment in the lowest Devonian in the Southern Uplands is also anomalous because of granite intrusion immediately adjacent to the presumed Iapetus suture. At the end of the Caledonian orogeny there were major changes in the regional stress field with subduction and collision giving way to major transcurrent movements. If a stagnant slab of subducted material was left behind after this change in stress field it could also have acted as a transient source of diamondiferous material. The subsequent intrusion of the regional swarm of potassic minettes right across the belt could have tapped this material before it was destroyed. The minettes which occur in the Lower Palaeozoic rocks of parts of northern England could be similar in origin and diamond potential.

**Diamond in a monchiquite, basanite and nephelinite host**

It has been suggested that many of the diamondiferous kimberlites in South Africa, Brazil and even North America dating from the Cretaceous period are controlled by major deep tensional fractures complementary to but remote from the major opening of the Atlantic Ocean. In Britain, Cretaceous igneous activity is represented only by the Wolf Rock nosean phonolite and volcanicity within the North Sea. Furthermore, Britain may have been too close to the sites of rifting associated with the opening of the Atlantic to provide an environment suitable for kimberlite intrusion.

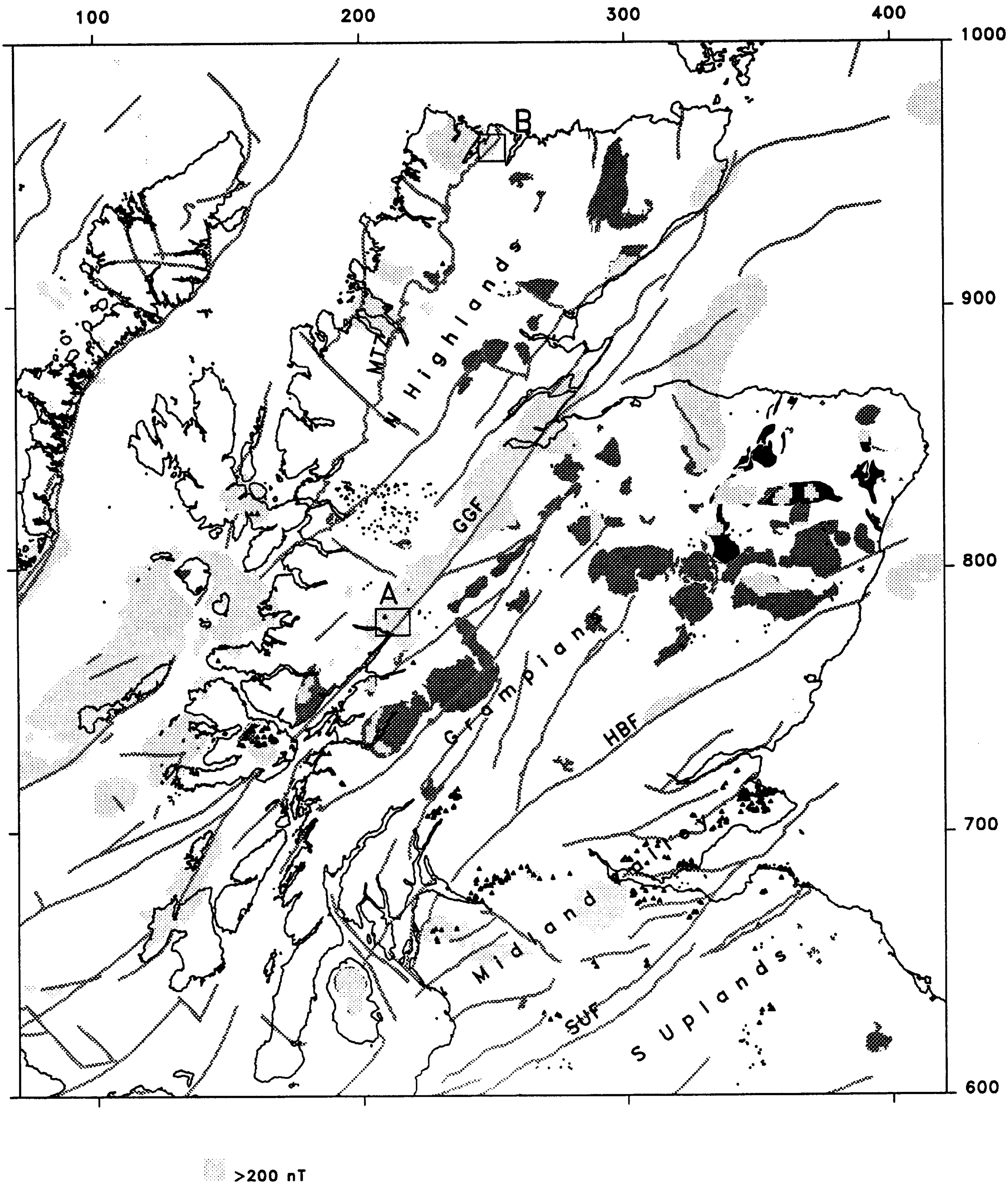


**Figure 3** Locations of anomalies shown in Figures 4 and 5 superimposed on map showing location of main outcrops of granitic rocks and location of major faults in northern Britain. Light shading shows zones with aeromagnetic anomalies > 200 nT after reduction to the pole and upward continuation to 1 km above observation level. Small dots represent sites of over 800 lamprophyre specimens in the BGS collection and triangles represent the sites of volcanic vents. (SUF = Southern Uplands Fault, HBF = Highland Boundary Fault, GGF = Great Glen Fault, MTZ = Moine Thrust Zone)

Prior to the opening of the Atlantic there was an episode of rifting in the Carboniferous and Permian which produced the Oslo graben in Norway and the central graben of the North Sea as well as the tensional faulting in the Midland Valley in Scotland. In southern Norway there are a small number of carbonatitic dykes of probable Carboniferous age (Dahlgren, 1994), similar to rocks associated with the end-Proterozoic Fen complex. These Carboniferous rocks are thought to have been associated with the earliest stages of the formation of the Oslo rift. Thus there was widespread but only locally intense alkaline basic igneous activity related to a regional tensional stress field. No evidence of diamondiferous rocks associated with this activity is known but there are parallels with the early phases of the opening of the Atlantic Ocean. Swarms consisting of typical monchiquites are unlikely to be prospective but some potential may exist where rocks of more extreme composition are present. In Scotland the most alkaline compositions, including an extremely potassic dyke, are associated with the dykes and pipes of the Orkney Islands which therefore may be considered the most favourable target area of this type. On the Scottish mainland the Eil-Arkaig swarm could perhaps be chosen as most prospective because of the presence of vents, its proximity to the Great Glen Fault and the possible presence of eclogitic rocks at depth in the area. There may be other types of intrusion of possible diamond-carrying potential associated with the monchiquite dyke at Loch Roag in Lewis.

### Diamond in palaeoplacers

Palaeoplacers are unlikely to be major sources of diamond in Britain but they could be the source of small amounts of diamond which could subsequently get into the present drainage sediment. The Torridonian sequence is probably the most likely source of isolated diamonds in the north-west Highlands of Scotland. Segments of the Stornoway Formation resting unconformably on the Lewisian of the Outer Hebrides may have some potential for a palaeoplacer in view of the age and fertility of the mantle beneath the Lewisian gneiss if there are some Permian or earlier igneous rocks of sufficiently deep-seated origin to act as potential primary source rocks.

## GEOPHYSICAL DETECTION OF KIMBERLITE

Fresh kimberlite can contain up to 10% iron oxides and has a magnetic susceptibility range of 0.001-0.100 SI. Predicted anomalies over magnetic kimberlites are generally well above the detection limits for aeromagnetic surveys and frequently of the order of 200 nT. Yellow-ground weathering of the upper parts of a kimberlite characteristically produces a prominent resistivity minimum which can be detected using electromagnetic or resistivity surveys. The conductivity anomaly can also be explored using the VLF technique, which often provides strong marginal anomalies to the diatreme. However diatremes within magnetically variable Archean or other cratonic rocks are difficult to detect (Urquhart and Hopkins, 1993). Data-enhancement techniques using operators designed to enhance high-frequency components of observed profile data are especially useful in the search for shallow magnetic sources. The most useful procedures are wavelength-filtering vertical derivative mapping techniques, amplitude trace processing and deconvolution. These methods can be used to identify local anomalies and estimate depths and magnetic properties of the sources, but as they also emphasise anomalies due to man-made sources, care needs to be taken in their interpretation. Assuming an average target size of 300 m, aeromagnetic surveys should ideally have a flight-line spacing of about 100 m with a sensor elevation of about 50 m, though frequently these parameters are relaxed by a factor of about 2. Thus typical values used in the search for kimberlite in Canada have been a line spacing of 250 m and a sensor height of 60 m (Reed and Sinclair, 1991).

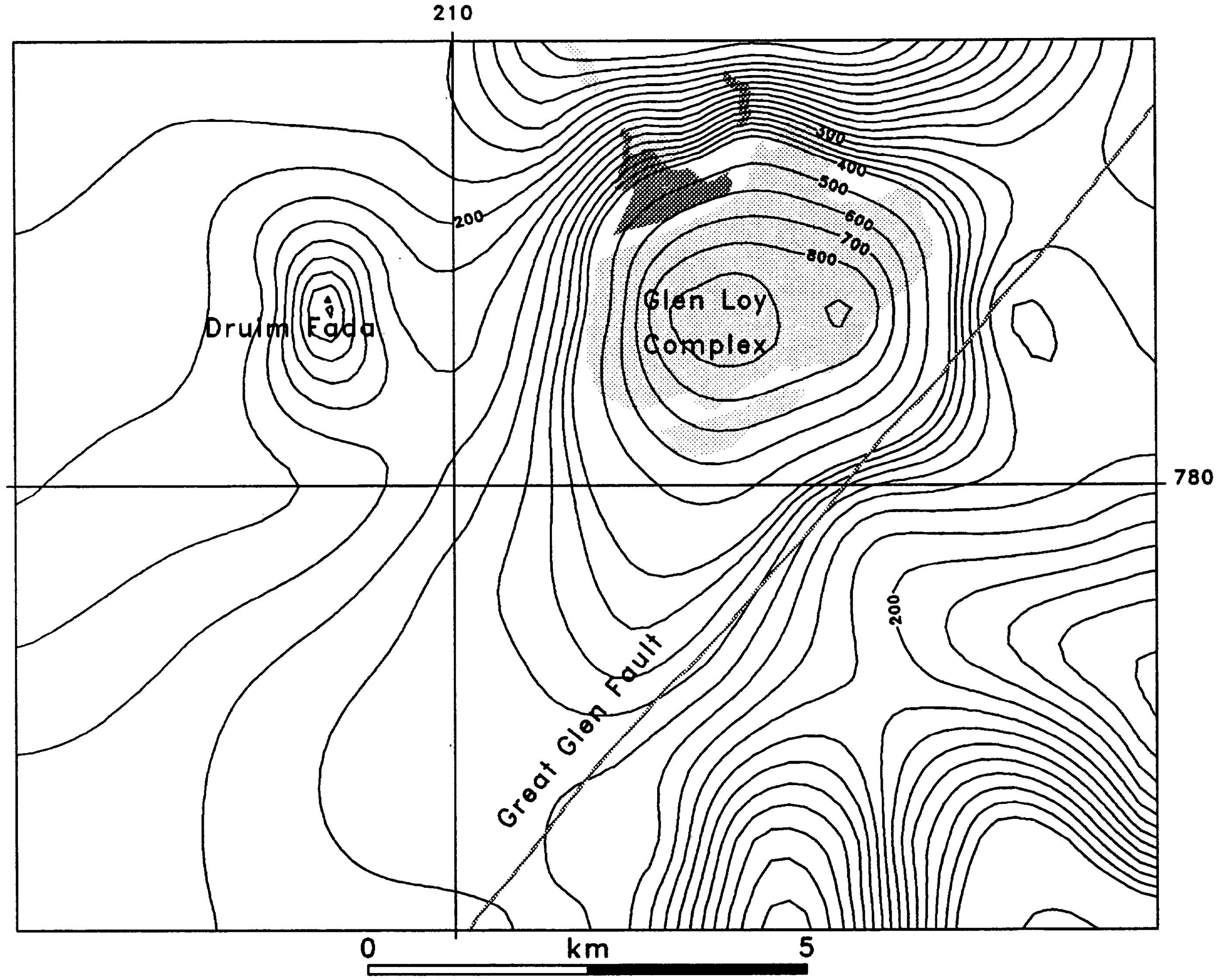


**Figure 4** Plot of aeromagnetic data around the Druim Fada vent (area A, Figure 3). The vent outcrop is shown as a triangle. The contours (in nT) show the observed aeromagnetic total field anomaly after regional correction and simple 9 points smoothing.

### Northern Britain

Regional aeromagnetic data for northern Britain were collected at a mean terrain clearance of 1000 feet (305 m) along flight lines spaced approximately 2 km apart. This data distribution is unsuitable for optimum detection of pipe-like bodies around 300 m in diameter, but it might detect up to one in ten of such features. Thus a few localised single-line anomalies could reflect magnetic diatremes. Figures 4 and 5 show the details of the regional aeromagnetic data over two anomalous areas of possible interest (A and B on Figure 3). The Druim Fada vent (A) has a distinct anomaly of about 100 nT above background (Figure 4). The unexplained anomaly near Loch Eriboll in the Moine Thrust Zone (B) has an amplitude of about 600 nT above background (Figure 5). It is worth recording that this anomaly is close to the area where Heddle believed that small diamonds occurred (McCallien, 1937). There are probably other isolated magnetic anomalies in excess of 100 nT in the northern Highlands which have no obvious explanation on the existing geological maps and these should be identified by digital enhancement and reprocessing of the aeromagnetic data. The available regional gravity and aeromagnetic data also allow recognition of major structures, which may be obscure at the surface. Prominent geophysical lineations can be important indications to basement fractures which can control subsequent igneous activity.

### South-west England

The south-west England regional aeromagnetic data date back to the mid 1950's, but were obtained along lines spaced 400 m apart at a height of 150 m and therefore provide much better coverage than in northern Britain. Figure 6A illustrates the type of anomaly arising from a 300 m diameter pipe-like body (x) at an elevation of 150 m above ground and the anomaly due entirely to a near-surface source like a lava flow (y). The anomaly shapes are practically indistinguishable if the thickness of the sheet-like body exceeds about 1/3 of its length, though the amplitude of the sheet is only about half of the amplitude of the pipe for the same magnetisation (in Figure 6 the amplitudes have been normalised). For comparison, the shape of the anomaly due to the same pipe has been modelled for an elevation of 305 m (Figure 6B).

Three areas in south-west England were selected for examination of the aeromagnetic data-set (Figure 7). Areas A and B were selected because of known occurrences of lamproitic rocks and area C was selected because of the occurrence of substantial amounts of basic volcanic rock.

*Area A (Tiverton area)*

This area is situated over the Culm Measures and includes the Permian Tiverton basin and several small outliers of Permian rocks (Figure 8). Isolated magnetic highs occur at several localities in the area but the most pronounced are near to the Tiverton basin. The largest anomalies occur over relatively small exposures of basic rocks at Holmead and Thorverton, while the larger areas of volcanic rocks at Loxbeare and Washfield do not give rise to significant magnetic features, possible because of the destruction of magnetite as a result of intense oxidative alteration. There are also three anomalies of uncertain origin (X in Figure 8) which merit follow-up to establish their cause. The anomalies present suggest that it would be worthwhile filtering the data in different ways to enhance the type of anomaly of most potential interest and to extend the area examined. Ground magnetic traverses should also be carried out to help define the anomalies detected from the airborne data.

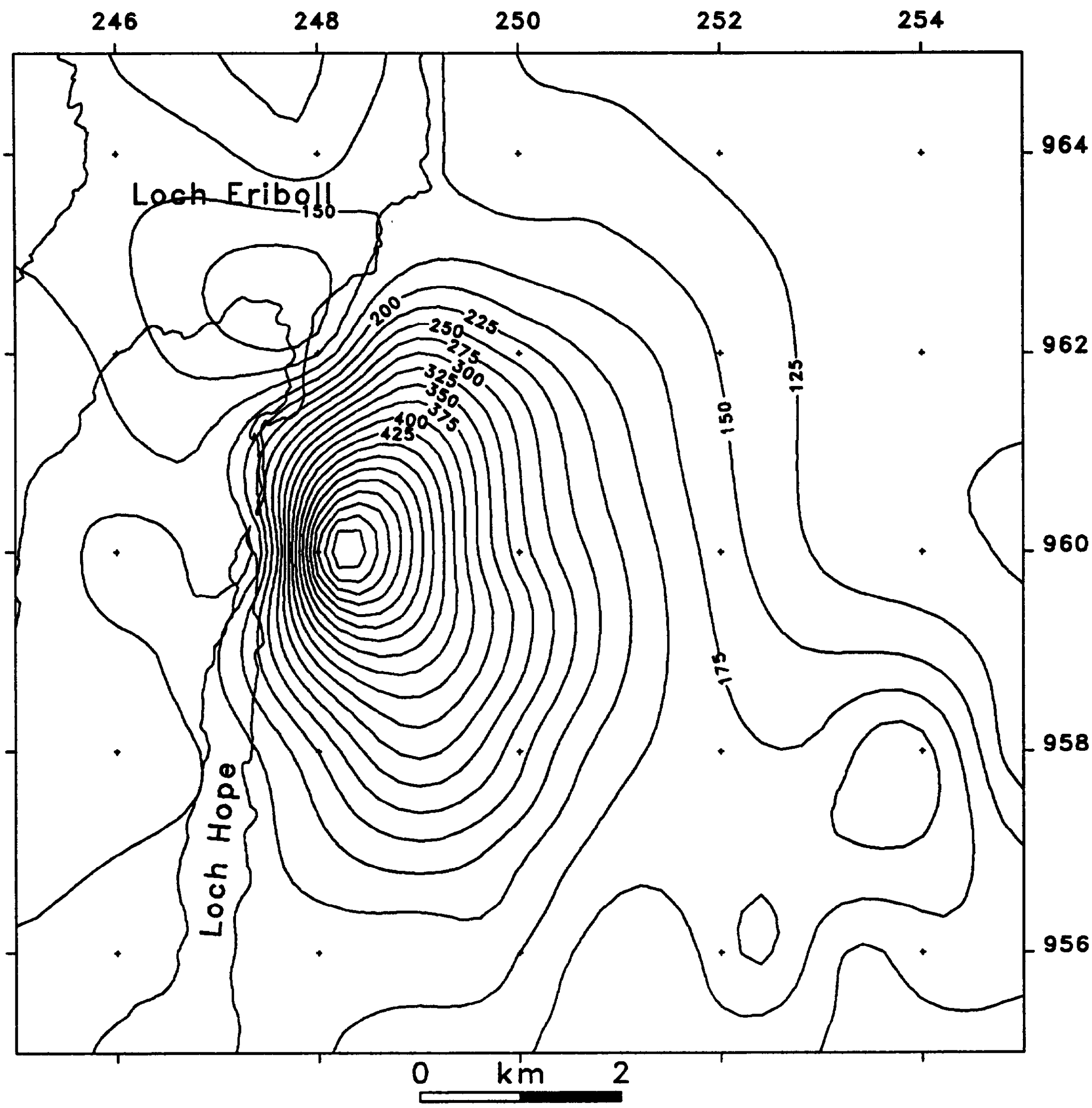


**Figure 5** Plot of aeromagnetic anomaly near Loch Eriboll (area B, Figure 3). The contours (in nT) show the observed aeromagnetic total field anomaly after regional correction and simple 9 points smoothing. The observed data have amplitudes up to 700 nT in a zone just west of the highest thrust within the Moine Thrust Zone.

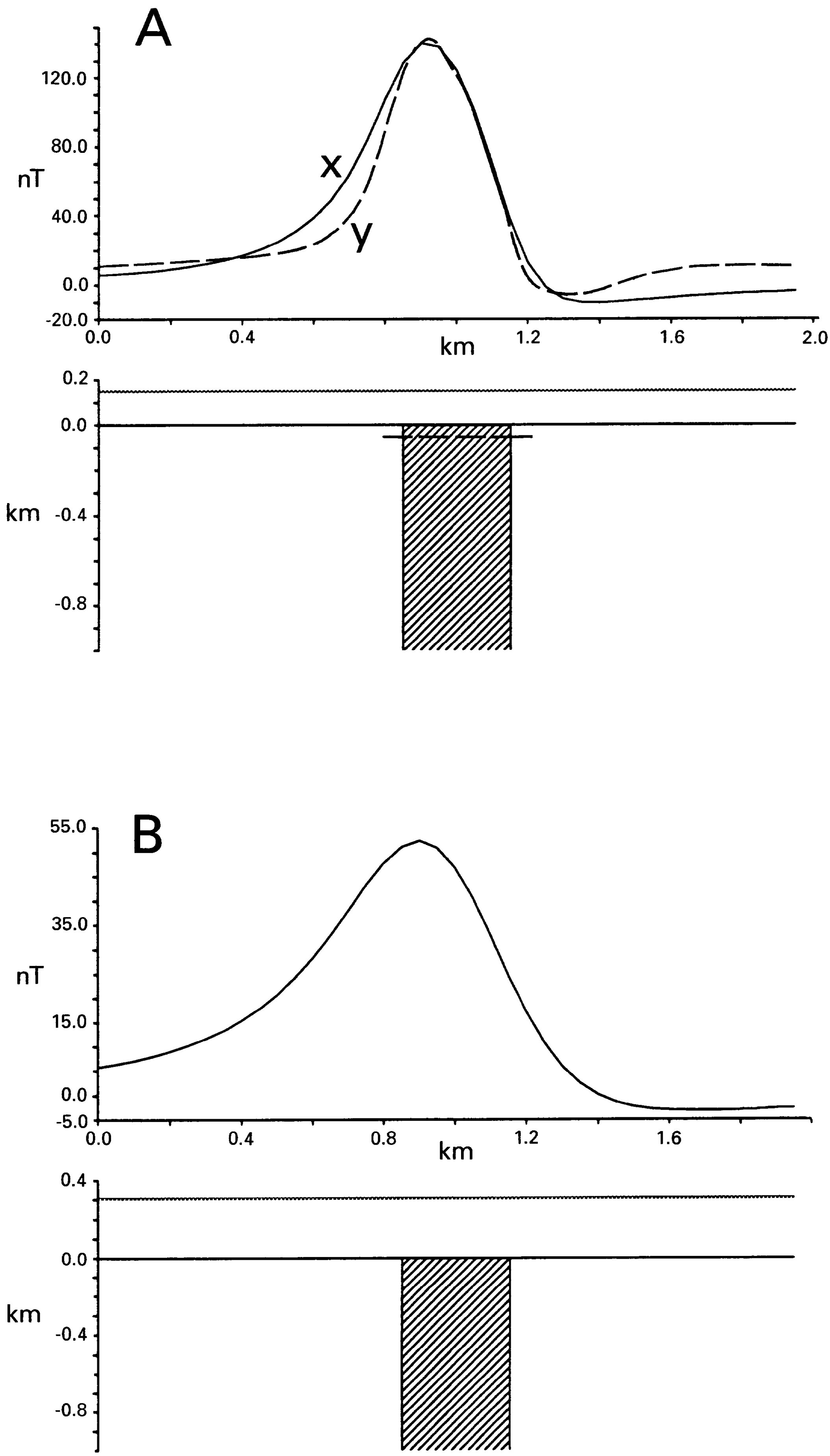


**Figure 6** A) Calculated magnetic anomaly profiles at an elevation of 50 m above ground for a pipe (x) and a horizontal sheet-like body above horizontal line (y); B) Calculated magnetic anomaly profiles for a pipe at an elevation of 305 m. (Strike of bodies same as width).

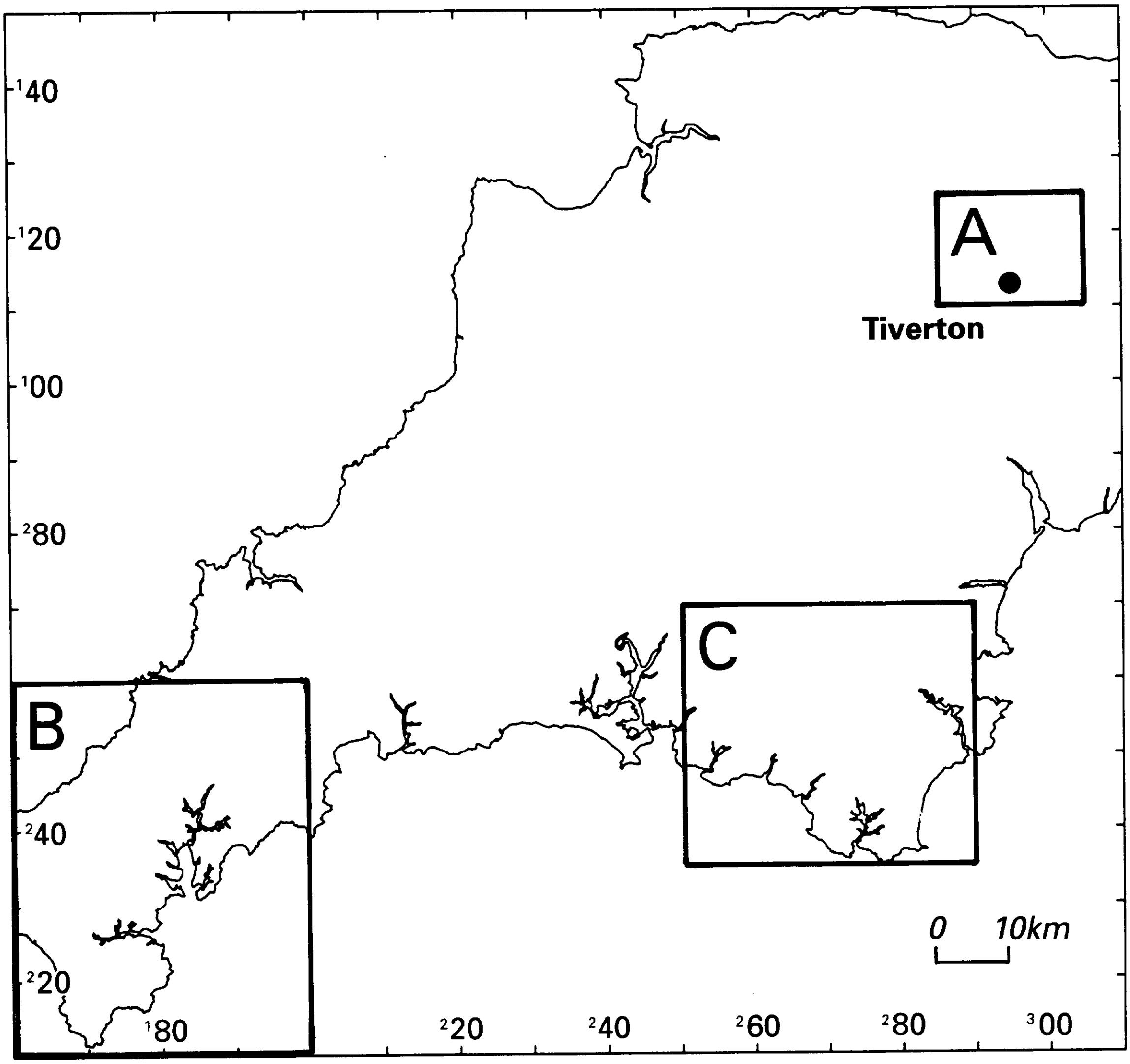


**Figure** 7 Location of three areas in south-west England where preliminary assessment of aeromagnetic data has been carried out.

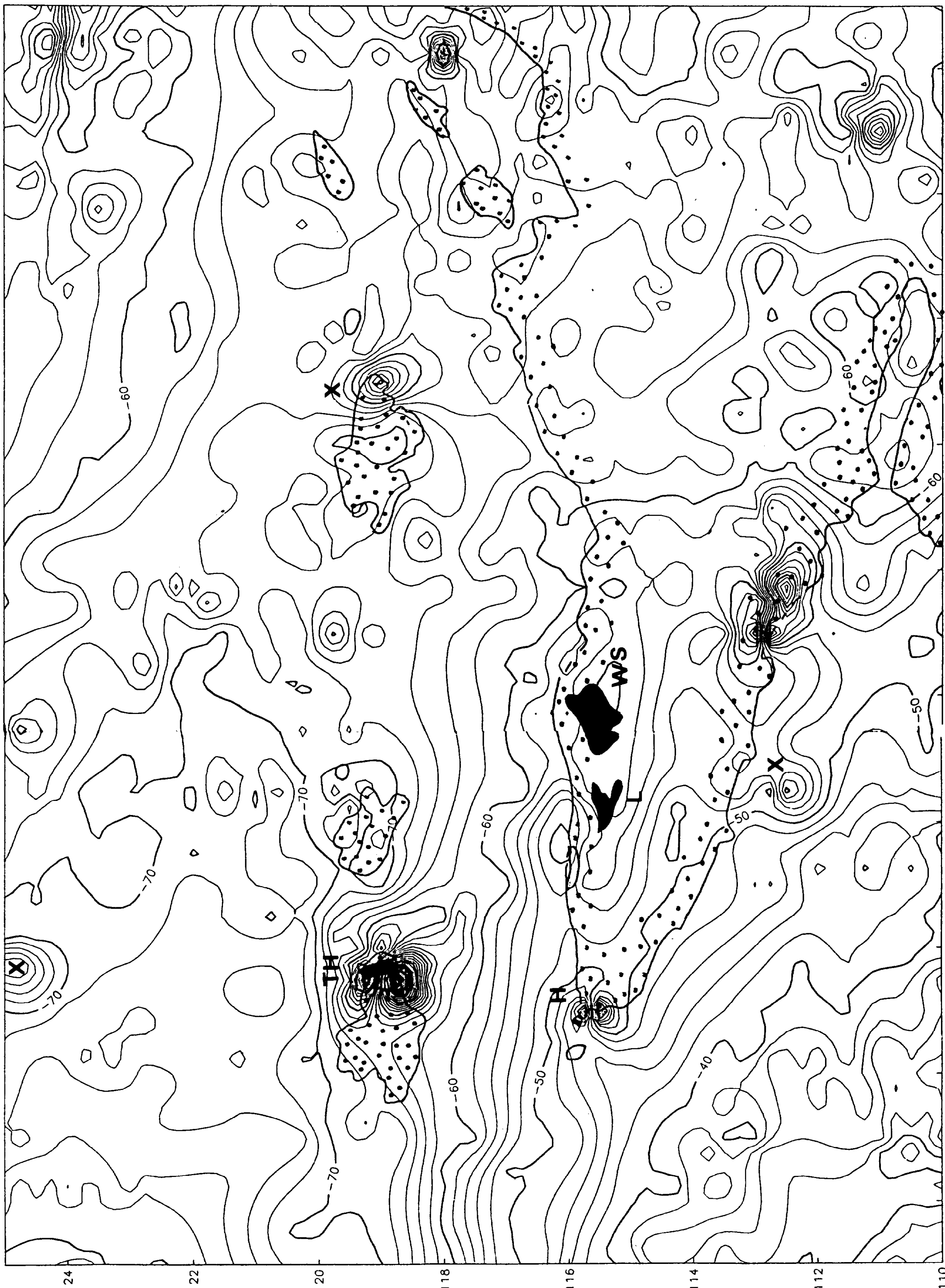


**Figure 8** Observed aeromagnetic data in area A (Tiverton area) with contours at 2 nT intervals, superimposed on the boundary of the Permian outcrop (highlighted with dots). Black areas are known outcrops of volcanic rocks at TH = Thorverton, L = Loxbeare and WS = Washfield. H = pipe intrusion at Holmead Farm and X = anomalies of uncertain origin.

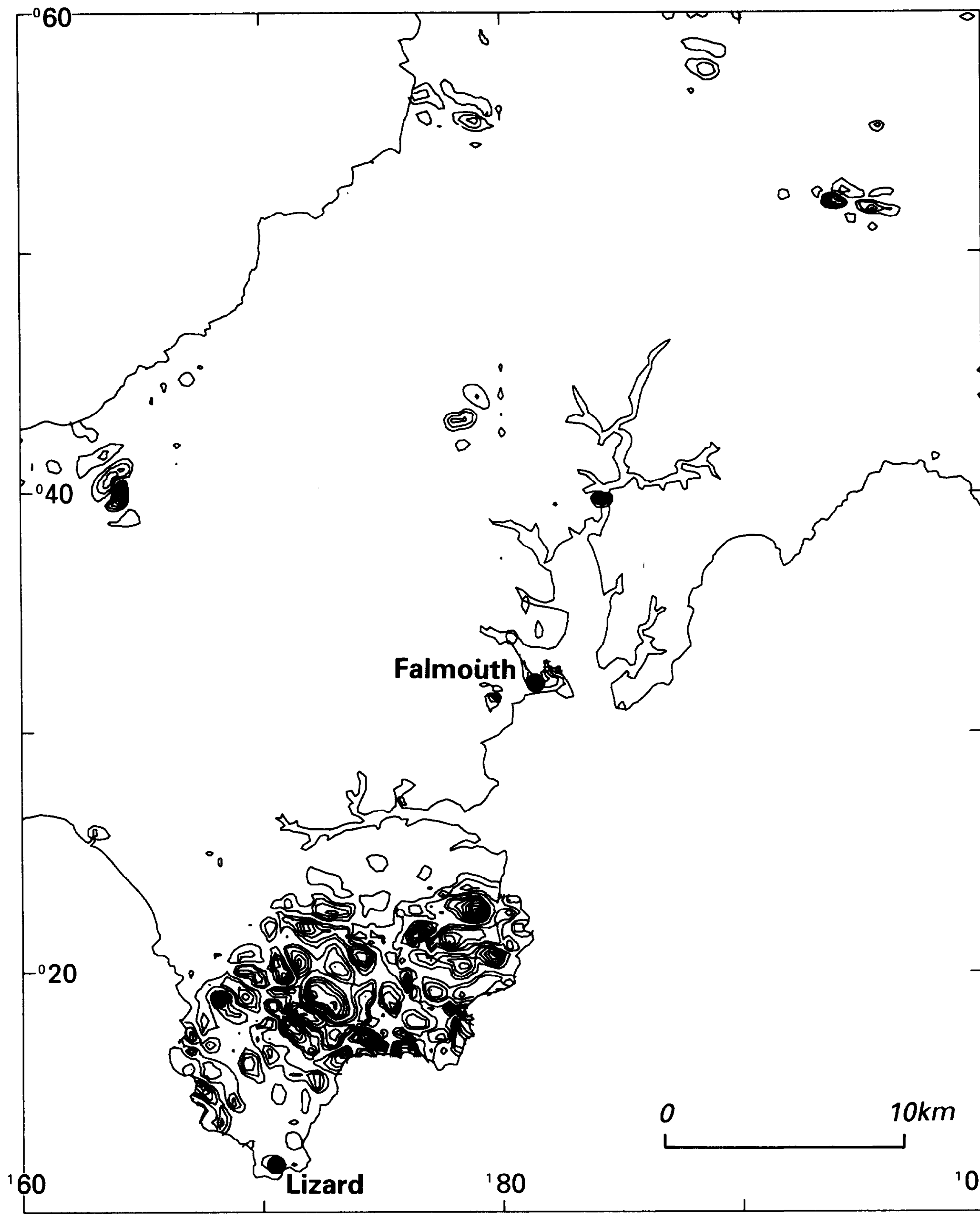


**Figure 9** Filtered aeromagnetic data (2.5 km high pass) from south-west Cornwall (area B). Contours at 10 nT intervals with 0 nT contour omitted.

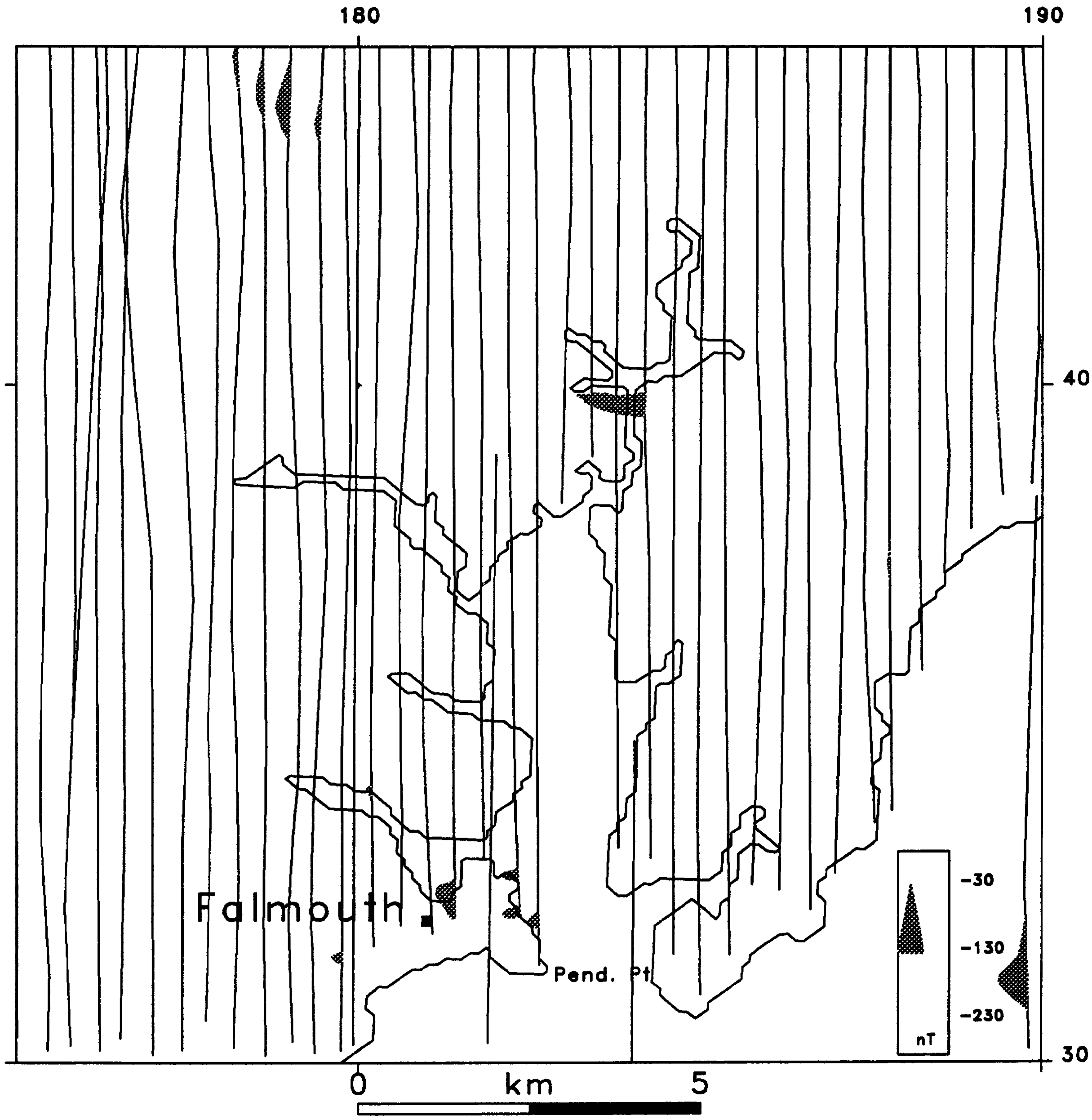


**Figure 10** Detail of aeromagnetic data around Falmouth, showing flight lines and position of data zones above -130 nT.

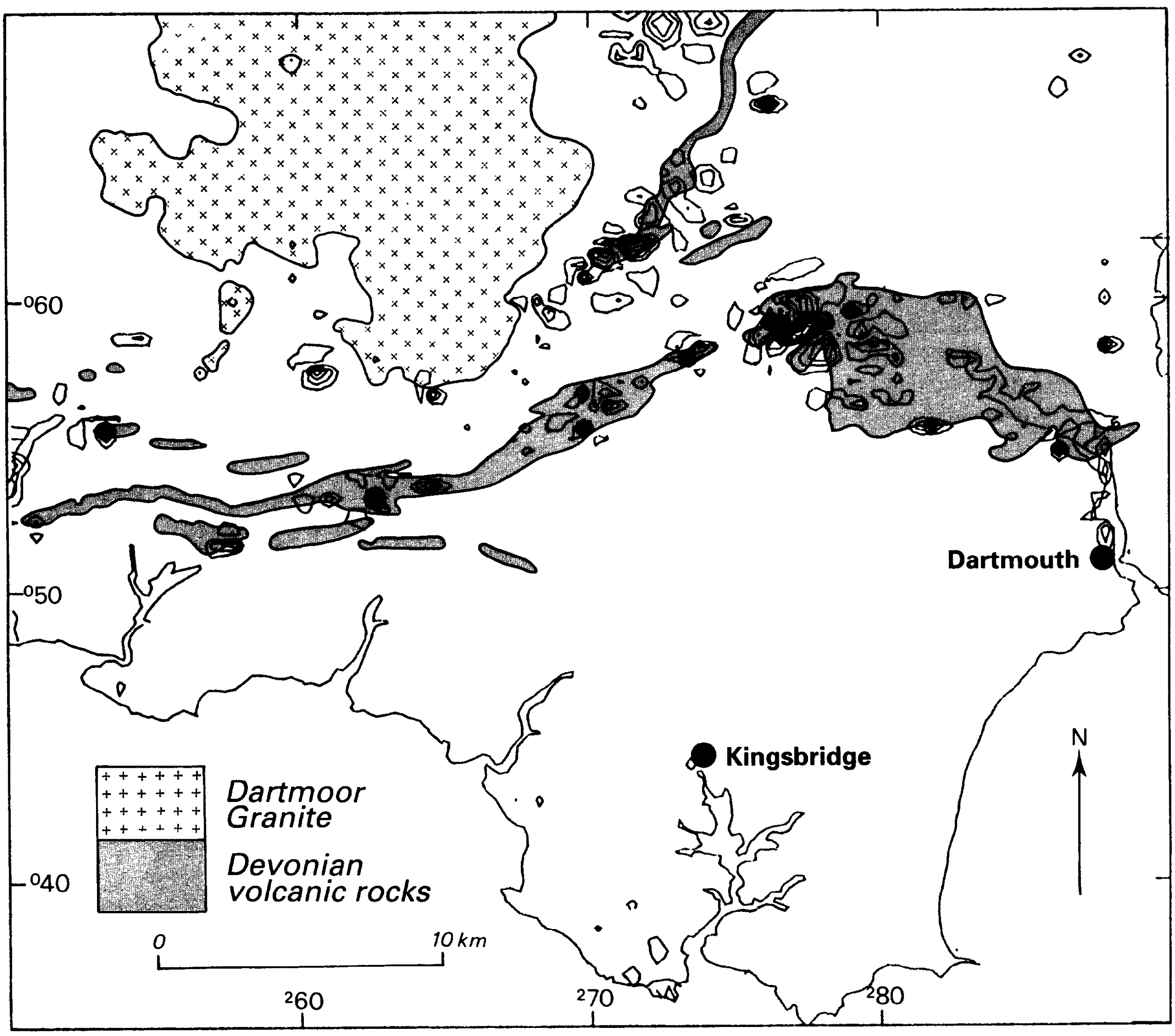


**Figure 11** Filtered aeromagnetic data (2.5 km high pass) from south Devon (area C) superimposed on map showing outcrop of Dartmoor Granite and Devonian mafic volcanic rocks. Contours at 10 nT intervals with 0 nT contour omitted.

*Area B (south-west Cornwall)*
The aeromagnetic data for area B have been obtained using a 2.5 km high pass filter to isolate anomalies of near-surface origin (Figure 9). Intense magnetic anomalies are associated with the Lizard ophiolitic complex, while elsewhere there is generally a quiet magnetic pattern. Outside the Lizard ophiolite there are a few anomalies indicating magnetic bodies of limited extent, often with no obvious geological explanation. Figure 10 shows a more detailed plot of the data around the locality of the lamproite at Pendennis Point, which does not appear to have an anomaly associated with it, though there is much interference from nearby Falmouth and the lines do not seem to have crossed the outcrop. However, there are also isolated anomalies just west of Falmouth and some 9 km further north which require interpretation. The location of the latter anomaly, close to a ferry crossing, suggests that it may be artificial in origin, possibly due to a ferry boat. The anomaly in the north-west corner of Figure 10 is larger in dimension and is thus less likely to be a pipe or dyke-like body of interest. The series of small anomalies trending north-south is an artefact of the data, resulting from the north-south direction of flight lines.

*Area C (South Devon)*
There are many anomalies in this area which persist in the high pass filtered data (Figure 11). They seem mostly to be associated with the belt of Middle Devonian basic volcanic rocks crossing the area. However, there are some small anomalies which lie outside the known outcrop of volcanic rocks, and these might merit further investigation.

## CONCLUSIONS AND RECOMMENDATIONS

The potential for diamond deposits in kimberlites tapping deep cratonic roots is probably not as high in Britain as in the Baltic shield. A favourable environment for such sources only exists under a small part of the country, the western Lewisian foreland, and no kimberlites have been discovered there so far. Since the geology of the country is probably the most comprehensively researched in the world, the likelihood of finding outcropping kimberlite is small. However, there are inland areas with poor exposure, particularly in the Outer Hebrides. An aeromagnetic survey with optimum flight-line spacing is required before the potential for kimberlite can adequately be assessed in these areas.

Some potential for diamonds in rocks other than kimberlite also exists particularly for the more novel sources that are not well understood at present. Three approaches should be adopted to establish more directly whether diamonds are present or not.

- Firstly, some direct exploration for the presence of diamond is advisable in areas considered to have most promise. Heavy mineral concentrates should be obtained from large volumes of sediment from major rivers draining large sectors of provinces of interest. These should be subjected to various fractionating techniques and searched for diamond and also for typical indicator minerals of deep-mantle xenoliths. Indicator minerals for lamproites and other potential diamond igneous hosts are not so well established as for kimberlites.

- Secondly, the intrusions which are known to approach lamproite composition should be sampled. In practice, the sampling of weathered rock material or overburden derived from rock is much more practicable than sampling hard rock as it is easier to extract physically the heavier fraction from a large volume of rock. Thus sampling of suitable rocks in south-west England would generally be much easier than the sampling of similar rocks in Scotland because of their highly altered state and the widespread development of residual overburden in the generally unglaciated landscape of south-west England. Heavy mineral concentrates should be obtained from a large volume of weathered rock or overburden and subjected to mineralogical analysis.

- Thirdly, the aeromagnetic data from south-west England should be examined in its entirety, anomalies of potential interest surveyed on the ground and their source evaluated. Similar treatment of existing data should be carried out in the Lewisian terrane and other areas of Scotland considered to have some potential, even though the data is generally inadequate.

The Proterozoic Torridonian sequence of predominantly fluvial sediments has some potential for the occurrence of diamond in palaeoplacers and could be the most likely source of any isolated diamonds in glacial drift and drainage sediment in north-west Scotland.

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