Igneous Rocks of South-West England

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Chapter 6

Post-orogenic volcanics (Group D sites)

INTRODUCTION

The five sites descibed in this chapter include examples of the small-volume extrusives and intrusives that developed after the emplacement of the main granite plutons of the Cornubian batholith. Their locations are shown in Figure 6.1. Volcanism occurred during the prevalence of the 'red-bed' environment of the late Carboniferous and the early Permian Periods; it includes the mixed volcanics of the Exeter Volcanic 'Series', as well as suprabatholithic rhyolite lavas which were fed by late granite porphyry dykes. The volcanics of this period are often referred to as being Permian in age, although recalculated isotopic age dates suggest that they could also represent late Carboniferous activity. These volcanics represent the last remnant of magmatic activity that developed largely after continent–continent collision in a post-orogenic, tectonic setting.

LIST OF SITES

Rhyolitic suite:

D1 Kingsand Beach (SX 435506)

Basaltic suite:

D2 Webberton Cross Quarry (SX 875871)
D3 Posbury Clump Quarry (SX 815978)

Potassic suite – lamprophyres:

D4 Hannaborough Quarry (SS 529029)
D5 Killerton Park (SS 971005)

LITHOLOGICAL AND CHEMICAL VARIATION

Although three series of post-orogenic volcanics are generally recognized (see Chapter 2), in

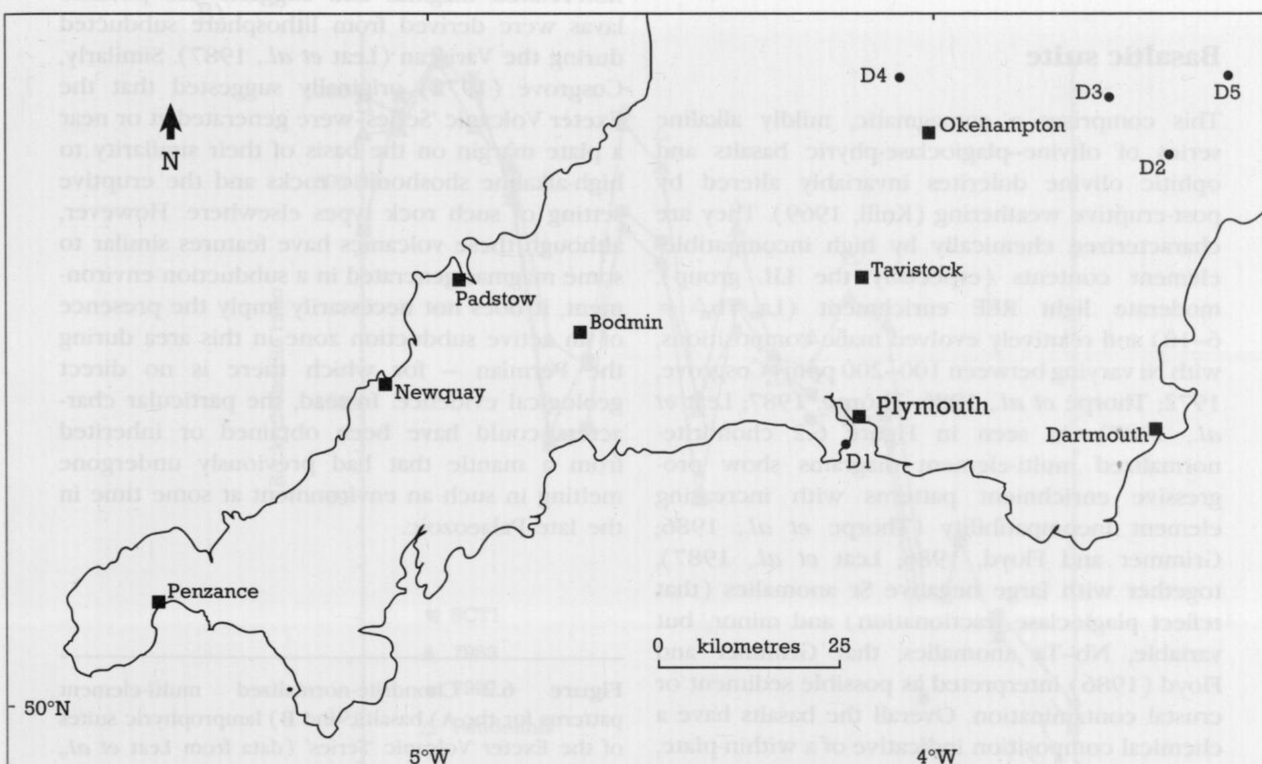


Figure 6.1 Outline map of south-west England, showing the location of Group-D sites.

compositional terms they can be grouped as follows:

1. basaltic suite (in Exeter Volcanic 'Series');
2. potassic suite (dominated by minette-type lamprophyres in the Exeter Volcanic 'Series' and regionally throughout south-west England);
3. rhyolitic suite (including pebbles of acidic volcanics in 'red bed' sequences).

The petrogenesis of these small-volume volcanics and high-level intrusives has often been linked to the Cornubian granites and cross-cutting granite-porphyry dykes. Rhyolites have been interpreted as the volcanic expression of the plutonic granites (Goode, 1973; Cosgrove and Elliott, 1976), whereas the highly potassic nature of some basic lavas was considered to reflect contamination by granitic material or fluids (Tidmarsh, 1932; Knill, 1969). Although this latter feature is no longer considered significant for the production of potassic magmas, Leat *et al.* (1987) have suggested that the granites could have been derived by fractionation of a mantle-derived potassic magma that contaminated melts mainly produced by crustal anatexis.

Basaltic suite

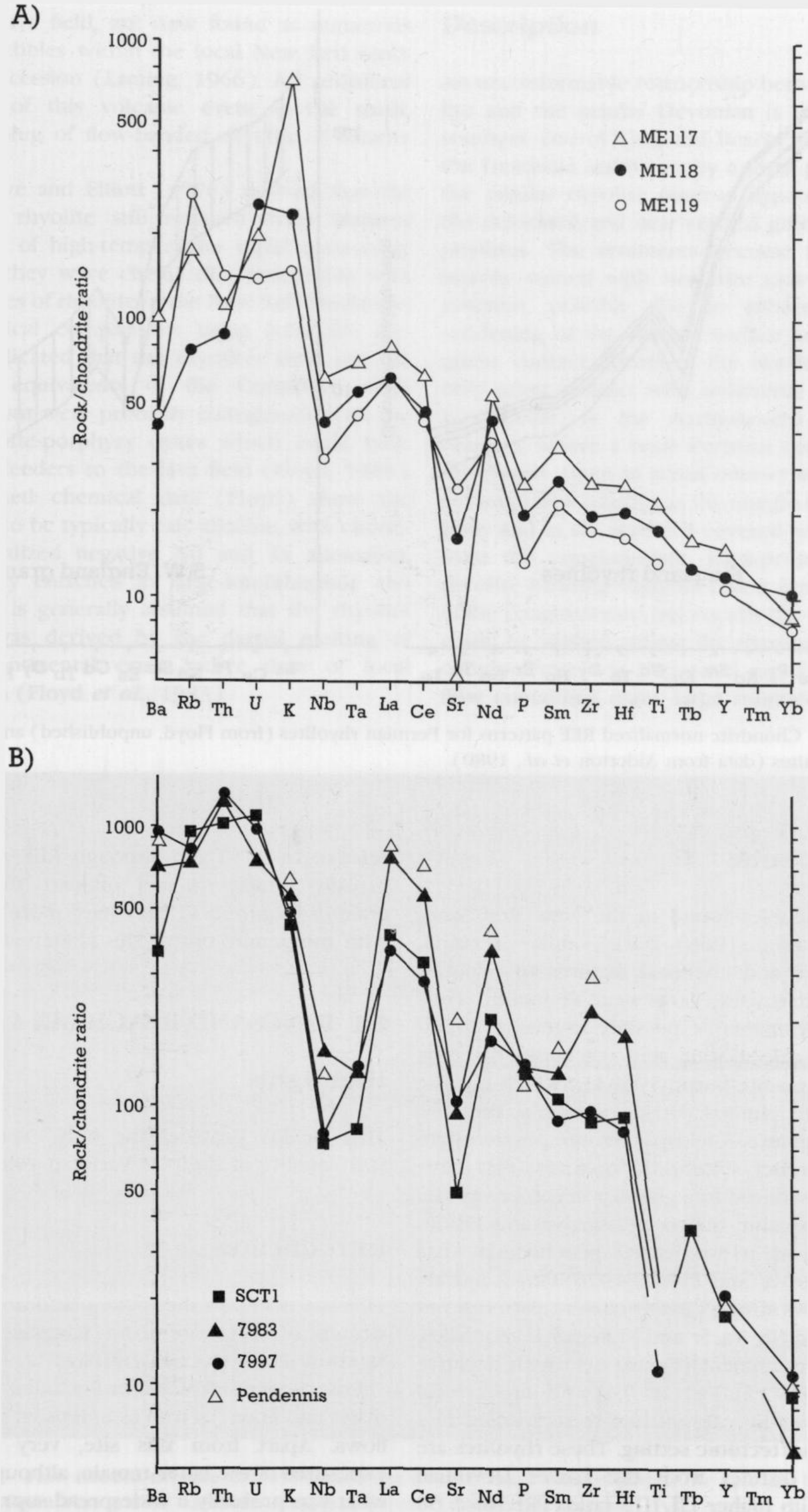
This comprises a comagmatic, mildly alkaline series of olivine–plagioclase-phyric basalts and ophitic olivine dolerites invariably altered by post-eruptive weathering (Knill, 1969). They are characterized chemically by high incompatible-element contents (especially the LIL group), moderate light REE enrichment (La_n/Yb_n = 6–10) and relatively evolved mafic compositions, with Ni varying between 100–200 ppm (Cosgrove, 1972; Thorpe *et al.*, 1986; Thorpe, 1987; Leat *et al.*, 1987). As seen in Figure 6.2 chondrite-normalized multi-element diagrams show progressive enrichment patterns with increasing element incompatibility (Thorpe *et al.*, 1986; Grimmer and Floyd, 1986; Leat *et al.*, 1987), together with large negative Sr anomalies (that reflect plagioclase fractionation) and minor, but variable, Nb–Ta anomalies, that Grimmer and Floyd (1986) interpreted as possible sediment or crustal contamination. Overall the basalts have a chemical composition indicative of a within-plate, continental, eruptive setting.

Potassic suite

This suite comprises all the lamprophyres (minettes) and minor trachybasalts, mafic syenites and leucitites (Knill, 1969, 1982), all of which feature abundant K-feldspar. The minettes are characterized by aligned phenocrysts of dark-rimmed phlogopitic biotite, rarer diopsidic augite, olivine and small idiomorphic apatites set in an often highly altered and reddened biotite–alkali–feldspar–Fe ore matrix (Knill, 1969; Exley *et al.*, 1982). Plagioclase may occasionally be common, but is very variable in its distribution; brown amphiboles are also recorded (Hall, 1982). Some of the lamprophyres may be vesicular, with infillings of alkali feldspar, quartz, calcite, chlorite and clays (Exley *et al.*, 1982). Sedimentary and granitic inclusions, together with a variety of xenocrysts, are relatively common (Smith, 1929).

By far the most interesting chemical feature of the potassic lavas and intrusives (Figure 6.2) are the strong enrichments in light REE and LIL elements, marked depletions of Nb, Ta and Ti (Cosgrove, 1972; Thorpe, 1987; Leat *et al.*, 1987) and high $^{87}Sr/^{86}Sr$ (Thorpe *et al.*, 1986). This chemical fingerprint is characteristic of subduction-related magmas and suggests the potassic lavas were derived from lithosphere subducted during the Variscan (Leat *et al.*, 1987). Similarly, Cosgrove (1972) originally suggested that the Exeter Volcanic 'Series' were generated at or near a plate margin on the basis of their similarity to high-alkaline shoshonitic rocks and the eruptive setting of such rock types elsewhere. However, although these volcanics have features similar to some magmas generated in a subduction environment, it does not necessarily imply the presence of an active subduction zone in this area during the Permian – for which there is no direct geological evidence. Instead, the particular characters could have been obtained or inherited from a mantle that had previously undergone melting in such an environment at some time in the late Palaeozoic.

Figure 6.2 Chondrite-normalized multi-element patterns for the A) basaltic and B) lamprophyric suites of the Exeter Volcanic 'Series' (data from Leat *et al.*, 1987).


A)
Rock/chondrite ratio
1000
500
100
50
10
ME117
ME118
ME119
Ba Rb Th U K Nb Ta La Ce Sr Nd P Sm Zr Hf Ti Tb Y Tm Yb
B)
Rock/chondrite ratio
1000
500
100
50
10
SCT1
7983
7997
Pendennis
Ba Rb Th U K Nb Ta La Ce Sr Nd P Sm Zr Hf Ti Tb Y Tm Yb

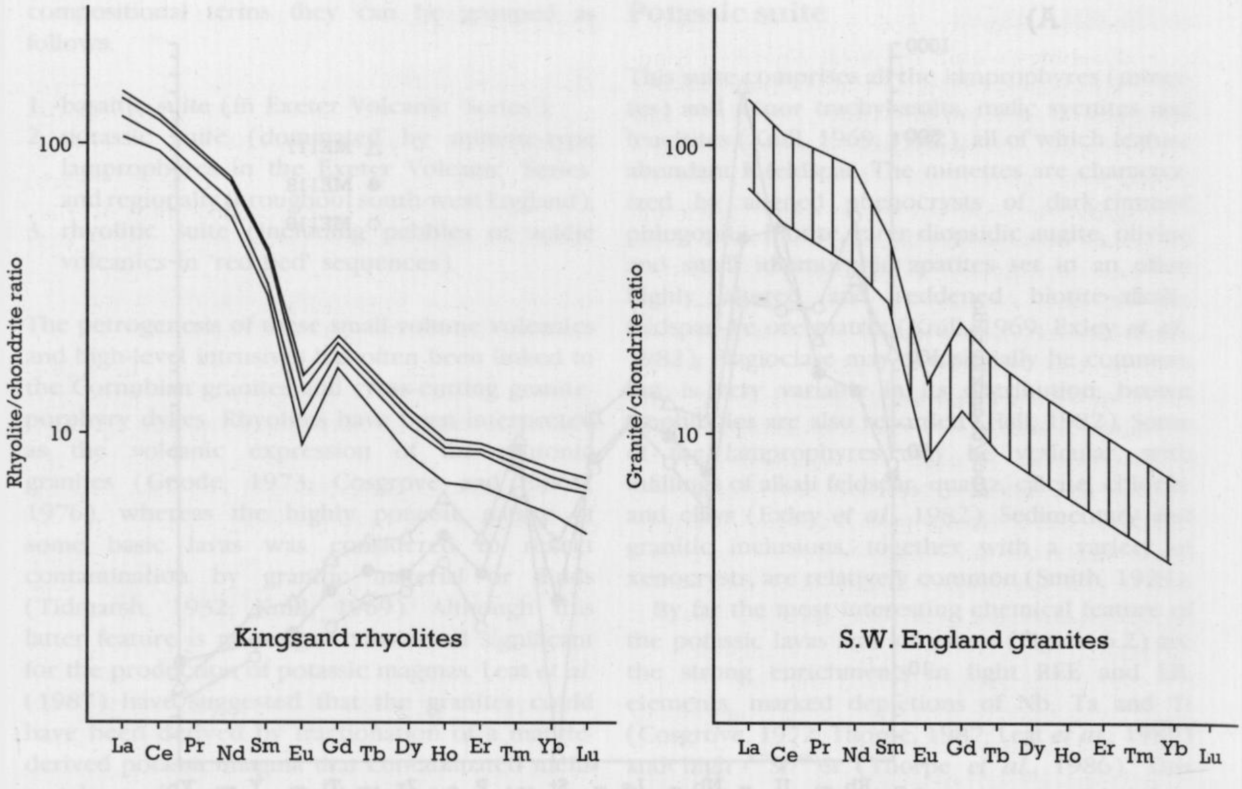


Figure 6.3 Chondrite-normalized REE patterns for Permian rhyolites (from Floyd, unpublished) and south-west England granites (data from Alderton *et al.*, 1980).

Rhyolitic suite

Rhyolitic pebbles found in the New Red Sandstone (Laming, 1966) have similar textural, petrographic and chemical features to exposed flow-banded rhyolite lavas near Plymouth. They form the remnants of possibly extensive suprabatholithic calc-alkaline acid volcanism that was fed by the granite-porphyry dykes which cut the main granite plutons. Most commonly, they are reddened quartz–K-feldspar–biotite-phyric rhyolites with relict spherulitic textures, that have often recrystallized to a granular cryptocrystalline quartzofeldspathic matrix (Cosgrove and Elliott, 1976). Chondrite-normalized geochemical data (from Cosgrove and Elliott, 1976; Floyd, unpublished) shows strong LIL enrichment patterns, but with marked Nb, Ta, Sr and Ti negative anomalies, light REE enrichment (Figure 6.3) with negative Eu anomalies (Eu/Eu* *c.* 0.4). All are typical features of acidic calc-alkaline rocks formed in a syncollisional tectonic setting. These rhyolites are chemically distinct from the Lower Devonian rhyolites with higher LIL/HFS ratios (Rb/Nb *c.* 50 relative to *c.* 5) and although REE patterns are broadly similar to, and overlap, those of the granites (Figure 6.3), they have more in common with the granite porphyries (Exley *et al.*, 1983).

D1 KINGSAND BEACH (SX 435506)

Highlights

This locality provides the only exposure of *in situ* rhyolite of the post-Variscan volcanics.

Introduction

This site occupies the rocky platforms of a 800 m stretch of foreshore from Kingsand Beach to Sandway Point in Cawsand Bay.

Post-orogenic volcanism included both mafic dykes and flows, as well as extensive rhyolite lava flows. Apart from this site, very few actual exposures of the latter remain, although relicts of what was probably a widespread suprabatholithic rhyolite lava field, are now found as numerous altered pebbles within the local New Red Sandstone succession (Laming, 1966). An additional example of this volcanic event is the small, circular plug of flow-banded rhyolite at nearby Withnoe.

Cosgrove and Elliott (1976) showed that the Kingsand rhyolite still retained many features indicative of high-temperature rapid quenching, and that they were chemically comparable with the pebbles of rhyolite in the New Red Sandstone. Geochemical comparisons using immobile elements indicated that the rhyolites were not the volcanic equivalents of the Cornubian main granites, but were probably comagmatic with the later granite-porphyry dykes which could have acted as feeders to the lava field (Floyd, 1983). Unpublished chemical data (Floyd) show the rhyolites to be typically calc-alkaline, with chondrite-normalized negative Nb and Ta anomalies, and highly enriched in large-ion-lithophile elements. It is generally assumed that the rhyolite magma was derived by the partial melting of lower continental crust rather than of local sediments (Floyd *et al.*, 1983).

Description

An unconformable relationship between the rhyolite and the nearby Devonian is inferred at the southern end of Kingsand Beach. Separated from the Devonian sediments by a small pebble beach, the tabular rhyolite outcrop apparently overlies the deformed and near-vertical green and purple phyllites. The sediments become bleached and heavily veined with hematite near the inferred junction, possibly due to subaerial oxidative reddening of the eroded surface and the subsequent contact effects of the hot lava flow. The only other contact with sediments is near Sandway Cellar, at the north-eastern end of the outcrop, where a basal Permian conglomerate is developed. Again an actual contact is not exposed, although flow banding at the margin of the rhyolite body and in the seaweed-covered reefs dips away from the conglomerate. Back-projection of the rhyolite banding suggests that it could lie on top of the conglomerate, but equally the conglomerate could be banked against the rhyolite margin. The conglomerate was deposited rapidly as a debris flow containing many large rounded/subrounded

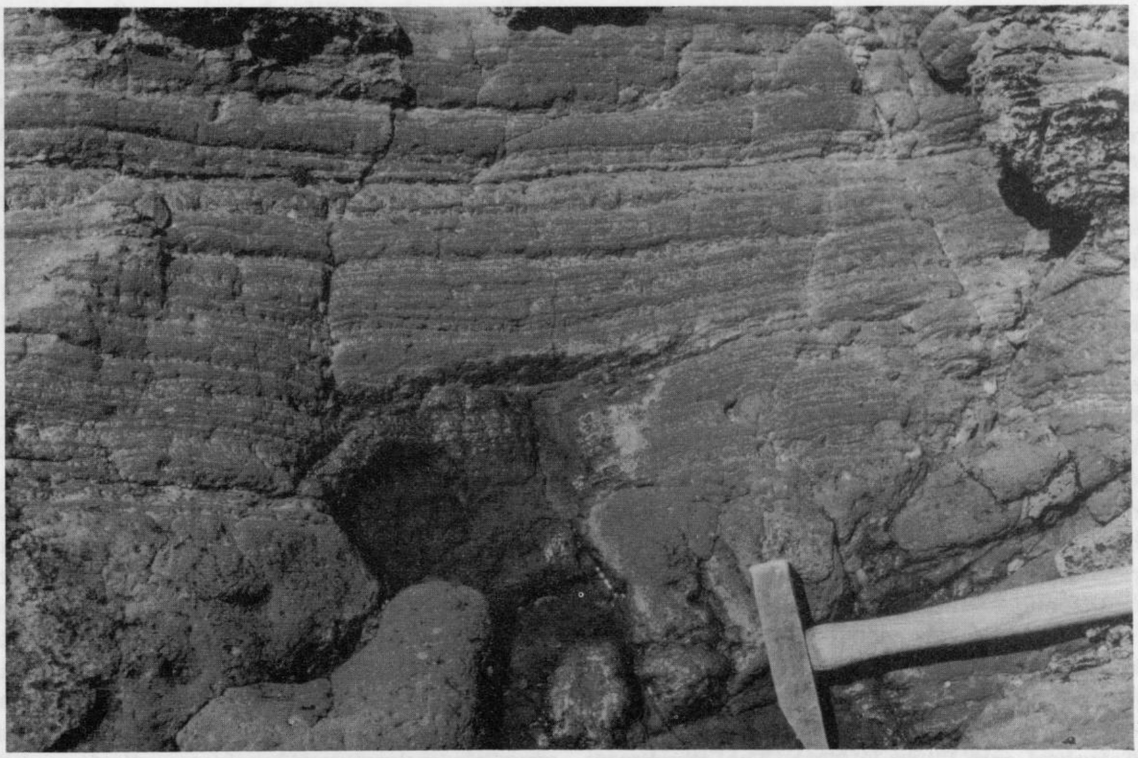


Figure 6.4 Flow-banded rhyolite lava of Permian age that may have formed part of the volcanic field developed above the Cornubian granite batholith. Kingsand, Devon. (Photo: P.A. Floyd.)

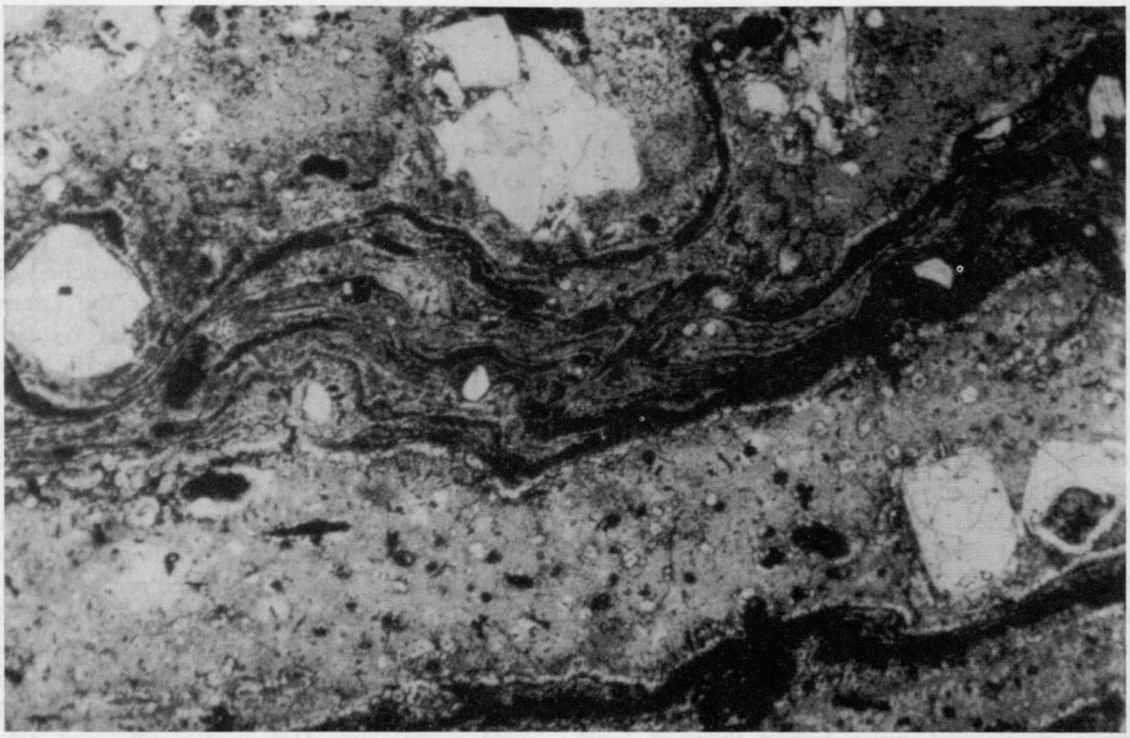


Figure 6.5 Silica phenocrysts in the flow-banded, partly devitrified matrix of the Permian rhyolite lava. Kingsand, Devon. (Photo: P.A. Floyd.)

pebbles and boulders (up to *c.* 1 m in diameter) of quartzite and flow-banded rhyolite. About 4 m is exposed before being succeeded by a uniform, red sandstone.

The general uniformity and tabular shape of the rhyolite along the beach, together with the lack of an extensive autobrecciated carapace, suggests that it is a lava flow, rather than a dome. Also, the lack of internal brecciated horizons indicates that the lateral extent of the outcrop probably represents a single flow. Most of the flow appears massive, with flow banding (Figure 6.4), when present, restricted to narrow, relatively uniform zones and, rarely, highly contorted on the small scale. All of the lava is pervasively reddened due to subaerial oxidation after eruption, although there are small green reduction spots (centred on spherulites) and linear zones adjacent to east–west-trending veins and fractures.

The lava contains many microscopic features indicative of rapid chilling, with a devitrified quartz–feldspar groundmass containing vestiges of glass, spherulites and high-temperature phases (Cosgrove and Elliott, 1976). The rhyolite is composed of interbedded phyric and aphyric flow units, with the former exhibiting variable proportions of quartz, feldspar (sanidine and orthoclase) and dark-red biotite phenocrysts (Figure 6.5). Chemical data on the Kingsand body (Cosgrove and Elliott, 1976; Floyd, unpublished) show it to be a typical calc-alkaline rhyolite, with high contents of large-ion-lithophile elements and chondrite-normalized negative Nb–Ta anomalies.

Interpretation

The importance of the site lies in the fact that it is the only sizeable *in situ* exposure of a supposed Permian rhyolite flow in south-west England. It also has wider regional implications, in that the rhyolites are considered to represent extensive acid volcanism genetically related to the Cornubian granite batholith. The evidence for late Carboniferous–early Permian acid volcanicity, that perhaps formed a volcanic superstructure to the high-level granite plutons, is now seen in rhyolite pebbles and feldspar crystals of extrusive origin in the New Red Sandstone. The Kingsand rhyolite is thus a solitary remnant of a once-extensive, suprabatholithic, volcanic lava field. However, comparisons based on limited chemical data suggest the rhyolites are more likely to be genetically related to the later granite-porphyry dykes than to the main granites of the batholith. The dykes could have acted as feeders to the rhyolite lavas above. Also, isotopic age dating of the granite porphyries overlaps the basal Permian at 280–270 Ma. However, the only age data on the rhyolites, quoted (Hawkes, 1981) for a pebble in a mass-flow conglomerate, adjacent to the Kingsand rhyolite, gives a Stephanian age of 295 Ma.

Other points of interest about the flow include its microscopic features and chemical characteristics. Although highly oxidized and reddened, the rhyolite flow still preserves primary features that indicate rapid quenching, together with the presence of high-temperature feldspar, and quartz and biotite phenocrysts. The rhyolite has a typical calc-alkaline composition, chondrite-normalized negative Nb–Ta anomalies and Zr/Nb ratios >10. It is chemically distinct from pre-orogenic Lower Devonian rhyolites in having higher large-ion-lithophile/high-field-strength element ratios which probably reflect derivation from a different crustal source by partial melting. When chemical plots that discriminate the nature of the eruptive environment of acidic rocks are employed (for example, Pearce *et al.*, 1984), the rhyolites apparently have a composition typical of the syncollisional tectonic environment. This chemical discrimination appears to be anomalous, as the rhyolites are clearly post-orogenic and probably later than the main granite emplacement events. The misinterpretation is an artefact of the chemical database used to construct the original tectonic discrimination plot; this assumed that the south-west England granites were typical of the syncollisional environment rather than post-collisional (Pearce *et al.*, 1984).

Conclusions

This site is unique in showing an isolated remnant of a rhyolite lava flow that was probably extruded around 295 million years ago. Apart from chemical differences these rhyolites are distinct from the Lower Devonian submarine lavas of similar composition, in being extruded after the main phase of Variscan mountain building had terminated in the late Carboniferous. It is generally considered that these rhyolites are representative of a large volcanic field situated on top of the granite batholith of south-west England. They were probably fed by late-stage granitic dykes that cut through the main granite and surrounding country rocks. They were once much more extensive, having been eroded away, such that evidence for their existence is largely in the form of pebbles in later sedimentary deposits, particularly the red sandstones and pebble beds of the Permian Period (also seen at Kingsand). Thus Kingsand yields important evidence for the latest phase of volcanic activity at the end of the Carboniferous to earliest Permian times that followed the deformation of the Variscide mountain-building phase.

D2 WEBBERTON CROSS QUARRY (SX 875871)

Highlights

This quarry provides one of the best exposures of a basalt of the post-Variscan volcanics; the basal lava/soft-sediment contact is also well exposed.

Introduction

The site covers the disused, elongate northern quarry of the pair located in School Wood, about 300 m south-west of Webberton Cross, near Dunchideock.

The late Carboniferous–early Permian post-orogenic volcanics of the Exeter Volcanic 'Series' comprise both basalts and a mixed bag of potassic lavas that includes lamprophyres (Tidmarsh, 1932; Knill, 1969, 1982). The site is representative of the basaltic group which was considered by Ussher (1902) to occur at the base of the Permian and to be the earliest expression of post-orogenic volcanism in the area. A K/Ar whole-rock date for the basalt from Webberton Quarry gave an age of 291 Ma (recalculated from 281 Ma quoted by Miller and Mohr, 1964), that is, late Stephanian relative to the Carboniferous–Permian boundary at 286 Ma.

The petrography of the basalt and others in the Exeter area has been described by Knill (1969). Chemical data on this basalt and other members of the suite have illustrated the highly incompatible-element-enriched nature of these rocks (Cosgrove, 1972; Thorpe *et al.*, 1986; Leat *et al.*, 1987; Thorpe, 1987). As a group, the basalts form a single, cogenetic, mildly alkaline series related by minor mafic and plagioclase fractionation (Floyd, 1983; Leat *et al.*, 1987). They (including the Webberton Cross basalt) are also characterized by small, variable Nb and Ta negative anomalies on chondrite-normalized multi-element diagrams, that are often a feature of subduction-related magmas. This chemical signature was interpreted as implying that the basalts might have come from a mantle source modified by subduction-related processes (Leat *et al.*, 1987), although similar features can be produced by crustal contamination by local sediments, as suggested by Grimmer and Floyd (1986).

Description

Although the quarry walls are somewhat overgrown and mainly composed of basalt, towards the existing quarry floor can be seen the highly vesicular base of a flow resting on an intimate admixture of lava and baked sediment (Figure 6.6). The sandy sediment originally represented the surface over which the lava flowed and which became incorporated into the base of the flow. Lithological change towards the base of the lava flow is gradational, with an increase in the size, proportion and irregularity of the vesicles in the slightly flow-banded lava, together with the incoming of hematitic sandstone and siltstone fragments in greater and greater abundance. Neither the lava nor the sediments are sharp-angled blocks in this zone; they exhibit very irregular, penetrating junctions and intimately mixed relationships. This feature suggests that the lava flowed over and penetrated wet, partly consolidated sediments that were baked, and which, in turn, rapidly chilled the hot lava. Further evidence for the reaction between lava and sediment is probably provided by the neptunean dykes mentioned by Knill (1969). Although sediments overlie the basalts (eastern half of the quarry), it seems more likely that the sediment fill of these structures was extruded up from the base, rather than infilling erosional gullies in the lava flow from the top.

Most of the quarry face (15–20 m high) is apparently composed of a single lava flow, as neither interflow breccias nor reddened horizons are visible. The lava is an olivine–plagioclase-phyric alkali basalt with a matrix of granular plagioclase, calcic augite, abundant Ti–Fe oxides and minor alkali feldspar. It is often highly altered with abundant secondary serpentine, hematite, carbonate, zeolites, analcite and clays. Olivine is always replaced by serpentine and Fe-oxides. The plagioclase phenocrysts are zoned labradorites with more sodic rims; they exhibit an unusual lacy texture of vermicular Fe-oxide inclusions (Knill, 1969). The lava is variably vesicular (Figure 6.7), although away from the basal contact, the vesicles are generally small and round. They are often infilled with zeolites or white clay. The secondary assemblages are typical of very low-grade, hydrothermal oxidative alteration, which is often characteristic of ancient subaerial flows.

Interpretation

The mildly alkaline lava of this site is representative of the basaltic suite of post-orogenic, graben-related volcanics that form part of the Exeter Volcanic 'Series' of Stephanian–Permian age. According to Whittaker (1975), they are confined to the Crediton Trough and environs, which is interpreted as a small graben. In the global context of Permian rift-related magmas, they are insignificant and very small-volume extrusives (Grimmer and Floyd, 1986). However, in south-west England they are temporally associated with a potassic suite of rocks (dominated by lamprophyres) and are seen to share some of their chemical characteristics. In particular, all the Exeter Volcanic 'Series' rocks are incompatible-element-rich and have chemical features generally considered to be indicative of magmas generated in subduction zones (Grimmer and Floyd, 1986; Thorpe *et al.*, 1986; Leat *et al.*, 1987), although the chemical signature is less marked in the basalts. Previously, Cosgrove (1972) had considered that the whole suite belonged to the highly alkaline shoshonite series and that they were generated at a continental-plate margin. On the basis of their chemistry, Leat *et al.* (1987) concluded that the basalts were derived from an asthenospheric mantle source possibly modified by processes related to subduction, e.g. LIL-element enrichment, although Grimmer and Floyd (1986) stressed that a similar chemical feature could be generated by sediment contamination. Trace-element geochemistry cannot give a definitive answer in this respect, although geological inference concerning the tectonic environment suggests that there may well have been a subduction zone somewhere to

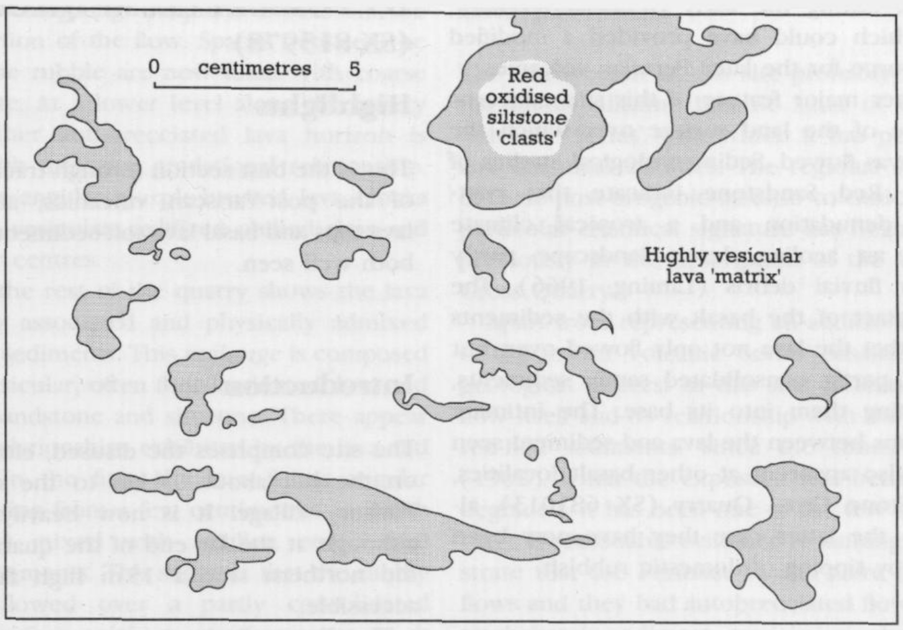


Figure 6.6 Sketch of the lava–sediment relationship at the base of a late Stephanian basalt lava flow of the Exeter Volcanic 'Series', Webberton Cross Quarry, near Exeter.

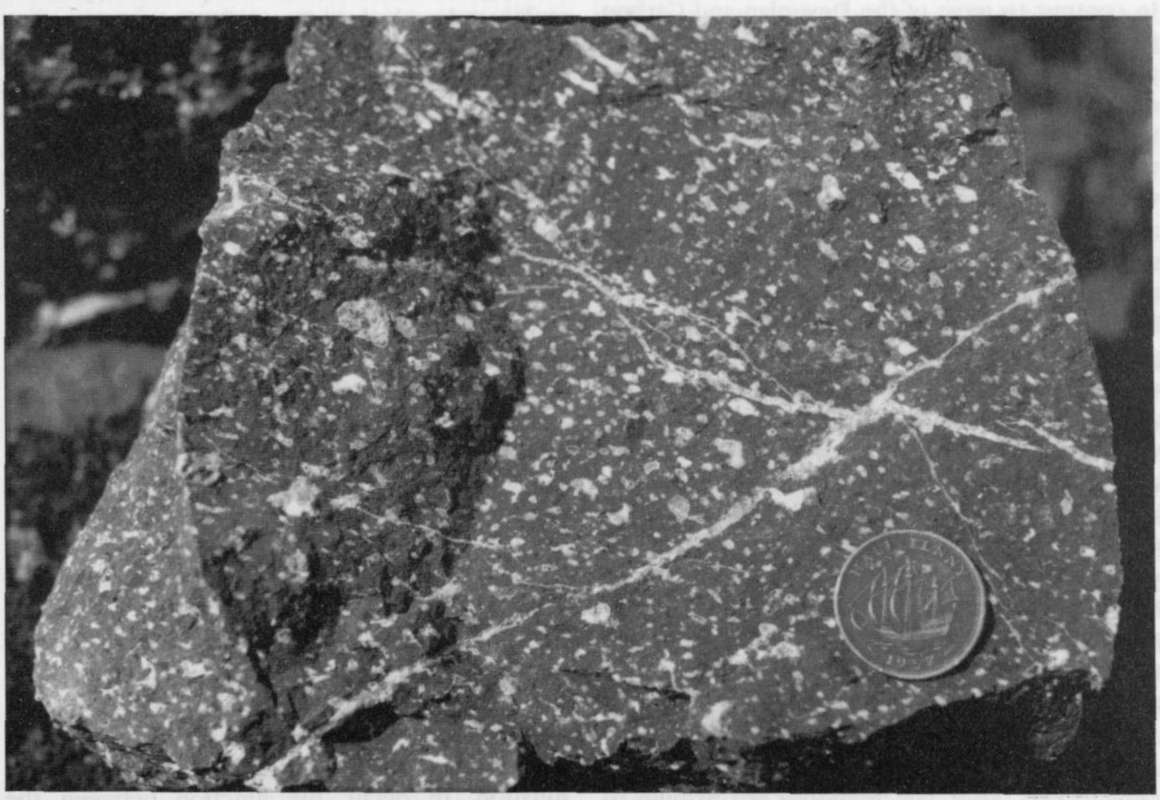


Figure 6.7 Highly amygdaloidal (vesicles infilled with white zeolites and/or clays) and oxidized subaerial basalt lava flow. Webberton Cross Quarry, Devon. (Photo: P.A. Floyd.)

the south during the early Devonian (Leeder, 1982), which could have provided a modified mantle source for the later Permian volcanics.

The other major feature of this site concerns the nature of the land surface over which the basaltic lavas flowed. Sedimentological studies of the New Red Sandstone indicate that post-orogenic denudation and a tropical climate produced an aeolian desert landscape partly buried in fluvial debris (Laming, 1966). The lower contact of the basalt with the sediments indicates that the lava not only flowed over, but into, wet, partly consolidated sandy sediments, incorporating them into its base. The intimate relationships between the lava and sediment seen here are also apparent at other basalt localities, such as Stone Cross Quarry (SX 681013), although in the latter case they have now been obscured by tipping of domestic rubbish.

Conclusions

Basaltic lavas in this area erupted near the junction of the Carboniferous and Permian periods. In contrast to most of the Devonian and Carboniferous lavas described in this volume, this was not in a marine setting, but eruption occurred over an arid, rocky desert landscape under a tropical climate. At this site, however, the lavas traversed still-wet, riverine sands, fragments of which were incorporated into the base of the lava as it flowed across the irregularities of the land surface. Faint banding within the lavas indicates the direction of liquid flow. Such lavas are a feature of the Exeter–Crediton area which was probably a downfaulted trough at the time, with magma seeping up along marginal fractures. They are associated with another group of basic lavas with characteristic high potassium levels, which are known as lamprophyres. The particular chemistry of these two lava groups has been used as evidence of their initial formation from a mantle source associated at some time with a subduction zone such as found under modern oceanic island arcs. This site presents key evidence for the last phase of volcanicity that affected onshore southern Britain.

D3 POSBURY CLUMP QUARRY (SX 815978)

Highlights

This is the best section through trachybasalt lavas of the post-Variscan volcanics; autobrecciated lava tops and basal lava/soft-sediment contacts are both well seen.

Introduction

The site comprises the disused, elongate quarry on the hill about 0.4 km to the north-east of Posbury village. It is now heavily overgrown, although at the far end of the quarry and along the northern side a 15 m high face is partly accessible.

The Exeter Volcanic 'Series' was divided by Knill (1969) into a basaltic suite and a potassic suite. The latter mainly consisted of lamprophyres together with minor syenites and trachybasalts. This site is representative of the trachybasalts, although these rocks are not particularly K-rich compared with the other volcanics in the potassic suite. It was also demonstrated by Floyd (1983) that the trachybasalts around Crediton, including this site, were chemically related to the olivine basalts of Dunchideock and Silverton, analysed by Cosgrove (1972). The general field and chemical features of the basaltic suite described at Webberton Cross Quarry (discussed above) also apply here.

Description

Most of the quarry was developed in a massive, purplish-grey, variably vesicular trachybasalt lava flow. At the northern end of the quarry (by the stepway), can be seen a crude flow foliation, marked by steeply dipping trains of elongate vesicles. Their trend is not uniform across the quarry face, but varies in direction and degree of dip. Towards the quarry top, the massive lava is replaced by a reddened rubbly top to the flow. The junction is very irregular, dipping down into the massive lava, but crudely parallels the flow foliation. In detail, the junction between the rubbly flow top and massive lava is gradational and probably indicative of local autobrecciation, with cracks outlining incipient blocks in the massive portion of the flow. Spaces between the blocks in the rubble are now filled with coarse sparry calcite. At a lower level along the quarry wall, a further autobrecciated lava horizon is exposed, with the same gradational relationship. Many of the angular, purple-hearted lava blocks have highly vesicular, oxidized chilled rims and vesicle-poor centres.

Much of the rest of the quarry shows the lava flow closely associated and physically admixed with clastic sediments. This *mélange* is composed of highly vesicular, often flow-laminated, lava and baked red sandstone and siltstone. There appear to be two relationships exhibited by the lava and sediments. In the first, the lava forms angular blocks (varying from a few centimetres in width up to 1 m) mixed with smaller, red, baked sediment fragments. This suggests that the rubbly lava base flowed over a partly consolidated sediment surface, picking up fragments as it travelled forward. In other instances, the two main constituents do not form discrete blocks as such, and the lava appears rather to net vein the sediment, so that lava fingers and tubes intimately penetrate a sediment matrix. Contacts are often very irregular, cuspate, or in some cases diffuse and wispy rather than sharp. This suggests that the lava flowed over wet, unconsolidated sediments with basal lava lobes penetrating deep into an unstable sandy surface. A further feature of interest in this connection is the neptunean dyke at the northern end of the quarry. This is a vertical sediment dyke with very irregular margins, a width of *c.* 1 m at the base, and composed of structureless dolomitic sandstone. The actual mode of emplacement is not clear, although there are no sedimentary features which suggest that it was formed by the infilling of sand from the top.

Petrographically, most of the trachybasalt is highly altered, although it can be inferred from the fresher rock samples that the lava was olivine- and plagioclase-phyric, with a matrix of olivine, plagioclase, augite, K-feldspar and magnetite. Hematite, carbonate and clays are the common alteration products, with calcite, quartz and zeolites infilling the vesicles (Knill, 1969). Quartz xenocrysts, presumably derived from the sandstones over which the lava flowed, are also present. A trachytic flow texture is sometimes discernible if the rock matrix is not too altered.

Interpretation

The trachybasalt of this site probably belongs to the mildly alkaline basaltic suite of the Exeter Volcanic 'Series' with which it has petrographic and chemical affinities. The regional significance of these post-orogenic basaltic volcanics and their particular chemical signature has been discussed previously in the description of the Webberton Cross Quarry.

Apart from representing an additional example of the Exeter Volcanic 'Series' basaltic suite, the geological interest in this site concerns the lava flow itself and its relationship with the associated red-bed sediments. Since the times of Ussher (1902), when the exposure was better and less degraded, it has been one of the few sites where there is reasonable evidence remaining to demonstrate that the Permian basalts were in fact lava flows and they had autobrecciated flow tops. The trachybasalt–sediment association also provides evidence for the nature of the land surface over which the lava was flowing. This was composed of a wet, partly consolidated sand into which the base of the flow ploughed to produce an intimate admixture. The highly vesicular nature of the basal portion of the lava suggests it was charged with volatiles that, together with steam generated from the sediments, fluidized and aided penetration of the sediments.

Conclusions

Posbury Clump Quarry shows graphic evidence for volcanic eruption on to the arid Permian landscape. Here basaltic lava, part of a suite of lavas called collectively the Exeter Volcanic 'Series', was erupted over newly deposited Permian sediments. Several features characteristic of lava flows may be seen to advantage at the site: evidence of the flow direction in the form of vesicle trains (former gas bubbles), aligned crystals in what is called a flow texture, rubbly broken tops to flows and an intricate relationship with the sediments below. This last feature takes the form of an intimate mixing between the lava and sediment, so that sharp contacts do not exist. This was produced by the effusion of the lava onto or partly into wet sediments. Apart from a mechanical mixing, water flashed to steam helped to fluidize the sediment and allow lava penetration through this medium. On the other hand, more rubbly mixture of lava blocks and sediment clasts resulted where consolidated sediments were ripped up from the surface as the lava flow moved across it. This is a key site for the study of the lavas which were formed after the Variscan Orogeny and for their relationship with Permian sedimentary rocks.

D4 HANNABOROUGH QUARRY (SS 529029)

Highlights

This is one of the best exposures of a minette-type lamprophyre of the post-Variscan volcanics; an associated breccia has been variously interpreted as a vent agglomerate and as a debris-flow infill.

Introduction

The site occupies the old, disused, overgrown and partly water-filled quarry 2 km south-west of Hatherleigh. The most accessible part of the quarry is a small 5-m-high face that (photographed in better condition) is illustrated in the *British Regional Guide to South-west England* (Edmonds *et al.*, 1969; plate 8A).

The post-orogenic Stephanian–Permian volcanics of the Exeter Volcanic 'Series' can be divided petrographically and chemically into a basaltic group and a potassic group (Knill, 1969; Cosgrove, 1972). The latter includes K-feldspar-rich lamprophyres of the minette type, which are exhibited at the Hannaborough Quarry site. The site and the rock type has been described previously as representative of the lamprophyre group (Ussher, 1902; Tidmarsh, 1932; Knill, 1969), although it differs from other minette localities in being olivine-, as well as biotite-phyric. The other feature noted by previous workers is that fissures within the minette are filled with 'vent agglomerate', which quarrying in the past has left as a small knoll or peak within the northern face (Edmonds *et al.*, 1968).

The actual form and mode of emplacement of the Hannaborough minette is not clear. Tidmarsh (1932) referred to it as a lava flow, and it is generally depicted as such on geological maps, although the dominant and gently dipping 'floor joints' suggest a sheet-like intrusive body relative to the adjacent sediments. Magnetic and resistivity surveying (Edmonds *et al.*, 1968) suggest that the body is largely restricted to the quarry area, and that it is either a vertical neck (which is at variance with the subhorizontal tabular jointing) or truncated by faults.

Chemical data by Cosgrove (1972) showed that it has a composition similar to other lamprophyres in the Exeter area, being highly enriched in incompatible elements, especially those of the large-ion-lithophile group. On the basis of the highly potassic nature of these rocks generally, it was considered by earlier workers (Tidmarsh, 1932; Knill, 1969) that they were generated from basic/ultrabasic magma contaminated by K-rich fluids or materials, possibly related to the nearby Dartmoor Granite. More extensive chemical data (Cosgrove, 1972; Thorpe *et al.*, 1986; Thorpe, 1987; Leat *et al.*, 1987), however, have demonstrated that the lamprophyres exhibit a strong subduction-related chemical signature (for example, negative Nb–Ta anomalies) that is typical of many continental lamprophyric rocks.

Description

The minette is generally massive throughout, and in the present exposure does not exhibit features clearly indicative of a lava flow. However, in the vicinity of the 'vent agglomerate' peak, the minette shows concentrations of small, yellow sediment blocks that may have been derived from a thin (20–60 mm), subhorizontal, yellow, baked siltstone lens just below. The attitude of the sediment lens suggests that it might be the remnant of an interflow sediment horizon, rather than an inclusion, although this is open to question. The minette outcrop is stucturally dominated by strong, shallow-dipping (25–35°) joints, although there is no evidence to suggest they are related to the emplacement mode of the body.

One of the major features of this site is the presence of the coarse breccia that rests on the minette and has generally been considered to be a 'vent agglomerate'. A number of east–west-trending fissures in the minette are filled with the breccia, the most prominent of which can be traced for about 85 m west of the quarry (Edmonds *et al.*, 1968). Whether this breccia is really a volcanic agglomerate filling a small vent cut through the minette, is questionable. The breccia appears to cut down into the minette along a sharp, but irregular junction, which is probably an erosion surface. The breccia fragments are mainly angular, poorly sorted (<0.1–0.15 m in size), baked mudstones, laminated siltstones and fine sandstones in a reddish clay matrix. It is predominantly a chaotic, matrix-supported deposit, with only crudely developed layering near at the base, and could represent a sediment-rich debris flow. Lamprophyre clasts are virtually absent, although Tidmarsh (1932) suggested the clay matrix might have been originally devitrified glass.

The pale, purplish-grey, non-vesicular, fine-grained lamprophyre is an olivine–biotite-phyric minette that has been variably oxidized and altered. The matrix is often obscured by secondary hematite, carbonate and clays, although primary minerals, either observed or inferred, are olivine, K-feldspar, biotite, apatite and possibly plagioclase. Phenocrystic olivine is always replaced by hematite–carbonate (seen as red spots in hand specimen), whereas biotite may be corroded and partially replaced by chlorite. Rounded and apparently corroded quartz xenocrysts are also present, and these probably represent disrupted sandstone clasts incorporated by the magma upon emplacement.

Interpretation

The site is representative of the minette-type of lamprophyre of the Exeter Volcanic 'Series' potassic group. However, it is atypical in that it also contains phenocrystic olivine, unlike the more normal biotite-phyric minettes of the Exeter area. Whether the minette body here is intrusive or extrusive is not clear, although it is generally assumed to be a lava flow, as inferred from its very fine-grained nature and subhorizontal baked sediment interlayers. It has also suffered extensive oxidation, with the production of hematite that gives the body its predominantly reddish-purple colour. Comparison with similarly reddened, but proven lavas in the general area, suggest this could have been due to subaerial weathering during the Permian.

Of questionable status is the so-called 'vent agglomerate' that rests on the minette. The chaotic nature of the deposit and its composition suggest that it is a sediment-dominated debris-flow deposited on a pre-existing erosional surface of the lava, rather than a volcanic vent blasted through the body and subsequently filled with debris. Under New Red Sandstone environmental conditions, such debris flows deposited by flash floods would have been common, scouring and transporting local sediments and subaerial flows alike.

In common with the Exeter Volcanic 'Series' potassic group, the minettes of the local area (and elsewhere in South-west England), exhibit a LIL-enriched chemistry similar to lavas found in a subduction-dominated tectonic setting. In this sense they are similar to other, earlier, continental lamprophyres as seen in the Caledonides of northern Britain (Macdonald *et al.*, 1985), that were generated in a similar, post-tectonic environment. Previous ideas that the high large-ion-lithophile enrichment of these rocks was due to the specific involvement of a facies of the potassic Dartmoor Granite are no longer considered to be viable (Floyd *et al.*, 1983). More recent petrogenetic models for the potassic group involve the melting of subcontinental lithosphere previously enriched via a subduction process (Thorpe *et al.*, 1986). On the other hand, Leat *et al.* (1987) suggest that another source for Cornubian post-collision minettes could have been highly variable lithosphere (different aged crust and mantle) downthrust during ocean closure and crustal shortening. Hydrous melting of this chemically heterogeneous material would have generated incompatible-element-enriched potassic melts distributed over a wide area of the resulting fold belt. On the basis of chemical studies of potassic lavas and lamprophyres elsewhere (for example, Backinski and Scott, 1979), it seems more likely, that the specific enrichments exhibited by the Cornubian minettes were a consequence of source enrichment processes rather than subsequent involvement by the Dartmoor Granite or its fluids. It seems likely, therefore, that they were generated by the melting of mantle that had been metasomatically enriched in LIL elements during a previous subduction episode, rather than via some form of crustal contamination process.

Conclusions

This old quarry shows evidence for volcanic eruptions during the Permian Period, that is around 280 million years before the present. Here a body of rock, assumed to be a thick lava flow, occurs and is part of a suite of lavas collectively called the Exeter Volcanic 'Series'. The Hannaborough lava is a lamprophyre composed of abundant feldspar and mica, as well as being characteristically rich in incompatible elements. Cutting down through the lava is a body of angular blocks (a breccia), composed mainly of sedimentary rocks and a few lamprophyre clasts. In the past, this breccia has been interpreted as a vent agglomerate refilling a feeder (vent) for surface eruptions. However, this has been disputed, and current ideas indicated that the breccia represents an infill of the eroded and irregular top to the lava flow. Chemical analyses of the lamprophyres in the Exeter area have been the subject of debate, and various origins and settings have been proposed to explain their specific features. In particular, it is proposed that they were derived from a specific mantle composition and/or genesis involving the melting and contamination of crustal rocks. This site is important for chemical studies of late-stage subaerial volcanism associated with the stabilization of continental crust after the Variscan Orogeny.

D5 KILLERTON PARK AND QUARRIES (SS 971005)

Highlights

This is the best locality for the study of compositional variation within the lamprophyres

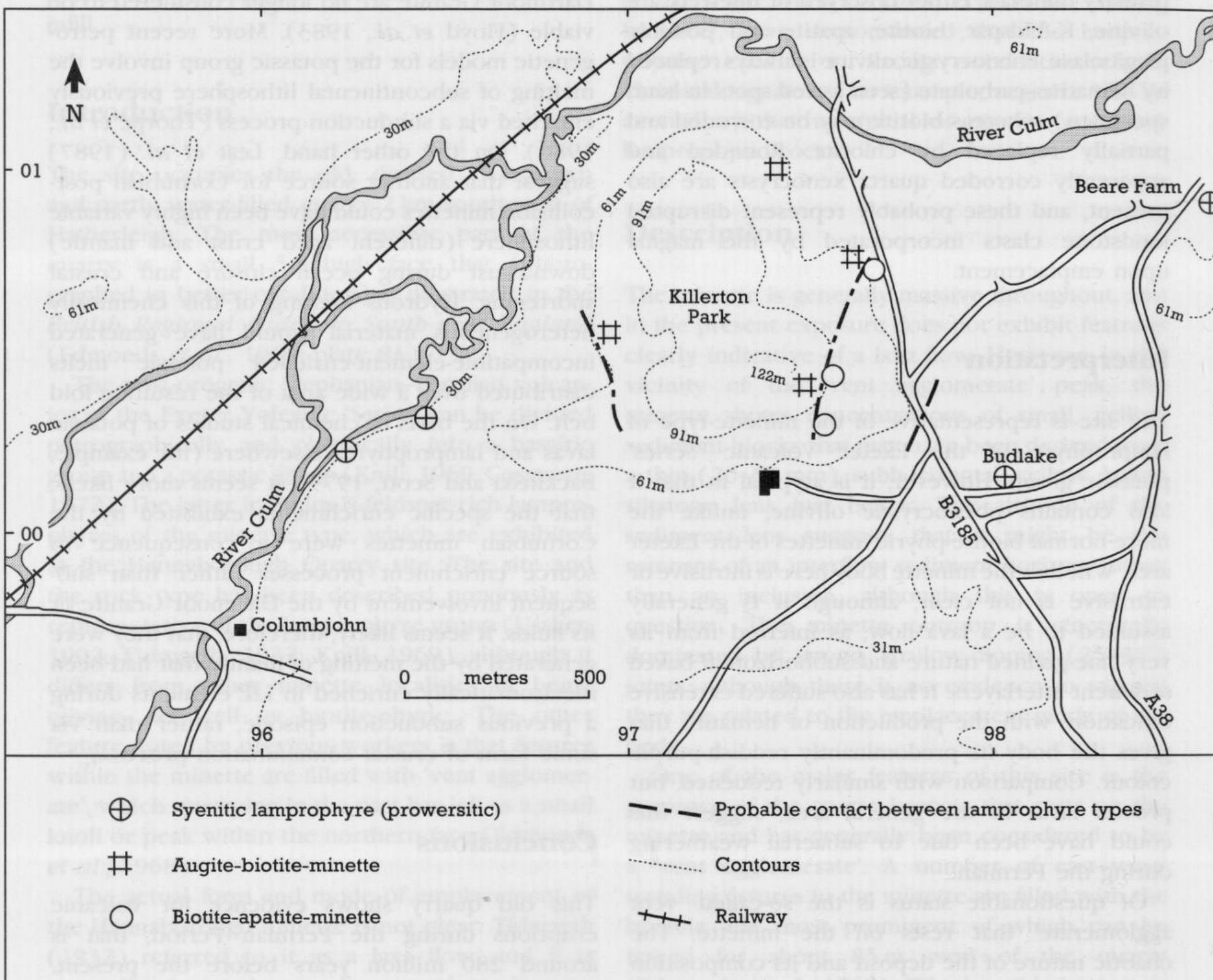


Figure 6.8 Outline map of Killerton Park, showing the distribution of the main lamprophyric types of the Exeter Volcanic 'Series' (after Knill, 1969).

of the post-Variscan volcanics; three distinct types of lamprophyres are clearly associated here.

Introduction

The lamprophyres of Killerton Park have been known for some time (Ussher, 1902), with petrographic details recorded by Tidmarsh (1932) and Knill (1969); the last placed them in the broad potassic group of the Exeter Volcanic 'Series'. A map showing the distribution of the various lamprophyric types in the area is shown in Figure 6.8.

The site covers much of Killerton Park (National Trust) and Columbjohn Wood. The disused quarry (SS 980001) at Budlake just outside the Park is also included, exposing a basaltic lava that belongs to the same volcanic province.

The few chemical analyses available (Cosgrove, 1972; Thorpe *et al.*, 1986; Leat *et al.*, 1987) exhibit the same high level of incompatible-element enrichment that is typical of the potassic group as a whole, as well as the characteristic subduction-related chemical signature (see Hannaborough Quarry above).

Description

Distribution of the lamprophyric lavas in Killerton Park (Figure 6.8) shows the close association of three main types: a biotite–apatite minette, an augite–biotite minette and a highly potassic minette or syenitic lamprophyre (Knill, 1969). The field relationships of the minettes are generally obscure, although Knill (1969) reports that the biotite–apatite-phyric variety occurs as xenoliths in the augite–biotite-phyric type. They are all assumed to be lavas fed by small fissures, but good evidence as to their mode of emplacement is lacking. In Columbjohn Wood, however, Permian red-bed sandstones were at one time seen to overlie the eroded surface of a lava flow (Knill, 1969).

One of the Killerton lavas has yielded a whole-rock K–Ar age of 291 Ma BP (Thorpe *et al.*, 1986; recalculated from Miller and Mohr, 1964) just below the Stephanian–Permian boundary and contemporaneous with the basaltic group of the Exeter Volcanic 'Series'.

One of the best exposures in the Killerton Park site is the quarry 100 m east of The Clump hillock and the surrounding area. This exposes approximately 20 m of a massive, fine-grained, blue-grey minette. Although generally considered to be a lava flow, it is poorly vesicular and does not show any internal flow features or flow boundaries. It is heavily jointed with a dominant subvertical set, the surfaces of which are reddened by hematite. There are small, apparently random differences in texture – in particular, grain-size changes from very fine-grained (almost glassy looking) to pitted and weathered coarser-grained areas. Small, brown biotite and rarer green, pyroxene phenocrysts can be seen in hand specimen, again irregularly distributed throughout the exposed body. The bulk of the lamprophyre is a biotite–pyroxene–phyric minette with a matrix of K-feldspar, biotite, titanomagnetite and apatite. Biotite may occur as both mega- and micro-phenocrysts which show different pleochroic schemes. A chemical analysis of a separated megacrystic biotite (Tidmarsh, 1932) shows it to be rich in Ti and Mg (with a chacteristically low FeO^*/MgO ratio of 0.67) distinct from the Dartmoor Granite high-Fe biotites. Much of the matrix may be composed of secondary minerals such as hematite, carbonate and clay.

Interpretation

This site shows representatives of the biotite-phyric minette, which is the typical lamprophyre type of south-west England, as well as the Exeter Volcanic 'Series'. A number of other minettes are present here in close proximity to each other, although their actual contact relationships are obscure. These volcanics are always assumed to be lavas (rather than high-level intrusives), although evidence for good flow features in the present outcrops is lacking.

The specific chemical features of the Killerton Park minettes are similar to other lamprophyres from south-west England, and the same general comments concerning their chemical petrogenesis apply (see Hannaborough Quarry).

Conclusions

The sections here show various lamprophyre lavas of the Exeter Volcanic 'Series' erupted around 290 million years ago. One of the sections here shows lava buried beneath red Permian sandstone, the latter having been deposited in the equatorial desert conditions of that time. Like the site at Hannaborough (as discussed above) the rocks here are characterized by very high incompatible-element contents, and are subject to debate over their origin and the nature of the source. Their unusual composition is considered generally to reflect a specific mantle composition, although crustal contamination is also a possibility. The site shows key sections in representatives of the biotite-phyric minette, which is a typical lamprophyre of south-west England.