

# Igneous processes within late Precambrian volcanic centres near Whitwick, northwestern Charnwood Forest

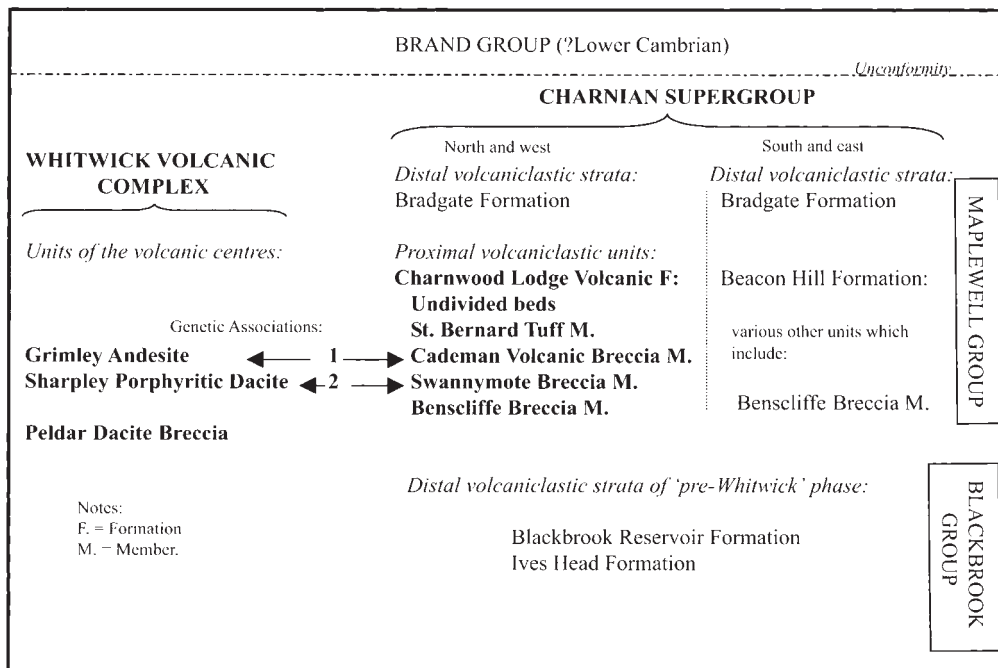
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**Abstract.** Precambrian rocks in northwestern Charnwood Forest differ markedly from their lateral equivalents to the east and south. They are subdivided into the Whitwick Volcanic Complex, of massive to intensely brecciated high-silica andesites and porphyritic dacites, and the Charnwood Lodge Volcanic Formation, which is a thickly bedded sequence of mainly andesitic to dacitic volcanic breccias and lapilli-tuffs. Lithological elements common to both of these units are indicated by field, petrographical and geochemical evidence, which suggests the existence of two 'genetic associations' of rock-types. These associations, and various other units that are distinctive to this region, form the basis of a model that views the Whitwick Complex as an aggregation of magmatic feeder bodies that supplied material, in the form of blocks and lapilli, to a volcanoclastic apron represented by the Charnwood Lodge Formation. The analogues for these rocks can be drawn from the axial magmatic zones of modern or geologically very young volcanic arc systems. The high-silica (dacitic and rhyolitic) Charnian magmas were intruded into unconsolidated wet sediments, resulting in physical interactions that generated peperitic lithologies and related breccias. By contrast, the andesitic magmas may have extruded subaerially as lava domes that periodically collapsed, giving rise to block and ash pyroclastic flows and lahars.

Throughout an exposed thickness of 3500 m, the Precambrian of Charnwood Forest is mainly a stratified succession, showing sedimentary features in keeping with deposition in fairly deep waters (Moseley and Ford, 1989). The accumulation of these strata at a time of active volcanism was nevertheless recognised long ago (Jukes *et al.*, in Potter, 1842; Jukes, 1857, summarised in Watts, 1947, p.121-122), and has since been confirmed by petrographic studies revealing that these rocks have a high content of pyroclastic material. The term 'volcanoclastic' is given to sequences of this type (terminology of Fisher, 1961; Fisher and Schmincke, 1984), which encompass a wide spectrum of clastic rocks composed in part or entirely of volcanic fragments formed and deposited by any mechanism. These fragments can be epiclastic in origin, consisting of abraded grains derived from the erosion of pre-existing volcanic deposits, or they can be of pyroclastic origin, derived directly from contemporary volcanic activity. These pyroclastic rocks may consist of euhedral crystals or angular crystal fragments, angular volcanic grains and non-abraded shards and scoria that were once glassy. Moseley and Ford (1985) gave the name 'Charnian Supergroup' to the stratiform rocks and it is the various subdivisions of the Maplewell Group that are among the main subjects of this account, together with another highly significant unit, the Whitwick Volcanic Complex, in the northwest. These divisions are listed in Table 1 in their stratigraphical and environmental context, and their outcrop areas are given in Figure 1.

The abundance of pyroclastic constituents in the Maplewell Group has prompted much speculation

as to where the volcanic centres were located. Many previous workers have proposed the northwestern part of Charnwood Forest to be the most likely magmatic source area (e.g. Hill and Bonney, 1891), a suggestion which is supported by two types of lithological variation. The first of these is a spatial variation, which is developed on a regional scale within the Maplewell Group, and has an important bearing on the location of the Charnian volcanic source(s). It involves a lateral transition from the predominantly distal-facies volcanoclastic rocks that characterise the Beacon Hill Formation, in the south and east of Charnwood Forest, to a coarse-grained proximal facies sequence that is represented by the fragmental lithologies of the Charnwood Lodge Volcanic Formation (Fig. 1, inset). The latter unit is best developed in the present study area, where it is closely associated with the Whitwick Volcanic Complex, containing massive igneous rocks that may be the remnants of magmatic feeder bodies (Table 1). The second variation is temporal, and is reflected by the up-section increase in pyroclastic content from the Blackbrook Group, which largely consists of tuffaceous rocks (with 25-75% of pyroclastic constituents) to the Maplewell Group in which tuffs (with over 75% of pyroclastic constituents), or their reworked equivalents, are more abundant. This is significant because it means that the Maplewell Group – and hence the volcanic region of north-west Charnwood Forest – contains the youngest phase of Charnian volcanism. Clues to the environment in which this volcanism occurred are provided by geochemistry, reviewed more fully below, which indicates that these rocks originated within a volcanic arc tectonic setting. The late



**Table 1.** Lithostratigraphical summary of north-west Charnwood rock units, highlighted in bold, showing their relationship to the other major components of the Charnian Supergroup and their likely environments. The double-headed arrows link genetically related rock types that constitute the Grimley/Cademan association (1) and the Sharpley/Swannymote association (2).

Precambrian (Neoproterozoic III) age of the Charnian arc is constrained by Ediacaran-type fossil assemblages found throughout the sequence (e.g. Boynton and Ford, 1995).

It should be noted that the Precambrian outcrop is discontinuous owing to the extent of the Triassic and Quaternary cover. Consequently, many exposures do not include important contact relationships and the various boundaries shown in Figure 1 should be regarded as interpretations based on rather meagre field evidence. Mapping problems are exacerbated by the fact that the Whitwick Complex and certain components of the Charnwood Lodge Formation are unbedded, and so provide little evidence for local structural dip. The entire Charnian sequence has been recrystallized at epizonal (mid- to high-greenschist) grades of metamorphism (Merriman and Kemp, 1997), with the synchronous development of a penetrative, subvertical cleavage. Despite this, many delicate original textures are preserved as relicts, enabling these rocks to be classified petrographically.<sup>1</sup>

This paper describes the principal components of the Whitwick Complex and Charnwood Lodge Formation. Several units are involved, and a brief guide to the main lithologies and their likely modes of origin is therefore provided (Table 2). Given the poor exposure of these rocks, much reliance is placed on interpretations of lithology and petrology, the aim being to assess the style of Charnian volcanism by drawing comparisons with similar lithologies from modern or geologically very young volcanic arc systems.

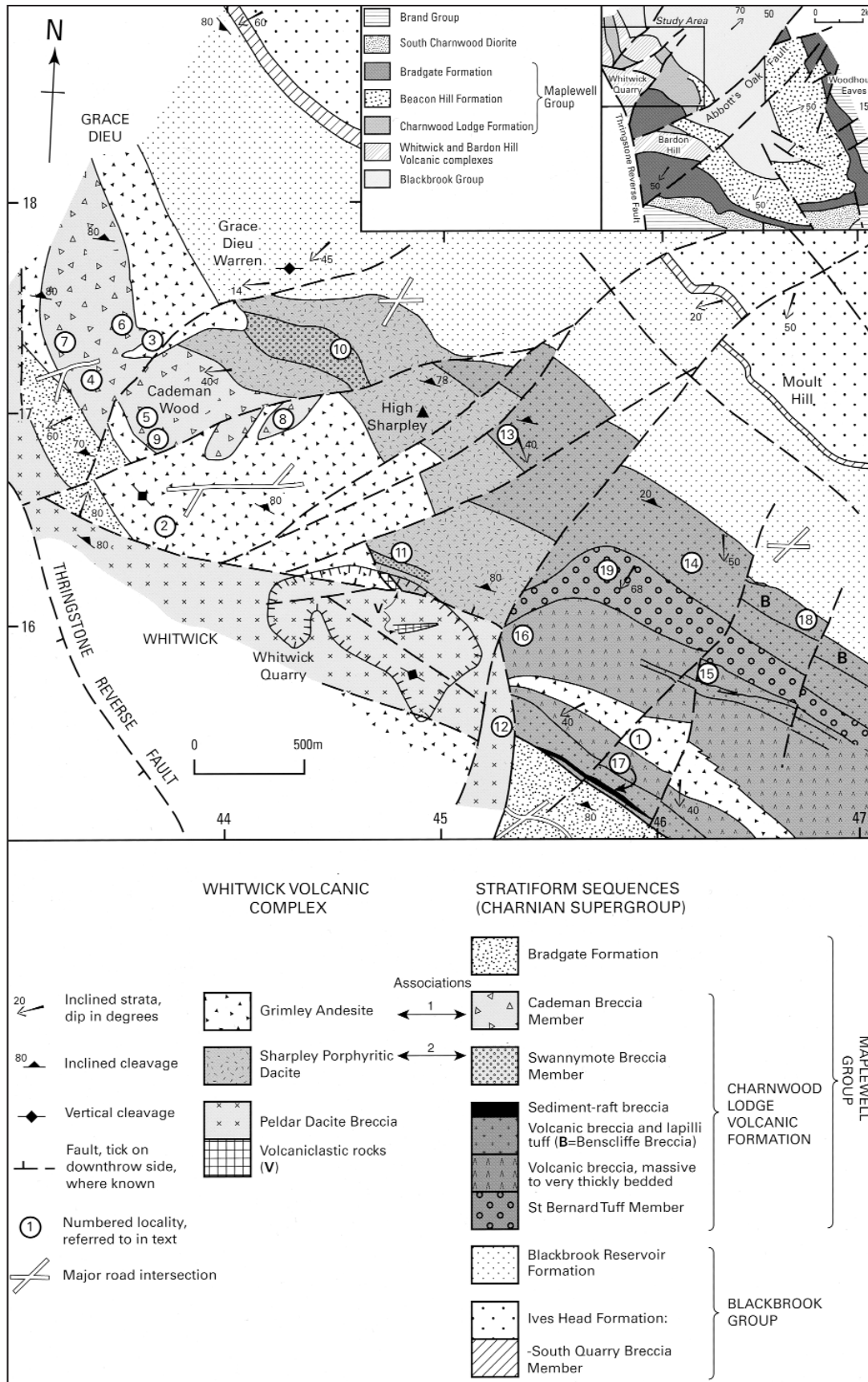
<sup>1</sup> Thin sections (E numbers) were cut from samples collected during the 1993-1996 re-survey of the Loughborough geological map (sheet 141), and may be examined at BGS at Keyworth.

## Lithostratigraphy and geological setting

A formal terminology for rocks in or relevant to the study area is presented in Table 1, which gives stratigraphical correlations and outline environmental information. This table highlights possible links between the Whitwick Volcanic Complex and Charnwood Lodge Volcanic Formation by emphasising the occurrence of two genetic associations, representing lithologies that may have had a common origin from the same episode of magma emplacement. Investigation of these magmatic linkages is one of the major themes of this account.

*The Whitwick Volcanic Complex* (Moseley and Ford, 1985) is here restricted to include the non-stratiform andesites and dacites that do not form part of the Maplewell Group. It consists of massive and brecciated igneous rocks that are in part faulted against various units of the Charnwood Lodge Volcanic Formation. The component lithologies (Table 1) are termed: Peldar Dacite Breccia, Grimley Andesite and Sharpley Porphyritic Dacite, after the earlier names for the 'porphyroids' of this region (Watts, 1947; Hill and Bonney, 1891). The type locality is designated as Whitwick Quarry (445158; all grid references belong to the 'SK' square), in which all of the three units are exposed (Carney, 1994; fig. 10). 'Grimley' and 'Peldar'-type rocks also occur 3.5 km farther south, where they constitute the Bardon Hill Volcanic Complex (Carney, 1999; Carney and Pharaoh, 2000). In reality, the Bardon and Whitwick complexes may have belonged to the same magmatic feeder zone, their present geographical separation being due to subsequent faulting. The Whitwick Complex is clearly not bedded, but an overall tabular geometry is suggested for the unit by the fact that it broadly follows the 'envelope' of outcrops that continues the

PRECAMBRIAN VOLCANIC CENTRES IN CHARNWOOD FOREST



**Figure 1.** Geological sketch map showing the distribution of the Precambrian rocks in north-west Charnwood Forest. Triassic strata and Quaternary drift deposits are omitted, but cover about 70% of this area. The inset shows the position of the study area in relation to the main outcrop of the Charnian Supergroup and Brand Group. This area is included in O.S. Sheet 129, and in BGS Sheets 141 (Loughborough) and 155 (Coalville), at 1: 50 000 scale. For explanation of Associations land 2, see caption to Table 1.

Maplewell Group along strike to the southeast (Fig. 1, inset). Some of its components are fault-bounded, with many offsets occurring along east to northeast trending fault systems, as also featured by Bennett *et al.* (1928, fig. 21).

The *Charnwood Lodge Volcanic Formation* is named after the 'Charnwood Lodge Member' of Moseley and Ford (1985); formational status is now favoured because this 900-1000 m thick sequence can be further subdivided into the members shown in Table 1. It is defined as the succession of thickly stratified to massive, coarse tuffs, lapilli-tuffs and volcanic breccias that crop out in northwest Charnwood Forest, over the Blackbrook Reservoir Formation (Blackbrook Group) and in turn overlain by the Bradgate Formation which is the youngest Maplewell Group component. Moseley and Ford (1985) designated a type section for this unit in the Charnwood Lodge Nature Reserve, between Flat Hill (465161) and Warren Hills (461148), although because of the sporadic exposure it is better to regard this as a type area. A south-westerly regional dip of between 40 and 50° is assumed, from what little bedding is seen in the Charnwood Lodge and adjacent formations, and from the structural position of this area on the south-western flank of the main Charnian anticline (Fig. 1).

### Magmatic feeders and extrusive products

This section investigates the basis for two major lithological associations, indicated in Table 1, that together link the activity of the Whitwick Complex to the genesis of certain rocks in the Charnwood Lodge Volcanic Formation. The object is to establish a model explaining the overall character of Charnian volcanism, and in particular the relative contributions made by the different magma sources during accumulation of the flanking volcanoclastic sequences.

### The Grimley / Cademan Association

This association is defined by sparsely to moderately porphyritic lithologies that encompass high-silica andesite to low-silica dacite compositions (Fig. 9a). An igneous component is represented by the Grimley Andesite, whereas the Cademan Volcanic Breccia is interpreted (below) as a complementary, extrusive pyroclastic rock with fragments derived from the Grimley Andesite.

*Grimley Andesite* forms a bifurcating, northwest trending body with an estimated thickness of about 940 m. The various scattered outcrops suggest that it narrows to the south-east, and is last seen in the crags to the east of High Tor Farm (Locality 1, Fig. 1). The type area is between Whitwick Quarry (447162), the crags around Cademan Street in Whitwick village (437164), and the disused quarry at Grimley Rock (434169). The only evidence for

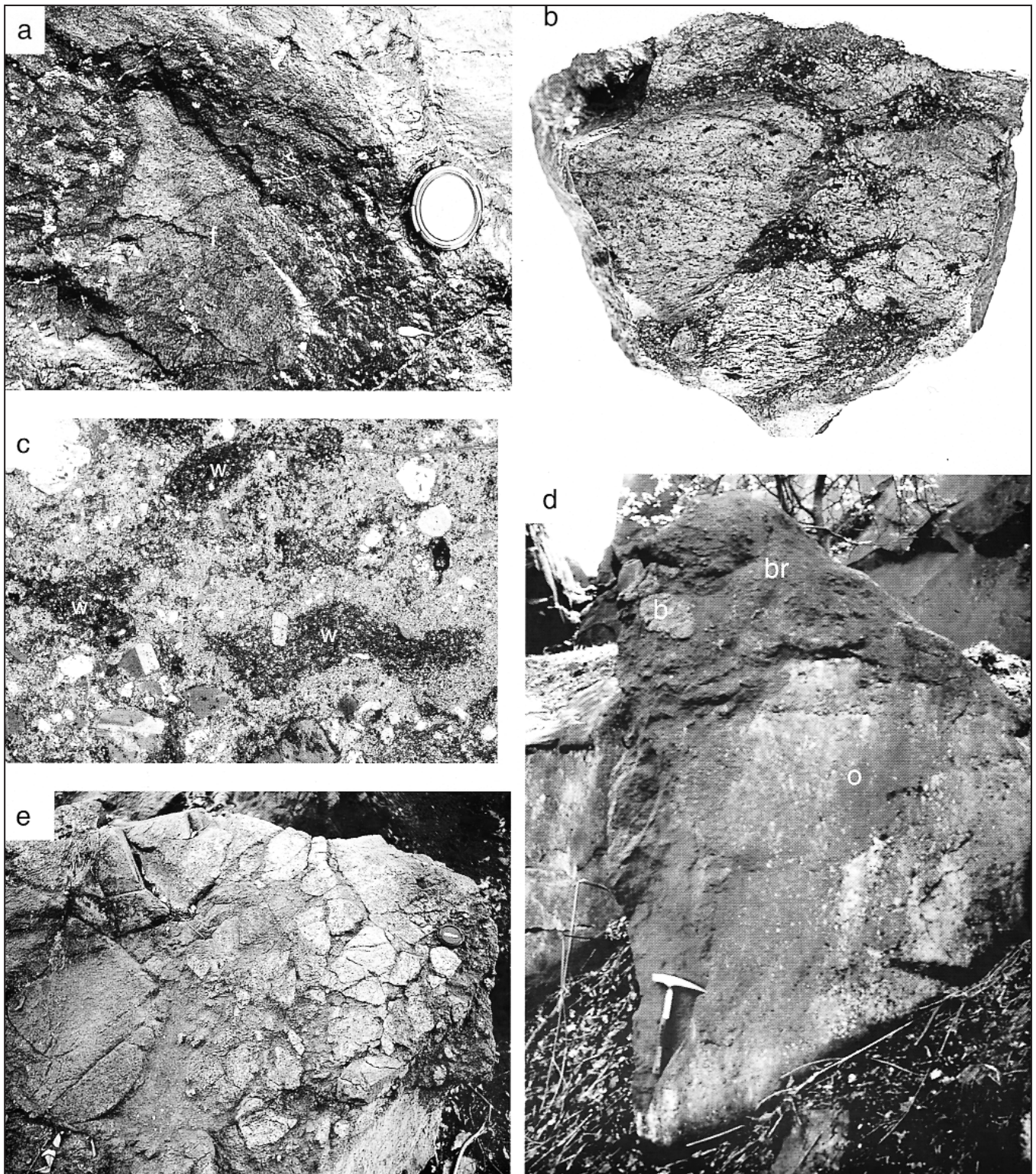
the unit's relative age within the Whitwick Complex is provided by an exposure on the south-western face of Whitwick Quarry. This shows a dyke of Grimley Andesite, about 20 m wide, with a subvertical, chilled contact against Peldar Dacite Breccia, which it must therefore pre-date.

*Lithology.* Exposures of Grimley Andesite show that it is a grey-green, sparsely to moderately porphyritic lithology (Table 3). Chemically analysed samples have silica contents between 56 and 65%, with basaltic andesite, andesite and low-silica dacite compositions all represented (Fig. 9a). Although the Grimley Andesite appears to be structureless, fresh surfaces commonly reveal a shadowy breccia texture, which is a highly significant feature of the lithology. Some of the most accessible examples of this brecciated facies occur in Whitwick village, on crags overlooking the garage yard on the western side of Cademan Street (Loc. 2). There, a northerly-trending contact, which is unexposed but probably is a fault, brings in the brecciated facies on the smooth rock surfaces that form the eastern part of the exposure. The breccia features abundant, closely-packed fragments that measure up to 0.2 m across. All of these fragments consist of the same type of fine-grained andesite. They are highly angular, with lozenge or rectangular shapes (Fig. 2a). The larger of the fragments commonly show internal orthogonal joints that are filled by a fine-grained, green-grey crystalline material, which also occupies the larger areas of matrix between individual fragments. Many fragment margins can be fitted together, producing a jigsaw-type of breccia structure (Fig. 2b). In places this texture is developed on a very fine scale (Fig. 3a) and can only be detected on freshly hammered surfaces.

Grimley Andesite exposed at Hob's Hole (Loc. 3) has a heterogeneous, mottled appearance, which is not caused by brecciation but is due to the presence of abundant angular to wispy inclusions of dark green-grey andesite set in a pale grey to cream matrix. In thin section (Fig. 2c), the green-grey andesite inclusions have aphanitic or spherulitic textures and their dark colour is due to chlorite and epidote. The abundance of these minerals indicates that the inclusions are more mafic in composition than typical Grimley Andesite, which here is represented by the surrounding leucocratic, microcrystalline andesite or dacite.

*Petrography.* Most Grimley Andesite lithologies compare with the sample from Grimley Rock, illustrated in Figure 3b. This has microcrystalline to cryptocrystalline textures dominated by interlocking, commonly polygonal, quartzo-feldspathic aggregates. The andesite or dacite fragments in the brecciated facies of the Grimley Andesite also have this texture. The matrix between these fragments is of a coarser grain size (Fig. 3a), however, and in many samples of brecciated andesite it includes well-crystallized aggregates of chlorite and epidote, suggestive of hydrothermal or metamorphic types of mineral assemblage. Intergranular textures occur less commonly in the Grimley Andesite, an example being a fragment from the brecciated andesite facies in Whitwick Quarry in which groundmass plagioclase laths show fluxional alignment and are interspersed with Fe-Ti oxide granules and secondary white mica/chlorite aggregates (Fig. 3c).

*Cademan Volcanic Breccia Member* is about 450 m thick in its type area, between High Cademan



**Figure 2.** Lithologies of the Grimley Andesite and the Cademan Volcanic Breccia Member.

**a.** Exposure of brecciated Grimley Andesite at Cademan Street, Whitwick (437164), with the outline of a discrete, highly angular andesite fragment (f).

**b.** Slabbed specimen (JNC569), about 80 mm wide, representing part of Figure 2a and showing closely packed andesite fragments with jigsaw fit.

**c.** Photomicrograph (E67538) of heterogeneous Grimley Andesite from Hob's Hole (436174); the dark grey, angular to wispy areas (w) represent aphanitic, chlorite-rich

fragments of ?basaltic andesite separated by more leucocratic, microcrystalline andesite or dacite. Field of view is about 5 mm wide.

**d.** Exposure of Cademan Volcanic Breccia at Calvary Rock (434172); the smooth rock faces represent an outsized dacite block (o), to right of hammer, surrounded by the lapilli-grade breccia matrix (br) enclosing a smaller dacite block (b).

**e.** Exposure of Cademan Volcanic Breccia in Grace Dieu Wood (435175). To the right of the photo, highly angular dacite blocks occur in clusters that show jigsaw fit.

(442169) and the northern end of Grace Dieu Wood (434176). These rocks were included by Watts (1947) within his 'Bomb-rocks' category, and mapped as part of the Whitwick Complex by Moseley and Ford (1985). The Cademan Breccia has been distinguished here (Table 1), because it differs in two respects from the breccias that are thickly interbedded in the undivided part of the Charnwood Lodge Formation (see below). Firstly, the Cademan Breccia does not appear to be interbedded with other pyroclastic lithologies, and secondly, it generally occurs in close proximity to the main mass of the Grimley Andesite (Fig. 1). The blocks in the Cademan Breccia are of a similar lithology to the non-brecciated parts of the Grimley Andesite, and are also chemically similar, although slightly more silica-rich, plotting in the low-silica dacite field of Figure 9a. Despite these similarities, and the close field association between the two units, no clear contacts between the Cademan Breccia and Grimley Andesite are exposed.

*Lithology.* The spectacular monomictic breccias at Calvary Rock (Loc. 4) show most of the lithological features summarised in Table 3. They contain abundant clasts, commonly of block size (in excess of 64 mm), with rectangular to subspherical shapes, the margins of which vary from being subrounded to highly angular. It is common to see both rounded-off and angular corners in the same individual clast. The block-size clasts typically stand proud on weathered surfaces, unlike the fragments in the brecciated facies of the Grimley Andesite. They are 0.7 m across on average, but some exposures feature very large blocks, over 2 m across (Fig. 2d). The matrix to these breccias is very coarse-grained to lapilli-grade (1-64 mm size clasts), and is poorly sorted with abundant lithic fragments and crystals. Variations in the ratio of matrix to clast constituents are seen at Calvary Rock, and also near Broad Hill (Loc. 5), where the matrix locally occupies 50-70% of some breccias. These matrix-rich rocks remain poorly sorted, with larger clasts scattered about, but the latter are relatively small in size (up to several centimetres across) when compared to blocks in the more typical Cademan Breccia lithology. A distinctive variant of breccia occurs in Grace Dieu Wood, north-west of Hob's Hole (Loc. 6). It features well-jointed and highly angular blocks of the usual fine-grained, sparsely porphyritic dacite, some so close to each other that their outlines have a jigsaw fit (Fig. 2e). Between these blocks is a poorly sorted, mainly lapilli-grade matrix consisting of lithic fragments and euhedral or fragmented plagioclase crystals. Farther north, and west (Loc. 7), in Grace Dieu Wood, there are breccias in which the andesite blocks have cream to pale pink colours, in marked contrast to the coarse-grained, grey-green breccia matrix.

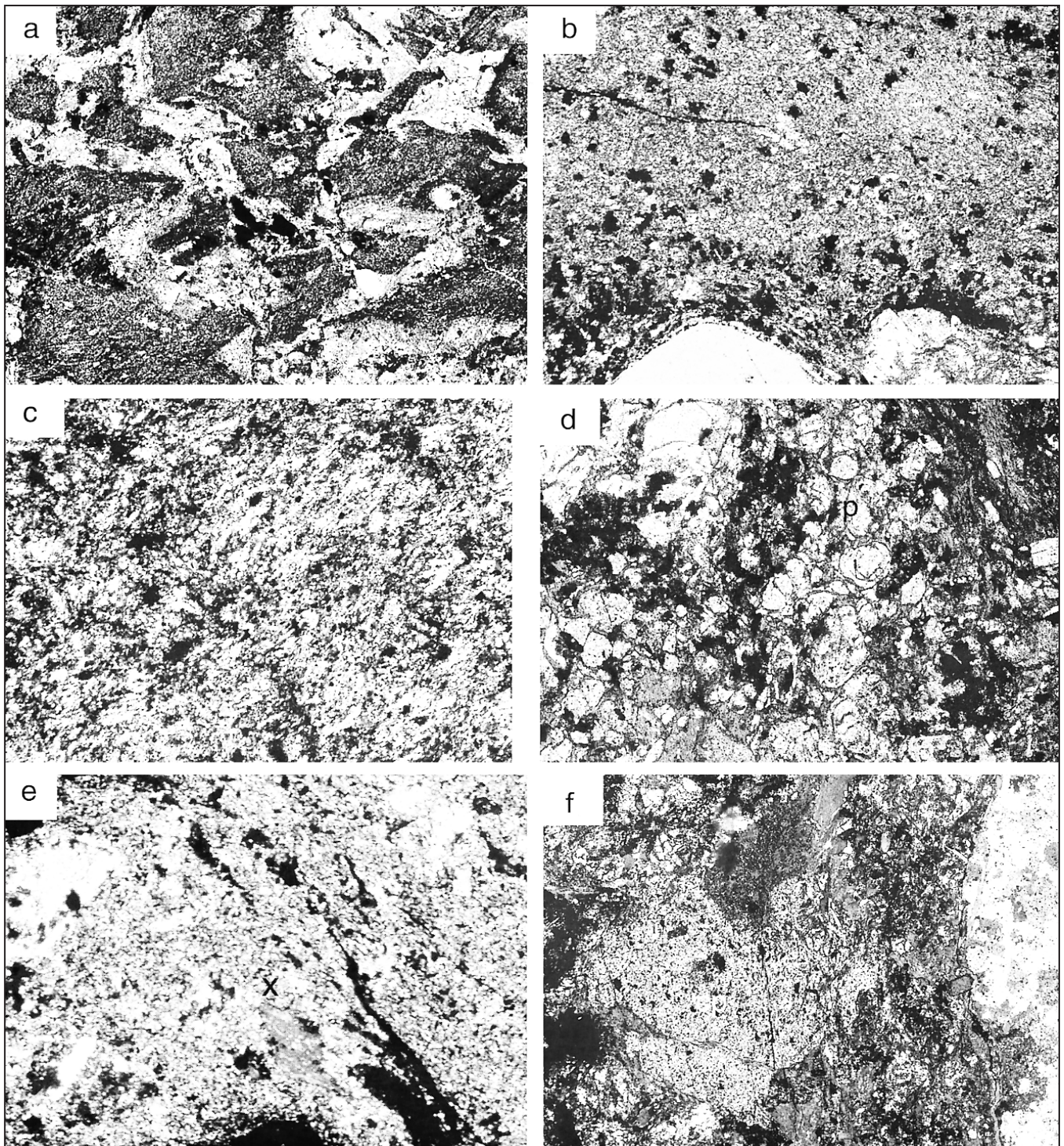
High Cademan is the only area where outcrops of the Cademan Volcanic Breccia and Grimley Andesite are observed close together. On the eastern flank of High Cademan (Loc. 8, 442169) most exposures show the rough rock surfaces and large blocks typical of the Cademan Volcanic Breccia. This breccia texture disappears westwards, however, and the summit of High Cademan is occupied by a massive, smooth-surfaced lithology equated with Grimley Andesite. The contact between the two is hidden, but immediately east some outcrops show metre-scale alternations, apparently

between Cademan Breccia and relatively more massive Grimley Andesite. This layering dips about 55° to NE 020, but an original vertical attitude results if a correction is made for the presumed 40-50° south-westward regional dip. Cademan Volcanic Breccia exposed farther north (439171) shows prominent planar surfaces that are inclined south-westwards, in the inferred regional dip direction. A rare exposure of a contact occurs by the footpath down the western flank of Temple Hill (Loc. 9), where volcanic breccia rests on a 50 mm-thick, dark grey, fine-grained fragmental layer. The latter is unique amongst the rocks sampled to date, in that it is composed of slivers or irregular masses of glassy volcanic rock showing well preserved perlitic texture (Fig. 3d). The layer is underlain by a grey, feldspar-rich andesite, suggesting that the glassy lithology may represent part of the latter's brecciated chilled margin.

*Petrography.* Dacite blocks in the Cademan Volcanic Breccia have predominantly microcrystalline to cryptocrystalline textures. At the Calvary Rock exposures, phenocrysts are small and include sporadic quartz and up to 30% of heavily altered euhedral plagioclase; these blocks also contain prismatic chloritic pseudomorphs after original hornblende. A thin section of a breccia block from west of Grace Dieu Wood (Loc. 7) features a microcrystalline groundmass that is typical of these lithologies. This sample shows textural heterogeneity, which is imparted by abundant rounded, elliptical or veinlet-like segregations of better-crystallized quartz-feldspathic material (Fig. 3e). In the same thin section there are domains that preserve shadowy, circular, microcrystalline areas reminiscent of a recrystallized spherulitic or micropoikilitic texture. Thin sections of the the jigsaw breccias described at Loc. 6 show that in the matrix between the blocks, lithic fragments locally predominate over plagioclase crystals. These lithic grains range from fine-ash to lapilli size and although they mostly have microcrystalline to cryptocrystalline textures, one lapilli-size clast (15 mm across) is of finely equigranular quartz microdiorite (Fig. 3f).

#### ***Interpretation of Grimley/Cademan Association:***

In the Cademan Breccia Member, the abundance of blocks suggests deposition by gravity processes operating in an environment of steep slopes. Angular corners indicate that many blocks experienced minimal abrasion, with those that are more rounded testifying to abrasion produced by clast collisions during transport. Metres-size blocks, some with jigsaw textures, indicate in situ fragmentation prior to consolidation of the deposit. The monomictic nature of the Cademan Breccia, and the fact that its clasts are closely similar in appearance and petrography to the Grimley Andesite (compare Figs. 3a&b with 3e&f) are features suggesting a genetic link between the two. For example, the Grimley Andesite may be a lava flow with the Cademan Breccia as the autobrecciated part of the lava. Alternatively, the Grimley Andesite could have been extruded as volcanic domes, with the Cademan Breccia representing their brecciated margins and talus and/or the deposits of block and ash pyroclastic flows that originated from the disintegration and collapse of the domes as recently witnessed on Montserrat (Young *et al.*, 1998).



**Figure 3.** Photomicrographs of rocks from the Grimley/Cademan association.

**a.** Grimley Andesite microbreccia (E67539) south-east of Hob's Hole (437174), with angular fragments of cryptocrystalline andesite (dark grey areas) in a coarser leucocratic microcrystalline matrix; field of view is 5 mm wide.

**b.** Grimley Andesite sample (E67535) from Grimley Rock (434169) showing microcrystalline to cryptocrystalline groundmass texture and magmatically corroded quartz phenocryst (at lower left); field of view is about 5 mm wide.

**c.** Grimley Andesite (E67549) from Whitwick Quarry, showing intergranular texture and fluxional alignment of plagioclase laths; field of view is about 7 mm wide.

**d.** Possible chilled margin (E67532) from a contact between

andesite and ?Cademan Volcanic Breccia on western flank of Temple Hill (437168). Circular areas of recrystallized perlitic volcanic glass are seen below 'p'; the field of view is 3 mm wide.

**e.** Dacite block (E67543) from the Cademan Volcanic Breccia in western Grace Dieu Wood (432173). A microcrystalline to cryptocrystalline groundmass has diffuse quartz-rich areas (just right of 'x'); field of view is 2 mm wide.

**f.** Matrix to the Cademan Volcanic Breccia (E67542) from the locality shown in Figure 2e. The fragments include equigranular quartz-microdiorite, at right-hand margin of photo, but more commonly are of ragged-margined cryptocrystalline dacite (cp); field of view is 3 mm wide.

Because of poor exposure, contact relationships are not sufficiently clear to differentiate between these hypotheses. However, apart from in the High Cademan area, the lack of intercalation of the two units does not support the idea that the Cademan Breccia represents an autobreccia of Grimley Andesite lavas. On the other hand, the textures of the Cademan blocks are generally cryptocrystalline or microcrystalline, albeit with some variation in the degree of crystallinity. They are similar to the many examples given by Murphy and Marsh (1993) of 'dense', non-vesicular and non-glassy material produced by repeated recrystallization within relatively slowly emplaced subvolcanic to extrusive domes or vent-filling dome plugs. The preferred interpretation is that the Grimley Andesite was emplaced in intrusive/extrusive domes, and the Cademan Breccia represents the brecciated margin or talus apron of the domes or, as suggested in Figure 10, block and ash pyroclastic flows generated by the collapse and disintegration of the domes. Such flows, once initiated, would travel down the sides of the volcanic edifices essentially as debris avalanches. Examples of the latter from the volcanoclastic apron of Ruapehu volcano in New Zealand show jigsaw-type clasts (McPhie *et al.*, 1993, plate 36.3) similar to parts of the Cademan Breccia.

Internal brecciation is an integral feature of the Grimley Andesite, and may have occurred in the late syn-volcanic environment, where processes such as autobrecciation or hydraulic fracturing (Cas and Wright, 1987) would be expected to operate during inflation of a consolidated extrusive andesite dome. The well-documented 1995-1997 eruptive phase of Montserrat offers a possible modern analogue for this type of deformation, which may be associated with the generation of the 'hybrid earthquake' swarms that were detected at shallow depths immediately beneath the active crater into which the domes were rising (Miller *et al.*, 1998). These earthquakes were attributed to multiple hydrofracturing events during the build up of conduit gas pressure (Voight *et al.*, 1999).

The heterogeneous sample of Grimley Andesite shown in Figure 2c may suggest that mixing has occurred between magmas of contrasting composition. This should be established by chemical analysis of the mafic inclusions, but if confirmed it would be an important observation, since magma mixing may have been involved in triggering eruptions at Montserrat (Murphy *et al.*, 1998).

A subaerial environment for the Grimley dome extrusion in Association 1 is suggested by the general lack of evidence for interaction with water or water-saturated sediment. In the absence of criteria such as sedimentary structures in fine-grained facies, this must remain a speculative conclusion. Subaqueous deposition of the Cademan Breccia is nevertheless a possibility, by analogy with the volcanism of Montserrat, where block and ash

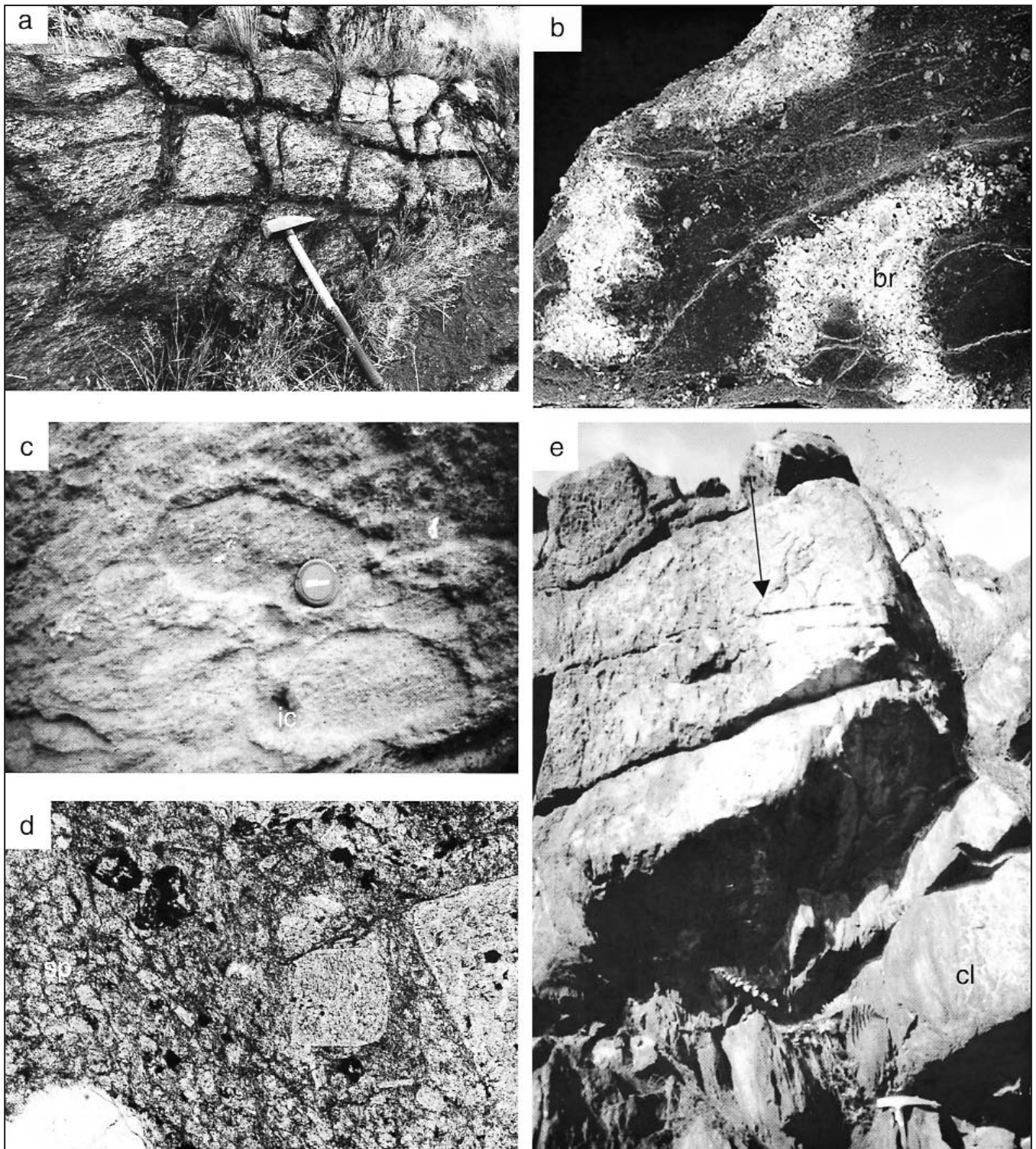
pyroclastic flows originating from sequential dome collapses have formed a fan complex that has prograded into the surrounding sea (Cole *et al.*, 1998). The great thickness of the Cademan Breccia militates against it being a single block and ash pyroclastic flow, but could suggest an origin as a series of amalgamated flows deposited on a subaqueous fan (Fig. 10). Variations in the proportions of matrix and clasts in the Cademan Breccia suggest that it may have a degree of stratification in keeping with an amalgamated flow origin. The accumulation of thick pyroclastic sequences would be favoured by 'ponding' of the various flows, perhaps against the wall of a caldera that contained the rising domes. It would be expected from this that block and ash pyroclastic flows would be thickest at their final resting site, some distance away from their point of origin. This is clearly not in keeping with the close field association seen here between the Grimley Andesite and very thickly developed Cademan Breccia. If this region experienced a long history of multiple dome activity, however, the present Grimley Andesite could represent the root zones of younger magmatic domes that had risen through pre-existing volcanoclastic accumulations that included the Cademan Breccia (Fig. 10).

### The Sharpley / Swannymote Association

This association is defined by highly porphyritic (plagioclase-quartz) lithologies that in chemical terms encompass dacitic and rhyolitic compositions (Fig. 9a). The Sharpley Porphyritic Dacite represents a possible shallow-level intrusive igneous rock, whereas the Swannymote Volcanic Breccia Member may be a complementary breccia component (e.g. Table 3) containing fragments from the Sharpley Dacite.

**Sharpley Porphyritic Dacite** is massive and homo-geneous, with 40-50% of phenocrysts represented by large (up to 10 mm) white plagioclase feldspar and subordinate but equally large, rounded, green-grey quartz (Table 2). The fine-grained groundmass has a grey to lavender colour on fresh surfaces, becoming pale grey when weathered. Silica contents are 70-72%, suggesting a dacitic to rhyolitic composition (Fig. 9a); however, the possible mobilisation of silica in the post-magmatic, metamorphic environment is a constraint on rock classifications based solely on chemical compositions. The principal exposures and the type locality are around High Sharpley (448171), and the unit maps out (Fig. 1) as a fault-segmented northwest trending body that may be up to 600 m thick in places.

The most obvious primary structure of the High Sharpley exposures consists of prominent planar surfaces inclined towards the southwest, parallel to the inferred regional dip. Viewed in plan, these surfaces display systems of rectangular to polygonal-



**Figure 4.** Lithologies of the Sharpley Porphyritic Dacite and the Swannymote Breccia Member.

**a.** Sharpley Porphyritic Dacite exposed on High Sharpley (448171), with polygonal jointing pattern.

**b.** Slabbed specimen of Swannymote Breccia (JNC 501) from an exposure to the west of Swannymote Rock (445172); complex intermixing has occurred between the crystal-rich breccia matrix (br) and darker-toned volcanoclastic siltstone. The slab is about 50 mm wide.

**c.** Typical appearance of the Swannymote Breccia on Ratchet Hill (447163); the block-size porphyritic volcanic fragments

have rounded to possibly incurved margins (eg. just above 'ic').

**d.** Photomicrograph of Swannymote Breccia (E67524) from Ratchet Hill (447163), showing an enlarged area of a lapilli-size volcanic fragment with spherulitic texture (sp); the field of view is 2 mm wide.

**e.** Near Ratchet Hill summit (447163), the eastern junction (arrowed) of the Swannymote Breccia (rough-textured lithology) with the Sharpley Porphyritic Dacite seen to the right (northeast). The dacite has a diffusely fragmental texture, with a possible ovoid clast occurring to the left of 'cl'.

shaped joints spaced at between 0.5 and 1 m (Fig. 4a). The joints continue into the rock for at least 2 m, dividing it into narrow, oblong-shaped domains in side-section; the structure is not related to the Charnian cleavage, and resembles deformed columnar joints.

Thin sections of fresh samples of Sharpley Dacite from Whitwick Quarry have homogeneous groundmasses consisting of a microcrystalline quartzo-feldspathic base interspersed with secondary laths of colourless mica (Fig. 5a). Stringers of leucogenised mafic material anastomose across the groundmass.

Contact relationships along the western margin of the Sharpley Porphyritic Dacite are exposed on the north face of Whitwick Quarry, immediately below Ratchet Hill. Here, the unit adjoins a 28 m-thick volcanoclastic succession ('v' in Fig. 1), which is subvertical and tectonically sheared. About one centimetre from the volcanoclastic rocks, phenocrysts become smaller and more scattered, and small flames and rafts of purplish grey siltstone occur within the otherwise intact Sharpley Dacite. The contact zone of the dacite is probably gradational for a further 12 m into the adjoining volcanoclastic succession since the latter includes at least four thin screens of 'Sharpley'-type porphyritic dacite and dacitic volcanic breccia. The sedimentary rocks mainly consist of crystal-rich volcanoclastic sandstones and siltstones. They show contortion and slump-folding of laminae and, despite the strong deformation, graded bedding can be seen, which indicates that the sequence 'youngs' to the west, away from the Sharpley Dacite. Natural exposures of a further contact, between the Swannymote Breccia and Sharpley Dacite, occur on the nearby Ratchet Hill and are described below.

**Swannymote Breccia Member** was named after its type area around Swannymote Rock (Loc. 10), the only other occurrence being at Ratchet Hill (Loc. 11). It may be up to 200 m thick, but this must be regarded as a tentative estimate since it is seldom exposed. The Swannymote Breccia has a close spatial relationship with outcrops of the Sharpley Porphyritic Dacite (Fig. 1), particularly between Ratchet Hill and Whitwick Quarry. It resembles the Cademan Breccia in that it is predominantly composed of unbedded volcanic breccia, but the blocks found in these rocks are different in that they are highly porphyritic, with large phenocrysts of white plagioclase and rounded, grey-green quartz (Table 3). The Swannymote blocks instead resemble typical Sharpley Porphyritic Dacite in their gross lithology, although not always in detail since some have darker grey groundmasses. The phenocrysts of the breccia blocks are also slightly smaller than those in the Sharpley Porphyritic Dacite; they average about 2 mm but are locally up to 5 mm in size. Chemical analyses (see below) indicate that the Swannymote blocks have generally higher silica contents than the Sharpley

Porphyritic Dacite. Their compositions are appropriate to rhyolite (Fig. 9a), but as discussed below this may in part reflect modification resulting from element mobility in the post-magmatic environment.

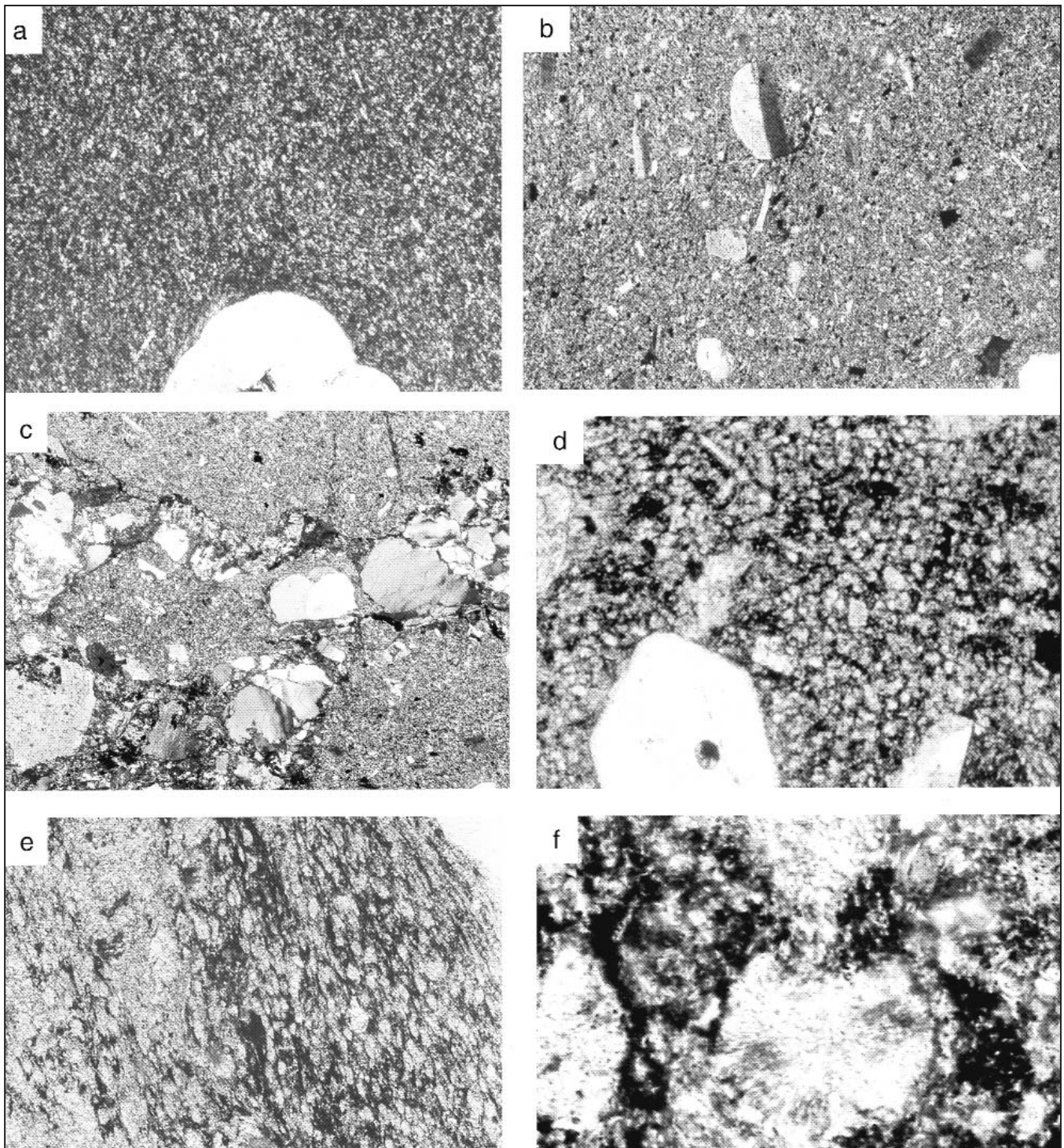
**Lithology.** The northeastern part of Swannymote Rock exposes massive volcanic breccia with abundant (c.50-60%) porphyritic rhyolite blocks, up to 1 m across, which are subrounded with elliptical to rectangular sections. The coarse-grained to lapilli-size breccia matrix contains closely packed plagioclase and quartz crystals. Southwest of the knoll, the breccia matrix becomes extensively admixed with very fine-grained, grey, faintly laminated volcanoclastic siltstone. A polished slab of this lithology (Fig. 4b) shows wispy lenticles and 'floating' crystal-rich aggregates representing elements of the breccia matrix dispersed within the siltstone. Thin sections of this disrupted part of the breccia show very fine-grained lithic fragments with pervasive spherulitic textures, similar to those illustrated in Figure 4d. About 20 m farther southwest, exposures show breccia crammed with small (2-3 cm size) porphyritic clasts, some with strongly arcuate to incurved and cusped outlines.

Field relationships at Ratchet Hill (Loc. 11) indicate that the Swannymote Breccia Member forms a screen that is wholly enclosed within the Sharpley Porphyritic Dacite. Here, it is a poorly sorted lithology composed of subspherical to elliptical porphyritic rhyolite blocks, up to 0.4 m in size, with subrounded or well-rounded margins (Fig. 4c); these blocks are typically recessed-in to the matrix due to differential weathering. The northeastern junction of this breccia is exposed 70 m west of the summit of Ratchet Hill, appearing as a sharp interface when viewed end-on (Fig. 4e). Close inspection shows that the adjacent Sharpley Porphyritic Dacite has a diffusely fragmental appearance, with ovoid-shaped enclaves that have not been observed elsewhere in this unit. This fragmental facies fades over about 100 m to the northeast, away from the contact shown in Figure 4e and towards exposures in the massive Sharpley lithology.

On the southern part of Ratchet Hill, the volcanic breccias contain rafts of grey, laminated siltstone. This recalls the situation at Swannymote Rock, except that there is no obvious breccia/soft-sediment intermixing and the lamination within the siltstone rafts is sharply truncated by the matrix of the breccia.

**Petrography.** Thin sections show that the blocks in the Swannymote Breccia contain common phenocrysts of wholly or partly disaggregated plagioclase and rounded, marginally embayed quartz. A typical breccia block from Ratchet Hill has a groundmass composed of microcrystalline quartzo-feldspathic aggregates interspersed with plagioclase microlites (Fig. 5b). A very coarse-grained and poorly sorted matrix intervenes between individual blocks of the breccia; this matrix consists of granulated crystals concentrated between abundant, ash- to fine-lapilli size (1-3 mm) fragments of microcrystalline dacite (Fig. 5c), some with relict spherulitic textures (Fig. 4d).

**Interpretation of the Sharpley/Swannymote Association:** In part, the Swannymote Breccia resembles the coarsely fragmental rocks of the Cademan Breccia Member, but relationships of the type seen at Swannymote Rock show that there was



**Figure 5.** Photomicrographs of the Sharpley, Swannymote and Peldar rocks.

**a.** Sharpley Porphyritic Dacite (E67678), showing microcrystalline groundmass and rounded quartz phenocryst at lower margin; the field of view is about 2 mm wide.

**b.** Porphyritic volcanic block (E67523) from the Swannymote Breccia at Ratchet Hill (447163), showing microcrystalline groundmass texture and plagioclase microphenocrysts; the field of view is about 2.5 mm wide.

**c.** Matrix of Swannymote Breccia (E67524; see also, Fig. 4d) showing microcrystalline to cryptocrystalline-textured lithic clasts with intervening areas rich in granulated quartz and plagioclase crystals; field of view is 4.5 mm wide.

**d.** Textures in a cognate fragment of porphyritic dacite

(E67547A) in Peldar Dacite Breccia from Whitwick Quarry (see Fig. 6a), showing oxides-rich groundmass in which quartzofeldspathic areas (pale grey) form microgranular clumps; a euhedral quartz microphenocryst is seen at lower photo margin. Field of view is about 1.3 mm wide.

**e.** Matrix of Peldar Dacite Breccia (E67476) from Whitwick Quarry, showing globulose 'micro-spherulitic' texture, which is an accentuation of that seen in Figure 5d. The attenuation of the spherulites is a superimposed effect caused by later deformation; field of view is about 3 mm wide.

**f.** Enlargement of an undeformed spherulite from image 'e'. Note the fibrous, radiating arrangement of quartz and feldspar crystallites and 'bow-tie' extinction; field of view is 0.7 mm wide.

interaction between the breccia and unconsolidated, water-saturated sediments. An important aspect of these mixing phenomena is their association with the development of spherulitic textures in some of the breccia fragments. Spherulites have commonly been attributed to the devitrification of volcanic glass, and Lofgren (1971) has demonstrated that their development would be favoured in magmas that had cooled to glass but were then subjected to slow, solid-state crystallization at sustained elevated temperatures in the presence of circulating fluids. McArthur *et al* (1998) further suggest that spherulites can nucleate above the glass transition temperature, during the cooling of magmas emplaced at shallow levels. Spherulites can form in a wide range of environments, including subaerial conditions, but, in the context of the field relations seen here, they could be attributed to the relatively slow cooling of magmas intruded into, and insulated by, a carapace of wet sediment. An interpretation of parts of this unit as peperitic breccias (formed by the disintegration of magma in contact with wet sediments) may also explain the rounded to incurved outlines of certain of the blocks at Swannymote Rock, indicative of pillow formation. The relationships seen near Ratchet Hill are of a different type, featuring sharp margins between breccia and rafted sedimentary clasts. They suggest that, at least locally, the host sediments were consolidated prior to their incorporation into the breccia.

The Sharpley Porphyritic Dacite constitutes the obvious source of porphyritic blocks in the Swannymote Breccia, but its precise mode of origin is uncertain. Except for its fragmental marginal contact zone with the Swannymote Breccia, and with the volcanoclastic rocks in Whitwick Quarry, it is a homogeneous body. A possible tabular geometry is indicated by the bedding-parallel internal planar structure of the dacite, and its columnar jointing further suggests that these planes may be the boundaries to internal cooling units. A mode of origin as a sill or laccolith, or perhaps a cryptodome, emplaced within an unconsolidated or partly consolidated sedimentary carapace, could explain the dacite's marginally brecciated condition and its intergradational relationship with the Swannymote Breccia. A parallel may be found in the Jurassic-age volcanic arc sequences of southern Chile (Hanson and Wilson, 1993), where spherulitic textures are described in association with 'hyaloclastites', including monolithological debris flow deposits and peperites, formed where silicic magmas have cooled within an insulating carapace of wet sediments. These terranes feature largely coherent silicic bodies, which are possible analogues for the Sharpley Porphyritic Dacite.

### **Peldar Dacite Breccia**

The most distinctive features of this unit, summarised in Table 3, are its dark grey to black

appearance, abundance of large phenocrysts, and textures indicative of thorough brecciation (Fig. 6a). The name for this unit is based on the terminology of Watts (1947), who referred to these rocks as the Peldar Tor variety of 'porphyroid'. The type locality is to the south of the major fault in Whitwick Quarry (Carney, 1994; fig. 10), occupying the former site of Peldar Tor. The unit is poorly exposed outside the quarry, but is interpreted as a laterally extensive body, about 520 m thick, with sharply-defined contacts that are at least in part faulted. It is related to the less brecciated porphyritic dacite ('Peldar Porphyroid' of Jones, 1926) of Bardon Quarry, farther to the south (Carney and Pharaoh, 2000). Although the best *in situ* exposures of the unit are confined to Whitwick Quarry, impressive specimens can be examined in the walls and grounds of the Mount St Bernard Monastery (458163).

In Whitwick Quarry the Peldar Dacite Breccia is juxtaposed against other components of the Whitwick Complex by a major fault. This structure consists of brecciated fault-rock tens of metres thick; a northerly downthrow (Fig. 1) is inferred from microfabric analysis of phyllonitic ductile shear zones coincident with the fault (Carney, 1994). The Peldar Dacite Breccia is typically devoid of stratification, but on the northeastern and southeastern lower levels of the quarry there are diffuse contacts between matrix-rich and matrix-poor breccia facies inclined steeply (70-50°) to the north-east; on correcting for the regional south-west dip, this would give an original subvertical orientation.

The Peldar Dacite Breccia has a heterogeneous lithology that consists of three components.

*Porphyritic dacite fragments* are essential, 'cognate' constituents of the Peldar Dacite Breccia. They vary in abundance, and in rare instances are not present at all, but in most exposures they comprise over 80% of the rock (averaging about 65%). The fragments range in size from about a centimetre (Fig. 6a) to over a metre, and though some are highly angular, many others have rounded to elliptical shapes as can be seen in some of the slabs set into the walls of Mount St. Bernard Monastery. Incurved embayments and cusped promontories characterize some of the larger and more irregularly shaped masses of porphyritic dacite; they resemble pillows, except that their margins are very sharp against the breccia matrix, with no obvious signs of marginal chilled rims. The porphyritic dacite fragments have dark grey to black, fine-grained groundmasses which enclose large (3-7 mm) creamy white euhedra or glomerophytic aggregates of plagioclase (comprising about 40% of the dacite) and equally large, rounded, phenocrysts of greenish grey quartz (about 10-15%). Their groundmasses have an unusual texture, which features numerous rounded, or rosette-like, microgranular clumps of strongly zoned quartz and feldspar (Fig. 5d). In the aphanitic matrix between these quartzo-feldspathic clumps there are finely disseminated iron-titanium (Fe-Ti) oxides, their abundance probably contributing to the dark grey or black appearance of the porphyritic dacite fragments.

*Quartz microdiorite fragments* are medium-grained and

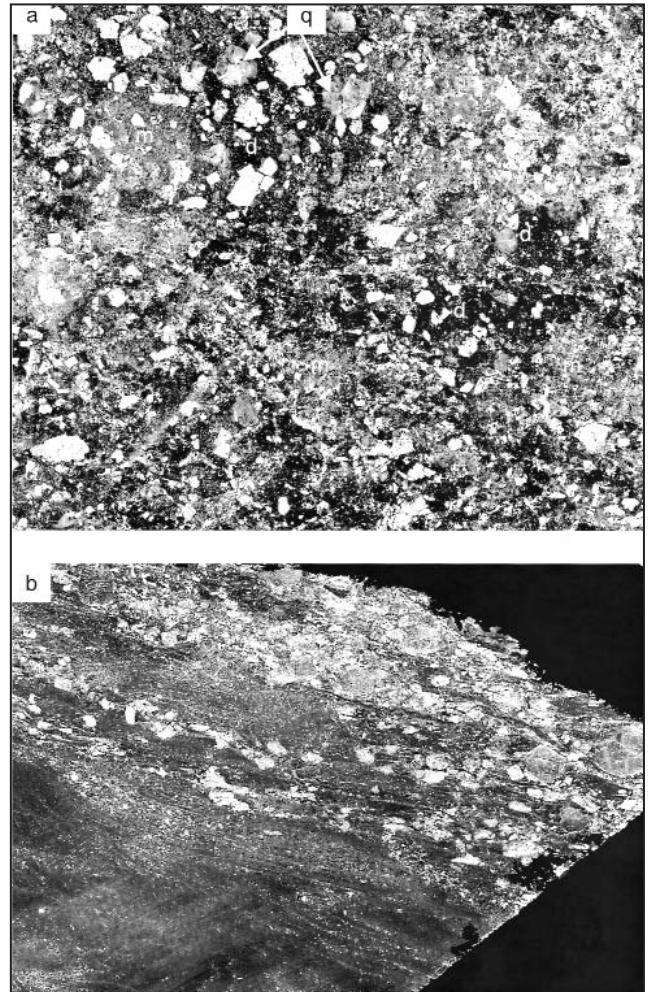
pale green, and generally measure from a few millimetres to several centimetres in size (average about 50 mm). Most are rounded or subangular, and have discoid to subspherical or ovoid shapes. They are enclosed within both the breccia matrix and the porphyritic dacite fragments and commonly comprise a few per cent of the rock, although in some parts of breccia they are the only type of fragment that is present. In thin sections quartz microdiorite fragments consist of abundant, stubby, hypidiomorphic plagioclase crystals which are part-enclosed by quartz crystals or aggregates, some with euhedral terminations. Interstitial albite, leucoxenized oxide minerals, and secondary chlorite-epidote aggregates, are the other constituents.

The matrix of the Peldar Dacite Breccia is a dark grey, fine- to medium-grained fragmental lithology (Fig. 6a), speckled with small, granulated plagioclase and quartz crystals. It is mostly composed of oval to sliver-shaped clasts of turbid, oxides-rich aphanitic volcanic rock studded with quartzo-feldspathic micro-globules of 0.2 mm average diameter (Fig. 5e). The globules are locally attenuated into ellipses by the penetrative cleavage, but where undeformed they exhibit a fibrous, radiating crystal growth (Fig. 5f) typical of spherulitic crystallization.

Intricate contact relationships are seen at the margins of a raft-like sedimentary inclusion, just over 100 m long, which is completely enclosed within the Peldar Dacite Breccia in the central part of Whitwick Quarry (Fig. 1). The sedimentary rocks consist of maroon to purple volcanoclastic siltstone exhibiting highly contorted and slumped lamination. Their contact with the Peldar Dacite Breccia is a complex zone of mingling, with coarse-grained lenticles of the crystal-rich breccia matrix in the siltstone, and rafts and wisps of maroon siltstone enclosed within the adjacent dacite breccia matrix (Fig. 6b). On a higher quarry level, the siltstone of the rafts passes into a grey, medium- to coarse-grained volcanoclastic rock, that strongly resembles the matrix component of the Peldar Dacite Breccia.

The Peldar Dacite Breccia is not obviously part of any lithological association, comparable to the Grimley/Cademan and Sharpley/Swannymote groupings, but possible 'extrusive' equivalents have been identified. One significant occurrence was noted on the northern face of Whitwick Quarry, where screens of Peldar Dacite Breccia between 2 and 8 m thick are interleaved within the 28 m thick succession of volcanoclastic rocks ('v' in Fig. 1), described earlier, sandwiched between Grimley Andesite and Sharpley Dacite. A rather more isolated exposure, in fields south-east of Whitwick Quarry (Loc. 12), shows volcanic breccia containing abundant dark-matrix feldsparphyric blocks, up to 0.4 m across, with margins recessed-in to the matrix. Some of the smaller volcanic clasts in this rock have globulose areas that are identical to the micro-spherulitic textures described above for the Peldar Dacite Breccia matrix. Other clasts are more coarsely textured, with strikingly well developed, rosette-shaped, quartzo-feldspathic spherulites.

**Interpretation:** The most significant features of the Peldar Dacite Breccia are its all-pervasive fragmentation and the textural variations between the matrix and the enclosed fragments or irregular masses of porphyritic dacite. The latter are particularly abundant, and are regarded as being cognate, in the sense of representing the remnants of the dacite magma that had disintegrated to form the breccia. The groundmasses of the porphyritic dacite fragments are texturally similar to rocks that have been cooled under hydrous conditions, permitting limited crystallization to occur (e.g. Murphy and Marsh, 1993). Possibly this crystallization regime



**Figure 6.** Lithologies of the Peldar Dacite Breccia from Whitwick Quarry.

**a.** Cut slab (JNC531), with contrast enhanced to show dark-toned areas representing scattered, cognate fragments of porphyritic dacite (d) with phenocrysts of euhedral plagioclase and rounded, radially fractured quartz (q). Paler-toned matrix (m) consists of spherulitic-textured dacite slivers (Fig. 5e) with smaller crystals; specimen is 95 mm wide.

**b.** Junction between Peldar Dacite Breccia and the raft of volcanoclastic siltstone in the centre of Whitwick Quarry (JNC550). Lenticles of crystal-rich material from the breccia are intercalated within darker-toned siltstone, the latter decreasing in abundance towards the top of the picture (closer to the main breccia mass); field of view is 80 mm wide.

resulted in the incipient development of a spherulitic texture, seen as the microgranular clumps in Figure 5d. The spherulitic textures of the small, sliver-shaped fragments that constitute the matrix of the breccia are interpreted as representing a greater extent of recrystallization within the matrix of the Pedlar Dacite Breccia compared to the textures of the porphyritic dacite fragments (compare Figs. 5d and e).

As previously noted, Lofgren (1971) has suggested that spherulites would be favoured in devitrifying volcanic glass that cooled relatively slowly, in the presence of elevated temperatures and circulating heated waters. It is therefore possible that the Pedlar Dacite Breccia is comparable to certain intrusive hydroclastic breccias in submarine volcanic arc sequences in California (Hanson, 1991). Such lithologies represent large volumes of silicic magma that were subjected to complete, non-explosive *in situ* disintegration when they were quenched within a carapace of wet sea-floor sediments. Kokelaar (1986) has described some of the processes that may operate in such environments. In the case of the Pedlar Dacite Breccia, these could include: *cooling contraction granulation*, in response to thermal stresses produced during rapid and uneven chilling, which would have shattered the dacite and its crystals, and *dynamic stressing*, which would have been exerted upon the chilled surfaces of the dacite masses by movements of the magma within the developing pillows. Acting in combination, these processes would have broken up the more rapidly cooled parts of the magma, thereby contributing the abundant spherulitic glass slivers seen in the breccia matrix. The lack of jigsaw fits between the porphyritic dacite fragments indicates that movements exerted during emplacement of the dacite largely destroyed *in situ* brecciation textures.

The margins of the sedimentary raft at Whitwick Quarry indicate that the breccia matrix and the host siltstone were both in an unconsolidated state, when disaggregation occurred; this is further support for interpretation of the Pedlar Dacite Breccia as a type of peperite, or hyaloclastite breccia. Magma emplacement within a carapace of unconsolidated wet sediment would provide the insulation and also the confining pressures (see Discussion below) necessary for relatively slow cooling, permitting cryptocrystalline or spherulitic crystallization styles to develop. Magma-wet sediment interactions could also explain the angular to incurved, cusped boundaries of the larger porphyritic dacite masses, some of which may be the kernels of original pillows. The quartz microdiorite fragments are xenoliths of a previously crystallized, hypabyssal intrusive rock, perhaps part of an earlier magma chamber through which the Pedlar dacitic magmas rose. The original form of the dacite magma body cannot be determined due to the structural complexity of this area, but a partly emergent dome or cryptodome is suggested in Figure 10.

The breccia at Locality 12 is tentatively

interpreted as a marginal, completely disaggregated facies of the Pedlar Dacite Breccia, either a peperite or a subaqueous debris flow. The developments of Pedlar Dacite Breccia within the volcanoclastic screen in the northern part of Whitwick Quarry may similarly argue for a local extrusive component of this magmatism, compatible with the activity of a partly emergent dome. The origin of these screens is largely obscured by deformation, however, and it is equally possible that they are intrusive peperites, representing tongues of dacitic magma that extended into, and reacted with, an unconsolidated sedimentary host.

### Proximal volcanoclastic strata of the Charnwood Lodge Volcanic Formation

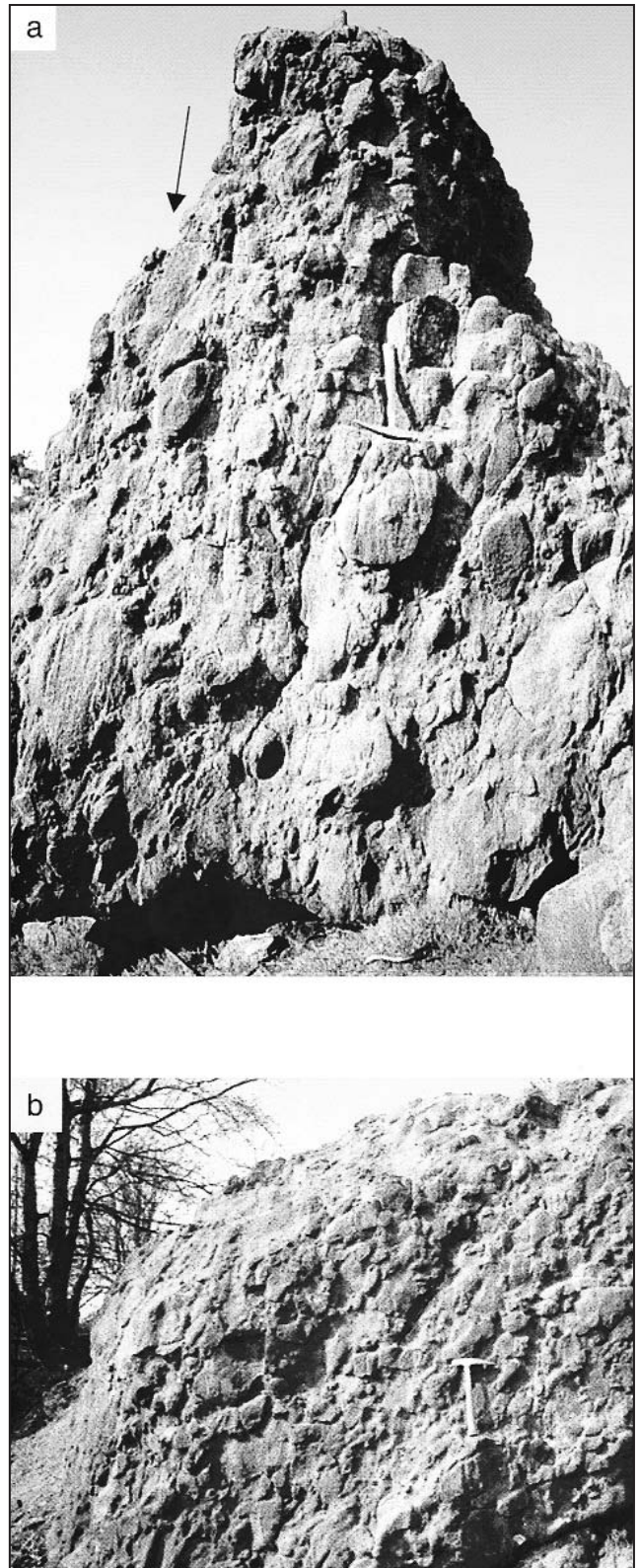
This formation includes the Cademan Breccia and Swannymote Breccia members, which were described earlier. Here are described the undivided part of the formation, as well as the *Benschliffe Breccia Member* and *St. Bernard Tuff Member*.

The undivided part of this formation consists of interbedded tuffs, lapilli-tuffs and breccias (Fig. 1). The Gunhill Rough (Loc. 13) and Charnwood Tower (Loc. 14) exposures show a diverse succession of poorly sorted breccias intercalated with thinly stratified lithic-lapilli tuffs and coarse-grained lithic-crystal tuffs (Fig. 7). At Gunhill Rough, the upper breccia bed is normally graded, with the larger subrounded andesite blocks (up to 0.7 m size) near the base. In contrast, size sorting in the lower breccia features blocks concentrated into discrete layers above the basal part of the bed, defining a parallel-stratified internal structure. The intervening tuffs include layers that show both normal and inverse grading. In thin section, a block from a Gunhill breccia has a fine-grained intergranular ground-mass texture, with abundant small plagioclase laths and microlites arranged in fluxional orientation; it also contains up to 30% of strongly zoned and generally euhedral plagioclase phenocrysts, rare quartz microphenocrysts and small, rounded inclusions of microgranular diorite. The breccia matrix contains much recrystallized, fine-grained quartzo-feldspathic material, but the outlines of plagioclase crystals and angular slivers of granular-textured microdiorite remain visible. Angular, microcrystalline-textured lapilli also comprise many of the lithic clasts in the parallel stratified and graded beds of Gunhill Rough.

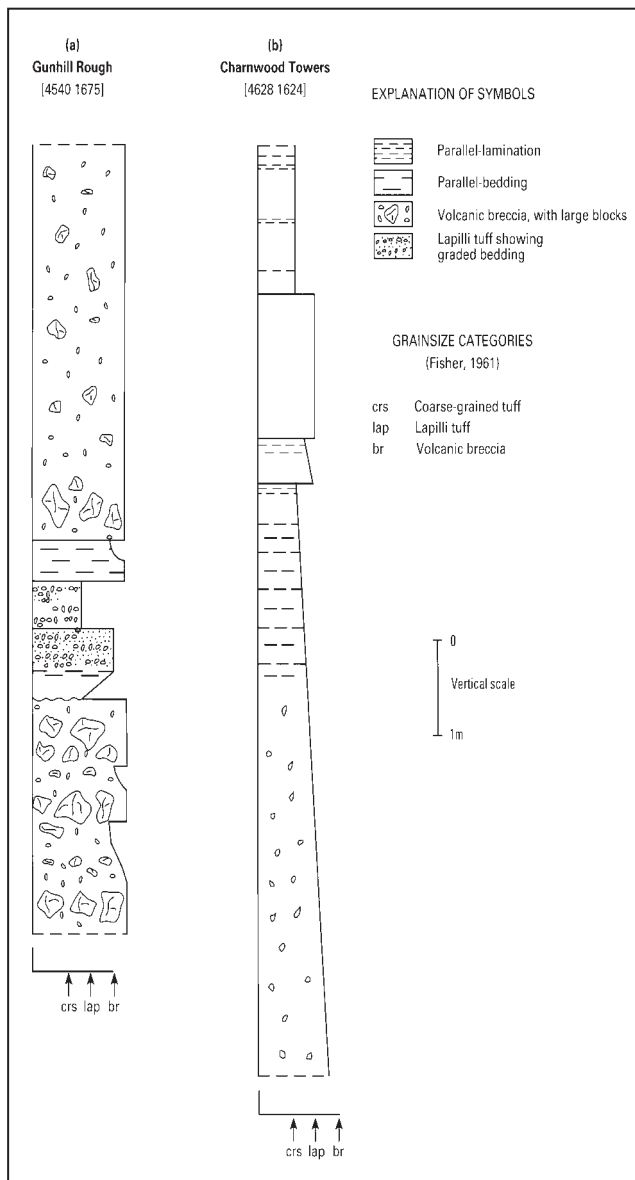
The middle to upper part of the Charnwood Lodge Formation (Fig. 1) includes, at the Charnwood Lodge Nature Reserve SSSI, the prominent knoll (Loc. 15) which is the classic 'Bomb rocks' locality of Watts (1947). These rocks contain abundant blocks with ovoid to rectangular or diamond shaped outlines, and the lithology is a volcanic breccia in most modern classifications (Fisher, 1961; Fisher and Schmincke, 1984). The example shown in Figure 8a contains about 60 per cent of andesite blocks, up to 1 m size (average

about 0.6 m), some being angular but others, more abraded, featuring rounded-off corners. This breccia appears to be unbedded, and hence similar to many parts of the Cademan Breccia Member; however, within a few tens of metres of the knoll it shows variations in clast to matrix proportions, and in clast size. For example, strongly clast-supported breccias, containing abundant closely-packed but relatively small blocks (Fig. 8b), are seen along the northern margin of the exposure. The ‘bomb rocks’ may therefore exhibit a very coarsely developed type of size grading of the clasts, which in turn suggests it forms part of a thickly stratified sequence.

Chemical analysis shows that a typical block sampled from a breccia at the Gunhill Rough locality is an andesite, with 57.6% SiO<sub>2</sub>. Some diversity of clast lithologies within the Charnwood



**Figure 8.** Volcanic breccias of the Charnwood Lodge Volcanic Formation exposed at the ‘Bomb rocks’ locality, Charnwood Lodge Nature Reserve (463157) **a.** Breccia at the main knoll, showing large subangular andesite or (low-silica) dacite blocks, slightly flattened in the plane of the subvertical Acadian (Silurian-Devonian) cleavage, the orientation of which is given by the arrow. **b.** A breccia, about 40 m north-east of the main knoll, with smaller, more closely-packed blocks.



**Figure 7.** Measured sections showing lithological variations that produce stratification in the undivided part of the Charnwood Lodge Volcanic Formation.

Lodge Formation is suggested by a further analysed block, from the breccia outcrop across the fault to the east of Whitwick Quarry (Loc. 16); on grounds of chemistry at least, this is a rhyolite, with 76.5 % silica (unpublished BGS analyses, adjusted for volatiles content). Two analysed samples of breccia matrix from the Charnwood Lodge area showed silica contents of between 60 and 65% (Moseley and Ford, 1989), in keeping with the transitional andesite/dacite compositions inferred for most of the blocks in the Charnwood Lodge Formation.

The top of the Charnwood Lodge Formation is exposed at Warren Hills ridge (Loc. 17). Here the unit has fined down, to a succession of massive to stratified, coarse-grained tuffs and lapilli-tuffs, with only subordinate intercalations of matrix-supported breccia. The stratigraphically highest lapilli-tuff beds contain sporadic, ellipsoidal fragments of laminated volcanoclastic siltstone or mudstone. These fragments become larger and more numerous in beds just below the volcanoclastic sandstones of the Bradgate Formation, developing into a sediment-raft breccia in which slivers of pale grey volcanoclastic siltstone, between 2 and 10 centimetres thick, show contortion and folding in a coarse-grained, crystal-rich volcanoclastic matrix.

**The Benscliffe Breccia Member** occupies the base of the Maplewell Group, and when traced around the nose of the Charnian anticline it thickens towards the northwest. In the study area the member is lithologically indistinguishable from the undivided part of the Charnwood Lodge Formation (Table 3), with which it is considered to merge (Fig. 1). On the southeastern flank of Flat Hill, the outcrop mapped as 'Benscliffe Agglomerate' by Worssam and Old (1988) consists of at least 100 m of interstratified lithic-lapilli tuff and volcanic breccia. Subtle variations in clast size and abundance suggest that several fining upward cycles may be present in this succession. For example, at Hanging Stone (Loc. 18), the lower part is a breccia containing about 40% of angular to subrounded clasts of grey, feldsparphyric andesite. There is then an upward gradation into about 5 m of lapilli tuffs. A further exposure, several metres stratigraphically higher than this, shows a similar passage from volcanic breccia at the base to lapilli-tuff, with only sporadic angular lapilli and blocks (5-10 cm size), at the top. Younger beds still, to the southwest (467159), feature breccias with subangular, cream-weathering, feldsparphyric andesite blocks up to 0.5 m across, which passes upwards into thickly bedded lithic-lapilli tuff.

**The St. Bernard Tuff Member** was named by Carney (1994), and consists of about 100 m of stratified, fine- to coarse-grained tuffs occurring in the vicinity of Mount St. Bernard Monastery (Loc. 19). Local bedding dips suggest that this unit may be contained within a syncline or basin, which closes to the northwest of the Monastery. The beds

immediately below the member are exposed in the Monastery grounds to the northeast of the crags at Calvary; they are unusual for this region in consisting of pale grey, thinly bedded to laminated volcanoclastic siltstone. They are overlain by a homogeneous, pale grey, massive lithic-crystal tuff, or lapilli-tuff, which at c. 60 m thick forms the main part of the member. On fresh surfaces this rock has abundant large white or pink feldspar crystals, etched out by weathering. Thin sections show that in addition to these plagioclase crystals, the tuff contains lapilli of microcrystalline andesite or dacite. The succession is capped by 3 m of grey-green crystal-lapilli tuff containing about 40 per cent of pinkish grey plagioclase feldspar crystals; a thin section showed common lapilli of microcrystalline dacite with possible relict vesicles, although most textural features are hidden by secondary recrystallization. Crags a few metres northeast of the Abbey wall show that the stratigraphically youngest part of the St Bernard Tuff Member consists of stratified, feldspar-rich crystal tuff which passes up to thinly bedded, repetitively graded, crystal tuff.

**Interpretation of the Charnwood Lodge Volcanic Formation.** With the exceptions of the Cademan and Swannymote breccias, described earlier, this formation is characterised by thickly bedded breccias and lapilli-tuffs. The low degree of sorting in the stratified breccia component, together with the occurrence of angular or subangular blocks of variable size within a coarse-grained matrix, are features found in mud-poor, cohesionless debris flows, or the 'gravelly high-density turbidity currents' of Lowe (1982). They imply very rapid transport and deposition with only localised abrasion, or transport over limited distances, with abrasion localised at the corners of blocks due to collisions with other clasts. The parallel bedding and variously graded lapilli-tuffs intercalated with the breccias (Fig. 7) are better-organised. They resemble the tractional division that is typically present at the base or the top of cohesionless debris flow deposits considered by Postma *et al* (1988), but are also akin to the deposits of residual, high-density sandy turbidites that have by-passed areas of breccia deposition (Lowe, 1982).

Cohesionless debris flows are characterised by a granular matrix with very little mud component; however, the occurrence of entrapped mud- or fine-ash-grade material in at least some of these Charnian lithologies cannot be ruled out. Such constituents would be difficult to detect now, because of the high degree of recrystallization that these rocks have suffered. It is noteworthy that only small proportions of these fines would be required for an alternative interpretation of some fragmental lithologies as the derivatives of cohesive debris flows, or mud-rich debris flows (Hampton, 1975). In the Charnian context these deposits, being rich in volcanic detritus, would further qualify as the representatives of 'lahars', which are essentially volcanoclastic debris

flows (e.g. Cas and Wright, 1987). Lahars can form at all scales, but they are commonly generated by large-scale collapse of the volcano flanks, as shown in Figure 10, and they consequently sample a more lithologically diverse source region than do dome-derived block and ash pyroclastic flows. This may explain some of the analysed blocks that indicate a relatively large compositional range of included detritus in the Charnwood Lodge Formation.

Some sedimentary debris flows form within subaqueous deltas that receive material from a steeply sloping, emergent hinterland (e.g. Kim *et al.*, 1995; Postma *et al.*; 1988). No criteria have yet been found to either support or militate against a waterlain origin for the Charnian material. However, the volcanoclastic sequences that both underlie (Blackbrook Group) and succeed (Bradgate Formation) them are thought to be entirely subaqueous (Moseley and Ford, 1989). Thus the most likely environment for the Charnwood Lodge Formation is that of a subaqueous volcanoclastic apron deposited adjacent to a Charnian volcanic centre.

The most proximal rocks of the Charnwood Lodge Formation are the Cademan and Swannymote breccias, and as discussed these probably represent the deposits of primary pyroclastic flows derived from dome-collapse eruptions. According to Cas and Wright (1991), pyroclastic flows upon entering water may split into separate components. The fine ashy material, would be separated at the air-water interface, either as eruption clouds or low-density overflows, and might be represented in the more distal-facies rocks of the Beacon Hill Formation (Fig. 1). The dense-clast-rich part may continue to run out as a subaqueous flow of pyroclastic debris. It is therefore conceivable that some of the interstratified volcanic breccias and tuff sequences of the Charnwood Lodge Formation may represent the resedimented, syn-eruptive products (McPhie *et al.*, 1993; p.98) of 'Cademan' type dome-collapse events.

The thickness and fining upward evolution of the St Bernard Tuff Member are features that recall the graded, predominantly coarse-grained, pyroclastic sequences found in some young volcanic arcs. For example, Fiske and Matsuda (1964) describe from the Miocene of Japan an analogous sequence, the Tokiwa Formation, consisting of a very thick (45 m) unbedded dacitic lapilli tuff capped by 7-15 m of parallel-stratified and multiply-graded turbidite-facies tuffs composed of sand-size ash and crystal fragments. The origin of the Tokiwa Formation is enigmatic, but has been linked to mechanisms associated with subaqueous pyroclastic eruptions (Cas and Wright, 1991).

**Geochemistry of the igneous rocks**

Pharaoh *et al.* (1987) used geochemistry to determine the tectonic setting of the Charnian igneous rocks. Their studies showed that typical

compositions have a strong subduction zone signature and are comparable to magmas erupted from modern volcanic arcs, including island arc chains, of a type founded upon oceanic or thin continental crust. In this section, geochemistry is mainly used to describe the compositional range of the Whitwick Volcanic Complex and Charnwood Lodge Volcanic Formation, and to compare and evaluate the relationships between these rocks, particularly those of the two genetic associations (Table 1). Representative chemical compositions are shown in Table 2; the full data set consists of only 20 samples, so the following discussion should not be interpreted as an in-depth geochemical treatment of these rocks.

The samples collected from northwestern Charnwood Forest are plotted on the TAS (total alkalis vs silica) diagram (Fig. 9a), which shows that with a single exception, these rocks encompass the andesite, dacite and rhyolite compositional fields. The most silica-rich compositions, with rhyolites represented, are restricted to the porphyritic Sharpley/Swannymote association. It should be noted that the TAS diagram may be of doubtful value for classifying these fine-grained rocks, because it is based on elements whose relative proportions are likely to be affected by secondary processes. For example, Table 2 shows wide variations in the contents of Na<sub>2</sub>O and K<sub>2</sub>O, the latter in particular being anomalously low in some samples, as is the related trace element, Rb. The

	Grimley Andesite breccia*	Grimley Andesite dyke	Dacite, in Cademan VBM*	Dacite, in Peldar DB*	Sharpley Porphyritic Dacite	Rhyolite, in Swannymote BM*
sample	JNC536	JNC548	JNC528	JNC531A	EM1	JNC499
NGR	447162	447159	434168	483158	448171	447163
%						
SiO <sub>2</sub>	55.95	61.01	64.57	67.58	72.11	76.73
TiO <sub>2</sub>	0.52	0.43	0.39	0.38	0.36	0.26
Al <sub>2</sub> O <sub>3</sub>	16.85	14.74	13.89	13.31	13.15	12.09
Fe <sub>2</sub> O <sub>3</sub> t	9.21	7.47	6.31	5.45	4.11	1.94
MnO	0.24	0.15	0.12	0.07	0.09	0.02
MgO	5.38	3.79	3.54	2.81	2.36	0.57
CaO	2.09	5.27	3.95	4.18	0.49	0.78
Na <sub>2</sub> O	2.95	3.26	2.96	2.46	7.22	6.19
K <sub>2</sub> O	2.39	0.24	1.73	0.67	0.09	0.25
P <sub>2</sub> O <sub>5</sub>	0.06	0.05	0.05	0.06	0.07	0.06
loi	4.14	3.33	2.27	2.17	nd	0.53
ppm						
Ba	865	97	489	250	60	68
Ce	8	12	7	16	28	15
Co	nd	26	22	16	7	4
Rb	49	nd	nd	12	2	2
Sr	40	75	70	78	55	73
V	368	173	165	97	38	35
Y	19	20	16	23	32	19
Zr	59	55	44	62	77	52
La	4	3	3	8	8	8
Nd	6	5	9	9	12	9

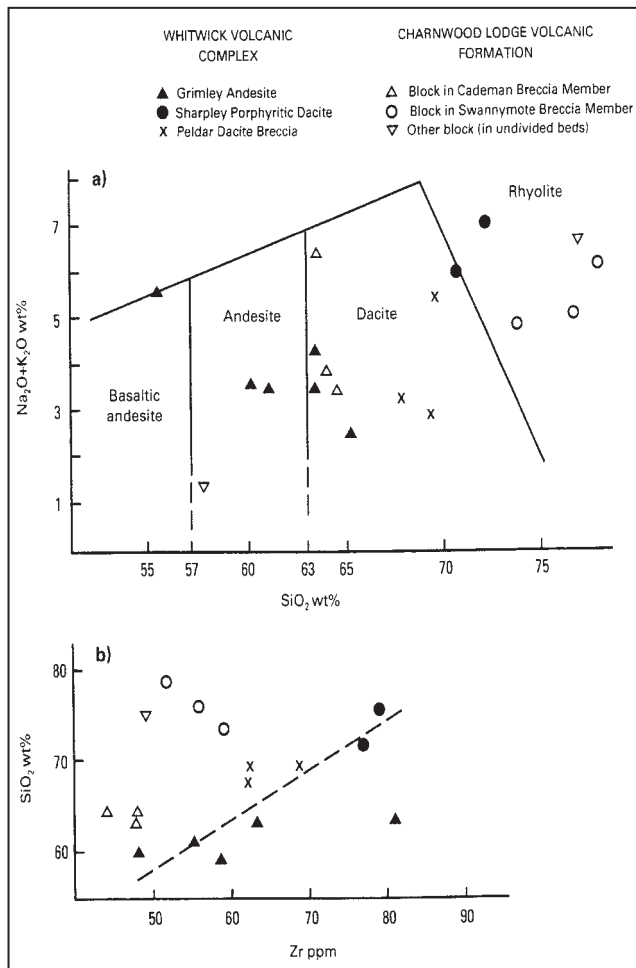
**Table 2.** Representative chemical compositions of rocks from the Whitwick Volcanic Complex and Charnwood Lodge Volcanic Formation (see Table 1 for lithostratigraphy). Analysed by XRF at BGS, except EM1 by P. C. Webb. \* — sample is from a block or fragment within a breccia

causes of these variations are attributed to element mobility, which can occur in a variety of environments. For example, in the late-magmatic environment hot rocks may chemically interact with the vapour phase of the magma, or with meteoric water or seawater. Similarly, in the immediately post-emplacment environment relatively slowly cooled rocks, such as the matrix and clast components of pyroclastic deposits, can also suffer complex element exchanges due to varying degrees of hydration (Jørgensen and Holm, 1998). Finally, element mobility is common during metamorphism and could have accompanied the episode of greenschist-facies recrystallization in these Charnian rocks.

Although the TAS diagram may not reflect primary magmatic element abundances, and must be viewed with caution as an aid to rock classification, it nevertheless does portray the

generally close chemical equivalence of the lithological pairings that constitute the two genetic associations. The two fragmental components of these associations (Cademan Breccia and Swannymote Breccia) are nevertheless more silicic than their putative parental material (respectively the Grimley Andesite and Sharpley Dacite). The reasons for this discrepancy, discussed further below; may lie in post-magmatic chemical exchanges of the type already mentioned, and cannot be evaluated without a more rigorous geochemical study.

For interpreting geochemical relationships, more reliance is generally placed on the relatively 'immobile' High Field Strength Elements (HFSE), also known as Incompatible Trace Elements (ITEs), which are resistant to the effects of low-temperature alteration and metamorphism (e.g. Pearce and Cann, 1973). Of these, Zr is relatively incompatible with most crystallizing phases (excluding zircon, see below) in a melt and consequently, in certain volcanic sequences, it has been used as an index of differentiation. In this case Zr abundances should increase in the more fractionated rocks, in the same way that  $\text{SiO}_2$  generally does, but without random variations caused by secondary element redistribution. Plotting these two elements together (Fig. 9b) is a simple way of testing whether Zr and  $\text{SiO}_2$  both act as reliable differentiation indicators, because if they do a linear trend should result. This plot shows that a reasonably linear trend can be drawn between the various components of the Whitwick Complex, with Zr abundances increasing in line with  $\text{SiO}_2$ , from the Grimley Andesite via the Peldar Dacite to the Sharpley Dacite. The breccia blocks of the two associations plot off this trend, with lower Zr than their putative parental igneous rocks in the Whitwick Volcanic Complex. It is possible that both the silica and Zr distributions of the breccia blocks in Figure 9b could be explained by invoking element gains (e.g. silica) or losses (e.g. zirconium) in the immediate post-magmatic environment, as discussed earlier. An alternative possibility is that the breccia blocks were derived from magmas that were slightly less evolved (in terms of their Zr contents) than those supplying the Grimley Andesite or Sharpley Dacite. This would be a complication to the model of Figure 10, and would imply that multiple generations of magma have occurred. Finally, it is possible that the Zr contents were lowered in the syn-magmatic environment due to the crystallisation of zircon. This would impoverish Zr in the more 'evolved' differentiates that here are represented by the blocks of the Cademan and Swannymote breccias. Although such zircon fractionation cannot be ruled out, it is a fact that no zircons have been observed in these particular Charnian rocks; for example, several kilograms of Sharpley Dacite were recently crushed for geochronological analysis (work in progress by BGS and NIGL), and not one zircon grain was obtained.



**Figure 9.** Major and trace element variations in the rocks of the study area. Compiled from BGS data and two analyses provided by P. C. Webb.

**a.** Plot of total alkalis vs silica, re-calculated on a volatiles-free basis, showing the compositional fields defined by Le Bas and Streckeisen (1991).

**b.** Plot of silica vs zirconium; dashed line shows the 'best fit' for the variation trend between rocks of the Whitwick Volcanic Complex.

**Discussion and review of Charnian igneous processes**

Precambrian magmatism centred upon north-western Charnwood Forest has produced two fundamentally different, but nevertheless closely linked rock sequences. The processes that were involved are summarised in Figure 10, which views the igneous rocks of the Whitwick Volcanic Complex as the remnants of a magmatic feeder zone that contributed material to a flanking sequence represented by the Charnwood Lodge Volcanic Formation (Fig. 10). Although the origin of these rocks remains obscure, none are likely to be unique in the geological record and analogies for some of them may be sought in the diverse magmatic products of modern volcanic arcs. W. W. Watts (1947) used this approach when he presciently suggested that certain fragmental Charnian rocks were comparable to deposits formed by the catastrophic 1902 eruptions of Mont Pelée, some being originally ‘...of the nature of the “spine” intruded

and extruded in the later stages of the eruption of Mont Pelee in 1902, the breaking up of it, such as then occurred, would give rise to aggregates of great “bombs”...’.

Problems with interpreting these rocks are partly due to the wide compositional range, and consequent diversity of physical properties, exhibited by the Charnian magmas. Such variations had an influence on emplacement mechanisms and, as modelled in Figure 10, the environments in which the magmas consolidated were correspondingly diverse and ranged from subaerial, to partly or wholly ‘intrusive’ in the case of the Sharpley/Swannymote Association and the Peldar Dacite Breccia. The latter have the most silicic compositions, possess abundant phenocrysts, and in consequence they would have formed viscous magmas. This may explain why they largely failed to reach the surface and instead consolidated as intrusive sheets or cryptodomes. The porphyritic dacites were therefore not important suppliers of volcanic material to the part of the Charnwood Lodge Volcanic Formation that is now exposed.

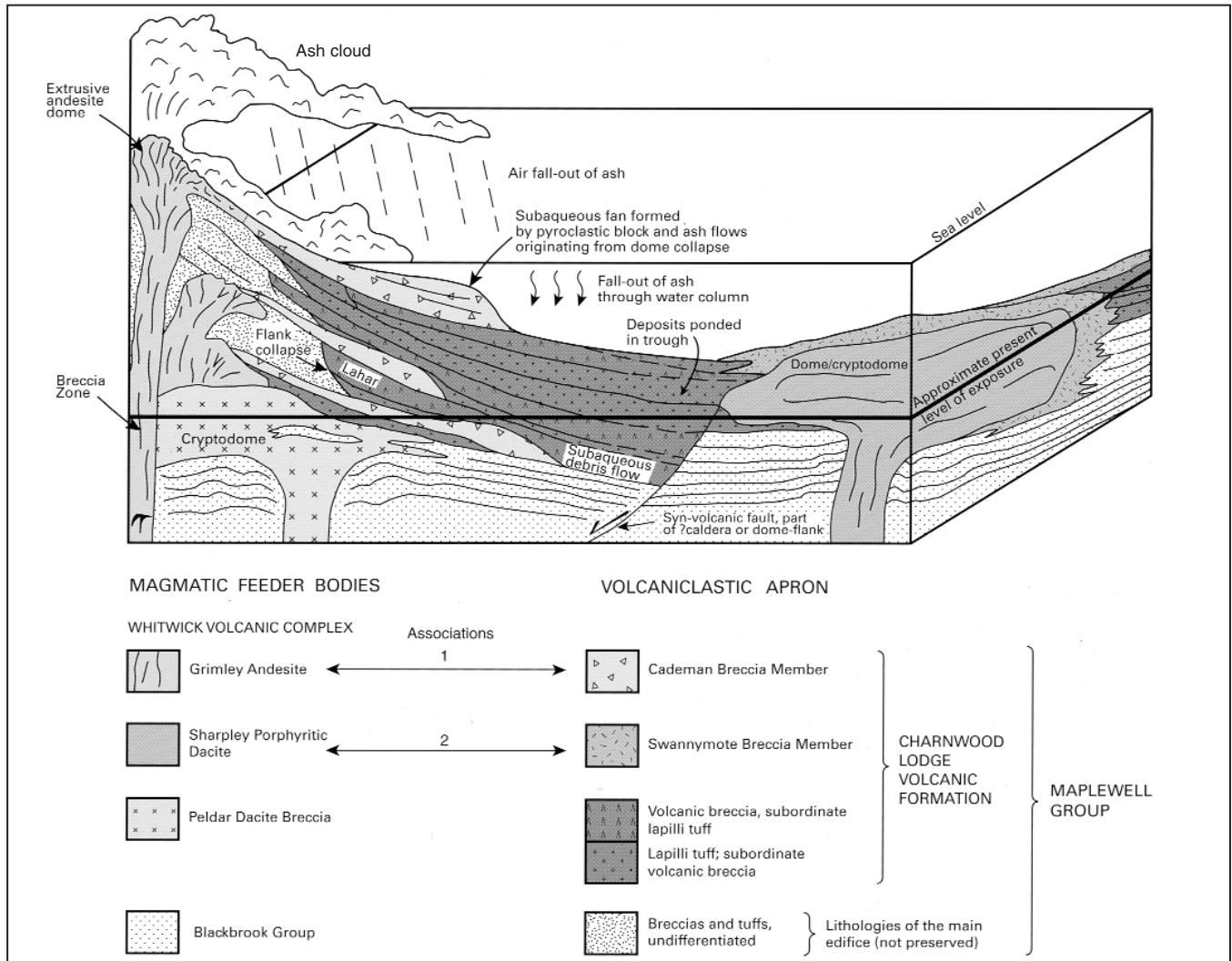


Figure 10. Simplified model showing the range of volcanic and depositional processes likely to have been occurring during the late Precambrian active phase of northwest Charnian magmatism. Note that this diagram is not intended to explain all of the field relationships depicted in Figure 1.

UNIT	DESCRIPTION	INTERPRETATION
<b>WHITWICK VOLCANIC COMPLEX</b>		
GRIMLEY ANDESITE	Grey-green, smooth-surfaced, microcrystalline, sparsely to moderately porphyritic (plagioclase, hornblende, minor quartz). Compositional range: high-silica andesite to low-silica dacite. Massive in places, but more commonly highly brecciated, with jigsaw fit of fragments. Up to 940 m thick.	High-level intrusion, possibly the root-zone of a subaerial extrusive dome affected by multiple fracturing during extrusion and/or inflation
SHARPLEY PORPHYRITIC DACITE	Pale grey to lavender, rough-surfaced, microcrystalline and highly porphyritic (plagioclase-quartz). Compositional range: dacite verging to rhyolite. Massive, locally columnar-jointed. Possible marginal breccia or pseudo-breccias. Up to 600 m thick	High-level intrusive sheet or cryptodome. Emplaced largely below sea-floor and marginally brecciated due to reaction with partly unconsolidated sediment
PELDAR DACITE BRECCIA	Dark grey to black, pervasively brecciated, with rounded to cusped margins masses of highly porphyritic (plagioclase-quartz) dacite in a grey, medium-grained, clastic matrix full of spherulitic-textured glassy fragments. Up to 520 m thick.	Cryptodome, emplaced at shallow depths below sea-floor and extensively disaggregated due to reaction with enclosing carapace of unconsolidated sediment.
<b>CHARWOOD LODGE VOLCANIC FORMATION</b>		
CADEMAN VOLCANIC BRECCIA MEMBER	Very coarse, poorly sorted volcanic breccias packed with angular to subangular blocks of microcrystalline, low-silica dacite. Outsized blocks and jigsaw-fit textures locally observed. Structureless, apart from variations in clast to matrix proportions. Up to 450 m thick.	Merapi-type block and ash pyroclastic flows, derived from collapse of 'Grimley' type domes. Possible subaqueous deposition on pyroclastic fan and/or 'ponded' in caldera.
SWANNYMOTE BRECCIA MEMBER	Very coarse, poorly sorted volcanic breccias, with angular, rounded or cusped margins blocks of microcrystalline to spherulitic, porphyritic (plagioclase-quartz) rhyolite. Locally with admixed sediment or sedimentary clasts. Up to ?200 m thick.	Ash and block pyroclastic flows and peperite breccias derived from marginal fragmentation of 'Sharpley' domes or cryptodomes.
BENSCLIFFE BRECCIA & UNDIVIDED BEDS	Thickly stratified and locally graded sequences of andesitic volcanic breccia and parallel-stratified lithic-crystal-lapilli tuff. Fines up to overlying Bradgate Formation. 900-1000 m thick locally.	Cohesionless and cohesive debris flows of volcanoclastic material; includes deposits of lahars and re-sedimented 'Cademan'-type pyroclastic flows. Probable subaqueous depositional environment
St BERNARD TUFF MEMBER	Mainly composed of massive, lithic-crystal tuff and lapilli-tuff. Fines up to a capping of thinly-bedded graded crystal tuff. About 100 m thick.	? Deposit of major subaqueous pyroclastic eruption

**Table 3.** Summary of the main lithological features and interpretations of the rocks in the study area.

Their emplacement would have both displaced and dewatered the host sediments, however, producing a rigid platform on which the emergent andesitic centres of the Grimley/Cademan Association were built.

The term 'intrusive' is used advisedly for the Peldar and Sharpley rocks, since as noted they were shallowly emplaced, into a column of unconsolidated wet sediments. Physical interactions between magma and sedimentary host occurred on a massive scale in order to cause the pervasive disaggregation that is such a feature of the Peldar Dacite Breccia. In this condition, the breccia would have been capable of secondary flowage, and could have back-intruded its host, to form the possible peperite-breccia layers interbedded with the volcanoclastic rocks in Whitwick Quarry. The Sharpley Porphyritic Dacite is by contrast a largely homogeneous lithology, although it does show marginal brecciation and clearly contributed blocks to the adjacent Swannymote Breccia Member. Limited intermingling between magma and wet sediment accounts for some of the lithologies at

Swannymote Rock, but the consolidated state of the sediment incorporated at Ratchet Hill suggests that the heat of dacite intrusion had dewatered parts of the sedimentary substrate. The Sharpley magma was therefore able to solidify as a relatively coherent body, perhaps an intrusive sheet or cryptodome.

The shallow-depth intrusive environment of the Sharpley/Swannymote Association and the Peldar Dacite Breccia may have produced vesicular or pumiceous lithologies, due to the release of exsolved gases under conditions of low confining pressures. The absence of such features indicates suppression of vesiculation upon chilling, in favour of spherulitic crystallisation, and may suggest that the magmas had been slowly degassed during their uprise. Alternatively, it is possible that in spite of the relatively shallow level of intrusion, the confining pressures were still high enough to prevent gas escape. In the Charnian context, there are no reliable indicators (e.g. fossils) for estimating either the water or sedimentary overburden depths that would have influenced the confining pressure. In a

case study on Permian-age volcanics by Hunns and McPhie (1999), however, it was suggested that for rhyolitic magmas of average water content (about 3%) a combination of 200 m water depth and a sedimentary thickness in excess of 400 m was necessary to suppress explosive vesiculation upon emplacement. Other examples previously discussed are from young (Mesozoic and Cainozoic) volcanic arcs whose activity is similarly well constrained. Such sequences include homogeneous silicic intrusions and marginal peperite breccias, some of which were emplaced within cryptodomes that were enclosed, and largely insulated, by a thick column of water-saturated sediments.

High-level intrusion of the Peldar and Sharpley porphyritic dacites is in keeping with the stratigraphical relationships, summarised in Figure 10, which indicate that these magmas encountered the upper parts of a volcanoclastic sedimentary sequence at least 2000 metres thick, represented by the Blackbrook Group. It is noteworthy that although the Blackbrook Group strata are composed entirely of volcanic material, sedimentary structures show that they are mainly of distal turbidite facies (Moseley and Ford, 1989; Carney, 1994) suggesting their deposition at some distance from the then-active volcanic centres. Formation of the igneous and proximal volcanoclastic rocks, discussed here, therefore followed a major change in the location of the Charnian magma source(s). This may have involved either a renewal of magmatism, or an extension of the magmatic axis into this region, and the causes may lie in readjustments to the plate-tectonic configuration of the Charnian arc as it entered the final stage of extrusive activity.

The Grimley Andesite and Cademan Breccia are interpreted here as the complementary products of dome-sourced eruptions (Fig. 10), and this is the main reason for comparing them with the recent activity on Montserrat (Young *et al.*, 1998). This style of Charnian volcanism may be further assessed by considering the nature of the extrusive dome material represented by blocks in the pyroclastic rocks of the Cademan Volcanic Breccia Member. In that unit, virtually all of the low-silica dacite blocks or lapilli consist of 'dense' (non-vesicular) lithologies, indicating that the causative eruptions were probably of 'Merapi' type (Williams and McBirney, 1979, p.152; see also discussion in Young *et al.*, 1998). Such activity is generally non-explosive, owing to the low content of gas remaining in the magma, and the block and ash pyroclastic flows result from gravity-collapse of the oversteepened flanks of the domes. This analogy suggests that the Grimley Andesite magmas may have been degassed during protracted cooling and high-level crystallization, causing microcrystalline and cryptocrystalline textures to develop, as the magma ascended and solidified. Peléan-type eruptions, on the other hand, are blast-induced and tend to involve more gas-rich, pumiceous material, although this is not always the case.

The Montserrat analogy proposed the Grimley/Cademan Association implies that dome extrusion occurred through subaerial volcanic edifices. At the present level of erosion, the rock sequences that might have formed these superstructures are not preserved (Fig. 10), which could suggest their prior removal by denudation. In modern intra-oceanic volcanic arcs, emergent andesitic edifices can occupy appreciable surface areas (about 70 km<sup>2</sup> for the active Soufrière Hills Volcano on Montserrat), but relative to many geological formations they are easy to erode and consequently difficult to preserve in the geological record. Erosion of the extinct Grimley edifice(s) may have continued until the Lower Cambrian marine transgression across central England, which has been timed at approximately Tommotian, or about 530-535 Ma, at Nuneaton, 40 km to the south (Brasier, 1992). The date of volcanic cessation is unfortunately not precisely constrained for the Charnian; it could be as old as about 600 Ma, or as young as 560 Ma (see discussion in McLroy *et al.*, 1998). These estimates allow a duration of 30-70 million years for this erosion.

The model in Figure 10 shows that some of the extrusive products of Whitwick Complex volcanism could be preserved in the Charnwood Lodge Volcanic Formation. The coarsely fragmental lithologies of that unit can broadly be interpreted as mass flows of volcanic debris, but exposures are generally too limited to determine their specific modes of origin. It is nevertheless possible that lahar deposits, in part triggered by volcano-flank collapses, are represented, as are the deposits of block and ash pyroclastic flows (Cademan Breccia) derived from the collapse of 'Grimley'-type extrusive domes. Similar successions characterise the medial or distal ring plain sequences surrounding modern andesitic composite volcanoes. For example, at Ruapehu Volcano in New Zealand, the ring plain consists of 'lensoid, coarse-grained volcanoclastic deposits, comprising both matrix-rich and laharc deposits and better sorted fluvial sediments' (Hackett and Houghton, 1989). The obvious lack of fluvial sediments here, combined with the evidence that the volcanoclastic units both above and below the Charnwood Lodge Formation are probably entirely waterlain, suggests that the Charnian 'ring plain' equivalent must have been accumulated subaqueously (Fig. 10). In this type of environment the blocky fragmental material derived from lahars, or various other forms of subaerial volcanoclastic debris avalanches, or from pyroclastic flows, may have entered water and transformed into subaqueous volcanoclastic debris flows. Modern sedimentological studies provide an explanation for some of the finer-scale stratification that has been described; they have shown that rock avalanches (pyroclastic flows or lahars) can grade into stratified debris flows with increased distance from the source, particularly if the runout is within standing water (Yarnold, 1993).

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