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The Lower Palaeozoic igneous rocks and Quaternary deposits of the area between Haweswater and Shap (part of Sheets 30 and 39, England and Wales)

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D Millward

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Haweswater and Harter Fell.

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NOTES

All grid references given in brackets [] throughout the report are within the 100 km square NY.
Numbers preceded by the letter E refer to registered numbers in the British Geological Survey sliced rock collection.

In this report the word 'district' refers to the whole area covered by the report.

The term 'pyroclastic density current' is used here as a term for the whole spectrum of volcanic density currents that includes what are conventionally referred to as pyroclastic surges and pyroclastic flows as its end members (Druitt, 1998).

Foreword

This report describes the bedrock and Quaternary geology, and the geological structure of the Borrowdale Volcanic Group and associated intrusive rocks of the area between the Haweswater reservoir, Swindale, Wet Sleddale and Shap in the eastern Lake District, Cumbria. In Section 11 new evidence is presented relevant to the interpretation of the form of the unconformity at the base of the Windermere Supergroup; the significance of pyroclastic rocks at the base of the Yarlside Volcanic Formation within the Dent Group, the lowest part of the Windermere Supergroup, is discussed. Section 16 comprises information on the Quaternary deposits in the area.

Field work was carried out between 1997 and 1999 as part of the Lake District Regional Geological Survey Project under the leadership of Dr P Stone. The Haweswater and Shap area is the final part of the volcanic outcrop to be resurveyed, representing a significant milestone in the survey of the Lake District. The area lies within the 1:50 000 Series geological sheets 30 (Appleby) and 39 (Kendal), and encompasses parts of 1:10 000 geological sheets NY 41 NE, and SE, NY 50 NW, and NY 51 NW, SW and SE. This report is best read in conjunction with these large-scale maps.

The geology of the Borrowdale Volcanic Group in areas adjoining the west and south-west of that covered by this report is described by Beddoe-Stephens (2000a), Woodhall (2000a) and Johnson (2001). The Haweswater intrusions that crop out around the Haweswater Reservoir are described by Millward and Beddoe-Stephens (1998). The Skiddaw Group, which lies to the north and east of the area, has been described by Bell (1997). Full reference to these accounts is given towards the end of this Research Report.

This report has been reviewed by Dr D G Woodhall and edited by Dr P Stone.

Contents

Summary

This report describes the geology of the igneous and associated rocks of the area between the Haweswater Reservoir and the Shap Fells in the north-eastern part of the Lake District National Park. Resurvey of the Borrowdale Volcanic Group began in 1981 and this report covers the final part of the outcrop to be examined.

The major volcanic succession in the Lake District is the Borrowdale Volcanic Group, a subaerial, continental-margin, calc-alkaline volcanic field of Caradoc age. The area that extends from Haweswater to Shap pro-vides a complete section through the group, from the un-derlying Skiddaw Group, exposed in the north and east of the district, to the overlying Windermere Supergroup, which crops out to the south. It probably totals about 4500 m thick.

The lowest 1000 m of the Borrowdale Volcanic Group comprises sheets of andesite and basaltic andesite with minor intercalations of bedded volcaniclastic sandstone and a massive unit of breccia. This succession forms part of a widespread, low-profile, plateau-andesite volcanic field that extended throughout the present Borrowdale Volcanic Group outcrop and possibly beyond.

The upper part of the group consists of a stratified sequence of silicic pyroclastic rocks intercalated with bedded volcaniclastic sedimentary rocks and subordinate pyroclastic rocks. The thick ignimbrite sheets within the succession extend beyond the district and were formed during violent eruptions and some may have been accompanied by volcanotectonic collapse. The sedimentary rocks represent the reworking of tephra and denudation of contemporaneously exposed rocks by fluvial and mass-flow processes. Though some thin pyroclastic deposits are represented in the bedded volcaniclastic sequence, the amount of pumice/scoria present in the latter suggest that deposits from relatively small-scale pyroclastic eruptions were rapidly reworked and are thus under-represented within the succession.

A substantial volume of andesite sills was intruded into the volcanic pile. Late in the volcanic cycle, plugs and masses of dolerite and gabbro were also emplaced to form the subvolcanic Haweswater intrusions.

Throughout the Lake District the Borrowdale Volcanic Group is separated from the overlying Windermere Supergroup by a major unconformity. In the Shap Fells area there is no significant difference in dip and dip azimuth above and below the unconformity. However, the unconformity is an irregular erosion surface with several hundreds of metres of relief. Hollows in this surface contain sedimentary rocks of the Stile End Formation and pyroclastic rocks of the Yarlside Volcanic Formation (Dent Group), the latter representing renewed volcanism during Ashgill times.

Volcanotectonic and basin-extensional faults active during the volcanism were re-activated in Early Devonian times as the entire Lower Palaeozoic succession in the Lake District was deformed and cleaved during the Acadian phase of the Caledonian Orogeny. The Shap Pluton and various silicic minor intrusions were emplaced late in this episode, probably during periods of stress relaxation.

The landscape owes much to glacial erosion and deposition during the Quaternary. The major valleys of Haweswater and Swindale were sculpted by ice and the terrain partially covered with a variable thickness of superficial deposits. The thick spreads of till, particularly in the valleys and on the north-eastern slopes of the Lowther valley, were laid down as a result of the last regional ice-sheet glaciation during the Dimlington Stadial. Small areas of moraine deposits and clearly defined corries represent further erosion and deposition during the subsequent Loch Lomond Stadial. Post-glacial fluvial deposits are found principally in the valleys, whereas widespread blanket peat covers much of the high fells in the southern part of the area.

1 Introduction

This report explains the geology of the volcanic and associated intrusive rocks, and the superficial deposits that cover them, within the area between Haweswater, Shap and Wet Sleddale (Figure 1). This area lies in the north-east of the Lake District Lower Palaeozoic inlier. The geology of this part of the Lake District National Park is portrayed as part of the 1:50 000 Series geological maps of the Appleby (30) and Kendal (39) districts.

Topographically the area is one of contrasts. The northern part, between Haweswater and Wet Sleddale, forms a low, rugged dissected plateau at 430 to 530 m above OD. By contrast, smooth, higher fells form the south-west of the area; these include Artlecrag Pike (713 m) [478 100], Selside Pike (655 m) [491 112], and the ridge from Harrop Pike [501 078] to Wasdale Pike [536 084] in the south. The sharp change in topography occurs across a segment of the Swindale Fault which broadly follows the line of the Old Corpse Road linking the southern end of Haweswater to Swindale. In the north-east of the district the fells gradually diminish in height towards the wide valley of the River Lowther which in this area approximately follows the unconformity between the Lower and Upper Palaeozoic rocks.

Three major valleys drain the district north-eastwards to the River Lowther (Figure 1). From the north-west, these are Haweswater Beck, Swindale Beck and Sleddale Beck. The valleys of the first and last of these are dammed and flooded to form the Haweswater and Wet Sleddale reservoirs respectively which were built to provide water for the Manchester conurbation (Davies, 1940). These ice-carved valleys have been sculpted along the major structural grain in the Lower Palaeozoic rocks, including fault trend and cleavage strike. The Haweswater valley is controlled by the lines of several faults, but also appears to follow an arcuate cleavage trend. The wide, main part of Swindale follows the Swindale Fault, and Wet Sleddale is parallel to a major set of north-east-trending faults.

1.1 GEOLOGICAL SUCCESSION

Lower Llanvirn mudstones of the Skiddaw Group are the oldest rocks present. They underlie the northern part of the district. These rocks have been described by Bell (1997). They are overlain by up to 4500 m of volcanic rocks belonging to the Borrowdale Volcanic Group (BVG) of Caradoc age. A complete succession through the BVG is seen between Haweswater and the Shap Fells. The base crops out just east of the Haweswater reservoir dam and around Keld Gill in the Ralfland Forest, and the over-lying Windermere Supergroup is seen in the Shap Fells in the south of the area. The generalised geological succession of the volcanic rocks in the Appleby and Kendal districts is shown in Table 1. Table 2 gives a more detailed lithostratigraphy for the volcanic rocks, and lists the main lithologies, key localities where the units are best exposed and a summary of their volcanological interpretation.

A key feature of the volcanic succession in this area is the high proportion of andesite present. The lowest 1000 m or so comprises andesitic lavas and sills, assigned to the Birker Fell Formation, and interpreted as a plateau-andesite sequence that formed a low-profile volcanic field (Petterson et al., 1992). A major change in the style of volcanism to violently explosive pyroclastic eruptions then produced widespread and voluminous sheets of silicic ignimbrite, some of which are believed to have been associated with volcanotectonic subsidence. Intervals between the ignimbrite-forming events are represented by thick sequences of volcaniclastic rocks comprising tephra reworked by sedimentary processes.

The stratified succession above the Birker Fell Formation in the Haweswater to Shap area hosts a large number of andesite sills, which exhibit features that suggest that they were emplaced as high level intrusions. The Haweswater intrusions represent subvolcanic plugs and associated masses of dolerite and gabbro, probably emplaced late in the volcanic cycle (Millward and Beddoe-Stephens, 1998).

A later, Early Devonian, magmatic episode saw the emplacement of the Shap Pluton accompanied by a variety of mainly silicic dykes. This episode occurred in the final stages of the Acadian phase of the Caledonian Orogeny, which folded, cleaved and faulted the Lower Palaeozoic rocks. The intensely faulted volcanic rocks typically form rocky outcrops and crags, separated by patchy thin superficial deposits, particularly in the area adjacent to Haweswater. By contrast, the major valleys and low, peripheral, margins of the volcanic outcrop in Ralfland Forest are extensively covered with till. The smooth hills in the south of the area on Ulthwaite Rigg and Shap Fells are blanketed with hill-peat and rock exposure is sparse.

1.2 PREVIOUS RESEARCH

The original geological survey of the area by J R Dakyns, R Russell, G H Lightfoot and W T Aveline was published on 1:63 360-scale geological Quarter Sheet 102SW (New Series Sheet 30) and 98NE (New Series Sheet 39) in 1893 and 1887 respectively. The geological memoirs for these areas were published in 1897 (Dakyns et al., 1897) and 1872 (Aveline and Hughes, 1872). The volcanic rocks south of Swindale were mapped by Mitchell (1934), who also described the geomorphology of this region (Mitchell, 1931). The Borrowdale Volcanic Group between Haweswater and Swindale was mapped in detail by Nutt (1970). Mitchell and Nutt established distinct local successions for the volcanic rocks. Approximate comparisons with the lithostratigraphy proposed in this report are shown in Table 3. The Shap granite and its contact metamorphic aureole has been the subject of continuing research over many years, summarised by S C Loughlin in Stephenson et al. (1999).

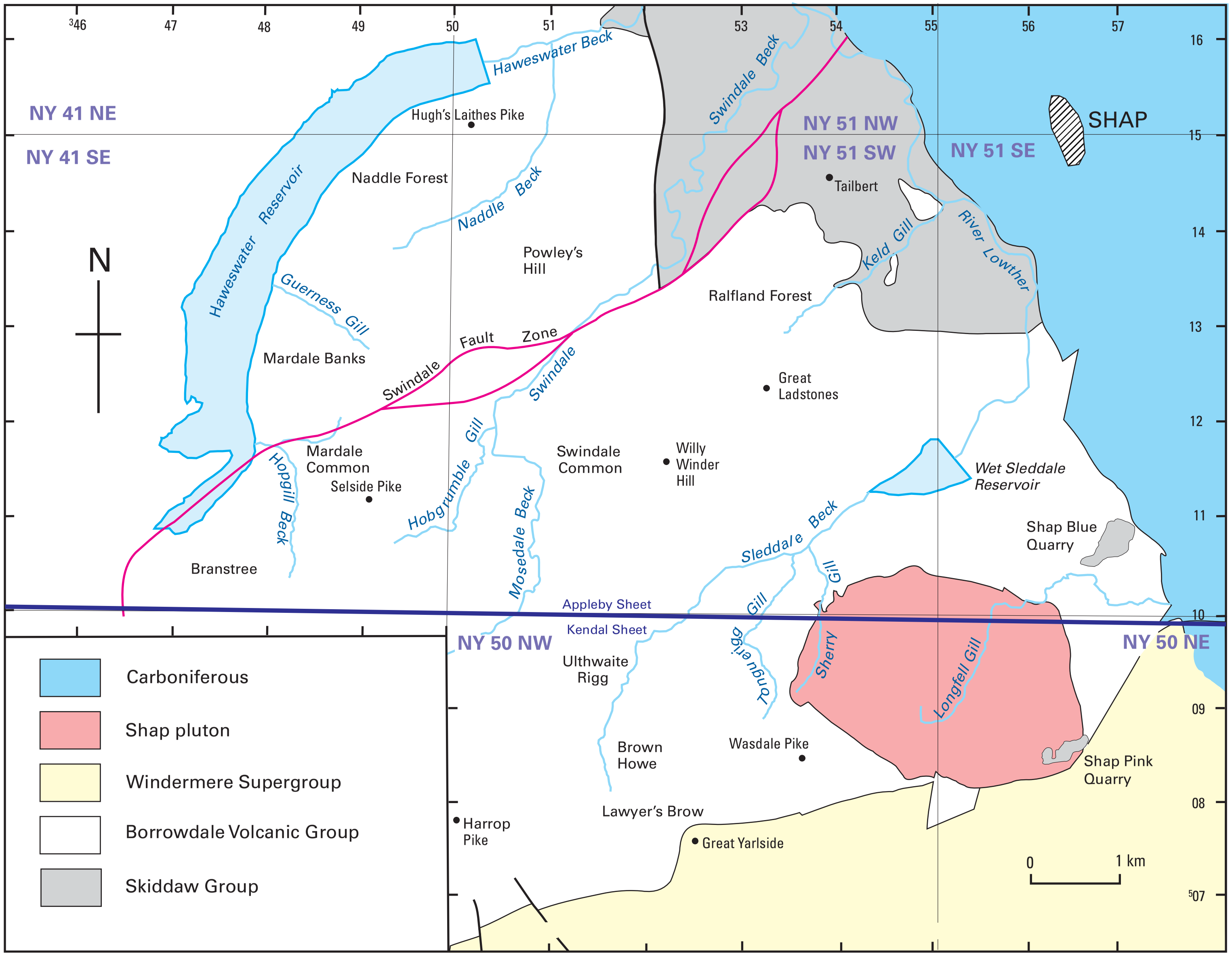

Figure 1 Principal geographical and geological features of the Haweswater and Shap area.

Table 1 General stratigraphy of the Lake District Lower Palaeozoic rocks present on 1:50 000 geological sheets Appleby (30) and Kendal (39).

			Formation	Lithology	Thickness (m)
ORDOVICIAN	Ashgill	DENT GROUP	Yarlside Volcanic	Mainly felsite; basal silicic pyroclastic rocks	
			Stile End	Sandstone and siltstone	
		Unconformity			
	?Llanvirn to Caradoc	BORROWDALE VOLCANIC GROUP	Deepdale	Volcaniclastic sandstone, intercalated, pebbly sandstone, breccia and silicic lapilli-tuff	c 350+
			Hogget Gill Fault		
			Brock Crag Andesite	Andesite, autobrecciated; intercalated volcaniclastic breccia, lapilli-tuff and tuff	0–290+
			Middle Dodd Dacite	Dacite	0–170
			Garburn	Dacite	0–100
			Esk Pike	Volcaniclastic sandstone, in part conglomeratic	155+
			Lincomb Tarns	Silicic lapilli-tuff and tuff (ignimbrite)	300+
			Kentmere Pike	Dacitic lapilli-tuff (high-grade ignimbrite)	0–350
			Wet Sleddale	Andesite sheets, intercalated volcaniclastic sandstone and tuff	c 1200
			Seathwaite Fell	Volcaniclastic sandstone, some intercalated breccia, tuff and lapilli-tuff	250–500
			Woundale	Andesitic tuff and lapilli-tuff (ignimbrite), with minor intercalated volcaniclastic sandstones	200
			Froswick	Andesitic to dacitic lapilli-tuff (ignimbrite)	c 250
			Mardale	Mixed succession of volcaniclastic sedimentary and pyroclastic rocks	Up to 980
			Whelter Knotts	Silicic tuff and eutaxitic lapilli-tuff (ignimbrite), garnetiferous	c 300
			Scalehow	Andesitic and dacitic lapilli-tuff and tuff, some volcaniclastic sandstone	0–340
			Birker Fell	Andesite sheets with subordinate basalt, basaltic andesite and dacite with intercalations of volcaniclastic rocks	980–2750
				Unconformity	
	Llanvirn	SKIDDAW GROUP	Tailbert	Sandstone with some interbedded mudstone units	200+
			Unconformity		
			Tarn Moor	Silty mudstone	

Formations present in the Haweswater to Shap area and described in this report are shaded.

Table 2 Borrowdale Volcanic Group stratigraphy in the area between Haweswater and Shap, with key localities and summary interpretation of the volcanism, depositional processes and environment.

Formation	Member	Key localities	Main lithologies	Interpretation	Volcanism and depositional environment
Lincomb Tarns		Shap Rhyolite Quarry [567 106]	Massive and eutaxitic, silicic lapilli-tuff and tuff; rare intercalated unit of bedded tuff and accretionary lapilli-tuff	Extensive sheet of welded ignimbrite; locally preserved pyroclastic surge and fall-out deposits	Large-magnitude explosive silicic volcanism producing blanket of pyroclastic-flow deposits across District.
Wet Sleddale		Tod Crags and Tongue Rigg [522 104–526 100] (type area)	Andesite sheets, much autobrecciated; intercalated bedded volcaniclastic sandstone and tuff	Lavas and possibly high-level sill succession; some explosive volcanism and sedimentary reworking	Effusive andesitic volcanism and possibly high-level sill emplacement
Seathwaite Fell		Howes [499 103]	Volcaniclastic sandstone, some intercalated breccia, tuff and lapilli-tuff	Mass-flow deposition (debris flows and turbidites). Extensive reworking of contemporaneous ash deposits. Many contemporaneous or later high-level sills.	Alluvial fan deposits sourced from fault scarps; possibly lacustrine background sedimentation during times of low sediment input.
Froswick		Swindale Common [5130 1175–5145 1080] (type area)	Massive and eutaxitic to parataxitic, andesitic to dacitic lapilli-tuff	Extensive sheet of welded/non-welded ignimbrite	Explosive intermediate volcanism forming an extensive ignimbrite plain
Mardale		Swindale [510 122–521 133] (type area)	Dominantly bedded volcaniclastic sandstone with intercalations of volcaniclastic breccia, tuff lapilli-tuff and pyroclastic breccia	High-energy tractional and mass-flow sedimentation with pyroclastic fall-out, surge and flow deposits. Localised soft-sediment deformation.	Subaerial, explosive, particularly phreatomagmatic, andesitic and dacitic volcanism with rapid fluvial and mass-flow reworking of tephra within fault-bounded depocentre. Apparent diminishing intensity of activity with time. Sequence much invaded by high-level andesite intrusions.
	Great Ladstones	Little Ladstones [535 126] (type area)	Volcaniclastic breccia and sandstone	Mass-flow deposit	
	Gouther Crag	Gouther Crag [514 126] (type area)	Massive volcaniclastic breccia	Mass-flow deposit	
	Rowantree-thwaite	Ritchie Crag [490 123] (type section)	Bedded dacitic lapilli-tuff and tuff; minor pyroclastic breccia and accretionary lapilli-tuff	Pyroclastic fall-out and subordinate surge deposits	
	Brown Howe	Mardale Banks [479 122–485 130] (type area)	Bedded acid andesitic/dacitic coarse tuff and lapilli-tuff; local intercalations of pyroclastic breccia	Pyroclastic fall-out and surge deposits, reworked locally by tractional currents and mass-flow.	
Whelter Knotts		Hugh's Laithes Pike to Naddle Beck [502 151 to 491 138]	Silicic tuff and eutaxitic lapilli-tuff, garnetiferous; locally nodular	Extensive sheets of welded ignimbrite	Major phase of explosive silicic subaerial volcanism, associated with contemporaneous faulting. Possible development of a caldera in the Haweswater area
	Pinnacle Howe	Hugh's Laithes Pike [505 152]	Foliated vitrophyric silicic tuff	High-grade ignimbrite	
	Powley's Hill	Powley's Hill [502 136] (type area)	Garnetiferous crystal, pumice and lithic silicic tuff and lapilli-tuff	Pyroclastic fall-out, surge and flow deposits	
Birker Fell		Barton and Swarth fells [450 199–466 214]; Hallin Fell [433 198]; Frith Crag to Harper Hills [510 142–517 157]	Andesite sheets with subordinate basalt, basaltic andesite and dacite, with intercalations of volcaniclastic sandstone, breccia and lapilli-tuff	Lavas and sills (relative proportion unknown); intermittently preserved pyroclastic fall-out, surge and flow deposits; eruption-induced mass-flow deposits; tractional current and mass-flow reworking of material.	Initial phreatomagmatic volcanism. Followed by dominantly effusive andesite volcanism. Construction of subaerial low-profile volcanoes throughout the Lake District
	Frith Crag	Swindale Foot Crag [5190 1383] (type locality)	Massive tuff-breccia, matrix to clast supported	Block-and-ash-flow deposit possibly from collapse of lava	

All grid references occur within the 100 km square NY.

Table 3 Comparison of previous lithostratigraphical classifications of the Borrowdale Volcanic Group in the Appleby district with that used in this report.

<table>
<tr><th>New litho-stratigraphy</th><th>NW Ullswater (Moseley, 1964)</th><th>SE Ullswater (Moseley, 1960)</th><th>NW Haweswater (Nutt, 1970)</th><th>SE Haweswater (Nutt, 1970)</th><th>Longsleddale & Shap (Mitchell, 1934)</th></tr>
<tr><td>Deepdale</td><td rowspan="11"></td><td rowspan="7"></td><td rowspan="7"></td><td rowspan="8"></td><td rowspan="4"></td></tr>
<tr><td>Helvellyn</td></tr>
<tr><td>Middle Dodd Dacite</td></tr>
<tr><td>Esk Pike</td></tr>
<tr><td>Lincomb Tarns</td><td>Coarse Tuffs</td></tr>
<tr><td>Wet Sleddale</td><td rowspan="2">Wrengill Andesites
Bedded Tuffs</td></tr>
<tr><td>Seathwaite Fell</td></tr>
<tr><td>Froswick</td><td rowspan="3">Place Fell Group</td><td>Atkinson & Fordingdale Ignimbrite Groups</td><td>Froswick Tuffs</td></tr>
<tr><td>Mardale</td><td>Keasgill Tuffs
Cawdale Tuffs</td><td>Bedded Tuffs
Thorney Knott Andesites
Hareshaw Tuffs
Nan Bield Andesites</td><td>Coarse Tuffs
Bedded Tuffs
Wrengill Andesites</td></tr>
<tr><td>Whelter Knotts</td><td>Atkinson & Fordingdale Ignimbrite Groups
Stanegarth & Whelter Knotts Ignimbrite Groups</td><td>Hugh’s Laithes Pike Ignimbrite Group
Haweswater Ignimbrite Group</td><td>Froswick Tuffs</td></tr>
<tr><td>Scalehow</td><td rowspan="2">Birk Fell Group
Angle Tarn Andesites
Ullswater Group</td><td></td><td></td><td></td></tr>
<tr><td>Birker Fell</td><td>Birk Fell Group
Ullswater Group</td><td>Lad Crags Andesites
Bampton Howes Andesite Group
Bampton Conglomerate</td><td>High Naddle Andesites
Haweswater Dam Andesites
Frith Crag Tuffs
Scalebarrow Andesites</td><td>Wrengill Andesites
Ralfland Forest Andesites</td></tr>
</table>

Shaded areas indicate that the newly defined formation is either not present in the area, or was not differentiated. The two columns at the right-hand side are applicable to the Haweswater to Shap area.

2 Birker Fell Formation

The lower part of the Borrowdale Volcanic Group east of Haweswater comprises a 1000 m-thick sequence of andesite sheets with an intercalation of breccia and thin, discontinuous units of bedded volcaniclastic sandstone (Table 2). The main outcrop of these rocks is north of the Mullender Fault, though small, fault-bounded blocks occur to the south, between Woodhowe Moss and Powley's Hill [495 133 to 505 136]. Nutt (1970) assigned the rocks north of the Mullender Fault to three formations, the Scalebarrow Andesites, overlain by the Frith Crag Tuffs and the Haweswater Dam Andesites; he referred to the outcrops on Woodhowe Moss as the High Naddle Andesites (Table 3). In this report all of these occurrences are assigned to the Birker Fell Formation, an andesite lithofacies association which occupies the same stratigraphical position throughout the western and northern parts of the volcanic outcrop (Millward et al., 2000; Woodhall, 2000b). The sequence east of Haweswater is thus the easternmost occurrence of the formation, which was interpreted as a major phase of effusive volcanism by Petterson et al. (1992).

The base of the Borrowdale Volcanic Group crops out to the north of the district (Beddoe-Stephens, 2000a), in the shallow valley of Haweswater Beck [518 162] and south of Tailbert to Ralfland Forest [531 142 to 540 133]. Bell (1997) interpreted the contact to dip south at 2 to 6°, based on structural contours drawn on the mapped boundary. The unconformable boundary is exposed only at one location, in Keld Gill [5396 1341], where near horizontal volcanic rocks overlie weathered, near-vertically dipping mudstones of the Skiddaw Group (Bell, 1997). Outcrops of volcaniclastic sandstone in the lower reaches of Keld Gill [546 135] and along the sides of the River Lowther [548 143] were interpreted by Bell (1997) as volcanic vents. However, herein, I ascribe a sedimentary origin to these rocks which are considered to be outliers of the basal bed of the Borrowdale Volcanic Group. Thus the basal contact of the volcanic group is inferred to be very irregular.

Throughout the district, the andesite succession is divided into lower and upper parts by a thick intercalation of tuff-breccia, referred to as the Frith Crag Member. In the area north of the Mullender Fault and west of the Rosgill Moor Fault, the lower part of the formation comprises massive, flow-banded and flow-jointed, highly porphyritic andesite, probably a single sheet. The closely spaced igneous jointing gives the exposures a platy appearance in parts, particularly around Bewbarrow Crag [5194 1415]. This andesite is noteworthy for the presence of scattered round xenoliths up to 40 mm across. The rock contains abundant plagioclase phenocrysts and glomerocrysts, the outer parts of which exhibit complex zoning patterns, and subordinate chlorite and carbonate pseudomorphs after pyroxene. The groundmass has a micropoikilitic (snowflake) texture (E71725).

East of Swindale, the lowest andesite is massive, sparsely amygdaloidal, blue-grey and 60 to 100 m thick. It is highly porphyritic with approximately equal proportions of plagioclase and pyroxene phenocrysts set in a turbid, very finely crystalline pilotaxitic groundmass. The feldspar is typically replaced by albite, sericite and carbonate (E71059) or sericite (E72191). Chlorite, carbonate and Fe-oxide pseudomorphs are after pyroxene, probably a monoclinic variety as indicated by the crystal shape (E72174). In E71059 some relict fresh augite occurs within mimetic replacements of fibrous amphibole and chlorite. In E72191 two mafic pseudomorph types are present: large euhedral turbid equant crystals and smaller tabular fine-grained sutured quartz aggregates.

The 415 m-thick succession above the Frith Crag Member west of Swindale is exposed on the spur north-east of Hugh's Laithes Pike and comprises at least three andesite sheets, overlain by lapilli-tuff. The lowest two sheets are basaltic andesite with less than 5% phenocrysts of plagioclase and subordinate pseudomorphs of chlorite and epidote, probably after clinopyroxene; the phenocrysts are set in a finely crystalline groundmass with a pilotaxitic texture and abundant tiny grains of iron oxide (E71754, E71755). The rocks are highly amygdaloidal and autobrecciated, particularly at the top and base of each sheet. A few metres of parallel, thin- to medium-bedded, medium to coarse-grained volcaniclastic sandstone separate the basaltic andesite from a conspicuously feldspar-phyric andesite which is intensely autobrecciated. The latter unit contains large euhedral plagioclase phenocrysts set in a fine groundmass of feldspar microlites and granular iron oxide with much secondary carbonate (E71762).

Apart from the Frith Crag Member, volcaniclastic units are relatively poorly represented in the Birker Fell Formation east of Haweswater. Furthermore, none are sufficiently widespread to provide stratigraphical markers. The most significant unit, probably sedimentary in origin, lies at the base of the formation east of Swindale on Ralfland Forest. There, massive, bluish grey volcaniclastic sandstone, up to about 20 m thick, overlies Skiddaw Group rocks. At the base of this unit and thus at the base of the BVG in Keld Gill, Bell (1997) described a 50 cm thick bed of pale grey, structureless mudstone containing abundant evidence of bioturbation.

Outliers of the basal volcaniclastic unit occur on the south side of the River Lowther at [549 142], and just south of Keld Gill, at [546 135]. North of Lanshaw Sike the sandstone is overstepped by the lowest andesite sheet of the formation. The poorly to well sorted sandstone is medium grained to granule grained and locally sparsely pebbly. The coarser grained rocks occur in the outlier adjacent to the River Lowther (E71063, E71064). The grains comprise mainly angular to rounded clasts of variably textured andesite and microcrystalline silicic rock along with varying amounts of vesicular ash. Abundant feldspar crystal grains, including K-feldspar, are present in the finer grained rocks (e.g. E72176). Scattered angular and platy clasts of siltstone derived from the underlying Skiddaw Group are conspicuous in the exposures on White Crag [5453 1346] (E72192) and 250 m to the north-east. Bedding in these rocks is weak and diffuse.

Units of bedded volcaniclastic sandstone a few metres thick separate andesite sheets on Harper Hills [510 144] and north of Long Rigg [509 139]. Beneath the Frith Crag Member on Swindale Foot Crag, a 6 m-thick unit of pebbly very coarse- and coarse-grained volcaniclastic sandstone is mainly strongly cross-bedded (E71791). At the base are lenses of planar, thin-bedded sandstone, and in the centre of the unit there are beds up to 0.8 m thick of uniform pebbly coarse-grained sandstone. South of Langhowe Pike [5288 1331], a few metres of thinly parallel bedded volcaniclastic sandstone are overlain by weakly medium to thickly bedded granule-grade conglomerate and very coarse-grained sandstone. West and north-west of Powley's Hill, plane parallel bedded, medium- and coarse-grained volcaniclastic sandstone fills pockets and irregularities in the upper surface of the uppermost andesite of the formation.

Pyroclastic units are few, and in places these units are intercalated with sedimentary layers. An example of this includes bedded pumice lapilli-tuff and fine volcaniclastic breccia exposed east of Langhowe Pike [5293 1343].

On Hollin Crag [5268 1349] andesite sheets are separated by a succession of about 2 m of parallel thin- to medium-bedded tuff and lapilli-tuff, sharply and conformably overlain by a 5 m-thick unit of massive, uniform lapilli-tuff. Both units contain abundant pumice, but only sparse pilotaxitic andesite fragments. A weak eutaxitic-like fabric is also present, probably resulting from the diagenetic collapse of the tephra; the amount of flattening varies considerably in a single thin section and few lapilli are deformed around rigid crystal fragments (E72161). These rocks record an episode of explosive volcanism with the lower unit representing pyroclastic fall-out deposits and the upper unit ignimbrite.

The uppermost unit of the Birker Fell Formation on Hugh's Laithes Pike comprises andesitic tuff and lapilli-tuff composed of chloritised ash and abundant feldspar and mafic crystals. Poorly defined parallel beds predominate with repeated units of lapilli-tuff capped by tuff.

2.1 FRITH CRAG MEMBER

The Frith Crag Member **(FrCr)** comprises massive tuff-breccia in a very distinctive unit 80 to 160 m thick and up to 600 m above the base of the Birker Fell Formation. Previously referred to as the Frith Crag Tuffs by Nutt (1970), these rocks crop out across the district and are particularly well exposed around Scalebarrow Fold [514 151] east of Naddle Farm and above Swindale Foot Crag [518 139]. East of the Swindale Fault Zone, pyroclastic breccia overlies a single, thick andesite on Thiefstead [530 139] and near White Cap [530 130]. The type locality is Swindale Foot Crag [5190 1383].

The breccia generally rests directly on, and is overlain by, autobrecciated andesite. Mostly the irregular basal contact appears to be gradational, and thus difficult to recognise. However, on Swindale Foot Crag [5192 1384] massive breccia rests on bedded volcaniclastic sandstone which overlies autobrecciated andesite; the contact here is sharp, discordant and irregular.

The member comprises mainly tuff-breccia, grading locally into pyroclastic breccia and lapilli-tuff. The rocks are massive, very poorly sorted and matrix to clast supported; in places the fragments have a jigsaw fit. Weak layering with coarse-tail reverse grading is present in zones of lapilli-tuff at [5138 1368]. Clasts of all sizes are angular to prismatic and mainly up to 15 cm across, though in parts there are many blocks, typically 50 to 80 cm across. Chloritised, slightly amygdaloidal to non-amygdaloidal porphyritic andesite comprises much of the clast population, though a small proportion of porphyritic dacite fragments is present everywhere and, east of Swindale, there are locally abundant siliciclastic sandstone, siltstone and claystone fragments (E72163). The dominant andesite contains about 20% phenocrysts of plagioclase and chlorite-carbonate pseudomorphs after a mafic mineral; some of the smaller crystals of the latter have a prominent secondary Fe-oxide rim (E72173).

The matrix comprises smaller fragments of the main clast lithologies and a very fine-grained indeterminate silicic mesostasis (E71710). Feldspar crystals are sparse. Patches of secondary carbonate overprint the textures.

Bedded coarse-grained volcaniclastic sandstone, at least 1.5 m thick, is intercalated within the breccia east of Naddle Farm, at [5119 1521]. The sandstone is trough cross-bedded and overlies an irregular breccia surface. Within the unit at another locality, west of Swindale Foot Crag at [5150 1378], the breccia contains interstitial patches of thinly laminated siltstone akin to that seen at the top of some andesite sheets (Millward et al., 2000).

Nutt (1970, p 243) interpreted the Frith Crag Member to comprise a mixture of pyroclastic fall-out deposits and those with 'an unwelded ignimbrite-like aspect'. Rocks of the first category have not been recognised, but the lithology, grain size and grading of the pyroclastic breccia to lapilli-tuff-grade deposits is consistent with a block-and-ash-flow-tuff origin, possibly resulting from the collapse of a lava dome or flow. The intercalations of bedded volcaniclastic rocks probably represent fluvial reworking during intervals between successive pyroclastic-flow events.

3 Whelter Knotts Formation

South-east of Haweswater, from Hugh's Laithes Pike [502 151] to the upper reaches of Naddle Beck [491 138] and Hareshaw [496 131], the Birker Fell Formation is overlain by a stratified sequence of pale weathered, massive, eutaxitic and parataxitic, garnet-bearing silicic tuff and lapilli-tuff. Similar lithofacies also crop out on the southern shores of the reservoir, near Mardale Head [471 106 to 479 112]. The Brant Street–Woof Crag faults mark the south-east limit of the formation. The sequence includes bedded lithofacies that are interpreted as pyroclastic fall-out and surge deposits, but the sequence is dominated by units of densely welded ignimbrite. Though extensively faulted, the formation is probably up to 300 m thick in the district. Abrupt thickness changes in component units across the closely spaced pattern of faults in the Naddle Beck area suggest that displacements of volcanotectonic faults may have resulted from the eruptions.

Nutt (1970) referred to the silicic rocks south-east of Haweswater as the 'Hugh's Laithes Pike Ignimbrite Group' to the north of the Kit Crag Fault, and the 'Haweswater Ignimbrite Group' to the south. However, the stratigraphical succession is similar in both these areas, and in this report they are considered to belong to a single unit, the Whelter Knotts Formation **(Wlt).** This formation is widespread west of Haweswater (Beddoe-Stephens, 2000a; Woodhall, 2000a), where the type area is designated as extending from Kidsty Pike to Whelter Knotts [447 125 to 473 137]; a reference section is located south-east of Haweswater around Guerness Gill [481 129 to 488 132].

The lower boundary of the formation is taken at the sharp base of the first bed of white-weathered garnetiferous silicic pyroclastic rocks overlying an irregular substrate of effusive andesitic rocks of the Birker Fell Formation. The contact crops out in the north and east of the area. In places, the pyroclastic rocks are underlain directly by a thin unit of bedded volcaniclastic sedimentary rocks filling hollows at the top of the Birker Fell Formation. The overall appearance is of general conformity. However, at one locality [502 146], south of Hugh's Laithes Pike there is an irregular, highly discordant contact between andesite of the Birker Fell Formation and felsite of the Whelter Knotts Formation. Also, a sharply discordant basal contact with bedded volcaniclastic sandstone is present at a single locality west of Powley's Hill [at 5026 1373].

The top of the formation is marked by the abrupt change to acid andesitic/dacitic volcaniclastic rocks marking the base of the Mardale Formation. South of Guerness Gill the relationship is conformable with a thin sequence of bedded tuff preserved at the top of the formation. Elsewhere, for example in the uppermost reaches of the Naddle Beck valley [at 4905 1378], these tuffs are absent and there is a marked angular discordance between the eutaxitic foliation in lapilli-tuff and bedding in the overlying rocks of the Mardale Formation.

The Whelter Knotts Formation south-east of Haweswater contains two members. At the base, bedded tuff and lapilli-tuff comprise the Powley's Hill Member. This is not present everywhere and varies abruptly in thickness and facies across the area. It is overlain by a flow-foliated felsitic unit, the Pinnacle Howe Member; in places this rests directly on the Birker Fell Formation where the basal unit is absent. The rest of the Whelter Knotts Formation comprises massive eutaxitic and parataxitic lapilli-tuff, locally with bedded tuff at the top.

The fiamme-rich lapilli-tuff that constitutes most of the formation is the only lithology seen at the southern extent of the Haweswater reservoir. Eutaxitic fabrics are consistently well developed and fiamme are abundant, commonly up to 80 by 10 mm and locally up to 150 by 50 mm. Feldspar crystals 3 mm across are common. Sporadic euhedra and resorbed fragments of garnet are present in some of the samples, the fragments commonly enclosed within aggregates of plagioclase and Fe-oxide; very small amounts of biotite are also present (e.g. E71719). The lithic clast population mostly consists of sparse quantities of dense silicic clasts, including some microgranite, generally less than 10 mm across. The lapilli-tuff is altered considerably with much very fine-grained sericite and overprints of carbonate. In the field the groundmass has a glassy appearance and in thin section exhibits perlitic cracking (e.g. E71724). A poorly preserved vitroclastic texture is present in a few samples (e.g. E71748).

Rheomorphic fabrics are seen locally, for example alongside the Haweswater road north of Mardale Banks [4800 1294], where minor flexures in the parataxitic fabrics are associated with ductile shears along planes dipping east. Near Mardale Head [4784 1120] eutaxitic fabrics in the lapilli-tuff are locally folded and brecciated with autoclasts of welded tuff up to 350 by 100 mm. Columnar-like jointing is present locally.

South of the Naddle Beck Fault [4907 1366] a distinctive set of lithofacies overlies the Pinnacle Howe Member. These include: even-textured eutaxitic lapilli-tuff; platy foliated to eutaxitic lapilli-tuff; splintery, massive, fine tuff in sharply bounded parallel beds up to 150 mm thick; a 60 mm-thick bed of pumice lapillistone; and a unit, 0.75 m thick, of weakly bedded, partly reverse-graded, fine lapilli-tuff. Such complex strata are not present 500 m to the north-east at the same stratigraphical level.

Towards the top of the formation, south of Guerness Gill, massive eutaxitic lapilli-tuff locally shows bedding [e.g. at 4862 1308]. Reverse coarse-tail-graded, fiamme-rich units are interbedded with lithic-rich layers. Some of the individual beds are traceable for tens of metres at outcrop. These rocks are overlain by bedded silicic vitric tuff, seen particularly well on slabs beneath the overlying bedded acid andesitic rocks of the Mardale Formation [4844 1312 to 4858 1303] and also just to the south-east of where the Haweswater road crosses Guerness Gill [4812 1337]. The uppermost 2 m of the formation at these localities comprise well bedded, fine and coarse vitric tuff with sparse interbeds of fine pumice lapilli-tuff. In places the base of this unit is sharp, but elsewhere it is an abrupt gradational reduction in grain size. There is no evidence that the junction is an erosion surface. The layered unit is generally parallel, thin to medium-bedded and laminated, though locally bedforms are gently undulating and there are some low-angle truncations.

The bedded tuff comprises mostly vitric shards and chloritised pumiceous ash up to 2 mm. Sorting is moderate to good. The pumice generally has wispy, angular to very irregular outlines. Most of the larger fragments have been flattened parallel to bedding, but the smaller ones retain a more equant shape. The crystal component, mainly sericitised or carbonated feldspar, varies from sparse up to about 10% (E71721 to 71723). Small, corroded relicts of garnet, along with tiny zircon and Fe-oxide crystals sporadically occur in the cores of feldspar aggregates (E71723). Lithic clasts up to about 1 mm are very sparsely distributed through the rocks.

3.1 POWLEY'S HILL MEMBER

Bedded silicic coarse tuff and lapilli-tuff comprise the Powley's Hill Member **(PlH),** the basal member of the Whelter Knotts Formation. These rocks crop out from Hugh's Laithes Pike to Naddle Beck and Powley's Hill which is designated as the type area. There is widespread and abrupt bed-to-bed lithological variation, with individual layers comprising variable proportions of fine vitric ash, pumice, crystals (feldspar, biotite and garnet), and lithic clasts. Bedforms include plane parallel bedding, lenticular bedding, and low-angle cross-bedding. The member varies from less than 1 m to a maximum of about 65 m thick; changes occur abruptly across the many faults affecting the unit.

The base of the member, and of the formation, is well exposed west of Powley's Hill [5014 1371], where planar thin beds of pumice lapilli-tuff with pseudo-eutaxitic texture sharply overlie the irregular top to autobrecciated andesite. The bedding and sorting in this unit suggest a pyroclastic fall-out origin. Above this typically heterogeneous, parallel laminated and thin bedded units comprise normally graded coarse tuff and lapilli-tuff. The units are up to 0.8 m thick and have sharply defined bases and tops. Many weakly bedded lithic-rich units are lenticular and reverse graded. Alternations of poorly sorted, ungraded lithic lapilli-tuff with clasts up to 2 cm occur in beds up to 1m thick.

The lithofacies variation in the member is perhaps best illustrated by a locality about 300 m west of Powley's Hill [5025 1360]. There the succession dominantly comprises units of uniform, massive, eutaxitic pumice-rich lapilli-tuff and coarse vitric tuff. Each unit is up to about 3 m thick, and probably emplaced by pyroclastic density currents. Intercalated with these units are beds of parallel, vaguely and well bedded, well sorted pumice lapilli-tuff 15 to 70 cm thick which exhibit both normal and reverse grading; these were emplaced by pyroclastic fall-out. Also present are units of medium and thin bedded, locally laminated, coarse tuff and lapilli-tuff approximately 1.5 m thick, with gently wavy, lenticular and low-angle cross-laminated bedforms. Other features of these units include: a wide range of sorting characteristics between layers, abrupt changes in grain size between layers, scattered lithic lapilli up to 1 cm within much finer grained beds, and the presence of garnet-rich layers and garnet 'lags' at the base of dune forms and 'scours'. Such units are interpreted as pyroclastic surge deposits. Thus, at this locality it is possible to demonstrate the interplay between pyroclastic flow, surge and fall-out during emplacement of this member.

On Hugh's Laithes Pike the lithofacies include: coarse-tuff and lapilli-tuff with abundant garnet (E71768); splintery fine vitric tuff without garnet but with weak eutaxitic foliation (E71767), and lithic-rich tuff with sparse large euhedral garnets (E71766). Individual beds are up to 1.5 m thick. In a fault block west of Kit Crag [at 4890 1446] the member is only 1.5 m thick and comprises bedded eutaxitic, garnetiferous lapilli-tuff. This is overlain by flow-laminated felsite of the Pinnacle Howe Member. Dip of the welding foliation for 1 to 2 m adjacent to the fault is steep and to the north, in contrast to the general southerly dip in the rest of the block. Such plastic deformation probably occurred during volcanotectonic displacement on the Kit Crag Fault.

In thin section the wide variation in rock fabric seen in the field is well illustrated despite intense overprinting with sericite and carbonate. Varying proportions of wispy sericitised pseudomorphs after pumice are accompanied by lithic clasts and a crystal component that includes feldspar (altered to sericite and carbonate), garnet, Fe-oxide, apatite and biotite. Crystals comprise up to 20% of some rocks. A relict vitric matrix is present in some of the rocks (e.g. E71767).

The Powley's Hill Member contains some of the most garnetiferous rocks seen in the Borrowdale Volcanic Group. Garnet occurs both as euhedral crystals up to 5 mm across (e.g. E71765) and as resorbed, or irregular fragments (e.g. E71779). The latter are commonly within aggregates of plagioclase and Fe-oxide. Garnet crystals are very unevenly distributed within the different lithofacies. Very small amounts (<1%) are typically present in lithofacies interpreted as pyroclastic flow and fall-out deposits. By comparison, there are some spectacular concentrations in lags at the base of some units interpreted as pyroclastic surge deposits. The garnet is usually fresh, though there is some alteration to chlorite and carbonate along cracks. Small inclusions of zircon and apatite are present.

The lithic content of these rocks varies from sparse to very abundant. Clasts are mostly less than 10 mm, though in many places large lapilli up to 40 mm are present. Very soft, fine-grained platy mudstone clasts, probably from the underlying Skiddaw Group, occur in abundance in some very poorly sorted units that are internally massive or very weakly bedded (e.g. E71782). In places, alignment of the platy fragments defines a crude foliation in the rock. At a locality just north-north-west of Powley's Hill [5045 1371], abundant platy siltstone clasts in beds of lithic-rich lapilli-tuff appear to be imbricated towards the south. Other lithologies present as clasts include variously textured andesite and some dacite.

3.2 PINNACLE HOWE MEMBER

Pink- to white-weathered, glassy, parataxitic silicic tuff and platy foliated vitrophyre comprise the Pinnacle Howe Member **(PnH)** which overlies the basal member in the east of the outcrop. On Hugh's Laithes Pike this relationship is complicated by the presence of an andesite intrusion along the contact. In the central part of the Naddle Beck area, where the basal unit is thin or absent, the felsite lies at the base of the formation. The base of the member is taken at the abrupt change to vitrophyre from underlying pyroclastic rocks. In places the vitrophyre overlies autobrecciated andesite of the Birker Fell Formation. The member is overlain abruptly by less densely welded silicic lapilli-tuff. The type area is on Pinnacle Howe north-west of Haweswater [497 167] (Beddoe-Stephens, 2000a).

Though most of the outcrop appears to be a strongly foliated felsite, in places there are well developed parataxitic fabrics in lapilli-tuff, for example between Naddle Forest

[4969 1465] and Naddle Beck. Several small outcrops of felsite occur on top of the main Kit Crag mass of the Haweswater intrusions (Millward and Beddoe-Stephens, 1998). In one of these, at [4922 1463], to the south of the Highfield Crag Fault, the welding fabrics in the felsite are intensely folded.

These rocks contain sparse felsitic lithic lapilli up to 5 mm diameter. Sericite and carbonate pseudomorphs after feldspar comprise less than 5% of the rock. Beddoe-Stephens (2000a) reported the presence of small amounts of biotite, but garnet has not been observed.

3.3 INTERPRETATION

The lithofacies and bedform characteristics of the Whelter Knotts Formation indicate that it is interpreted best as a complex, stratified pyroclastic succession, dominated by sheets of welded ignimbrite. Though exposures of contacts between the various major units within the formation are sparse, there is little evidence for any significant break in deposition within the sequence which was probably emplaced during a single episode of violently explosive silicic volcanism. If so, the variation in lithofacies must be related to the changes in the rate of eruption and to the geometry of the vent system.

The initial stages are represented in the Powley's Hill Member by an intimate mixture of lithofacies deposited from pyroclastic fall-out and pyroclastic density currents. At a number of localities at the base of the member, bedded, well sorted pumice lapilli-tuff represent an initial pyroclastic fall-out deposit. Similar lithofacies throughout the member testify to the continued record of fall-out, but these deposits were interposed with thin, non-welded ignimbrite sheets and units of pyroclastic surge origin. The presence of lithofacies of the last type suggests that substantial amounts of water came into contact with magma, periodically producing phreatomagmatic explosions.

The ensuing sequence of welded ignimbrite sheets represent the climactic part of the eruption. The Pinnacle Howe Member, mapped over only a small part of the outcrop of the Whelter Knotts Formation, is a particularly high-grade, lava-like tuff. Rheomorphism is locally present.

The facies characteristics and lithology of the bedded uppermost few metres are mostly indicative of a dominantly pyroclastic fall-out origin for this unit, though cross-bedding and undulating bedforms may be indicative of a pyroclastic surge component. The conformable relationship with the underlying eutaxitic member indicates a minimal time interval between the change of depositional mechanism so that the unit represents the final preserved phase of explosive silicic volcanism that produced the Whelter Knotts Formation. Characteristics of the bedded unit are consistent with their interpretation as a co-ignimbrite ash-fall deposit or co-ignimbrite ash-cloud surge. However, the preservation potential of such deposits in the geological record is poor (Cas and Wright, 1987) and co-ignimbrite deposits of this type are not typically as thick as the unit at the top of the Whelter Knotts Formation. Hence, deposition from unsteady, waning pyroclastic flows seems more likely (cf. Branney and Kokelaar, 1992).

There is considerable evidence from the Haweswater area to indicate that emplacement of the Whelter Knotts Formation was accompanied by faulting and differential subsidence. The full extent of this cannot be fully investigated in the area because only the top and base of the Powley's Hill Member is consistently seen in the same fault blocks. Thickness changes in this unit occur across the arcuate Woodhowe Moss Fault which has a significant throw down to the north. Similar changes occur also across north to south faults west of Powley's Hill. There are also some abrupt changes in strike of the strata across some of these faults. Syndepositional displacement down to the north across the Kit Crag Fault is implied by the geometry of the plasticly deformed welding fabrics there. Foliation in the parataxitic tuffs on the north side mostly dip gently to the south, except in a zone 2 to 3 m wide adjacent to the fault where the fabrics dip very steeply northward.

The lithofacies association and the contemporaneous faulting suggest that the Whelter Knotts Formation may represent a caldera fill. The presence of the basal member only in the Haweswater area suggests proximity to major early vent site(s) (see also Beddoe-Stephens 2000a). The presence of unequivocal pyroclastic surge deposits indicates a subaerial environment.

Attention was drawn to the similarity between silicic pyroclastic rocks in the Scafell and Haweswater areas by Millward et al. (1978) and their possible contemporaneous emplacement. Both the Whelter Knotts Formation and Scafell caldera succession overlie the Birker Fell Formation. They are compositionally similar and are garnet bearing. High-grade ignimbrites are represented at Scafell by the Oxendale Tuff and Crinkle Member, and in Haweswater by the Pinnacle Howe Member. However, the lithological sequences are significantly different and correlation between them is precluded. At Haweswater, there is no voluminous andesitic phreatomagmatic deposit equivalent to the Whorneyside Formation, and the basal Powley's Hill Member has much in common with the Lingmell Formation at the top of the Scafell succession.

The relative emplacement ages of the Airy's Bridge and Welter Knotts formations are not known. No marker units have been found to be common to the two pyroclastic successions, nor to the uppermost part of the underlying Birker Fell Formation. It is likely that the upper part of the latter is strongly diachronous.

4 Mardale Formation

The Mardale Formation **(Mrl)** encompasses a mixed succession of mainly bedded volcaniclastic rocks separating two major, welded pyroclastic units, the Whelter Knotts Formation beneath and the Froswick Formation above. Though present west of Haweswater (Beddoe-Stephens, 2000a; Woodhall, 2000), the formation is best developed east of the reservoir. The type area is designated between Swindale and Great Ladstones [514 130 to 535 121]. The lower boundary crops out north of Mardale Banks [485 130] where bedded acid andesitic tuffs rest conformably with sharp contact on welded silicic tuffs of the Whelter Knotts Formation. The upper boundary is equally well defined by the base of the Froswick Formation though, along much of the contact, andesite intrusions intervene. The Mardale Formation is cut by the Swindale Fault, but in the absence of distinctive marker units occurring on both sides of the fault, the full thickness of the formation is not known; it is estimated to be at least 980 m. The original thickness has been inflated by a considerable number of andesite intrusions.

A wide range of sedimentary and pyroclastic lithofacies comprise the formation, but acid andesitic pyroclastic rocks dominate in the lower part, particularly north-west of Swindale. There, two extensive, thick and distinctive bedded pyroclastic units are assigned member status: the Brown Howe Member at the base of the formation, and the Rowantreethwaite Member a little above this. Thick units of massive lapilli-tuff, interpreted as ignimbrite, are also present, the first beneath the Rowantreethwaite Member and the second within the upper part of the formation, south of Swindale. The upper part of the formation is dominated by volcaniclastic sedimentary rocks, but even in this part there are numerous units of bedded pyroclastic rocks that are too thin and limited in extent to be mapped separately. In the uppermost part of the formation are two volcaniclastic breccia units, the Gouther Crag and the Great Ladstones members.

Bedded volcaniclastic sandstone is dominant, particularly in the upper part of the formation. West of Swindale in the lower part, this lithofacies is poorly represented. A few metres, or locally a few tens of metres, of bedded volcaniclastic sandstone separate successive andesite sheets above the Rowantreethwaite Member north-west of Swindale east of Woof Crag and around Hannah Crag. Rather thicker units of volcaniclastic sandstone occurs around Swindale Head, cropping out within fault blocks of the Swindale Fault Zone.

Underlying the Gouther Crag Member on the south side of Swindale most of the volcaniclastic sandstone occurs in very well bedded, parallel, thin to very thin and laminated units of fine- to coarse- grained material. Locally, some of these are intensely disturbed with convolute lamination. Channels up to 20 cm deep containing trough cross-bedded sandstone are present in some places (e.g. at [5095 1248]). Medium-thick beds of coarse-grained sandstone contain cross-bedding, with identifiable foreset lamination suggesting transport to the south-east. Medium and thick beds of granule and pebble conglomerate are massive to weakly normal graded and some have thin reverse graded bases, indicative of mass-flow. Soft-sediment faulting is sporadically present throughout these rocks, dominantly with displacements down to the south-east.

The bedded volcaniclastic rocks between the Gouther Crag and Great Ladstones members are, in general, coarser grained than the rest of the formation, with mainly pebbly medium- and coarse-grained sandstone, pebble conglomerate and breccia. Beds up to 5 m thick are typically massive to weakly bedded and in places crudely cross-bedded. Typically, weathered surfaces are pock marked and substantial proportions of pumice or scoria are present in some units. These sandstones are typically poorly sorted and matrix supported containing a substantial proportion of silt and clay (e.g. E72193). The angular lithic clasts include a wide range of volcanic lithologies from amygdaloidal basalt through to felsite. Crystal fragments of feldspar and subordinate pyroxene comprise up to 20% of some rocks. Interbedded with the coarse-grained rocks are variable proportions of thin- and medium-bedded or laminated, moderately to well sorted, coarse- and medium-grained sandstone; some units are strongly trough cross-bedded. One of these units is also characterised by abundant soft-sediment faults, many of which are thrusts indicating consistent movement to the north-west [5200 1251].

Planar bedded sandstones in the lower part of the sequence are interpreted generally as probable lacustrine sediments, interrupted periodically by fluvial activity and turbidites. The single occurrence of foreset lamination indicates sediment derivation from the north-west. The coarser upper part was deposited largely from mass flows, probably reworking contemporaneously erupted pyroclastic deposits. The probable rapid accumulation rate of much of this sediment and the evidence for soft-sediment deformation testify to the instability of the sediment pile.

4.1 BROWN HOWE MEMBER

The Brown Howe Member **(BnH)** is the basal unit of the Mardale Formation in the Haweswater area and crops out from Low Forest [499 151] south to Rowantreethwaite Beck. The member is distinguished from the main part of the Mardale Formation because it wholly comprises bedded acid andesitic/dacitic pyroclastic rocks, which show complex intercalation with autobrecciated andesite sheets that are interpreted as contemporaneous, high-level sills. The base of the member, and also of the formation, is sharp and generally conformable on the uppermost rocks of the Whelter Knotts Formation; the junction marks an abrupt change in eruption style. South of Guerness Gill, the Brown Howe Member rests on a thin sequence of bedded silicic ash-fall tuff at the top of the Whelter Knotts Formation. Elsewhere, the silicic tuff is missing and there is probably a relatively minor discordance, but no change in dip, as seen about 800 m east of the Haweswater Hotel. The excellent exposures between Mardale Banks and Guerness Gill are designated the type area [479 122 to 486 130]. The Brown Howe Member is estimated to be about 135 m thick, but extensive faulting and the presence of andesite intrusions makes this uncertain.

Well-bedded, well-sorted, coarse tuff and fine lapilli-tuff comprise the Brown Howe Member. The sequence is mostly planar bedded, but locally there is some thinning and thickening accompanied by low-angle cross-lamination. The average bed thickness apparently decreases upwards. Overall, a greater proportion of coarser units are present in the lower part, where packages from 30 cm to 2.5 m thick are characterised by abrupt bed to bed alternations in grain size and sorting. The highest parts are dominated by monotonously parallel laminated, well-sorted, even-grained coarse tuff and intercalations of fine tuff; there are sparse medium to thick beds of fine lapilli-tuff.

A variety of lithofacies is recognised and these are outlined below with brief interpretations:

- thick and very thick beds of scoria-rich lapilli-tuff with strong diagenetic flattening fabric (pyroclastic fall unit)
- massive, medium to thick beds of well sorted coarse tuff (pyroclastic fall unit)
- well-sorted coarse tuff with intercalations of fine tuff in normally graded, parallel, thin-bedded to laminated units up to about 5 m thick; at one locality [4858 1281], there are many layers of accretionary lapilli; some units are capped by 10–15 cm of splintery, very fine-grained tuff with abundant cross-lamination (pyroclastic fall unit, reworked at top)
- thick beds of poorly sorted, lithic-rich fine lapilli-tuff up to about 1 m thick with faint internal lamination, non-graded or in part normally coarse-tail graded (possibly pyroclastic density flow or debris flow deposit)
- thick beds of coarse lapilli-tuff with sharp channel-like bases; internally massive or weakly stratified; normal and reverse graded; reverse-graded bases to some beds; (pyroclastic density flow or debris flow deposit)
- strongly trough cross-laminated units occur locally throughout the succession, and some have lags of breccia at the base of channels. Locally, a 2–3 m-thick, east-facing rotational landslip is preserved on the margin of a steep channel [4832 13160]; (fluvial reworking of pyroclastic deposits and evidence of contemporaneous erosion).

Soft-sediment slumping and minor convolute lamination affect some of the finer grained units; localised, intense deformation of tuffs in the form of steep dips and dome-like folds is probably related to andesite intrusions; early indurated or lithified tuff is in places brecciated [4839 1313].

The tuffs contain numerous pyroclast lithologies (e.g. E71709). Angular and irregular pieces of vesicular scoria with sparse feldspar and chloritised mafic phenocrysts probably represent a juvenile component. Some of these pyroclasts are elongate and flattened against adjoining clasts. Variable proportions of other clasts include angular fragments of silicic vitrophyre with feldspar phenocrysts and perlitic cracking, dacite with snowflake texture, and several texturally distinct types of basalt/basaltic andesite. The crystal component in the tuffs includes altered feldspar and mafic pseudomorphs.

Intercalated with the bedded pyroclastic rocks is a unit, 4 to 6 m thick, of massive, very poorly sorted, clast- to matrix-supported coarse pyroclastic breccia. Only a few small outcrops of this unit occur on the south-east side of Mardale Banks [4792 1228; 4802 1253; 4812 1240]. Its sharp base is overlies autobrecciated amygdaloidal andesite containing pockets of laminated sandstone. The pyroclastic breccia comprises angular lapilli and bombs from 2 cm to about 35 cm, many of them exceeding 10 cm. The main characteristic of this unit is the presence of abundant elongate bombs of finely banded, intensely amygdaloidal and sparsely feldsparphyric andesite (E71712), giving the deposit a crude planar fabric. Some of the bombs are folded and twisted around other clasts, or envelop matrix and scattered extraneous lithic pyroclasts. A thin chilled rind to the bombs contains highly irregular vesicles that have been elongated parallel to the clast margin. Other pyroclasts present include equant, knobbly andesite and sporadic silicic clasts. Though juvenile pyroclasts are ubiquitous, the proportion of lithic pyroclasts is substantial in some parts of the unit (e.g. E71708). The matrix comprises smaller fragments of amygdaloidal andesite and the other lithic clasts. The lowest few metres are matrix supported and, at one locality [4830 1283], the lowest 2 m are reversely graded.

North of the Naddle Beck Fault, 700 m east-north-east of the Haweswater Hotel, is an heterolithic conglomerate [4906 1412] about 15 m thick. This unit varies from clast to matrix supported, and is poorly sorted and unbedded. The clast population comprises andesite and some acid tuff, generally well rounded and highly spherical. Clast size is mostly up to 150 mm, but the largest is up to 300 mm.

Interpretation

The pyroclastic rocks of the Brown Howe Member show evidence in places of local reworking by fluvial and mass-wasting processes. Grain size and bed forms in the pyroclastic rocks suggest that fall-out processes dominated, interrupted by periodic pyroclastic density currents. The large number of intrusions was probably emplaced contemporaneously causing considerable disruption to the unconsolidated deposits.

The plastically deformed bombs in the pyroclastic breccia indicate incorporation of spatter and emplacement of the deposit whilst hot. The massive nature and the reverse-graded base are indicative of emplacement as a pyroclastic density current. The only other recorded example of spatter-rich breccias in the Borrowdale Volcanic Group is the Pavey Ark Member on the Langdale Pikes (Kneller and McConnell, 1993). It is possible that this breccia is similar in origin to spatter-rich pyroclastic flow deposits described from Santorini (Mellors and Sparks, 1991).

4.2 ROWANTREETHWAITE MEMBER

The Rowantreethwaite Member is distinguished from the Brown Howe Member on grain-size, composition and bed-form characteristics. A sequence of very distinctive, pale weathered, well bedded dacitic pyroclastic rocks crops out within a number of fault blocks between Rowantreethwaite Beck and the Mullender Fault to the east of Woof Crag [at 496 129], a distance of about 2 km. In the south-west, on Rowantreethwaite, the member overlies a massive, lithic-rich lapilli-tuff. To the north-east, on Ritchie Crag [490 123], it is underlain by a few metres of bedded volcaniclastic sandstone on andesite and near Woof Crag it is underlain by andesite. The base is a sharp contact. At all localities the member is overlain by andesite sheets, interpreted as sills. An almost complete sequence through the member is exposed on Ritchie Crag, the designated type section; the thickness varies between 40 and 100 m.

The Rowantreethwaite Member **(Rwt)** comprises planar, well bedded lapilli-tuff and tuff. The pale weathered surfaces of the rock suggest a silicic (?dacitic) composition. Grain size varies from pebble to silt, though individual beds are generally moderately to well sorted. Broadly, the deposit becomes finer grained, better sorted and thinner bedded upwards, but on a smaller scale characteristically abrupt bed-by-bed changes in grain size give the unit a striped appearance. Clasts are dominantly angular and non-amygdaloidal, up to 40 mm, but generally less than 10 mm. Accretionary lapilli occur within some laminated tuff units. On Ritchie Crag [4892 1236 to 4901 1231] the base of the member is not exposed, but is taken at the prominent bench below where a few metres of bedded volcaniclastic sandstone overlie andesite. The 80 m-thick sequence there comprises four parts:

1. Unit D (top): planar, thin and very thin-bedded coarse tuff. Some beds are gently undulating, weakly lenticular or with minor pinch and swell structures. Accretionary lapilli, generally 1 to 7 mm diameter, are present in a number of beds. The tuff is generally well sorted. The basal contact is sharp and irregular, and the unit is more than 20 m thick.
2. Unit C: chaotic, poorly sorted, convoluted breccia of material similar to Unit D; intraclasts within this breccia contain relict bedding structures. 0.7 m thick, sharp, locally steep, cross-cutting channel-like base.
3. Unit B: planar-bedded tuff and lapilli-tuff in which bed thickness decreases upwards from dominantly thick at the base to medium and thin at the top; medium beds of lapilli-tuff are typically capped by a thin unit of whitish weathered fine tuff. Numerous localised bedding discordances with amplitudes up to about 50 cm, particularly in the lowest 10 m, are mantled by plane parallel beds. Some soft-sediment faulting affects the beds. Approximately 25 m thick, passes abruptly down into unit A.
4. Unit A (base): even, planar thin beds of rhythmically layered, well sorted tuff and fine lapilli-tuff; 4.5 m thick.

Almost all of the tuff and lapilli-tuff are composed of closely packed, wispy, ragged juvenile pyroclasts of pumice and crystals. In many beds the larger clasts are elongate parallel to bedding, whereas the smaller fragments are approximately equant (e.g. E71757). The proportion of free feldspar crystals is estimated to be up to 15%, but this may be inaccurate because alteration commonly masks fragment boundaries and similar feldspars also occur within the pumice. Lithic pyroclasts are generally sparse, though there are concentrations, particularly of angular microcrystalline silicic rock, in some beds (e.g. E71798).

Laminated units of silt- and clay-grade silicic material are locally characteristic of this deposit. In one example (E71798), individual laminae are structureless, with few recognisable crystal and lithic fragments. In another (E71758), the tuff appears to be strongly striped comprising alternating layers up to 5 mm thick of silt/clay grade with medium to coarse sand-grade layers of feldspar and mafic crystals and silicic ash. In this example, the very fine-grained layers contain faint circular outlines, 0.4–0.7 mm in diameter, reminiscent of closely packed, accretionary lapilli.

Interpretation

The dominance of well-bedded units of well-sorted pumice pyroclasts suggests that pyroclastic fall-out was the main mechanism of deposition. However, lenticular beds and units rich in accretionary lapilli probably indicate a subordinate pyroclastic surge component. The absence of extensive interbeds of reworked tephra suggests that the Rowantreethwaite Member represents a single eruptive episode.

4.3 UNNAMED PYROCLASTIC UNITS

Thin packages of pyroclastic rocks are intercalated with the volcaniclastic sedimentary succession in the upper part of the formation. Some are clearly recognisable, but there may be many other beds the characteristics of which are more equivocal. Pyroclastic rocks are notably present just below the Gouther Crag Member. For example, just south of Dog Crag a 5 to 6 m thick unit of massive, very poorly sorted, lithic-rich, eutaxitic lapilli-tuff, is interpreted as an ignimbrite [5109 1246]. It locally contains ovate dacite blocks up to 250 by 60 mm. To the north-east of this locality, the lapilli-tuff is overlain by rhythmically layered, planar thin to medium beds of coarse tuff, intercalated with 20 to 40 cm thick beds of well sorted lapillistone. Some units are capped by very fine-grained layers up to 5 cm thick. Though the ignimbrite is not identified within the succession north-east of Gouthercrag Gill, bedded pyroclastic rocks, containing abundant beds of accretionary lapilli and pumice lapillistone, occur in a similar stratigraphical position at [5201 1312], 600 m east of Truss Gap. These bedded pyroclastic rocks are interpreted as fall-out and/or surge deposits.

The lower of two units of massive lapilli-tuff crops out within fault blocks between Rowantreethwaite Beck and the Mullender Fault, east of Woof Crag, a distance of about 2 km. It is well exposed on Rowantreethwaite [4871 1224], comprising unwelded, very poorly-sorted, matrix-supported, lithic-rich andesitic lapilli-tuff containing chloritised equant and wispy pumice (E71790). The angular lithic clasts are dominantly nonvesicular pilotaxitic and scoriaceous basaltic andesite, but also include glassy and snowflake-textured silicic clasts; sporadic clasts of a relatively soft rock type weather to form subspherical hollows on the rock surface. Clasts are generally less than 40 mm across but, east of Woof Crag [at 4985 1297], blocks up to 45 cm are present. A crystal component comprises 5–10% altered feldspar. Bedding is mostly absent, except north of Ritchie Crag [at 4916 1256] where lithic lapilli-tuff is intercalated with weakly bedded tuff units up to 30 cm thick.

The upper unit crops out from the top of Outlaw Crag to Waite Howes [511 123 to 521 127], south of Swindale. It comprises very poorly-sorted, ungraded, lithic-rich dacitic coarse tuff and lapilli-tuff that is weakly eutaxitic. There are abundant irregular juvenile clasts, altered to aggregates of chlorite, quartz and feldspar, and enclosing sparse, altered feldspar crystals (E71815). A crystal component comprises similarly altered feldspars and the lithic clast population is dominated by prominent pale angular glassy silicic clasts (as indicated by perlitic cracking).

4.4 GOUTHER CRAG MEMBER

Volcaniclastic breccia, characterised by abundant, conspicuous, pink rhyolitic clasts, crops out south of the Swindale Fault, for approximately 2 km between the Dry Grove Gill and Mullender faults. This distinctive breccia is named the Gouther Crag Member **(GrCg).** It is underlain by volcaniclastic sandstones of the main part of the formation and overlain by eutaxitic, dacitic lapilli-tuff. The base of the breccia is sharp and generally conformable, though locally there is some minor channelling into the underlying beds. Thickness increases north-eastwards from 80 m above Dog Crag, to 145 m on Gouther Crag [514 126], and 180 m on Waite Howes [519 128]. In the southern part of the outcrop the breccia is divided by an andesite sill up to 80 m thick, but to the north-east the sill is discordant, passing up to the top of the member. The sill was possibly emplaced along the boundary between two component sheets though there is no other evidence to support this.

The Gouther Crag Member comprises a unit of massive volcaniclastic breccia. Sorting is poor but overall the deposit fines upwards; the breccia is matrix to clast supported in the lower part, becoming matrix supported in the upper. The angular, polylithic clast population is dominated by lapilli and blocks of pink nonamygdaloidal rhyolite, along with eutaxitic lapilli-tuff, banded vitrophyre, and some elongate slabs of banded andesite. The size of these mostly ranges from 20 to 200 mm, but scattered blocks of 500 to 800 mm are present in places. The alignment of platy clasts approximately with the boundaries of the deposit gives a crude fabric locally. East of Waite Howes [at 5204 1283] the uppermost few tens of metres comprise very poorly sorted, crudely bedded pebble conglomerate and pebbly very coarse-grained sandstone.

Interpretation

The grain-size distribution, the poor sorting, lack of organisation and matrix support suggest that the breccia is best interpreted as a debris-flow deposit. The dominant pink, nonamygdaloidal rhyolite clast is a lithology that is not seen in adjacent parts of the succession. Its abundance suggests local derivation either from a contemporaneous lava dome of that composition or from rocks formerly exposed in nearby fault scarps; collapse of either of these may have triggered the debris flow. The direction of transport is not known.

4.5 GREAT LADSTONES MEMBER

Unbedded volcaniclastic breccia of the Great Ladstones Member **(GtLa)** comprises the uppermost unit of the Mardale Formation south-east of Swindale. The member crops out between Glede Howe [520 120] and Little Ladstones [535 126]. The breccia overlies volcaniclastic sandstone of the main part of the formation and is up to 250 m thick. Andesite intrusions interdigitate with breccia at the western margin and occur both within the member and at its base throughout the outcrop. The eastern limit of the member is faulted.

The Great Ladstones Member comprises massive to weakly bedded, pebbly coarse-grained sandstone and volcaniclastic breccia in which the clasts are mostly 10 to 40 mm in diameter, but sporadic clasts reach 0.8 by 1.3 m. The breccia is clast to matrix supported and very poorly sorted. The clast population is heterolithic, and dominated locally either by silicic or andesite fragments; the former are acutely angular, glassy (perlitic cracking), sparsely feld-sparphyric or aphyric rhyolite or dacite (e.g. E72179). Other texturally distinct andesite and dacite clasts are present, along with sparse clasts of pilotaxitic-textured amygdaloidal clinopyroxene-phyric basalt. Most of the larger blocks are of bedded volcaniclastic rocks. Pumice is typically absent, except locally on Little Ladstones (see below).

A number of discrete depositional units, 3 to 20 m thick, are recognised within the lower part of the member on Little Ladstones [5345 1267]. These comprise unbedded, very lithic-rich breccia containing variable proportions of lithic clasts and pumice. The thickest (15 to 20 m) of the units present is normally coarse-tail graded and towards the top there is about 5% of pumice clasts up to about 10 mm across. This overlies a crudely bedded lithic breccia (3 to 4 m thick) and a uniform pumice-rich volcaniclastic breccia (<5 m, base not seen). Those parts of units with substantial pumice content have a weak eutaxitic-like texture locally.

Interpretation

The sorting and grading characteristics within the unit are consistent with a debris-flow depositional mechanism. The presence of pumice locally in units on Little Ladstones could suggest either a debris-flow or pyroclastic density current origin. The apparent eutaxitic texture in these rocks is probably due to diagenetic flattening.

5 Froswick Formation

Massive and eutaxitic to parataxitic, acid andesitic to dacitic lapilli-tuff comprises the Froswick Formation **(Fsw)** which forms a broad outcrop across the district from the north-western slopes of Branstree [472 103] to Stackhouse Brow, north of the Wet Sleddale reservoir [547 124]. These pyroclastic rocks form some of the prominent topographical features in the district, including Selside Pike (655 m) [491 112], Nabs Crag [502 112], Willy Winder Hill (484 m) [522 116] and Seat Robert (515 m) [526 114]. This newly defined formation is based on the Froswick Tuffs which Mitchell (1934) recognised throughout the area between Longsleddale and the Shap Fells (Johnson, 2001). In the east of the district the lapilli-tuff sharply overlies breccias at the top of the Mardale Formation, but westwards a substantial thickness of andesite sills has been emplaced between the Mardale and Froswick formations. The Froswick Formation is overlain by volcaniclastic sandstones of the Seathwaite Fell Formation. On Swindale Common, the formation is between 570 and 640 m thick, but elsewhere the sequence is faulted. The type area is designated as Swindale Common [5130 1175 to 5145 1080], where the formation is extremely well exposed, including the base and top contacts.

At the base of the formation in the type area, lenticular masses up to about 10 m thick comprise matrix-supported lithic lapilli-tuff and tuff-breccia, with heterolithic clasts up to 200 mm across [e.g. at 5111 1153]. Adjacent to the Brant Street Fault in Rowantreethwaite Beck [484 118] and on Mardale Common [486 114], lithic tuff-breccia and coarse lapilli-tuff form the lowest part of the formation seen. The lithofacies is very poorly sorted, clast to matrix supported, but is not bedded nor graded. Clasts are angular to subrounded and mostly less than 100 mm, though blocks up to 0.8 m are locally common. They comprise variously textured, dense andesite and dacite, vesicular andesite and a few of eutaxitic silicic lapilli-tuff. The breccia passes abruptly up into lithic-rich lapilli-tuff. Though this tuff-breccia on Mardale Common crops out adjacent to faults it is thought to be near to the base of the formation. By contrast, the lowest few metres of the formation in a fault block east of Selside Pike near Black Wood comprise white-weathered, bedded lapilli-tuff [4970 1122]. Bedding is thin, faint and planar with layers of single lithic lapilli mostly 10 to 20 mm in diameter and a few up to 60 mm.

In the type area the lower part of the formation comprises mostly splintery, white-weathered lapilli-tuff with a pronounced eutaxitic texture in which the fiamme are deformed around rigid lithic clasts indicating that the rock is welded (E72528). This grades into massive lapilli-tuff with sparse fiamme but abundant lithic lapilli. The angular lithic clasts dominantly comprise felsitic rocks with banded, spherulitic and snowflake textures; variously textured andesitic fragments are subordinate (E72530). The lithic-rich lithofacies is well exposed on High Wether Howe [515 109]. There are no textures in these rocks to indicate whether they are welded. Towards its top the formation becomes finer grained, the massive tuff comprising angular equant chloritised ash fragments up to 0.5 mm in a very finely crystalline mosaic of quartz and feldspar (E72532); there is no evidence that this rock is welded. Weak bedding is patchily present in this part of the unit, for example at [5174 1112]. Locally at the top of the formation, for example at [5225 114], welding fabrics in the tuff are folded and brecciated.

A sharp change in lithofacies, here marked by a prominent feature, is seen also in the middle part of the formation from Selside Pike to Nabs Crag. The lower part of the formation there comprises lithic-rich lapilli-tuff, typically without mesoscopic evidence of welding fabrics. This is overlain by splintery, glassy tuff containing up to 25% crystals of plagioclase and pseudomorphs after a mafic mineral, passing up into parataxitic lapilli-tuff with intrafolial isoclinal folds [5002 1106]. These rocks contain very few lithic clasts (E72157, E72158). This division cannot be traced farther west, nor east, but another internal boundary occurs farther east from the type area to Willy Winder Hill [521 115], where eutaxitic and parataxitic lapilli-tuff overlies lithic lapilli-tuff with a sharp contact.

In much of the outcrop on Brant Street, Selside, High Birkin Knott [495 120] and south of Hobgrumble Gill [495 106], the formation comprises massive, lithic-rich, fine lapilli-tuff that is matrix supported, very poorly sorted and ungraded (E71816). Locally, this grades into pumice lapilli-tuff with few lithic clasts, as for example on Mardale Common [4872 1142]. Outcrop-scale welding fabrics appear to be sparse in this area, though locally a fine eutaxitic texture is seen with a hand lens. On Brant Street, fiamme-rich, eutaxitic lapilli-tuff is weakly bedded [4755 1075]. Throughout, lithic clasts are mostly less than 20 mm across, but a few up to 60 mm are present locally. The clasts are predominantly felsitic. The lapilli-tuff is typically strongly cleaved.

The widespread distribution, lithofacies and petrography indicate that the Froswick Formation is a dacitic ignimbrite emplaced during a large-magnitude pyroclastic eruption. The lithofacies variations present indicate complex eruption dynamics that produced systematic changes in the bulk volume of pumice and lithic clasts. Deposition was from multiple pyroclastic density currents. The coarse, lithic breccia facies at the base in some areas is interpreted as co-ignimbrite breccia and may be lag breccia. Petrographical evidence shows that the eutaxitic parts of the ignimbrite sheet are welded, but it is not known whether the lithic-rich zones have undergone a similar process. These widespread pyroclastic rocks constitute the second major ignimbrite-forming event within the Borrowdale Volcanic Group succession of the eastern Lake District.

6 Seathwaite Fell Formation

The Seathwaite Fell Formation **(Set)** comprises a sequence of strongly cleaved, bedded volcaniclastic sandstones. Its outcrop extends from Branstree [477 101], eastwards to Mosedale [506 105] and thence to Sleddale Beck [530 105]. With local exceptions, exposure is generally poor. The base of the formation in the area is defined by the sharp change in lithology from massive, silicic lapilli-tuff of the underlying Froswick Formation to bedded volcaniclastic sandstone. The irregular upper surface of the Froswick Formation has been infilled with volcaniclastic deposits. The Seathwaite Fell Formation is overlain by a thick succession of andesite sheets, and a dacite sill is located at the base of the formation south of Captain Whelter Beck [485 107]. The formation is 200 to 230 m thick, except on Howes [499 103] where there are only about 120 m.

The Seathwaite Fell Formation in the district is best exposed on Howes [499 103]. The irregular upper surface of the underlying Froswick Formation is overstepped sharply by the sandstone lithofacies. On the north-east side of Howes, at [505 106], a few metres of fine-grained volcaniclastic sandstone at the base of the formation are overlain by a massive unit of very fine-grained silicic tuff in which the only identifiable clasts are minute feldspar crystal fragments (E72170). Above this, the formation comprises alternations of well-bedded and sorted units of fine- to coarse-grained volcaniclastic sandstone and poorly sorted, pebbly coarse-grained sandstone and breccia. The finer grained units are typically planar, normally graded, laminated to medium thick beds. Some units have been intensely disrupted with load casts and convolute lamination. By contrast, the coarser units are matrix- and clast-supported and poorly sorted. These units are up to 5 m thick, massive to weakly bedded and locally include discontinuous, lenticular beds and trough-like cross-sets.

The basal part of the formation is also well exposed south-east of Haskew Tarn [522 110]. There, the irregular upper surface in massive and brecciated lapilli-tuff of the Froswick Formation is filled in by a succession of white to pink-weathered, bedded tuff, overlain by volcaniclastic breccia and sandstone. The planar thin- and very thin-bedded tuff is fine to coarse grained, and well sorted with normal-, reverse- and multiple-graded units. Locally there is low-angle cross-bedding and some soft-sediment faulting. Bedding and grading characteristics suggest that these rocks are pyroclastic fall-out and surge deposits.

The overlying volcaniclastic rocks are medium to very thickly bedded extremely poorly sorted pebble-breccia and very coarse-grained sandstone. The following lithofacies are present:

1. Chaotic, very poorly sorted, clast- to matrix-supported, laterally impersistent units of heterolithic breccia up to 3 m thick; mainly coarse pebbles and some cobbles of andesite, dacite and lapilli-tuff; locally some boulders up to 0.5 m; interpreted as debris-flow deposits.
2. Units 1 to 1.5 m thick showing alternations of thin- and medium-thick beds of breccia and sandstone; granule- and pebble-breccia typically occurs in lenticular units and the very coarse-grained and pebbly sandstone is locally cross-laminated; interpreted as high-energy stream deposits.
3. Units up to 30 cm thick of massive to weakly laminated coarse-grained sandstone with cross-laminated tops; interpreted as mass-flow deposits.

The sandstones are generally composed of close-packed angular to rounded, equant grains of dense volcanic rock and scoria/pumice. The lithic grains are mostly of variously textured andesite, with subordinate dacite (e.g. E72195). Rare flakes of mudstone in a few samples were either derived from phreatomagmatic deposits, or eroded from exposures of Skiddaw Group (E72171; E72195). The crystal component is mostly very small, though locally, some coarse-grained sandstone beds are very rich in feldspar crystals (e.g. at [5269 1090]). The sandstones are intensely altered with abundant carbonate, chlorite and sericite associated with development of a strong cleavage. Rocks in the eastern part of the outcrop are within the metamorphic aureole to the Shap Pluton and contain much metamorphic biotite (e.g. E72165).

Ash-grade scoria or pumice, and chloritised vitric fragments comprise a substantial proportion of all thin sections examined; one sample (E72168) consists almost entirely of scoria and pumice. In the same sample, the grains vary from equant with circular amygdales to elongate with intensely flattened amygdales, a feature that probably results from differing degrees of diagenetic alteration. The highly irregular, angular shapes testify to little abrasion and transport. The abundance of scoria/pumice in all the samples examined suggests that in this district the Seathwaite Fell Formation was formed mainly of reworked tephra from penecontemporaneous eruptions, and not just from erosion of pre-existing volcanic rocks.

North of Tongue Rigg [5307 1024], planar thin beds of lapilli-tuff, intercalated with low-angle cross-laminated units of tuff, occur within a sequence of pebbly and very coarse-grained sandstones. The tuffs contain abundant spheres, many of which are identified as cordierite crystals in thin-section (E72166). However, also present are whole, and many fragments of, accretionary lapilli, up to 3 mm diameter. These have a narrow finer grained margin and a partially recrystallised quartz-feldspar mosaic centre.

7 Wet Sleddale Formation

The Seathwaite Fell and Lincomb Tarns formations are separated stratigraphically by a poorly exposed, strongly cleaved and extensively faulted succession of feldspar-phyric andesite sheets with sparse intercalations of volcaniclastic rocks, defined herein as the Wet Sleddale Formation **(WetS).** Previously, these rocks have been included within the 'Wrengill Andesites' (Mitchell, 1934). Many sheets within this widespread unit have been shown to be high-level sills (Millward et al., 2000; Johnson, 2001). The base of the formation is defined at the base of the lowest andesite sheet overlying volcaniclastic sedimentary rocks of the Seathwaite Fell Formation. In the Mosedale valley, north of Ash Knott at [5035 1044], many fragments of andesite at the base of the lowest, peperitic, andesite are suspended in sandstone. By contrast, beneath Todcrags to the east, andesite rests sharply on sandstone. The type area for the formation is Todcrags and Tongue Rigg [522 104 to 526 100]. The thickness of the formation is not known because of the extensive faulting and absence of diagnostic marker units to facilitate correlation between individual blocks. A minimum thickness of 1030 m is present in the area between Tongue Gill [533 100] and Wasdale Pike [538 087].

In the lower parts of the formation, massive andesite alternates with blocky autobreccia. By contrast, in the higher parts on Harrop Pike [501 078] and Great Saddle Crag [525 087], at least four sheets of basaltic andesite, 50 to 70 m thick, are highly amygdaloidal with scoriaceous autobreccia that comprises most of the thickness of some of these sheets. Interstices in the autobreccia contain laminated fine-grained sandstone. Flow banding is locally present on Brunt Tongue [5055 0930] and Little Saddle Crag [5264 0827].

An unusual autobreccia occurs below Todcrags [5241 1022]. The brecciated top to the andesite comprises knobbly, lapilli- to small block-sized fragments with angular, pillow-like, and subrounded, cauliform shapes; matrix present consists of fine grains of the same material. The textures suggest that the andesite has been quenched.

The rocks are extensively altered. In the west the rocks are generally grey and grey-green, and contain much carbonate, sericite and chlorite associated with anastomosing, spaced-cleavage domains. By contrast, in the east of the district, the andesites lie within the contact metamorphic aureole of the Shap pluton. Here, the abundant biotite overprinting of the igneous textures gives the rocks a brownish hue (see Chapter 14).

Most of the andesites have a very fine-grained groundmass containing up to 15% phenocrysts of feldspar, a mafic mineral and, in some rocks, Fe-oxide. The feldspar is sericitised or replaced by carbonate. The proportion of mafic phenocrysts is small but variable; these are replaced by chlorite and carbonate, or aggregates of quartz with an opaque rim (E72517). Feldspar-microphyric basaltic andesite within the sequence comprises a fine-grained aggregate of sericitised feldspar within a chlorite and opaque mesostasis (E72515). Amygdales typically comprise carbonate with smaller amounts of chlorite and opaques. In some rocks these minerals replace original chalcedonic structure (e.g. E72515).

Thin intercalations of volcaniclastic rocks occur locally within the formation, particularly between Todcrags and Tongue Rigg, around Great and Little Saddle Crags, and near Harrop Pike. These units appear to be absent in the area between Mosedale, Harrop Pike and Ulthwaite Rigg. On Todcrags, a unit less than five metres thick comprises laminated fine- and coarse-grained sandstone with numerous very thin layers of white siltstone, thoroughly disrupted in places. Another unit, south-west of Widepot includes normally graded, thin, planar bedded, medium- to coarse-grained volcaniclastic sandstone overlying autobrecciated andesite with interstices of laminated sandstone. On Harrop Pike, sheets of intensely amygdaloidal and scoriaceous andesite autobreccia are separated by planar laminated, medium- and coarse-grained volcaniclastic sandstone dipping gently north-west.

The uppermost of the volcaniclastic intercalations that crop out on Great Saddle Crag is 7 m thick altogether. The lowest 2 m comprises very faint, planar thin-bedded, lithic-rich, fine lapilli-tuff with angular, equant to elongate, pale grey, glassy looking dacitic fragments. This is interpreted as a pyroclastic fall-out deposit. The lapilli-tuff is overlain sharply by normally planar bedded medium- to coarse-grained volcaniclastic sandstone. Locally, there are troughs up to 20 cm deep filled with laminated sandstone, and channels with rip-up clast conglomerate. Poorly exposed, hornfelsed, unbedded, lithic-rich, lapilli-tuff crops out to the south of Wet Sleddale, on Tongue Rigg, above Tongue Rigg Gill, on Poor Hag [545 110], and Low Fell [560 110]. The lapilli-tuff is composed of poorly sorted clasts of various andesitic and silicic lithologies, generally up to 10 cm diameter.

The emplacement mechanism of this considerable thickness of andesite is largely uncertain because of the poor exposure. Few exposures of the upper contacts of the sheets provide criteria for interpretation and other considerations are permissive of both lava and sill origins. The intercalated volcaniclastic rocks within the Wet Sleddale Formation are indistinguishable form those in the underlying Seathwaite Fell Formation. Such sediments, capped by the highly competent Lincomb Tarns Formation welded ignimbrite would provide an environment that would typically favour sill emplacement. However, the very thick succession and the abundance of autobreccia might indicate that lava dominates. Unequivocal peperitic rocks occur at the base of the lowest andesite, but this is neither indicative of sill emplacement, nor is it typical of the whole formation. Andesite sheets at a similar stratigraphical level to the south-west of the district are interpreted as sills by Johnson (2001). However, on balance, it is felt that the Wet Sleddale Formation in the Shap Fells is a lava pile that may contain sills.

8 Lincomb Tarns Formation

A massive unit of lithic-rich, welded dacitic lapilli-tuff, interpreted as ignimbrite, crops out in two areas, separated by the Shap pluton. To the west of this intrusion, in the higher reaches of Crookdale Beck, across Lawyer's Brow, Yarlside and Wasdale Pike (Figure 1), poorly exposed lapilli-tuff overlies the sheeted andesite succession and is succeeded by further andesite sheets and Windermere Supergroup rocks. In this area the formation is 150 to 320 m thick. East of the Shap pluton and east of the A6 trunk road, the formation is largely covered by till, but it is exposed in the Shap Rhyolite Quarry [567 106], and in a number of small localities, mainly adjacent to Blea Beck. Here the formation is faulted against the underlying andesite succession, but is overlain unconformably by Carboniferous rocks. In this area, the thickness of the formation cannot be estimated because the dip of the strata is unknown. These volcanic rocks represent the easternmost occurrence of the Lincomb Tarns Formation **(LTa),** the most widespread ignimbrite in the Lake District.

The main lithofacies of the formation comprises intensely cleaved, unbedded, poorly sorted, matrix-supported lapilli-tuff. A weak to very pronounced eutaxitic texture is commonly present and the fiamme are strongly deformed around the rigid crystal and lithic clasts. The matrix in these rocks is turbid and highly altered. Though no vitric shards are preserved, variations in the devitrification textures (E72522) and the mineralogy of the thermal aureole over-prints (E72501) suggest that these rocks are strongly welded. Sericitised and carbonated feldspar crystals form less than 10% of the rocks. Conspicuous lithic clasts are common. They include within the rock pink-weathered felsite, and abundant dacitic, andesitic and probably basaltic clasts. These are typically angular and up to 10 mm across, though in places they are up to 60 mm and even to 100 mm across.

Splintery, white-weathered felsitic rocks, locally with a crude platy jointing, crop out on Brown Howe [520 084] and Wasdale Pike [537 085]. At the second of these locations the rocks underlie the main lithofacies of the Lincomb Tarns Formation and are considered to be the basal unit of the formation; they are also within the thermal aureole of the Shap intrusion and fresh surfaces of the glassy rock have a brownish hue. The basal part of the unit and of the formation is poorly exposed at the base of peat hags on the north side of Wasdale Pike at [5369 0866]. There, a few metres of eutaxitic lapilli-tuff overlie amygdaloidal, auto-brecciated andesite and pass up into splintery felsitic rock. The lapilli-tuff has a streaky matrix and common small, elongate to subspherical lithic clasts up to 10 mm. The felsitic rocks have typically finely crystalline devitrification mosaics of quartz and feldspar with less than 5% sparsely distributed phenocrysts up to 1.5 mm of feldspar and pseudomorphs of chlorite, probably after biotite (E72499, E72505).

The two-fold lithological division is also present east of the A6 trunk road, with felsitic rocks exposed in, and just to the south of, the Shap Rhyolite Quarry. The felsitic rocks are closely jointed, uniformly fine-grained, dark grey to pinkish grey and intensely hornfelsed (E72509, E72510). A fine-scale, flow-like foliation is present in exposures 350 m south-south-east of the quarry [5681 1023] (E72507). Near to Bleabeck Bridge [569 101] and farther to the east [573 104], adjacent to the unconformity with Carboniferous rocks, is lithic-rich eutaxitic lapilli-tuff (E72500, E72508).

9 Undifferentiated volcaniclastic rocks

Planar bedded, fine-, medium- and coarse-grained volcaniclastic sandstone is interdigitated with andesite sheets at the top of the Borrowdale Volcanic Group in the Shap Fells. These rocks crop out from the head of Stockdale Beck eastwards into the upper reaches of Crookdale Beck [500 067 to 520 072]. Locally, there are strongly trough cross-bedded units and lenticular beds with low-angle cross-sets. Typically the troughs are filled with pebbly coarse-grained sandstone. There are also some massive, pebbly coarse-grained sandstone units up to 1 m thick. These sedimentary rocks are interpreted as fluvial deposits and lie at the same stratigraphical level as the Esk Pike Formation of the Ambleside and Keswick districts.

10 Contemporaneous andesite sheets

Tabular sheets of andesite are particularly abundant in the Mardale Formation and at the top of the volcanic succession in the district; a single sheet of dacite has also been recognised. Sills are probably also present within the largely extrusive Birker Fell and Wet Sleddale formations, though the proportions are unknown. The Brown Howe Member is intensely disrupted by sills that vary from 20 to 50 m thick. Between the Brown Howe and Gouther Crag members sills range in thickness up to 210 m. More than 600 m of sills around Low Blake Dodd [495 115] and Fewling Stones [511 117] interdigitate eastwards with the upper part of the Mardale Formation. Farther east, sills at this stratigraphical level are fewer and lenticular.

Many of the sheets are largely massive, though others are highly amygdaloidal and comprise mostly autobreccia. Examples of the latter include the units around Low Blake Dodd and Fewling Stones. Flow-banded and flow-jointed central zones to sheets are particularly well developed for example above Guerness Wood [488 142], Brown Howe [484 124] and on Woof Crag [493 129]. The lowest andesite within the Brown Howe Member contains rounded to elongate, chloritised xenoliths up to 10 cm across.

At the margins to the sheets, accumulations of angular blocks pass vertically and laterally into massive andesite, in places with jigsaw-fit fabrics. These autobreccias typically have an open framework, in which the interstices are filled with laminated fine-grained volcaniclastic sandstone. Blocks and pillow-like masses of andesite are present some metres away from the main andesite mass at some localities. Peperitic breccias and disruption of the adjacent pyroclastic rocks are typical of andesite within the Brown Howe Member. These andesites may have been penecontemporaneous with emplacement of the pyroclastic rocks, but this has not been proved geochemically.

Most of the andesites are intensely altered with abundant secondary carbonate and sericite. They are normally porphyritic, with 10 to 25% plagioclase and mafic phenocrysts and a few Fe-oxide microphenocrysts (e.g. E71794).

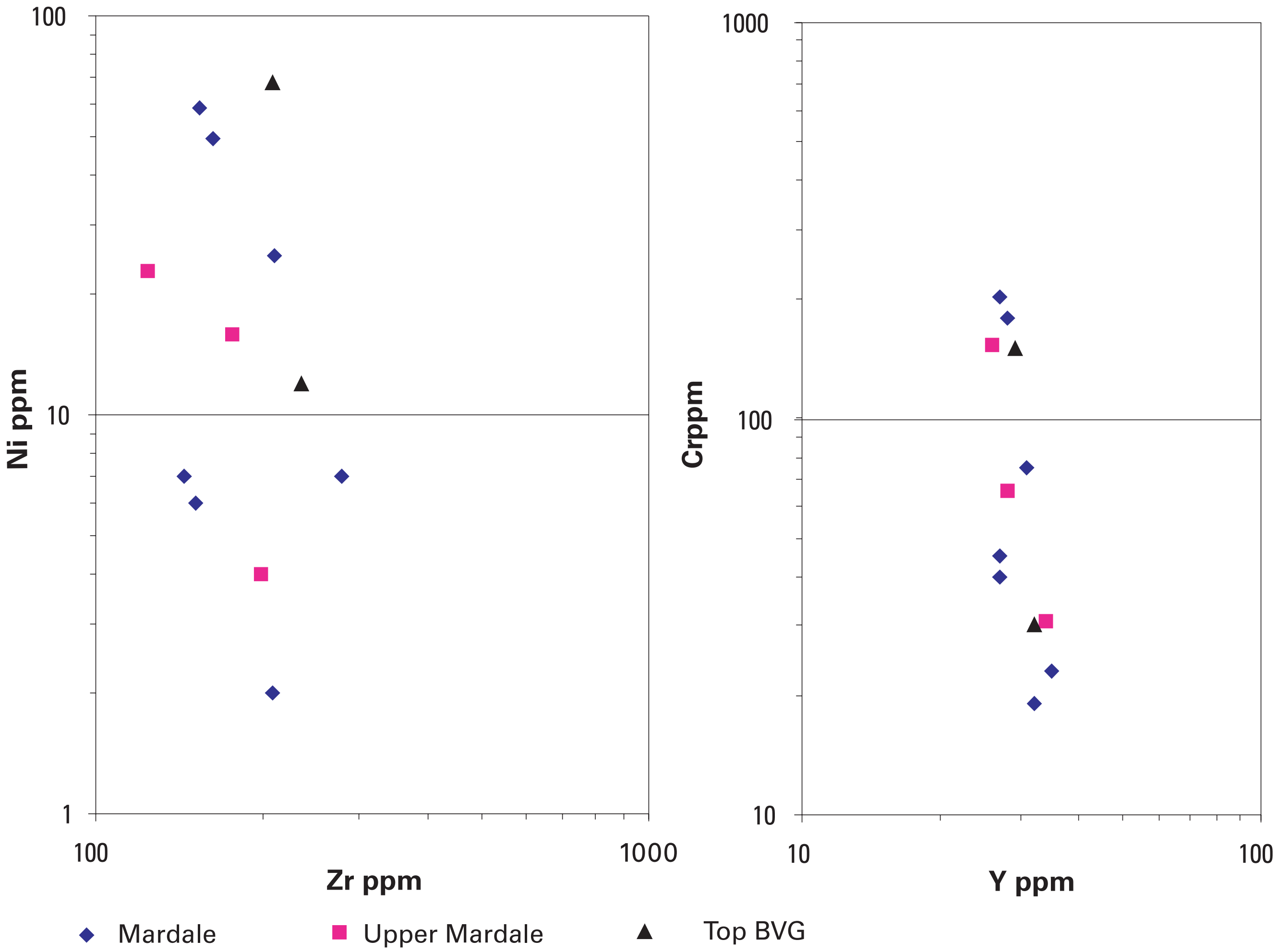

Figure 2 Ni-Zr and Cr-Y plots for sills from the middle and upper parts of the Mardale Formation and from the uppermost part of the Borrowdale Volcanic Group in the Shap Fells.

Plagioclase is dominant, except in a few samples where mafic crystals constitute up to 30% of the phenocrysts (e.g. E71793). Pseudomorphs after the mafic crystals have an elongate habit, typical of orthopyroxene; in some rocks these are accompanied by fresh clinopyroxene (augite), particularly within glomerocrysts (e.g. E72536). A few of the sills are aphyric (E71727) or contain less than 5% plagioclase and mafic microphenocrysts (E72536). A very finely crystalline groundmass is typical, with pilotaxitic, and intergranular textures; some devitrified glass may be present as represented by micropoikilitic (snowflake) texture (e.g. E72534). Fresh clinopyroxene is present in the groundmass of some samples (E71794, E72534).

On Woof Crag flow-banded, porphyritic andesite contains some fresh, but intensely fractured garnet. This mineral is present as anhedral grains, euhedral crystals, and within glomerocrystic aggregates (E71800). In this rock, a large euhedral crystal has an inner zone relatively free of inclusions, a central intensely fractured zone with many small inclusions of Fe-oxide, apatite and devitrified melt, and an outer zone with larger but fewer inclusions.

A 170 m-thick dacite sheet at the base of the Seathwaite Fell Formation on Swirle Crag in the upper part of Hopgill Beck [485 108], is massive to intensely autobrecciated. Angular to subrounded clasts in the autobrecccia are typically 1 to 15 cm across; some areas exhibit jigsaw-fit fabrics. A micropoikilitic groundmass hosts up to 5% phenocrysts of feldspar and a mafic mineral (?orthopyroxene), along with microphenocrysts of Fe-oxide (E72148).

Sheets of porphyritic acid andesite form the uppermost 180 m of the Borrowdale Volcanic Group succession on the Shap Fells. These rocks crop out from the head of Stockdale Beck eastwards into the upper reaches of Crookdale Beck [500 067 to 520 072], where they are truncated by the unconformity at the base of the Windermere Supergroup. Three sheets are present, the thickest of which is up to 70 m. Much of each of the sheets comprises autobreccia, but in some of the central parts the andesite is massive to flow banded. Autobreccia at the top of each sheet contains enclaves of laminated sandstone and siltstone and some substantial slabs of thinly bedded to laminated sandstone. The transition from autobreccia with internal sediment to slabs of sedimentary rock separating autobreccia strongly suggests that these andesite sheets are sills.

The andesites contain up to 15% phenocrysts and glomerocrysts, typically up to 2 mm, set in a turbid devitrified and altered groundmass of quartz, sericite, opaques and carbonate (E72540, E72541). The phenocrysts were dominantly feldspar, now replaced by carbonate, sericite and epidote. Also present is a small proportion of strongly pleochroic green biotite, occurring both as single crystals and in aggregates of feldspar, apatite and opaques. The biotite is in part replaced by carbonate, chlorite, opaques and titanite.

Thirteen samples of andesite from the district have been analysed geochemically, including examples of most occurrences described above, except for the dacite and sills from the lowest part of the Mardale Formation. The range in composition is from basaltic andesite to andesite and all are compositionally similar to other Borrowdale Volcanic Group andesites as reported by Beddoe-Stephens et al. (1995) and Kanaris-Sotiriou et al. (2002).

Ni-Zr and Cr-Y plots (Figure 2) show at least two elongate compositional fields parallel to the average fractionation trend calculated by Beddoe-Stephens et al. (1995, fig. 17), suggesting that samples in each field are related by crystal fractionation. The discrete groups suggest also that the abundant sills were derived from more than one batch of primary magma by fractional crystallisation and/or possibly magma mixing processes. However, there is no systematic relationship between geochemistry and the stratigraphical location of the sills.

11 The unconformity between the BVG and the overlying Windermere Supergroup

Independent mapping by N J Soper and D Millward of the interface between the uppermost rocks of the Borrowdale Volcanic Group and the lowest formations of the overlying Dent Group at the base of the Windermere Supergroup in the area from Mere Crag [504 066] to Wasdale Head [550 081] has shown that it is marked by an irregular erosion surface with several hundreds of metres of relief.

There is no significant change in strike or dip azimuth of beds above and below the unconformity, the inferred position of which accords with that on Mitchell's (1934) map. However, the localised presence of pyroclastic rocks at the base of the Yarlside Volcanic Formation (Dent Group) adds significantly to our understanding of Ashgill volcanism. Though the formations within the higher parts of the Windermere Supergroup have continuous, parallel outcrops, the very distinctive pink-weathered vitrophyre that comprises most of the Yarlside Volcanic Formation has a discontinuous outcrop and its irregular base oversteps successive units in the BVG beneath, indicating deposition within topographical hollows. The steep contact on the western flank of Great Yarlside between lithic-rich lapilli-tuff of the Lincomb Tarns Formation and the pink vitrophyre is interpreted as a simple contact and is not faulted, as suggested by Millward and Lawrence (1985). Thus, the outcrops of the vitrophyre between Mere Crag and Red Crag, and between Great Yarlside and Wasdale Head filled adjacent depressions, as originally suggested by Gale et al. (1979).

Within the topographical depressions, the vitrophyre is locally underlain by other rocks. Just to the north-west of the summit of Great Yarlside thinly bedded to laminated, grey, fine- and coarse-grained feldspathic sandstone and purple mudstone are exposed in a small excavation. Many blocks of these lithologies are seen in the nearby fell walls. About 1.5 km to the west in several places in Bleaberry Gill [5080 0686; 5148 0699] are exposures of pale, buff-weathered, grey, thinly laminated, fine-grained sandstone and siltstone. The rocks at these localities contain a volcanic component, but have proved to be barren of microfossils (Molyneux, 2000). Their overall appearance suggests that they should be included as part of the Stile End Formation, the lowest unit of the Windermere Supergroup.

Located stratigraphically between the laminated sandstone and mudstone of Bleaberry Gill and the pink vitrophyre are pyroclastic rocks. Mitchell (1934) includes these rocks within the Stile End Beds on his map, though he gives no further details. However, lithologically they form the basal beds of the Yarlside Volcanic Formation and are described below.

11.1 PYROCLASTIC ROCKS AT THE BASE OF THE YARLSIDE VOLCANIC FORMATION

The Dent Group, at the base of the Windermere Supergroup of northern England, contains the Yarlside Volcanic Formation (see Kneller et al., 1994), the most voluminous volcanic unit in this area that postdates the Borrowdale Volcanic Group. The geological setting, stratigraphy and petrography of the Yarlside Volcanic Formation, also known as the 'Stockdale Rhyolite' and 'Stockdale Rhyolite Member', were described and interpreted by Millward and Lawrence (1985); previous work on the rocks was reviewed recently by Millward (in Stephenson et al., 1999). The formation is dominated by a pink-weathered vitrophyric unit, interpreted by Millward and Lawrence as a rheomorphic ignimbrite, but there are also lenses of pyroclastic rocks underlying this unit in the western part of the outcrop.

Pyroclastic rocks underlying the vitrophyric component of the Yarlside Volcanic Formation crop out from north-west of Mere Crag [5020 0665] to north of Lord's Seat [516 069], apparently partially filling a hollow in the palaeotopography. Approximately 90 m of these rocks are estimated from the dip and outcrop width. They are exposed at two places. At the first [5027 0668], north-west of Mere Crag, a bedded sequence of coarse tuff and fine lapilli-tuff overlies autobrecciated andesite at the top of the Borrowdale Volcanic Group; there is no intervening Stile End Formation here. Bedding is generally planar, though in the lower part low-angle cross-lamination is common. Some beds of lapilli-tuff are internally massive. The second group of small exposures [5080 0686; 5095 0679; 5106 0682] lies between Red Crag and Bleaberry Gill. These silicic rocks consist of massive, crystal-rich, eutaxitic lapilli-tuff.

Thin sections of two samples (E72520; CT1942) from the second area show that these rocks comprise abundant crystal fragments (25–30%) and sparse chloritised pumice lapilli supported in a fine-grained vitroclastic matrix. Tiny vitric shards are evident, particularly in strain-shadow zones, and indicate that the rock is not welded (E72520). The crystal component is plagioclase feldspar, quartz and subordinate chlorite and opaque pseudomorphs after biotite. A very small proportion of lithic clasts is present in CT1942, comprising pilotaxitic basic rock fragments.

The abundant crystal content and vitroclastic nature of these beds, along with the bedforms present, suggest a primary pyroclastic origin, probably involving pyroclastic fall-out as well as deposition from pyroclastic density currents. By contrast, the vitrophyre and volcaniclastic rocks beneath it in the west of the outcrop of the Yarlside Volcanic Formation do not contain a crystal component. Thus, the record from the Mere Crag and Bleaberry Gill area is new and adds to the volcanogenetic significance of the Ashgill Yarlside Volcanic Formation.

12 Intrusive rocks

Intrusive rocks in the Lake District belong to two major phases of magmatism (Table 4; Hughes et al., 1996). The earlier episode occurred during Caradoc times associated with volcanism. In the Haweswater and Shap areas this episode includes the Haweswater intrusions (Millward and Beddoe-Stephens, 1998), numerous dykes, and the large number of andesite sheets within the volcanic succession. The sheets are an integral part of the Borrowdale Volcanic Group. The later magmatic episode took place during the Early Devonian and includes the Shap Pluton and associated dykes.

12.1 HAWESWATER INTRUSIONS (ORDOVICIAN)

Recent field, petrographical and geochemical investigations of the Haweswater intrusions have been described by Millward and Beddoe-Stephens (1998). More recently, two outcrops of dolerite have been located south of the main occurrences of these intrusions and these are described below.

The first dolerite [4928 1257] is located 450 m south-south-west of Woof Crag. A near-vertical contact with andesite is seen in part of the outcrop. The rock is leucodolerite (E71771), predominantly composed of aggregates of plagioclase feldspar and subordinate pseudomorphs after mafic crystals 0.5 to 1.2 mm across. Between these aggregates is a finer, largely crystalline phase, with a grain size of 0.1 to 0.2 mm and composed of euhedral plagioclase, small granules of an opaque mineral and small pools of anhedral granular quartz; some interstitial chlorite mesostasis is probably after glass. The two-phase type of texture seen in this rock is typical of many of the medium and coarse-grained rocks of the Haweswater intrusions.

A subcircular outcrop [4949 1267], 50 m in diameter, forms the second occurrence, 300 m east-south-east of Woof Crag. The dolerite also probably has a two-phase texture, but is dominated by interlocking plagioclase laths and euhedral tabular to interstitial oikocrysts of altered mafic mineral (E71799). The latter mineral is altered to chlorite with granules of iron oxide and some patches of carbonate and quartz. Within some of the pseudomorphs are small irregular patches and shreds of a greenish brown hornblende, similar in appearance to that described from the Haweswater gabbros by Millward and Beddoe-Stephens (1998). The fine-grained interstitial aggregate includes euhedral plagioclase and K-feldspar, and a microgranophyric mesostasis.

12.2 BASALT DYKES (ORDOVICIAN)

A few basalt dykes crop out within the area and may be related to the volcanism. They occur at the head of Guerness Gill [4884 1296], on Mardale Common [4866 1143] and between the top of Gouther Crag and Waite Howes [515 126 to 518 129], east of Swindale where they are up to 8 m wide. A thin section of the Guerness Gill dyke (E71760) shows this to be a very altered fine-grained basaltic rock with abundant secondary carbonate overprints. The preserved, primary igneous textures are weakly feldspar and mafic phyric and a holocrystalline, intergranular groundmass containing abundant rods of iron oxide, a feature typical of the finer grained members of the Haweswater intrusions.

12.3 SHAP PLUTON (EARLY DEVONIAN)

There is an extensive literature on the Shap granite, an Early Devonian pluton of considerable significance to the understanding of the timing of cleavage formation in the Lower Palaeozoic of northern England. The radiometric age of the granite is 397±7 Ma (K-Ar, biotite; Rundle, 1992). Previous work has been reviewed recently by S C Loughlin (in Stephenson et al., 1999) and a detailed description of the granite is not given here. However, two localities where the contact relationships are exposed are described below to demonstrate that the relationship between granite emplacement and cleavage formation.

In Sherry Gill [5385 1012], on the north-west side of the pluton both near vertical and gently inclined contacts are exposed. The granite is coarse and megacrystic up to the contact, except where 2 to 3 cm of aplitic microgranite or quartz veins locally occur along the contact. The granite appears to truncate the cleavage fabric in the country rock and does not appear to contain a tectonic fabric itself.

Irregular, intricate contacts between granite and country rock are exposed in Longfell Gill [5613 1009]. Here also the granite is coarse grained and megacrystic right up to the contact and is cut by microgranite veins. The granite and microgranite truncate the cleavage fabric in the hornfelsed country rock, and a few veins of granite have been intruded along the foliation. Further, there are rotated xenoliths of hornfelsed country rock within the granite. Hence the granite appears to postdate cleavage formation (see 14.1.1).

12.4 PORPHYRITIC MICROGRANITE AND MICROGRANODIORITE DYKES (EARLY DEVONIAN)

Dykes of pale pinkish weathered porphyritic microgranite are numerous in the Haweswater area, particularly between Kit Crag and Wallow Crag [491 145] where they cut the Haweswater intrusions, and also on Mardale Banks [480 128] within the Borrowdale Volcanic Group. Single dykes occur on Selside End [4938 1187], north-west of Powley's Hill [5022 1379], on Ash Knott [5042 1027] in the Mosedale valley, on Poor Hag [5440 1106] at the western end of the Wet Sleddale reservoir, and in Howe Gill [5556 1131]; there is also a single occurrence in Poor Hag Gill within the Shap granite [5465 1026]. Most of these dykes are orientated within 20° of west to east. However, the microgranodiorite dyke on Poor Hag trends 10° west of due north. Contacts are typically vertical and most of the dykes are less than ten metres wide, though one example on Mardale Banks locally reaches 55 m and can be traced for up to

Table 4 Lower Palaeozoic intrusive rocks in the Haweswater to Shap area belonging to the Caledonian Igneous Supersuite.

Suite	Lithodeme	Form	Lithology	Mineralogy and texture	Key localities	Notes
North Britain Siluro-Devonian calc-alkaline dyke suite		Dykes	Lamprophyre (spessartite)	Acicular brown hornblende, plagioclase and interstitial quartz; augite microphenocrysts; accessory apatite	Haweswater quarry [4947 1526]	Single example seen.
Lake District Devonian minor intrusion suite		Dykes	Porphyritic microgranite	Plagioclase-quartz-biotite-phyric with micropoikilitic feldspar and quartz groundmass; single example with K-feldspar phenocrysts	Mardale Banks [480 128]; Poor Hag Gill [5465 1026]	Except for Poor Hag Gill dyke most are partly cleaved; those within the aureole of the Shap Pluton are not hornfelsed
Northern England Devonian plutonic suite	**Shap Pluton**	Pluton	Orthoclase-perthite-megaphyric granite; sparse microdioritic enclaves and veins of aplitic microgranite	Quartz-K-feldspar-biotite with up to 30% K-feldspar megacrysts; accessory titanite, apatite, magnetite, zircon etc.	Sherry Gill [5384 1012]	Granite best exposed in Shap Pink quarry in adjacent Kendal district. Radiometric age 397±7 Ma (K-Ar, biotite)[1]
Lake District Ordo-vician mafic plutonic suite	**Haweswater intrusions**[2]	Plugs and dyke-like masses	Dolerite and gabbro (including hornblende-gabbro)	Plagioclase, augite, edenitic amphibole; accessory ilmenite, apatite, biotite, tourmaline; leucrocratic to melanocratic, intergranular and subophitic; in part porphyritic and two-phase	Lad Crags [4802 1509]; Haweswater quarry [4947 1526]; Wallow Crag and Naddle Forest [492 144–495 150]	Locally with igneous layering. Weakly cleaved. Geochemically very similar to mafic rocks in the Borrowdale Volcanic Group
		Plug	Microdiorite	Plagioclase, clinopyroxene, othopyroxene; accessory garnet	Great Birkhouse Hill [494 161]	Mineralogically and chemically distinct
		Marginal dyke-like zone	Intrusive breccia	Fragments of dolerite, gabbro, andesite and felsite in altered feldspathic clastic matrix	Kit Crag [4901 1447]	Marginal zone of Wallow Crag plug and scattered dykes
Lake District Ordo-vician minor intrusion suite		Dykes	Andesite, basaltic andesite and basalt	Typically plagioclase phyric	Sporadic throughout district	Probably related to Borrowdale Volcanic Group
Borrowdale Volcanic Group sill suite[3]		Sills	Andesite		Caudale Moor–Raven Crag [413 101–419 111]	In Esk Pike Formation only; with chilled margins
			Mainly andesite; also basaltic andesite and dacite		NW of Blea Water [444 110– 447 106]	Mostly emplaced into volcani-clastic sandstone formations; many with peperitic margins

All grid references, e.g. [494 161], are within the 100 km square NY. [1] *Rundle, 1992*; [2]*See Millward and Beddoe-Stephens (1998);* [3]*See also Woodhall (2000a).*

1.5 km. The geochemical composition and radiometric age of the dykes have not been determined. Field evidence suggests that the dykes were emplaced contemporaneously with Shap granite intrusion.

The three pink-weathered microgranite dykes cutting the Haweswater intrusions in the Kit Crag and Wallow Crag area have been described previously by Millward and Beddoe-Stephens (1998). The dykes are curved and have mapped lengths of 150 to 350 m. The southernmost of these dykes is 10 m wide and postdates the dolerite on Kit Crag [4904 1456]. The other dykes crop out within the dolerite mass and are generally 3 to 5 m wide; they appear to postdate faulting within the intrusion. The northern dyke contains a closely spaced cleavage defined by a white mica fabric (E71745).

A swarm of microgranite dykes in a narrow zone on Mardale Banks [479 128] spreads out eastwards over a distance of nearly two kilometres to Hare Shaw [499 133] and High Birkin Knott [494 120]. Four dyke segments are present on Mardale Banks and the other occurrences may be en echelon to these. The largest of these dykes varies in width from 10 to 55 m over a distance of 1.5 km. The width of the other dykes in the swarm varies from 10 to 30 m. Chilled margins are generally not present, though in places the outer parts are finer grained and less porphyritic than the centres. The marginal zones, and locally the central portions, of the dykes are typically flow-banded.

The Mardale Banks dyke swarm is mineralised locally. At one locality [4804 1286], microgranite is replaced by buff-coloured alteration products including well rotted feldspar and is riddled with quartz veins. The strongly sheared margin of the widest of the dykes at [4854 1263] is intensely altered with much gossany staining and is riddled with vuggy quartz veins.

Porphyritic microgranite contains typically between 2 and 20% phenocrysts of plagioclase feldspar, quartz and altered biotite. Commonly, the feldspar is sericitised or replaced by variable proportions of epidote, carbonate and chlorite. The quartz phenocrysts are typically corroded and embayed, and many have spherulitic overgrowths. The mica is normally replaced by chlorite and opaques and was probably biotite originally, but in some thin sections it is replaced by muscovite and opaques (e.g. E71761). In general, the groundmass textures are a fine-grained micropoikilitic intergrowth of feldspar and quartz, locally with radiate intergrowths of plagioclase laths set in a single quartz crystal; spherulites are present in places. Microgranite dykes within the Haweswater intrusions are finely pilotaxitic (E71733, E71738). Some of these rocks have a fine-grained devitrification texture of anhedral quartz and feldspar. They also contain variable amounts of carbonate, white mica, quartz and locally, epidote.

The age of these dykes is not entirely clear. They cut the northerly trending fault of probable volcanotectonic origin on Mardale Banks. The marginal zones of some of the dykes are cleaved, but other dykes are apparently uncleaved. Where present, the fabric is a rough, disjunctive cleavage defined by narrow, discontinuous to anastomosing seams of white mica, which show considerable variation in the spacing of the cleavage domains (e.g. E71817; E72172). The petrography and variable presence of cleavage suggest perhaps that these dykes belong to the Shap swarm of dykes as described from the Windermere Supergroup by Morrison (1918), and Soper and Kneller (1990). However, most of the Shap-related dykes seen elsewhere in the Lake District are much fresher mineralogically (Millward et al., 2000). The commonly intense alteration of these dykes is similar in style to that seen in the Borrowdale Volcanic Group rocks in the area. Coupled with the presence of cleavage this might suggest emplacement during an earlier intrusive phase. The dyke phenocryst mineralogy of plagioclase feldspar, quartz and biotite is also seen in pyroclastic rocks at the base of the Yarlside Volcanic Formation on Red Crag suggesting a possible association with the Ashgill volcanic rocks (see Chapter 11).

Three dykes on Powley's Hill, at Poor Hag and in Poor Hag Gill are uncleaved. The first is up to 8 m wide and has strongly flow-banded margins; it trends 055°, and dips 65-90° to the north-west. The Poor Hag dyke is approximately 2 m wide and strikes 350°. It cuts pervasively cleaved and hornfelsed andesite, but itself is neither cleaved, nor hornfelsed. This dyke is porphyritic microgranodiorite (E72153), containing conspicuous, relatively fresh, tabular plagioclase feldspar phenocrysts up to 30 mm long with strong oscillatory zoning. Other phenocrysts include brown biotite and some corroded quartz. The holocrystalline groundmass contains abundant euhedral biotite, fibrous amphibole pseudomorphs after amphibole and plagioclase feldspar; anhedral quartz is interstitial. Biotite crystals commonly contain abundant opaque exsolution lamellae. This dyke probably belongs to the Shap swarm (Morrison, 1918) that cuts Windermere Supergroup rocks south of the Shap intrusion.

Further up Poor Hag Gill [5465 1026] there is a poor exposure in the stream side of strongly flow-banded, highly porphyritic, biotite-quartz-feldspar-phyric microgranite. This occurs within the granite outcrop and is probably also a dyke, though contacts are not exposed. This dyke is distinguished from the other microgranitic dykes by the presence of large phenocrysts of micro-perthitic K-feldspar which poikilitically enclose plagioclase (E72180). It contains up to 40% phenocrysts and glomerocrysts, and is also somewhat fresher than the other dykes. This dyke is probably also part of the Shap swarm.

12.5 LAMPROPHYRE DYKE (EARLY DEVONIAN)

A single vertical dyke of pinkish brown lamprophyre (spessartite) cuts gabbro in the disused quarry on the shore of Haweswater [4947 1526] (Millward and Beddoe-Stephens, 1998). The melanocratic lamprophyre contains euhedral microphenocrysts of almost colourless augite up to 1 mm and scattered glomerocrysts up to 2 mm, set in a groundmass of randomly to slightly flow-aligned acicular brown hornblende crystals up to 1.5 mm and interstitial very turbid feldspar, much of which appears to be plagioclase (E71814). The rock is uncleaved and thus probably postdates the Early Devonian Acadian orogenic event.

13 Structure

The structure of the volcanic rocks in the area to the south-east of Haweswater is dominated by faulting and the presence of a pervasive cleavage (Figure 3). Earlier accounts of the structure of the district by Green (1915), Mitchell (1934) and Nutt (1970) over-emphasised the importance of the related folding. Green and Mitchell considered that there were two episodes, the first 'pre-Bala' and the second during Devonian times. The principal structure in the area was referred to as the 'Main Anticline' by Mitchell (1934), but subsequently this has become known as the Nan Bield Anticline (Nutt, 1970; Soper and Moseley, 1978).

Mitchell (1934) and Nutt (1970) both showed the north-east-trending Nan Bield Anticline extending into the area south-east of Haweswater. However, the resurvey shows no evidence for a fold here. Changes in the amount of dip and orientation of the strike of bedding occur across both minor and major faults. Of particular importance here is the Brant Street-Woof Crag Fault (see below). Similar disorientated fault-blocks in the Wrynose area, west of Windermere were interpreted by Branney and Soper (1988) to have resulted from volcanotectonic displacements associated with caldera collapse.

13.1 SUMMARY OF STRUCTURAL HISTORY

The volcanic rocks in the Haweswater to Shap area are affected principally by many faults and a regional cleavage (Figure 3). Most of these structures formed in response to north-west to south-east crustal shortening associated with the Acadian tectonic event, the latest phase of the Caledonian Orogeny. However, some pre-Acadian deformation is recognised, and some post-Acadian fault movements are strongly suspected.

13.1.1 Synvolcanic deformation

Contemporaneous deformation is characteristic of many parts of the bedded volcano-sedimentary sequence within the Borrowdale Volcanic Group, and includes, for example, soft-sediment convolutions and faults with generally small normal and reverse displacements. Elsewhere in the group, many larger scale faults associated with thickness and facies changes within sequences of generally welded pyroclastic rocks have been interpreted as volcanotectonic structures (Branney and Soper, 1988; Branney and Kokelaar, 1994). One such example is the arcuate Woodhowe Moss Fault, south-east of Haweswater, across which there are significant facies and thickness changes within the Whelter Knotts Formation.

Broader scale, intra-arc extensional faults are also considered to have controlled both eruption and preservation of the Borrowdale Volcanic Group (Petterson et al., 1992; Millward et al., 2000). Bell (1997) considered that movements on the Rosgill Moor Fault were associated with aggradation of the volcanic pile. As discussed above, the north-easterly trending Brant Street and Woof Crag faults, along with the north-west to south-east Mullender Fault, are considered to be extensional structures with contemporaneous displacements associated with the very thick development of the Mardale Formation. The Mullender Fault has very substantial displacement down to the south, juxtaposing some of the youngest Borrowdale Volcanic Group rocks against the lowest part of the Birker Fell Formation.

13.1.2 Acadian deformation

During the Early Devonian, Acadian phase of the Caledonian Orogeny, the earlier formed volcanotectonic structures were tightened and cleavage imposed; significant displacements occurred on most of the major faults in the area. A major effect of Acadian deformation in the Haweswater and Shap area is the imposition of a regional cleavage, the intensity of which varies from a weak, spaced fabric to a penetrative and slaty one. The relationship between cleavage formation and emplacement of the Shap pluton is discussed in 14.1.1.

A branching set of north-east-trending vertical faults dominates the structure in the Wet Sleddale area. The changing bedding dip pattern in the Seathwaite Fell Formation there suggests that the faults have developed through dislocation along the common limbs of upright folds with axial plane traces nearly parallel to the fault trend. Similar structures in the Coniston area have been associated with development of the Westmorland monocline (Kneller and Bell, 1993; Millward et al., 2000).

The Swindale Fault Zone is a notable structure within the district. The associated fault duplexes, particularly south-west of Haweswater, and the high internal strain suggest that this may be a shear zone, which has a component of sinistral displacement. The fault zone is broadly coincident with the Brant Street and Woof Crag faults. Such a complex deformation history suggests re-activation of a major basement fracture.

13.1.3 Post-Acadian deformation

The extent of post-Acadian deformation within the Lower Palaeozoic rocks is difficult to assess, though a number of major faults cutting these rocks can be traced into overlying Carboniferous strata. Soper and Moseley (1978) attributed most of these displacements to end-Carboniferous re-activation of existing structures. Some of the east-north-east-trending faults in Wet Sleddale have poorly lithified and vuggy fault-rocks that are intensely hematised in places; elsewhere in the Lake District, faults with similar features have been shown to have a post-Acadian movement history dated at between 180 and 115 Ma (Milodowski et al., 1998).

13.2 FAULTING

The area south-east of Haweswater is dominated by major north-east-trending (Caledonian) faults, most notably the Swindale Fault Zone and a closely spaced set in the region

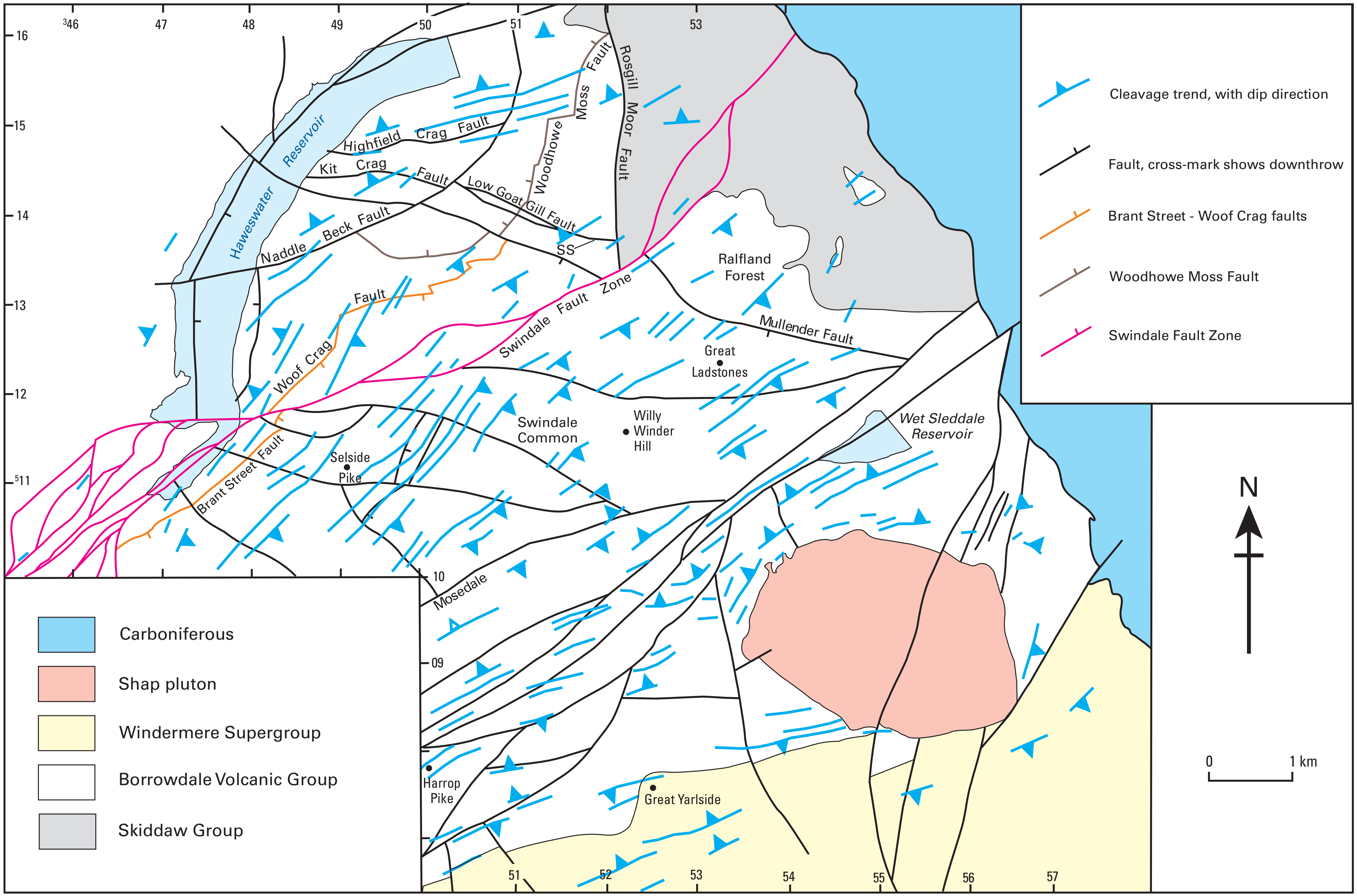

Figure 3 Summary of the main structural features of the Haweswater and Shap area. SS — block of Skiddaw Group within Low Goat Gill Fault.

south-west of Wet Sleddale (Figure 3). The area can be divided into a number of structural domains:

- north-west of the Swindale Fault the volcanic rocks are intensely faulted with a number of distinct sets having a complex history of movement
- the Brant Street, Woof Crag and Mullender faults
- the Swindale Fault Zone, which approximately follows part of an earlier structure formed by the Brant Street, Woof Crag and Mullender faults
- a zone of north-east-trending faults in Wet Sleddale
- a set of east-south-east-trending fractures across Swindale Common linking the Swindale Fault Zone and the faults in Wet Sleddale, and possibly conjugate with them
- northerly trending faults in the Shap Fells area, some of which pass from the Borrowdale Volcanic Group into the Windermere Supergroup.

13.2.1 North-west of the Swindale Fault Zone

The area between the Haweswater reservoir and the Swindale Fault Zone is intensely faulted and many of the component normal faults were probably largely formed during the volcanic episode (Figure 3). This applies not only to the larger structures described below, but also to numerous apparently smaller north to north-west-trending structures across which there are lateral thickness and facies changes affecting particularly the Whelter Knotts Formation. On Mardale Banks the throw down to the west on a northerly trending fault predates emplacement of the microgranite dykes there.

The Rosgill Moor Fault has been described previously by Bell (1997). Its trace is due north from Swindale [521 133], where it juxtaposes rocks of the lower part of the Birker Fell Formation against the Skiddaw Group. In the south the fault terminates against the Swindale Fault Zone; because the Swindale Fault is a late structure (see 12.1.3), the Rosgill Moor Fault probably originally terminated against the Mullender Fault, a major synvolcanic structure. Bell calculated that this normal fault has a shallow dip of 30° to the west and a throw of about 80 m. He considered the fault to be a pre- or syn-Borrowdale Volcanic Group extensional structure and possibly caldera related. There is no direct evidence for this latter association, but evidence elsewhere in the Haweswater and contiguous areas show that northerly trending faults have significant extensional synvolcanic components of throw.

The Highfield Crag Fault is a sinuous, easterly trending structure on Naddle Forest that divides the main Kit Crag-Wallow Crag dolerite-gabbro mass (Millward and Beddoe-Stephens, 1998). It is a steep normal fault and probably has a complex early displacement history. The fault plane is not exposed. There is currently a substantial throw down to the north in the volcanic stratigraphy, juxtaposing Mardale Formation rocks to the north against Birker Fell Formation to the south. A substantial change in dip and strike of the volcanic rocks across the fault suggests a synvolcanic displacement. Within the intrusion, coarser grained rocks predominate to the north: Millward and Beddoe-Stephens inferred that these rocks probably represent deeper levels in the intrusion, implying significant post-emplacement throw on the fault down to the south. A narrow microgranite dyke is not displaced by the fault.

The Kit Crag Fault has a similar orientation to the Highfield Crag Fault. It appears to have only a small throw affecting the Haweswater intrusions, but a substantial displacement down to the south affecting the earlier volcanic rocks. Thus, the major displacement on this fault seems to have occurred during Caradoc times.

East of Haweswater, Naddle Beck follows the line of the Naddle Beck Fault, a gently curved north-east-trending fault that becomes an east–west structure west of the reservoir. It is probably a vertical fault and may have a wrench component in addition to dip slip. The fault displaces all other faults in the area and therefore records the latest relative movement episode.

The Woodhowe Moss Fault is an arcuate, probably vertical, normal fault that crops out between the Naddle Beck and Woof Crag faults; no clear continuation north-west of the Naddle Beck Fault has been recognised. An early displacement history is inferred for the Woodhowe Moss Fault because it is offset by all other faults in the area. A throw of about 100 m down to the north repeats the uppermost strata of the Birker Fell Formation and the lowest units of the Whelter Knotts Formation. Thickness and facies changes in the pyroclastic succession of the Whelter Knotts Formation occur across this structure, which therefore has a principal volcanotectonic component.

The Low Goat Gill Fault is a multiple-stranded, near-vertical normal fault parallel to the Mullender Fault. It crops out between the Naddle Beck and Rosgill Moor faults. The fault plane is exposed in Low Goat Gill and was formerly exposed as a 6 m wide zone of faultrock in a pipe trench above the incised part of the stream (Nutt, 1970). Displacement on the fault is small, but the fault is important for containing a narrow sliver of grey mudstones of the Tarn Moor Formation (Skiddaw Group) beneath Swindale Foot Crag [5182 1374] (SS, Figure 3). Nutt (1970) suggested that the fault has a significant dextral wrench component, but offsets are very small on the volcanotectonic Woodhowe Moss Fault and across vertical contacts of small masses of Haweswater dolerite.

13.2.2 Brant Street, Woof Crag and Mullender faults

The Brant Street, Woof Crag and Mullender faults are linked structures, probably associated with the development of a major, basin-bounding growth fault with a substantial throw down to the south-east. The first two of these faults is approximately parallel with the later Swindale Fault Zone. These faults separate structural domains in which strata generally dip in different directions. To the north, bedding mostly dips gently to the south-west or west, whereas to the south, strata are inclined increasingly steeply to the south-east. This is well illustrated in the Rowantreethwaite area [485 121].

The Brant Street Fault trends north-east and has a throw at least equivalent to the thickness of the Mardale Formation, down to the south-east. The throw on the east-north-east-trending Woof Crag Fault is uncertain because of the lack of correlation across it and the numerous small fault blocks within the footwall.

The Mullender Fault trends west-north-west. The throw on this fault in its segment to the north-west of the junction with the Woof Crag Fault is small, perhaps a few tens of metres. By contrast, the throw down to the south across the segments to the south-east of the junction is very large. For example, in the Ralfland Forest the Froswick Formation is juxtaposed against the lowest part of the Birker Fell Formation, implying a displacement of the order of 2.0 km.

13.2.3 Swindale Fault Zone

The east-north-east-trending Swindale Fault Zone is a strike-slip fault with left-lateral displacement and several duplexes along an irregular outcrop (cf. Woodcock and Fischer, 1986). The southernmost stretch of the Haweswater reservoir and the lower reaches of Swindale have been carved out along the fault which also divides the rolling, relatively low fells of Naddle Forest from the higher fells of Selside and Branstree. The fault zone broadly follows the trace of the Brant Street and Woof Crag faults which are believed to have been major basin-bounding faults during the accumulation of the Borrowdale Volcanic Group. Continuation of the Swindale Fault Zone to the south-west is unknown at present, but to the north-east, the fault is truncated by the unconformity at the base of the Carboniferous strata. Significant changes in cleavage strike and dip are seen to the north of the Swindale Fault Zone.

Several duplexes occur along the structure. In Swindale, the main outcrop of the Tailbert Formation (Skiddaw Group) is within such a structure; all remaining outcrops of this formation are small. Extensional duplexes containing rocks of the Mardale Formation occur at Swindale Head [502 125], but the most complex of these occurs to the south-west of Haweswater on Dudderwick (Woodhall, 2000). The shear sense on these duplexes is sinistral. This is in agreement with the left-lateral displacement of 150 m on the Brant Street–Woof Crag faults and of 550 m on the Mullender Fault. However, the cumulative dip-slip component associated with these structures is unknown.

The age of the principal movement and formation of the duplexes is not well constrained, but faults with a strike-slip component have been taken elsewhere in the Lake District to be late Caledonian. Though the main displacement on the Swindale Fault Zone clearly postdates movement on the Brant Street–Woof Crag faults, there is no ‘distortion’ of the cleavage within the duplexes. This suggests that the duplexes formed prior to the cleavage. However, the arcuate form of the cleavage strike to the north of the fault zone may indicate further later sinistral strike-slip movement.

The strike-slip geometry, associated duplexes and the probable Ordovician and Devonian movement history suggest that the Swindale Fault Zone developed by episodic reactivation of a long-lived, basement shear zone.

13.2.4 North-east-trending faults of Wet Sleddale

An anastomosing set of north-east-trending vertical faults dominates the structure in the area between Mosedale [500 096], Harrop Pike [500 077] and Wet Sleddale [555 115]. These fells are covered extensively by peat and till, making precise tracing of the faults difficult in parts, but evidence for the location of these faults comes mainly from the relatively well exposed area around Sleddale Beck, between Todcrags and the western end of the Wet Sleddale reservoir [520 100 to 540 110]. There, the changing bedding dip pattern in the Seathwaite Fell Formation between adjacent fault blocks suggests that the faults have developed along the common limbs of upright folds with axial plane traces nearly parallel to the fault trend. Further south-west the faults have been traced on changes in the topography and through the variation in intensity of the cleavage seen in small, isolated exposures.

The northernmost of these faults is exposed along an incised part of a tributary of Sleddale Beck [5256 1076]. Hematite-stained, poorly lithified fault-breccia comprising angular clasts up to 20 cm across in a zone up to 5 m wide occurs along the vertical north wall of the gorge and in the stream. The south wall shows an intensely fractured fault damage zone at least another 5 m wide.

The north-east-trending faults considerably displace the approximate margin to the contact metamorphic aureole of the Shap pluton, indicating that fault movement largely postdates emplacement of the intrusion (Figure 4). The orientation of the faults and their association with folding is typical of Acadian deformation in the Lake District. For example, steep north-east trending reverse faults and associated folds in the Ambleside district are interpreted to be part of a set of back-thrusts associated with development of the Westmorland monocline late in the Caledonian orogeny (Kneller and Bell, 1993). The north-east-trending faults in the Shap area may have an extended fault history as implied by the later displacement of the base of the Carboniferous strata and by the presence of hematitic mineralisation of the fault rock. The latter is a common feature of faults in west Cumbria with re-activation dated at between 180 and 115 Ma (Milodowski et al., 1998).

13.2.5 Faults in the area between the Swindale and Wet Sleddale faults

Three east-south-east-trending faults link the Swindale and Wet Sleddale faults across Selside and Swindale Common. All are probably normal faults with small throws down to the south. Fault-rocks from these structures are exposed at two localities: on the south side of Scam Matthew [5160 1054] and in a bluff [5221 1069] at the side of a small stream 550 m east of Scam Matthew. At the first site, angular fragments of highly altered volcanic rock are cemented by chalcedony and granular quartz, associated with small amounts of pyrite (E72156). The second occurrence is a rib of lithified fault breccia at least 2 m wide. Clasts in the fault rock include various cleaved volcanic lithologies along with vein quartz and a quartz-phyric felsite. The fragments are cemented with carbonate and there are some remaining voids. In both fault-rocks there is no consistent orientation of the cleavage in the volcanic clasts, suggesting that fault movement postdates cleavage formation. The mineralogy of the fault infills and their clear late displacement age suggest that these structures may be coeval with the Swindale and Wet Sleddale faults.

In the north-eastern part of this zone, mainly between Gouther Crag and the Mullender Fault, there is also a set of north-west to north-north-west-trending normal faults with throws down to both the south-west and to the north-east.

13.2.6 Faults in the Shap Fells area

A set of north-north-east-trending faults cut the volcanic rocks in the vicinity of the Shap Blue Quarry. Faults of a similar orientation also displace units of the Windermere Supergroup south of the Shap pluton (see 1:10 000-scale map NY 50 NE). Though exposure of these faults is generally poor, field evidence indicates that most of them probably pre-date emplacement of the granite. However, a mineralised fault with this orientation was located in the upper reaches of Longfell Gill at [5548 0949] by B Beddoe-Stephens, suggesting that at least one of these faults postdates emplacement of the granite.

Some of the north-north-east faults are exposed in the Blue Shap Quarry. The faults are steep, dipping about 70º to the west, and comprise a zone of gouge and crush breccia up to 1 m wide. The adjacent damage zone in the foot-wall is typically up to 2 m wide and that in the hanging wall at least 3 m.

13.3 CLEAVAGE

A cleavage, defined mainly by domains of aligned sericite crystals, affects all the rocks in the area except for the Shap granite. The fabric varies from spaced to continuous and from disjunctive to slaty. Cleavage is best developed in the finer grained volcaniclastic rocks, though even dacite and andesite lithofacies are intensely affected, particularly in the poorly exposed area between Mosedale, Harrop Pike and the upper reaches of Sleddale Beck. Generally strain increases south-eastwards.

The cleavage orientations in the area can be divided into three domains (Figure 3). Firstly, north of the Swindale Fault Zone the cleavage strikes describe an arc trending from 030 to 080°, similar in shape to the Haweswater reservoir. Here, cleavage dips are consistently to the north-west with values as low as 60°. Locally within this domain two closely spaced fabrics appear to be present in some of the finer grained volcaniclastic rocks. A particularly well developed example lies just north of Rowantreethwaite Beck [at 4840 1195]. In the field, these fabrics are reminiscent of shear band cleavage commonly seen in ductile shear zones. However, thin-section evidence supporting such an interpretation is inconclusive.

The second domain comprises most of the area south of the Swindale Fault Zone. The cleavage strike is more consistent here at between north-east and east-north-east (040–066°), and it dips very steeply generally to the south, though dips to the north are also present locally (Figure 3). In the third domain, strong perturbations of the cleavage are seen in the area around the Shap Pluton (Figures 3, 4). North-west of the pluton outcrop, the cleavage appears to wrap around the body, dipping consistently away from the granite. By contrast to the south-west the cleavage strike appears to be truncated by the pluton. Further local changes are present in the vicinity of the Shap Blue Quarry (Figure 4). The relationship of the cleavage to the emplacement of the granite is discussed in Chapter 14.

14 Metamorphism

Varying degrees of hydrothermal, contact, and low-grade regional metamorphism are known to have affected Lower Palaeozoic rocks of the Lake District (Meller, 1998; Millward et al., 2000). Widespread mineralogical changes to rocks of the Borrowdale Volcanic Group in the Haweswater and Shap areas result from these events. Many of the rocks are intensely cleaved as a result of Early Devonian deformation (Soper et al., 1987), with the pervasive presence of white mica and carbonate, along with chlorite, quartz, epidote, leucoxene/titanite and opaque oxide. However, even though the volcanic rocks are moderately to strongly altered, primary igneous and volcaniclastic textures are usually still recognisable. White mica growth, in particular, is associated with cleavage fabrics, and was formed during regional metamorphism associated with the Early Devonian Acadian tectonic event (Millward et al., 2000; Meller, 1998). The volcanic rocks in the district do not contain much evidence for the earlier phases of hydrothermal and low-grade burial metamorphism found in the western Lake District by Meller (1998) and Millward et al. (2000). These early phases may be represented in the district by, for example, carbonate and quartz amygdales in andesite which are pseudomorphs after chalcedonic structure, and by radial aggregates of acicular amphibole overgrowing chlorite in relatively fresh rocks from the Haweswater intrusions (Millward and Beddoe-Stephens, 1998).

In the south-east of the district, volcanic rocks adjacent to the Shap Pluton have been strongly thermally metamorphosed; a field and petrographical description of these rocks is given below. The most important previous description of the metamorphic aureole is by Harker and Marr (1893). Amphibole-epidote-garnet-bearing hydrothermal veins are present in the Shap Blue Quarry [563 106] and were described by Firman (1957). The geochemical and isotopic composition of the metamorphic rocks and veins has not been studied.

14.1 CONTACT METAMORPHIC AUREOLE OF THE SHAP GRANITE

A substantial area of thermally metamorphosed volcanic rocks surrounds the Shap Pluton (Figure 4). For a distance of 1 to 1.3 km from the granite contact, cleaved andesite and associated volcaniclastic rocks have a purplish or brownish hue, produced by the presence of substantial amounts of tiny brown biotite flakes. This mineral is characteristic of all Borrowdale Volcanic Group rocks near to the granite. In the field the change from the purplish or brownish hue to the normal greenish grey colour of the volcanic rocks is taken to represent the approximate outer limit of the aureole.

Petrographical examination of samples from the aureole show progressive recrystallisation of the volcanic rocks to biotite-quartz-hornfels. Cordierite, amphibole and epidote also occur in some of the rocks. The mineral assemblages present allow the aureole to be divided into two regions: an outer zone where there has been significant overprinting with fine-grained biotite, but where the original igneous and clastic textures are preserved, and an inner zone where a granoblastic texture has overprinted the primary rock fabrics. The prograde sequence through the aureole is particularly well exposed to the north-west of the pluton in the upper part of Wet Sleddale (Figure 4). The effects on the silicic pyroclastic rocks from the Lincomb Tarns Formation to higher grades of metamorphism are not recorded here, as these rocks are very poorly exposed immediately south-west and east of the granite.

Original textures are generally still clearly evident in the outer zone where the dominant contact metamorphic mineral is brown biotite. However, at the outer margin of the zone, and in a few localities outside the aureole as defined in the field, the biotite is a 'muddy' green colour (E72495, E72497, E72498). Small amounts of mid-green amphibole (E72164), cordierite (E72155, E72166, E72190), epidote and titanite are also present. In the porphyritic intermediate rocks the groundmass and mafic phenocrysts are heavily replaced by biotite, which has also grown mimetically along the original mica-rich cleavage domains. Feldspar phenocrysts are usually saussuritised and partially recrystallised along the margins and in small patches to fine anhedral granular sutured aggregates of quartz and feldspar (E72181). Amygdales are typically recrystallised to sutured granular aggregates of unstrained quartz along with biotite and chlorite.

Lapilli-tuff and sedimentary rocks intercalated with the andesite sheets are similarly recrystallised, though it is the fragments and in particular, the pumice/scoria, that are preferentially replaced in the coarser grained clastic rocks. Small amounts of granoblastic quartz and feldspar are seen locally. A few of the finer grained clastic rocks may also contain cordierite (see below).

Silicic rocks of the Lincomb Tarns Formation crop out extensively around the south-west and north-east contacts of the granite. In the outer zone, the original devitrification (e.g. 'snowflake'), eutaxitic, parataxitic and vitroclastic textures are well preserved, and there are generally much smaller quantities of biotite which preferentially tends to replace the fiamme and lithic clasts (e.g. E72509, E72514). However, as the inner zone is approached the felsic groundmass becomes increasingly recrystallised with areas of granoblastic quartz and feldspar. Cleavage domains in these rocks are typically defined by abundant very fine sericite. The relative modal abundance of biotite is probably controlled by the bulk-rock composition.

In the inner zone original textures are obliterated by granoblastic recrystallisation. In many rocks evidence for the protolith is sparse, though small areas with differing grain size and proportions of the metamorphic minerals may be interpreted as relicts of crystals, lithic clasts or amygdales in some rocks. The mineral assemblage here is typically quartz + biotite + opaques ± plagioclase (andesine) ± amphibole ± epidote ± cordierite (E72183, E72185, E72186). The hornfels is commonly strongly foliated and has a crudely parallel, fine layering, reflecting differing mineral proportions. The foliation probably originated as cleavage, though it is uncertain whether the layering was originally bedding or a metamorphic fabric.

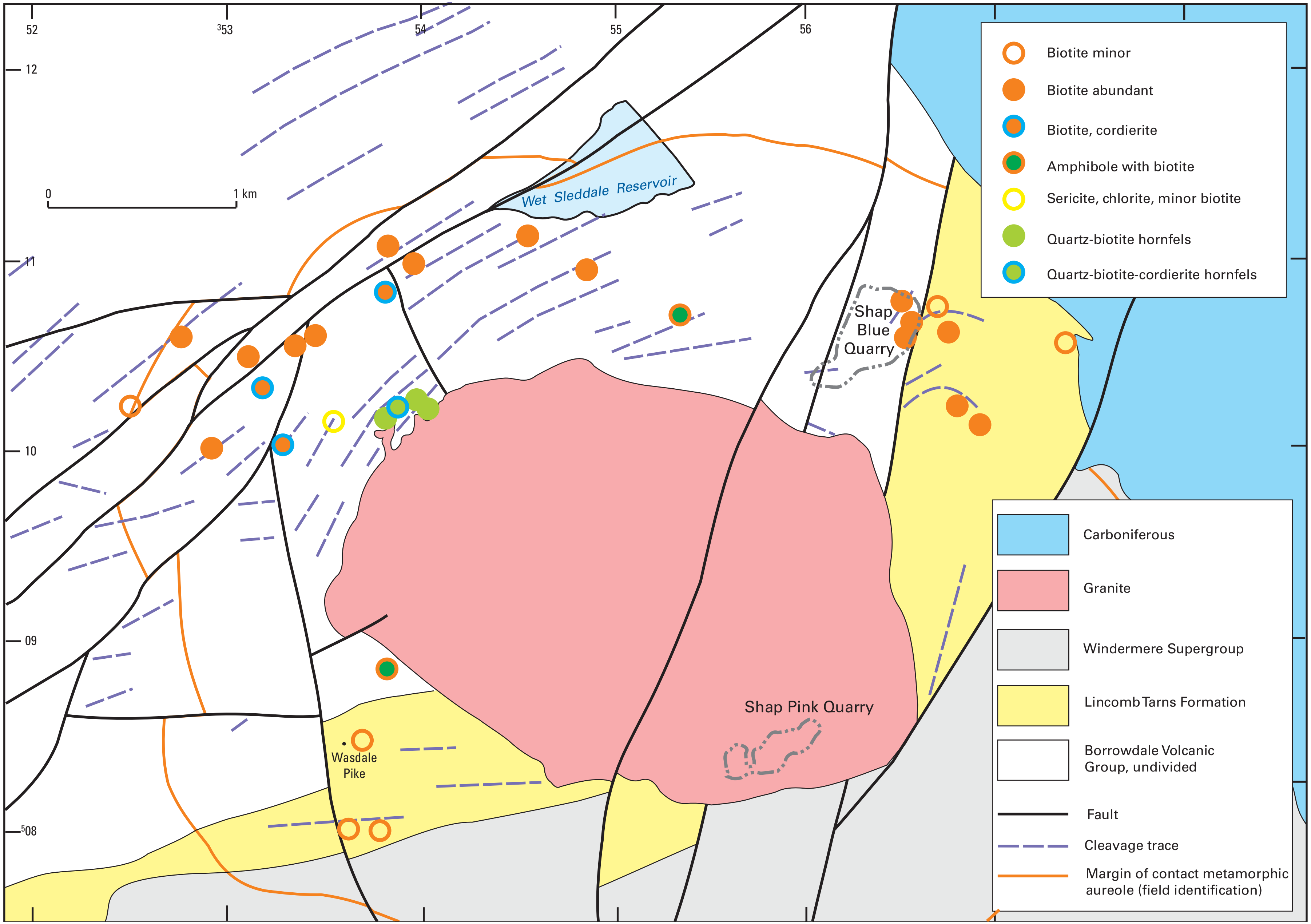

Figure 4 The Shap Pluton and its metamorphic aureole, showing mineral assemblages and cleavage pattern.

Pale yellow-green to mid-green, pleochroic amphibole (probably hornblende) occurs in the inner zone as bladed to prismatic crystals but is generally subordinate to biotite. However, on Low Fell, amphibole is the dominant mafic mineral and this example probably approximates to the outer margin of the inner zone. On the north side of Wasdale Pike [538 088] amphibole is abundant in volcaniclastic sandstone protolith within 100 m of the granite contact (E72506). The localised abundance of amphibole is probably related to the bulk-rock composition.

In Sherry Gill [5385 1012] the hornfels adjacent to the granite contains abundant pseudomorphs of chlorite and carbonate, possibly after amphibole: fresh granoblastic plagioclase and small amounts of brown biotite are present, suggesting that the amphibole has been preferentially altered by late-stage fluids (E72187). Carbonate is also associated with quite coarse-grained quartz in elongate lenses, possibly recrystallised amygdales. Similar retrogressive metamorphic effects are seen in a sample from the outer part of the inner zone west of Sherry Gill (E72189). In addition to quartz and small amounts of biotite, this rock contains abundant chlorite and sericite. There appear to be three distinct generations of sericite present: aligned fine-grained crystals representing the cleavage fabric; later, randomly orientated aggregates replacing pseudomorphs; and finally 'coarse' muscovite.

Cordierite is an unusual mineral within the volcanic rocks of the Shap aureole. Its occurrence was recorded here first by Firman (1954) from the Shap Blue Quarry, presumably in the more aluminous volcanic or volcaniclastic rocks. Cordierite was not recorded from samples from this location during the recent survey, but is recorded in thin sections from four localities in Wet Sleddale, three from the outer zone and one from the inner. In the outer zone cordierite occurs in strongly cleaved volcaniclastic siltstone (E72155, E72166) as 'spots' 0.5 to 2 mm across. In places the mineral is fresh, though it is generally altered to aggregates of sericite, chlorite and quartz. One of the samples (E72166), also contains some accretionary lapilli. Small amounts of cordierite also occur in a lapilli-tuff, overgrowing fragments, possibly of mudstone. Abundant cordierite, mostly altered to pale yellow pinite, is present in hornfels adjacent to the granite contact near Sherry Gill (E72186). Here the mineral is concentrated locally within layers of particular composition in the foliated hornfels. The cordierite is riddled with tiny inclusions of biotite, opaques and quartz.

Veins containing hydrothermal mineral assemblages are noted at several localities. The most significant of these occurrences is the amphibole-epidote-garnet veins within the outer zone of the aureole in the Shap Blue Quarry. Three zones within the veins were observed by Firman (1957): a thin marginal zone of amphibole, followed by granular pale green to yellow epidote and a central zone of andradite garnet. The garnet contains inclusions of epidote and fractures in the garnet masses are filled with quartz, calcite and ?pyrophyllite. In an exposure on Low Fell [at 5534 1070], 600 metres to the west of the quarry, irregular veins and stringers have an outer zone of amphibole (in part replaced by carbonate) and epidote, along with some titanite and a little allanite and idocrase (E72504). Their inner zone consists of quartz with amphibole and minor amounts of carbonate. In both localities the country rock adjacent to the veins has been significantly altered. Epidote and chlorite replace wall rock adjacent to the veins, whilst farther away biotite is altered to chlorite and Fe-oxide, and sericite, titanite and carbonate are abundant (E72523).

14.1.1 Relationship of deformation to metamorphism

The random orientation of the mineral flakes overgrowing cleavage fabrics led Boulter and Soper (1973) to conclude that the granite was emplaced after the cleavage-forming episode. This is supported by field evidence from Sherry Gill [5385 1012], where a strong cleavage fabric in the hornfels cannot be traced into the adjacent granite. Also, in Longfell Gill [5613 1009], south of the Shap Blue Quarry, cleavage fabrics are truncated by the irregular contact with the megacrystic granite; here also, xenoliths of hornfels within the granite are cleaved and in places there are fingers of granite along the cleavage in the country rock. At these localities, or elsewhere, there is no clear evidence of a deformation fabric in the granite itself.

However, more recently it has been shown by Soper and Kneller (1990) that weakly cleaved felsic dykes cut both the granite and country rocks of the Windermere Supergroup, suggesting emplacement during the cleavage forming episode. The pronounced arcuate form of the cleavage strike around the northern part of the pluton shown in Figure 4 can also be taken as evidence that compression continued after granite emplacement. The sequence of structural and metamorphic events seen within the aureole is summarised in Figure 5.

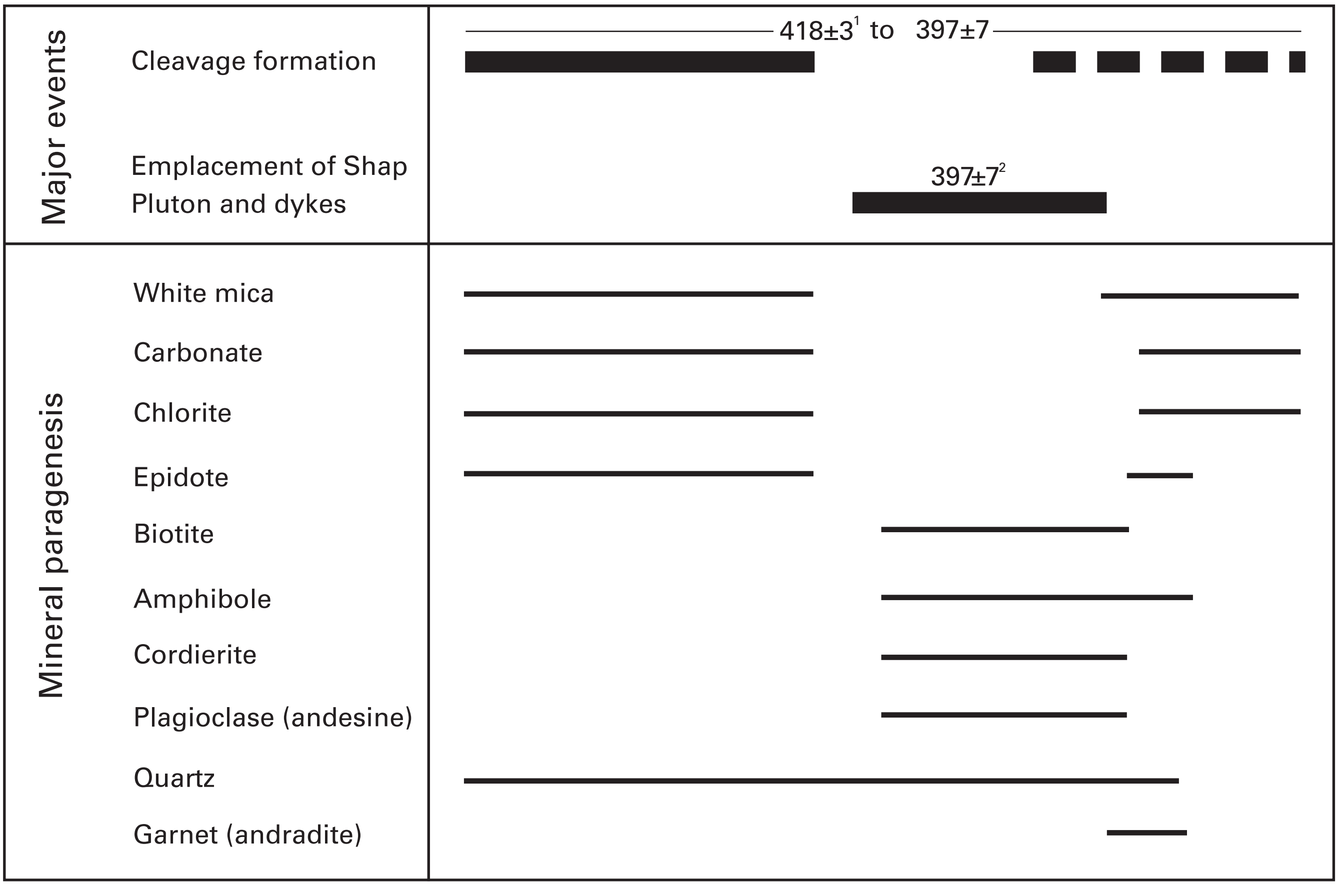

Figure 5 Illustration of the relative ages of the mineral assemblages seen in Borrowdale Volcanic Group rocks in the aureole of the Shap Pluton. [1]Merriman et al (1995), [2]Rundle (1992).

15 Mineralisation

The wide variety and occurrences of mineralised veins that are hosted by the Lower Palaeozoic rocks of the Lake District have been the subject of numerous studies summarised by, for example, Firman (1978), Stanley and Vaughan (1982) and Millward et al. (2000). However, there are comparatively few occurrences of mineralisation within the Borrowdale Volcanic Group rocks of the Haweswater and Shap area, and most of them are associated with the emplacement of the Early Devonian Shap Pluton. The extensive hydrothermal mineralisation associated with this event has been described in detail by Firman (1957; 1978), but no modern interpretation of the deposits has been published.

The occurrences of mineralisation in the Haweswater and Shap area are given in Table 5.

Table 5 Mineralisation in the Haweswater and Shap area.

<table>
<tr><th>Age</th><th>Characteristic mineral assemblage</th><th>Localities</th><th>Structure and style of mineralisation</th><th>Mining history</th><th>Reference</th></tr>
<tr><td>Late Carboniferous</td><td>Baryte</td><td>Sherry Gill [5386 1039]</td><td>Vein</td><td>Small spoil heap with no mineral</td><td>Young (1987); Adams (1988)</td></tr>
<tr><td rowspan="4">Early Devonian; associated with Shap Pluton</td><td>Quartz-fluorite-pyrite-molybdenite-bismuthinite-native bismuth-pyrrhotine, chalcopyrite-magnetite-scheelite</td><td>Scattered in granite</td><td>High temperature mineralisation; joint coatings in Shap Pluton</td><td rowspan="4">None</td><td rowspan="4">Russell (1925); Firman (1957; 1978) Young (1987)</td></tr>
<tr><td>Quartz-calcite-hematite-fluorite-baryte nacrite; late pectolite-laumontite-saponite</td><td>Scattered in granite; also in Shap Blue Quarry [563 105]</td><td>Low-temperature hydrothermal; coatings on blocky joints in Shap Pluton and veins filling joints and faults in country rock</td></tr>
<tr><td>Garnet and epidote-hornblende-quartz-calcite</td><td>Shap Blue Quarry [563 105] Old Rhyolite Quarry [567 106]</td><td>Metasomatic lenticular ‘veins’ and wall-rock replacement approx along c. E–W cleavage; associated with Shap Pluton</td></tr>
<tr><td>Pyrite-epidote-calcite-chalcopyrite</td><td>Shap Blue Quarry [564 105]</td><td>Vein-like replacements associated with wall-rock sericitisation; associated with Shap Pluton</td></tr>
<tr><td>Ordovician</td><td>Quartz-chlorite-arsenopyrite-pyrite-chalcopyrite</td><td>Haweswater: Great Birkhouse Hill [493 160]; Guerness Gill [482 133])</td><td>NNW and NW-trending fault veins cutting microdiorite and Whelter Knotts Formation</td><td>Trial levels and shaft on vein; 19th C</td><td>Stanley and Vaughan (1982); Young (1987)</td></tr>
</table>

Mining history information from Shaw (1970) and Adams (1988).

16 Quaternary deposits

Spreads of Quaternary deposits overlie the bedrock formations and are particularly extensive and thick in the main valleys of Swindale and Wet Sleddale, and in the peripheral, rela-tively low-lying areas of Ralfland Forest and the River Lowther to the north-east. Widespread Quaternary deposits also blanket the southern part of the district. However, the area between Haweswater and Wet Sleddale is remarkably free of Quaternary cover, except in the numerous hollows.

The main north-easterly draining valleys in the area owe their current form to glacial erosion and subsequent deposition of glacial and post-glacial detritus. The Haweswater valley is a major glacial trough, the excavation of which was probably structurally controlled. Segments of several major faults follow the line of the reservoir and its arcuate shape closely follows the strike direction of the cleavage in the contiguous area. Mosedale and Swindale are part of a complex valley system that includes the hanging valley of Mosedale, the U-shaped glacial trough of Swindale and a prominent cirque in the upper reaches of Hobgrumble Gill. The head of Swindale is regarded as a cirque by Evans and Cox (1995) and the moraine ridges and mounds at Dodd Bottom have been noted previously by Marr (1894), Mitchell (1931), Manley (1959), Pennington (1978) and Lunn (1990); these have been described in detail recently by Wilson and Clark (1998). Sleddale Beck and Tonguerigg Gill, tributaries of the River Lowther, also occupy hanging valleys.

There is ample evidence of ice-movement directions in the district and the orientation of glacial striae are depicted on the Primary Survey 1:10 560-scale geological maps. Streamlined landforms are numerous. The Knott [505 120], in Swindale is a very fine example of a crag-and-tail feature. A small field of south to north-orientated drumlins and ridges covers the Lowther valley in the north-east of the district. Erratic blocks of Shap granite are particularly common in the Lowther valley some four kilometres north of the outcrop, but by contrast they are absent west of Stackhouse Brow [543 123] and from the area south-west of the granite outcrop, thus confirming northwards ice flow.

Widespread glacial deposits in the Lake District are generally considered to be associated with the Dimlington Stadial ice-sheet, whereas localised deposits formed as a result of corrie glaciation during the Loch Lomond Stadial (Boardman, 1991; Boulton et al., 1977; Sissons, 1980). The extent of Loch Lomond Stadial glaciers in the Lake District has been studied by Sissons (1980), but he did not include the head of Swindale or Todcrags, in Wet Sleddale, as sites of ice accumulation during that period. Wilson and Clark (1998) found evidence for Loch Lomond Stadial glaciers at both localities and argued that the Swindale glacier was relatively small and developed below Nab Crags. The cirque in Hobgrumble Gill and the hanging valley of Mosedale contain no morainic deposits to suggest that ice accumulated there, though they may have collected and held snow at that time. With an estimated area of 0.03 km^2 the Todcrags glacier is the smallest known Loch Lomond Stadial glacier in the Lake District (Wilson and Clark, 1998).

16.1 GLACIAL DEPOSITS

Quaternary deposits in the district can be divided into two groups. Extensive sheets of glacial deposits comprise mostly till and localised morainic deposits. Post-glacial deposits include fluvial and organic deposits. The thickness of the Quaternary cover in the district is poorly known. Over much of the high ground it is probably only a few metres, though much thicker amounts are likely in the valleys and on the peripheral areas of the Ralfland Forest and Wet Sleddale. A number of boreholes sunk in the area around the Haweswater dam show the Quaternary in the valley there to be up to 15 m thick. The boreholes and associated seismic refraction survey indicate a very irregular rockhead surface (British Geological Survey archive). An irregular rockhead surface elsewhere in the district is implied by the large number of small rock exposures in areas of Quaternary deposits such as that between Harrop Pike and Widepot.

16.1.1 Till

Till is the most widely distributed of the glacial deposits in the district. Extensive deposits occur along the valley sides of Swindale, Mosedale and Wet Sleddale. These pass into more extensive sheets to the north-east of the district in Ralfland Forest and the Lowther valley. There, till is extensively moulded into drumlins and ridges, the long axes of which have a generalised north to south orientation. Extensive spreads of till may also underlie the peat blanket, for example between Mosedale, Harrop Pike and Widepot.

The till typically consists of brown to greyish brown silty clay with abundant subangular to subrounded granules, pebbles, cobbles and boulders, mainly of locally derived volcanic lithologies. The clay locally passes into more sandy and gravelly lithologies. Over much of the upland area the till is probably no more than 5 to 10 m thick, though greater amounts may be present beneath the valley floors and peripheral area.

16.1.2 Morainic deposits

Morainic deposits, shown as Hummocky Glacial Deposits on the 1:10 000-scale geological maps, form a conspicuous topographical feature across Swindale Beck in Dodd Bottom [503 117]. The poorly sorted sands and gravels, commonly with large boulders, form ridges, mounds and crag-and-tail landforms such as at The Knott [505 119]. The morainic deposits were probably marginal to a Loch Lomond Stadial ice-mass located beneath Nab Crags. They have been described in detail by Wilson and Clark (1998), who also estimated the maximum size and extent of the glacier. They also described a small moraine ridge approximately 150 m by 60 m, beneath Todcrags adjacent to Sleddale Beck.

16.2 POST-GLACIAL DEPOSITS

With the exception of peat, post-glacial deposits are of limited extent in the district and are associated mainly with river valleys. They include lacustrine deposits, alluvial fans and cones, alluvium, head and scree.

16.2.1 Lacustrine deposits

A small area of lacustrine silt and sand, probably with peat, is located in Dodd Bottom [502 116], near the confluence of Hobgrumble Gill with Sleddale Beck. The thickness is not known.

16.2.2 Alluvial fan and cone deposits

Within the district, deposits of angular gravel and sand in the form of alluvial fans and cones are generally of limited extent. They occur at the change in gradient of tributary watercourses where they enter the main valleys. Examples occur along the shore of Haweswater and in the valleys of Naddle Beck, Swindale, Mosedale Beck and Tonguerigg Gill. The thickness of these deposits is generally not known.

16.2.3 Alluvium

Spreads of alluvium occur along many of the valley floors in the district, associated with local base levels of streams. The deposit is particularly widespread along the course of Mosedale and Swindale becks, but enclosed areas also occur along Naddle Beck [502 143], Guerness Gill [487 130], and the River Lowther [536 106]. Alluvium is exposed in many of these stream banks and typically consists of 0.5 to 1 m of silty clay, silt and sand, locally with lenses of gravel, overlying pebble and cobble gravel. The thickness of alluvium in the area is unknown, but is probably variable.

16.2.4 Peat

In the southern part of the district, very extensive ombrogenous spreads of peat blanket the generally rounded hills between Mosedale, Harrop Pike and the Shap Fells. In general, the deposit of dark brown peat is 1 to 1.5 m thick though this may increase to 3 m or more within some of the larger depressions and on wide benches, as for example south-west of Todcrags. Considerable wasting of the deposit is seen particularly around the margin of the outcrops. The peat overlies either boulder clay, rock regolith, or rarely bedrock.

In the northern part of the district in Naddle Forest and Swindale Common, intricate-shaped hollows between rock exposures are filled with peat, but here the deposit is rarely more than 1.5 to 2 m thick.

16.2.5 Head and scree

Most of the outcrops of till shown on the steeper valley sides along the shore of Haweswater and along the sides of Swindale have been affected by solifluction processes subsequently forming a thin blanket of head. This has not been shown on the 1:10 000-scale maps. The downhill movement of head may be accompanied by cambering of material immediately beneath rockhead, particularly where bedding and/or cleavage dip steeply into the hillside.

Aprons of scree occur beneath crags in the district but are generally small and localised. The most extensive occurs on the north-west facing slopes adjacent to Haweswater between Guerness Wood and Wallow Crag. Small outcrops are shown on Naddle Forest [506 150], beneath Bewbarrow Crag [520 142] and Outlaw Crag [510 124], and east of Nabs Crag [504 111]. The deposits comprise angular gravel.

Information sources

MAPS

Old series 1:10 560 geological maps

Westmorland 13, 20, 21, 27

New series 1:10 000 geological maps

NY 41 NE	Bampton Common
NY 41 SE	Haweswater
NY 50 NW	Shap Fells
NY 51 NW	Bampton
NY 51 SW	Swindale
NY 51 SE	Hardendale

1:63 360 geological maps

Appleby. England and Wales Sheet 30
Kendal. England and Wales Sheet 39

Geochemical atlases

The Geochemical Baseline Survey of the Environment (G-BASE) is based on the collection of stream sediment and stream water samples at an average density of one sample per 1.5 km^2. The fine (minus 150 µm) fractions of stream sediment samples are analysed for a wide range of elements, using automated instrumental methods.

The samples from the Lake District were collected in 1978–80. The results (including Ag, As, Ba, Be, Bi, B, CaO, Cd, Co, Cr, Cu, Fe_2O_3, Ga, K_2O, La, Li, MgO, Mn, Mo, Ni, Pb, Rb, Sb, Sn, Sr, TiO_2, U, V, Y, Zn and Zr in stream sediments, and pH, conductivity, fluoride, bicarbonate and U for stream waters) are published in atlas form (British Geological Survey, 1992).

The geochemical data, with location and site information, are available as hard copy for sale or in digital form under licensing agreement. The coloured geochemical atlas is also available in digital form (on CD-ROM) or floppy disc) under licensing agreement. British Geological Survey offers a client-based service for interactive GIS interrogation of G-BASE data.

OTHER INFORMATION

Field notes

Field notes covering the survey area are archived as field cards which are identified as follows:

NY 41 NE MI295, 352–359
NY 41 SE MI163–184, 196–255, 260–277, 284–294, 314–318, 348–350, 377–381, 387, 388, 424–426, 438–457, 477–482, 509, 540–547, 580, 581, 602–605
NY 50 NW MI550–556, 560–579, 585, 593–598, 600, 601, 608–614
NY 51 NW MI185–195, 256–259, 278–280, 333
NY 51 SW MI281–283, 296–313, 319–332, 334–347, 351, 360–376, 382–386, 389–423, 427–437, 458–465, 467–476, 483–508, 510–539, 606
NY 51 SE MI466, 548, 549, 557–559, 582–584, 586–592, 599, 607

Borehole and site investigation record collection

Collections of records of borehole and site investigations, relevant to the district, are available for consultation at the British Geological Survey, Edinburgh, where copies of most records can be purchased. The collection consists of the sites and logs of about 30 boreholes. The logs are either hand-written or typed.

Mine and quarry information

The British Geological Survey maintains a collection of information on mining and quarrying in the district.

MATERIAL COLLECTIONS

Rock samples and thin sections

Approximately 225 thin sections of rocks from the Haweswater and Shap area are included within the British Geological Survey's archive of English Sliced Rocks. These are representative of the various lithologies within the district. The registered numbers, which include those collected for a study of the Haweswater intrusions (Millward and Beddoe-Stephens, 1998), are as follows:

E71705–71821; E72142–72195; E72487–72541

Samples collected for geochemical analysis

The following samples were analyse by XRFS for major oxides and selected trace elements in the laboratories of the British Geological Survey, Keyworth. The list does not include the Haweswater intrusions already listed by Millward and Beddoe-Stephens (1998).

Whelter Knotts Formation	DMA181–184
Froswick Formation	DMA286–290
Intrusive rocks	DMA283–285; 291–299

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Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

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