GEOCHEMICAL CORRELATION OF PYROCLASTIC SHEETS OF SCAFELL AND LANGDALE CALDERAS, N.W. ENGLAND

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by

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Abstract

Several caldera volcanoes lie within the ~6 km thick Ordovician Borrowdale Volcanic Group of north-west England, which is a remnant of a Palaeozoic subaerial continental arc. Scafell caldera, >140 km$^2$, is best known and intensively studied because it is a rare example, worldwide, where exhumation and glacial dissection reveals the entire succession of pre-caldera, caldera-fill and post-caldera lake succession along with the caldera floor faults, vents and domes.

Several calc-alkaline high-K silicic ignimbrites and andesite pyroclastic units are associated with Scafell caldera and nearby Langdale caldera. Correlation of individual ignimbrites from the caldera fills to distal outflow sheets is hampered by their large number (>18), by hydrothermal alteration, Acadian cleavage, thrusting, and regional prehnite-pumpellyite metamorphism. Therefore, most outflow ignimbrites have not yet been traced to their source areas.

Building upon previous work on the calderas and to the south of those (around Coniston), targeted field-mapping has been successfully used in combination with a range of mostly ‘immobile’ trace-element ratios (e.g. Nb/Y, Zr/TiO$_2$, Th/Nb, Th/Y, V/Y) to resolve local successions and to confirm the presence of the Scafell caldera tuffs outflow sheets as far as 11 km south from Scafell caldera. The Coniston Fells succession is significantly revised, with new thickness estimates and the discovery of three high-level intrusions, the Oxendale-, Wetherlam-, and Glassy Crag Dacites, each geochemically distinct from Scafell units. A welded outflow sheet from Langdale caldera is identified ~14 km southwest of the caldera for the first time. Moreover, the Lincomb Tarns Formations in the central Lake District differs geochemically from the unit mapped as this in the Coniston area, for which a new name (Foul Scrow Tuff Member) is proposed. Whole-rock trace-element geochemistry combined with detailed fieldwork proves to be an effective tool for correlating ancient ignimbrites even where there has been locally limited tectonic deformation and alteration.
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List of Abbreviations

BVG = Borrowdale Volcanic Group
BGS = British Geological Survey
LOI = Loss on ignition
XRF = X-ray fluorescence
1. Introduction

1.1 Problems interpreting caldera structures and forming eruptions

Large explosive volcanic eruptions, known as ‘super-eruptions’, are amongst the most cataclysmic events to affect the Earth’s surface: they devastate vast regions and affect global climate (Self & Blake, 2008). During these events, large calderas (≤100 km wide, >1 km deep basins) form by subsidence as magma reservoirs depressurise beneath the volcano (Lipman, 1984, 1997; Branney & Acocella, 2015). This subsidence generates new cracks (faults and dykes) that act as new pathways for the erupting magma to rise (Druitt & Sparks, 1984) dramatically changing the eruption flux and style especially when in contact with water.

It is essential to understand how caldera volcanoes erupt and collapse, yet little is known about the physical processes involved, particularly how propagating and dilating faults form by subsidence affect the eruptions. At modern volcanoes research is hindered by concealment of critical features (caldera faults, eruption-conduits, vents and caldera-fill tuffs) beneath ash, lavas and caldera-lakes, preventing direct study of caldera structures and evolution. For this reason, research must be by analogue (experimental or computer) modelling (Roche et al., 2000; Holohan et al., 2015) or directed on older exposed caldera volcanoes. Models are useful but can be too simplistic, such as assuming a single, sub-spherical or cylindrical liquid-filled ‘magma chamber’ whereas modern ideas view magma reservoirs as complex lenses of crystal mushes interconnected by a channel system with each other (Keith, 2010; Branney & Acocella, 2015). Thus models need verification at real volcanoes. Fortunately, in rare cases mostly ancient volcanoes have been uplifted and eroded (exhumation) allowing direct examination of the eruption conduits and internal structures. One of the best exposed of this type is Scafell caldera, in the English Lake District, the subject of the present research project.

The key for our understanding of a caldera complex is the lithostratigraphic succession. Detailed studying of the volcanoclastic sequence gives evidence about how a caldera volcano erupted, in which environmental setting did the eruption happen, what eruption styles were prevalent, what scale was the eruption, how did the geochemistry of the magma reservoir change, how and in which stages did the volcanic complex collapse?
All of these questions can be addressed by investigating the caldera fill and outflow succession. The pyroclastic outflow sheets (Fig. 1) of Scafell caldera will be the main focus of this study due to its excellent deep glacial dissection and.

Fig. 1. Schematic representation of an explosive piecemeal caldera volcano with outflow ignimbrites (to be studied) fed by interconnected magma reservoirs via eruption conduits (adapted from Branney & Acocella, 2015; Clarke, 2015, unpublished).

1.2 Introduction to the Lake District calderas

The Borrowdale Volcanic Group in the English Lake District contains Scafell caldera, one of the world’s best-exposed and complete, dissected caldera volcanoes (Fig. 2; Branney & Kokelaar, 1994). Intense studies of this volcaniclastic succession in the 1980’s revealed a complex stratigraphy of the caldera-fill tuffs, caldera floor arcuate faults, eruption-conduits and post-climactic lava extrusions. Post-volcanic uplift, exhumation and deep glacial dissection provides excellent three-dimensional access to the caldera complex (e.g. Branney & Soper, 1988; Branney 1991; Kneller & Bell, 1993; Branney & Kokelaar, 1994; Brown et al., 2007; Kokelaar et al., 2007).

Fig. 2. Overview map of the Borrowdale Volcanic Group with the main research area of this project (modified after Firman & Lee, 1986).
Recently, an approach has been trialled by the Leicester volcanology group to chemically differentiate ignimbrites that fill Scafell caldera using techniques they developed to investigate super-eruptions of the Yellowstone hotspot, USA (Branney et al., 2008; Knott et al., 2016a, b). In their approach XRF whole-rock trace-element ratio plots are used to distinguish between individual ignimbrites, and to correlate them regionally. This study at Scafell has also successfully fingerprinted several ignimbrites using a combination of field and trace-element data. Data of a first approach has revealed the successive tapping of at least 3 interconnected andesitic and rhyolitic magma reservoirs during Scafell’s caldera-forming eruptions, suggesting that the piecemeal nature of the subsidence may relate to the successive evacuation of localised magma reservoirs beneath the volcano, rather than a single ‘magma chamber’ (Clarke, 2015). Although the surrounding volcaniclastic rocks within the Borrowdale Volcanic Group have been mapped and studied over a long period (Mitchell, 1940, 1956; Johnson & Millward, 1987; Millward et al., 2000a; Millward, 2007), surprisingly little is known about their exact vent localities, their stratigraphic chronology and how far the outflow ignimbrites extend from their source calderas.

The presence of only one caldera, Scafell caldera, has been documented with certainty within the Borrowdale Volcanic Group (Branney & Kokelaar, 1994). However, the large number of voluminous ignimbrites within the Borrowdale Volcanic Group as well as their lateral inconsistency and local distribution throughout the Lake District suggests that it is likely that multiple calderas exist. The Scafell caldera fill itself is overlain by later volcaniclastics (i.e. Seathwaite Fell Formation; Lincomb Tarns Formation) that must have emerged from later eruptions in the Borrowdale Volcanic Group and may be related to a separate caldera. One potential source might be the less studied Langdale caldera (Branney, 1988a; informally named), which is situated midway between Great and Little Langdale and comprises a younger pyroclastic succession than Scafell caldera (Fig. 2; Brown, 2001; Branney, 2007). Some outflow sheets in the Lake District are likely to be from Scafell caldera, whereas others may derive from neighbouring volcanoes (e.g. Langdale caldera).

Exposure of the Borrowdale Volcanic strata is excellent due to deep dissected glaciation SW of Scafell and Langdale calderas, but has undergone intense tectonic deformation (cleavage, faults and thrusts), metamorphism and alteration, and so the affiliations of
several outflow ignimbrites, and their source areas have not been resolved. Consequently, the full extent and shape of the Scafell and Langdale calderas are only tentatively known, and mapped vents within the calderas have not yet been correlated with outflow ignimbrites. Published geological maps exist (BGS, 1991; 1998; 2003) but do not distinguish individual eruption-units that correlate with known units in Scafell caldera, or the nearby Langdale caldera. Ancient volcanic complexes like Scafell caldera allow a rare insight into otherwise concealed critical features. However, the piecing together of the stratigraphy is often hindered by the exact discrimination of lavas, sills and pyroclastics. These cause various affects: i.e. by alteration of original glass fragments, no preservation of pumiceous textures, hydrothermal alteration (particularly of caldera fills), regional burial and tectonic overprinting. Distal as well as proximal outflow units can be difficult to correlate, especially where calderas have produced multiple ignimbrites of broadly similar compositions as well as where more than one caldera volcano overlap with another (Lipman, 1984, 1997). These problems may also be compounded by post-volcanic tectonic deformation e.g. cleavage overprinting eutaxitic fabrics, stratigraphic repetition by thrusting, as in the English Lake District. Though an exact affiliation of various formations in the Upper Borrowdale Volcanic Group has yet to be accomplished.

1.3 Aims and objectives
One of the most essential parts for our understanding of how caldera volcanoes erupted and collapsed, is the clarification of the volcaniclastic stratigraphy both in- and outside of the caldera complex. Only a complete stratigraphic succession enables conclusions on the eruption style, size and magma pluming system that has driven the eruptions.

At ancient caldera volcanoes like Scafell caldera, field observations can be hindered by faulting, cleavage, thrust-repetition and alteration. Most of the volcaniclastic rocks of the Borrowdale Volcanic Group are overprinted and show a very similar appearance in the field due to alteration of original glass fragments, a lack of preservation of pumiceous textures, hydrothermal alteration (particularly of caldera fills), regional burial, metamorphism and tectonism. These rocks are therefore very hard to distinguish in the field, i.e. hindering a correlation between Scafell caldera and the extra-caldera succession to the south-west in the Coniston Fells and Duddon valley areas. An easy,
relatively inexpensive and independent analytical method could give support to
discriminate and correlate a large number of volcaniclastic rocks.

This project is a case study testing the hypothesis if geochemical fingerprinting using
XRF whole-rock analysis in combination with previously undertaken fieldwork and
detailed mapping can be used to distinguish and correlate ancient pyroclastic units of
the Borrowdale Volcanic Group.

The Coniston Fells was chosen as the main project area on the basis of:
(1) A large number of different pyroclastic rocks is exposed within 6 km².
(2) The pyroclastic units have been previously mapped and studied, so a general
knowledge and stratigraphy has been established, but many formations are
problematic and source areas for most of these have yet to be accomplished.
(3) The succession is relatively proximal to Scafell and Langdale caldera, both
representing two potential source areas.
(4) The Coniston Fells is part of the Westmorland monocline, rocks are laying steep
(~ 70° SE) and are often highly cleaved but also well exposed with a large number of
formations to be compared and analysed.
(5) The pyroclastic rocks have undergone low-grade metamorphism (prehnite-
pumpellyite) and are weathered and altered at the surface but are also still fresh
underneath the surface when sampled.

Based on the above summarized field area criteria for the Coniston Fells the following
objectives will be tested and discussed:
(1) Can whole-rock geochemistry be used to fingerprint (distinguish between) different
tuff layers and ignimbrites from Palaeozoic caldera volcanoes?
(2) Can outflow sheets from Scafell caldera be identified and traced in the Coniston
Fells and further south-west to the Duddon valley?
(3) Can outflow sheets from Langdale caldera be identified and traced in the Coniston
Fells area and further south-west, i.e. different formations be merged?
(4) Can intrusions be discovered in the Coniston Fells area?
(5) Can other post-Scafell caldera units be identified and/or correlated in the Coniston
Fells area?
2. Geological setting and stratigraphy

The Lake District hosts a magmatic complex of the Lower Palaeozoic volcanism that is mainly represented by the lithostratigraphic successions of the Borrowdale Volcanic Group (BVG; Fig. 3) in the Central Fells and the smaller Eycott Volcanic Group (EVG) at its northern margin (Millward et al., 2000a, b). In Ordovician times, southern Britain and adjacent parts of continental Europe were situated on the microcontinent Eastern Avalonia. To the north, this micro-plate was separated from the Laurentian continent hosting Scotland, Greenland and north-east North America, by the Iapetus Ocean. The marine Skiddaw Group, dominated by siliciclastic mudstones and siltstones, was deposited in a deep-water environment onto the continental margin at the beginning of the Iapetus Ocean closure (Cooper et al., 1993, Cooper et al., 1995). During the later stage of the Iapetus closure the Eastern Avalonian microcontinent was uplifted, forming a shallow aqueous to sub-aerial setting where the predominantly marine Skiddaw Group was depositing. On top of this marine Group rests unconformably a major volcanic province, generated due to the associated melting in the mantle wedge, named the Borrowdale Volcanic Group (Fitton & Hughes, 1970; Millward et al., 2000a).

2.1 Stratigraphy of Scafell caldera

2.1.1 Andesitic basement and Lingcove Formation

The Lower Borrowdale Volcanic Group volcanism started with explosively erupted tuff cones and tuff-rings followed by the Lingcove Formation, comprising effusive, andesitic lavas forming a low-profile terrain (Fig. 4; Millward et al., 2000a; Millward, 2007). The succession comprises several lavas and high-level sills as well as pyroclastic units that have only been tentatively mapped. This effusive pre-caldera phase is followed by the Upper Borrowdale Volcanic Group that includes Scafell and Langdale calderas.

The volcaniclastic successions in the project area, with the major Scafell caldera to the north and the minor Langdale caldera further in the centre, are illustrated in a simplified geological map (Fig. 3). An overview of the lithostratigraphic succession of Scafell caldera (Fig. 4) followed by the succession of Langdale caldera as described in the previous literature is summarised hereafter.
Fig. 3. Simplified geological map of Scafell and Langdale calderas and the succession around Wetherlam and the Coniston Fells - 1:50 000 solid sheet (after BGS 1968, 2003 and Brown, 2001). Pre-caldera succession not shown as well as andesitic and dacitic intrusions.
Fig. 4. Simplified general vertical stratigraphy of the Borrowdale Volcanic Group within Scafell caldera. (modified after Branney & Kokelaar, 1994; Brown et al., 2007).
2.1.2 Whorneyside Formation

Above the dominantly effusive Lingcove Formation an unconformity marks the boundary to the Upper Borrowdale Volcanic Group and a fundamental change to a climactic explosive and pyroclastic eruption style. The Whorneyside Formation can be subdivided into two units (Fig. 4). The lower Whorneyside Ignimbrite (Branney, 1991) (or Wet Side Edge Member by BGS, 1991) consists of massively welded, eutaxitic andesitic lapilli-tuff. It is poorly sorted and comprises several massive layers up to 30 m thick with internal variations in fiamme and lithic lapilli contents. The unit is about 120 m thick at Scafell caldera and reaches up to 400 m thick around the Duddon valley. The lower Whorneyside Ignimbrite is gradationally overlain by the Whorneyside Bedded Tuff, a finely laminated and parallel bedded, phreatomagmatic fall deposit. The coarse-fine grained laminated and parallel bedded tuff has a general fining upward trend in the laminated beds (Branney, 1991). The change from eutaxitic lapilli-tuff to an ash-fall deposit is interpreted as a change in the eruption style resulting from subsidence of the caldera complex allowing the area to be flooded and changing the eruption style to phreatomagmatic (Branney, 1991). The Whorneyside Bedded Tuff laterally changes thickness from 0 to 100 m resulting from post-depositional faulting and slumping due to an early stage of the piecemeal subsidence of the caldera complex (Branney, 1988b, 1991; Branney & Kokelaar, 1994).

2.1.3 Airy’s Bridge Formation

The Airy’s Bridge Formation displays the bulk of the explosive caldera-collapse phase and the majority of the subsidence of Scafell caldera. It is an up to 1000 m thick dacitic to rhyolitic pyroclastic succession that can be divided into the lower Long Top Tuffs and the upper Crinkle Tuffs members or 8 units (Fig. 4; Branney & Kokelaar; 1994).

Oxendale Tuff

At the end of Great Langdale at Oxendale/The Band, a 60 to 100 m thick pink-weathered, lava-like, rhyolitic welded tuff is situated in between the Whorneyside and the Airy’s Bridge formations. The Oxendale Tuff rests unconformably on top of the Whorneyside Bedded Tuff with a sharp and irregular contact. It differs to the overlying Long Top Tuffs Member by its lava-like flow banding, rheomorphic folding and autobrecciation (Branney, 1988). The Oxendale Tuff has also been described in a few
localities within the Side Pike Complex [NY 293 053], further south on Wetherlam [NY 288 011] and south-east of Seathwaite Tarn [SD 252 988] (Millward et al., 2000a).

**Long Top Tuffs Member including ‘marker units’**
Welded massive eutaxitic, silicic lapilli-tuff with large scale bedding characterizes the Long Top Tuffs Member. The ignimbrite includes three distinct marker units (Stonesty Tuff, Cam Spout Tuff and Hanging Stone Tuff) consisting of fine to coarse-grained, parallel bedded and laminated tuff. Common structures include sand-wave bedforms, pinch-and-swell structures and low-angle cross-bedding (Branney, 1993). All three marker units contain abundant accretionary lapilli. The Stonesty Tuff is white-weathered and flinty and overlies the Whorneside Bedded Tuff. The tuff is generally about 1 m thick and up to 3 m thick on Wet Side Edge. The Cam Spout Tuff is the second ‘marker unit’ within a third of the Long Top Tuffs Member. It is low-angle cross stratified, accretionary lapilli rich and more brownish-weathered (Branney, 1993). The Cam Spout Tuff varies from normally 1 to 2 m to up to 6 m thick near Sourmilk Gill [NY 2275 1203]. The Hanging Stone Tuff is situated at the top of the Long Top Tuffs and comprises a 1m thick, brownish-weathered, low angle-cross-bedded tuff with abundant accretionary lapilli in distinct layers (Davis, 1989).

**Crinkle Tuffs Member**
The upper part of the Airy’s Bridge Formation consists of the rhyolitic Crinkle Tuff Member. In the Central Fells, this can be subdivided into the lower lava-like rheomorphic Bad Step Tuff, the thin tuff layer Rest Gill Tuff and the upper other undifferentiated Crinkle Tuffs. The Bad Step Tuff is a lava-like ignimbrite that comprises a basal breccia, a thick central flow-laminated to flow-folded tuff and an upper autobreccia. It records the first eruption of the Crinkle Tuffs eruption and is ponded entirely in the southern part of Scafell caldera where it reaches a thickness up to 400 m (Branney et al., 1995). The overlying Rest Gill Tuff is interpreted as a phreatomagmatic, locally reworked tuff deposit that partly infills the uppermost part of the autobrecciated Bad Step Tuff (Branney et al., 1995). The upper other Crinkle Tuffs comprises eutaxitic to parataxitic, foliated lapilli-tuff with interbedded breccia layers and an autobrecciated top. A common feature in the Crinkle Tuffs are the elongated eutaxitic and parataxitic fiamme curving around lithic lapilli (Branney & Kokelaar, 1994). Within Scafell caldera it is up to 200 m thick. Outflow sheets of the Crinkle
2.1.4 Pavey Ark Member
The Pavey Ark Member is part of the Seathwaite Fell Formation (Fig. 4). It post-dates the explosive caldera-collapse phase as part of the Scafell caldera-lake phase. The member consists of massive to diffuse-bedded, spatter- and scoria-rich breccia that vertically grades into lapilli-tuff and tuff at the top of the unit. It varies in thickness from 80 to 200 m in the Central Fells to more than 500 m north of Grasmere (Fig. 3). The ignimbrite comprises clast- to matrix-supported blocks, fluidal-shaped spatter and lapilli of vesicular andesite which was interpreted as proximal to the source deposited due to the large clast sizes (Kokelaar et al., 2007). The Pavey Ark Member was deposited in a subaqueous environment carrying juvenile clasts ranging from fine ash to metre-scale blocks (Kokelaar et al., 2007). The source of the eruption is inferred to be easterly of Pavey Ark north of Grasmere, where the member is thickest and mainly consists of coarse, massive breccias and agglomerate.

2.1.5 Glaramara Member
The Glaramara Member comprises subaerial medial to distal phreatomagmatic tuff and pyroclastic density current deposits of a large tuff ring within the lower Sprinkling Tarn Formation (Fig. 4). The type locality of the Glaramara Member is around the summit of Glaramara [NY 246 104] in the Central Fells. The succession conformably overlies coarse sandstones, gravel conglomerates and fine-grained breccias with a maximum thickness of 7 m around Coombe Head [NY 249 109] (Brown et al., 2007). The member can be divided into three lithostratigraphic units of a waxing and waning eruption. Unit 1 comprises diffuse to cross-stratified fine-grained tuff, abundant lapilli-sized ash and accretionary lapilli-tuff that thins systematically towards Scafell (Brown et al., 2007). Unit 2 comprises bedded massive lapilli-tuff mainly deposited in the Central Fells with its maximum thickness around Coombe Head. Unit 3 comprises accretionary lapilli-tuff beds intercalated with stratified tuff (Brown et al., 2007). Unit 1 and 3 have been traced throughout the Central Fells to the Side Pike Complex in the south of Scafell caldera. Due to the accretionary lapilli layer below the Side Pike Ignimbrite, the Side Pike
Complex is interpreted to be younger than the Seathwaite Fell Formation and younger, or of similar age to the Sprinkling Tarn Formation (Brown, 2001).

### 2.2 Geochemistry of Scafell caldera

The volcanic succession of Scafell caldera shows a basaltic to mainly dacitic and rhyolitic compositional range. At the beginning of the explosive caldera-collapse phase the eruption produced the andesitic Whorneyside Formation. With the increasing rate of subsidence and the phreatomagmatic eruption style, the composition changed towards the more evolved dacitic Long Top Tuffs and the most evolved rhyolitic Bad Step Tuff and Crinkle Tuffs during the latter subsidence phase. Several petrogenetic approaches have been undertaken for the Borrowdale Volcanic Group (Oliver, 1954, 1961; Fitton & Hughes, 1970; Beddoe-Stephens et al., 1995; Millward et al., 2000a) but a geochemical correlation has not yet been accomplished.

The Borrowdale Volcanic Group has been affected by processes that have chemically altered the abundances and ratios of many elements. The most significant is hydrothermal alteration related to hydrothermal systems coincident with the Ordovician magmatism, and regional metamorphism related to the Arcadian orogeny. Early major and trace element analysis of the Borrowdale Volcanic Group showed that the scatter appearing when plotting elements in Harker diagrams was caused by variations in phenocrysts and by post-emplacement chemical alteration of the volcanic sequence (Oliver, 1954, 1961; Fitton, 1971). Subsequent authors described alteration as a problematic feature in these Ordovician rocks (Oliver, 1961; Allen et al., 1987; Beddoe-Stephens et al., 1995). The volcaniclastic succession has been affected by a variety of hydrothermal alteration processes including silicification, albitization, actinolite-sericite alteration, chlorite-epidote-actinolite-sphene veining and carbonate veining (Allen et al., 1987). The volcaniclastic rocks within the Borrowdale Volcanic Group host various metalliferous mineralisations accompanied to hydrothermal alteration and the latter metamorphism (Millward et al., 2000a). Effects of alteration on whole-rock geochemistry for correlation purposes will be discussed in chapter 5.1.

Metamorphism was described as potentially burial metamorphism (Oliver et al., 1984) and reached the grade of prehnite-pumpellyite facies (Beddoe-Stephens et al., 1995;
Meller, 1998). The Acadian orogeny causing the low-grade metamorphism was associated with slaty cleavage in the volcaniclastic rocks that is particularly strong to the south and south-west of Scafell caldera in the Coniston and Duddon areas (Firman, 1957; Thomas, 1986; Millward et al., 2000a). An overview map of the cleavage in the Lake District is presented in chapter 4.1.

The low-grade regional metamorphism in the Borrowdale Volcanic Group has been subdivided into areas of three different mineral assemblage zones: (1) the Biotite zone; (2) the Actinolite zone and (3) the Epidote and carbonate-phyllosilicate zone (Millward et al., 2000a). These zones have been described as indicators for a regional metamorphism (Millward et al., 2000a). The volcanic setting of the Borrowdale Volcanic Group has been described as an island arc/continental margin setting (Chapter 5.1.3) (Fitton & Hughes, 1970; Fitton, 1971). Explosively erupted tuff cones and tuff-rings were followed by effusive lavas forming a low-profile terrain (Millward et al., 2000a; Millward, 2007). This effusive pre-caldera phase was followed by an explosive caldera-collapse phase of Scafell caldera.

A first attempt at a new approach used immobile and trace elements to investigate the magma pluming system that drove the piecemeal collapse system (Clarke, 2015; unpublished). Two discrete magma reservoir groups underneath Scafell caldera were distinguished and one of these groups was then further subdivided. The differentiation between the two magma groups was based on a plot of Zr/TiO$_2$ vs. dimensionless stratigraphic height (Fig. 5). A low Zr/TiO$_2$ group was described as andesitic and homogenous. It is characterised by a steady Zr/TiO$_2$ ratio throughout the eruption series. This yielded the Whorneyside Formation and the Cam Spout Tuff, Hanging Stone Tuff and Rest Gill Tuffs. A second, high Zr/TiO$_2$ group is characterised by increasing Zr/TiO$_2$ values with increasing stratigraphic height. The increasing amount of Zr/TiO$_2$ infers a normally zoned magma reservoir during the eruption sequence. This second group produced the Stonesty Tuff, the Long Top Tuffs, the Bad Step Tuff and the Crinkle Tuffs (Clarke, 2015; unpublished). The eruptions of these reservoir groups were described as periodical with successive opening and closing of the eruption conduits due to the piecemeal collapse of Scafell caldera.
Based on the possibility to distinguish between eight units of the Scafell caldera fill succession by whole-rock geochemistry, a potentially larger number of caldera fill and extra-caldera units across the Borrowdale Volcanic Group could be correlated as well.

**Fig. 5.** Zr/TiO₂ vs. stratigraphic height to distinguish the andesitic units of Scafell caldera from the more evolved dacitic to rhyolitic units (modified after Clarke, 2015; unpublished). All samples taken from within Scafell caldera.
2.3 Stratigraphy of Langdale caldera

The Langdale caldera, also known as the Side Pike Ignimbrite or Side Pike complex, is a potential smaller caldera at the south-eastern margin of Scafell caldera (Barnes et al., 2006). The area of the caldera is about 5 km$^2$ mainly comprising the Side Pike Ignimbrite around Side Pike [NY 293 053] and the former Lingmoor Fell Formation around Lingmoor Fell [NY 302 046] centred between Great- and Little Langdale (Fig. 6). The area is dominated by exceptionally coarse and chaotic megabreccia. The megablocks comprise a well-preserved succession of pyroclastic and fallout deposits of magmatic, phreatomagmatic and phreatic eruptions (Branney, 1988; Brown, 2001).

Langdale caldera is highly faulted with megabreccia blocks of 10 to 1000 m in size. These blocks mainly consist of the Side Pike Ignimbrite. The blocks are also referred to as Lingmoor Fell Formation or Side Pike Member (Millward et al., 2000a). Some of the volcanoclastic units can be correlated with surrounding lithostratigraphy but some of the megabreccia blocks can only be directly correlated from one block to the other but cannot be matched with any other part of the surrounding stratigraphy of Scafell or the Duddon Basin succession (Branney, 1988b). Therefore, Branney (1988b) called these blocks ‘exotic’. The succession of the Side Pike Ignimbrite is illustrated in more detail in Fig. 7. A general vertical section for the Side Pike Ignimbrite is presented in Fig. 8.
Fig. 7. Simplified geological map of the Side Pike Ignimbrite on Side Pike and Lingmoor Fell; the red line indicates the location of the general vertical stratigraphy in Fig. 8 (after Branney, 2007).
The Lingmoor Fell Formation mainly outcrops in Little Langdale. At the type locality on Lingmoor Fell (Fig. 7; NY 302 046) the unit reaches a thickness of 600 m (Branney, 1988b). It consists of a dacitic welded pyroclastic deposit with interbedded accretionary lapilli horizons. The unit also incorporates andesitic lava flows, rhyolitic welded tuff, phreatomagmatic deposits and fine bedded tuff layers (Branney & Kokelaar, 1994; Brown, 2001). The exact relationship between the volcaniclastics of Lingmoor Fell and Side Pike is uncertain because some of the volcanoclastic units can be correlated from
one block to the other but they cannot be correlated any further with any other part of the surrounding stratigraphy (Branney, 1988b). Our understanding of the succession is also hindered due to a lack of detailed mapping of the whole Langdale caldera. The Lingmoor Fell Formation is mapped and described as part of the Duddon Basin succession (BGS, 1998; Millward et al., 2000a). The Scafell as well as the Duddon basin successions have been previously interpreted as underlying the Seathwaite Fell Formation (Millward et al., 2000a). The Lingmoor Fell Formation includes the Side Pike Ignimbrite however, the exact relationship, whether the Side Pike Member is part of the Lingmoor Fell Formation or whether it actually also is the same formation is unclear. The term Lingmoor Fell Formation is considered to be obsolete and is now referred to as the Side Pike Complex (Millward, 2007). This term is considered to be obsolete and will now be referred to as Langdale caldera for the intracaldera succession and as Side Pike Ignimbrite for the extra-caldera succession.

2.3.2 Side Pike Ignimbrite

The Side Pike Ignimbrite (after Branney, 1988a) is an intensely welded ignimbrite named after Side Pike [NY 289 053], a hill in Great Langdale (Fig. 7). The ignimbrite overlies a parallel-bedded to cross-bedded tuff with low-angle cross-stratification and abundant accretionary lapilli mapped as the Glaramara Member (Fig. 8; Brown, 2001), followed by a few meters of massive pebbly sandstone, parallel-bedded and stratified tuffs and low angle cross-stratified tuff. The Side Pike Ignimbrite is about 30 m thick and comprises massive, welded rhyodacitic to rhyolitic lapilli-tuff, cross stratified tuff and layers of accretionary lapilli-tuff (Branney, 1988b). Fiamme are abundant in the ignimbrite and get progressively flattened towards the centre of the unit and then less flattened towards the top. The ignimbrite is directly overlain by half a meter of bedded and stratified tuff with abundant accretionary lapilli (Brown, 2001). This is followed by about 25 m of parallel-bedded and low-angle cross-stratified tuff. A breccia with incorporated clasts of the underlying ignimbrite is overlain by more parallel-bedded and cross-stratified tuff. The top of Side Pike comprises a massive andesite lava sheet (Fig. 8).

The Langdale caldera fill (Lingmoor Fell Formation) and Side Pike Ignimbrite were previously mapped as part of the Duddon Basin succession underlying the Seathwaite Fell Formation and Sprinkling Tarn Formation (BGS, 1998; Millward et al., 2000a).
Detailed logging of the Glaramara Member, a thin bedded tuff layer with accretionary lapilli within the upper Sprinkling Tarn Formation, mainly outcropping in the Central Fells, revealed that the Side Pike Ignimbrite must be younger than the Seathwaite Fell Formation and younger, or of similar age to the Sprinkling Tarn Formation (Brown, 2001). The Langdale caldera fill was tentatively interpreted as possibly equivalent to the Low Water Formation (Chapter 2.5.5), another welded dacitic lapilli-tuff unit (Brown, 2001). Though, this has not been proven geochemically.

2.4 Geochemistry of Langdale caldera

Only little work has been done on the geochemistry of the Langdale caldera. Whole-rock XRF data of one dacitic sample of the Lingmoor Fell Formation and data points plotted of four samples for the Lingmoor Fell Formation as well as for the Side Pike ignimbrite are published in five trace element graphs (Millward et al., 2000a). No description is giving for these samples in the text. Some unpublished geochemical data of the Side Pike ignimbrite and the Lingmoor Fell Formation will be used for correlation from previous studies (Branney, unpublished at Leicester).

2.5 Stratigraphy of the Coniston Fells area

The Coniston Fells area in the English Lake District is about 3 to 7 km south of Scafell caldera. The area from Wetherlam to Coniston Fells/Old Man of Coniston [SD 272 978] comprises a large variety of extra-caldera pyroclastic rocks that have been tentatively mapped but source areas for the units have not been correlated, yet (Fig. 9). Most pyroclastic rocks in the Coniston Fells area dip about 75° to the SW, are overprinted by steep Arcadian cleavage and show a very similar appearance in the field. The rocks have been affected by alteration, tectonism and metamorphism. Four additional units (Duddon Hall Formation, Paddy End Member, Low Water Formation and Lincomb Tarns Formation) are exposed in the Coniston Fells area and will be incorporated in this geochemical correlation project. The units post-date the explosive Scafell caldera-collapse and caldera-lake successions and will be investigated for their capability for a correlation with the succession of Langdale caldera. This has the potential, for the first time, to geochemically correlate the Langdale caldera fill with possible outflow sheets to the south of the complex and to confine the eruption period and stratigraphic relationships of Langdale caldera within the Borrowdale Volcanic Group.
Fig. 9. Simplified general vertical stratigraphy of the Coniston Fells area in the southern Lake District (modified from BGS, 1998).
An overview of the lithostratigraphic successions in the Coniston Fells area as described in the previous literature is given in Fig. 9. A brief description of each unit is given below.

2.5.1 Whomeyside Formation
The oldest and lowermost unit of the extra-caldera succession on Wetherlam is the Whorneyside Formation (Fig. 9). It consists of the lower Wet Side Edge Member a eutaxitic lapilli-tuff and an upper bedded tuff unit mapped as the Whorneyside Bedded Tuff (Millward et al., 2000a), that comprises thin laminated and parallel-bedded phreatoplinian ash-fall tuff.

2.5.2 Airy’s Bridge Formation
The Airy’s Bridge Formation is a dacitic to rhyolitic pyroclastic succession mainly comprising thickly bedded to massive lapilli-tuff. In the Coniston Fells area, only the Oxendale Tuff and the Long Top Tuffs Member has been previously described (Fig. 9; Millward et al., 2000a). However, marker horizons within the Long Top Tuffs Member as well as the Crinkle Tuffs Member have not been described, yet. The Whorneyside and the Airy’s Bridge formations are overlain by the Duddon Hall Formation.

2.5.3 Duddon Hall Formation
The Duddon Hall Formation comprises a large variety of volcaniclastic rocks, predominantly medium to coarse grained, parallel-laminated to thickly bedded tuff. Secondary are thickly bedded coarse bedded tuffs, massive and very poorly sorted lapilli-tuffs, tuff-breccias and finer parallel, thin bedded ash-fall tuffs (Fig. 9; Millward et al., 2000a). The Formation was first described as the Duddon Bridge Tuffs and later extended and combined with the Dunnerdale Tuffs as the Duddon Hall Tuffs (Mitchell, 1956; Firman, 1957). The Formation extends from Wetherlam in the Coniston Fells area over its type area around Hollin House Tongue [SD 227 965] to the Ulverston area [SD 280 780] further south-west in the Lake District. Focus of the description will be on the succession around Wetherlam where about 450 m are exposed. The formation thins to the west to 250 m around Dow Crag (SD 262 977; Millward et al., 2000a). The base is a sharp contact from welded tuff to the overlying andesitic bedded tuff passing into varying sheets of medium to coarse tuff and lapilli-tuff. In the Coniston Fells, the
formation is dominated by 50 to 140 m thick sheets of massive and very poorly sorted, ungraded lapilli-tuff and tuff-breccia. A common feature in these rocks are accidental scoria and lithics of pebble size as well as angular, ragged and fiamme-like juvenile fragments (Millward et al., 2000a).

2.5.4 **Paddy End Member**

The Paddy End Member is a pink-weathered, flinty rhyolitic, high-grade ignimbrite (Fig. 9). It varies from homogeneous and vitric-crystal rich to a lava-like pyroclastic deposit. The Paddy End Member unconformably overlies the Duddon Hall Formation in the Coniston Fells and at its type locality around Levers Water [SD 278 989] to the south-west (Mitchell, 1950, 1956). The member is overlain by volcaniclastic sandstone units of unclear origin, followed by the Low Water and Lag Bank formations, two welded dacitic lapilli-tuffs. Further to the west in the Duddon valley, the ignimbrite mainly overlies the Kiln Bank Member, a dacitic lapilli-tuff and is overlain by the Stickle Pike Member, a rhyolitic lapilli-tuff, and the Caw Formation, another volcaniclastic sandstone succession. The thickness of the Paddy End Member is 150 to 170 m around Coniston, thinning to 30 m in the Duddon valley (Millward et al., 2000a). The ignimbrite has a very hackly/flinty appearance on Steel Edge [NY 295 014] north-east of Coniston with small elongated fiamme. Lithics are rare in the fine devitrified matrix. The general fiamme distribution changes from abundant to less frequent to again abundant with stratigraphic height, although fiamme are hard to see due to weathering, cleavage and the hackly surfaces. In the Duddon valley, textures are highly cleaved and even harder to distinguish.

2.5.5 **Low Water Formation**

The Low Water Formation (Fig. 9) widely overlies the Paddy End Member and crops out from Greenburn Beck north of Tilberthwaite [SD 302 975] to Low Water [SD 275 983] in the south-west. At the type area on Above Beck Fells [SD 296 999] the formation is up to 600 m thick and consists of two massive welded sheets of lapilli-tuff interbedded with bedded tuff and volcaniclastic sandstone (Millward et al., 2000a). At its southernmost appearance it intercalates with the Lag Bank Formation. The Low Water Formation was first described as the Upper Tilberthwaite Tuff (Mitchell, 1940). The base of the formation consists of up to 220 m thick bedded volcaniclastic sandstone
and the base of the ignimbrite is brecciated. It is brown-weathered with a well-developed eutaxitic texture containing up to 20% of up to 12 x 2 cm large fiamme (Millward et al., 2000a). The two ignimbrites are divided by an up to 35 m thick sheet of laminated volcaniclastic tuff with occasionally layers of accretionary lapilli. The Low Water Formation is overlain by the Seathwaite Fell Formation in the Coniston Fells.

2.5.6 Lincomb Tarns Formation
The Lincomb Tarns Formation is situated in the uppermost Borrowdale Volcanic Group post-dating the Scafell caldera succession (Fig. 9). It predominantly consists of eutaxitic, dacitic lapilli-tuff that is interbedded with tuff-breccia, bedded tuff and thin intercalations of volcaniclastic sandstone (Millward et al., 2000a). The thickness of the formation varies in the Central Fells from 150 to 290 m further west at its type locality around Lincomb Tarns/ Allen Crags (NY 241 093; McConnell, 1993). South of Scafell Caldera, around Tom Heights (NY 326 002], the thickness of the Lincomb Tarns Formation increases to up to 800 m (Millward et al., 2000a). The ignimbrite is of dacitic composition containing fiamme with aspect ratios 3:1 to 10:1. Feldspar is the dominant crystal component both in the fiamme and in the pyroclastic matrix with common alteration to chlorite (Millward et al., 2000a). The formation has been extensively correlated in the Central Fells and to the south and east of Scafell caldera with the underlying Seathwaite Fell Formation a thick volcaniclastic sandstone unit with interbeds of tuff, lapilli-tuff, breccia and conglomerates (BGS, 1998). The pyroclastic succession has a sharp base and the depositional environment is described as partly subaerially and partly subaqueously on a westerly inclined palaeoslope (McConnell, 1993). In the Coniston Fells columnar jointing is described as a prominent feature of the Lincomb Tarns Formation. The jointing zones differ with column diameters of 5.5 to 11 cm at Long Crag [NY 154 122] to 9 to 23 cm at Torver Beck [SD 273 963] (Millward, 1980; Millward et al., 2000a). Also the plunge and angle of the columns slightly varies.
3. Methods
A more thorough and detailed description of the following chapters 3.1 (fieldwork and sample collection) to 3.3 (analytical precision and accuracy) can be found in the Appendix.

3.1 Fieldwork and sample collection
Fieldwork was undertaken in two periods from August to November 2016 and from April to May 2017. Samples were collected in the main study areas (on Wet Side Edge and Wetherlam) and in various other localities in the Central Fells, Langdales, Coniston Fells, Dunnerdale valley and on Hesk Fell. Aerial images of sample localities and a more detailed description is given in Appendix I.

3.2 Sample preparation
Sixty-four samples were processed during this project for XRF whole-rock analysis. Weathered surfaces were carefully removed and samples were mechanically ground and milled in order to prepare fusion beads and powder pellets for geochemical major and trace element analysis (detailed description in Appendix II).

3.3 XRF analysis, analytical precision and accuracy
All major and trace element analyses for this research project were analysed at the University of Leicester using a PANalytical Axios Advanced X-ray Fluorescence spectrometer (XRF). For analytical precision and accuracy major and trace element analysis were controlled by international reference materials during each run (detailed description in Appendix II).

3.4 Geochemical data base
Sixty four samples were collected during fieldwork of this project. Other geochemical data used in this project are data from the research group at the University of Leicester. This includes samples from Branney (37 samples) which have not yet been used for publications and MGeol projects of Clarke (12 samples; 2015, unpublished) and Mobley (3 samples; 2015, unpublished). Sample locality tables are presented in Appendix I and geochemical data tables in Appendix II.
3.5 Correlation attempts of ignimbrites reviewed

The correlation of ignimbrites between proximal to distal deposits can be a challenging task. For example, ignimbrites can vary in thickness, they can be homogenous or heterogeneous, welded or non-welded, internally zoned, they can change in lithofacies over distance and they can be faulted due to post-emplacement tectonism (Branney & Kokelaar, 2002).

So what are typical techniques for ignimbrite correlation? Criteria can be divided into 5 groups: lithological, magnetic, petrographical, chemical and isotopical (Hildreth & Mahood, 1985). The subchapters will include examples of where and why each different technique has been previously used on pyroclastic successions when lithological and stratigraphical criteria were insufficient for correlation. It will also discuss the limitations of each technique on the ancient successions of Scafell and Langdale calderas.

3.5.1 Mapping and stratigraphic continuity

The strongest lithological criteria is mapping. Differences in colour, weathering and alteration, welding, crystal content, jointing, sorting, proportions and sizes of pumice and lithics can give a large amount of distinguishing information for each ignimbrite sheet. Mapping to establish physical and stratigraphic continuity is a very reliable tool for correlation except in structural complex, hydrothermally altered or poorly exposed areas. This is of high relevance in both modern and ancient systems where sheets are covered by later deposits or have been eroded away, i.e. by glaciation. Stratigraphic relationships as part of the overall geological setting can also give evidence for lithological correlation of outflow sheets (Hildreth & Mahood, 1985). In the following subchapters a number of different techniques for correlation are summarized if mapping is hindered.

3.5.2 Petrography

Petrographic criteria focus on the total content, sizes and relative proportions of phenocrysts within an ignimbrite and the textures and fabrics within the matrix of an ignimbrite sheet. Problematic for these criteria are the possible zoning of the magma reservoir and the mechanical fractionation during the eruption and transport in the
current (Hildreth & Mahood, 1985). The amount of phenocrysts within certain areas of an ignimbrite depends on the ignimbrite architecture. The depositional conditions at the flow boundary zone can vary from proximal to distal within a pyroclastic density current due to changes in the rate of deposition, the mass flux or the rate of supply (Branney & Kokelaar, 2002).

3.5.3 Phenocryst and glass shard composition

Another approach can be made analysing phenocrysts and glass shards. This technique is related to petrography and they are often complemented with each other. Single glass shard and phenocryst analysis has become a common tool for the correlation of pyroclastic deposits. Trace elements in the glass shards and phenocrysts are analysed by electron microprobe or laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). This correlation technique is mostly used on Cenozoic pyroclastic deposits because glass shards have to be relatively fresh and unaltered for analysis (Harangi et al., 2005; Pearce et al., 2008; Cassel et al., 2009).

Glass shard and phenocryst analysis has been described being of little use for tephro-correlation studies on pyroclastic rocks of the Ordovician Llewelyn and Snowdon Volcanic groups, North Wales (Orton, 1992). Glass shards are affected by devitrification, hydration and recrystallization during diagenesis and hydrothermal alteration and are therefore inappropriate for analysis. Also the main phenocryst phases feldspar and pyroxene have been altered in the Snowdon volcanics. Scafell and Langdale calderas are of similar age and setting to the Snowdon volcanic centre. The volcaniclastic rocks have been affected by hydrothermal alteration and metamorphism (Chapter 5.1.1; Millward et al., 2000a).

3.5.4 Geochronology

Geochronology is a diagnostic method using isotopic ratios to calculate ages for rock successions. Different isotopes are used depending on the relative age of the rocks. Typical methods are 40K/40Ar, 40Ar/39Ar, 87Sr/86Sr and U-Pb isotopes in zircons (Mahood & Drake, 1982; McDougall & Harrison, 1999; Nomade et al., 2014).
Geochronology has been proven to be a helpful and precise tool mainly on Cenozoic pyroclastic successions. A basic assumption for dating as a correlation tool is an age of each ignimbrite sheet more accurate than the dating uncertainty. If several layers have been rapidly accumulated, the interval of their emplacement must still be larger than the minimum precision of the dating method being used otherwise the scatter can blur a reliable affiliation of an unclear unit within a succession (Pasci et al., 2001; Gisbert & Gimeno, 2016). Dating for correlation has been undertaken on Neogenic ignimbrite sheets on Sardinia, Italy. The timespan in between the eruption units was 0.17 Ma using \(^{40}\text{Ar}/^{39}\text{Ar}\) (Pasci et al., 2001). Other examples for correlation purposes on Neogenic volcanics are in Turkey (Le Pennec et al., 2005; Aydar et al., 2012; Sumita & Schmincke, 2013), in the Andes (Paquereau Lebti et al., 2006; Freymuth et al., 2015) and in the Massif Central, France (Nomade et al., 2014).

In volcanic systems, the differentiation between ignimbrites from the same volcanic centre using geochronology is often hindered by analytical precision. Geochronology has been applied on ancient ignimbrites for correlation purposes to determine ages for the pyroclastics within their surrounding stratigraphy or for their general emplacement settings (Deutsch & Somayajulu, 1970; Breitkreuz & Van Schmus, 1996; Zhong et al., 2014; Gaggero et al., (in press)). U-Pb geochronology has been undertaken on the pyroclastic rocks of the Borrowdale Volcanic Group for depositional ages (Millward & Evans, 2003). Though geochronology has not been used for the correlation of individual outflow sheets in the Lake District.

### 3.5.5 Palaeomagnetism

If the use of geochemistry is hindered, another attempt for the correlation can be made by magnetic polarities and thermal remanent magnetization (TRM). This is commonly used for drift record of continental and oceanic igneous rocks to analyse their palaeomagnetism (Stacey, 1960; Fuller, 1963). It has also been helpful to correlate ignimbrites because most welded tuffs have stable magnetic properties and show laterally and vertically uniform thermal remanent magnetizations (Hildreth & Mahood, 1985). This technique has been used in both devitrified welded zones as well as in young glassy welded and even non-welded deposits (Reynolds, 1977, 1979).
Paleomagnetism has been used to resolve correlation issues on a variety of Cenozoic pyroclastic rocks (McIntosh, 1991; Speranza et al., 2012; Best et al., 2013; Ort et al., 2013; Vigliotti, 2015). To clearly separate and distinguish between two units these must show a clear difference in their thermo-remanent magnetization (TRM) directions. To minimize errors in determination and analytical uncertainty, polarities must differ to a minimum of 10 degrees. Problematic magnetics like induced remanent magnetization (IRM) or chemical remanent magnetization (CRM) have to be removed as well as post-cooling strata tilts (volcano-tectonic or tectonic) have to be rotated back for an exact correlation (McIntosh, 1991; Knott et al., 2016a, b).

Tectonism causing cleavage of the rock or fault block rotation can highly affect the thermal remanent magnetization. Palaeomagnetism has been tried in the Borrowdale Volcanic Group but the strong cleavage and faulting of the volcaniclastic succession SW of Scafell caldera limits the usage of paleomagnetism (Channell & McCabe, 1992).

3.5.6 Whole-rock geochemistry

Whole-rock geochemistry has been used more frequently for the correlation on younger, Cenozoic ignimbrite successions (Gençalioğlu-Kuşcu & Floyd, 2002; Peate et al., 2003; Ellis et al., 2012; Vidal-Solano et al., 2013). These rocks have undergone less alteration and metamorphism than the ancient Borrowdale Volcanic Group and should be therefore less affected by secondary mineralization processes. Recently, two studies are of particular interest. A combination of field mapping and sampling for petrographic, geochemical, radiometric and palaeomagnetic analysis were used on the pyroclastics of Snake River, which are of rhyolitic composition and comprise rheomorphic ignimbrites and extensive ash-fall deposits (Knott et al., 2016a, b). The rocks are Miocene and have undergone less alteration than the Borrowdale Volcanic Group. Whole-rock geochemistry plots (Rb/Sr vs. Th/Nb) were used for discrimination between several units (Knott et al., 2016a). An ignimbrite sequence of 19 units was correlated on Sardinia, Italy, using a total of 242 samples for XRF whole-rock analysis (Gisbert & Gimeno, 2016). Of the total, 92 representative and fresh samples were also analysed by ICP-OES. Immobile trace element ratios were plotted in binary diagrams to differentiate between chemically overlapping pyroclastic groups. The study showed the possible differentiation of a large number of pyroclastic units by plotting overlapping units against other using differing single trace elements and ratios.
An early approach for the correlation of ignimbrites in a similar setting and of similar age to the Borrowdale Volcanic Group has been made in North Wales. Two ignimbrites of the Snowdon volcanic succession, a lower and an upper rhyolitic tuff, were both distinguished and laterally correlated by different Zr and Nb abundances relative to each other (Leat et al., 1986). Known and unidentified pyroclastic successions of the Capel Curig Volcanic Formation, Snowdonia, were correlated over a range of >5 km by the use of only three trace elements (Zr, Y, Nb) with whole-rock geochemistry (Orton, 1992).

Whole-rock geochemistry has some very positive aspects for correlation. This technique is offering a large number of major and trace elements including some important immobile and incompatible trace elements. Those elements enable a variety of correlation and characterization aspects. Furthermore, whole-rock geochemistry is independent of the degree of crystallization and the mineral assemblage of the magma. For correlation purposes this can be an advantage, because the mixed composition of the whole-rock sample is already an average and a large number of major and trace elements are available for correlation. It is independent of the degree of welding and consolidation. Another advantage, compared to geochronology, is the independence of the emplacement time span between two ignimbrite sheets because geochemistry records a change between magma reservoir conditions more precisely over a longer time period than isotope ratios due to their potential large uncertainties (Gisbert & Gimeno, 2016).

On the other hand, whole-rock analysis is often treated with caution because the chemical composition of an ignimbrite can significantly differ from the chemistry of its source magma by several emplacement mechanisms. This can be caused by (1) the elutriation of fine ash and the incorporation of accidental lithics (xenocrysts and xenoliths) during the generation, transport and deposition of a pyroclastic density current (Walker, 1972; Branney & Kokelaar 1992, 2002; Gisbert & Gimeno, 2016); (2) fractionation and contamination mechanisms in the moving pyroclastic density current (Hildreth & Mahood, 1985); (3) depositional mechanisms causing heterogeneity, sorting and mixing (Branney & Kokelaar, 2002); and/or (4) a zoned pyroclastic deposit caused by a change in the source magma (zoned magma reservoir) (Sumner & Branney, 2002; Milner et al., 2003; Fedele et al., 2016).
(5) The geochemistry can also be significantly changed by secondary alteration of the ignimbrite. This can be caused by oxidation, hydration, leaching and the exchange of ions in glass fragments (Lipman, 1965) as well as by hydrothermal alteration and metamorphism of the other mineral phases within the ignimbrite. Another potentially disadvantage for the geochemical correlation between caldera fill, proximal and distal outflow sheets can be the increased hydrothermal alteration of the intracaldera succession and the proximal volcaniclastics, because these were closer to the volcanic heat centre (Donoghue et al., 2008). If the pyroclastic succession, i.e. in the Borrowdale Volcanic Group, is affected by alteration, whole-rock geochemistry should still give a representative value of immobile and incompatible trace elements, because an average composition of each sample is analysed.
4. Results

4.1 Fieldwork for stratigraphic and volcanological relations

The cleavage directions around Scafell and Langdale calderas and the pyroclastic succession towards the Coniston Fells are illustrated in the synoptic structural map of Fig. 10 (after BGS, 1998; 2003; Millward et al., 2000a; Brown, 2001). The cleavage of the Borrowdale Volcanic Group is dominated by Acadian cleavage forming a great arc across the Lake District. This arc strikes with a proximal sixty degree angle trending north-north-east in the south-west to increasingly east-north-easterly to the north-east of the Borrowdale Volcanic Group (Millward et al., 2000a). In the Central Fells cleavage is weak whereas to the south from Wetherlam to Coniston and the Duddon valley cleavage is intensively developed.

Fig. 10. Simplified geological map focusing on the Acadian cleavage in the Lake District. Cleavage increases from the Central Fells to the Coniston Fells area further south – 1:50,000 solid sheet (after BGS, 1998; 2003; Millward et al., 2000a; Brown, 2001).
The type localities of the various units discussed in this project are illustrated in Fig. 11.

Field reappraisal of the pyroclastic succession on Wet Side Edge and Wetherlam revealed several new units that will be discussed in detail in chapter 5.3 to 5.5. The following presents aerial images of the successions on Wet Side Edge and Wetherlam as previously mapped and as revised during this project and the tables of samples used during this project.
Fig. 12. Aerial image of the succession on Rough Crag as mapped by British Geological Survey (1998). The Whorneyside Formation is overlain by the Long Top Tuffs Member, with only the Stonesty Tuff mapped at the base of the member (areal image adapted from Google Earth, 2017).
Fig. 13. Aerial image of the revised succession on Rough Crag during this study. The Whorneyside Formation is overlain by the Long Top Tuffs Member (now including the Stonesty Tuff, Cam Spout Tuff and Hanging Stone Tuff). It is overlain by the Crinkle Tuffs Member (areal image adapted from Google Earth, 2017).
Fig. 14. Aerial image of the succession on Wetherlam as mapped by British Geological Survey (1998). The Scafell caldera succession comprises the Wet Side Edge Member and Whorneyside Bedded Tuff overlain by the Oxendale Tuff and a very thick Long Top Tuffs. This is overlain by the Duddon Hall Formation and the Paddy End Member (areal image adapted from Google Earth, 2017).
Fig. 15. Aerial image of the revised succession on Wetherlam during this study. The Scafell caldera succession now comprises the Whorneyside Ignimbrite and Whorneyside Bedded Tuff overlain by the Long Top Tuffs and Crinkle Tuffs members. The Wetherlam Dacite and Glassy Crag Dacite intrusions lie within this succession. It is overlain by the Duddon Hall Formation and the Paddy End Member. Also shown are the sample localities taken for geochemical analysis (areal image adapted from Google Earth, 2017).
Fig. 16. Aerial image of Langdale caldera on Lingmoor Fell and the extra-caldera succession on Side Pike. The base of the caldera fill ignimbrites is not exposed. Localities of samples taken by Branney and during this project are shown (Branney unpublished work; areal image adapted from Google Earth, 2017).
4.2 Geochemical characteristics

4.2.1 Major-element variations

About half of the samples throughout the Borrowdale Volcanic Group have <2 wt. % LOI (loss on ignition) suggesting that these samples have not been altered to a high degree by replacement of hydrous minerals. About the other half of the samples have 2 to 5 wt. % LOI suggesting that these samples have undergone some alteration and element mobilisation. Higher LOI values are not only related to either the caldera fill or extra-caldera samples but particularly occur in certain units (Table 3 and 4). These are in stratigraphical order: the pre-caldera Lincope Formation lavas, some of the Whorneyside Formation, the Cam Spout Tuff (Wetherlam), the Hanging Stone Tuff caldera fill, the Rest Gill Tuff caldera fill, the Glassy Crag Dacite, few of the Side Pike Ignimbrite, the Low Water Formation, the Pavey Ark Member, the Duddon Hall Formation and the Lincomb Tarns Formation (Table 3 and 4). Seven samples of the Pavey Ark Member, the Duddon Hall Formation and the Low Water Formation have >5 wt. % LOI values. These samples have undergone further alteration and weathering.

Fig. 17. Major elements plotted for all data used of the Borrowdale Volcanic Group (in wt. %). (a) SiO$_2$ vs. MgO. (b) SiO$_2$ vs. TiO$_2$. (c) SiO$_2$ vs. Al$_2$O$_3$. (d) SiO$_2$ vs. Fe$_2$O$_3$ (all data includes: this study; Branney, unpublished; Clarke, unpublished; Mobley, 2015, unpublished).
Major elements of the Borrowdale Volcanic Group are considered for the general geochemistry of an island arc calc-alkaline trend (Miyashiro, 1974). TiO$_2$, MgO, Al$_2$O$_3$, Fe$_2$O$_3$ in wt. % are plotted against SiO$_2$ (Fig. 17). The data show negative correlation trends with increasing silica content suggesting that Fe and Ti are removed by Fe-Ti oxides (magnetite) and amphibole whereas Mg is removed by pyroxene and Al and Ca are removed by plagioclase. K$_2$O plotted against silica behaves generally incompatible causing a positive correlation with increasing silica within island-arcs (Fig. 18). K$_2$O shows a very wide scatter throughout the dataset suggesting that the major element has been more affected by alteration and mobilisation. Also Na$_2$O which behaves similar and in relation to K$_2$O is very wide scattered. Petrographically, there is abundant evidence for alteration of the primary mineralogy of the rocks. Plagioclase, alkali feldspar and pyroxene pheoncrysts are strongly altered to secondary minerals. Groundmass mineralogy is also pervasively replaced. This suggests mobilisation of major elements including Mg, Fe, Ca, Na and K during the alteration. Rock classifications of the Borrowdale Volcanic Group will be discussed in chapter 5.1.

![Fig. 18. Major element plots for all data used of the Borrowdale Volcanic Group (in wt. %). (a) SiO$_2$ vs. K$_2$O. (b) SiO$_2$ vs. Na$_2$O (all data includes: this study; Branney, unpublished; Clarke, unpublished; Mobley, 2015, unpublished).](image)

4.2.2 Trace-element variations

Various immobile trace elements (Sr, Nb, Th, Zr in ppm) are plotted against SiO$_2$ (wt. %) to show the general fractionation trends in the Borrowdale Volcanic island-arc suite (Fig. 19). Sr shows a negative correlation trend with increasing silica content suggesting that it has been removed by plagioclase during fractionation. Sr has a relative wide scatter in the andesitic and dacitic compositional range which can be caused by mobilisation processes during alkali metasomatism and will not be further
considered for correlation purposes (Orton, 1992). The other three plotted trace elements Nb, Th and Zr behave more incompatibly and will be used for discrimination and correlation purposes. Nb and Th show positive correlation trends with increasing SiO$_2$. Nb behaves compatible in magnetite and ilmenite and is also incorporated in rutile or biotite. Th also behaves incompatibly and becomes enriched in the melt. Th can be incorporated by apatite. Zr shows a positive correlation trend with increasing silica content suggesting that it has been enriched in the melt. This is due to the incompatible behaviour of Zr throughout the fractional crystallisation process until Zr becomes incorporated in zircon.

**Fig. 19.** Trace element plots for all data used of the Borrowdale Volcanic Group (in wt. % and ppm). (a) SiO$_2$ vs. Sr. (b) SiO$_2$ vs. Nb. (c) SiO$_2$ vs. Zr. (d) SiO$_2$ vs. Th (all data includes: this study; Branney, unpublished; Clarke, 2015, unpublished; Mobley, 2015, unpublished).

Major and trace element data for the samples collected and for the other samples used during this project are presented in the tables hereafter.
4.3 Short summary of previous ICP-MS whole-rock correlation attempt

The first attempt for a geochemical analysis of the Borrowdale Volcanic Group using inductively coupled plasma mass spectrometry (ICP-MS) was undertaken by Hammerson (unpublished MGeol thesis, 2017) subsequent on the XRF attempt of Clarke (2015; unpublished) to better understand the magma pluming system of Scafell caldera. For this case study, 25 whole-rock samples were processed. In a first attempt the sample material was molten to fusion beads with a lithium metaborate flux and then crushed and digested. The produced data showed wider uncertainties and various anomalies than expected due to the lithium metaborate flux. In a second attempt the whole-rock sample powders were directly dissolved in hydrofluoric acid and analysed. This analysis generated a better analytical precision and accuracy (Hammerson, 2017; unpublished).

The ICP-MS data had a higher level of correlation precision in comparison to the XRF data for Sr, Y, La and Nd. On the other hand, the study showed, that the data accuracy with ICP-MS for most of the analysed rare earth elements exceeded an error of ±15 % on either the dissolved beads or powders or both (Er, Tm, Yb, Lu). A combination of XRF data for certain important trace elements (Nb, Th, Y, Zr, TiO₂) as well as ICP-MS for some useful rare earth elements (La, Sm, Gd, Yb) would provide the most reliable element set according to the study of Hammerson (2017; unpublished).

Due to the time-consuming preparation of the large number of samples used hereafter, ICP-MS analysis will not be further considered for the correlation of pyroclastic rocks of the Borrowdale Volcanic Group in this study.
5. Discussion

5.1 Processes responsible for chemical variation

5.1.1 Element mobility associated with alteration and regional metamorphism

The ancient volcanic succession of the Borrowdale Volcanic Group has undergone extensive weathering, a wide range of hydrothermal alteration processes as well as regional metamorphism (Millward et al., 2000a). All of these processes could have potentially influenced and mobilised various major and trace elements of the volcanic rocks. In order to reliably interpret the geochemical data from XRF whole-rock analysis and to correctly classify the different units, the effects of element mobility due to alteration and metamorphism have to be discussed first.

Major and trace elements from whole-rock XRF were analysed for 64 samples (complemented by 54 samples from Branney, unpublished; Clarke, 2015, unpublished; Mobley, 2015, unpublished). Standard analytical error values were calculated for all immobile elements at the University of Leicester and analytical precision and accuracy was considered as previously discussed in Chapter 3.3/Appendix II.

Major elements for classification

Major elements (except TiO\textsubscript{2}) were considered to be unreliable for classification purposes due to the large amount of element variabilities and their widely known sensitivity for mobilization which is consistent with petrographic evidence and the degree of regional metamorphism (Hastie et al., 2007). SiO\textsubscript{2} values range from 46.84 to 75.84 wt. % over the whole data set. On a plot of K\textsubscript{2}O vs. SiO\textsubscript{2} (after Peccerillo & Taylor, 1976; Ewart, 1982) the samples show a very wide scatter with a range from low-K over medium-K to mostly high-K throughout the data set (Fig. 20). The K\textsubscript{2}O values range from 0.24 to 10.02 wt. %. The high-K values of the samples illustrate that the K\textsubscript{2}O values have been highly affected by alteration.
The $K_2O+Na_2O$ plot (Total Alkali Silica Diagram) is a classification chart for volcanic rocks (after Le Bas et al., 1986). The data also show a wide scatter with a range from 3.87 to 12.03 wt. % in this plot (Fig. 21). The samples of the Borrowdale Volcanic Group are expected to mainly plot within the calc-alkaline series with an andesitic to rhyolitic composition (Beddoe-Stephens et al., 1995) but most samples scatter from the
trachyandesite/trachydacite to rhyolite fields. This scatter is caused by alteration of the primary mineralogy of the rocks due to regional metamorphism and alkali metasomatism due to the convection and interaction of alkali (K and Na)-rich hydrothermal fluids which are added to the host rock (Millward et al., 2000a). Closely related to the alteration of K$_2$O and Na$_2$O are the alkaline and alkaline-earth elements Rb, Sr and Ba. These elements were mobilized as well during alkali metasomatism and will not be further considered for correlation purposes.

Trace elements for classification
Trace elements have been considered of being more reliable for classification for the different rock types and as a starting point for a first overview correlation between the various units (chapter 5.2; Floyd & Winchester, 1975). The Nb/Y vs. Zr/TiO$_2$ plot (after Winchester & Floyd, 1977) is a commonly used classification chart for volcanic rocks. The plot has been developed as a proxy for the Total Alkali Silica diagram (Fig. 21). The alkaline majors K$_2$O+Na$_2$O have been replaced by the Nb/Y ratio and SiO$_2$ has been replaced by the Zr/TiO$_2$ ratio. The Nb/Y vs. Zr/TiO$_2$ plot shows less scatter of the samples for each unit with several distinct characteristics for various units. This will be discussed in more detail in chapter 5.2.

Fig. 22. Nb/Y vs. Zr/TiO$_2$ classification (after Winchester & Floyd, 1977). The samples of the Borrowdale Volcanic Group mainly plot in the andesite, dacite and rhyolite fields (all data includes: this study; Branney, unpublished; Clarke, 2015, unpublished; Mobley, 2015, unpublished).
A new classification diagram has been developed using Th as a proxy for $K_2O$ and Co as a proxy for $SiO_2$ (Hastie et al., 2007). These trace elements are more robust to weathering and metamorphism effects but still behave equivalent to $SiO_2$ vs. $K_2O$. The study was concentrated on Cretaceous volcanic arc lavas from Jamaica that had undergone hydrothermal alteration and intense tropical weathering (Hastie et al., 2007). To test the applicability of the classification chart for the ancient Borrowdale Volcanic Group the geochemical data set has been plotted in Fig. 23.

The data shows little scatter with most samples plotting in the andesite and dacite to rhyolite fields, similar to the Nb/Y vs. Zr/TiO$_2$ plot in Fig. 22. Compared to previous classifications of the Borrowdale Volcanic Group, which suggested a prevalent calc-alkaline composition, the Co vs. Th plot suggests a high-K/shoshonite composition for most of the Borrowdale Volcanic Group samples (Hastie et al., 2007).

![Co vs. Th classification](after Hastie et al., 2007). The samples of the Borrowdale Volcanic Group mainly plot in the andesite and dacite to rhyolite fields (similar to Fig. 22) but most samples plot within the high-K and shoshonite field (all data includes: this study; Branney, unpublished; Clarke, 2015, unpublished; Mobley, 2015, unpublished).
5.1.2 The process of fractional crystallisation

Fractional crystallisation, besides partial melting, is the principal component of magmatic differentiation of volcanism related to subduction zones. The segregation of the melt from the crystallising minerals, mainly caused by gravitational crystal settling and extraction of melt from semi-crystalline mushes, results in the relatively depletion in some elements and the enrichment in other elements of the remaining melt (Wilson, 1989). This process defines the amount and the consequent variation of element values within each sample. The process of fractional crystallisation can be further demonstrated by the Zr/TiO\textsubscript{2} ratios that are plotted vs. SiO\textsubscript{2} in Fig. 24. The Zr/TiO\textsubscript{2} ratios were also used in the previously discussed Nb/Y vs. Zr/TiO\textsubscript{2} classification diagram as a proxy for silica (Winchester & Floyd, 1977). The crystallisation in a large igneous reservoir commences with high temperature minerals such as olivine followed by pyroxene and iron/titanium rich phases. During the ongoing processes of fractional crystallisation, the melt becomes more and more enriched in silica and incompatible large-ion lithophile elements (LILE) and high field strength elements (HFSE). Zr becomes enriched during fractional crystallisation in the melt (Fig. 24). This is due to the incompatible behaviour of Zr throughout the fractional crystallisation process until Zr becomes incorporated in zircon. Ti behaves compatibly throughout fractional crystallisation and is removed by Fe-Ti oxides (magnetite, ilmenite) and amphiboles. Ti becomes depleted in more evolved melts. Therefore the Zr/TiO\textsubscript{2} silica proxy

![Fig. 24. Data of the Borrowdale Volcanic Group in a SiO\textsubscript{2} vs. Zr/TiO\textsubscript{2} plot, where Zr becomes enriched with increasing silica content (all data includes: this study; Branney, unpublished; Clarke, 2015, unpublished; Mobley, 2015, unpublished).](image)
approximates the fractionation and evolution state of a melt (Winchester & Floyd, 1976).

5.1.3 Subduction influence

To test the influence of the subduction zone on the geochemistry of the Borrowdale Volcanic Group, a Nb/Y vs. Th/Y diagram can be used (Fig. 25; Pearce, 1983; Pearce & Peate, 1995). The ratios of Nb/Y and Th/Y are both strongly affected by partial melting but not affected by fractional crystallisation. The MORB-OIB array (depleted to enriched) is caused by the varying partial melt degree of the mantle. A low partial melt degree gives high Th/Y and Nb/Y melts, and high degree partial melts give low ratios. All samples of the Borrowdale Volcanic Group are enriched in Nb against N-MORB and in Th by the subduction zone and hence plot above the MORB-OIB-array. This enrichment could provide evidence, that the Borrowdale Volcanic Group source magma could mainly come from an enriched mantle and could have undergone an enrichment in the subduction zone. A detailed investigation of REEs and other trace elements from the Borrowdale Volcanic Group could confirm the geochemical source magma and influence of the subduction zone.

Fig. 25. Nb/Y vs. Th/Y plot to show the behaviour of the Borrowdale Volcanic Group against N-MORB. The samples plot in the magmatic arc field suggesting an enriched in Nb/Y relative to N-MORB, followed by a subduction zone enrichment in Th (data for diagram after Sun & McDonough, 1989; Pearce, 1983; all data includes: this study; Branney, unpublished; Clarke, 2015, unpublished; Mobley, 2015, unpublished).
5.2 Chemical and stratigraphical correlations

5.2.1 The Nb/Y vs. Zr/TiO₂ plot

The Scafell caldera succession can be first geochemically characterised by two starting plots (Fig. 26 and 27). The first useful overview plot for the later unit separation and correlation is the Nb/Y vs. Zr/TiO₂ plot (Fig. 26) (after Winchester & Floyd, 1977). The diagram uses Nb/Y as a proxy for the alteration affected alkaline majors K₂O+Na₂O and Zr/TiO₂ for SiO₂. Samples from the Scafell caldera succession (black squares) and samples that post-date the Scafell caldera units (grey circles) are plotted together. Less evolved andesitic samples and more evolved dacitic to rhyolitic samples of the Scafell caldera succession (black squares) spread widely as well as the post-Scafell caldera samples. The plot also gives a first general overview how close several different possible correlative units plot to each other. Further discrimination plots are required due to this overlap of the samples on the Nb/Y vs. Zr/TiO₂ plot.

![Fig. 26. Nb/Y vs. Zr/TiO₂: The Scafell caldera succession samples (black squares) widely overlap with samples that post-date Scafell volcano (grey circles) (plot after Winchester & Floyd, 1977; data includes: this study; Branney, unpublished; Clarke, 2015, unpublished; Mobley, 2015, unpublished).](image)

5.2.2 The Zr/TiO₂ vs. dimensionless stratigraphic height plot

Zr/TiO₂ vs. dimensionless stratigraphic height (Fig. 27) separates less evolved units from more evolved units by their Zr/TiO₂ ratios in combination with their logical dimensionless stratigraphical height throughout the Borrowdale Volcanic Group (Clarke, 2015; unpublished). This enables a first differentiation of the Scafell caldera
succession itself and a differentiation from units that post-date the Scafell caldera units. The Zr/TiO$_2$ vs. dimensionless stratigraphic height plot illustrates, that some of the units that widely overlap in the Nb/Y vs. Zr/TiO$_2$ plot (Fig. 26) do not necessarily have to be further compared by geochemistry to each other because of their explicit stratigraphic disparity in the field.

The following Scafell succession chapter 5.3 discusses geochemical fingerprinting of each individual unit for discrimination purposes as well as the reliability of the whole-rock geochemistry for correlation between the Scafell caldera fill and the extra-caldera succession in the Coniston Fells area. The post-Scafell succession will be discussed in chapter 5.5.
5.3 Scafell caldera succession

Most pyroclastic units of Scafell caldera are lithologically distinctive and seen in mapped continuity in the Central Fells of the Lake District (Fig. 28 and Fig. 29). However, away from the Central Fells to the South in the Coniston area the succession of strata that contains potential outflow sheets has undergone more tectonic deformation (Chapter 4.1) and alteration compared to the Scafell caldera area (Chapter 5.1.1). To help identify these pyroclastic units geochemical fingerprinting is required.

Fig. 28. Simplified geological map showing the main explosively erupted pyroclastic succession of Scafell volcano. Also shown are dacitic intrusions that will be discussed in chapter 5.3.3. The boxes mark the main study areas of this project illustrated in Fig. 13 and Fig. 15; Chapter 4.1 – 1:50,000 solid sheet (after BGS, 1998, 2003; Brown, 2001).
Fig. 29. General vertical sections comparing the Scafell caldera fill succession (after Branney & Kokelaar, 1994) and the extra-caldera succession in the Coniston area (Wetherlam; after BGS, 1998).
At Scafell caldera, the andesitic pyroclastic units can be distinguished from the more evolved dacitic to rhyolitic units by a Zr/TiO$_2$ vs. dimensionless stratigraphic height plot (Fig. 30; Clarke, 2015, unpublished). The andesitic units show consistent Zr/TiO$_2$ ratios around 0.02 with increasing stratigraphic height. The more evolved dacitic to rhyolitic units show higher Zr/TiO$_2$ values (>0.6) increasing with stratigraphic height.

![Key to Scafell caldera units](image)

**Fig. 30.** Zr/TiO$_2$ vs. dimensionless stratigraphic height to distinguish the andesitic units of Scafell caldera from the more evolved dacitic to rhyolitic units (modified after Clarke, 2015; unpublished). All samples taken from within Scafell caldera.

To classify and compare the Scafell caldera fill succession with possible extra-caldera units from the Coniston Fells area immobile trace elements will be used (Chapters 5.3 and 5.4). A Nb/Y vs. Zr/TiO$_2$ plot will be presented for each correlation hereafter in addition to other plots as required. The andesitic units will be considered first.
5.3.1 Andesitic units of Scafell caldera

Several pyroclastic units of the caldera fill succession of Scafell volcano plot within the andesite field on a Nb/Y vs. Zr/TiO₂ plot (black squares on Fig. 31): the Whorneyside Formation and the Cam Spout Tuff, Hanging Stone Tuff and Rest Gill Tuff of the Airy’s Bridge Formation. The units show wide scatter in Zr/TiO₂ values from 0.013 to 0.025. Other units from Scafell caldera fill plot in the basalt field (Rest Gill Tuff) and rhyodacitic-rhyolite fields (Stonesty tuff and ignimbrites of the Airy’s Bridge Formation). The more evolved units will be considered later. At Wetherlam, in the Coniston area 2 km South of Scafell caldera, other extra-caldera pyroclastic units also plot in the andesite field (blue circles). These will now be considered in turn.

![Figure 31. Nb/Y vs. Zr/TiO₂ for andesitic pyroclastic units in the caldera fill of Scafell volcano (black squares). The andesite field is from Winchester & Floyd (1977). Samples from individual stratigraphic units cluster together, but the compositions of different units show a wide scatter. Also shown are potential correlative andesitic units from the Wetherlam area (blue circles).]
5.3.1.1 Whorneyside Formation correlation

*(Scafell caldera fill to potential outflow correlation)*

At Scafell caldera

The oldest, lowermost unit of Scafell caldera succession is the andesitic Whorneyside Formation (Fig. 29). At the type area (Crinkle Crags; 1 in Fig. 11) it is up to 130 m thick and consists of a lower massive, slightly eutaxitic lapilli-tuff, the Whorneyside Ignimbrite. It is gradationally overlain by a parallel-bedded ash-fall tuff of the same composition, known as the Whorneyside Bedded Tuff. The formation overlies pre-caldera andesitic lavas of the Lingcove Formation, and is unconformably overlain by the Stonesty Tuff, a silicic marker unit within the base of the Long Top Tuffs Member (Fig. 29). Its brown-weathering colour in the field reflects its andesitic composition (Branney, 1991). The ignimbrite contains abundant fiamme (Fig. 32a) with aspect ratios 2:1 to 10:1, lithic lapilli supported in a recrystallized tuff matrix, and has a stratified base (Branney, 1988b). It varies from 30 to 100 m thickness.

![Fig. 32. Lithofacies of the Whorneyside Formation and correlatives. (a) Massive, eutaxitic lapilli-tuff of the Whorneyside Ignimbrite of Scafell caldera fill at Crinkle Crags. (b) Massive, eutaxitic lapilli-tuff of the Wet Side Edge Member on Wetherlam.](image)

The overlying Whorneyside Bedded Tuff characteristically shows parallel fine lamination and parallel thin beds with abundant soft-state faults and slide structures on various scales (Fig. 33a). Away from its source (NW of Scafell caldera) it is widely about 25 to 35 m thick.

At Wetherlam *(Coniston area)*

About 2 km South of Scafell caldera (northern slope of Wetherlam; Fig. 15) an andesitic ignimbrite has been mapped as Wet Side Edge Member (Millward et al., 2000a) and is overlain by an andesitic bedded tuff, mapped as Whorneyside Formation (Millward et
al., 2000a; Fig. 29). The succession here dips 75° SE and shows steep Acadian cleavage. Field reappraisal shows that the ignimbrite overlies sheets of autobrecciated andesites that may be block lavas (Fig. 15).

It is 60 m thick, with fiamme (aspect ratios 2:1 to 10:1) and angular lapilli supported in a tuff matrix (Fig. 32b). It is gradationally overlain by 15 to 25 m thick parallel bedded tuff with predominantly parallel fine laminations, thin beds and abundant soft-state faults and slide structures (Fig. 33b). Some fine tuff layers contain small ash pellets.

Both the ignimbrite and the ash-fall tuff are brown-weathered, and the ash-fall tuff is discordantly overlain by pale grey silicic rocks (Fig. 15).

**Geochemical classification and correlation**

The Whorneyside Ignimbrite and Bedded Tuff at Scafell caldera both have Zr/TiO$_2$ values around 0.02 and Nb/Y values of 0.44 to 0.53 (brown squares in Fig. 34a). Zr/Y values are 5.19 to 7.35 and Th/Nb values are 0.52 to 0.61 (Fig. 34b). The andesitic ignimbrite and overlying bedded tuff on Wetherlam have Zr/TiO$_2$ values of 0.02 and Nb/Y values of 0.40 to 0.48 (brown circles in Fig. 34a). Zr/Y values are 5.61 to 6.84 and Th/Nb values 0.57 to 0.59 (Fig. 34b).
Fig. 34. Discriminant plots of ‘immobile’ trace elements of the Whorneyside Formation at Scafell caldera (brown squares) and possible extra-caldera correlatives of the Wet Side Edge and Whorneyside formations (brown circles; from Wetherlam, Coniston Fells). (a) Nb/Y vs. Zr/TiO$_2$ classifying both units as andesitic. (b) Zr/Y vs. Th/Nb: Whorneyside Formation samples showing a wide overlap to each other. Note, however, that some other andesitic pyroclastic units at Scafell caldera (open circles) also overlap.
**Geochemical distinction from other andesitic pyroclastic units**

On the plots of Nb/Y vs. Zr/TiO$_2$ and Zr/Y vs. Th/Nb the Whorneyside Formation and its possible correlatives (brown symbols in Fig. 34a and b) overlap with several other andesitic units (Lingcove Formation, Cam Spout, Hanging Stone Tuff and Rest Gill Tuff sample, black circles). However, the Whorneyside Formation can be distinguished from the other andesitic units of Scafell caldera (and also from the slightly more evolved dacitic post-Scafell units) on a Cr vs. Ni plot (Fig. 35). The Whorneyside Formation as Scafell caldera has Cr values of 72.78 to 100.37 ppm (brown squares in Fig. 35). One sample has an odd higher Cr value of 185.42 ppm plotting apart from the other data points. The extra-caldera samples have Cr values of 76.66 to 106.36 ppm. Cr and Ni are likely to have been affected by fractional crystallisation. However, their constant values in the Whorneyside and correlatives may be caused by a relatively well mixed or otherwise relatively homogeneous magma.

**Fig. 35.** Cr vs. Ni plot showing the Whorneyside ignimbrite and bedded tuff at Scafell caldera (brown squares) and their likely extra-caldera correlatives (brown circles) from Wetherlam widely overlapping. The plot also distinguishes the samples from the other andesitic units from the Scafell succession (open circles).
**Whorneyside Formation correlation conclusion**

The Whorneyside Formation at Scafell caldera (by Branney, 1988) is here correlated with units on Wetherlam previously designated as Wet Side Edge Member and Whorneyside Member within the Whorneyside Formation (by British Geological Survey). It is concluded that the andesitic ignimbrite (Wet Side Edge Member) and bedded tuff (Whorneyside Member) on Wetherlam are the extra-caldera equivalents of the Whorneyside ignimbrite and bedded tuff within Scafell caldera on the basis of: (1) they both overlie pre-caldera autobrecciated andesite sheets and are overlain by younger paler, rhyodacitic units, and (2) the units have closely similar brown-weathered colours and thicknesses. (3) Both have a lower massive, slightly eutaxitic lapilli-tuff that grades into an upper parallel bedded tuff with sedimentation structures. (4) The correlated units plot widely overlapping to each other in the Cr vs. Ni plot and separated from other andesitic units; however one sample value plots offset.

**Fig. 36.** Sketch comparing the Whorneyside Formation within Scafell caldera and the extra-caldera outflow sheets on Wet Side Edge and Wetherlam.
5.3.1.2 Cam Spout Tuff correlation

At Scafell caldera

The andesitic Cam Spout Tuff is situated about 20 m above the base of the Long Top Tuffs Member (Fig. 29). It is typically less than 2 m thick and comprises a cream- to brown-weathered fine tuff with thin parallel and lenticular bedding, local low-angle cross-stratification and abundant accretionary lapilli (Fig. 37a). It is underlain and overlain by pale-grey, welded bedded ignimbrites of the Long Top Tuffs Member.

At Wet Side Edge and Great Carrs (Coniston area)

Half a kilometre South of Scafell caldera, on the ridge of Wet Side Edge to Great Carrs [NY 271 009] (Fig. 11), a 1 to 2 m thick cream- to brown-weathered, fine tuff was discovered. It is underlain and overlain by grey-weathered massive, welded, eutaxitic lapilli-tuffs, all mapped as the Long Top Tuffs Member (Millward et al., 2000a). The succession dips about 65° SE with steep cleavage. The tuff is thinly bedded with pale low-angle cross-stratification (mainly overprinted by cleavage). Accretionary lapilli are abundant, 0.5 to 1.0 cm long and weathered, particularly on Great Carrs (Fig. 37b). Accretionary lapilli are variously whole and broken and supported in a fine tuff matrix.

At Wetherlam (Coniston area)

Another thin 1 to 2 m thick tuff was discovered on Wetherlam (Fig. 37c and d). It is underlain and overlain by thick-bedded, welded, eutaxitic lapilli-tuff mapped as the Long Top Tuffs Member. In one locality [NY 28970 01297], the surface colour is paler grey, more silicic and flinty with very faint thin bedding. Abundant whole and few broken accretionary lapilli are white weathered and up to 10 mm in size (Fig. 37c). Further uphill, the ash-fall tuff is characteristically brown weathered and the thin bedding is overprinted by cleavage (Fig. 37d). The unit was poorly exposed and not traced further southwest.
The Cam Spout Tuff from Scafell caldera fill has a Zr/TiO$_2$ value of 0.03 and a Nb/Y value of 0.29 (red square in Fig. 38a). It plots in the andesite field, close to the border of the dacite field. The Cam Spout Tuff at Wet Side Edge has a Zr/TiO$_2$ value of 0.02 and a Nb/Y value of 0.29 (red circles) and plots close to the Cam Spout Tuff fill sample. The distal Cam Spout Tuff at Wetherlam has a Zr/TiO$_2$ value of 0.02 but a higher Nb/Y value of 0.39 (red triangle). This slightly shifts the sample towards the other andesitic Scafell caldera units. The samples can also be compared by a Nb/Y vs. La/Y plot (Fig. 38b). All three samples have similar La/Y values of 0.49 to 0.57.

On a Cr vs. Ni plot (Fig. 39) all three compared samples plot closely together.
Fig. 38. The Cam Spout Tuff (red square) and possible correlatives at Wet Side Edge (red circle) and Wetherlam (red triangle). (a) Nb/Y vs. Zr/TiO$_2$ classifying all three samples as andesitic. (b) Nb/Y vs. La/Y: The Cam Spout Tuff from Scafell caldera plots close to the extra-caldera samples from Wet Side Edge and Wetherlam. All three samples differ to the other andesitic units of the Scafell succession.
**Geochemical distinction from other andesitic pyroclastic units**

The Cam Spout Tuff and correlative tuff layers at Wet Side Edge and Wetherlam can be distinguished from other andesitic units at Scafell caldera (Whorneyside Formation, Hanging Stone and Rest Gill tuffs) on a Cr vs. Ni plot on which the Cam Spout Tuff and correlatives are the only units to have low (<14 ppm) Cr values together with low Ni values (Fig. 39).

![Fig. 39. Cr vs. Ni plot showing the Cam Spout Tuff at Scafell caldera (red square) and the extra-caldera correlatives (red circle and triangle) that have closely similar values. The plot also distinguishes the samples from the other andesitic units at Scafell caldera (open circles).](image)

**Cam Spout Tuff correlation conclusion**

The newly discovered thin andesitic tuff layer exposed at Wet Side Edge, Great Carrs and Wetherlam (Fig. 11) is an extra-caldera correlative of the Cam Spout Tuff at Scafell caldera, on the basis of the following: (1) Both units are underlain and overlain by grey-weathered, welded ignimbrites of the Long Top Tuffs Member; (2) the units are of similar thickness; (3) the weathering colour and bedding are similar at Scafell, Wet Side Edge and Swirl How but getting finer grained (paler, more flinty) distally towards Wetherlam. (4) Matrix-supported whole and broken concentric-rimmed accretionary lapilli are abundant both at Scafell and in the extra-caldera sites. (5) The units plot close together on the Cr vs. Ni plot and similar in other ratio plots (e.g. Nb/Y vs. La/Y).
5.3.1.3 Hanging Stone Tuff correlation

At Scafell caldera

At Scafell caldera the Hanging Stone Tuff is situated at the top of the Long Top Tuffs Member (Fig. 29). It is a cream- to brown-weathered fine tuff ≤3 m thick, laminated and thinly bedded with abundant low-angle cross-stratification and matrix-supported accretionary lapilli, like the Stonesty Tuff and the Cam Spout Tuff (Fig. 40a).

![Fig. 40. Lithofacies in the Hanging Stone Tuff and its correlative. (a) Brown-weathered, thin laminated fine tuff with abundant accretionary lapilli in certain layers of the Hanging Stone Tuff of the Scafell caldera at Crinkle Crags [NY 248 048]. (b) Few small accretionary lapilli in a brown-weathered fine tuff matrix on Wet Side Edge.](image)

At Wet Side Edge (Coniston area)

A fine tuff layer with small accretionary lapilli (< 4mm) was discovered at Wet Side Edge (Fig. 11), a less than 1 m thick tuff has been discovered, underlain by grey-weathered massive, eutaxitic lapilli-tuff of the Long Top Tuffs Member. It dips about 70° SE and is steeply cleaved. The weak exposure shows a highly weathered, brownish surface with few accretionary lapilli and weak cross-stratification (Fig. 40b). The layer is overlain by grey-weathered massive lapilli-tuff that was mapped as Long Top Tuffs Member. Field reappraisal (Fig. 13) shows that the strata above the tuff changes to a paler grey ignimbrite with sparser and more flattened fiamme. Fiamme become less abundant and are smaller and more stretched.

Due to the poor exposure of the tuff, the outcrop was not sampled for geochemistry. The unit was not found on Great Carrs or Wetherlam. The geochemical characteristics of Hanging Stone Tuff at the Scafell caldera fill will be discussed next for comparison and discrimination to the other andesitic units of Scafell caldera.
**Geochemical classification and distinction from other units**

The Hanging Stone Tuff samples (blue squares) from Scafell caldera have Zr/TiO$_2$ values of 0.02 to 0.03 and Nb/Y values of 0.46 to 0.53 (Fig. 41a). This composition is not unique at Scafell caldera because some Whorneyside Formation and Rest Gill Tuff samples also plot within this field (open circles, respectively in Fig. 41a). Although incompatible trace elements do not satisfactorily distinguish the Hanging Stone Tuff from the Whorneyside and Rest Gill Tuff, this distinction can be readily made using Cr vs. Ni (Fig. 41b). The Hanging Stone Tuff differs by $>30$ ppm Cr to the Whorneyside and by $>100$ ppm Cr and about 40 ppm Ni to the Rest Gill Tuff.

![Discriminant plots of 'immobile' trace elements](image)

**Fig. 41.** Discriminant plots of 'immobile' trace elements of the Hanging Stone Tuff (blue squares) at Scafell caldera. (a) Nb/Y vs. Zr/TiO$_2$ classifying the unit as andesitic. (b) Cr vs. Ni plot clearly distinguishes the Hanging Stone Tuff fill from the other andesitic units from the Scafell succession.
Hanging Stone Tuff correlation conclusion

The newly discovered tuff on Wet Side Edge is a potential extra-caldera correlative of the Hanging Stone Tuff at Scafell caldera, on the base of: (1) both units are underlain by a grey-silicic lapilli-tuff mapped as the Long Top Tuffs; (2) the units are of similar thickness and brown-weathering colour. (3) Accretionary lapilli are present in distinct layers. (4) At Scafell caldera the Hanging Stone Tuff is overlain by the Crinkle Tuffs Member and the tuff layer on Wet Side Edge is overlain by a massive, eutaxitic lapilli-tuff that was reinterpreted as the Crinkle Tuffs Member. (5) Due to poor exposure, the tuff layer on Wet Side Edge was not sampled hindering a geochemically comparison of the units.

5.3.1.4 Rest Gill Tuff correlation

At Scafell caldera

The Rest Gill Tuff is the uppermost marker horizon in the Airy’s Bridge Formation, situated in between the Bad Step Tuff and the other Crinkle Tuffs (Fig. 29). The marker unit has a distinct brown to turquoise weathering colour, is up to 3.5 m thick and comprises laminated and thinly bedded ash-fall tuff. The Rest Gill Tuff differs from the other Airy’s Bridge marker units by the absence of accretionary lapilli.

In the Coniston area

Field reappraisal on Wet Side Edge to Wetherlam could not identify the Rest Gill Tuff in the extra-caldera succession of Scafell volcano. Therefore, only the caldera infill samples can be geochemically described and separated from the other andesitic units of Scafell caldera.

Geochemical classification and distinction from other units

The Rest Gill Tuff (dark blue squares) from the Scafell caldera fill has Zr/TiO₂ values of 0.01 to 0.02 and Nb/Y values of 0.49 to 0.50. It plots in the andesite field, overlapping with the Whorneyside Formation and the Hanging Stone Tuff (Fig. 42a). A Cr vs. Ni plot can be used to separate the Rest Gill Tuff from the other andesitic units (Fig. 42b). The Rest Gill Tuff has higher Cr values of 164.70 to 199.50 and distinct higher Ni values of 59.70 to 67.93 than all other andesitic units of the Scafell caldera succession.
The Rest Gill Tuff could not be identified in the field. However, previous studies only defined the Long Top Tuffs to be exposed on Wetherlam, but field reappraisal shows the Crinkle Tuffs Member to be exposed as well (Chapter 5.3.2.3). Therefore the Rest Gill Tuff may be potentially present South of Scafell caldera in the Coniston Fells area as well.

**Rest Gill Tuff conclusion**

The Rest Gill Tuff could not be identified in the field. However, previous studies only defined the Long Top Tuffs to be exposed on Wetherlam, but field reappraisal shows the Crinkle Tuffs Member to be exposed as well (Chapter 5.3.2.3). Therefore the Rest Gill Tuff may be potentially present South of Scafell caldera in the Coniston Fells area as well.

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*Fig. 42.* Discrimination plots of ‘immobile’ trace elements of the Rest Gill Tuff (dark blue squares) at Scafell caldera. (a) Nb/Y vs. Zr/TiO$_2$ classifying the unit as andesitic. (b) Cr vs. Ni plot clearly distinguishes the Rest Gill Tuff by its higher Cr and Ni values from the other andesitic units from the Scafell succession.
5.3.2 Dacitic and rhyolitic units of Scafell caldera

The Long Top Tuffs Member (apart from Cam Spout Tuff and Hanging Stone Tuff) and overlying Crinkle Tuffs (apart from Rest Gill Tuff) of the Central Fells area of the Lake District, are dacitic to rhyolitic intracaldera pyroclastic units of Scafell caldera (Fig. 29). They plot within the dacite to rhyolite fields of Winchester & Floyd (1977) using Nb/Y vs. Zr/TiO$_2$ (black squares in Fig. 43). Zr/TiO$_2$ values range from 0.062 to 0.136.

Possible extra-caldera pyroclastic correlatives south of Scafell caldera in the Coniston Fells area, on Wet Side Edge and Wetherlam, also plot in the dacite to rhyolite fields (blue circles). Zr/TiO$_2$ values range from 0.056 to 0.123. The individual units will now be considered in stratigraphic order.

![Fig. 43. Nb/Y vs. Zr/TiO$_2$ for the dacitic to rhyolitic pyroclastic units of the caldera fill of Scafell volcano (black squares). Rhyodacite and rhyolite fields after Winchester & Floyd (1977). Dacitic to rhyolitic possible outflow sheets from the Coniston Fells area also plot in these fields (blue circles).]
5.3.2.1 Stonesty Tuff correlation

At Scafell caldera

The dacitic Stonesty Tuff lies at the base of the Long Top Tuffs Member immediately above the Whorneyside Formation (Fig. 29). It is typically less than 1 m thick and comprises a flinty white-weathered, laminated fine tuff (Fig. 44a). It exhibits low-angle cross stratification and some layers have abundant accretionary lapilli. It is overlain by pale-grey, bedded and massive, welded ignimbrites of the Long Top Tuffs Member.

At Wet Side Edge, Great Carrs and Wetherlam (Coniston area)

About 0.5 km South of Scafell caldera the Stonesty Tuff occurs at the top of Rough Crags on Wet Side Edge (overview of localities on Fig. 11; Branney, 1988; NY 28430 02683). The succession dips about 65° SE and is steeply cleaved. The Stonesty Tuff is a 1 m thick white-weathered, fine tuff that unconformably overlies fine parallel laminated and parallel thin bedded tuff of the andesitic Whorneyside Bedded Tuff (Chapter 5.3.1.1). White-weathered accretionary lapilli are abundant, 0.5 to 1.0 cm long.

Fig. 44. Lithofacies of the Stonesty Tuff and correlatives. (a) White-weathered, thin laminated fine tuff with abundant accretionary lapilli (acc. LT) of the Stonesty Tuff of the Scafell caldera fill at Crinkle Crags. (b) White-weathered abundant accretionary lapilli in a fine tuff matrix on Rough Crags [NY 28430 02683]. (c) In another locality on Wet Side Edge the white-weathered accretionary lapilli-tuff overlies the Whorneyside Bedded Tuff (pbT) and is only 20 cm thick [NY 27230 01723]. (d) Boundary between the Whorneyside Bedded Tuff (pbT) and the Long Top Tuffs (mLT) on Wetherlam, the Stonesty Tuff seems to be absent [NY 28992 01397].
supported in a fine tuff matrix (Fig. 44b). It is overlain by thick-bedded, welded, eutaxitic lapilli-tuff of the Long Top Tuffs. At another locality 1.6 km SW [NY 27230 01723] on Wet Side Edge, the fine tuff layer is only >20 cm thick, white-weathered with some accretionary lapilli up to 7 mm in size (Fig. 44c). Field reappraisal on Great Carrs and Wetherlam identified several contacts between the Whorneside Bedded Tuff and the Long Top Tuffs, but at these localities the Stonesty Tuff was not found (Fig. 44d; NY 28992 01397). The Stonesty Tuff might be absent due to erosion by the following pyroclastic density currents of the Long Top Tuffs Member.

**Geochemical classification and correlation**

The Stonesty Tuff in Scafell caldera fill has Zr/TiO₂ values of 0.06 and 0.07 and Nb/Y values of 0.39 and 0.38 (pink squares in Fig. 45). They plot in the dacite field between the other dacitic units of Scafell caldera. The Stonesty Tuff on Wet Side Edge has a Zr/TiO₂ value of 0.07 and a Nb/Y value of 0.41 (pink circle). It is dacitic and plots close to the other Stonesty Tuff samples. Of the various ‘marker units’ within Scafell caldera fill, the Stonesty Tuff is the only dacitic accretionary lapilli bearing bedded fine tuff example, the others being andesitic. The correlation of the Stonesty Tuff between Scafell caldera and Wet Side Edge is also supported by their closeness on Th/Y vs. Th/Nb plots (Fig. 46a and b).

![Fig. 45. The Stonesty Tuff (pink squares) at Scafell caldera and the Stonesty Tuff at Wet Side Edge (pink circle) classify as dacitic on a Nb/Y vs. Zr/TiO₂ plot (after Winchester & Floyd, 1977).](image)
Geochemical distinction from the other Airy’s Bridge Formation units

On plots of Ti/Zr vs. Th/Y and V/Y vs. Th/Nb the Stonesty Tuff samples have Ti/Zr ratios of 8.03 to 9.60 and V/Y ratios of 0.54 to 0.66 (pink symbols in Fig. 46a and b). The Stonesty Tuff plots in a discrete field within the Long Top Tuffs. This is consistent with the Stonesty Tuff belonging to the Long Top Tuffs (Branney & Kokelaar, 1994). The Stonesty Tuff has slightly higher Ti/Zr (>7) and V/Y (>0.4) values than the Crinkle Tuffs Member (yellow diamonds), but lower Ti/Zr (<10) and V/Y (<1) values than the andesitic units of Scafell caldera.

Fig. 46. The Stonesty Tuff at Scafell caldera (pink squares) and at Wet Side Edge (pink circle) plot discrete within the other dacitic Long Top Tuffs (orange diamonds), but differ to andesitic units of Scafell caldera (open circles) and the Crinkle Tuffs Member (yellow diamonds). (a) Ti/Zr vs. Th/Y: The Stonesty Tuff has higher Ti/Zr values (>7) than the Crinkle Tuffs Member, but also distinctly lower values (<10) than the andesitic units of Scafell caldera. (b) V/Y vs. Th/Nb: The Stonesty Tuff has higher V/Y values (>0.5) than the Crinkle Tuffs Member, and distinctly lower values (<1) than the andesitic units of Scafell caldera.
Stonesty Tuff correlation conclusion

Geochemistry successfully confirms that the Stonesty Tuff on Rough Crags and Wet Side Edge are extra-caldera equivalents of the Stonesty Tuff within Scafell caldera. The correlation is made on the following evidence: (1) Both units are underlain by the andesitic parallel bedded tuff of the Whorneyside Formation; (2) both are overlain by grey-weathered, welded ignimbrites of the Long Top Tuffs; (3) they are of similar thickness; and (4) bedding characteristics and weathering colours are similar at Scafell caldera and Wet Side Edge; and (5) matrix-supported whole concentric-rimmed accretionary lapilli are abundant both at Scafell caldera and in the extra-caldera sites; and (6) both Stonesty Tuff units plot indistinguishably from each other in Ti/Zr vs. Th/Y and V/Y vs. Th/Nb plots (Fig. 46).
5.3.2.2 Long Top Tuffs ignimbrites correlation

At Scafell caldera

The Long Top Tuffs Member consists of the silicic welded ignimbrites and the interstratified Stonesty Tuff, Cam Spout Tuff and Hanging Stone Tuff (Fig. 29). At Scafell caldera ignimbrites of the Long Top Tuffs are grey-weathered, massive to bedded, welded, eutaxitic lapilli-tuffs. Individual beds reach 30 m thick. In the Central Fells the Long Top Tuffs reach 200 m thick and unconformably overlie the Whorneyside Formation, and are overlain by the Crinkle Tuffs Member. Abundant fiamme (Fig. 47a) have aspect ratios 10:1 to up to 40:1. Most are less than 5 cm long, but some reach 15 cm long. They are generally thicker than those in the overlying Crinkle Tuffs Member. Fiamme and angular lithic lapilli are supported in a recrystallized tuff matrix.

![Fig. 47. Lithofacies of the Long Top Tuffs ignimbrites and correlatives (b = bedding, c = cleavage, f = fiamme). (a) Massive, eutaxitic lapilli-tuff of the Long Top Tuffs of Scafell caldera fill at Long Top, Crinkle Crags (photo from Branney). (b) Massive, eutaxitic lapilli-tuff of the extra-caldera Long Top Tuffs on Rough Crags [NY 28477 02661], Wet Side Edge. (c) Massive, eutaxitic lapilli-tuff of the extra-caldera Long Top Tuffs on Wetherlam. (d) Distal massive, eutaxitic lapilli-tuff of the Long Top Tuffs on Hesk Fell [SD 176 946] in the Devoke Water area.](image-url)
At Wet Side Edge (Coniston area)

Half a kilometre South of Scafell caldera, on Rough Crags [NY 272 014] to Wet Side Edge, about 250 m of rhyodacitic rock have been mapped as Long Top Tuffs (Fig. 12; 47b; BGS, 1998). The succession dips 75° SE and has steep Acadian cleavage. Field reappraisal shows a grey-weathered, welded, eutaxitic lapilli-tuff with abundant fiamme (aspect ratios 10:1 to 30:1). The Stonesty Tuff (Chapter 5.3.2.1), Cam Spout Tuff (Chapters 5.3.1.2) and Hanging Stone Tuff (Chapter 5.3.1.3) have been newly discovered interstratified with these ignimbrites (Fig. 13). In the present study field evidence of the newly identified tuff layers and geochemistry led to the recognition of another eutaxitic lapilli-tuff (Chapter 5.3.2.3) on top of the Long Top Tuffs Member. This indicates that the Long Top Tuffs Member only reaches 90 m thick with 160 m thick of other units on Wet Side Edge.

At Wetherlam (Coniston area)

About 2 km South of Scafell caldera, on Wetherlam, about 320 m of rhyodacitic rock have been mapped as Long Top Tuffs (Fig. 14; 47c; BGS, 1998). It dips 75° SE and has steep Acadian cleavage. Field reappraisal revealed a grey-weathered, welded, eutaxitic lapilli-tuff overlying bedded tuff of the Whorneyside Formation. With respect to internal ‘marker units’ within the Long Top Tuffs, the Cam Spout Tuff has been newly discovered (Chapters 5.3.1.2), but the Stonesty and Hanging Stone tuffs were not found (Fig. 15). It was revealed that the top of the Long Top Tuffs on Wetherlam is marked by a 3 to 5 m thick layer of abundant lithophysae (Fig. 48). Field evidence in combination with geochemistry led to the recognition of the Glassy Crag Dacite intrusion (Chapter 5.3.3) and another eutaxitic lapilli-tuff (Chapter 5.3.2.3) on top of the Long Top Tuffs Member. It was found that the Long Top Tuffs Member on Wetherlam are only 50 to 90 m thick.
At Hesk Fell (Devoke Water area)

About 10 km SW of Scafell caldera, on Hesk Fell [SD 176 946] in the Devoke Water area, a rhyodacitic ignimbrite has been mapped as Airy’s Bridge Formation with no distinction having been made between Long Top Tuffs and Crinkle Tuffs members (Fig. 11; BGS, 1991). Field reappraisal shows a grey-weathered, poorly exposed and strongly cleaved, welded, eutaxitic lapilli-tuff overlying the bedded tuff of the Whorneyside Formation. The ignimbrite contains few lithic lapilli and small fiamme supported in a recrystallized tuff matrix (Fig. 47d). The thickness of the unit was not solved but should not exceed 120 m.

Geochemical classification, correlation and distinction

The Long Top Tuffs Member within Scafell caldera have Zr/TiO$_2$ values of 0.07 to 0.10 and Nb/Y values of 0.31 to 0.46 (orange squares in Fig. 49). Those from Wetherlam have Zr/TiO$_2$ values of 0.06 to 0.09 and Nb/Y values of 0.32 to 0.49 (orange circles). The distal Long Top Tuffs from Hesk Fell has a Zr/TiO$_2$ value of 0.08 and a Nb/Y value of 0.49 (orange triangle). All samples plot in the upper part of the dacite field (Fig. 49).
Within Scafell caldera the Long Top Tuffs Member can be distinguished by their darker-grey colour, the welded eutaxitic appearance with large scale bedding and bigger fiamme and the distinct ‘marker units’ from the Crinkle Tuffs Member. These characteristics are generally less obvious in the extra-caldera succession. Plots of Nb/Y vs. Th/Y and V/Y vs. Th/Nb (Fig. 50a and b) are useful showing the Long Top Tuffs (including the Stonesty Tuff) plot distinct from the other dacitic and rhyolitic units of Scafell caldera (orange symbols). The Long Top Tuffs at Scafell caldera and its extra-caldera correlatives have lower Nb/Y, Th/Y and Th/Nb values than the Crinkle Tuffs Member.

Fig. 49. The Long Top Tuffs (orange squares) from the fill of Scafell caldera and its extra-caldera correlatives from Wetherlam (orange circles) and Hesk Fell (orange triangle) classify as dacitic on a Nb/Y vs. Zr/TiO$_2$ (rhyodacite and rhyolite fields after Winchester & Floyd, 1977).
Fig. 50. Discriminant plots of ‘immobile’ trace elements of the Long Top Tuffs at Scafell caldera (orange squares) and possible extra-caldera correlatives at Wetherlam (orange circles) and Hesk Fell (orange triangle). (a) Nb/Y vs. Th/Y: The Long Top Tuffs (orange symbols) plot below the Crinkle Tuffs Member. (b) V/Y vs. Th/Nb: The Long Top Tuffs separates from the Crinkle Tuffs Member by its lower Th/Nb values. The Stonesty Tuff (pink symbols) plots in between the other Long Top Tuffs.
It is concluded that the dacitic proximal and distal ignimbrites (at Wet Side Edge, Wetherlam and Hesk Fell) are the extra-caldera equivalents of the Long Top Tuffs Member within Scafell caldera (Fig. 51), on the basis of: (1) ‘immobile’ trace elements of all these units on Nb/Y vs. Th/Y and V/Y vs. Th/Nb plots show them to be indistinguishable from each other. (2) The units all unconformably overly andesitic parallel bedded tuff of the Whorneyside Formation. (3) The Long Top Tuffs on Wet Side Edge are further confirmed by the identification of the Stonesty Tuff, Cam Spout Tuff and Hanging Stone Tuff, and the Long Top Tuffs on Wetherlam by the identification of the Cam Spout Tuff within it. On Hesk Fell, none of the internal ‘marker beds’ could be found possibly due to poor exposure. (4) All units have closely similar grey weathered colours; (5) the proximal Long Top Tuffs outflow sheets on Wet Side Edge and Wetherlam have similar thicknesses of about 100 and 90 m. This supports the units to be outflow sheets because it marks a massive change in thickness from the caldera fill succession (Fig. 51). The thickness of the outflow sheet on Hesk Fell should not exceed 120 m, and (6) they are bedded to massive, eutaxitic lapilli-tuffs. (7) The Long Top Tuffs outflow sheets on Wet Side Edge and Wetherlam are overlain by the Crinkle Tuffs, and the Crinkle Tuffs might be exposed on Hesk Fell.

Fig. 51. Sketch comparing the Long Top Tuffs Member within Scafell caldera and the outflow sheets on Wet Side Edge, Wetherlam and on Hesk Fell. The Stonesty, Cam Spout and Hanging Stone tuffs within the Long Top Tuffs Member were identified on Wet Side Edge and the Cam Spout Tuff was identified on Wetherlam.
5.3.2.3 Crinkle Tuffs Member correlation

The Crinkle Tuffs Member consists of the rhyolitic Bad Step Tuff, the andesitic Rest Gill Tuff (Chapter 5.3.1.4) and other undistinguished rhyolitic Crinkle Tuff ignimbrites. The Crinkle Tuffs Member including the Bad Step Tuff will now be considered for correlation.

**Bad Step Tuff at Scafell caldera**

The Bad Step Tuff is an extremely high-grade, lava like, rheomorphic ignimbrite that forms the lowermost unit of the Crinkle Tuffs Member (Fig. 29). It only occurs in the southern part of Scafell caldera and varies in thickness from 40 m at Rest Gill [NY 246 054] to over 400 m in Great Langdale [NY 280 063]. The Bad Step Tuff is characterised by a bedded heterolithic, pyroclastic breccia 15 m thick that grades upwards into massive rheomorphic ignimbrite via a lithophysae zone. The ignimbrite overlies the Hanging Stone Tuff (uppermost Long Top Tuffs) and is overlain by the Rest Gill Tuff (Chapter 5.3.1.4) and other undifferentiated Crinkle Tuffs ignimbrites. The Bad Step Tuff records the first eruption of the Crinkle Tuffs eruptions, and is ponded entirely in the southern part of Scafell caldera (Branney et al., 1992).

**Crinkle Tuffs at Scafell caldera**

The Crinkle Tuffs above the Bad Step Tuff is a grey-weathered, eutaxitic to parataxitic, rheomorphic folded lapilli-tuff. At Scafell caldera the undifferentiated Crinkle Tuffs overlies the Rest Gill Tuff and is overlain by the Lingmell and Seathwaite Fell formations (Fig. 29). It is up to 200 m thick in the Central Fells and comprises abundant extremely flattened and stretched fiamme (Fig. 52a) with aspect ratios 5:1 to 200:1 (Millward et al., 2000a). Fiamme are bending around small lithic lapilli. The Crinkle Tuffs has only been sporadically described outside of Scafell caldera and as absent in the Coniston Fells area (Millward et al., 2000a).

**At Wet Side Edge (Coniston area)**

About 0.5 km South of Scafell caldera on Rough Crags (Fig. 13), a rhyodacitic ignimbrite has been discovered above the revised Long Top Tuffs Member (Chapter 5.3.2.2). The unit is a grey-weathered, welded, eutaxitic lapilli-tuff with thin fiamme (aspect ratios 10:1 to 50:1) and small lithic lapilli supported in a tuff matrix (Fig. 52b).
The fiamme occasionally wrap around the lithics but these fabrics are widely overprinted by steep Acadian cleavage. The Crinkle Tuffs Member on Wet Side Edge is about 140 m thick.

At Wetherlam (Coniston area)

About 2 km South of Scafell caldera, on Wetherlam, a grey-weathered, welded, eutaxitic lapilli-tuff has been discovered above the revised Long Top Tuffs Member (Chapter 5.3.2.2) and a grey-weathered, massive intrusion (Fig. 15; Chapter 5.3.3). A gully on each side marks the boundary of the Crinkle Tuffs Member to the underlying Glassy Crag Dacite intrusion and the overlying Duddon Hall Formation (Chapter 5.4.1). Well exposed abundant thin fiamme (aspect ratios 10:1 to 30:1) and few lithics, supported in a tuff matrix, are exposed in one locality [NY 29300 01335] on Wetherlam Edge (Fig. 52c). Fiamme elsewhere in the Crinkle Tuffs Member on Wetherlam are widely overprinted by steep Acadian cleavage (Fig. 52d).

Fig. 52. Lithofacies of the Crinkle Tuffs Member at Scafell caldera and its correlatives on Wet Side Edge and Wetherlam (c = cleavage, f=foliation). (a) Massive, eutaxitic lapilli-tuff of the Crinkle Tuffs above the Bad Step Tuff in Scafell caldera (photo from Branney). (b) Newly discovered massive, eutaxitic lapilli-on Wet Side Edge. (c) Newly discovered massive, eutaxitic lapilli-tuff at Wetherlam (photo from Branney). (d) The same massive lapilli-tuff further downhill on Wetherlam Edge [NY 29300 01335].
Geochemical classification and correlation

The Crinkle Tuffs Member (including the Bad Step Tuff) at Scafell caldera has higher Zr/TiO$_2$ values than the Long Top Tuffs. The Bad Step Tuff has Zr/TiO$_2$ values of 0.11 to 0.14 and Nb/Y values of 0.34 to 0.40 (purple squares in Fig. 53). The other Crinkle Tuffs has Zr/TiO$_2$ values of 0.12 to 0.13 and Nb/Y values of 0.34 to 0.37 (yellow squares). The newly discovered Crinkle Tuffs Member on Wet Side Edge has a Zr/TiO$_2$ value of 0.10 and a Nb/Y value of 0.41 (yellow triangle) and the Crinkle Tuffs Member on Wetherlam has Zr/TiO$_2$ values of 0.12 and Nb/Y values of 0.34 to 0.38 (yellow circles). All Crinkle Tuffs Member (including the Bad Step Tuff) plot in the rhyolite field. One sample from Wet Side Edge (yellow triangle) has a slightly higher Nb/Y value compared to the other Crinkle Tuffs samples. This small shift may have been caused by several processes including inhomogeneity within the magma by melting of country-rock, contamination of the erupting magma during emplacement of the Crinkle Tuffs and alteration. The shift in Nb/Y is rather small and it is difficult to assess which of these possibilities is more likely. Breakdown of amphibole may have released HREE and Yttrium and these elements may have been removed in a sufficiently active hydrothermal fluid. However, this is contrary to the regional low metamorphic grade. Contamination of the ignimbrite during deposition would require a high Nb/Y and low Zr/TiO$_2$ contaminant such as alkali basalt which are not identified in Scafell caldera.

Fig. 53. Nb/Y vs. Zr/TiO$_2$ classifying the Crinkle Tuffs Member (including the Bad Step Tuff; yellow and purple squares) from Scafell caldera fill and its extra-caldera correlatives from Wet Side Edge (yellow triangle) and Wetherlam (yellow circles) as rhyolitic (fields after Winchester & Floyd, 1977).
Partially melted xenoliths are common in granites and assimilation of melt arrived from these may have caused small shifts in Nb/Y values in the Crinkle Tuffs.

In other ‘immobile’ trace element plots of Nb/Y vs. La/Y, Ti/Y vs. Th/Nb and Nd/Nb vs. Th/Nb the Crinkle Tuffs Member (including the Bad Step Tuff) from Scafell caldera plot indistinguishable to its extra-caldera correlatives from Wet Side Edge and Wetherlam (yellow and purple symbols in Fig. 54). This underpins the interpretation of the Bad Step Tuff being the first ponded eruption of the Crinkle Tuffs eruption (Branney et al., 1992).

**Fig. 54.** Correlation of the Crinkle Tuffs Member (including the Bad Step Tuff; yellow and purple squares) from Scafell caldera fill with its extra-caldera correlatives from Wet Side Edge (yellow triangle) and from Wetherlam (yellow circles). The caldera fill samples and the extra-caldera samples plot indistinguishable to each other on plots of (a) Nb/Y vs. La/Y, (b) Ti/Y vs. Th/Nb and (c) Nd/Nb vs. Th/Nb. Also shown are other rhyodacitic to rhyolitic units for comparison (grey circles).
**Geochemical distinction from other units of Scafell caldera**

The Crinkle Tuffs Member (including the Bad Step Tuff) from Scafell caldera and its correlatives from Wet Side Edge and Wetherlam can be distinguished from other dacitic to rhyolitic units of Scafell caldera on a V/Y vs. Th/Nb plot (Fig. 55). The Crinkle Tuffs Member (including the Bad Step Tuff) caldera fill and outflow sheets have V/Y values <0.34 and Th/Nb values >0.8, whereas most other dacitic to rhyolitic units have V/Y values >0.4 and Th/Nb values <0.8.

**Fig. 55.** V/Y vs. Th/Nb discriminant plot: The Crinkle Tuffs Member (including the Bad Step Tuff; yellow and purple squares) from Scafell caldera and its outflow sheets on Wet Side Edge and Wetherlam have lower V/Y values (<0.34) and higher Th/Nb values (>0.8) compared to most other dacitic to rhyolitic units of Scafell caldera.
**Crinkle Tuffs Member correlation conclusion**

It is concluded that the rhyolitic, parataxitic ignimbrites on Wet Side Edge and Wetherlam are the extra-caldera equivalents of the Crinkle Tuffs Member (including the Bad Step Tuff) within Scafell caldera (Fig. 56). The correlation is based on the following evidence: (1) the Crinkle Tuffs Member (including the Bad Step Tuff) caldera fill and outflow sheets plot indistinguishable on various ‘immobile’ trace element plots of Nb/Y vs. La/Y, Ti/Y vs. Th/Nb, Nd/Nb vs. Th/Nb and V/Y vs. Th/Nb. (2) They overlie massive, eutaxitic lapilli-tuff of the Long Top Tuffs Member. (3) The other undiscriminated Crinkle Tuffs at Scafell caldera and on Wet Side Edge and Wetherlam have similar lithologies with thin fiamme wrapping around small lithic clasts, and (4) the units have similar grey-weathered colour, and (5) the extra-caldera successions have similar thicknesses.

![Fig. 56. Sketch comparing the Crinkle Tuffs Member within Scafell caldera and the outflow sheets on Wet Side Edge and Wetherlam. The Bad Step Tuff is ponded in the southern part of Scafell caldera. The Rest Gill Tuff were not found south of the caldera margin. The upper undifferentiated Crinkle Tuffs were identified on Wet Side Edge and Wetherlam.](image-url)
5.3.3 Dacitic intrusions discovered in Scafell caldera and on Wetherlam

Fieldwork in combination with geochemical analysis of the Oxendale Tuff in Great Langdale for correlation with the proposed Oxendale Tuff on Wetherlam led to the discovery of three high-level dacitic intrusions: ‘Oxendale Tuff’ intrusion, Wetherlam Dacite and Glassy Crag Dacite. They were discovered because the chemistry didn’t match that of the pyroclastic units.

‘Oxendale Tuff’ intrusion (Great Langdale; Scafell caldera)

The Oxendale Tuff on Oxendale (Fig. 11; NY 260 052) in Great Langdale is a pink-weathered, lava-like, rhyodacitic tuff with a thickness of 60 to 100 m (Fig. 29). The unit rests unconformably on top of the Whorneyside Bedded Tuff with a sharp and irregular basal breccia. The Oxendale Tuff is rheomorphic and flow-banded, separating it from the overlying Long Top Tuffs Member (Branney, 1988b). The unit has been sporadically mapped on Green Tongue and near Horse Crags and further to the south on Wetherlam and south-east of Seathwaite Tarn (SD 253 988; BGS, 1998; Millward et al., 2000a).

Wetherlam Dacite intrusion (on Wetherlam; Coniston area)

On the summit of Wetherlam a dacitic pink- to dark-grey-weathered, lava-like, welded tuff was tentatively mapped as the Oxendale Tuff with a dip of 62° SE (Fig. 14; Millward et al., 2000a; BGS, 2003). The ‘Oxendale Tuff’ intrusion in Great Langdale appears similar to the intrusion on Wetherlam in the field, but they are geochemically different as presented latter in this chapter. The unit was therefore renamed Wetherlam Dacite. It is a lava-like tuff that unconformably overlies the Whorneyside Bedded Tuff with a sharp, irregular and autobrecciated contact at the bottom and top (Fig. 58a and b). Downslope to the north-east of Wetherlam the intrusion unconformably cuts the contact between the Whorneyside Bedded Tuff to the overlying Long Top Tuffs Member. It then bends round within the Long Top Tuffs (Fig. 57) and continues back uphill on Wetherlam to the south-west towards Black Sails [NY 282 007]. The Wetherlam Dacite is pink- to dark-grey-weathered whereas the Long Top Tuffs are paler grey-weathered with abundant large fiamme (Fig. 59a). Fine to medium grain size parallel bedding is present in the centre dipping 70° NE (Fig. 59b). The Wetherlam Dacite intrusion has steep Acadian cleavage and a maximum thickness of about 130 m on top of Wetherlam.
Fig. 57. Wetherlam [NY 288 011] viewed from the north-east, showing the Whorneyside Formation, the Long Top Tuffs and Crinkle Tuffs members. Two intrusions have been discovered: the Wetherlam Dacite (yellow), which was previously mapped as the Oxendale Tuff, is exposed on the top of Wetherlam and the Glassy Crag Dacite (yellow) situated in between the members.

Fig. 58. (a) Lower contact zone between the Wetherlam Dacite and the Long Top Tuffs Member at Wetherlam; for location see inset in Fig. 57. (b) Grey-weathered, massive, eutaxitic lapilli-tuff of the Long Top Tuffs Member. (c) Dark brown-weathered massive, brecciated top of the Wetherlam Dacite.
Glassy Crag Dacite intrusion (on Glassy Crag/Wetherlam; Coniston area)

Field reappraisal discovered a dacitic, lava-like, welded unit with decimetre bedding and flow-banding features that was tentatively mapped as the Long Top Tuffs Member on Glassy Crag [NY 291 011] (NW slope of Wetherlam; Fig. 15; Millward et al., 2000a; BGS, 2003). The unit overlies the revised Long Top Tuffs Member (Chapter 5.3.2.2) and is overlain by the newly discovered Crinkle Tuffs Member (Chapter 5.3.2.3). Due to its grey-weathered surface, steep Acadian cleavage and the contact

Fig. 59. Lithofacies of the Wetherlam Dacite on Wetherlam. (a) Detail of massive breccia at the top of the Wetherlam Dacite; blocks are angular of various sizes in a fine matrix. (b) Fine to medium grain size parallel bedding in the centre of the Wetherlam Dacite with a dip of 70° NE.

Fig. 60. Lithofacies of the Glassy Crag Dacite on Glassy Crag, Wetherlam. (a) Parallel bedding structures dip 80° NE at the base of the unit. (b) Detail of brecciated top of the Glassy Crag Dacite at Wetherlam Edge. (c) Flow-bending structures and a similar grey-weathered surface to the Crinkle Tuffs.
zones being covered by grass, the unit was first considered a part of the Crinkle Tuffs Member in the field. But this decision was challenged by the contact zone to the underlying Long Top Tuffs, being characterised by a 5 to 10 m thick zone of lithophysae, the absents of characteristic features of the Crinkle Tuffs (i.e. thin long fiamme wrapping around small lithic lapilli), parallel-bedding structures at the base of the unit dipping 80° NE (Fig. 60a), autobrecciation in the bottom and top (Fig. 60b) and flow-banding (Fig. 60c) within the unit. Geochemical analysis was used to solve this question and the unit was named Glassy Crag Dacite intrusion.

*Geochemical classification of the intrusions*

The intrusions plot within the dacite field of Winchester & Floyd (1977) using Nb/Y vs. Zr/TiO$_2$ (brown and green symbols in Fig. 61) and do not overlap with dacitic and rhyolitic units of Scafell caldera (open diamonds). The ‘Oxendale Tuff’ intrusion from Great Langdale has a Zr/TiO$_2$ value of 0.10 and a Nb/Y value of 0.21 (brown square). The sample plots in the upper rhyodacite field with its Nb/Y value being significantly lower compared to units of Scafell caldera. The Wetherlam Dacite has Zr/TiO$_2$ values of 0.04 and Nb/Y values of 123.48 to 141.67 (brown triangles). The unit plots in the lower dacite field separating from the Scafell caldera units. The Glassy Crag Dacite has Zr/TiO$_2$ values of 0.03 to 0.04 and Nb/Y values of 0.49 to 0.51 (green diamonds). The

![Fig. 61. Nb/Y vs. Zr/TiO$_2$: The ‘Oxendale Tuff’ (brown square), the Wetherlam Dacite (brown triangles) and the Glassy Crag Dacite (green diamonds) classify as dacitic on a plot after Winchester & Floyd (1977).](image)
unit also plots in the lower dacite field, overlapping with the Wetherlam Dacite. The Wetherlam Dacite and Glassy Crag Dacite overlap with some other dacitic samples (grey circles), which will also be included for distinction.

**Geochemical distinction of the intrusions**

All dacitic intrusions already separate from the Scafell caldera units (Long Top Tuffs and Crinkle Tuffs members) on the Nb/Y vs. Zr/TiO$_2$ plot (Fig. 61; after Winchester & Floyd, 1977). To confirm this and to clearly separate the intrusions from each other, the intrusions have also been plotted on Nb/Y vs. Zr/Y, Zr/Y vs. Ti/Y and V/Y vs. Th/Nb plots (Fig. 62). The Wetherlam Dacite and the Glassy Crag Dacite are also compared to the Foul Scrow Tuff (former Lincomb Tarns in the Coniston Fells; Chapter 5.5.2), which has been identified as the overlapping other andesitic unit on Fig. 61. The ‘Oxendale Tuff’ clearly separates from all other units in its significantly lower Nb/Y and Zr/Y values (Fig. 62a). The ‘Oxendale Tuff’ plots distinctly separated from the Long Top Tuffs in the presented ratios and does not correlate with the unit. The Wetherlam Dacite plots overlapping with the Long Top Tuffs in Nb/Y vs. Zr/Y (Fig. 62a) but clearly separates from this and the other intrusions on the Zr/Y vs. Ti/Y and V/Y vs. Th/Nb plots (Fig. 62b and c). The higher Ti and V values of the Wetherlam Dacite suggests a less evolved dacitic composition. The Wetherlam Dacite separates from the Glassy Crag Dacite and also differs to the Foul Scrow Tuff from the Coniston Fells in all ratio:ratio plots. The Glassy Crag Dacite shows no overlap with any Scafell caldera unit, but the intrusion widely overlaps with the Foul Scrow Tuff on all presented ratios.
No plot was found to separate the Glassy Crag Dacite from the Foul Scrow Tuff, suggesting that they are indistinguishable in their whole-rock geochemical values.
Dacitic intrusions conclusions

Geochemistry successfully separates the dacitic intrusions ‘Oxendale Tuff’ in Great Langdale and the Wetherlam Dacite and Glassy Crag Dacite on Wetherlam from the Airy’s Bridge Formation. The following conclusions can be made:

‘Oxendale Dacite’ intrusion: The previous Oxendale Tuff cannot be considered a tuff anymore and is here re-named the Oxendale Dacite on the basis of: (1) ‘immobile’ trace element ratios of Zr/TiO$_2$, Nb/Y and Zr/Y clearly separate the unit from the previously related Long Top Tuffs Member and the Crinkle Tuffs Member and other dacitic intrusions. (2) The ‘Oxendale Tuff’ unconformably overlies the Whorneyside Bedded Tuff, (3) it is autobrecciated at the bottom and potentially at the top, and (4) the unit is pink-weathered whereas the Long Top Tuffs are paler grey-weathered.

Wetherlam Dacite intrusion: (1) the unit plots clearly separated from Scafell caldera units and the other dacitic intrusions on plots of Zr/Y vs. Ti/Y and V/Y vs. Th/Nb. (2) The unit unconformably overlies the Whorneyside Bedded Tuff and bends round within the Long Top Tuffs on Wetherlam, (3) it is autobrecciated at the bottom and top, and (4) the intrusion dips 70° NE whereas the general dip of the succession on Wetherlam is about 70° SE, and (5) the Wetherlam Dacite is darker pink-weathered than the Long Top Tuffs.

However, the emplacement of the Oxendale Dacite and the Wetherlam Dacite may have happened under similar circumstances because both units unconformably intruded in between the Whorneyside and Airy’s Bridge formations and the Stonesty Tuff seems to be backed or absent.

Glassy Crag Dacite intrusion: (1) ‘immobile’ trace element ratios of Zr/TiO$_2$, Nb/Y, Zr/Y, Ti/Y and V/Y clearly separate the intrusion from Scafell caldera units and the other dacitic intrusions. (2) The contact zone to the underlying Long Top Tuffs is characterised by a 5 to 10 m thick zone of lithophysae, suggesting a potential heat-up during emplacement of the intrusion. (3) Characteristic features of the similar appearing Crinkle Tuffs (i.e. thin long fiamme wrapping around small lithic lapilli) are absent, (4) the parallel-bedding structures at the base of the unit dip 80° NE, (5) autobrecciation is present at the bottom and top, and (6) the Glassy Crag Dacite is flow-banded.
5.4 Scafell caldera-lake phase units

A caldera-lake post-dated the explosive caldera-collapse phase of Scafell caldera. It is recorded by a succession of sedimentary and pyroclastic units of the Seathwaite Fell Formation, including the pyroclastic Pavey Ark Member and the Glaramara Member (Fig. 29).

5.4.1 Pavey Ark Member and Duddon Hall Formation correlation

*Pavey Ark Member within Scafell caldera*

The Pavey Ark Member lies in the upper Seathwaite Fell Formation that records the Scafell caldera lake (Fig. 29). A large explosive eruption produced a density current that erupted from near Grasmere in the east (Fig. 64), deposited over 500 m thick, and entered Scafell caldera lake, deposited 80 to 200 m thick (Kokelaar et al., 2007). At the type locality, Pavey Ark [NY 284 079], it is a brown-weathered, massive to diffuse-bedded, scoriaceous block breccia (Fig. 63a) that grades vertically into lapilli-tuff and tuff (Kokelaar et al., 2007). Spatter-rich layers up to 5 m thick are present with ragged clasts up to several decimetre (Fig. 63b). Amoeboid, fluidal-shaped bombs or spatter

![Fig. 63. Lithofacies of the Pavey Ark Member at Scafell caldera and its potential correlative the Duddon Hall Formation on Wetherlam.](image)

(a) Massive, scoriaceous block breccia of the Pavey Ark Member at Pavey Ark, Central Fells. (b) Amoeboid, fluidal-shaped clast at Pavey Ark. (c) Massive, scoriaceous block breccia with amoeboid fragments of the Duddon Hall Formation on Wetherlam. (d) Amoeboid, fluidal-shaped clast in massive lapilli-tuff of the Duddon Hall Formation on Wetherlam.
with small lithic fragments, locally wrap around angular blocks and lapilli of the surrounding breccia (Kokelaar et al., 2007). The Pavey Ark Member has only been described within Scafell caldera. During the present study, a similar breccia contains amoeboid clasts was identified in the Coniston Fells. Spatter clasts were sampled from both units in order to compare the juvenile compositions.

**Duddon Hall Formation at Wetherlam (Coniston area)**

About 3 to 5 km South of Scafell caldera, on the ridge of Wetherlam towards Levers Water [SD 279 994], a massive brown-weathered massive layer of spatter-rich lapilli-tuff and breccia, 70 m thick, has been mapped within the uppermost third of the 400 m thick Duddon Hall Formation (Fig. 29). The formation comprises parallel-laminated to thickly-bedded volcaniclastic sediments, tuff and thick layers of massive lapilli-tuff and breccia. The spatter clasts are amoeboid and fluidal-shaped (Fig. 63c and d) and some include small lithic fragments. The Duddon Hall Formation has been reported around

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**Fig. 64.** Simplified geological map showing the Pavey Ark Member within Scafell caldera and the Duddon Hall Formation in the Coniston Fells – 1:50,000 solid sheet (after BGS, 1998, 2003; Brown, 2001; Kokelaar et al., 2007).
Coniston Fells and further south-west in the Duddon valley (Fig. 64; Millward et al., 2000a), but it has not been reported in the Central Fells, and it has not been correlated with units of Scafell caldera. It overlies dacitic to rhyolitic ignimbrites now assigned to the Crinkle Tuffs Member (Chapter 5.3.2.3), and is overlain by the Paddy End Member. The succession dips 75° SE and shows steep Acadian cleavage.

**Geochemical classification and correlation**

On a Nb/Y vs. Zr/TiO$_2$ plot (Fig. 65; after Winchester & Floyd, 1977) the clasts in the Pavey Ark Member have Zr/TiO$_2$ values of 0.01 (red x’s in Fig. 65), and in the Duddon Hall Formation have Zr/TiO$_2$ values of 0.01 to 0.02 (purple crosses). The Pavey Ark Member clasts have Nb/Y values of 0.37 to 0.69 and those of the Duddon Hall Formation have Nb/Y values of 0.39 to 0.55. The units plot slightly above each other in the sub-alkaline basalt to andesite fields separating from most other andesitic units except of a sub-alkaline basaltic pre-caldera lava sample and the Rest Gill Tuff. However, these two units are stratigraphically and lithologically different.

![Fig. 65. Nb/Y vs. Zr/TiO$_2$ classifying the juvenile rags of Pavey Ark Member (red x’s) as sub-alkaline basalt to alkali basalt and juvenile rags in its potential extra-caldera correlative of the Duddon Hall Formation (purple crosses) are sub-alkaline basaltic to andesite.](image-url)
Geochemical distinction to other basaltic to andesitic units

‘Immobile’ trace element values of Nb/Y vs. Th/Y, Zr/Y vs. Ti/Y and V/Y vs. Th/Nb are plotted to compare rags of the Pavey Ark Member (red x’s in Fig. 66) and of the Duddon Hall Formation (purple crosses) with other andesitic units of Scafell caldera (Chapter 5.3.1). The rags plot widely overlapping to each other but also to other units on the Nb/Y vs. Th/Y plot (Fig. 66a). They plot slightly separated to the other andesitic units on the Zr/Y vs. Ti/Y plot (Fig. 66b), but also slightly separate from each other similar to Fig. 65. On the third presented plot of V/Y vs. Th/Nb the rags also overlap with the other presented andesitic units (Fig. 66c).

Fig. 66. Correlation of rags from the Pavey Ark Member (red x’s) within Scafell caldera and the potential extra-caldera correlative from the Duddon Hall Formation (purple crosses) on Wetherlam. The caldera fill samples and the extra-caldera samples plot very similar to each other but also plot widely overlapping with other andesitic units (grey circles) of Scafell caldera. (a) Nb/Y vs. Th/Y. (b) Zr/Y vs. Ti/Y. (c) V/Y vs. Th/Nb.

On a Cr vs. Ni plot (Fig. 67), rags of the Pavey Ark Member and Duddon Hall Formation have lower values than most other little evolved units, including the pre-caldera lavas and the Rest Gill Tuff. Only the thin ‘marker unit’ Cam Spout Tuff within the Long Top Tuffs plots similar but this unit is stratigraphically distinct as well. The
Duddon Hall Formation also comprises three other massive breccia units below the one sampled. These should be considered as well for a final correlation.

Pavey Ark Member to Duddon Hall Formation correlation conclusion

The Pavey Ark Member at Scafell caldera is tentatively correlated with the upper massive breccia layer towards the top of the Duddon Hall Formation on Wetherlam. It is concluded, that the extra-caldera succession on Wetherlam is a potential equivalent of the Pavey Ark Member within Scafell caldera, but more fieldwork and other correlation methods are needed for consolidation. Evidence for correlation is given by: (1) ‘Immobile’ trace element plots of Nb/Y vs. Zr/TiO₂ and Cr vs. Ni separate the spatter clasts best from other andesitic units of Scafell caldera. (2) On plots of Nb/Y vs. Th/Y, Zr/Y vs. Ti/Y and V/Y vs. Th/Nb overlap the rags, but they also widely overlap with other units. (3) The Pavey Ark Member (situated in the upper Seathwaite Fell Formation) overlies the Airy’s Bridge Formation in the Central Fells, and the unit on Wetherlam overlies the newly discovered Crinkle Tuffs (also upper Airy’s Bridge Formation). (4) The Pavey Ark Member is a massive lapilli-tuff breccia, 80 to 200 m thick, rich in amoeboid, fluidal-shaped spatter clasts. The unit mapped as Duddon Hall Formation comprises about four breccia layers, 40 to 150 m thick, of amoeboid, fluidal-shaped spatter clasts, and (5) the units have similar grey-weathered colours.
5.4.2 Glaramara Member correlation

Glaramara Member at Scafell caldera

The Glaramara Member lies within the lower Sprinkling Tarn Formation being the upper part of the Seathwaite Fell Formation of the caldera-lake phase (Fig. 29). At its type area (Glaramara; 7 in Fig. 11) the Glaramara Member is surrounded by bedded tuff of the Sprinkling Tarn Formation (Fig. 68a). It is up to 7 m thick and presents a medial to distal tuff ring deposit (Fig. 68b). The Glaramara Member can be divided into three lithostratigraphic units of phreatomagmatic to magmatic explosive, waxing and waning eruptions (Fig. 69b). Unit 1 comprises diffuse to cross-stratified fine-grained tuff, abundant lapilli-sized ash and accretionary lapilli tuff that thins systematically towards Scafell Pike (Brown et al., 2007; NY 215 072). Unit 2 comprises bedded massive lapilli-tuff mainly deposited in the Central Fells with its maximum thickness around Coombe Head. Unit 3 comprises accretionary lapilli-tuff beds intercalated with stratified tuff (Brown et al., 2007). Unit 1 and 3 have been traced throughout the Central Fells to below the Side Pike Ignimbrite south of Scafell caldera.

![Fig. 68](image_url). Lithofacies of the discussed units (photos from Branney). (a) Parallel fine lamination and thin beds with soft-state faults and slide structures of the Sprinkling Tarn Formation at Coombe Head, Glaramara. (b) Bedded fine-grained tuff with accretionary lapilli of the Glaramara Member at Coombe Head, Glaramara. (c) Bedded fine-grained tuff of the Lingmoor Tuff at Side Pike.
Fig. 69. (a) Simplified geological map of the Glaramara Member showing the localities of the tuff (modified after Brown et al., 2007). The Glaramara Member at Coombe Head, within Scafell caldera, is compared with the Glaramara Member at Side Pike, Great Langdale. (b) Measured logs of the Glaramara Member (modified after Brown et al., 2007): At Coombe Head in the Central Fells the member comprises several lithofacies and is several meters thick. At Side Pike, the Glaramara Member is thinner and mainly comprises massive and cross-stratified tuff and underlies the Side Pike Ignimbrite. The previously correlated Lingmoor Tuff, overlying the Side Pike Ignimbrite, will be included for a geochemical comparison.
**Glaramara Member at Side Pike (Langdales)**

About 6.5 km south-east of Glaramara, on Side Pike in Great Langdale (Fig. 69a), a dacitic tuff unit has been mapped as the Glaramara Member (Brown, 2001). The unit unconformably overlies the Black Wall Member (lowermost Sprinkling Tarn Formation) and is unconformably overlain by pyroclastics of the Side Pike Ignimbrite. On Side Pike, only unit 1 and 3 have been recognised of the Glaramara Member (Fig. 69b; Brown, 2001). Unit 1 comprises several decimetres of bedded and stratified tuff with accretionary lapilli. A thin poorly sorted, eutaxitic lapilli-tuff marker horizon lies between the accretionary lapilli tuff (Brown, 2001). Unit 3 comprises several decimetres of low-angle cross-stratified and bedded tuff also with accretionary lapilli.

**Lingmoor Tuff (Swinescar Pike Tuff) at Side Pike (Langdales)**

Another dacitic tuff unit is exposed above the Side Pike Ignimbrite on Side Pike in Great Langdale (Fig. 8 and Fig. 69b). The unit was previously mapped as the Glaramara Tuff (Kneller & McConnell, 1993) but it was revised and renamed as Lingmoor Tuff (informally by Branney) or Swinescar Pike Tuff (informally by Brown, 2001). The unit contradicted the lithostratigraphic succession of the Seathwaite Fell Formation and Sprinkling Tarn Formation to underlay the pyroclastic succession of the Side Pike Ignimbrite and Langdale caldera.

The Glaramara Member at Scafell caldera, the Glaramara Member at Side Pike, the underlying Sprinkling Tarn Formation at Scafell caldera and the Lingmoor Tuff above Side Pike Ignimbrite have been sampled and will be compared using whole-rock geochemistry. Samples are numbered from A-I on the logs of Fig. 69b to easier compare the geochemical values of the individual samples with stratigraphic height to each other.
**Geochemical classification and correlation**

The Glaramara Member from Scafell caldera has Zr/TiO$_2$ values of 0.03 to 0.04 and Nb/Y values of 0.34 and 0.36 classifying as dacitic (red circles in Fig. 70). The Glaramara Member from Side Pike has Zr/TiO$_2$ values of 0.02 to 0.03 and Nb/Y values of 0.47 to 0.60 (orange squares). The unit plot in the lowermost dacite to andesite fields. The Lingmoor Tuff from Side Pike has Zr/TiO$_2$ values of 0.02 to 0.08 and Nb/Y values of 0.45 to 0.47 (green triangles). The samples scatter from the andesite to the upper dacite fields. The Sprinkling Tarn Formation from Scafell caldera has a Zr/TiO$_2$ value of 0.02 and a Nb/Y value of 0.53 classifying as andesitic (blue diamond).

![Fig. 70. Nb/Y vs. Zr/TiO$_2$ classifying the units with sample height: the Sprinkling Tarn Formation (blue diamond) at Scafell caldera and the Glaramara Member (orange squares) at Side Pike are andesitic. The Glaramara Member (red circles) at Scafell caldera plots slightly higher in the dacite field. The Lingmoor Tuff (green triangles) at Side Pike plots in the andesite and dacite fields.](image)

The Glaramara Member within Scafell caldera and at Side Pike do not overlap, on the plot after Winchester & Floyd (1977). On plots of Zr/Y vs. Ti/Y, Zr/Y vs. Th/Y and V/Y vs. Th/Nb (Fig. 71) the two units also show no direct overlap or correlation potential. Samples seem to plot randomly with the Sprinkling Tarn Formation and Lingmoor Tuff plotting overlapping and with not clear distinction from each other. No clear trend or differentiation can be undertaken. The Glaramara Member samples at Side Pike may have undergone more hydrothermal alteration due to the proximity to Langdale caldera.
Geochemical distinction from other units of Scafell caldera

On a Cr vs. Ni plot (Fig. 72) the Glaramara Member from Scafell caldera has low Cr values of 25.3 to 32.8 and Ni values of 8.2 to 14.9 and scatters less than the Glaramara Member from Side Pike with Cr values of 65.9 to 153.2 and Ni values of 14.0 to 57.7. The units scatter and do not overlap. The Lingmoor Tuff plots slightly separated with Cr values of 0.6/0.7 to 95.6 and very low Ni values of 0.6 to 1.1. The Sprinkling Tarn Formation plots in between the Glaramara Member samples with a Cr value of 64.4 and a Ni value of 25.1. Compared to the andesitic Scafell caldera units (open circles) which plot distinct from each other (Chapter 5.3.1) on the Cr vs. Ni plot, plot these units widely scattered, hindering a correlation or separation.

**Fig. 71.** Units plotted with sample height (A-I) for correlation of the Glaramara Member at Scafell caldera (red circle), the extra-caldera Glaramara Member (orange squares), the Lingmoor Tuff (green triangles) and the Sprinkling Tarn Formation (blue diamond). Units scatter and do not undoubtedly correlate or separate from each other on plots of (a) Zr/Y vs. Ti/Y, (b) Zr/Y vs. Th/Y and (c) V/Y vs. Th/Nb.
Correlation was attempted for the Glaramara Member at Scafell caldera with the designated Glaramara Member at Side Pike and its former correlative the Lingmoor Tuff. It is not undoubtedly clarified whether the andesitic to dacitic Glaramara Member at Side Pike is the extra-caldera equivalent of the Glaramara Member within Scafell caldera. The correlation was hindered by: (1) ‘Immobile’ trace element plots of Nb/Y vs. Zr/TiO$_2$, Zr/Y vs. Ti/Y, Zr/Y vs. Th/Y and V/Y vs. Th/Nb do not clearly determine the units to correlate and also do not clearly discriminate the units from the Sprinkling Tarns Formation and the Lingmoor Tuff. (2) The limited number of samples and their geochemical variability hinders this correlation. However, a correlation attempt could be further undertaken by ICP-MS.

**Fig. 72.** Cr vs. Ni: Units plotted with sample height (A-I) of the Glaramara Member at Scafell caldera (red circle), the extra-caldera Glaramara Member (orange squares), the Lingmoor Tuff (green triangles) and the Sprinkling Tarn Formation (blue diamond). A correlation or discrimination of the units is hindered by the wide scatter. Also plotted are andesitic units of Scafell caldera for comparison (open circles).
5.5 Post-Scafell succession

The pyroclastic units post-dating Scafell caldera are lithologically not as distinctive and less continually mapped as units in the Central Fells of the Lake District (Fig. 3). To date, besides the Side Pike Ignimbrite, no attempt has been undertaken to correlate potential extra-caldera correlatives with Langdale caldera, though some units in the Coniston Fells area have correlation potential. The Side Pike Ignimbrite, the Paddy End Member and the Low Water Formation have been considered potential extra-caldera correlatives to Langdale caldera (Fig. 73 and Fig. 74). The succession of strata that contains potential outflow sheets in the Coniston area to the South, has undergone more tectonic deformation (Fig. 10) and alteration compared to Scafell caldera in the Central Fells (Chapter 5.1.1). Geochemical fingerprinting will be used to potentially correlate these extra-caldera units with Langdale caldera.

Fig. 73. Simplified geological map showing Langdale caldera and its possible outflow sheets: Side Pike Ignimbrite, Paddy End Member and Low Water Formation. The map also shows the Lincomb Tarns Formation in the Central Fells and the revised Foul Scrow Tuff Member (Chapter 5.5.2) in the Coniston Fells – 1:50,000 solid sheet (after BGS, 1998, 2003; Brown, 2001 and this study).
Fig. 74. General vertical sections (not to scale) comparing the upper Scafell caldera fill succession (after Branney & Kokelaar, 1994) with the outflow succession of Langdale caldera (after Brown, 2001) and the so far partly revised extra-caldera Scafell succession in the Coniston area (Wetherlam; after BGS, 1998).
The fill of Langdale caldera, in the Lake District, post-dates the Scafell caldera succession and plots within the andesite to rhyolite fields of Winchester & Floyd (1977) using Nb/Y vs. Zr/TiO$_2$ (black squares in Fig. 75) with Zr/TiO$_2$ values from 0.019 to 0.119. Possible outflow sheets on Side Pike, Great Langdale and further south of Langdale caldera, in the Coniston Fells area, plot in the andesite to rhyolite fields (blue circles), with Zr/TiO$_2$ values from 0.022 to 0.146. These units are considered to be potential extra-caldera correlatives of Langdale caldera and will now be considered in stratigraphic order.

**Fig. 75.** Nb/Y vs. Zr/TiO$_2$ for dacitic to rhyolitic pyroclastic units in the caldera fill of Langdale volcano (black squares; after Winchester & Floyd, 1977). Also shown are potential correlative dacitic to rhyolitic units from the Langdale to Coniston Fells area (blue circles). Samples from individual stratigraphic units cluster together, but some units also show some scatter.
5.5.1  Langdale caldera succession and its potential correlatives

_Langdale caldera fill at Lingmoor Fell (Langdales)_

Langdale caldera is a well-preserved succession of pyroclastic and fallout deposits of magmatic, phreatomagmatic and phreatic eruptions (Branney, 1988b; Brown, 2001). At the type area on Lingmoor Fell (9 in Fig. 11), the caldera fill succession mainly comprises massive breccia, welded eutaxitic lapilli-tuff of the dacitic to rhyolitic Side Pike Ignimbrite and other dacitic welded pyroclastic deposits, some with interbedded accretionary lapilli. The succession also comprises andesitic lava flows, rhyolitic welded tuff, phreatomagmatic deposits, fine bedded tuff layers and sediments (Brown 2001). The succession is highly faulted and broken into several megabreccia blocks of 10 to 1000 m in size. The base of the caldera fill is not exposed but the succession has a minimum thickness of 250 m on Lingmoor Fell (Branney, 1988b). In one locality (NY 30117 03465; sample GH-17-29) the unit mapped as fill of Langdale caldera is a white-weathered, eutaxitic lapilli-tuff with thin and long, chloritic fiamme very similar to the Crinkle Tuffs Member (Chapter 5.3.2.3).

5.5.1.1  Side Pike Ignimbrite to Langdale caldera fill correlation

_At Side Pike (extra-caldera correlative; Langdales)_

At the type locality Side Pike, an intensely welded rhyolitic ignimbrite has been mapped as the Side Pike Ignimbrite (10 in Fig. 11; NY 289 053; Branney, 1988b). It overlies parallel-bedded to cross-bedded tuff with low-angle cross-stratification and abundant accretionary lapilli mapped as the Glaramara Member (Brown, 2001). The Side Pike Ignimbrite is a massive, eutaxitic welded lapilli-tuff. It is 30 m thick, with fiamme supported in a tuff matrix (Fig. 76a). Fiamme are getting progressively more flattened towards the centre (Fig. 76b and c) of the unit and again less flattened towards the top of the ignimbrite. The Side Pike Ignimbrite at Side Pike is overlain by half a meter of bedded and stratified tuff with abundant accretionary lapilli (Brown, 2001). This is followed by a breccia incorporating clasts of the underlying Side Pike Ignimbrite and parallel to cross-bedded deposits with accretionary lapilli. A massive andesite sheet with an autobrecciated base comprises the top of Side Pike.
On a Nb/Y vs. Zr/TiO$_2$ plot (Fig. 77; after Winchester & Floyd, 1977) the ignimbrite of the Langdale caldera fill has Zr/TiO$_2$ ratios of 0.02 to 0.12 and Nb/Y ratios of 0.36 to 0.50 classifying as andesitic to rhyolitic (green squares). Except for two odd samples, the bulk of the Langdale caldera fill plots close together in the dacite field. The Side Pike Ignimbrite has Zr/TiO$_2$ ratios of 0.04 to 0.16 and Nb/Y ratios of 0.46 to 0.57 (green circles). Two samples plot in the dacite field, very similar to the bulk of the Langdale caldera fill, but most samples are more evolved and plot in the rhyolite field.

To further compare and correlate the Langdale caldera fill (green squares) to the Side Pike Ignimbrite (green circles), plots of Th/Y vs. Zr/Y, Nb/Y vs. Zr/Y and Ti/Zr vs. V/Y (Fig. 78) are used. Other post-Scafell caldera units will be discussed in individual chapters hereafter. All Scafell caldera units that plot similar to the Langdale caldera fill are stratigraphically distinct lower and can therefore be excluded from the correlation and separation.

*Fig. 76. Lithofacies of the Side Pike Ignimbrite at Side Pike, Great Langdale. (a) Massive, eutaxitic lapilli-tuff with bigger fiamme at the base of the unit. (b) Central parataxitic lapilli-tuff. (c) Massive, eutaxitic lapilli-tuff with smaller fiamme of the Side Pike Ignimbrite.*
Fig. 77. The Langdale caldera fill (green squares) classifies as andesitic to rhyolitic and the Side Pike Ignimbrite (green circles) classifies as dacitic to rhyolitic on a Nb/Y vs. Zr/TiO₂ plot (after Winchester & Floyd, 1977). The caldera fill sample that appeared similar to the Crinkle Tuffs Member in the field, also plots within the Crinkle Tuffs Member field (yellow border).

Fig. 78. Correlation of the Langdale caldera fill with the Side Pike Ignimbrite. The units widely overlap on plots of (a) Th/Y vs. Zr/Y, (b) Nb/Y vs. Zr/Y. The more evolved Side Pike Ignimbrite plots on a line with the less evolved caldera fill in (c) Ti/Zr vs. V/Y. Also plotted are other post-Scafell caldera units (grey circles) widely overlapping with these units. They will be further considered hereafter.
Langdale caldera fill and Side Pike Ignimbrite plot widely overlapping on plots of Th/Y vs. Zr/Y and Nb/Y vs. Zr/Y. Due to the similar ratio in Ti/Zr vs. V/Y, plots the Langdale caldera fill with generally higher Ti/Zr and V/Y values than the Side Pike Ignimbrite. The topmost Side Pike Ignimbrite samples plot indistinguishably to the Langdale caldera fill samples. The odd rhyolitic caldera fill sample plots close to the Crinkle Tuffs Member. This rhyolitic caldera fill sample is also compared to the Crinkle Tuffs Member on a plot of Nb/Y vs. Th/Nb (Fig. 79). Most Langdale caldera fill, as well as Side Pike Ignimbrite, other post-Scafell caldera units and Scafell caldera units have lower Th/Nb values than this sample and the Crinkle Tuffs Member. This sample also plots directly in between the Crinkle Tuffs Member on this plot. No whole-rock plot could be found to clearly separate this sample from the Crinkle Tuffs Member. They plot indistinguishable from each other.

**Fig. 79.** Nb/Y vs. Th/Nb plot showing the fill of Langdale caldera (green squares) and the Side Pike Ignimbrite (green circles) widely overlapping. Sample GH-17-29 (predicted Crinkle Tuffs) plots directly within the other Crinkle Tuff samples (yellow diamonds). Other units of Scafell caldera (open circles) and post-Scafell caldera (open triangles) plot below the Crinkle Tuffs Member.
The Langdale caldera fill is correlated with the Side Pike Ignimbrite. It is concluded that the dacitic to rhyolitic ignimbrite is the extra-caldera equivalent of Langdale caldera. The fill and outflow successions are illustrated in Fig. 80 and Fig. 81. The correlation is based on the following evidence: (1) ‘Immobile’ trace element plots of Th/Y vs. Zr/Y and Nb/Y vs. Zr/Y show the units to plot indistinguishable from each other. In plots of Nb/Y vs. Zr/TiO$_2$ and Ti/Zr vs. V/Y the units are linked with each other by the top most samples of the Side Pike Ignimbrite suggesting the unit to be zoned. The base of the thick caldera fill is not entirely exposed, i.e. the lower part of the fill is missing for geochemical correlation. (2) The succession overlying the caldera fill and the Side Pike Ignimbrite are identical. (3) The thickness of the Langdale caldera fill suddenly drops from >250 m to 30 m when overstepping the proposed caldera margin.

At the southern Langdale caldera margin in Little Langdale (NY 30117 03465; GH-17-29; Fig. 16), a ‘mega-block of Crinkle Tuffs Member may be placed, suggesting large movements of the caldera margin. Re-mapping of the area is recommended.

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**Fig. 80.** Simplified Langdale caldera sketch to compare the caldera fill with the possible extra-caldera successions on Side Pike, Steel Edge and on the Dunnerdale Fells (thicknesses not to scale).
Fig. 81. The Langdale caldera fill is compared to the Side Pike Ignimbrite, the Paddy End Member and the Low Water Formation. (a) Samples are presented in stratigraphical order (colours match up with data points in b; tables of sample sights are presented in Appendix I; thicknesses not to scale). (b) Vertical section shows the gradational compositional variations in Zr values of the compared units with dimensionless stratigraphic height.
5.5.1.2 Paddy End Member to Side Pike Ignimbrite correlation

At Steel Edge (Coniston area)

The Paddy End Member is a pink-weathered, rhyolitic ignimbrite. On Steel Edge (Fig. 11), about 3 km SW of Langdale caldera, the unit unconformably overlies the Duddon Hall Formation with a thickness of 150 to 170 m. It has a flinty and hackly appearance with generally small, less than 2 cm long fiamme at the base (Fig. 82a and b). Fiamme are silicified and are getting progressively rare towards the centre of the ignimbrite (Fig. 82c). Up to 5 cm long, non-silicified fiamme are present at the top of the Paddy End Member on Steel Edge (Fig. 82d). Lithics are very small and generally rare throughout the unit. The Paddy End Member is overlain by 10 to 30 m of volcaniclastic sandstone followed by welded dacitic lapilli-tuff of the Low Water Formation.

![Fig. 82](image)

**Fig. 82.** Lithofacies of the Paddy End Member on Steel Edge. (a) Flinty and hackly surface of the member. (b) Silicified fiamme in the lower part. (c) Fiamme are very small to nearly absent towards the centre of the massive, eutaxitic lapilli-tuff. (d) Long, thin fiamme in the uppermost Paddy End Member.

At Dunnerdale Fells (Duddon valley area)

About 14 km SW of Langdale caldera, on Dunnerdale Fells (Fig. 11; SD 207 918) in the Duddon valley area, a rhyolitic ignimbrite has been mapped as the Paddy End Member, about 30 m thick (BGS, 2003). The succession is moderately exposed and strongly
cleaved. The unit is a brown- to grey-weathered, welded, eutaxitic lapilli-tuff. Fiamme and lithic lapilli are present but are mostly overprinted by the strong Acadian cleavage.

**Geochemical classification**

The Paddy End Member at Steel Edge has Zr/TiO$_2$ values of 0.11 to 0.14 and Nb/Y values of 0.43 to 0.50 (green diamonds in Fig. 83). The distal Paddy End Member from the Dunnerdale Fells has a Zr/TiO$_2$ value of 0.12 and a Nb/Y value of 0.42 (green triangle). All Paddy End Member samples plot in the rhyolite field (Fig. 83). The samples widely overlap with the Side Pike Ignimbrite (green circles).

**Fig. 83.** Nb/Y vs. Zr/TiO$_2$ classifying the Paddy End Member (green diamonds and triangle) as rhyolitic (after Winchester & Floyd, 1977). The Langdale caldera fill (green squares) plots below but its extracaldera correlative the Side Pike outflow (green circles) plots widely overlapping to the Paddy End Member.

**Geochemical correlation to the Side Pike Ignimbrite and the fill of Langdale caldera**

In the Nb/Y vs. Zr/TiO$_2$ plot (Fig. 83) the Paddy End Member (green diamonds) plots widely overlapping to the Side Pike Ignimbrite (green circles) but it does not overlap with the Langdale caldera fill (green squares). Plots of Th/Y vs. Zr/Y, Nb/Y vs. Zr/Y and Ti/Zr vs. V/Y (Fig. 84) are used to further compare the Paddy End Member to both units. In the Th/Y vs. Zr/Y plot (Fig. 84a) the Paddy End Member plots indistinguishable to both. In the Nb/Y vs. Zr/Y plot (Fig. 84b) the Paddy End Member
plots overlapping with the Side Pike Ignimbrite but slightly above the Langdale caldera fill. This could be caused by the slightly more evolved rhyolitic composition of the Paddy End Member being erupted first and deposited distally but not proximal to Langdale caldera. Ti/Zr vs. V/Y (Fig. 84c) shows the Paddy End Member to plot in between the caldera fill and outflow.

Fig. 84. Correlation of the Paddy End Member (green diamonds), the Side Pike Ignimbrite (green circles) and the Langdale intracaldera succession (green squares). The Paddy End Member samples and the Side Pike Ignimbrite plot indistinguishable to each other on (a) Th/Y vs. Zr/Y, (b) Nb/Y vs. Zr/Y and (c) Ti/Zr vs. V/Y plots. The Paddy End Member also plots very similar to the fill of Langdale caldera on the Th/Y vs. Zr/Y and Nb/Y vs. Zr/Y plots.

**Geochemical separation from other units**

The only other unit to appear similar in the field with a rhyolitic composition is the Crinkle Tuffs. The units can be clearly separated from each other on a Zr/Y vs. Th/Nb plot (Fig. 85). The Paddy End Member has Zr/Y values of 7.25 to 8.64 and Th/Nb values of 0.63 to 0.70. The Crinkle Tuffs has lower Zr/Y values of 5.14 to 6.10 and higher Th/Nb values of 0.89 to 1.05. The Paddy End Member clearly differs to all other units (except the Side Pike Ignimbrite) by its combined higher Zr/TiO<sub>2</sub> and Nb/Y values on a Nb/Y vs. Zr/TiO<sub>2</sub> plot (Fig. 83; after Winchester & Floyd, 1977).
The Paddy End Member at Steel Edge and Dunnerdale Fells is correlated with the Langdale caldera fill and the Side Pike Ignimbrite. It is concluded that the rhyolitic ignimbrite is the distal extra-caldera equivalent of the Side Pike Ignimbrite, being part of the earliest eruption of Langdale caldera, on the basis of:

1. The unit plots very close to the Langdale caldera fill on the Th/Y vs. Zr/Y but slightly offset on other ratio plots.
2. ‘Immobile’ trace element plots of Nb/Y vs. Zr/TiO$_2$, Th/Y vs. Zr/Y, Nb/Y vs. Zr/Y and Ti/Zr vs. V/Y show the Paddy End Member to plot consistently very similar and indistinguishable to the Side Pike Ignimbrite. This could be due to the Paddy End Member being part of the earliest eruption of Langdale caldera (which is not exposed within the caldera fill) and due to a potential chemical zoning of the highly silicic to less silicic tuffs of the caldera complex (i.e. Bishop Tuff, USA; Wolff et al., 2015).
3. The Side Pike Ignimbrite overlies the Duddon Hall Formation which is revised to potentially correlate with the Seathwaite Fell Formation in the Central Fells and below Side Pike Ignimbrite (including the Glaramara Member also underlying the Side Pike Ignimbrite; Chapter 5.4).
4. Both units have silicified fiamme, progressively decreasing in size towards the centre and increasing towards the top of the units.

**Fig. 85.** Discriminant plot of Zr/Y vs. Th/Nb to separate the Paddy End Member (green diamonds) from the Crinkle Tuffs (yellow diamonds). The plot also shows the Paddy End Member to plot close to the Side Pike Ignimbrite (green circles) and the fill of Langdale caldera (green squares).
5.5.1.3 Low Water Formation to Langdale caldera fill correlation

At Above Beck Fells (Coniston area)

A potential extra-caldera correlative to the Langdale caldera fill is the dacitic Low Water Formation (Fig. 87). At the type area on Above Beck Fells (12 in Fig. 11; SD 296 999) it is mapped as up to 600 m thick and consists of two massive welded sheets of lapilli-tuff interbedded with bedded tuff and volcaniclastic sandstone (BGS, 2003). The formation overlies welded rhyolitic lapilli-tuff of the Paddy End Member and dacitic lapilli-tuff of the Lag Bank Formation to its southern end (Millward et al., 2000a). The Low Water Formation is overlain by fine to coarse-grained volcaniclastic sandstone mapped as the Seathwaite Fell Formation (BGS, 2003). The base of the formation consists of up to 220 m thickly bedded volcaniclastic sandstone (Fig. 86a; Millward et al., 2000a). The base of the ignimbrite is a clast-supported, poorly sorted breccia (Fig. 86b). The Low Water Formation has a brown-weathered colour and contains abundant large fiamme (up to 10 cm long) and abundant angular lithic lapilli (up to 6 cm) supported in a recrystallized tuff matrix (Fig. 86c). Up to 35 m of fine to coarse-grained volcaniclastic sandstone is deposited in between the two massive lapilli-tuffs (Fig. 86d).

Fig. 86. Lithofacies of the Low Water Formation on Above Beck Fells, Coniston Fells area (b = bedding, c = cleavage). (a) Thickly bedded volcaniclastic sandstone at the base of the formation. (b) Clast-supported, poorly sorted breccia comprises the base of the ignimbrite. (c) Upper massive, eutaxitic lapilli-tuff. (d) Fine to coarse-grained volcaniclastic sandstone between the ignimbrite sheets.
Geochemical classification

The Low Water Formation has Zr/TiO$_2$ values of 0.02 to 0.08 and Nb/Y values of 0.38 to 0.50 (blue triangles in Fig. 88). This scatters the samples and classifies them as andesitic to dacitic. The samples partly overlap with the Side Pike Ignimbrite (green circles) and the fill of Langdale caldera (green squares).
**Geochemical correlation to the Side Pike Ignimbrite and the fill of Langdale caldera**

In the Nb/Y vs. Zr/TiO$_2$ plot (Fig. 88) the Low Water Formation (blue triangles) plots widely scattering and only overlaps with the Langdale caldera fill (green squares) in three samples. Plots of Th/Y vs. Zr/Y, Nb/Y vs. Zr/Y and Ti/Zr vs. V/Y (Fig. 89) are used to further compare the Low Water Formation to the Langdale caldera fill and the Side Pike Ignimbrite. In the Th/Y vs. Zr/Y and Nb/Y vs. Zr/Y plots (Fig. 89a and b) most Low Water Formation samples plot below the other units. In the Ti/Zr vs. V/Y plot (Fig. 89c) the Low Water Formation plots more overlapping with the fill of Langdale caldera.

**Fig. 88.** Nb/Y vs. Zr/TiO$_2$ showing the Low Water Formation (blue triangles) widely scattered (after Winchester & Floyd, 1977). The samples plot in the andesite to rhyodacite field. Three Low Water Formation samples plot close to the Langdale caldera fill (green squares).
The Low Water Formation is plotted with other rhyodacitic units of Scafell caldera and post-Scafell caldera on a Zr/Y vs. Th/Nb plot (Fig. 90). The Low Water Formation has Zr/Y values of 4.20 to 6.51 and Th/Nb values of 0.62 to 0.88. The unit plots in between the Long Top Tuffs and the Lincomb Tarns Formation. No ratio:ratio plot was found to clearly separate the Low Water Formation from the other units. However, the unit is stratigraphically and lithologically relatively distinct in the field.

**Geochemical separation from other units**

The Low Water Formation is plotted with the Side Pike Ignimbrite and the Langdale intracaldera succession. No ratio:ratio plot was found to clearly separate the Low Water Formation from the other units. However, the unit is stratigraphically and lithologically relatively distinct in the field.

**Fig. 89.** Correlation of the Low Water Formation (blue triangles) with the Side Pike Ignimbrite and the Langdale intracaldera succession. On (a) Th/Y vs. Zr/Y and (b) Nb/Y vs. Zr/Y plots the Low Water Formation overlapping with some of the intracaldera samples. On (c) Ti/Zr vs. V/Y plots the Low Water Formation in one line with the Paddy End Member and the intracaldera samples.
The Low Water Formation on Above Beck Fells is correlated with the fill of Langdale caldera. It is concluded that the dacitic ignimbrite is a potential extra-caldera equivalent of Langdale caldera, but evidence and data values are insufficient for a tight correlation. Evidence for its correlation potential is: (1) on a plot of Nb/Y vs. Zr/TiO$_2$ and Ti/Zr vs. V/Y the unit scatters but overlaps with the Langdale caldera fill samples. (2) In other ‘immobile’ trace element plots of Th/Y vs. Zr/Y and Nb/Y vs. Zr/Y the unit does not directly plot overlapping with the majority of the caldera fill samples. (3) The general appearance of the Low Water Formation in the field is similar to the fill of Langdale caldera. (4) As potential part of the upper caldera fill (later eruption sequence), the unit stratigraphically overlies the Paddy End Member and is less evolved than the Side Pike Ignimbrite and the Paddy End Member. (5) However, the thickness of the Low Water Formation is huge for being a potential outflow succession.

**Fig. 90.** Discriminant plot of Zr/Y vs. Th/Nb to separate the Low Water Formation (blue triangles) from other dacitic units. The formation plots in between the Long Top Tuffs and the Lincomb Tarns Formation and close to few Langdale caldera fill samples (green squares).
5.5.2 Lincomb Tarns Formation correlation

At Scafell caldera

At its type locality in the Central Fells (around Allen Crags; Fig. 29; 7 in Fig. 11), is the Lincomb Tarns Formation a grey-weathered, massive, eutaxitic, dacitic lapilli-tuff about 290 m thick (Fig. 92a). The base of the formation consists of crystal-rich parallel- to cross-stratified tuff that cut unconformably into the underlying Seathwaite Fell Formation (McConnell, 1993). The Lincomb Tarns Formation is generally massive with some flow-unit boundaries and locally associated bedded horizons. It contains abundant eutaxitic fiamme with ragged flame-like ends varying in size throughout the unit from <5 cm to up to 40 cm with aspect ratios 3:1 to 10:1 (McConnell, 1993). Lithic lapilli are abundant and generally less than 4 cm in size, but this varies in different localities to larger lithic lapilli. The Lincomb Tarns Formation is associated with various ash-fall and surge deposits, interbeds of tuff-breccias, bedded tuffs and intercalated sandstones. In the Central Fells it is overlain by the Esk Pike Formation forming the topmost unit of the Scafell caldera succession (Fig. 91). Further to the south-west of Ambleside the formation thickens to 800 m around Tom Heights [NY 326 002], and thins towards Coniston to 250 m, overlying a unit mapped as the Seathwaite Fell Formation (BGS, 2003). Field reappraisal of the Glaramara Member suggested the underlying unit not to correlate with the Seathwaite Fell Formation in the Central Fells (Fig. 91b; Brown, 2001). This raises the question, whether the Lincomb Tarns Formation south of Scafell caldera still correlates with the formation in the Central Fells.

At Foul Scrow (Coniston area)

About 5 km South of Scafell caldera, on Foul Scrow [SD 293 978] (Coniston Fells; Fig. 11), a grey-weathered, eutaxitic, dacitic lapilli-tuff dacitic has been mapped as the Lincomb Tarns Formation (Millward et al., 2000a). It is about 250 m thick and dips about 55° SE with Acadian cleavage. The Lincomb Tarns Formation in the Coniston Fells unconformably overlies the Seathwaite Fell Formation (BGS, 2003) or revised Upper Volcaniclastic Sandstones (Brown, 2001) and is unconformably overlain by the Dent Group, the lowermost unit of the Silurian Windermere Supergroup. Field reappraisal shows abundant, slightly curved <2 cm fiamme (aspect ratios 2:1 to 10:1) and angular, small <1 cm lithic lapilli supported in a tuff matrix at the base of the unit (Fig. 92c). To the top of the formation the fiamme are still abundant and relatively small but lithics become more abundant (Fig. 92d).
Fig. 91. Stratigraphic comparison of the Lincomb Tarns Formation and its surrounding units from Scafell caldera to the Coniston Fells (a) Stratigraphy after Millward et al. (2000a). (b) Revised stratigraphy after Brown (2001): Changed the correlation of the Glaramara Member to underlie the Lingmoor Fell Formation, revised as ‘Side Pike Complex’ (now Langdale caldera fill and Side Pike Ignimbrite); concluding that the mapped Seathwaite Fell Formation in the Coniston area cannot be a correlative to the unit in the Central Fells; and concluding a potential correlation of the ‘Side Pike Complex’ with the Low Water Formation; the Lincomb Tarns Formation is still consistently correlated.
Columnar jointing is prominent of the unit around the Coniston Fells from Long Crag [SD 299 983] over Foul Scrow [SD 293 978] to Torver Beck [SD 273 963] (Millward et al., 2000a). On Foul Scrow the columns have diameters of 10 to 15 cm (Fig. 92b).

**Fig. 92.** Lithofacies of the Lincomb Tarns Formation and its proposed correlative. (a) Massive, eutaxitic lapilli-tuff nicely bedded and foliated at the type locality Allen Crags, Central Fells. (b) Columnar jointing of the massive, eutaxitic lapilli-tuff on Foul Scrow, Coniston Fells. (c) Massive, eutaxitic lapilli-tuff with abundant steep fiamme (indicated by pen), only few lithics in the lower part of the unit, Foul Scrow. (d) Centre of massive, eutaxitic lapilli-tuff with abundant fiamme and more lithics, Foul Scrow.

**Geochemical classification and correlation**

The Lincomb Tarns Formation samples from the type locality at Scafell caldera have Zr/TiO$_2$ values of 0.05 and Nb/Y values of 0.33 to 0.37 (blue squares in Fig. 93). The samples plot close together in the central dacite field. The distal Lincomb Tarns Formation samples from Foul Scrow in the Coniston Fells have Zr/TiO$_2$ values of 0.03 and Nb/Y values of 0.47 to 0.53 (blue circles). The samples also plot in the lower dacite field separated from the Lincomb Tarns Formation samples at Scafell caldera.
The Lincomb Tarns at Scafell caldera samples and distal samples from Foul Scrow (Coniston Fells) are plotted for comparison on Zr/Y vs. Th/Nb and Ti/Y vs. Nb/Y plots (Fig. 94a and b). The Lincomb Tarns at Scafell caldera has Zr/Y values of 5.34 to 5.86 and the samples from Foul Scrow has slightly higher Zr/Y values of 6.01 to 7.19. The sample localities clearly differ in Th/Nb values of 0.77 to 0.85 from Scafell caldera compared to lower Th/Nb values of 0.58 to 0.62 from Foul Scrow. Samples plot even more separated in Fig. 94b. The Scafell caldera samples have Ti/Y values of 63.62 to 73.30 and Nb/Y values of 0.34 to 0.37. The distal samples from the Coniston Fells have higher Ti/Y values of 121.11 to 155.76 and Nb/Y values of 0.47 to 0.53. No ‘immobile’ trace element plot shows the Lincomb Tarns at Scafell caldera and the extra-caldera correlative to overlap or to plot similar to each other.

A correlation approach to compare the evolution of the samples using Ti/Y vs. dimensionless stratigraphic height shows the samples to clearly evolve in different directions (Fig. 94c). If the units are related to each other, they should plot in a trend line, due to Ti behaving as a fractionation indicator, even if the samples do not overlap. But the type locality samples show a decreasing Ti/Y trend whereas the distal Lincomb...
Tarns samples show an increasing Ti/Y trend with stratigraphic height. The previously discussed Langdale caldera fill and designated extra-caldera successions (Chapter 5.5.1) are plotted for comparison. The units show a consistent trend line from the more evolved rhyolitic samples (< Ti/Y; Paddy End Member and Side Pike Ignimbrite) to the less evolved Langdale caldera fill (>Ti/Y; caldera fill and possibly Low Water Formation). The whole-rock geochemical data suggest that the units are not part of the same eruption system. Therefore will be the distal pyroclastic unit on Foul Scrow in the Coniston Fells informally be re-named as Foul Scrow Tuff Member.

**Fig. 94.** Correlation plots for the Lincomb Tarns Formation at Scafell caldera (blue squares) and its designated extra-caldera correlative in the Coniston Fells (blue circles). (a) Zr/Y vs. Th/Nb separates the correlatives from each other. (b) Ti/Y vs. Nb/Y also clearly separates the correlatives from each other. (c) Ti/Y vs. dimensionless stratigraphic height shows the correlated units evolving into different directions away from each other with dimensionless height. The Langdale caldera correlatives are plotted for a comparison showing the units to clearly evolve together into one direction.
**Geochemical comparison to other post-Scafell caldera units**

Based on the previous assumption that the distal pyroclastic unit may not be a correlative of the Lincomb Tarns Formation within the Central Fells, other units of the Borrowdale Volcanic Group are considered for a geochemical comparison and their correlation potential. On the Nb/Y vs. Zr/TiO$_2$ classification (Fig. 93), plots the Foul Scrow Tuff widely overlapping with the newly discovered intrusions Glassy Crag Dacite and Wetherlam Dacite (Chapter 5.3.3) and close to the fill of Langdale caldera (Chapter 5.5.1.1).

![Discriminant plot](image)

**Fig. 95.** Discriminant plot for the Lincomb Tarns Formation, Central Fells (blue squares) and the Foul Scrow Tuff, Coniston Fells (blue circles). (a) Ti/Y vs. Nb/Y: the Lincomb Tarns Formation clearly separates from the other units. The Foul Scrow Tuff plots close to Langdale caldera fill and overlaps with the Glassy Crag and Wetherlam Dacites. (b) Th/Y vs. Th/Nb: The Lincomb Tarns Formation separates but the Foul Scrow Tuff overlaps with the fill of Langdale caldera and the Glassy Crag Dacite.
Ti/Y vs. Nb/Y and Th/Y vs. Th/Nb are used for comparison (Fig. 95a and b). The Lincomb Tarns Formation within Scafell caldera separates from the other units on both ratio:ratio plots. The Foul Scrow Tuff plots widely overlapping with the Langdale caldera fill on the Th/Y vs. Th/Nb plot (Fig. 95b) but also separates from this on the Ti/Y vs. Nb/Y plot. The tuff overlaps with the Wetherlam Dacite on the Ti/Y vs. Nb/Y plot but also separates from this on the Th/Y vs. Th/Nb plot. The Foul Scrow Tuff consistently overlaps with the Glassy Crag Dacite on both plots. No ratio:ratio plot was found to distinguish between these units, suggesting a potential geochemical relationship between the pyroclastic outflow unit in the Coniston Fells and the dacitic intrusion on Wetherlam.

**Lincomb Tarns Formation correlation conclusion**

The Lincomb Tarns Formation within Scafell caldera has been compared to the mapped Lincomb Tarns Formation (re-named Foul Scrow Tuff Member) on Foul Scrow in the Coniston Fells. Based on the geochemical data it is concluded that the dacitic distal ignimbrite is most likely not an equivalent of the Lincomb Tarns Formation (revised stratigraphy in Fig. 96): (1) ‘Immobile’ trace element plots of Zr/Y vs. Th/Nb, Ti/Y vs. Nb/Y and Th/Y vs. Th/Nb show the units to plot consistently separated from each other. (2) The units show a clear separation from each other on a Th/Nb vs. dimensionless stratigraphic height plot. (3) The previously undertaken correlation of the Glaramara Member from Scafell caldera to Side Pike suggested a change of the stratigraphic order below the Lincomb Tarns Formation in the Coniston Fells (Brown, 2001). (4) This is supported by the correlations discussed during this project (i.e. Pavey Ark Member to Duddon Hall Formation; Side Pike Ignimbrite to Paddy End Member) also suggesting a change of the stratigraphical order below the Lincomb Tarns Formation. (5) These revisions cause a massive stratigraphical gap between the Lincomb Tarns Formation in the Central Fells to the unit on Foul Scrow.
Fig. 96. Revised stratigraphy of the Lincomb Tarns Formation and its surrounding units from Scafell caldera to the Coniston Fells. (a) Stratigraphy after Brown (2001). (b) Revised stratigraphy (this study): Added the Paddy End Member and the proposed Low Water Formation to correlate with the Langdale caldera fill (Side Pike Ignimbrite); concluded that the Lincomb Tarns Formation in the Central Fells do not correlate with the mapped unit in the Coniston Fells – re-named the Foul Scrow Tuff Member.
5.6 Applicability of whole-rock geochemistry for the correlation of Palaeozoic ignimbrites

Whole-rock geochemistry is an applicable tool for pyroclastic units of the Ordovician Borrowdale Volcanic Group. The method enabled a distinct discrimination and correlation of several units of the fill of Scafell caldera with previously uncertain, potential extra-caldera correlatives. A schematic overview of the process about which plots were required and which units were separated and correlated is given in Fig. 97.

Determination was started by applying the previously undertaken outline of Scafell caldera into successions: the explosive Scafell caldera-collapse succession, the Scafell caldera-lake succession and the post-Scafell caldera succession (Brown et al., 2007). The discrimination and correlation process for units of each phase was started by the use of a Nb/Y vs. Zr/TiO$_2$ plot (after Winchester & Floyd, 1977), to classify the compositions from basaltic to rhyolitic. The lowermost units of Scafell caldera (Whorneyside Formation and Long Top Tuffs) are already characteristically distinct in the field. Samples of these units from the Coniston Fells area confirmed the field evidence. Newly discovered units in the Coniston Fells area were proven to correlate with equivalents of the Scafell caldera fill (i.e. Stonesty Tuff, Cam Spout Tuff, and Crinkle Tuffs Member). The tuff units within the Long Top Tuffs Member are distinct in their stratigraphic order but determination of the Crinkle Tuffs Member on Wetherlam was complicated by the underlying very similar intrusive Glassy Crag Dacite. Other units of the successions could also be proven to not correlate with previously expected correlatives (i.e. ‘Oxendale Tuff’ and revised Wetherlam Dacite, Lincomb Tarns Formation).

Advantages and limitations of whole-rock geochemistry for correlation of previous studies have been discussed in chapter 3.5. Issues that have been recognized for the correlation of Palaeozoic ignimbrites during this study are summarized below and include:

(1) Whole-rock geochemistry for correlation is most successful when applied in combination with field criteria. Lithology, petrology and stratigraphic order of units can give several criteria for potential equivalents.
(2) If units appear rather similar in the field, a classification of the rocks by a Nb/Y vs. Zr/TiO$_2$ plot (after Winchester & Floyd, 1977) can be undertaken. The classification can already separate previously combined units from each other (i.e. Oxendale Tuff in Great Langdale from the previously mapped Oxendale Tuff on Wetherlam; now Wetherlam Dacite).

(3) XRF whole-rock geochemistry provides some useful trace elements for correlation (Ti, Cr, Ni, Th, Nb, V, Y, Zr), if complimentary ‘immobile’ trace element plots (trace and ratio values) are required. However, other ‘highly immobile’ trace elements (rare earth elements) have to be measured by ICP-MS for correlation.

(4) Despite the variable hydrothermal alteration of the volcanic successions the use of XRF whole-rock analysis proved effective in correlation.

(5) Welding does not constrain the applicability of the method. If anything, the massive, welded pyroclastic units analysed were the most straight forward units, even if highly cleaved.

(6) Less welded tuff units and breccias (Glaramara Member, Low Water Formation) scattered more in ‘immobile’ trace element values because of their higher abundance of accidental lithics and their greater degree of inhomogeneity and could therefore not undoubtedly be correlated to their potential equivalents.

(7) Because of the large number of pyroclastic units in the Borrowdale Volcanic Group a wide variety of methods needs to be tested to explore how to prove or disprove correlations. Exploring different trace element plots has proved effective in finding useable plots and ratios that can be used in correlation.
Fig. 97. Flow diagram showing the procedure for units to be discriminated and correlated using the Nb/Y vs. Zr/TiO$_2$ plot in combination with the major stratigraphic divisions of the Scafell caldera succession. Each succession is subdivided into units classifying as basaltic to andesitic and dacitic to rhyolitic (after Winchester & Floyd, 1977). They can then be further discriminated and correlated using a range of ‘immobile’ trace elements.
6. Conclusions

The study in the Coniston Fells of the English Lake District has revealed seven new conclusions:

(1) This study has demonstrated that whole-rock geochemistry is a useful tool to fingerprint and correlate Palaeozoic ignimbrites and ash-fall layers.

(2) Because of the hydrothermal alteration and regional metamorphism, major elements and mobile trace-elements cannot be used for stratigraphic discrimination in this tectonised Lower Palaeozoic setting.

(3) The primary way of distinguishing and correlating the units is by combining detailed stratigraphic fieldwork with the Nb/Y vs. Zr/TiO₂ diagram. A range of other mostly incompatible trace-element ratios are used to further discriminate units, e.g. Cr vs. Ni diagram, and the ratios Th/Nb, V/Y, Th/Y, Zr/Y. Certain pyroclastic units (e.g. Glaramara Member) have thus far proved less easy to discriminate in this way and require more fieldwork, and more comprehensive data sets.

(4) Several outflow sheets 0.5-10 km from Scafell caldera have been successfully correlated using geochemistry for the first time, this confirming some correlations based on stratigraphic fieldwork (Branney, 1988a; BGS, 1998).

(5) The Side Pike Ignimbrite, inferred to be the outflow from Langdale caldera (Branney, 1988a) has been successfully correlated across the Coniston Fells for the first time.

(6) Three high-level dacitic intrusions have been identified for the first time, primarily by their distinctive ‘immobile’ trace-element chemistry, two on Wetherlam and one in Great Langdale.

(7) The study has led to significant revision of the regional stratigraphy in SW Lake District: A unit designated as ‘Lincomb Tarns Formation’ in the Coniston area is not the Lincomb Tarns Formation as it differs significantly from the Lincomb Tarns Formation of the type areas.

In the following are specific stratigraphic correlations listed in more detail.
6.1 Scafell caldera

A revised general stratigraphy for Scafell caldera, and outflow succession at Wetherlam in the Coniston Fells is presented (Fig. 98).

**Fig. 98.** General vertical sections comparing the Scafell caldera fill succession (after Branney & Kokelaar, 1994) and the revised extra-caldera succession on Wetherlam, Coniston Fells (not to scale).
(1) The Whorneyside ignimbrite and overlying bedded tuff at Scafell caldera are correlated with the Wet Side Edge Member and Whorneyside Formation as mapped on Wetherlam (BGS, 2003). This confirms the previous correlation based on fieldwork alone.

(2) The Long Top Tuffs Member of Scafell caldera, has been correlated with the lower part of the ‘Long Top Tuff Member’ as mapped on Wetherlam (BGS, 2003). The Stonesty, Cam Spout, and Hanging Stone tuffs within the Long Top Tuffs Member on Scafell caldera have been correlated with the Wet Side Edge (all three) and on Wetherlam (the Cam Spout Tuff only). Part of what was mapped as ‘Long Top Tuffs Member’ on Wetherlam (BGS, 2003) comprises the Crinkles Tuffs and two intrusions (see below).

(3) The thickness of the Long Top Tuffs Member on Wet Side Edge is 90 m, and on Wetherlam is 50-90 m, which is considerably less than that previously mapped (250 m, BGS, 1998). This is consistent with the outflow sheet being 0.45 times the thickness of the caldera fill equivalent (200 m) of the member. This constrains the southern boundary of Scafell caldera to lie between Wet Side Edge and Long Top, e.g. around Wrynose Pass (Fig. 11; Branney & Kokelaar 1994).

(4) The geochemistry supports the presence of the Long Top Tuffs Member 11 km southwest of the caldera, at Hesk Fell (Fig. 11) where it has been previously mapped as Airy’s Bridge Formation (BGS, 1991). This is the most distant confirmed outflow sheet from Scafell caldera. The component Stonesty, Cam Spout, and Hanging Stone tuffs have not been recognised in this distal area.

(5) The Crinkle Tuffs are recognised for the first time in the Coniston Fells (at Wet Side Edge and Wetherlam) outside Scafell caldera. The Bad Step Tuff and Rest Gill Tuff, which both lie within the Crinkle Tuff Member within Scafell caldera fill, have not been recognised at Coniston (the Bad Step Tuff is indistinguishable from other Crinkle Tuffs ignimbrites on the basis of trace element values).

(6) The ‘Oxendale Tuff’ within Scafell caldera (Branney & Kokelaar, 1994) is geochemically distinct from the Long Top Tuffs Member with which it was previously thought to be a lava-like facies variant. It is reinterpreted as a dacitic intrusion, re-named the ‘Oxendale Dacite’. Its contact relations warrant re-evaluation. Moreover, it is geochemically distinct from all other pyroclastic units of Scafell caldera.
(7) A new high-level dacitic sill, here named the ‘Wetherlam Dacite’ is identified for the first time on Wetherlam. Parts of it had been mapped as ‘Oxendale Tuff’ and ‘Long Top Tuffs’ on Wetherlam; however, the Wetherlam Dacite is geochemically distinct from both those units. It may reflect a local (younger) volcanic centre in the Coniston area.

(8) Another intrusion, here named the Glassy Crag Dacite has been discovered on the eastern slopes of Wetherlam. Its chemistry is distinct from the Scafell pyroclastic units and other intrusion (Oxendale and Wetherlam dacites).

6.2 Post-Scafell caldera

(1) The Duddon Hall Formation (BGS, 2003) on Wetherlam is a potential correlative of the Seathwaite Fell Formation within Scafell caldera (Branney & Kokelaar 1994), because it has the same stratigraphic position, and contains 4 massive lapilli-tuff breccias, the upper most of which contains fluidal-shaped spatter clasts similar to those in the Pavey Ark Member (massive lapilli-tuff breccia) with the upper part of the Seathwaite Fell Formation of Scafell caldera. The spatter show similar, but not identical basaltic andesite chemistries. Further investigation is warranted.

(2) The Glaramara Member within the Sprinkling Tarns Formation at Glaramara (Central Fells) plots geochemically distinctive on the Nb/Y vs. Zr/TiO₂ plot. The tuff unit below the Side Pike Ignimbrite might be an extra-caldera correlative to the Glaramara Member at Scafell caldera. Because of the limited number of samples and their geochemical variability this could not be proven. A correlation attempt could be further undertaken by ICP-MS.

(3) The geochemistry of the Lincomb Tarns Formation in the Central Fells, forms a close cluster that plots quite distinct from other pyroclastic units in the Central Fells. This cluster plots quite differently than samples from what has been designated as ‘Lincomb Tarns Formation’ in the Coniston Fells (BGS, 2003). Therefore the unit at Coniston has been re-named the ‘Foul Scrow Tuff Member’. The Lincomb Tarns Formation has yet to be recognised in the Coniston area.
6.3 Langdale caldera

The correlation of pyroclastic units from Langdale caldera to the Coniston Fells area, 3 to 7 km south, and for test purposes to the Dunnerdale valley, 14 km south-west of Langdale caldera, revealed several implications for the succession. Implications for the successions are:

(1) The Side Pike Ignimbrite is the rhyolitic extra-caldera equivalent of the fill of Langdale caldera.
(2) The Side Pike Ignimbrite shows a variation from dacite to rhyolite which could represent zonation from early erupted more silicic to later erupted less erupted magma.
(3) The caldera fill is mainly the later erupted dacitic magma type, which is consistent with the later ignimbrite being ponded in the caldera.
(4) The Paddy End Member is the distal extra-caldera equivalent of the Side Pike Ignimbrite in the Coniston Fells and in the far distal Dunnerdale valley. The Paddy End Member has a similar composition to the rhyolitic part of the Side Pike Ignimbrite, but there are insufficient samples to show these compositions extend in the dacitic part or that might be that the dacitic part did not travel that far.
(5) The Low Water Formation might be an extra-caldera equivalent of dacitic part of the Langdale caldera eruption, but the data values are insufficient for an unequivocal correlation.
(6) The revised Foul Scrow Tuff Member in the Coniston Fells is geochemically indistinguishable from the Glassy Crag Dacite intrusion on Wetherlam and is likely to be the same magma batch. Geochemically the Foul Scrow Tuff is also similar to the Langdale caldera fill.
(4) The provisional identification of the Pavey Ark Member in the Coniston Fells has significant implications for whether the Seathwaite Fell Formation forms a continues formation from the Central Fells to the Coniston Fells, which was also suggested by Brown (2001).

An overview how the stratigraphic successions of Scafell and Langdale calderas developed from Millward et al. (2000a), over Brown (2001) to this study is presented in Fig. 99.
Fig. 99. General vertical stratigraphies for the successions of Scafell caldera, Langdale caldera and the Coniston Fells. (a) Stratigraphy after Millward et al. (2000a). (b) Stratigraphy after Brown (2001). (c) Revised stratigraphy (this study): Concluded that the Long Top Tuffs Member is thinner in the Coniston Fells with the Crinkle Tuffs Member also to be present; potential correlation of the uppermost Duddon Hall Formation with the Pavey Ark Member (Seathwaite Fell Formation) in the Central Fells; correlation of the Langdale caldera fill (and Side Pike Ignimbrite) with the Paddy End Member and possibly with the Low Water Formation; concluded that the Lincomb Tarns Formation in the Central Fells do not correlate with the mapped unit in the Coniston Fells – re-named the Foul Scrow Tuff Member.

Key

- Scafell Dacite (ScD)
- Crinkle Tuffs Member (CT)
- Long Top Tuffs Member (LTT)
- Whorneyside Formation (Wny)
- Gliamara Tuff (GMT)
- Pavley Ark Member (Pav)
- Seathwaite Fell Formation (Set)
- Paddy End Member (PER)
- Duddon Hall Formation (DH)
- Langdale caldera fill (LCF)
- previously Side Pike Complex (SPC)
- previously Lincomb Fell Formation (LrF)
- Low Water Formation (LwW)
- Lag Bank Formation (LBT)
- Tam Hows Formation (Thw)
- Esk Pike Formation (Esp)
- Foul Scoot Tuff Member (FST)
- Lincomb Tarns Formation (LTa)

with Volcaniclastic Sandstone (UVS)
7. **Recommended further work**

This research thesis was a case study investigating whether or not whole-rock geochemistry is applicable for the correlation of ancient pyroclastic deposits in the structural complex Borrowdale Volcanic Group. For a more thorough and robust story the following work is recommended hereafter:

1. Determine the Scafell units further SW along the strike to the Devoke Water to Ulpha area and ultimately towards Black Combe in the SW corner of the Lake District to estimate how far beyond the source calderas the pyroclastic density currents travelled.

2. Continue to map the distinct ‘marker units’ of the Airy’s Bridge Formation (Stonesty, Cam Spout, Hanging Stone, Rest Gill tuffs) in the Coniston Fells. This would distinguish the previously mapped Long Top Tuffs Member from potentially overlying Crinkle Tuffs Member.

3. Further explore the Coniston Fells: investigate the newly discovered dacitic intrusions (possible sills/previous Oxendale Tuff) and compare them to the revised Foul Scrow Tuff Member. This could lead to a new Coniston volcanic centre.

4. Sample the Oxendale Tuff in the Seathwaite Fells area to determine its geochemical affinity and whether this is also a dacitic intrusion.

5. Resolve the structural configuration of the pyroclastics to the SW, by recognising and mapping the assumed stratigraphic repetition due to Acadian thrusting (particularly the Scafell and Langdale units and the Lickle and Caw formations).

6. I.e. by a more complete lateral sampling of the Paddy End, Lickle, Caw, and Lag Bank formations in the Dunnerdale Fells area for whole-rock analysis.

7. Explore the extension of Scafell and Langdale calderas to the East to determine and compare their outflow successions (only tentatively mapped).

8. Estimate areas covered, deposit thicknesses, and eruption volumes for Scafell and Langdale calderas.

9. Chemically characterise the exhumed tuff-filled eruption-conduits (vents) in order to see which vent sourced which outflow ignimbrite, and how this changed with time.
Appendix I

I. Fieldwork and sample collection

Fieldwork was undertaken in two periods from August to November 2016 and from April to May 2017. At the beginning of August 2016, two field visits with supervisors Prof Mike Branney and Dr Phil Leat reconnoitred the Scafell caldera fill succession and the possibility of mapping south of the Wrynose Fault on Wet Side Edge and on Wetherlam. One day was spent on sampling of the Lincomb Tarns Formation (6 samples) at the type area [NY 241 093] in the Central Fells to provide geochemistry reference material for correlation with unknown units in the Coniston Fells further south. During independent fieldwork in 2016 a total of 44 days were spent around different localities in the southern Lake District. Mapping onto aerial images was undertaken on Wet Side Edge [NY 272 020], Great Carrs [NY 271 009] to Swirl How [NY 273 006] and on Wetherlam [NY 288 011] to find and identify distinct marker units south of Scafell caldera.

Thirty one samples were taken on Wetherlam through the whole exposed extra-caldera succession. Sampling was pursued on Wet Side Edge to extend and complete missing phreatomagmatic marker units (3 samples). One-day was spent in the Devoke Water area on Hesk Fell [SD 176 946] for a possible extension of the fieldwork area to determine the dimensions of the distal outflow succession of Scafell caldera. One sample was taken to test the use of whole-rock geochemistry for determination of an uncertain rock sample. In the Coniston Fells area 5 samples of the distal Lincomb Tarns Formation were collected.

Extended fieldwork was undertaken in April and May 2017. The focus was complementary sampling of key units for this research project to solidify the data set and to get more reference material for the correlation. One sample of the Paddy End Member was taken in the Dunnerdale Fells and one at the very top of the unit on Wetherlam as well as 6 samples of the overlying Low Water Formation for correlation with the Side Pike Ignimbrite. One day each was spent on sampling of the Pavey Ark Member and the Glaramara Member (6 samples each) at the type areas in the Central Fells to provide geochemistry reference material for correlation. This was complemented with 8 more samples from the Side Pike area.
II. Aerial images of sample localities

Aerial images and tables of sample localities are presented hereafter.

Fig. 100. Overview map with sample areas during this project (red boxes), presented hereafter.
Fig. 101. Aerial image from Glaramara and Coombe Head with sample localities (box 1 in Fig. 100; adapted from Google Earth, 2017).

Fig. 102. Aerial image from Allen Crags with sample localities (box 2 in Fig. 100; adapted from Google Earth, 2017).
Fig. 103. Aerial image from Side Pike and Lingmoor Fell with sample localities (box 3 in Fig. 100; adapted from Google Earth, 2017).

Fig. 104. Aerial image from Little Langdale with sample localities (box 4 in Fig. 100; adapted from Google Earth, 2017).
Fig. 105. Aerial image from Rough Crags with sample localities (box 5 in Fig. 100; adapted from Google Earth, 2017).
Fig. 106. Aerial image from Wetherlam with sample localities (box 6 in Fig. 100; adapted from Google Earth, 2017).
**Fig. 107.** Aerial image from Steel Edge with sample localities (box 7 in Fig. 100; adapted from Google Earth, 2017).

**Fig. 108.** Aerial image from Above Beck Fells with sample localities (box 8 in Fig. 100; adapted from Google Earth, 2017).
**Fig. 109.** Aerial image from Foul Scrow with sample localities (box 9 in Fig. 100; adapted from Google Earth, 2017).

**Fig. 110.** Aerial image from Dunnderdale Fells with sample locality (box 10 in Fig. 100; adapted from Google Earth, 2017).
Fig. 111. Aerial image from Hesk Fell with sample locality (box 11 in Fig. 100; adapted from Google Earth, 2017).

Fig. 112. Aerial image from Pavey Ark with sample localities (box 12 in Fig. 100; adapted from Google Earth, 2017).
### III. List of samples

Table 1. List of samples collected during this project.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Sample</th>
<th>Stratigraphic position</th>
<th>Relative stratigraphic height</th>
<th>Grid reference (British National Grid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lincove Formation</td>
<td>GH-16-01</td>
<td>20 m below top/contact to Wig (Wetherlam)</td>
<td>4</td>
<td>NY 28874 01497</td>
</tr>
<tr>
<td>Whorneyside Formation</td>
<td>GH-16-02</td>
<td>lapilli-tuff, 50 m above base (Wetherlam)</td>
<td>7</td>
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</tr>
<tr>
<td>Whorneyside Formation</td>
<td>GH-16-03</td>
<td>lapilli-tuff, 5 m below top (Wetherlam)</td>
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<td>Whorneyside Formation</td>
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<td>bedded tuff, 3 m below top (Wetherlam)</td>
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<td>NY 28990 01393</td>
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<tr>
<td>Wetherlam Dacite</td>
<td>GH-16-38</td>
<td>150 m from GH-16-37 (Wetherlam)</td>
<td>(14)</td>
<td>NY 28767 01127</td>
</tr>
<tr>
<td>Wetherlam Dacite</td>
<td>GH-16-37</td>
<td>20 m below brecciated top (Wetherlam)</td>
<td>(14)</td>
<td>NY 28829 01042</td>
</tr>
<tr>
<td>Stonesty Tuff</td>
<td>GH-16-34</td>
<td>about 1.0-1.5 m thick (Wet Side Edge)</td>
<td>15</td>
<td>NY 28469 02684</td>
</tr>
<tr>
<td>Long Top Tuffs</td>
<td>GH-16-05</td>
<td>1 m above base (Wetherlam)</td>
<td>16</td>
<td>NY 28996 01398</td>
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<tr>
<td>Long Top Tuffs</td>
<td>GH-16-06</td>
<td>50 m above last loc. (Wetherlam)</td>
<td>17</td>
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</tr>
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<td>Cam Spout Tuff</td>
<td>GH-16-07</td>
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<td>18</td>
<td>NY 28970 01297</td>
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<tr>
<td>Cam Spout Tuff</td>
<td>GH-16-35</td>
<td>about 2 m thick (Wet Side Edge)</td>
<td>18</td>
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<tr>
<td>Long Top Tuffs</td>
<td>GH-16-45</td>
<td>20 m above base (Hesk Fell)</td>
<td>19</td>
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<tr>
<td>Long Top Tuffs</td>
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<td>6 m above contact to Cam Spout (Wetherlam)</td>
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<td>Long Top Tuffs</td>
<td>GH-16-09</td>
<td>40 m below top (Wetherlam)</td>
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<tr>
<td>Glassy Crag Dacite</td>
<td>GH-16-10</td>
<td>10 m above base (Wetherlam)</td>
<td>(22)</td>
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<tr>
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<td>GH-16-11</td>
<td>3 m above base (Wetherlam)</td>
<td>(22)</td>
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<td>Glassy Crag Dacite</td>
<td>GH-16-12</td>
<td>45 m above last loc. (Wetherlam)</td>
<td>(22)</td>
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<td>100 m above base (Wetherlam)</td>
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<td>NY 28552 02596</td>
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<td>Crinkle Tuffs</td>
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<td>15 m below top (Wetherlam)</td>
<td>32</td>
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<tr>
<td>Pavey Ark Member</td>
<td>GH-17-16</td>
<td>(Pavey Ark)</td>
<td>33</td>
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<td>Pavey Ark Member</td>
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<td>(Pavey Ark)</td>
<td>33</td>
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<tr>
<td>Pavey Ark Member</td>
<td>GH-17-18</td>
<td>(Pavey Ark)</td>
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<td>Pavey Ark Member</td>
<td>GH-17-19</td>
<td>(Pavey Ark)</td>
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<td>NY 28512 07927</td>
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<tr>
<td>Pavey Ark Member</td>
<td>GH-17-20</td>
<td>(Pavey Ark)</td>
<td>33</td>
<td>NY 28511 07924</td>
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<tr>
<td>Duddon Hall Formation</td>
<td>GH-16-17</td>
<td>30 m left of main path to Wetherlam</td>
<td>33</td>
<td>NY 29062 00350</td>
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<td>Unit</td>
<td>Sample</td>
<td>Stratigraphic position</td>
<td>Relative stratigraphic height</td>
<td>Grid reference (British National Grid)</td>
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<td>--------------------------</td>
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<td>------------------------------------------------</td>
<td>------------------------------</td>
<td>----------------------------------------</td>
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<tr>
<td>Duddon Hall Formation</td>
<td>GH-16-18</td>
<td>4 m south of GH-16-17</td>
<td>33</td>
<td>NY 29061 00343</td>
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<tr>
<td>Duddon Hall Formation</td>
<td>GH-16-19</td>
<td>left of Henfoot Beck (Steel Edge)</td>
<td>33</td>
<td>NY 29327 00739</td>
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<td>Duddon Hall Formation</td>
<td>GH-16-20</td>
<td>left of Henfoot Beck (Steel Edge)</td>
<td>33</td>
<td>NY 29318 00724</td>
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<td>Duddon Hall Formation</td>
<td>GH-16-21</td>
<td>left of Henfoot Beck (Steel Edge)</td>
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<td>NY 29320 00692</td>
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<td>left of Henfoot Beck (Steel Edge)</td>
<td>33</td>
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<td>Duddon Hall Formation</td>
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<td>left of Henfoot Beck (Steel Edge)</td>
<td>33</td>
<td>NY 29322 00675</td>
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<tr>
<td>Glaramara SPB</td>
<td>GH-17-26</td>
<td>5 m above base (Side Pike)</td>
<td>35</td>
<td>NY 28886 05361</td>
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<tr>
<td>Glaramara SPM</td>
<td>GH-17-36</td>
<td>8 m above base (Side Pike)</td>
<td>36</td>
<td>NY 28888 05358</td>
</tr>
<tr>
<td>Glaramara SPT</td>
<td>GH-17-27</td>
<td>3 m below top (Side Pike)</td>
<td>37</td>
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<tr>
<td>Sprinklin Tarn</td>
<td>GH-17-30</td>
<td>1-2 m below top (Combe Head)</td>
<td>34</td>
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<tr>
<td>Glaramara Tuff</td>
<td>GH-17-31</td>
<td>1-2 m above base (Combe Head)</td>
<td>35</td>
<td>NY 25129 10860</td>
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<tr>
<td>Glaramara Tuff</td>
<td>GH-17-33</td>
<td>1 m below top (Combe Head)</td>
<td>37</td>
<td>NY 25131 10852</td>
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<tr>
<td>Paddy End Member</td>
<td>GH-17-01</td>
<td>2 m from base (Dunnerdale Fells)</td>
<td>38</td>
<td>SD 20858 93217</td>
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<tr>
<td>Paddy End Member</td>
<td>GH-16-24</td>
<td>3 m above base (Steel Edge)</td>
<td>39</td>
<td>NY 29229 00293</td>
</tr>
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<td>Paddy End Member</td>
<td>GH-16-25</td>
<td>30 m above last loc. (Steel Edge)</td>
<td>40</td>
<td>NY 29266 00294</td>
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<td>Paddy End Member</td>
<td>GH-16-26</td>
<td>55 m above last loc. (Steel Edge)</td>
<td>41</td>
<td>NY 29296 00294</td>
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<td>GH-16-27</td>
<td>45 m above last loc. (Steel Edge)</td>
<td>42</td>
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<td>Paddy End Member</td>
<td>GH-17-05</td>
<td>1 m below top (Steel Edge)</td>
<td>44</td>
<td>NY 29369 00146</td>
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<td>Low Water Formation</td>
<td>GH-17-10</td>
<td>0.3 m above base (Above Beck Fell)</td>
<td>47</td>
<td>SD 29356 99728</td>
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<td>Low Water Formation</td>
<td>GH-17-11</td>
<td>60 m above base (Above Beck Fell)</td>
<td>48</td>
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<tr>
<td>Low Water Formation</td>
<td>GH-17-12</td>
<td>2 m below thin SV (Above Beck Fell)</td>
<td>49</td>
<td>SD 29358 99613</td>
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<tr>
<td>Langdale caldera fill</td>
<td>GH-17-28</td>
<td>Lowermost exposure, base not exposed</td>
<td>53</td>
<td>NY 30716 03604</td>
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<tr>
<td>?Crinke Tuffs?</td>
<td>GH-17-29</td>
<td>Lower Lingmoor Fell, base not exposed</td>
<td>54</td>
<td>NY 30117 03465</td>
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<td>Lincomb Tarns Formation</td>
<td>GH-16-39</td>
<td>10 m above base (Allen Crags)</td>
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<td>Lincomb Tarns Formation</td>
<td>GH-16-40</td>
<td>30-40 m above last loc. (Allen Crags)</td>
<td>65</td>
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<td>Lincomb Tarns Formation</td>
<td>GH-16-41</td>
<td>50 m above last loc. (Allen Crags)</td>
<td>66</td>
<td>NY 24170 08392</td>
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<tr>
<td>Lincomb Tarns Formation</td>
<td>GH-16-42</td>
<td>50 m above last loc. (Allen Crags)</td>
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<tr>
<td>Lincomb Tarns Formation</td>
<td>GH-16-43</td>
<td>50 m above last loc. (Allen Crags)</td>
<td>68</td>
<td>NY 24033 08368</td>
</tr>
</tbody>
</table>
### Table 2.
List of previously collected samples used during this project (unpublished data, Branney\(^{(1)}\), Clarke\(^{(2)}\), Mobley\(^{(3)}\); University of Leicester).

<table>
<thead>
<tr>
<th>Unit</th>
<th>Sample</th>
<th>Stratigraphic position</th>
<th>Relative stratigraphic height</th>
<th>Grid reference (British National Grid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lincomb Tarns</td>
<td>GH-16-44</td>
<td>5-10 m below top (Allen Crags)</td>
<td>69</td>
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<td>Foul Scrow Tuff</td>
<td>GH-16-29</td>
<td>5 m above base (Foul Scrow)</td>
<td>64</td>
<td>SD 29231 97856</td>
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<td>Foul Scrow Tuff</td>
<td>GH-16-30</td>
<td>55 m above last loc. (Foul Scrow)</td>
<td>65</td>
<td>SD 29251 97803</td>
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<td>Foul Scrow Tuff</td>
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<td>66</td>
<td>SD 29292 97762</td>
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<tr>
<td>Foul Scrow Tuff</td>
<td>GH-16-32</td>
<td>100 m above last loc. (Foul Scrow)</td>
<td>67</td>
<td>SD 29368 97582</td>
</tr>
<tr>
<td>Foul Scrow Tuff</td>
<td>GH-16-33</td>
<td>25 m below top (Foul Scrow)</td>
<td>68</td>
<td>SD 29376 97623</td>
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<td>Lincomb Tarns</td>
<td>W1And3(3)</td>
<td>15 m below boundary (Wrynose Pass)</td>
<td>1</td>
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<td>Lincomb Tarns</td>
<td>W9And2(3)</td>
<td>Middle of sheet (Wrynose Pass)</td>
<td>2</td>
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<td>Lincomb Tarns</td>
<td>W6And1(3)</td>
<td>Middle of sheet (Wrynose Pass)</td>
<td>3</td>
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<td>lapilli-tuff, base</td>
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<td>unknown</td>
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<td>Whorneyside</td>
<td>29(1)</td>
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<td>6</td>
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<tr>
<td>Whorneyside</td>
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<td>8</td>
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<td>Whorneyside</td>
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<td>Whorneyside</td>
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<td>10</td>
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<td>Oxendale Tuff</td>
<td>BVG-15-18(1)</td>
<td>(The Band)</td>
<td>(14)</td>
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<td>Stonesy Tuff</td>
<td>S8(1)</td>
<td>Stonesy Tuff</td>
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<td>Cam Spout Tuff</td>
<td>BVG-14-04(2)</td>
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<td>Mid</td>
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<td>Long Top Tuffs</td>
<td>BVG-14-07(2)</td>
<td>Mid</td>
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<tr>
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<td>H9(1)</td>
<td>long top/bad step</td>
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</tr>
<tr>
<td>Unit</td>
<td>Sample</td>
<td>Stratigraphic position</td>
<td>Relative stratigraphic height</td>
<td>Grid reference (British National Grid)</td>
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<td>Bad Step Tuff (3m from top)</td>
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<tr>
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<td>BVG-14-12(2)</td>
<td>(Sour Milk Gill)</td>
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<td>Rest Gill Tuff</td>
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<td>(Grave Gill)</td>
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<td>(Grave Gill)</td>
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<td>unknown</td>
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Appendix II

I. Sample preparation

Sixty-four samples were processed for XRF whole-rock analysis. In the field, samples were selected to minimise weathered surfaces, with weathered surfaced being removed by hammer. During sample preparation, some samples were first sliced into 10 cm thick slices using a rock saw. To provide the freshest, least altered sample material, weathering and alteration products were carefully removed using a rock cutting saw, a hammer as well as a hydraulic splitter. A representative amount of each sample was crushed into fine rock chippings using a fly-press with the apparatus cleaned with water and paper towels between each sample crushing. Around 50 ml of each sample was milled for 20-30 min at 275 rpm to a fine powder using four agate crucibles. Around 15 g of each sample was placed in a drying oven at 100°C for a minimum of 24 hours to remove any atmospheric moisture. After cooling in a dry atmosphere, 8g of powder was precisely weighed into a ceramic crucible. Each sample in a ceramic crucible was then reheated to 950°C for 2 hours to remove volatiles from the samples. Each sample was reweighed in the ceramic crucible to measure the differences between pre- and post-ignition masses. Loss on ignition (LOI) was calculated for each whole-rock sample. For major element analysis, fusion beads were made. To lower the melting temperature, the ignited powder was weighed, mixed and molten with Lithium Metaborate flux in a Palladium crucible at a precise ratio of 1:5.

A total of 118 samples were used in this thesis. The LOI of the samples lies in between 0.57 wt. % (GH-16-24) and 12.85 wt. %. (GH-16-18). For analytical precision, seven samples with LOI over 5 wt. % were handled with special-care. The samples were plotted with the other samples and show no particular scatter error.

For trace element analysis powder pellets were made. Depending on each sample about 7 g of sample powder was mixed with 12-16 drops of PVA solution. The mixture was then pressed into ø 32 mm powder pellets at a pressure of 10 tons per square inch.
II. XRF analysis, analytical precision and accuracy

All major and trace element analyses for this research project were analysed at the University of Leicester using a PANalytical Axios Advanced X-ray Fluorescence spectrometer (XRF). The machine runs a 4 Kw. Rhodium (Rh) anode X-ray tube. The totals of the major elements for each sample of the Borrowdale Volcanic Group was reviewed. They range from 97.24 wt. % to 101.46 wt. %. For purposes of plotting, oxides were recalculated to 100 wt. % to account for potential alteration processes. For analytical precision and accuracy major and trace element analysis were controlled by International Reference Materials during each run. Standard deviation values were calculated for major and trace elements. Reference materials analysed as unknowns were NIM-G, MRG-1, BE-N and JR-3. for the most important elements used in this project standard deviations values of these samples are as follows for Nb (± 0.14 - 0.28), for Th (± 0.02 - 0.40), for Zr (± 0.26 - 0.73), for V (± 0.66 - 2.46), for Nd (± 1.02 - 1.79) and for Y (± 0.16 - 0.24). These standard deviations are normally within the size of symbols on the trace element plots and therefore are not presented as error bars. Tables for geochemical data and the reference materials used can be found hereafter.
Table 3. XRF major element data and recommended values for international reference material. Batch IDs indicate individual runs.

<table>
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<tr>
<th>Batch ID</th>
<th>Reference Material</th>
<th>SiO₂ (wt. %)</th>
<th>TiO₂ (wt. %)</th>
<th>Al₂O₃ (wt. %)</th>
<th>Fe₂O₃ (wt. %)</th>
<th>MnO (wt. %)</th>
<th>MgO (wt. %)</th>
<th>CaO (wt. %)</th>
<th>Na₂O (wt. %)</th>
<th>K₂O (wt. %)</th>
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AFUS401  | WS-1               | 51.56        | 2.51         | 13.88        | 13.45        | 0.18        | 5.32        | 8.64        | 2.82         | 1.32        | 0.30         |
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| AFUS418  | WS-1               | 51.87        | 2.52         | 14.02        | 13.56        | 0.18        | 5.36        | 8.77        | 2.85         | 1.33        | 0.30         |
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| STDv     |                   | 0.29         | 0.02         | 0.11         | 0.11         | 0.00        | 0.05        | 0.08        | 0.03         | 0.01        | 0.00         |
| % STDv   |                   | 0.57         | 0.86         | 0.78         | 0.79         | 0.97        | 0.88        | 0.90        | 1.11         | 0.98        | 1.53         |
Table 3. Continued.

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<th>Ba (ppm)</th>
<th>La (ppm)</th>
<th>Ce (ppm)</th>
<th>Nd (ppm)</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
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% StDv    1.65  -55.85  2.67  0.66  1.37  1.67  0.13  1.45  0.11  0.09  0.25  0.70
Devi. from rec. value [%] -8.89  148.34  3.57  -4.49  -6.86  -8.96  -0.30  -27.42  -1.29  3.84  -5.87  -1.78
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<th>Ba (ppm)</th>
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9. References


Pearce, J.A. 1983. Role of the sub-continental lithosphere in magma genesis at active continental margins: Destructive plate margin magmas. 230-249.


