A Buried Caldera-Collapse Topography, Scafell Caldera, Former Side Pike Complex, Borrowdale Volcanic Group

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Abstract

Multiple lines of evidence support the interpretation of the former Side Pike Complex being situated on the margin of the Scafell Caldera. A pronounced caldera-collapse topography, with initially steeply-dipping margins, defines the boundary between intra-caldera ignimbrites and infilling sedimentary successions. These latter start with a pre-inundation subaerial sequence of talus slope breccias and pyroclastics mainly from low-volume, low-density, pyroclastic density currents. Caldera-lake sedimentation, correlated with the Seathwaite Fell Formation, buried most of the caldera-collapse topography and includes a distinctive zone of pumice breccia from subaqueous explosive eruptions. Further evidence for a caldera-margin setting comes from the massively reduced Scafell ignimbrite sequence indicating the region was a topographic high whilst the Scafell Caldera was forming. An irregular topography also characterizes the subsequent Langdale Caldera demonstrated by abrupt thickness changes in units associated with this highly explosive event.

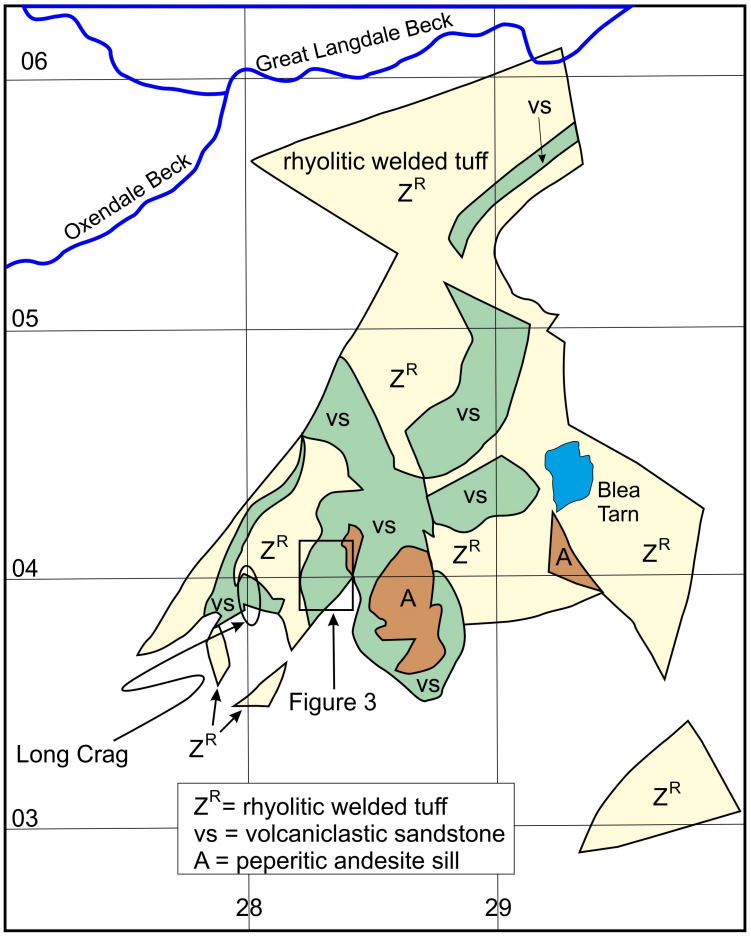


Figure 1 The former Side Pike Complex as mapped by the British Geological Survey (1996) showing rhyolitic welded lapilli-tuff and volcaniclastic sandstones. Unornamented areas are Borrowdale Volcanic Group rocks assigned to lithostratigraphic units. NY grid square reference.

Introduction

Branney (1988) was the first researcher to apply modern volcanological analysis to the region between Side Pike and Pike o' Blisco but having established a well-defined stratigraphy in the Scafell Caldera he was not able to extend correlations into this area. Thus the concept of the Side Pike Complex (Figure 1) came into being; an area of exotic stratigraphy not exposed anywhere else in the Borrowdale Volcanic Group. Correlations could be made between kilometric-scale blocks, regarded as parts of a megabreccia, but not to any units beyond the complex. A sector collapse origin was presented to explain the inability to tie the stratigraphy of the complex to regional sequences though it was not possible to rule out the correlation problem stemming from the difficulties associated with matching intra- and extra-caldera units. Branney and Kokelaar (1994) reinforced the megabreccia model by highlighting the perceived intensity of soft-sedimentary deformation in the Side Pike Complex invoking collisions between mega blocks as a cause of the disruption. In a series of accounts they emphasised their model using descriptors such as "geologically chaotic", "rocks far more chaotic and disturbed than elsewhere", "their complexity has prevented the application of conventional lithostratigraphy", and "intense internal soft-state deformation". A major breakthrough in our understanding came about when Brown (2001) extended detailed logging of the latter part of the Scafell Caldera infill sedimentary sequence into the area. In particular, one couplet of Glaramara Tuff, and the informal Black Wall unit, provided a secure reference point. From here it was obvious that this couplet of units, plus the underlying 40 m of turbidites, was all that represented the Seathwaite Fell Formation which is the up to 500 m thick sedimentary

infill to the Scafell Caldera on the nearby Crinkle Crags. Even more dramatically, the 1000 m of Scafell intracaldera ignimbrites was reduced to around 20 m of flow-banded rhyolite. It is evident from these observations that the area in question occupies a position on the margins of the Scafell Caldera but bounding structures were not identified. Interpretations of depositional settings were not definitive of a caldera-margin setting referring to a shallow basin on a palaeo-topographic high. The comments about the nature of the caldera margin include Kokelaar et al. (2007) who stated that "caldera margins were broad and complex, with inward-tilted strata and extensive gentle slopes, rather than steeply-walled". In contrast we report here direct observations of steeply-dipping caldera margins which define a palaeo-topography created by caldera collapse processes.

Other major ramifications of Brown's work included huge changes to stratigraphic correlations throughout the southern crop of the Borrowdale volcanics. A significant conclusion by Brown (2001) was that the use of the term Side Pike Complex can no longer be regarded as being valid because stratigraphy can be correlated beyond its boundaries. Also significant was his conclusion that a series of major caldera -forming explosive eruptions post-dated the Scafell Caldera in this area.

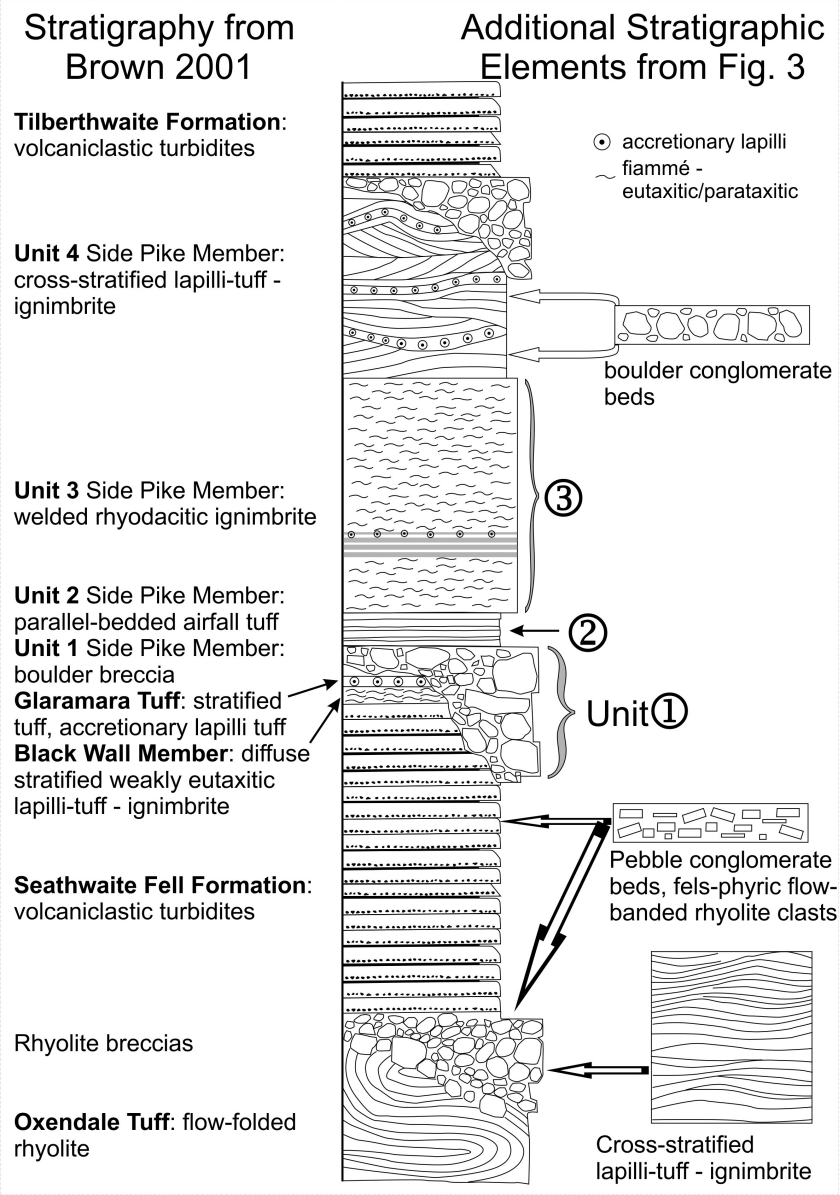


Figure 2 Simplified stratigraphy of the former Side Pike Complex according to Brown (2001). On the right-hand side are additional elements from the mapping in Figure 3.

We report here new observations from a small but crucial area within the former Side Pike Complex which support a radically different origin for the relationships between units proposed in some earlier publications.

Previously Documented Stratigraphy, Scafell Caldera

On Long Crag (Figure 1) Brown (2001) logged a reference section from the drastically reduced Oxendale Tuff Member of the Airey's Bridge Formation (Scafell Caldera ignimbrites) through the Seathwaite Fell Formation to the top of the Side Pike Member of the Lingmoor Fell Formation. The Side Pike Member was originally defined as the Side Pike Ignimbrite by Branney (1988) which is well exposed on Side Pike. Figure 2 is a simplified representation of the stratigraphy on Long Crag. The Oxendale Tuff is represented by around 20 m of flow-folded and brecciated rhyolite overlain by 40 m of turbiditic sandstones. These latter sedimentary rocks are clearly part of the Seathwaite Fell Formation because they pass upwards into the Black Wall Member and Glaramara Tuff just before an erosional contact with the Side Pike Member. In the Central Fells the Seathwaite Fell Formation can be readily subdivided into several members (Kneller & McConnell 1993) but there are no distinctive sub-units evident at Long Crag. It is therefore uncertain whether one member, or the whole depositional history of the formation, is represented. Only a short strike length of Glaramara Tuff is present because it is incised by canyon-like gullies approximately 10 m deep and tens of metres wide. Infilling this erosional contact is a boulder

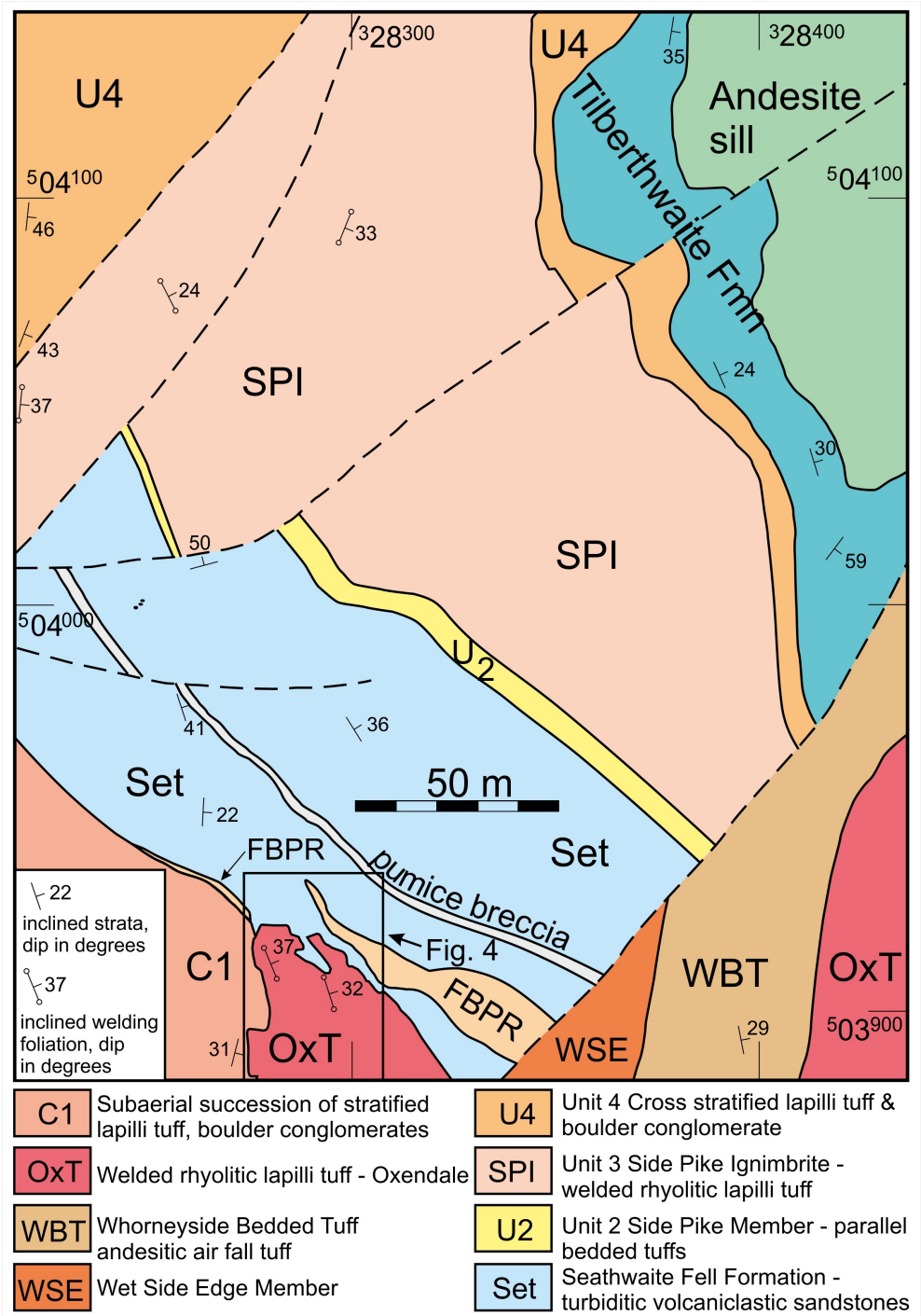


Figure 3 Geological map illustrating the relationships between deposits within the Scafell Caldera and those of the Langdale Caldera. FBPR = a pebble-grade sedimentary breccia with clasts almost exclusively comprised of white-weathering flow-banded feldspar-micro-phyric rhyolite. Approximate location of Figure 4 is indicated

conglomerate up to 20 m thick with many of the underlying formations represented in the clast population. Brown (2001) refers to this intraformational conglomerate as Unit 1 of his informally defined Side Pike Member. Unit 2 is around 5 m of parallel bedded airfall tuff partly showing evidence of fluvial reworking. Unit 3 forms the bulk of this member; it is a 30 m welded rhyodacitic ignimbrite (the Side Pike Ignimbrite of Branney 1988). Internal subdivisions within Unit 3 have been documented by Brown (2001) and these have proved useful during our mapping to identify where isolated exposures are in the sequence. Typically the basal 8 m is massive to partly silicified tuff overlain by 3.5 m of readily recognizable thinly, to thickly, stratified lapilli tuff with low-angle cross stratification. These are followed by 1.5 m of thinly-stratified partly-silicified tuffs and lapilli tuffs with minor accretionary lapilli horizons. Above the zone of stratified tuffs 5 m of massive eutaxitic welded lapilli tuff has a 1 m massive tuff interface with 20 m of massive parataxitic lapilli-tuff. Fiamme increase in size within the 5 m thick subdivision and in the thickest unit some reach 20 cm in length. In the uppermost 9 m of the ignimbrite fiamme markedly decrease in aspect ratio at the same time as large (to 20 cm) white-weathering felsite lithics make an appearance. A thin (<50 cm) accretionary lapilli tuff caps Unit 3. Brown (2001) records an unconformable relationship between Units 3 & 4 though there is no difference in attitudes between the two subdivisions. Unit 4 is very variable in thickness varying from zero to at least 40 m. Part of this variation is caused by erosion before deposition of the overlying Tilberthwaite Formation but to understand the upper end of the thickness range would require mapping of a much larger area. Complexity within Unit 4 is indicated by several boulder conglomerate

horizons which may have been formed during reactivation of volcanotectonic faults.

Above the upper erosive contact of the Side Pike Member a volcanogenic turbidite sequence marks a return to lacustrine sedimentation, not in the Scafell Caldera but in the younger Langdale Caldera. This unit is similar to the Seathwaite Fell Formation and in British Geological Survey publications (BGS 1996 & Millward et al. 2000) it was erroneously assigned to this formation. A major outcome of Brown's work (2001) was a clear demonstration that this is a second volcaniclastic turbiditic unit (informally termed the Upper Volcaniclastic Sandstone) as it overlies the Side Pike Member of the Lingmoor Fell Formation which in turn overlies the Seathwaite Fell Formation. Millward (2004) accepted the correlations proposed by Brown (2001) and formalized the lithostratigraphy of the upper turbidites by naming them the Tilberthwaite Formation. Currently no BGS publication directly shows the extent of the Tilberthwaite Formation. It probably equates to the mapped distribution of the Ambleside Basin succession on a small-scale map in Stone et al. (2010, Figure 17) though this account still refers to the Side Pike Complex in its original formulation leaving undocumented the full revision of stratigraphy required by Brown's discoveries.

Scafell Caldera Margin

The area mapped in Figure 3 provides the context for the following account of the relationships observed between the Scafell Caldera ignimbrite and later deposits. Essentially the mapped area is a faulted homoclinal succession striking SSE/NNW and dipping around 30 degrees to the ENE. Given the emphasis in earlier publications (e.g. Branney & Kokelaar, 1994) about the intensity of deformation and disruption in the former Side Pike Complex such a simple map pattern might be surprising but it does support the case for a simpler interpretation of the area. On Figure 3 the oldest rocks occupy a triangular area in the southeast corner. These lowermost stratigraphic units are readily recognizable as the two classic subdivisions of the Whorneyside Formation; the Wet Side Edge Member is an andesitic lapilli-tuff with a moderately developed welding fabric demonstrating its ignimbrite origins and overlying this is the Whorneyside Bedded Tuff which is a parallel-bedded andesitic air-fall tuff. The bedded andesitic tuff is overlain by a rheomorphic rhyolitic lapilli-tuff that we correlate with the Oxendale Tuff Member of the Airey's Bridge Formation. The contact between these two units is planar and parallel to the bedding in the bedded tuff. Erosion is not evident along this contact.

In the southwest corner of Figure 3 a small area of rhyolitic welded ignimbrite displays key relationships with a bedded sequence. This ignimbrite is at the same level as, and overlain by, turbidites which in turn are overlain by the Side Pike Member. We therefore correlate this small inlier of ignimbrite with the Oxendale Tuff because the turbidites are equivalent to the Seathwaite Fell Formation on Long Crag and share a distinctive pumice horizon. Immediately south of Figure 3 there is no exposure of the Oxendale Tuff but its map extent is limited to the south by truncation on a NE-SW fault. The oldest sedimentary deposits (C1 on Figure 3) are a mixture of boulder conglomerates and weakly-stratified rhyolitic lapilli-tuffs with complex lateral relationships. Clasts in the conglomerate are predominantly welded ignimbrite displaying degrees of welding comparable to the adjacent Oxendale Tuff. Welding foliation attitudes within the clasts are variable showing that they are not part of a coherent body of ignimbrite. The remainder of the clasts are also rhyolitic lapilli-tuff either unwelded or with a fabric that is largely obscured by alteration and/or weathering. Boulders are sub-equant (e.g. 50x60 cm) or moderately tabular (e.g. 35x10, 40x20 cm) and are sub-rounded. No bedding structure is evident and matrix/groundmass accounts for less than 10% of these deposits. These characteristics suggest derivation from talus slopes with minor debris flow style transport. The stratified and cross-stratified lapilli-tuff deposits are typical of ignimbrite deposits from low-density pyroclastic currents. There is a highly irregular distribution of the boulder conglomerates and they are very variable in thickness seemingly creating an irregular substrate for both the subsequent stratified-ignimbrite and turbidite deposits. As an example just to the north of Figure 4 over 10 m on the ground there is an extra 5.8 m of the turbidite sequence probably caused by the turbidites onlapping a palaeo-high. Sub-aerial conditions are inferred for the pre-turbidite deposits.

The turbidites belonging to the Seathwaite Fell Formation are approximately 70 m thick and mark a change to subaqueous sedimentation. Ta and Tb Bouma subdivisions are common but Tc horizons are rare as are dewatering structures such as elutriation channels and convolute lamination though one example is 3 m across the bedding and 4 m tall with a fluidized core. Soft-sedimentary deformation structures are present but no more so than typical sections of the Seathwaite Fell Formation and possibly less than many areas e.g. Seathwaite Fell. As is the case in the main outcrop soft-sedimentary deformation is enhanced next to some faults which

are, therefore, likely to be syn-depositional in their origin. Pre-lithification structures include extensional and contractional faults. A prominent breccia dyke around 1 m thick, and 14 m in vertical extent, is dominated by clasts of ignimbrite with a very strong welding foliation; a rock type not exposed in the pre-turbidite stratigraphy. Two laterally discontinuous pebble-grade sedimentary breccias (FBPR on Figure 3) provide an interruption to the dominance of the turbidites; the clasts are almost exclusively white-weathering, angular flow-banded rhyolite which contain red feldspar micro-phenocrysts typically one millimetre in length. In the upper bed large boulders of ignimbrite (e.g. 40x26 cm and 55x48 cm), matching the Oxendale Tuff, form less than one percent of the clast population. The lower bed forms the base of the Seathwaite Fell Formation to the north of the palaeo-high previously described but does not cap the inferred highest point. The lack of internal structures for both these beds implies debris flow emplacement. Another variant within the Seathwaite Fell Formation is an 11 m thick zone characterized by white-weathering beds approximately one third of the way up the unit. Towards the top of this zone a 70 cm thick bed contains large (e.g. 71x16, 57x16, 46x12, 22x14 cm) blocks of pumice with a eutaxitic foliation. These pumice blocks can be explained by a rhyolitic eruption into a body of water with eventual sinking of waterlogged pumice rafts (Allen & Stewart, 2003). Unit 1 of the Side Pike Member is missing in the area of Figure 3 and the Seathwaite Fell Formation is overlain by Unit 2.

Figure 4 documents the intricate nature of the contact between the Oxendale Tuff and the stratified units. Overall there is a height difference of 20 m between the upper and lower points on the contact measured perpendicular to the bedding in the sedimentary rocks. Several bedding readings in the area covered by Figure 4 have been chosen to reflect the overall attitude of the layering but close to the contact there are localized examples of steeper dips probably a product of contact strain during the Acadian Orogeny. There are many sections of the contact that are sub-perpendicular to the bedding such that layers abut the contact sharply without any deflection from the general attitude and without any evidence of deformation either tectonic or soft-state. Many such examples are found close to the GPS reference point on Figure 4 and in the fissured ignimbrite in the 6 m to the south of this marker. Some minor soft-sedimentary deformation is present along the contact in a limited number of localities but beds above and below these examples are parallel showing that these disturbed zones are strata-bound. The steeply-dipping contacts, usually along approximately planar surfaces, have very variable orientations as annotated on Figure 4. Attitudes of these contacts show a wide range of orientations e.g. 335/85, 175/85, 245/90, 080/55, and 330/70 (dip two figures and strike three measured clockwise from the dip). Fissures in the ignimbrite, infilled with sedimentary material, are prominent close to the contact and, though the network of fissures may have complex geometry, the welding fabrics in the ignimbrite are constant in attitude. This arrangement shows that the fractures have not linked to produce isolated blocks and that no rotation/transport has taken place. Where the Oxendale Tuff – Seathwaite Fell Formation contact is gently dipping (upper right, Figure 4) several metres of boulder conglomerate overlie the coherent ignimbrite. Here it is difficult to precisely locate the boundary because there is very little groundmass/matrix in the conglomerate and there is a gradational change from intact ignimbrite to boulder conglomerate. A stack like feature of welded ignimbrite 110 cm tall by 60 cm wide at its base tapers upwards to a point. It is surrounded by undisturbed bedded sedimentary rock and indicates preservation of intricate topography during inundation by a caldera lake.

None of the diagnostic structures associated with volcanotectonic faults (Branney & Kokelaar, 1994) has been observed on the boundary between the Oxendale Tuff and the Seathwaite Fell Formation together with its underlying pre-innundation succession (Figure 4). The attitude of the eutaxitic foliation in the Oxendale Tuff shows no signs of the abrupt deflections that would be expected close to volcanotectonic faults. We therefore interpret the steeply-dipping fractures that bound the Oxendale Tuff as having been formed by the breakup of unstable fault scarps and subsequent degradation of these slopes. Because of their highly fractured state syn-eruptive fault zones when exposed on fault scarps probably undergo modification before stabilization. It is, however, likely that slope retreat was not on a large-scale and the contact between the Oxendale Tuff and younger deposits is near the site of a Scafell Caldera volcanotectonic fault. An alternative, though less likely, explanation is that, because the welding fabric in the Oxendale Tuff is not strong, and this unit formed early in the evolution of the Scafell Caldera, volcanotectonic faults may have been simple fractures not involving any ductile deformation or broad damage zones. If this latter scenario held then some of the steeply-dipping

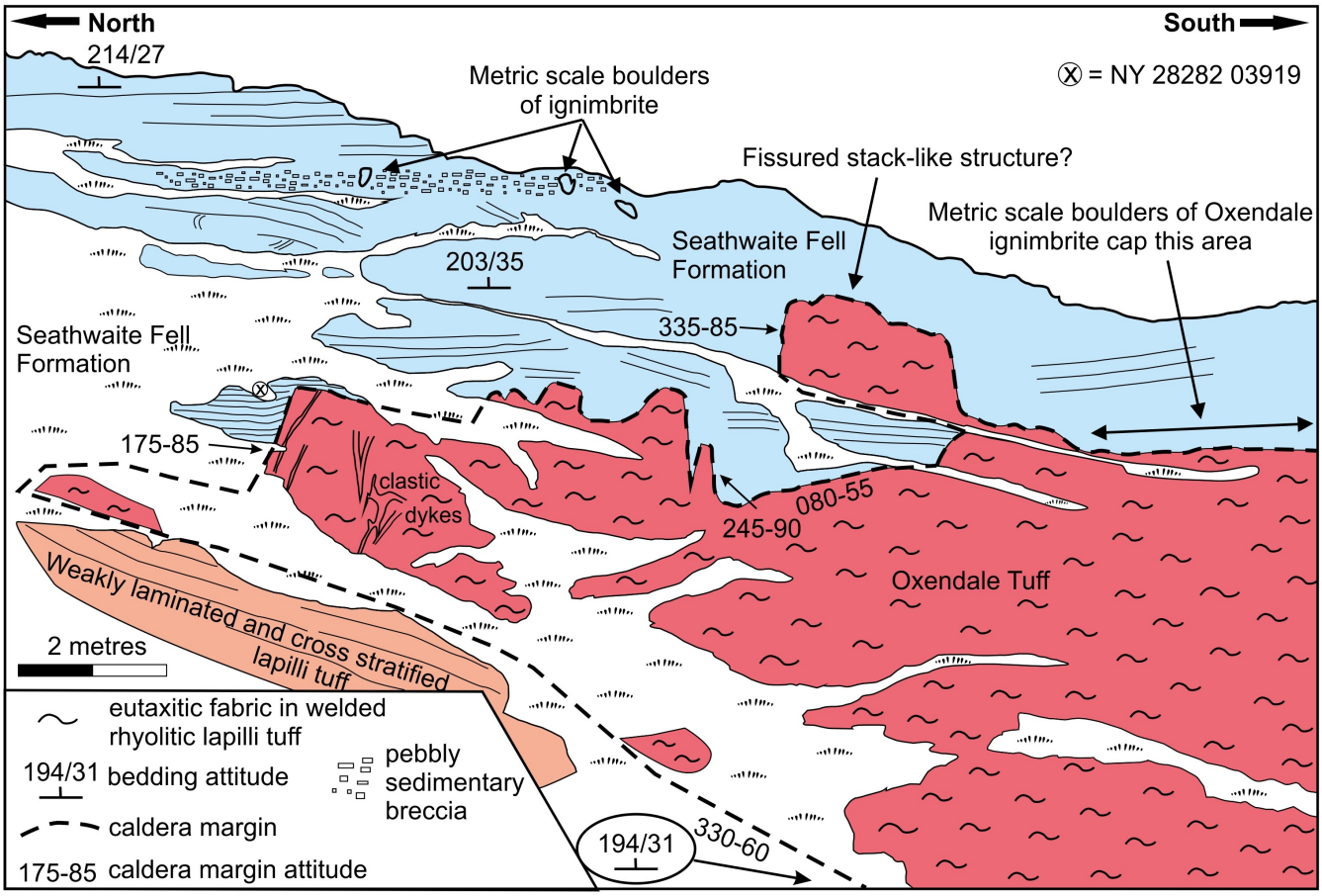


Figure 4 Tracing of a photograph taken looking east illustrating the shape of the margin to the Oxendale ignimbrite and its relationship with the surrounding sedimentary succession. The sketch covers the southern end of Figure 12 of Branney & Kokelaar (1994). Attitudes are quoted using the British right-hand-rule — two figures for the dip and three figures for the strike which is clockwise from the dip direction. A GPS reference point is shown to specify location.

boundaries to the Oxendale block could be primary volcanotectonic faults.

Figure 4 is a section at the southern end of a locality used by Branney & Kokelaar (1994, Figure 12) to demonstrate extreme complexity in the Side Pike Complex. Our observations counter this interpretation. Soft-state deformation in the Seathwaite Fell Formation is possibly less intense than in many other outcrop areas of this formation. Also the sub-aerial units below the turbidites show no signs of this style of deformation which indicates that penecontemporaneous deformation of the turbidites was controlled by high pore-fluid pressures in these sediments. Additionally the relatively simple map pattern displayed on Figure 3 would not be expected in a geological chaos. Complexity in the former Side Pike Complex may well be a combination of its caldera margin position in the Scafell Caldera coupled with overprinting structures formed during the evolution of the Langdale Caldera. Outside the area of Figure 3 ductile deflections of welding fabrics in the Side Pike Ignimbrite probably mark the position of volcanotectonic faults that were active as the Langdale Caldera evolved.

Conclusions

By finding correlatives of the Scafell Caldera succession in the area under consideration Brown (2001) was able to call for the use of the term Side Pike Complex to be discontinued. We have projected the stratigraphy identified by Brown (2001), with minor additions, into an area that contains critical relationships between the main explosive phase of the Scafell Caldera and its eventual burial by lake sediments. Both Branney (1988) and Brown (2001) made a case for the area we mapped being in a caldera margin position but for different reasons; the latter convincingly documented massively reduced intra-caldera pyroclastics and caldera-lake sedimentary deposits, relationships

expected on the edge of a caldera bounded by volcano -tectonic faults. Direct observation of a fracture-bounded ignimbrite body overlapped by sedimentary deposits contributes to the case for this being the location of a caldera margin. Previous interpretations of chaotic relationships between megablocks and extreme deformation associated with block-block collisions are not supported.

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