Sour Milk Gill

[NY 235 122]

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Introduction

The Sour Milk Gill GCR site contains a superb record of volcanic and sedimentary processes that occurred during a major explosive eruption in a volcanic lake that was proximal to the vent (Figure 4.16). The rocks were produced by the first major explosive eruption associated with the Scafell Caldera ((Figure 4.12); Branney and Kokelaar, 1994a). They belong to the Whorney-side Formation, which comprises an ignimbrite overlain by a bedded phreatomagmatic tuff (Figure 4.12). Substantially more than 100 km^3 of magma were erupted, burying the western Lake District beneath more than 30 m of fallout ash (Branney, 1991). This ash-fall layer is believed to record the largest magnitude phreatoplinian eruption yet documented (Branney, 1991). Facies associations, and the size of impacted lithic clasts in the tuff indicate that the volcanic vent lay just to the NW of Sour Milk Gill, where subsidence had created a large volcanic lake, possibly connected to the sea. Though the recent interpretation of the bedded tuff succession in the Whorneyside Formation is the main reason for the selection of this GCR site, the overlying Airy's Bridge Formation also contains important features that are additional to those seen in the Ray Crag and Crinkle Crags and Rosthwaite Fell GCR sites.

Oliver (1961) did not distinguish the succession at Sour Milk Gill from the dominantly andesitic lower part of the Borrowdale Volcanic Group (BVG). The rocks at Sour Milk Gill were described in detail first by Suthren (1977) and Suthren and Fumes (1980), who recognized the lacustrine character. Branney (1988b, 1991) presented evidence that these rocks are the proximal facies of the Whorneyside phreatoplinian eruption. Davis (1989) interpreted the overlying Airy's Bridge Formation and a further account of the area is by Suthren and Davis (1990). The following details are derived mainly from the most comprehensive account by Kokelaar and Branney (1999). Arthropod tracks have been recorded from a loose block of bedded volcaniclastic rocks from this site (Johnson *et al.,* 1994).

Description

Strata at Sour Milk Gill dip 50° S, towards the centre of the Scafell Caldera. On the north side of Sour Milk Gill a stack of andesite sills, more than 300 m thick, dips beneath the 160 m-thick stratified upper part of the Whorneyside Formation (Figure 4.12), (Figure 4.17). The sills were intruded into wet ash and sediment during, and shortly after, the Whorneyside eruption, and their upper contacts locally show discordant, invasive, apophyses of peperite (see the Pets Quarry GCR site report for discussion of peperite). The Whorneyside ignimbrite crops out farther NE, where it underlies the sills. To the SE of Sour Milk Gill, for example around Seathwaite Farm, the Whorneyside phreatomagmatic tuff is subaerial. Its pyroclastic origin is indicated by abundant accretionary lapilli, ballistic lithic blocks with impact structures, and draping of topography. The parallel thin stratification records unsteady ash-shower fallout from a vast umbrella cloud (Branney, 1991). Rainfall during the eruption produced surface water that eroded minor rills into the subaerial ash. The 'V'-shaped fluvial rills draped by succeeding fallout ash layers [NY 2422 1222] are probably the best examples seen in Britain.

At Sour Milk Gill the ash fell into shallow, standing water. Volcaniclastic lithofacies have been divided into six categories (Kokelaar and Branney, 1999), listed here in decreasing order of abundance:

1. Parallel-stratified very fine to very coarse tuff, interpreted as lithified fallout ash, exhibits rare impact structures, and can be subdivided into water-settled and subaerial varieties, based on the lamination and grading patterns, and on occurrences of loading structures and polygonal desiccation cracks.
2. Massive to laminated, fine-grained to pebbly sandstone, in places with matrix-supported intraclasts and/or dewatering structures, is thought to have been deposited by shallow water turbidity currents.
3. Cross-laminated, scoured and rippled siltstone and sandstone, is interpreted to represent wave and current reworking of fallout ash in shallow water.

4. Lenticular beds, up to 4 m thick, of very poorly sorted, block-rich sandstone and breccia are interpreted as debris-flow deposits. Most blocks are of andesite and are probably derived from proximal ballistic fallout and/or high-level intrusions that emerged onto the lake floor. One bed contains numerous blocks of subaerial tuff containing accretionary lapilli, and must have been derived from the lake shore.
5. Rare cross-stratified, medium- to very coarse-grained sandstone and gravel conglomerate is thought to have been deposited from dilute stream-flow currents that caused migration of sediment sheets and dunes.
6. Poorly sorted, parallel-stratified medium- to very coarse-grained sandstone and gravel conglomerate, with some low-angle truncations, is interpreted to represent deposition from laminar hyperconcentrated currents. A unit of massive, andesitic lapilli-tuff, 11 m thick, is considered to be a non-welded ignimbrite, and is overlain by a probable co-ignimbrite fallout tuff with accretionary lapilli.

The succession passes up into the Long Top Tuffs, which here comprise interbedded and mixed andesitic and silicic tuffs, and volcaniclastic sedimentary rocks. Some beds grade from andesitic to silicic, and contemporaneous fallout from two sources is indicated. Several of the silicic beds contain chlorite- and epidote-rich fiamme in a laminated or massive, fine-grained silicic matrix. These fiamme probably represent pumice lapilli that collapsed during diagenesis and burial (Davis, 1989; Branney and Sparks, 1990). Though this mechanism of fiamme formation is best seen in the Pets Quarry GCR site, Sour Milk Gill is also a good place to examine such features, and to compare them with fiamme formed by welding of hot tuff, as seen in silicic eutaxitic ignimbrites of the Crinkle Tuffs exposed higher in the section.

In the Airy's Bridge Formation, the Cam Spout Tuff is well exposed on the south side of Sour Milk Gill [NY 228 121]. It is a spectacular cross-bedded tuff, 6 m thick, with abundant large accretionary lapilli and lapilli-impact structures and has been traced around the Scafell Caldera 'to Cam Spout in Eskdale and southwards to Wrynose (Branney and Kokelaar, 1994a). The turquoise, laminated Rest Gill Tuff is the lowest recognizable unit of the Crinkle Tuffs at Sour Milk Gill, and probably represents a particularly wet, large-scale phreatomagmatic eruption. Overlying the Rest Gill Tuff is a thick silicic ignimbrite with superb columnar polygonal cooling joints (at Hanging Stone; 228 120). Thin-sections show intense welding of the shards, with perlitic cracks and pseudomorphs after spherulites. Ignimbrites of the Crinkle Tuffs reach 500 m thick in this part of the Scafell Caldera.

Graphite, which gave rise to the Keswick pencil industry, can be found on disused spoil tips 500 m north of Sour Milk Gill [NY 231 128]. The mineral occurs in irregular pipe-like bodies within altered basic intrusions into the Whorneyside Formation (Firman, 1978a). The origin of the graphite is enigmatic, and may be related to underlying Skiddaw Group rocks (see the *Mineralization of Great Britain* GCR volume).

Interpretation

Rocks within the Whorneyside Formation in the Sour Milk Gill GCR site record the evolution of a dynamic, near-vent lake environment during a major explosive eruption accompanied by rapid differential volcanic subsidence. Beautifully preserved sedimentary structures record rapid ash fallout into shallow water, with sediment reworking by wave and current action, and the deposition of block- and ash-rich slurries. The spectacular soft-state deformation, Neptunian dykes, and dewatering structures resulted from rapid burial, shaking and tilting of watery lake sediment during the eruption. The accumulating ash and sediment at Sour Milk Gill were intruded by coeval andesitic magma, forming shallow, peperitic intrusions. Blocks, ash, sediment, and peperitic sills are all broadly of the same andesitic composition and may be co-magmatic. Primary volcanic aggradation by fallout from pyroclastic flows and from reworked equivalents of these produced about 69% of the succession, whereas secondary input from a variety of ash- and breccia-laden flows contributed the remaining 31% (Kokelaar and Branney, 1999). Sedimentation was demonstrably rapid, despite the deceptive fine grain-size and intricate stratification, because the 160 m-thick succession is a time correlative of *c.* 30 m of subaerial fallout ash to the south and was deposited during a single eruption, possibly lasting a few months or years. However, despite the rapid aggradation, water depth generally seems to have kept up with aggradation, because throughout the succession very small wave ripples indicate very shallow water and periodic emergence is indicated by polygonal mud cracks. The SE margin of the subsiding proximal basin was probably controlled by an active fault through Seathwaite (Kokelaar and Branney, 1999).

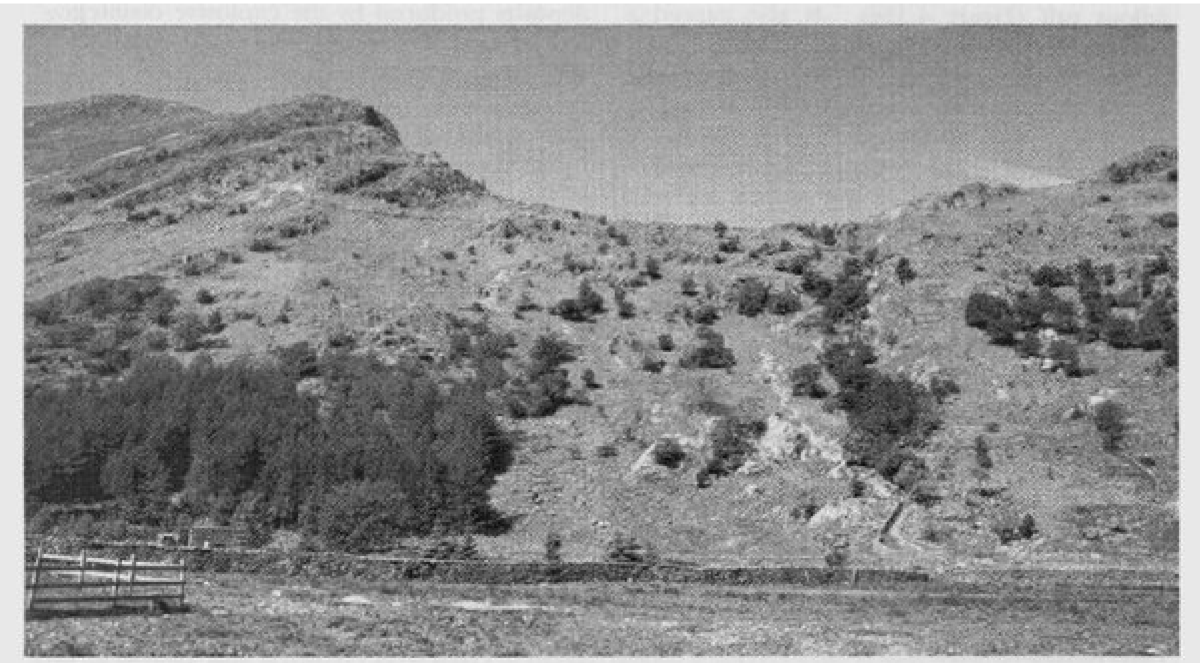
Elsewhere in the Lake District, the Whom-eyside phreatomagmatic tuff is widely overlain by the Airy's Bridge Formation with an angular unconformity (see the Ray Crag and Crinkle Crags GCR site report) but at Sour Milk Gill the contact is conformable and gradational. Andesitic and silicic layers are interstratified, showing that the Airy's Bridge silicic eruption started before the andesitic Whorneyside eruption had ceased. Therefore, the widespread unconformity at the base of the Airy's Bridge Formation elsewhere must record a geologically instantaneous event, namely rapid caldera collapse, associated soft-state deformation and burial. This is in contrast to a protracted period of uplift and erosion. During the Airy's Bridge eruption the centre of subsidence shifted southwards with time from Sour Milk Gill, which became persistently emergent. This is illustrated by the Cam Spout Tuff (Figure 4.12), (Figure 4.17) which represents another important phreatomagmatic phase in the formation of the Scafell Caldera. Its presence at Sour Milk Gill shows that the area had become emergent, because pyroclastic surges are gaseous and too buoyant to invade standing water. This southward migration of subsidence means that the upper, subaerial part of the succession at Sour Milk Gill is thinner than ponded equivalents to the south. For example, the Bad Step Tuff is absent at Sour Milk Gill, but is over 400 m thick in Langdale (see the Langdale Pikes GCR site report), indicating the development of highly irregular caldera-floor topography as it subsided.

Conclusions

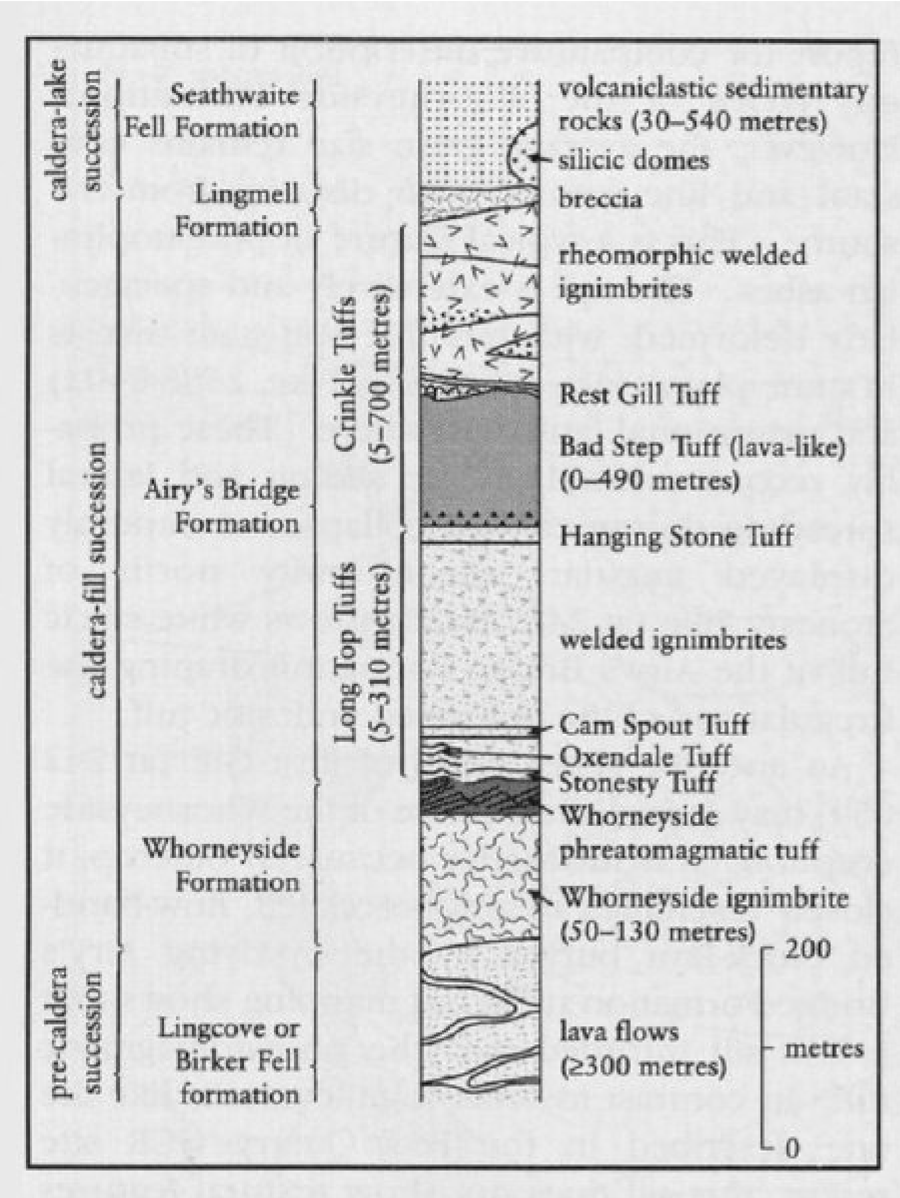
The Sour Milk Gill GCR site is internationally important because the exposed rocks were deposited in a volcanic lake situated near the vent of an exceptionally large-magnitude eruption caused by the explosive interaction of water and andesitic magma. The volcaniclastic rocks record particularly energetic explosions, rapid unsteady (pulsatory) ash fallout near to the vent, and contemporaneous reworking. Near-vent deposits of major phreatomagmatic eruptions at modern volcanoes, such as Lake Taal in the Philippines, and Lake Taupo in New Zealand, are mostly submerged and inaccessible. Therefore, this GCR site provides a rare view of the accumulation of these deposits, subsidence near to the vent, and how such watery basins are invaded by magma during the eruption to form stacks of sills. The site is particularly instructive because the volcanological context is well known from the continuity of outcrop around the Scafell Caldera, and the quality of the exposures allows individual beds to be traced for hundreds of metres.

Within the overlying Airy's Bridge Formation the Cam Spout Tuff at Sour Milk Gill is possibly the best example of a cross-bedded pyroclastic surge deposit in Britain, and the overlying welded tuffs show superb welding textures and polygonal columnar joints. Marked differences between the Sour Milk Gill succession and those of the Rosthwaite Fell and Ray Crag and Crinkle Crags GCR sites demonstrate that caldera subsidence can occur in a complex, piecemeal manner with adjacent fault blocks subsiding at different rates and being flooded at different times. This evidence has been highly influential in the way ideas about caldera collapse have developed in recent years.

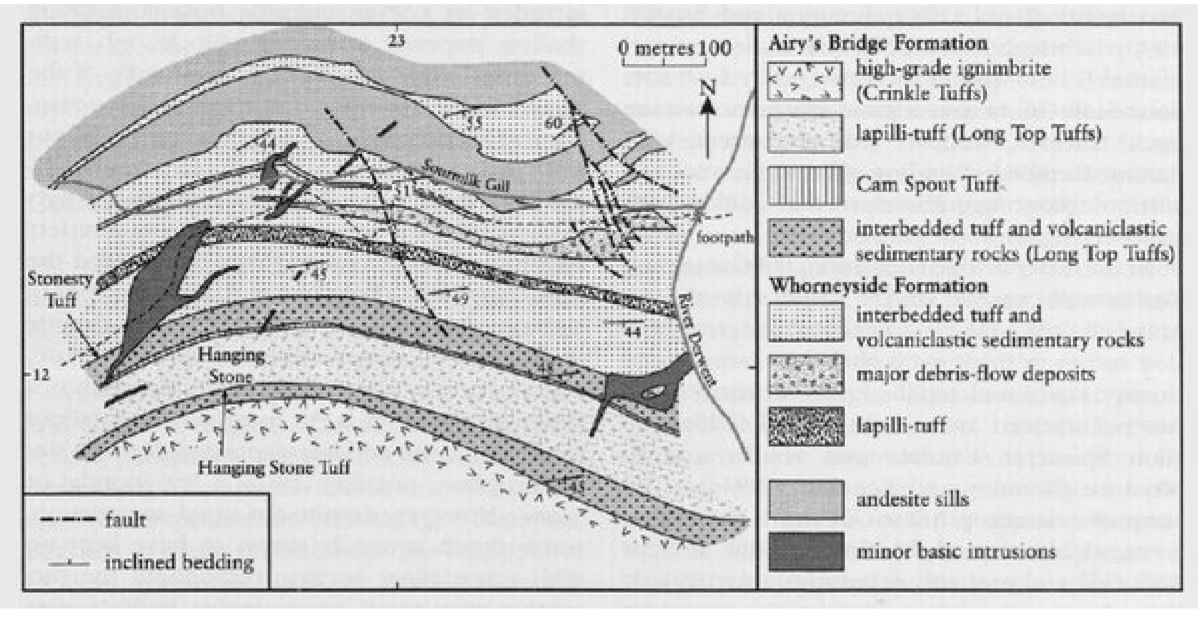
References



(Figure 4.16) Sour Mill Gill from Seathwaite Farm, Borrowdale. Southward-dipping proximal lacustrine Whorneyside phreatomagmatic tuff (centre of the picture), intruded by andesite sills (right) is overlain by silicic ignimbrites of the Airy's Bridge Formation (left). (Photo: M. J. Branney.)



(Figure 4.12) Generalized lithostratigraphy of the Scafell Caldera succession (after Branney and Kokelaar, 1994a).



(Figure 4.17) Simplified map of Sour Milk Gill (after Kokelaar, in Kokelaar and Branney, 1999).