The Role of Deformation Bands in the Collapse of Subglacial Hyaloclastite Ridges: an Example from Valahnúkar, Iceland

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Abstract

Deformation band zones (DBZs) are common in subglacially erupted basaltic tuffs in Iceland and form resistant ribs and fins cutting primary layering. The majority are compactional shear bands formed by cataclasis and granular flow, although rare dilation bands occur. Field and microscopic evidence indicates that DBZs formed while hyalotuffs were unconsolidated, prior to substantial palagonitization.

The 10 km-long tindar at Valahnúkar displays DBZs with three general geometries. Geometry 1: the most common deformation bands occur in dominantly steeply dipping clusters. Ladder and conjugate geometries are consistent in most places with dominantly normal displacement, with vectors raking at least 65-70° in the DBZ plane. DBZs occur in sets that have local orientations related to tindar geometry. Cross-cutting relationships among multiple sets are locally consistent and indicate local changes over time in conditions promoting deformation band formation. Geometry 2: DBZs also occur as curved bounding surfaces separating underlying hyalotuff from tongues and masses of pillow breccia and hyaloclastite. These DBZs commonly truncate older geometry 1 DBZs in the underlying hyalotuff. Geometry 3: rare DBZs occur in circular to oval concentric sets of outwardly dipping, paired cataclastic shear bands and dilation bands. These concentric dbzs are commonly cored by disrupted hyalotuff or are associated with disrupted layering in adjacent hyalotuff and are cut by geometry 1 DBZ sets, including rare sets with a larger strike slip component of motion.

DBZ geometry 1 formed as hyalotuffs accumulated and shifted in response to changes in size and shape of the enclosing sub-ice vault. Different sets developed in succession as local stress conditions changed. Geometries of the youngest sets in many places are consistent with collapse parallel to the local trend of the tindar. DBZ geometry 2 postdates many of the sets with geometry 1 and bounds the lower surfaces of slide and slump masses higher in the tindar. DBZ geometry 3 occurs only in SW Valahnúkar, where the tindar splays into a wide foot. These concentric DBZs and related disrupted layering may have formed in an early, transient, high pore fluid pressure event involving diapiric rise and disruption of original layering perhaps related to collapse of the SW end of the tindar.

What are deformation bands?

- Deformation of porous rocks and materials such as porous sandstones, tuffs, and unconcolidated sediments does not initially occur by the development and propagation of through-going extension fractures and shear fractures. **Instead, strain is accommodated by granular flow, with or without cataclasis, and either pore space collapse or expansion, forming structures known as deformation bands.** Subsequent failure of deformation bands can result in formation of faults.
- Deformation bands can be zones of compaction, dilation, shear, or any combination of the three (Fossen et al., 2007). Dilational shear bands are rare but may form in the early stages of shear band formation.
- Deformation mechanisms involved in the formation of deformation bands include granular flow (forming disaggregation bands), cataclasis (forming cataclastic deformation bands), phyllosilicate smearing, and dissolution and cementation (Fossen et al., 2007).
- Most deformation bands described in the literature are compactional shear bands formed by cataclasis and granular flow. In these rocks, pore space collapse accompanied by grain shattering and cataclastic flow allowed offset of one side of the zone with respect to the other without development of a discrete through-going fault.
- Formation of compactional shear bands can locally reduce the porosity of a rock from 25-30% or more down to a mere few percent.
- Deformation bands have been extensively studied in porous sandstones and weakly lithified sediments by Aydin (1977, 1978), Aydin and Johnson (1978), Antonellini et al. (1994), Davis (1999), and Schultz and Sidaharthan (2005). Deformation bands have been recognized and studied in porous volcanic tuffs (Wilson et al., 2003; Evans and Bradbury, 2004), in faulted, poorly lithified sediments (Rawling and Goodwin, 2003), and in unconsolidated sand above major fault zones (Cashman and Cashman, 2000; Cashman et al., 2007).
- Prior to our work, deformation bands had not been previously studied in Iceland and, to the best of our knowledge, had not been previously reported in the literature of palagonitized tuffs.

Purpose of the study

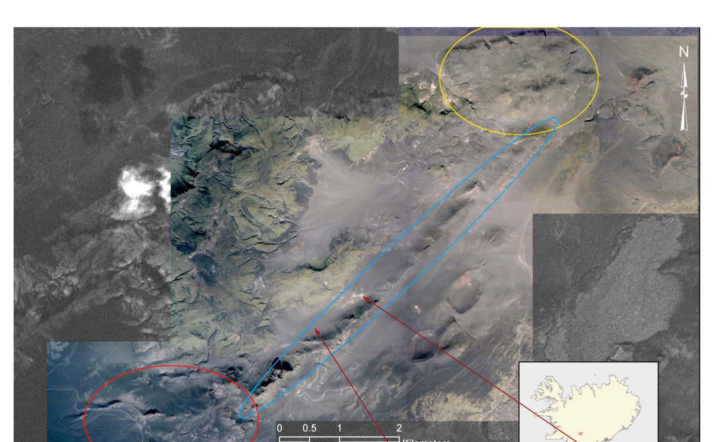
Many exposures of subglacially erupted porous tuffs in Iceland contain light-colored, resistant zones that cross-cut primary layering (photo at right). These have been variously interpreted by other workers both in Iceland and in similar rocks in Antarctica as hydrothermal veins, zones of selective palagonitization, and faults.

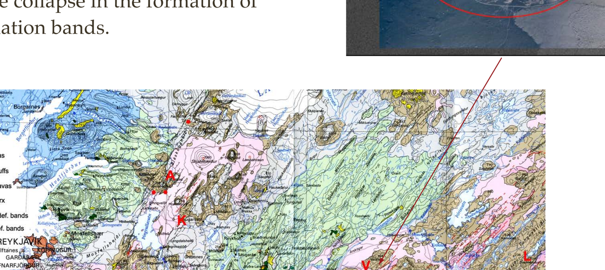
Our previous work (Tewksbury et al., 2008 and 2009; Hoffman and Tewksbury, 2006) at a number of sites in Iceland (shown with red letters on map below right) has demonstrated that these zones are, in fact, deformation bands. The bands studied in our work are dominantly compactional shear bands produced by pore space collapse and cataclasis in **unconsolidated** hyalotuff. In our previous work, we developed a general model for deformation band formation in unconsolidated hyalotuff. In the middle section of the poster (below), we have repeated the model and supporting evidence from our 2009 work, because the evidence is critical to our analysis of the role of deformation bands in syn-accumulation subglacial edifice collapse.

The purposes of this study are to:
- map the geometry and kinematics of deformation bands relative to ridge geometry in several critical areas of Valahnúkar.
- study the distribution and origin of "soft sediment" features that we had postulated in Tewksbury et al., 2009 were related to mobilization of unconsolidated hyalotuff prior to deformation band formation.
- to determine whether structures such as deformation bands can provide constraints on the character and timing of edifice adjustment and collapse.

Study Area

The study area at Valahnúkar northeast of Hekla in south central Iceland is a well-exposed Late Pleistocene tindar of pillow lavas, pillow breccias, and palagonitized hyalotuffs, hyaloclastites, and tuffaceous sediments. The existing geologic map of the area at 1:250,000 (South Iceland Sheet 6 of the Iceland Geological Map) shows no mapped faults. We chose this area for mapping in part for this reason, because we wished to investigate an area that did not appear to be dominated by regional tectonic structures in order to explore the role of local edifice collapse in the formation of the deformation bands.





Valahnúkar is a 10-km long subglacial volcanic deposit consisting of a narrow, 8-km long ridge of discontinuous and en echelon ridge segments (outlined in blue) with a "foot-shaped" terminus on each end (yellow and red ovals). The red circled area of Valahnúkar is dominated by hyalotuffs. The northern end of the ridge, circled in yellow, is dominantly hyaloclastite underlain by pillow breccias and pillow lavas.
The long ridge circled in blue has hyalotuff at its base and along the flanks (photo below right), but the ridges are capped by pillow lavas and pillow breccias, with some hyaloclastite.

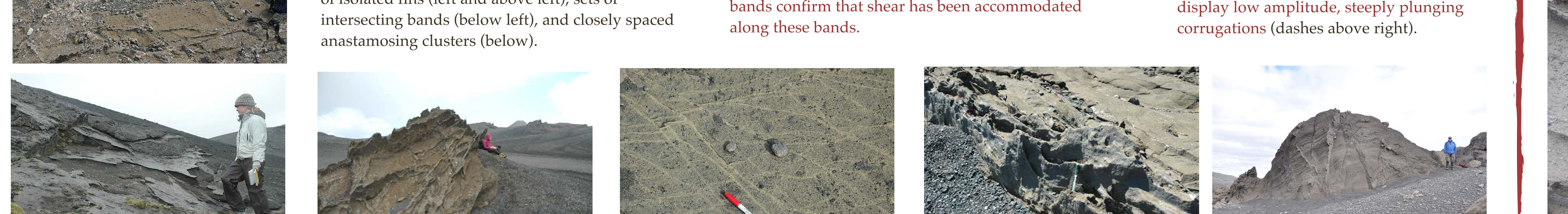
View looking SW along Valahnúkar and flanking valley. The presence of isolated patches of pillow lava on the ridge crests suggests that glacial erosion may have removed a significant amount of the original erupted material.

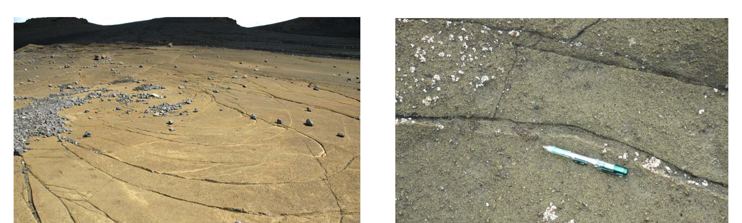
Outcrop characteristics of the deformation bands

The vast majority of the deformation bands at Valahnúkar occur as resistant ribs that cross-cut primary layering in the surrounding tuffs (above), indicating that they are secondary, rather than primary structures. They occur as quasi-parallel sets of isolated fins (left and above left), sets of intersecting bands (below left), and closely spaced anastamosing clusters (below).

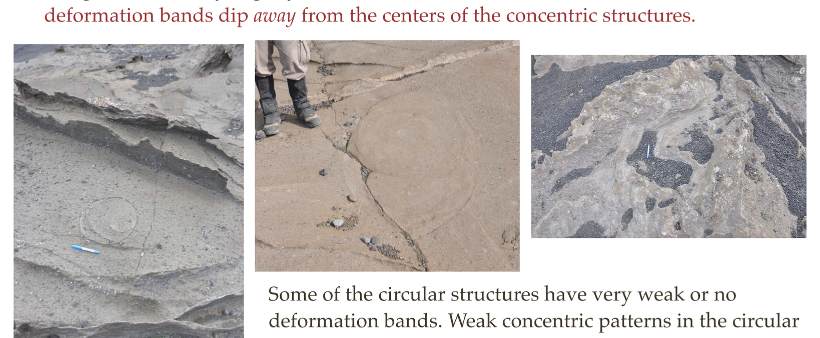
Deformation bands occur both as single bands (above and below left) as little as a few mms thick to wide and anastamosing sets (below right) that range in thickness up to a half meter or more. Offsets of both primary tuff layering and deformation bands by other deformation bands confirm that shear has been accommodated along these bands.

Deformation bands are almost exclusively planar, gently curved, and anastamosing zones in all dimensions. Stepover/linking band geometry is very rare. The surfaces of prominent deformation bands typically display low amplitude, steeply plunging corrugations (dashes above right).





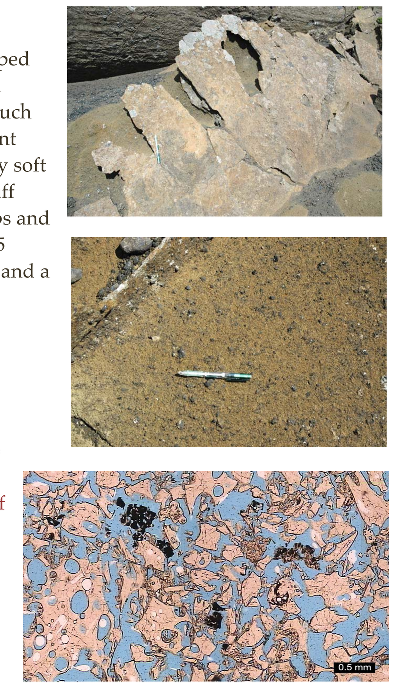
Deformation bands also occur in rare concentric sets from 1 m to over 10 m in diameter. Unlike the deformation bands described at left, these deformation bands are dominantly *less* resistant than the surrounding tuff and erode as troughs bordered by slightly more resistant deformation bands (below). These deformation bands dip *away* from the centers of the concentric structures.



Some of the circular structures have very weak or no deformation bands. Weak concentric patterns in the circular structures cut across layering in surrounding tuffs. Exposures of tuffs with circular structures commonly also have portions with contorted layers.

Characteristics of the resistant deformation bands at Valahnúkar (from Tewksbury et al., 2009)

Well-developed deformation bands are much more resistant than the very soft host hyalotuff and form ribs and fins up to 1.5 meters high and a meter thick.

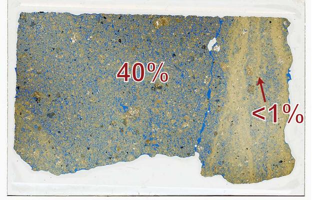


- The best-developed deformation bands occur in very porous, coarse grained brown to black hyalotuff with scattered scoria fragments up to several mm across (above right).
- Thin sections reveal that the hyalotuff consists of large, angular, irregular, and highly vesicular basaltic glass fragments with very little fine-grained matrix.
- Palagonitization is limited to thin rims on the glass fragments.

Porosity Reduction

Visual comparison of thin sections shows dramatically lower porosity in all deformation bands, which are conspicuously tan in thin section. Thin sections impregnated with blue epoxy are particularly striking and show that the light-colored deformation bands in hand samples coincide with areas in thin section that are nearly free of pore space.

Note: All samples were impregnated with blue epoxy before thin sectioning in order to highlight porosity.

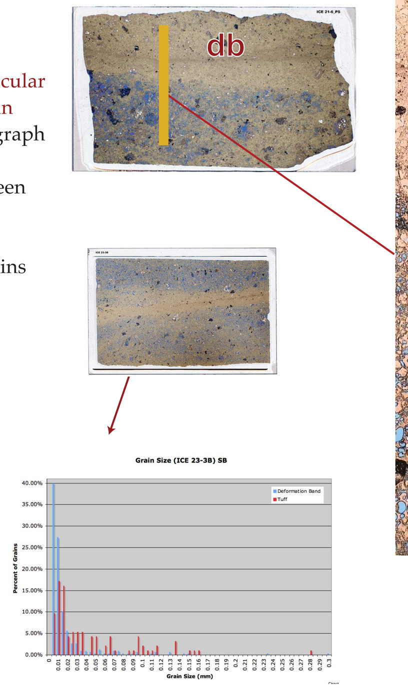


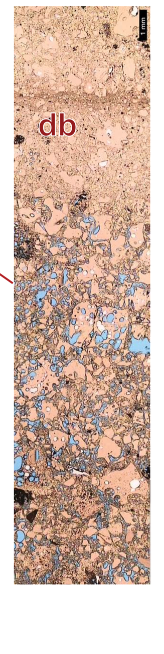
Porosity calculations were made using Image J software on scanned photomicrographs. Images were prepared in PhotoShop by selecting all blue pixels in the image (the pore space filled with blue epoxy). Because the hyalotuffs contain vesicular grains, the intergranular porosity is somewhat overestimated by this method. Despite this, the tremendous reduction in porosity in the deformation bands is clear (see porosity values on the photomicrograph above).

Grain size decrease

Resistant deformation bands in the porous hyalotuffs at Valahnúkar typically show spectacular grain size reduction in the deformation bands in comparison to the adjacent tuff. A photomicrograph traverse across a typical thin section (right) illustrates the striking grain size contrast between the porous host rock hyalotuff (with the blue epoxy-filled pore spaces) and the light-colored deformation band (labelled "db"), which contains only scattered coarser grains.

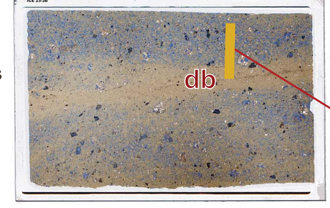
- Grain size calculations were made using Image J software on scanned photomicrographs. All visible distinct grains were selected and filled in Image J, and grain sizes were determined using the Analyze Particles function.
- The thin section above right is representative of the main deformation bands and their host rocks and shows clear grain size reduction in the deformation band in comparison to the host rock.





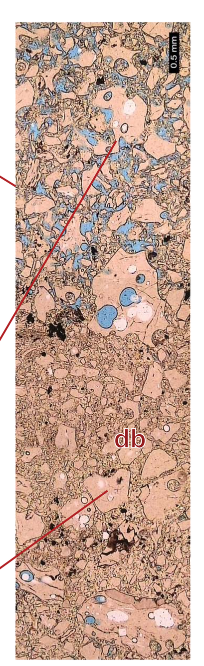
Grain shape change

Thin sections reveal that grain shapes in the deformation bands are very different from those in the adjacent hyalotuffs. The photomicrograph traverse above and right shows that grains in the deformation band ("db") are less vesicular and more equidimensional than those in the surrounding tuff.

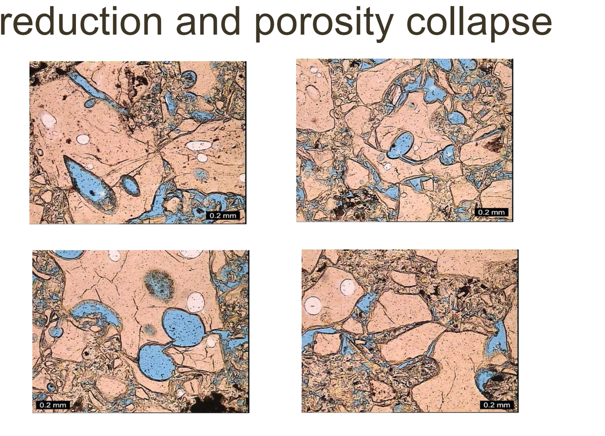


In the hyalotuffs adjacent to the deformation bands, grains of basaltic glass (sideromelane) are typically angular. Large grains are vesicular and highly irregular in shape.

In the deformation bands, grains are subangular and more homogenous in shape. Few grains within the deformation bands have skeletal protuberances, and grains are conspicuously less vesicular.



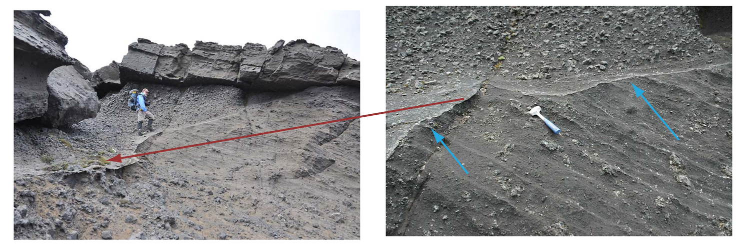
Mechanism of grain size reduction and porosity collapse



Grain size reduction in the high porosity hyalotuffs occurs when stress concentrations develop at the impingement points between grains (top left). Bubble necks in vesicular grains are particularly weak, and grains preferentially break through bubble walls, producing smaller, more equidimensional, and less vesicular grains (above and above right) as cataclasis proceeds.

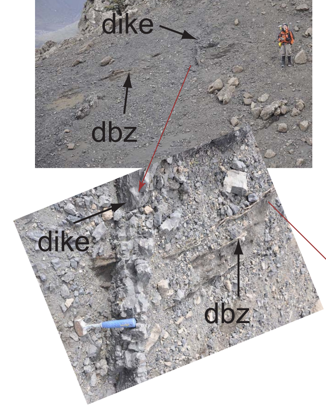
The presence of dramatic porosity reduction, coupled with evidence for grain size reduction, grain shape change, and shear offsets is consistent with compactional shear bands produced by shear, cataclasis and pore space collapse.

Origin and timing of deformation bands at Valahnúkar

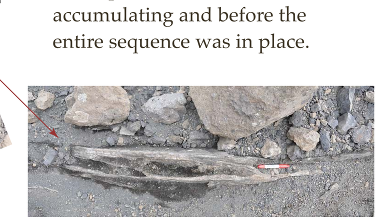


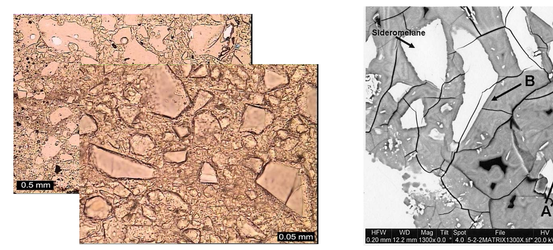
Two structures on the east side of Valahnúkar provide strong evidence that deformation bands formed as the eruptive pile was accumulating. The photos above show a prominent deformation band zone (blue arrows) that lies at the base of a set of hyaloclastites and pillow breccias and that truncates a set of previously-formed deformation bands in the underlying hyalotuff. The photos below show a scoop-shaped deformation band zone (blue arrows) with pillow breccias above and hyalotuffs below. We interpret both of these structures as slump masses of pillow breccias that formed as the eruptive pile grew. The truncated deformation bands must have formed even earlier in the growth of the pile.

The truncation of clusters of deformation bands by the youngest hyaloclastite layers at Valahnúkar (right) suggests not only early deformation band formation but also a complicated history of accumulation, slumping and adjustment of the pile, and continued accumulation.



Near the crest of central Valahnúkar, a basalt dike feeding overlying layers cross-cuts a cluster of deformation bands in the hyalotuff (left and below). This cross-cutting relationship indicates clearly that deformation bands were forming in the pile as it was accumulating and before the entire sequence was in place.



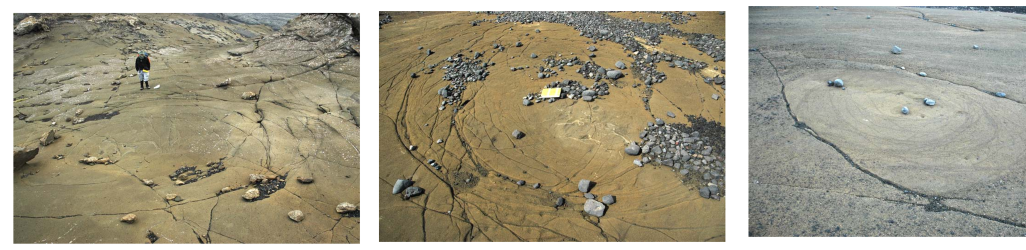


- Microscopic evidence also supports early deformation band formation, before significant palagonitization in the hyalotuffs. At moderate magnification (40X) (above), the matrix is nearly featureless palagonite, rather than fine, shattered grains that one might expect in a deformation band. At 1300X (above right), however, SEM photomicrographs reveal that the palagonitic matrix is not featureless but consists of tiny ghost grains converted to and rimmed by palagonite.
- Palagonitization effectively obliterated the fine-grained cataclastic fabric so typical of deformation bands in sandstones. Increase in the surface area/volume ratio accompanying grain size reduction likely promoted more complete palagonitization in the deformation bands than in the adjacent tuff.
- Work on rates of palagonitization of tuffs at Surtsey by Jakobsson (1978) and Jakobsson and Moore (1986) and at Gjálp by Jarosch et al. (2008) suggest that significant consolidation by palagonitization occurs surprisingly fast, within 1-2 years of eruption of the tuffs.
- Both of the above are consistent with outcrop evidence (presented at left) for penecontemporaneous accumulation of tuffs and formation of deformation bands.

Taken together, our evidence suggests that shearing, cataclasis, and formation of cataclastic compactional shear bands at Valahnúkar occurred during and shortly after the hyalotuffs formed, before significant palagonitization had occurred in the rocks. Field exposures of slump masses point to local edifice collapse as the likely cause of formation of the deformation bands.

- **Until fairly recently, structural geologists have been skeptical that deformation bands could form in completely unconsolidated materials.**
- **Cashman and others (2000 and 2007) have shown that very shallowly buried unconsolidated granular material consisting of quartz and feldspar grains can form deformation bands in association with seismic activity on underlying faults.**
- **We argue that even smaller stresses were required to create deformation bands in our hyalotuffs, because the grains of vesicular basalt glass are much more fragile than quartz and feldspar grains and break readily at stress concentrations at bubble necks. We argue further that the stresses generated by edifice collapse of subglacial deposits was weak enough that it was only able to trigger breakage and pore space collapse in hyalotuffs with very high porosity, where vesicular grains were not protected from one another by a matrix of fine grains. Transient shock associated with hydrovolcanic explosions may have played a contributing role.**

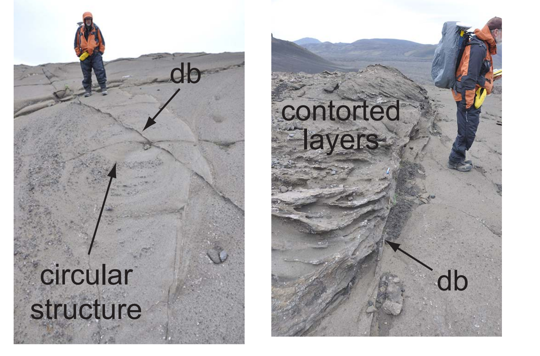
Mobilization in the hyalotufts and the origin of the circular structures



The circular structures occur in tuff that is finer-grained than that containing the main deformation bands. The structures are defined by concentric rings of outward-dipping deformation bands.

The nonresistant deformation bands in the circular structures consist of two zones. The central zone is 1-2 cm wide, slightly darker in color, and less resistant than the country rock tuff, creating shallow troughs on an eroded surface. The troughs are bordered by a zone a few mms thick that is lighter in color and slightly more resistant than the country rock tuff, creating a steeply-dipping "wall" on one or both sides of the trough that sticks up slightly above the surrounding surface.

- Thin sections show clearly that the slightly resistant portion of the deformation band has lower porosity than the country rock tuff. Porosity measurements by Tewksbury et al. (2009) confirm this, showing 12-18% porosity in the deformation band and 23-44% porosity in the adjacent country rock.
- The non-resistant portion of the deformation band may have a slightly higher porosity than the country rock tuff.



The main deformation bands in the hyalotuff (which are cataclastic compactional shear bands) post-date both the circular structures and the contorted layering associated with the circular structures.

The cores of some of the circular structures are occupied by contorted inclusions of tuff (above and above right), and the circular structures are spatially associated with hyalotuff with locally contorted layering (right).

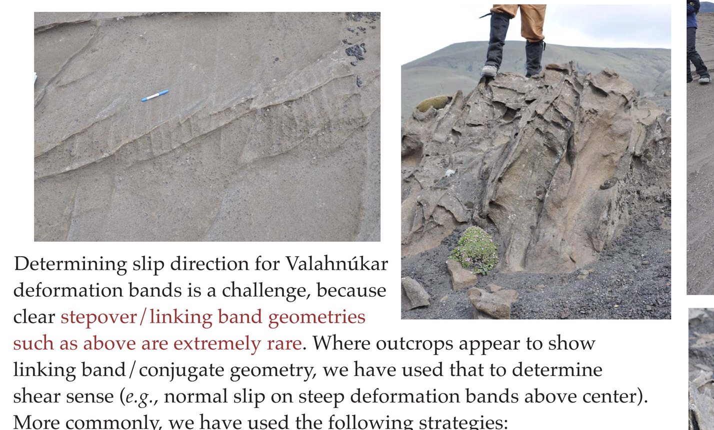
Early mobilization of unconsolidated hyalotuff

- The outward dip of concentric deformation bands suggests rise of the center or collapse of the margins of the structure, rather than vice versa. The contorted core inclusions, as well as localized folding in surrounding tuffs, suggest soft-sediment deformation.
- Both of the above are most consistent with diapiric rise of unstable, probably water-saturated tuffs shortly after accumulation of the tuffs.
- Formation of the concentric deformation band zones likely happened late in this process, as they do not appear to have accommodated much local shear and are only weakly developed (no cataclasis). Elevate pore pressures may have played a role in formation of these deformation bands.
- **The features suggest that the nonresistant deformation bands in the circular structures likely began as wide dilational shear bands formed by disaggregation of grains that evolved along the edges to weak compactional shear bands (the more resistant portions) without much cataclasis .**

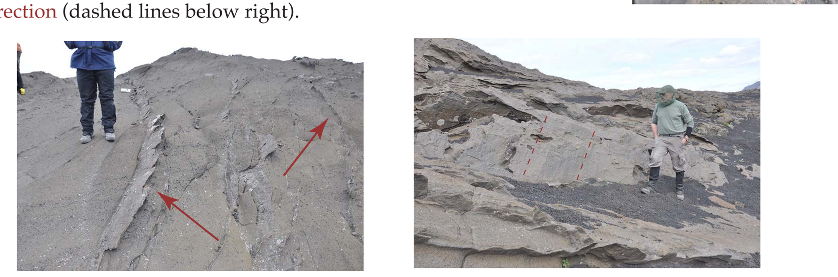
Our evidence suggests that the circular structures formed by soft sediment deformation, likely by diapiric rise of water-saturated deposits before they were consolidated, as suggested by LeMasirier (2002) for soft sediment structures in hydrovolcanic deposits in Marie Byrd Land. Early formation of circular structures by flow in unconsolidated deposits is consistent with our primary conclusion that the main deformation bands formed during or shortly after accumulation and before consolidation of the hyalotuffs. Because the main deformation bands formed after the circles but before consolidation by palagonitization, the circles must have formed by a process that occurred even earlier than deformation band formation.

Collapse of ridge flank and the formation of deformation bands

Determining slip direction



Determining slip direction for Valahnúkar deformation bands is a challenge, because clear stepover/linking band geometries such as above are extremely rare. Where outcrops appear to show linking band/conjugate geometry, we have used that to determine shear sense (*e.g.*, normal slip on steep deformation bands above center). More commonly, we have used the following strategies:
- Offset of curved layering allows determination of dip slip on some deformation bands (above right, where curved, left-dipping layers are dropped down along a left-dipping deformation band).
- The slip direction is perpendicular to the line of intersection between conjugate deformation bands (directly visible at right, dashed line, and determined from stereonet below left, conjugate set shown with arrows). In addition, we have observed that corrugations commonly occurring on the deformation band surfaces lie parallel to the slip direction (dashed lines below right).



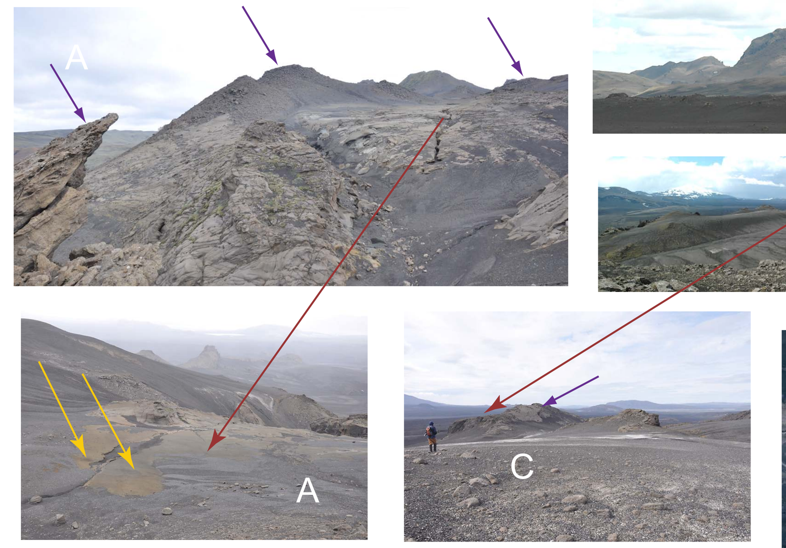
Deformation bands and ridge collapse

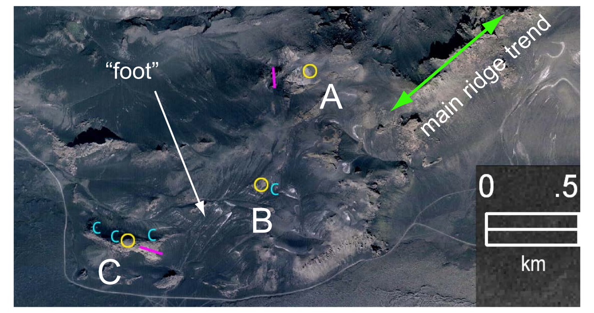
In the example above from an area west of the main ridge (at A on the map at far right), deformation band clusters strike parallel to the ridge and dip W away from the core of the ridge. Conjugate structures and rare linking bands indicate a normal slip sense consistent with flank collapse.

Although many collections of deformation bands at Valahnúkar do not have clear geometric relationships to ridge geometry, we have studied a number of sections of the deposits where steeply dipping deformation band swarms lie parallel to ridge flanks (left) and have normal shear sense, suggesting collapse of the ridge flanks.

The example above from a ridge on the SW "toe" of the deposit (at C on the map at far right) contains both deformation bands and major fractures.
- The most prominent deformation band set dips SSW away from the crest of the ridge and displays offsets of layering that are consistent with a normal slip sense, which was determined from corrugations and intersections with less prominent conjugate deformation bands.
- Deformation bands are cut by prominent fractures, also dipping SSW away from the ridge crest. In the photo above left, the prominent structure slanting down to the left across the outcrop face is this set of fractures.
- **Ridge collapse here was likely at least a two-phase event. Deformation bands accompanied early collapse when the hyalotuffs were unconsolidated, and fractures were formed by a later collapse after the hyalotuffs had been consolidated by palagonitization.**

Conclusions and implications



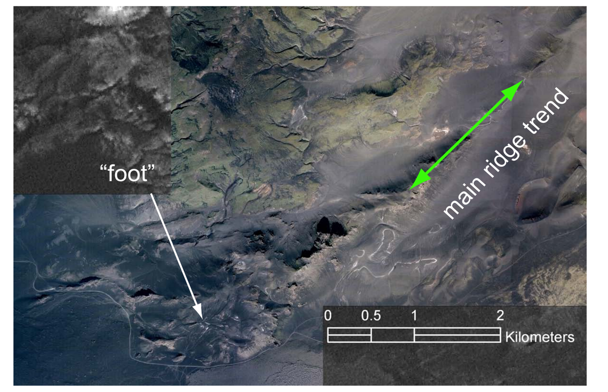


The three areas where we have mapped circular structures (yellow circles at right) and associated contorted layering (turquoise Cs at right) occur in areas that do not lie on the main Valahnúkar ridge (green line at right).
- Area A lies in a flat area NW of the main ridge and is bordered on the west side by a ridge of hyalotuff with steeply west-dipping, normal slip deformation bands (magenta line at C).
- Area B lies in a very broad, flat area in the core of the wide "foot" at the SW end of the main Valahnúkar ridge.
- Area C lies on the NE side of a prominent WNW-trending ridge along the SW edge of the wide "foot". The south side of the ridge is cut by steeply SSW-dipping normal slip deformation bands and by steeply SSW-dipping fractures that cut the deformation bands (magenta line at C).

In all three areas, the hyalotuffs containing the circular structures, contorted layering, and deformation bands are overlain by younger, surface-parallel, layered hyaloclastite that appears to be largely undisturbed (dipping surfaces at purple arrows above) .

Color key for map at above:
yellow circles: locations of circular structures
turquoise Cs: locations of contorted layering
magenta lines: orientations of major zones of locally ridge-parallel, normal slip deformation bands
Letters keyed to photos above and above left.

Summary of key points
- **Mobilization of unconsolidated, probably water-saturated hyalotuffs occurred in the "foot" at the SW end of Valahnúkar ridge, creating circular diapiric structures and contorted layering before the main set of deformation bands formed.**
- **Deformation bands formed in unconsolidated hyalotuff both before palagonitization and before the entire subglacial volcanic sequence had accumulated.**
- **Deformation bands are related to local edifice geometries, rather than to regional tectonic patterns. We established in several places that steeply dipping deformation bands oriented parallel to local ridges show normal slip consistent with edifice collapse. In each of these places, however, the presence of other sets of (typically older) deformation bands and younger fractures point to locally complex deformation histories as the hyalotuffs accumulated.**



Taken together, the evidence suggests that the SW end of Valahnúkar (the "foot" at right) collapsed early in the accumulation history, forming the circular diapiric structures in water-saturated portions and spreading large, partly coherent blocks of hyalotuff into a broad foot characterized by discontinuous blocks and ridges of different orientations. Some deformation bands likely formed before and during this event, but the clear spatial relationship of the youngest of the deformation bands to ridge geometry (magenta lines above left) suggests that these deformation bands formed as rafted blocks of the "foot" adjusted. The last phase of the eruption emplaced surface-parallel sheets of hyaloclastite across the area.

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