Fragile Glass: Deformation Band Formation in Unconsolidated Hyalotuff, Valahnúkar, Iceland

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Abstract

Deformation bands in subglacially erupted hyalotuffs at Valahnúkar tindar in Iceland are lighter in color and more resistant to erosion than the surrounding host rock and cluster in deformation band zones (DBZs) to form ribs and fins. The majority show significant pore space and grain size reduction, grain shape change to more equant and less vesicular grains, and offsets of primary layering, indicating that most are compactional shear bands formed by cataclasis and granular flow. Microscopic evidence indicates that deformation band formation occurred while the hyalotuffs were unconsolidated prior to substantial palagonitization.

Valahnúkar tuffs that contain the most well-developed deformation bands are dominated by large, irregular, vesicular grains. During granular flow, these large, fragile glass grains impinged on each other and shattered, breaking at weak bubble necks into more equant, non-vesicular pieces. Lithologies that initially contained a fine matrix or that consisted of porous hyaloclastite with blockier, less vesicular grains, contain fewer deformation bands or no deformation bands at all.

We suggest that Valahnúkar deformation bands formed primarily as a result of local stresses in the tindar edifice as pyroclastic deposits adjusted and collapsed during and shortly after emplacement. This model is consistent with 1) slump masses of pillow breccias separated from underlying hyalotuffs by DBZs that dip away from the tindar crest and truncate swarms of older DBZs in the underlying hyalotuff; 2) results of detailed mapping that fail to reveal any obvious correlation with regional tectonic features in the Valahnúkar area; 3) petrographic evidence that Valahnúkar deformation bands formed prior to consolidation of the tuffs by palagonitization; 4) work by others at Surtsey and Gjálp showing that palagonitization of subglacial tuffs occurs within 1-2 years of eruption, and 5) recent work by others that demonstrates that deformation bands can form in unconsolidated materials subjected to stress. We argue that the fragile nature of large, unsupported vesicular glass grains made Valahnúkar hyalotuffs susceptible to deformation band formation even though they were unconsolidated. This ongoing work represents the first documentation of cataclastic deformation bands in subglacial hyalotuffs.

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

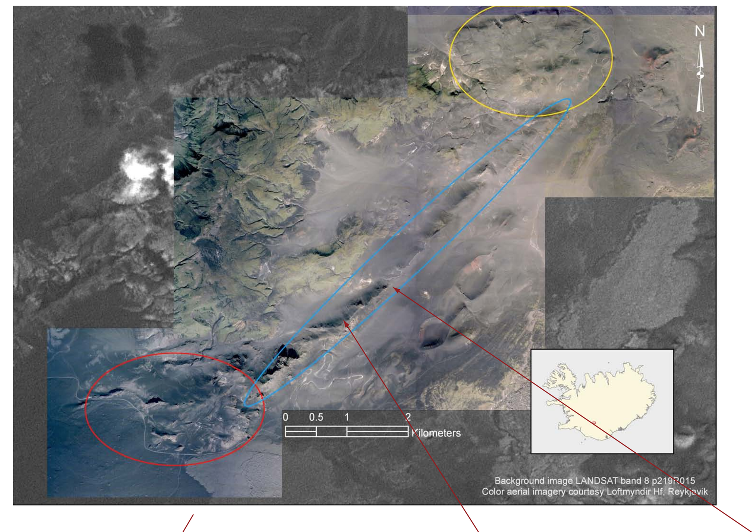
Many exposures of subglacially erupted porous tuffs in Iceland contain light-colored, resistant zones that cross-cut primary layering (photo at right). These have been variously interpreted by other workers both in Iceland and in similar rocks in Antarctica as hydrothermal veins, zones of selective palagonitization,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

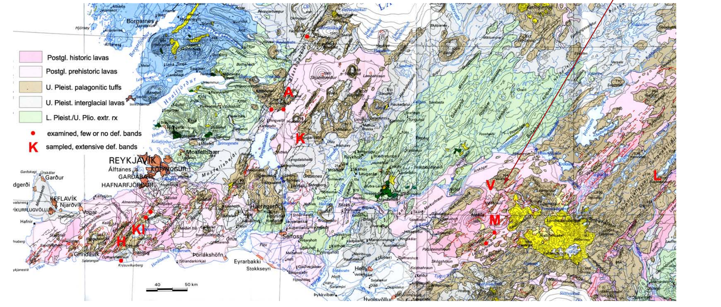
The purposes of this study are to:
- extend previous detailed mapping and sampling of deformation bands in a well exposed, young tindar at Valahnúkar.
- test the hypothesis, developed as a result of previous work, that the hyalotuffs were unconsolidated at the time of formation of the deformation bands.
- develop a model for why subglacial hyalotuffs are susceptible to deformation band formation.
- evaluate the relative roles of edifice collapse, regional tectonism, and ice flow in forming the deformation bands.
- compare occurrences of deformation bands at Valahnúkar to deformation bands in faulted tuffs on Reykjanes.
- compare Valahnúkar deformation bands with tectonic deformation bands from Reykjanes.

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 whether local edifice collapse played a role in formation of the deformation bands.



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 circle 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. This is not typical for tindar, which commonly are cored by pillow lavas and breccias and capped by hyaloclastites and hyalotuffs. This suggests either significant changes in water depth during the eruption or (less likely) multiple eruptions at Valahnúkar.

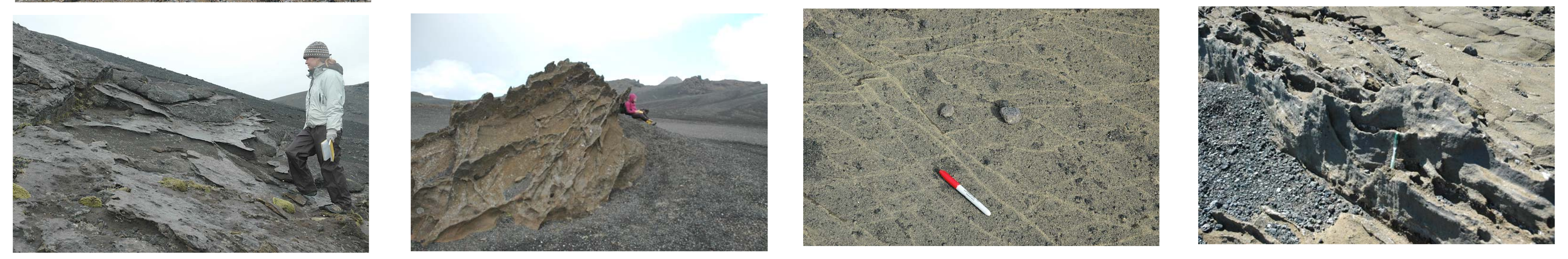


View looking SW along Valahnúkar and flanking valley. The presence of isolated patches of pillow lava on the ridge crests suggests that glacial erosion has removed a significant amount of the original erupted material.

Outcrop characteristics of the deformation bands

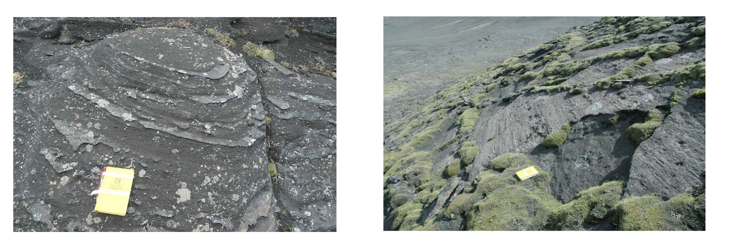
The vast majority of the deformation bands at Valahnúkar occur as resistant ribs that cross-cut primary layering in the surrounding tuffs (above), indicating that they are secondary, rather than primary structures. They occur as quasi-parallel sets of isolated fins (left and above left), sets of intersecting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



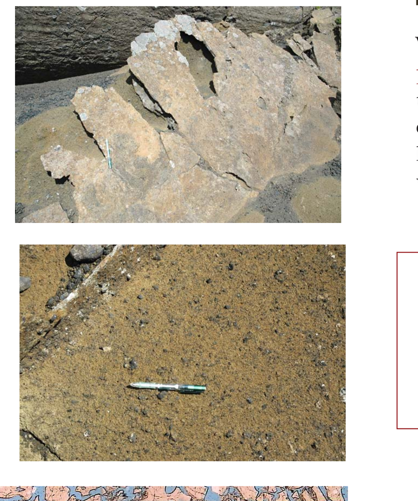
Deformation band-like, surface-parallel resistant layers

Large portions of the central and northern part of Valahnúkar are capped by a hyaloclastite with resistant layers a few millimeters to a centimeter in thickness (above and below left). These layers are like deformation bands in that they are conspicuously less porous (shiny in the rain) and more resistant than the enclosing hyaloclastite. What makes them different from deformation bands is that, everywhere they occur, they lie parallel to the topographic surface (they define the light-colored layers "draping" the knoll above right) and are prominently lineated (below right).

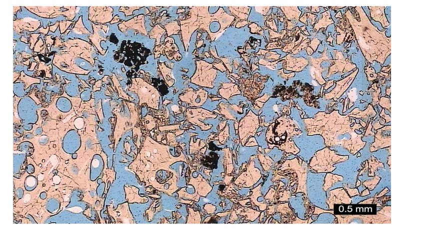


Characteristics of rocks with deformation bands

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.

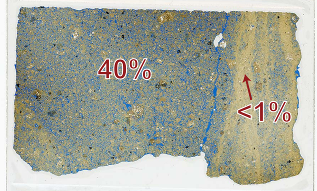


Thin section characteristics of the resistant deformation bands at Valahnúkar

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.

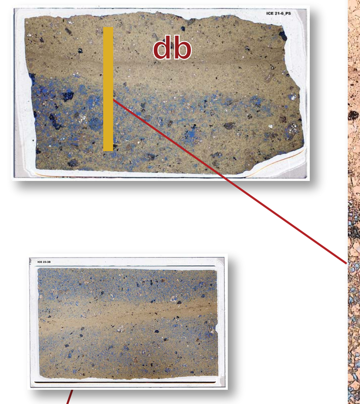


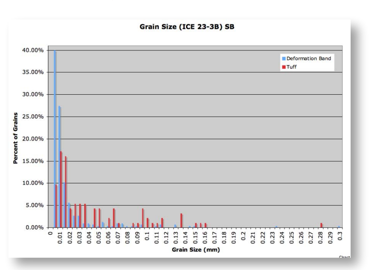
Porosity calculations were made using Image J software on scanned photomicrographs. Images were prepared in PhotoShop by selecting all blue pixels in the image (the pore space filled with blue epoxy). Because the hyalotuffs contain vesicular grains, the intergranular porosity is somewhat overestimated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

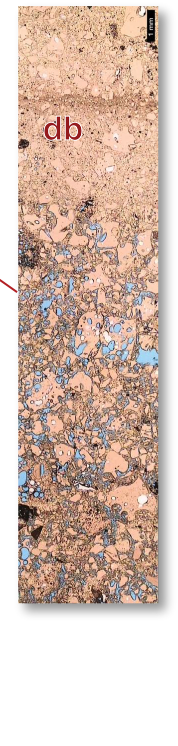
Grain size decrease

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.

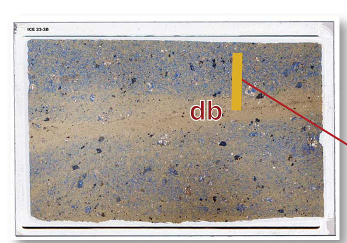
- Grain size calculations were made using Image J software on scanned photomicrographs. All visible distinct grains were selected and filled in Image J, and grain sizes were determined using the Analyze Particles function.
- The thin section above right is representative of the main deformation bands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







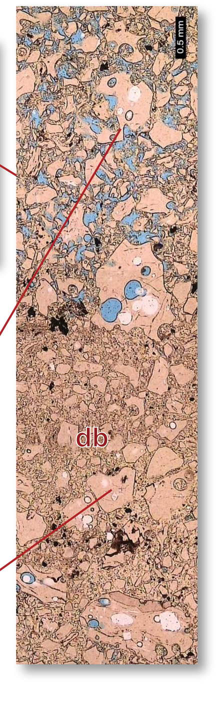
Grain shape change



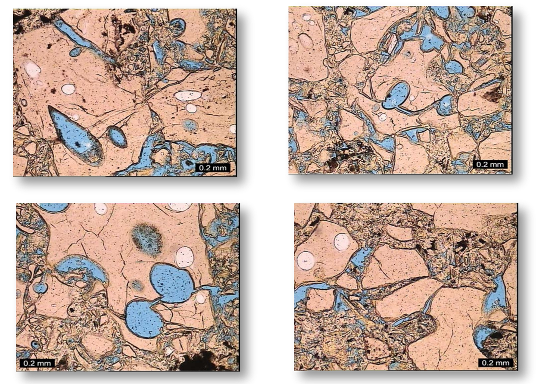
Thin sections reveal that grain shapes in the deformation bands are very different from those in the adjacent hyalotuffs. The photomicrograph traverse above and right shows that grains in the deformation band ("db") are less vesicular and more equidimensional than those in the surrounding tuff.

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.



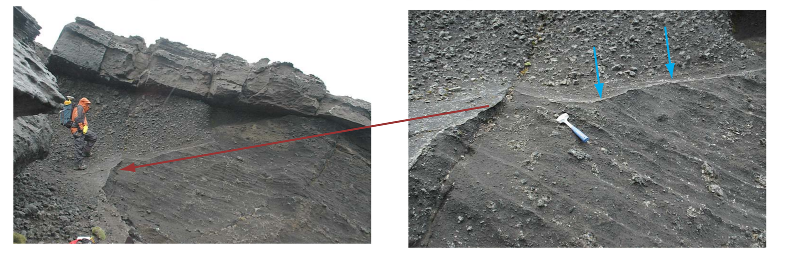
Mechanism of grain size reduction and porosity collapse



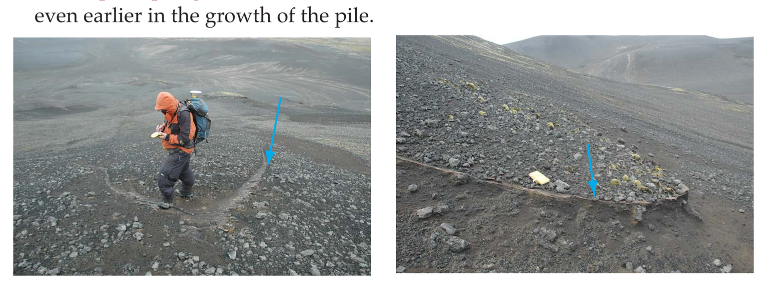
Grain size reduction in the high porosity hyalotuffs occurs when stress concentrations develop at the impingement points between grains (top left). Bubble necks in vesicular grains are particularly weak, and grains preferentially break through bubble walls, producing smaller, more equidimensional, and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

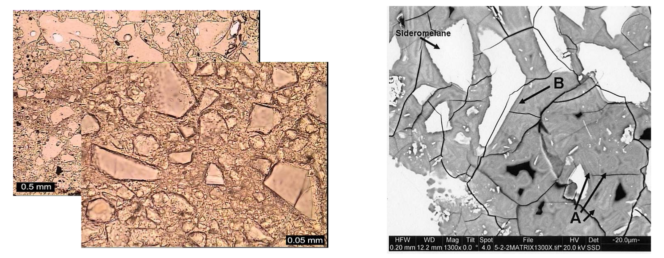
The presence of dramatic porosity reduction, coupled with evidence for grain size reduction, grain shape change, and shear offsets is consistent with compactional shear bands produced by shear, cataclasis and pore space collapse.

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.





- Microscopic evidence strongly suggests that deformation bands at Valahnúkar formed 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.

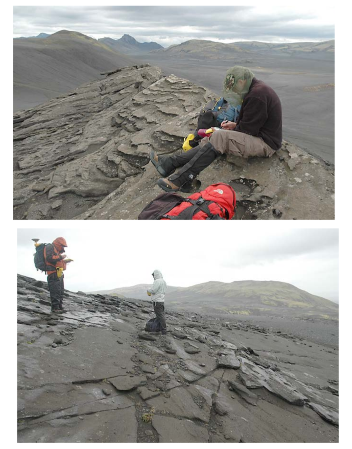
Taken together, our evidence suggests that shearing, cataclasis, and formation of cataclastic compactional shear bands at Valahnúkar occurred during and shortly after the hyalotuffs formed, before significant palagonitization had occurred in the rocks. Field exposures of slump masses point to local edifice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

Characteristics and origin of the surface-parallel resistant layers

Outcrop characteristics

In outcrop, the surface-parallel resistant layers form micro ledges typically a few centimeters apart that give many outcrops a terraced appearance (right). The resistant layers have low porosity and, on rainy days, are shiny, in contrast to the porous hyaloclastites. Not all outcrops are "terraced" – what look like shiny irregular patches at right are actually thin continuous resistant layers that dip slightly more steeply than the slope of the outcrop.

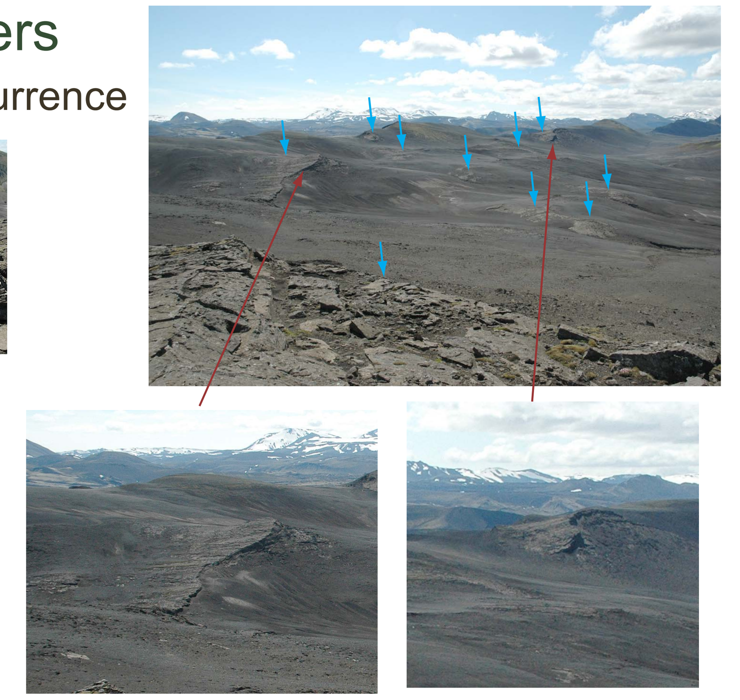


In many areas, the layers are underlain by less resistant hyaloclastite with few or no resistant layers (above), suggesting that the causative mechanism is a surface or near-surface phenomenon. Slope-parallel resistant layers dipping toward the observer can be seen in the background.

Although some layers are irregular (above), and some merge (above right), branch (right), or cross-cut local layering in the hyaloclastites (far right), we did not see any that either clearly cross-cut or offset each other, as is common in deformation bands at Valahnúkar.

Layer geometry & occurrence

With the exception of the main Valahnúkar ridge crests, which are capped by pillow lavas and pillow breccias, outcrops in the central and northern part of Valahnúkar consist of hyaloclastite with resistant layers (photo above) that lie parallel to the local topography, giving the appearance of layers draped over knolls and down valleys. The photo below shows a typical exposure with layers dipping toward the observer on the near side of the knoll, to the right and left on the sides of the knoll, and away from the observer on the far side of the knoll.

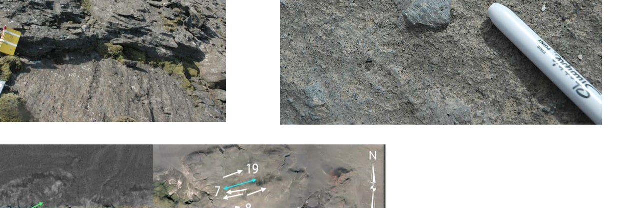


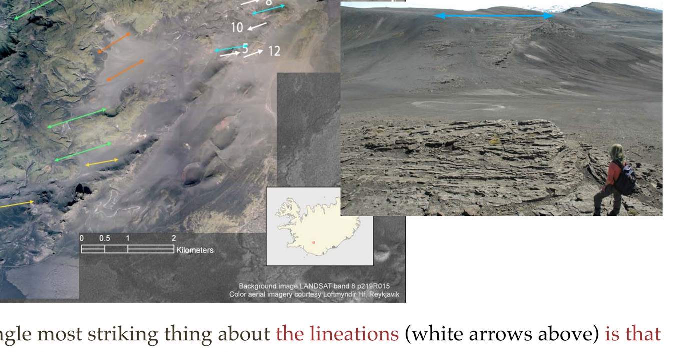
In the photo at top looking south, every light-colored patch (representative examples marked by arrows) consists of layers lying parallel to the local topography. The widespread distribution is striking. The inset photos show enlargements of two areas with surfaces that are broadly curved, broadly lineated ~070-250°, and truncated on the WSW side.

The view at left shows both the surface-parallel resistant layers in the foreground and on the slopes in the background and the non-resistant hyaloclastites underneath the layered surface.

Lineations

The surface-parallel resistant layers are prominently lineated with wide, shallow corrugations (right). The lineations are a property of each layer, as shown below where the lineations extend into the outcrop underneath the next overlying layer. They are not surface features such as glacial striae.





The single most striking thing about the lineations (white arrows above) is that they have the same trend (roughly 070-250°) *regardless of the orientation of the layers.* The orientation is parallel to broad grooves in Valahnúkar itself (blue arrows above), to spurs of the ridge (yellow arrows), to broad regional grooves in older palagonite (green arrows), and to aligned valleys (red arrows), all suggesting a connection to local ice flow direction.

Thin section characteristics

The grains in the rocks that host the surface-parallel resistant layers are blockier and less vesicular than those in the hyalotuffs with the deformation bands described in the sections above. Some layers have features consistent with weak compaction bands. Others, however, have too much fine-grained matrix (while retaining shapes and sizes of coarser grains similar to that in the host rock) to be deformation bands.

The most striking characteristic in thin section is the evidence for mobilization and erosion of grains.
- Some grains show evidence of having been palagonitized *in situ* (above left); others show evidence of having been palagonitized, then remobilized and abraded forming a rounded grain outline and dark rim (above center left), and then accumulated in the layer and palagonitized again. Some grains show evidence of multiple episodes of palagonitization and mobilization (above center right).
- Where resistant layer boundaries are sharp, large grains sticking up above the contact appear to have had their palagonite rims removed (above right, blue arrows). The contact is clearly not a shear surface and appears to show evidence of erosional scour.

Origin of the surface-parallel resistant layers

- The layers lie parallel to the local topography and are less prominent farther away from the local surface.
- Although the lineations occur on all layers in a stack (*i.e.*, they are not surface glacial striae), the lineations lie parallel to a trend that is likely the local ice flow direction, regardless of the orientation of the surface.
- Some layers clearly branch, merge, and crosscut layering in the tuffs.
- Thin sections of the layers do not show features typical of deformation bands.
- Some resistant layers have micro scour features at their bases.
- The hyaloclastites contain grains that have been mobilized and abraded after initial palagonitization, and palagonitized again *in situ*.

We are currently evaluating possible models for the origin of these layers. The evidence seems to require a mechanism that reflects the glacial flow direction but that isn't simple glacial scouring of the surface. The layering in the hyaloclastites, the common occurence of unabraded grains plus the high porosity and *in situ* palagonitization of most of the hyaloclastites suggests that these were not directly deposited by ice. On the other hand, the presence of mobilized and abraded palagonite grains and micro scour surfaces bounding some of the layers clearly indicates reworking and that these deposits are not primary hydrovolcanic deposits.

Tectonic and nontectonic deformation bands at Reykjanes

Active plate boundary

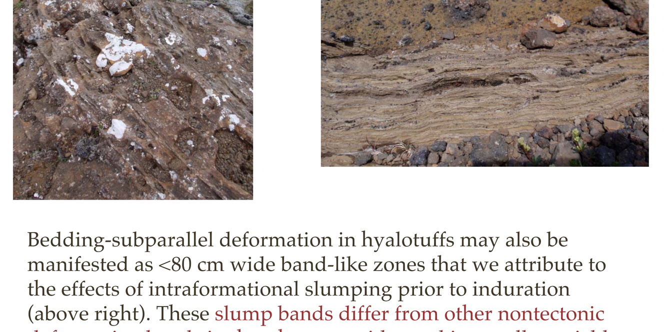
In contrast to Valahnúkar, the Reykanes Peninsula in SW Iceland is along the active plate boundary, with a spreading rate of ~2 cm/yr. Deformation is focused within 4-5 NE-oriented fissure swarms oblique to the plate boundary. Holocene activity has involved temporally partitioned strike-slip and normal faulting events and episodic basaltic volcanism from eruptive fissures. Pleistocene eruptions were subglacial, resulting in prominent linear tindars that define the geomorphic expression of the fissure swarms. Ongoing tectonic activity has resulted in structural dissection of the tindar ridges by normal faults (top right), manifested as DBZs, shear fractures, and vertical joints .

Assuming that the same processes that typify deformation band development at Valahnúkar occurred on Reykjanes, it is important to be able to differentiate between pre- induration, pre-palagonitization band growth during synformational collapse of the tindar edifice and later tectonic deformation bands that progressively developed in consolidated hyalotuffs over the past 10+ ka.

Tectonic deformation bands (left) form < ~10 m wide fault zones comprised of many parallel bands, each with up to a few cm of offset. They form positive relief structures but no high-standing ribs like the bands at Valahnúkar. The internal architecture of the fault zone (above) is reminiscent of DBZs in siliciclastic rocks. Conjugate sets of bands occur along NE-oriented normal fault zones (right). In one locality, the normal fault bands crosscut older, vertical tectonic bands associated with right-lateral strike-slip faults (far right).

Nontectonic deformation bands commonly crosscut the bedding in the hyalotuffs and are consistently cut by younger tectonic bands. The nontectonic bands may be related to early tindar collapse, analogous to those at Valahnúkar. They form irregular networks of thin, inosculating, positive relief bands with no preferred orientations.

Nontectonic deformation bands may form "scoop-shaped" geometries consisting of broad (tens of m), concave-upward structures with curving surface traces. These features consist of tabular bands a few cm wide (above far right) and may exhibit polished slip surfaces. They form prominent ribs in fine-grained hyalotuffs (above right) but more subdued bands in coarser-grained tuffs (right photo) that may indicate lithology-dependent developmental differences.



Bedding-subparallel deformation in hyalotuffs may also be manifested as <80 cm wide band-like zones that we attribute to the effects of intraformational slumping prior to induration (above right). These slump bands differ from other nontectonic deformation bands in that they are wider and internally variable, consisting of alternating layers of coarse and fine-grained material that may imply localized compaction and sorting within saturated sediments during slumping. Future thin section analysis will determine whether these features can be accurately classified as a type of deformation band.