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The development of cavities and clastic infills along fault-related fractures in Tertiary basalts on the NE Atlantic margin

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ABSTRACT

Field-based geological observations have revealed the hitherto unrecognised development of post-magmatic, brittle deformation structures cutting Tertiary volcanic rocks in the Faroe Islands. These faults and fractures are characteristically associated with different styles of clastic sedimentary infill including: 1) 0.3–1.0 m thick clastic units infilling open fractures formed along pre-existing steeply-dipping to sub-vertical faults; 2) 0.1–0.6 m thick sub-horizontal clastic units displaying internal features consistent with deposition from flowing water passing through complex open subterranean cavity systems within fractured basalts; 3) Anastomosing mm-scale and planar dm-scale clastic intrusion features mobilised and emplaced during transient, fault-related overpressuring events along pre-existing fractures cutting the surrounding volcanic units. The infill features provide evidence for the existence of sustained open cavities in the sub-surface. The clastic materials are commonly internally affected by later fault-related deformation and lack mineralisation, unlike all preceding faulting episodes in the Faroes region, perhaps reflecting their near-surface development. We believe structures equivalent to these features may occur widely in other parts of the NE Atlantic margin, particularly along the outer arcs of gentle regional-scale fold hinges. The uncemented fracture-hosted clastic infills potentially represent important fluid migration pathways within the otherwise low permeability Cenozoic volcanic sequences of the NE Atlantic region.

1. Introduction

Many upper crustal fault zones contain significant volumes of brecciated wall rock, which can potentially form high permeability pathways for the migration of mineralising hydrothermal fluids or hydrocarbons (Sibson, 1986, 1989; Roberts, 1994; Caine et al., 1996; Cowan, 1999; Woodcock et al., 2006, 2007). These fault-related breccias are formed by a variety of processes that operate at different rates. For example, at depths below 2 km, fault-breccia formation is widely believed to occur due to two different mechanisms: gradual abrasion and wear during fault slip (e.g. Woodcock et al., 2006) and/or implosion due to large, geologically instantaneous changes in fluid pressure adjacent to dilational fault jogs (e.g. Sibson, 1986). At shallower crustal depths (0–2 km, as a conservative estimate), however, mechanically strong rocks (e.g. crystalline or carbonate rocks) may be able to support fault-related dilational features as persistent, open subterranean cavities with fluid flow properties similar to karstic aquifers found in limestone terrains. These voids can be filled by sedimentary breccias that may be deposited gradually or injected rapidly due to overpressure events (e.g. Beacom et al., 1999). Understanding the development of these fault-related breccias is scientifically and economically important, since the different breccia types (abrasion vs. implosion vs. cavity-fill) have contrasting sealing and fluid flow histories. Breccias resulting from implosion or abrasion may become sealed relatively quickly after faulting, as the associated mineralising fluids enter and rapidly cement newly formed cavities between breccia blocks. On the other hand, cavities that are open for longer time periods, particularly those formed in shallow crustal settings (0–2 km), will be associated with much longer-lived and persistent fluid flow, operating prior to, during and after the development of breccia along the fault (e.g. Wright et al., 2009).

The present paper focuses on the nature and development of well-exposed examples of weakly or uncemented cavity fills associated with fractures cutting Palaeogene basaltic lava sequences in the Faroe Islands. It is shown that the formation of open cavities in the sub-surface occurred with post-magmatic fault reactivation, probably

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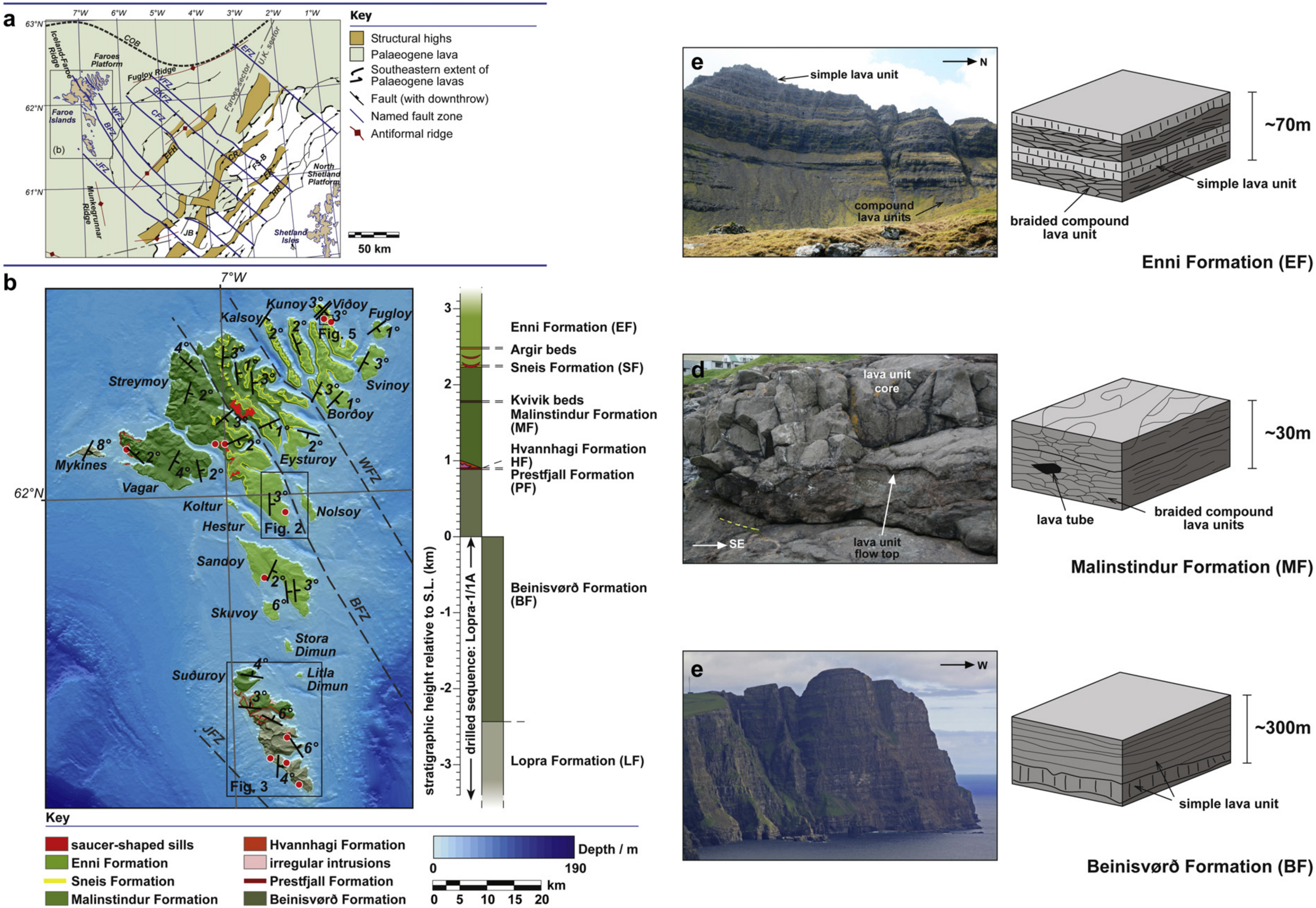


Fig. 1. (a) Simplified structural elements map of the Faroe-Shetland Basin, NE Atlantic margin with location of the Faroe Islands: EFH, East Faroe High; FS-B, Flett Sub-Basin; JB, Judd Basin; CR, Corona Ridge; FR, Flett Ridge; RR, Rona Ridge; BFZ, Brynhild Fault-Zone; CFZ, Clair Fault-Zone; EFZ, Erlend Fault-Zone; GKFZ, Grimur Kamban Fault-Zone; JFZ, Judd Fault-Zone; VFZ, Victory Fault-Zone; WFZ, Westray Fault-Zone. (After Stoker et al., 1993; Rumph et al., 1993; Lundin and Doré, 1997; Sørensen, 2003; White et al., 2003; Jolley and Morton, 2007; Ellis et al., 2009). (b) Simplified geological map of the Faroe Islands and gross stratigraphic column for the Faroe Island Basalt Group (after Passey, 2009). Red dots indicate locations of clastic-filled fault cavities. (c–e) Photographs of the Beinisvord (c), Malinstindur (d) and Enni (e) Formations with block diagrams displaying the typical characteristics and stacking styles of the lava units (after Passey and Bell, 2007).

during regional uplift. The implications for regional tectonic models and sub-surface fluid flow are then briefly discussed.

2. The Faroe Islands: geological setting

2.1. Regional context

Much of the NE Atlantic passive margin is covered in a thick pile of trap-style crystalline volcanics (Fig. 1a), as part of the North Atlantic Igneous Province (NAIP; emplaced ~62–54 Ma; Saunders et al., 1997), of which the Faroe Islands Basalt Group (FIBG; Passey and Bell, 2007) is a constituent. From a petroleum industry perspective, basins along the margin are relatively underexplored, in part due to the presence of this volcanic cover. In the past decade, the Faroes sector of the margin has opened for licensing, and based on the presence of several large hydrocarbon-producing fields in the nearby UK sector (e.g. the Clair, Foinaven and Schiehallion fields) exploration activity increased rapidly.

The FIBG was emplaced at or around sea-level during the Palaeocene. The lavas display a progradational stacking geometry, with a true vertical thickness of about 2–3 km, requiring therefore a comparable magnitude of subsidence during the eruption period. To date, most structures preserved on the Faroe Islands are attributed to subsidence-related deformation (Geoffroy et al., 1994; Ellis et al., 2009; Passey, 2009). A progressive anticlockwise rotation in the regional extension vector, from NE–SW to NW–SE, is recorded by analysis of cross-cutting fault, fracture and dyke sets (see below) which is related to changes in the location and kinematics of ocean spreading in the North Atlantic region (Walker, 2010; Walker et al., 2011). No onshore structures have been related to the subsequent uplift that must have occurred to bring the Faroe Islands up to their current elevation (the highest peak, Slættaratindur, lies at 882 m A.S.L.). The principal aim of this study is to highlight the roles of post-magmatic to recent fault reactivation in forming open, subterranean cavities, fissures and caves that subsequently become infilled by clastic sediments. Unlike other earlier faulting episodes, these infills lack widespread mineralisation and may therefore have acted as preferential channel ways for the migration of hydrocarbon accumulations developed beneath or within the volcanic cover sequences of the NE Atlantic region.

2.2. Stratigraphy

The FIBG is a prograding sequence creating a gross stratigraphic thickness in excess of 6.6 km, dominated by tholeiitic basalt lavas and divided into seven formations based on lithology and the presence of regionally recognised disconformity surfaces (see Rasmussen and Noe-Nygaard, 1969, 1970; Passey and Jolley, 2009) and geochemistry (Waagstein, 1988). The formations relevant to the present onshore study are from oldest to youngest: the Beinisvørð; Malinstindur; and Enni Formations (Fig. 1b–e).

The Beinisvørð Formation (BF) is stratigraphically ca.3.3 km thick with only the upper 900 m exposed above sea level on the Islands (Fig. 1b and c). The BF comprises aphyric, laterally extensive sheet lobes, commonly separated by minor volcaniclastic horizons (Passey and Bell, 2007). The sheet lobes display well-developed columnar joints that are commonly observed to be exploited during faulting, and can result in greatly steeper fault-plane dips compared to faults cutting clastic horizons located between lava flow units.

The overlying Malinstindur Formation (MF) is stratigraphically ca.1.4 km thick (Fig. 1b and d) and comprises subaerially emplaced, compound basalt lavas that are initially olivine-phyric evolving to aphyric, and then plagioclase-phyric types. Again, lavas are commonly separated by minor clastic horizons, typically volcaniclastic sandstones and siltstones, which were deposited during periods of volcanic quiescence (Ellis et al., 2002).

The lowermost 900 m of the Enni Formation (EF), is exposed on the islands (Fig. 1b and e), and comprises interbedded simple (sheet lobes) and compound tholeiitic lavas. The 900 m represents a minimum stratigraphic thickness, with 200–300 m likely eroded from the top of the volcanic pile based on the nature and abundance of amygdale mineral fills (Waagstein et al., 2002).

Units on the Faroe Islands display a gentle anticlinal pattern that represents the onshore expression of the Fugloy and Munkegrunnar ridges (Fig. 1a). The largest dips are observed in the Beinisvørð Formation on Mykines (~8°) decreasing up-stratigraphy to become sub-horizontal (i.e. ~1°) in the Enni Formation on Fugloy, Svinoy and Viðoy (Fig. 1b). This geometry suggests regional-scale tilting due to fold-growth throughout the Palaeocene during emplacement of the FIBG (e.g. Doré et al., 2008; Walker, 2010; Walker et al., 2011).

2.3. Structural evolution

Walker et al. (2011) describe the results of a detailed field study where they analysed the cross-cutting relationships between faults and dykes exposed on the Faroe Islands. They also used fault plane and slickenline data to perform stress inversion analysis to constrain the orientations of the principal stress axes. Together, these results show that structures developed in the FIBG record a five-phase rift-reorientation through time before and during continental break-up, followed by a phase of uplift. Walker et al. (2011) show that most faulting phases occurred during, and for a period immediately after, regional magmatic activity (lava extrusion, emplacement of dykes and sills). The five distinct phases of extension recognised in the Faroes, occurring before, during and probably for a time following Eocene age continental break-up, begin with ENE–WSW to NE–SW extension (Stage 1), accommodated by N–S- and NW–SE-trending dip-slip faults. Continued NE–SW extension (Stage 2) was then accommodated by the emplacement of a regionally significant swarm of NW–SE- and NNE–SSW-trending dykes. Collectively, Stages 1 and 2 affect the majority of the FIBG stratigraphy, into the lower third of the Enni Formation. Continued magmatism and an anticlockwise rotation of the extension vector (during Stage 3) led to the emplacement of ENE–WSW and ESE–WNW conjugate dykes, marking the onset of N–S crustal extension. This N-S extension continued together with E–W shortening (Stage 4) facilitated primarily by slip on ENE–WSW (dextral) and ESE–WNW (sinistral) conjugate strike-slip faults. Many faults were developed within the immediately preceding conjugate dykes. A component of the E–W shortening was facilitated additionally by the development of numerous minor-offset thrust faults, which dip mainly to the SW or NE. Stage 4 has resulted in a thickening of the Enni formation across major fault zones, as well as large (100–300 m) offsets of the uppermost parts of the Formation, and therefore began toward the end of magmatism associated with the FIBG, and continued for a period afterward. The regional extension vector then rotated into a more NW–SE orientation that was preferentially accommodated by slip along NE–SW trending dip-oblique-slip faults with a dextral motion sense (Stage 5).

Stages 1 to 5 are associated with multiple generations of calcite and zeolite mineralisation hosted in linked arrays of extension and extensional-shear veins. Field and thin-section observations suggest that mineral growth occurred both as a precursor to the development of through-going slip surfaces, and during fault slip with precipitation of minerals along irregular fault surfaces (Walker, 2010). For the sake of simplifying reference to relative timings throughout the present paper, these five stages of fault-related deformation are referred to as 'syn-magmatic'. The final phase of deformation (Stage 6), the focus of this paper, reactivates and cross-cuts existing syn- to early post-magmatic structures, and in contrast to previous stages lacks mineralisation (Walker et al., 2011). Using cross-cutting relationships and, combined with the relative timings of stages 1–5, Walker et al. (2011) inferred that Stage 6 post-dates regional magmatism.

3. Post-magmatic structures: detailed geological characteristics

Stage 6 structures on the Faroe Islands consistently cross-cut and reactivate structures formed during Stages 1–5. Unlike earlier structures, Stage 6 faults typically contain entrained clastic sedimentary materials. Detailed sedimentological analyses (e.g. of petrography, grain size and sedimentary structures) and studies of shear-related fabrics and faults reveal two modes of emplacement: infilling and intrusion. The infills are more widespread and are further sub-divided into two sets based on their geometry and location relative to causative faults.

3.1. Subvertical clastic infills

In several locations within the FIBG (eleven separate examples for the present study; Fig. 1), uncemented clastic sediments along existing mineralised faults indicates the development and filling of cavities in the absence of mineralising fluids. The clastic sediment infills, which are sometimes bedded, have in most cases undergone internal deformation during subsequent fault movements. Here we present two type-examples of such clastic fault infills: one of predominantly fine sediments at Glyvursnes, Streymoy (Figs. 1 and 2), and one of matrix-supported breccia at Vagseiði, Suðuroy (Figs. 1, 3 and 4).

3.1.1. Fine sediment fills

Glyvursnes quarry is located about 3.5 km south of the Faroese capital, Torshavn, in the SE of Streymoy (Fig. 2a and b). A near vertical (dip ~85–90°) ESE–WNW trending fault, with a small apparent offset (~5–10 cm) down to the south (Fig. 2c) displays minor faults, fault rocks and fractures that are typically mineralised by calcite and zeolite. Vuggy growths on the wall rocks indicate a predominantly extensional (mode I) opening, and can therefore be kinematically and texturally linked to Stage 4 N–S extension. Lenses of unmineralised sediment are developed over a vertical distance of ~15 m along the irregular central master fault (Fig. 2d and e). Individual lenses range from 2–25 cm thick, and are up to ~3 m high. At the base of the exposure, the sediment consists of a clay to silt matrix, which supports sub-angular to sub-rounded clasts. This base is overlain by horizontally laminated fine sands, silts and clays (Fig. 2d–f) that alternate sharply. In some cases, laminations of fine sands to silts contain clasts of clay (up to 1 mm diameter). Laminae are offset by a linked network of minor normal faults that typically dip at ~70°, with mm- to cm-scale offsets. At no point are faults observed cutting from the sediment into the surrounding basalt, or vice versa, and no mineralisation is observed within the sediment infills.

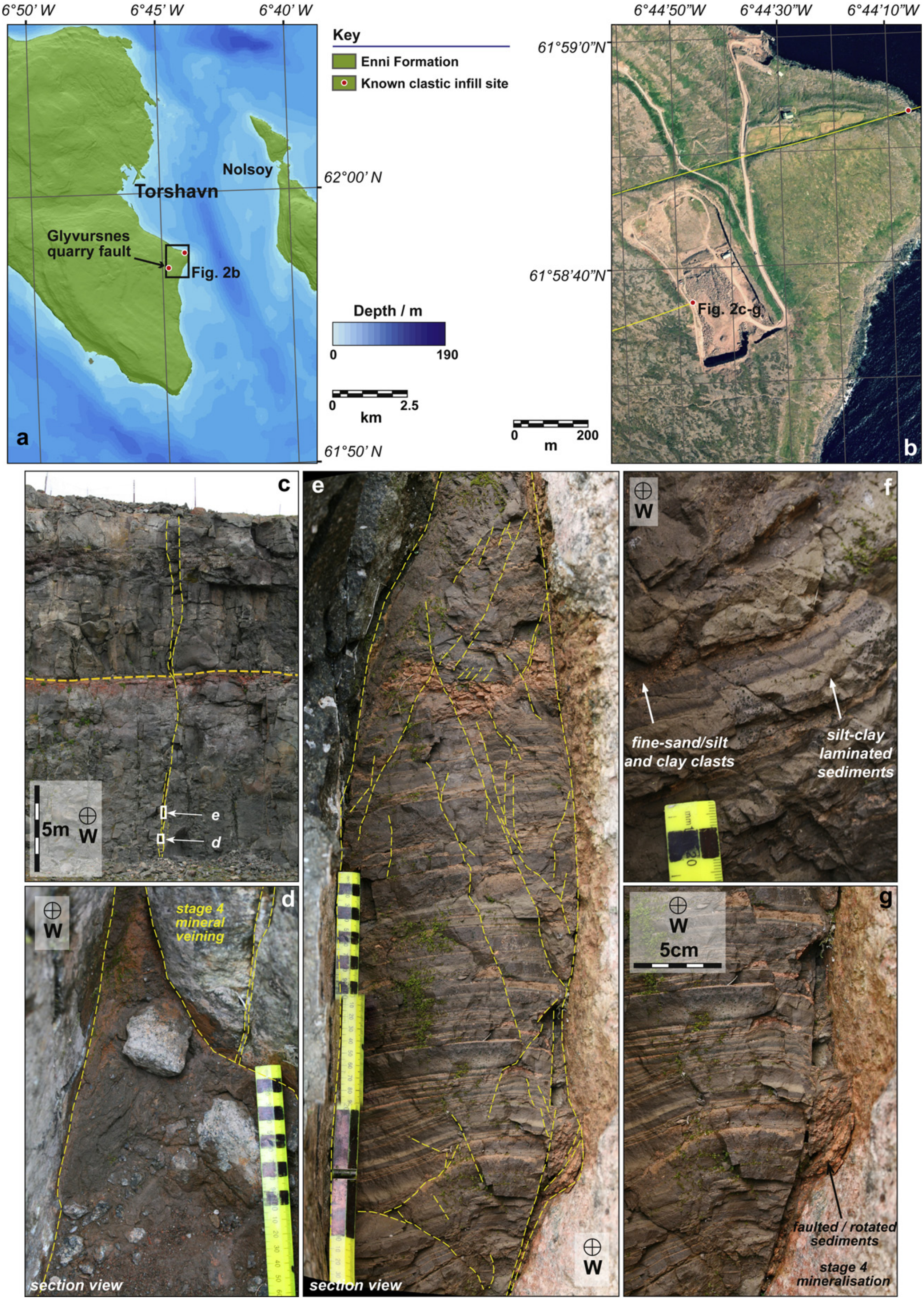
The fine grain size and lack of well defined cross-laminations indicates that deposition was probably dominated by gravitational settling, although the small clay clasts may represent ripped-up intraformational material formed during transient periods of higher energy fluid flow. Locally, laminations appear to thicken at mm-scales across some faults, indicating that some fault motion was coeval with sedimentation. Offset laminations across faults, without observed thickness variation indicate that faulting also postdated deposition. In some places, the laminations in fault-bound blocks are rotated into sub-vertical dips (e.g. Fig. 2g). In such instances, we suggest that contiguous blocks of laminated sediments were dragged and rotated during repeated displacements and minor dilation along the main fault, perhaps following detachment from the adjacent crystalline wall rocks. The lack of mineralisation within the sediment fill, either as a cement or along faults, indicates that sedimentation post-dates the hydrothermal mineralisation associated with Stage 4 or 5 faulting, hence they are post-magmatic.

3.1.2. Mixed breccia fills

The second type-example of infilling is found at Vagseiði (Figs. 3 and 4), located on the west coast of Suðuroy (Fig. 3a). The fault trends NW–SE (152°) (Fig. 3a) and displays a well-developed damage zone about ~3–5 m thick (Walker, 2010). Fault rocks here display calcite and zeolite mineralisation within mode I and mixed-mode veins, as well as vuggy growths within zones of basaltic breccia. Marker horizons on either side of the fault indicate a throw of ~10–15 m, and available calcite slickenfibres indicate a dip slip, down to the east motion sense, resulting in a NE–SW extension. These mineralised fault rocks are therefore kinematically linked to Stage 1 (Walker et al., 2011). The fault zone contains lenses of unmineralised volcaniclastic, chaotic breccia that is mainly matrix-supported (Fig. 4a–e) (breccia classifications after Woodcock et al., 2006).

Sediment lenses occur sporadically along the vertical extent of the exposed fault and range in thickness from 10 cm to ~1.5 m and they are typically vertical over a distance of 1–5 m. The sediments are composed of clay to fine-sand sized matrix, which generally supports sub-angular to sub-rounded clasts, of which ~90% are variably altered aphyric basalt, similar to that of the surrounding basalt flow units. Some clasts host zeolite amygdales, and calcite and zeolite veins. The rest of the clast population is comprised of dull-brown volcaniclastic sandstones and bright red claystone, which in some areas can be traced back via a continuous set of aligned clasts into the source volcaniclastic horizons found in between lava units. These examples probably represent local dragging of the source horizon following gravitational deposition of clastic sediments (e.g. Fig. 4b). The lower exposures (from 40–70 m A.S.L., e.g. Fig. 4a, b and d) are generally massive, whilst the upper exposures (90–100 m A.S.L., e.g. Fig. 4c and e) display a crude, highly inclined grading (with layers dipping 65° W) defined by zones of matrix-supported breccia, smaller-clast-supported breccia, and fine sediment material (Fig. 4e). The sediment is cut by unmineralised dip-slip faults (see stereonet in Fig. 4) that do not cut the surrounding basalt units, and near to which the graded layering is steepened further (dipping ~75° W), as picked out by alignments of high aspect ratio clasts (Fig. 4e).

Based on the lack of mineralisation in the sediment infills, and the cutting and entrainment of mineralised fault rocks, we interpret that the sediments post-date initial (syn-magmatic) fault formation. As with the Glyversenes fault, grading in the sediments is attributed to gravitational settling processes, requiring the development of a set of open subterranean cavities along the pre-existing master fault. Based on the absence of large thickness variations, or folds related to soft-sediment slumps, the grading in the deposit was probably initially sub-horizontal, and was subsequently tilted into its present orientation due to drag associated with later fault movements. The drag sense within the sediment indicates down to the west movements, whereas the motion sense of the Stage 1 host fault is down to the east (Fig. 4a–e and 3b respectively). The clasts at Vagseiði are assumed to be mostly related to the succession exposed in the immediate surroundings, based on mineralogical and petrological similarities to the wall


6°50' W
6°45' W
6°40' W
Key
Enni Formation
Known clastic infill site
Nolsoy
Torshavn
62°00' N
Glyvursnes quarry fault
Fig. 2b
Depth / m
0
190
0
2.5
km
a
61°50' N
6°44'50"W
6°44'30"W
6°44'10"W
61°59'0"N
61°58'40"N
Fig. 2c-g
0
200
m
b
c
5m
W
e
d
e
section view
W
f
W
fine-sand/silt and clay clasts
silt-clay laminated sediments
d
W
stage 4 mineral veining
section view
g
W
5cm
faulted / rotated sediments
stage 4 mineralisation

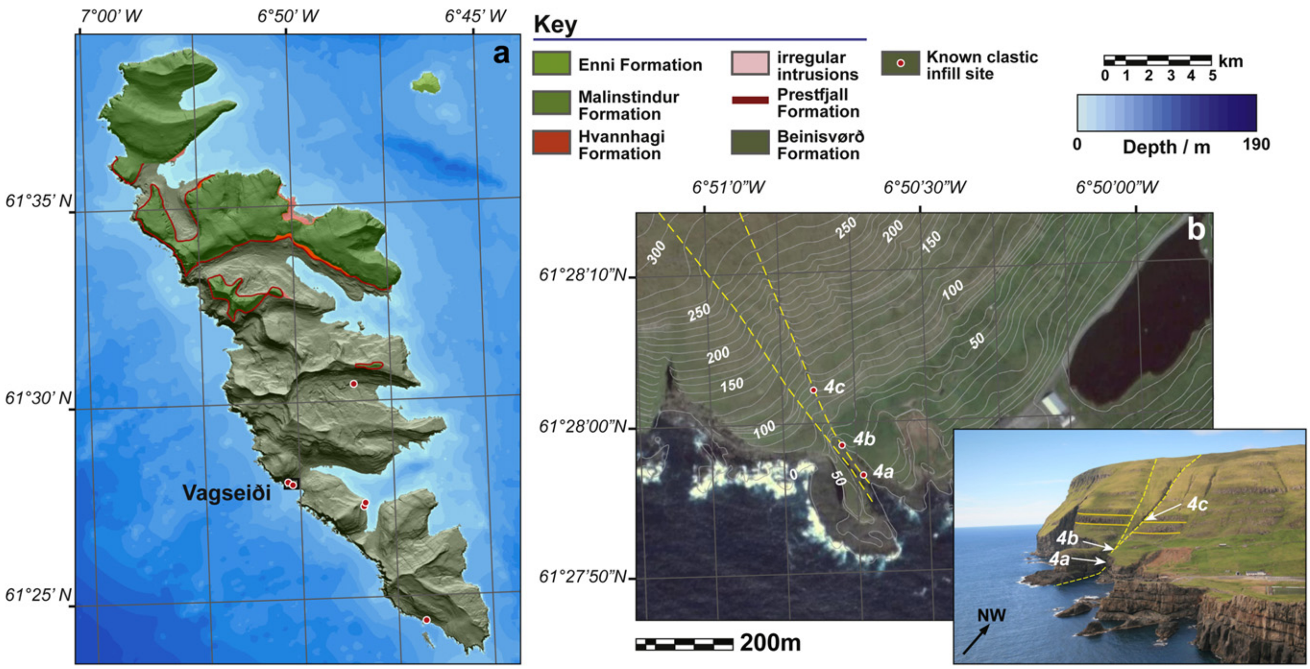


Fig. 3. (a) Simplified hill-shaded geological map of Suðuroy with surrounding bathymetry. Location of Vagseiði (Fig. 5) indicated by the labelled box, and locations of similar infill structures indicated by red circles. (b) Contoured satellite photograph of the coast at Vagseiði (base image from *GoogleEarth: NASA image, 2009 DigitalGlobe*). (inset b) Overview of the NW–SE trending fault at Vagseiði, which displays a ~10–15 m displacement, down to the east (height to 'd' is ~95 m A.S.L.). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

rocks (i.e. a mixture of aphyric simple lava units and volcanic tuff fragments). However, in the absence of a zone of intense alteration and comminution of the host basalt lava units (to fine-sand sized particles), it is clear that some sediment grains, particularly the fines forming the matrix within this and the Glyversnes example, are not solely sourced from the surrounding wall rocks.

3.1.3. Infill summary

It is well known that displacements along irregular fault planes can lead to the development of dilational features, such as jogs, in the sub-surface. At shallow crustal depths (0–2 km), dilation along faults can result in the formation of persistent cavities or even cave systems (e.g. Loucks, 1999; Woodcock et al., 2006; Wright et al., 2009). The gravitationally deposited fills presented here require the opening and maintenance of such subterranean cavities along pre-existing faults (Fig. 4f). Deformation structures developed in the sediment fills also indicate that initial dilation was followed by repeated subsequent minor faulting episodes. The development of these open cavities and the lack of mineralisation, suggests that these features probably formed at very shallow crustal depths, near the surface.

3.2. Off-fault sub-horizontal clastic fracture-infills

Irregular fracture-hosted sub-horizontal clastic infills are preserved in a number of localities on the island of Viðoy in the NE of the Faroe Islands (Fig. 5a). The best exposures occur on the western coast near the village of Viðareiði (Fig. 5) within the Malinstidur Formation (Fig. 1). The topographic low in which the village sits is bounded by oblique-slip, large offset (≥20 m throw) faults, creating a local E–W trending graben (Fig. 5). Faults, fractures and fault rocks in the area display calcite and zeolite mineralisation, as is typical of the syn-magmatic fault events. ENE and ESE conjugate strike-slip faults linked with abundant NW and SE dipping thrust and low-angle normal faults are prevalent. These structures are kinematically linked to Stage 4. Locally they are cut by NNE–SSW and NE–SW trending oblique-slip faults, characteristic of Stage 5 (Walker, 2010). The stratigraphy of the area is dominated by 2–4 m thick compound lavas with occasional intercalated minor (30–50 cm thick) volcaniclastic horizons. On the western coast of Viðareiði (Fig. 5b; the Viðareiði coastal section henceforth), the lava units are individually thinner, forming a set of overlapping, perhaps braided, flow channels and lobes (e.g. Fig. 1d; Passey and Bell, 2007). The section is also host to a number of generally sub-horizontal volcaniclastic horizons (10–60 cm thick with 0–3° dips) that locally cut diagonally (45–75° dips) through the lava units (Fig. 6).

Lava units in the Viðareiði coastal section typically preserve well-developed lower crusts, core regions, and upper crusts (e.g. Fig. 1d). The lower crust is characterised by the development of pipe amygdales that start a centimeter or so from the base of the unit and are often inclined, with the top pointing in the palaeoflow direction. The lava unit core is generally a massive zone with more spherical-shaped amygdales, and irregular joints ranging in orientation from sub-horizontal to sub-vertical. In the upper crust, amygdales are again spherical and the groundmass often exhibits a progressive reddening towards the top. Upper lava unit crusts commonly exhibit classic pressure-ridge "rope-structures" that are

Fig. 2. (a) Simplified hill-shaded geological map of south Streymoy with surrounding bathymetry. (b) Aerial photograph of Glyvursnes quarry with fault traces indicated by yellow lines. (c) Overview of the fault at Glyvursnes quarry, one of many Stage 4 (ENE–WSW trending) faults observed in the quarry walls (yellow dash) with offset marker horizon indicated by the dashed orange line. (d) Close-up view of the lowermost section of the fault exposure: matrix-supported sub-angular to sub-rounded clastic material abutted against Stage 4 mineralisation. (e–f) Fine clastics (≤1 mm, clays and silts) are arranged in sub-horizontal parallel laminations, suggesting filling of the cavity from the bottom upward. Extensional-shear faults offset the laminae. (g) Localised rotated and faulted laminations at the fault margin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

characteristic of pahoehoe-type lavas. These lava flow unit features are particularly important when considering the nature of the contact relationships between the clastic horizons and the lava units.

The red–brown volcaniclastic horizons are extremely variable laterally and vertically, displaying a wide range of sedimentary structures (Fig. 7). These include: horizontal laminations (e.g. Fig. 7a and c); planar cross laminations (e.g. Fig. 7b); erosional scours (e.g. Fig. 7b and f); and gravel lenses (e.g. Fig. 7a). The matrix is loosely held together by clay minerals and preserves no clear mineral cement. Laminations of silts and clays at the tops of the clastic horizons commonly undulate following the underside of the immediately overlying lava unit (e.g. Fig. 7d–f). Sediments in direct contact with the lavas display no evidence of baking or induration, and in some areas abut against mineralised fault/fracture surfaces (Fig. 7e) and even incorporate mineralised basalt fault rocks as clasts. Most clasts are basaltic (i.e. >90%) and display features typical of the surrounding lava units (e.g. amygdales, etc.). In one example (Fig. 7a) a 50 cm long line of lava fragments, displaying a cooled lower crust and pipe amygdales, must have fallen into the sediment, as it exactly matches the discontinuous cooling crust and amygdale features of the unit directly above. Other clasts (~5%) cannot be matched with the surrounding exposed stratigraphy. Some clasts appear to be intraformational, derived from the clay materials that form more continuous layers within the sedimentary horizons (e.g. Fig. 7a and c). These intraformational clay clasts account for <1% of the total clast population within these volcaniclastic horizons, but locally, are the only clast lithology present.

Volcaniclastic horizons exposed along the Viðareiði coastal section cross-cut solid-state features in the lavas, and mineralised fault rocks (Fig. 6), but are not themselves mineralised. These observations demonstrate that the volcaniclastic materials were emplaced after the lava sequence, and after the Stage 4 and 5 faulting episodes that deform the Malinstindur Formation. The clastic infills were emplaced along reactivated or re-opened mineralised faults and must, therefore, be post-magmatic.

The intricate sedimentary structures preserved in the sub-horizontal horizons suggest that the sediments were deposited by water currents flowing through open cavities. The preservation of reworked clay intra-clasts indicates that deposition was not a continuous process, and implies that clay settling and cohesion could occur before further fluid flow through the system. Based on this compelling evidence, we interpret the sub-horizontal clastic horizons as representing an infilled cave system that originally developed in the sub-surface. The sediments were water-lain and, at times, the stream power was sufficient to rip up cohesive laminated clays, and transport 1–3 cm diameter basaltic clasts. Evidence is lacking for multiple cave-opening events, which suggests that the caves possessed apertures at least as wide as the present-day sediment thickness, but potentially greater allowing for compaction and remobilization of clastic fills (see Section 3.3). The apertures were sufficient to allow sedimentation and fluid flow, whether it be a single waxing and waning event, or multiple events.

3.3. Clastic intrusion networks

The sub-horizontal clastic sedimentary fills at the Viðareiði coastal section (Figs. 6 and 7), are locally cut by two styles of variously oriented tabular bodies of massive clastic sediments. These styles are: (1) 0.1–0.3 m thick planar veins that are predominantly found along pre-existing mineralised faults (e.g. Figs. 6a and 8b); and (2) thin anastamosing veins that cross-cut both solid-state features in the lavas (Fig. 8c) and sedimentary structures within the sub-horizontal clastic horizons (Fig. 8d and e). Gravitationally-deposited bedded sediments are cut and dragged upward by massive clastic sediments that are continuous from the sub-horizontal horizons (Fig. 8b). Drags of fine laminations indicate that most are upward-directed from the sub-horizontal source horizon, and hence these features must represent clastic intrusions.

The basalt walls of the thicker intrusions (Fig. 8b) display calcite strike-slip slickensides. These surfaces bound structureless units of matrix-supported volcaniclastic sediment, ranging from chaotic breccias to fine (clays to fine-sand) sediment lacking clasts. No mineralisation is observed within the matrix, though clasts (>90% of which are basaltic) do display zeolite and calcite mineralisation in the form of amygdales and discrete veining. Where the clastic intrusions meet the cave-fill units, coarse clastic material forms a continuous pathway between the two (Fig. 8b). However, the horizontal laminations toward the top of the cave-fills are discontinuous at the intersection, and appear to be dragged upward, with a rapid thinning and pinching-out of the package as it meets the vertical intrusion (Fig. 8b). The apparent truncation indicates that the clastic materials in the vertical intrusions were sourced from the cave-fills below, requiring upward remobilization of the sediment. Since the basalt surfaces of the conduit are mineralised, the clastic intrusions must occur along reactivated faults in the section, but with a predominantly tensile mode of failure.

The thinner intrusion types generally range from 0.1–1 cm thick (Fig. 8c) with individual intrusions continuous for up to 5 m. Internally, these intrusions are composed of fine materials (≤1 mm), such as silts and fine sands. In rare cases, they display a poorly developed margin-parallel lamination. Like the thicker intrusions, no mineralisation is observed within these sediments. The thinner units vary in orientation along a single intrusion, and cut across solid lava unit features such as cooling crusts, pipe amygdales (Fig. 8c), and mineralised fractures. Intrusions are also developed along and through the upper and lower cooling crusts of the lava units. Similar intrusions are observed within the cave-fills at meso- to micro-scopic scales (Fig. 8d and e), and are most evident where light-brown clays cut through dark-brown/grey coarse clastic materials.

So-called clastic intrusions (i.e. generally tabular bodies of clastic sediment that appear to have been forcibly injected along fractures into their host rocks under conditions of elevated fluid pressure) are reported from several geological settings worldwide with various proposed causative mechanisms (e.g. Richter, 1966; Jolly et al., 1998; Rijsdijk et al., 1999; Beacom et al., 1999; Phillips and Alsop, 2000; Jonk et al., 2004; Le Heron and Etienne, 2005; Goździk and van Loon, 2007). Based on the relative cross-cutting relationships at Viðareiði, it is clear that the intrusions post-date the basalt lava units at Viðareiði, and since they are demonstrably sourced from the cave sediments, must also post-date their deposition. Intrusion may have been triggered by the closure of the Viðareiði cave network (see Section 3.2), resulting in differential compaction of the water-saturated sediments, which would lead to the local generation of overpressures within the infilled cave network. Sediment pore-fluids would be expelled resulting in localized remobilization and upward injection of the sediments toward areas of lower pressure (see below).

3.4. Summary

The clastic infills and intrusions occur along and adjacent to locally reactivated or re-opened faults and fractures that initiated during magmatism and subsidence (i.e. Stages 1–5; see Section 2.3;

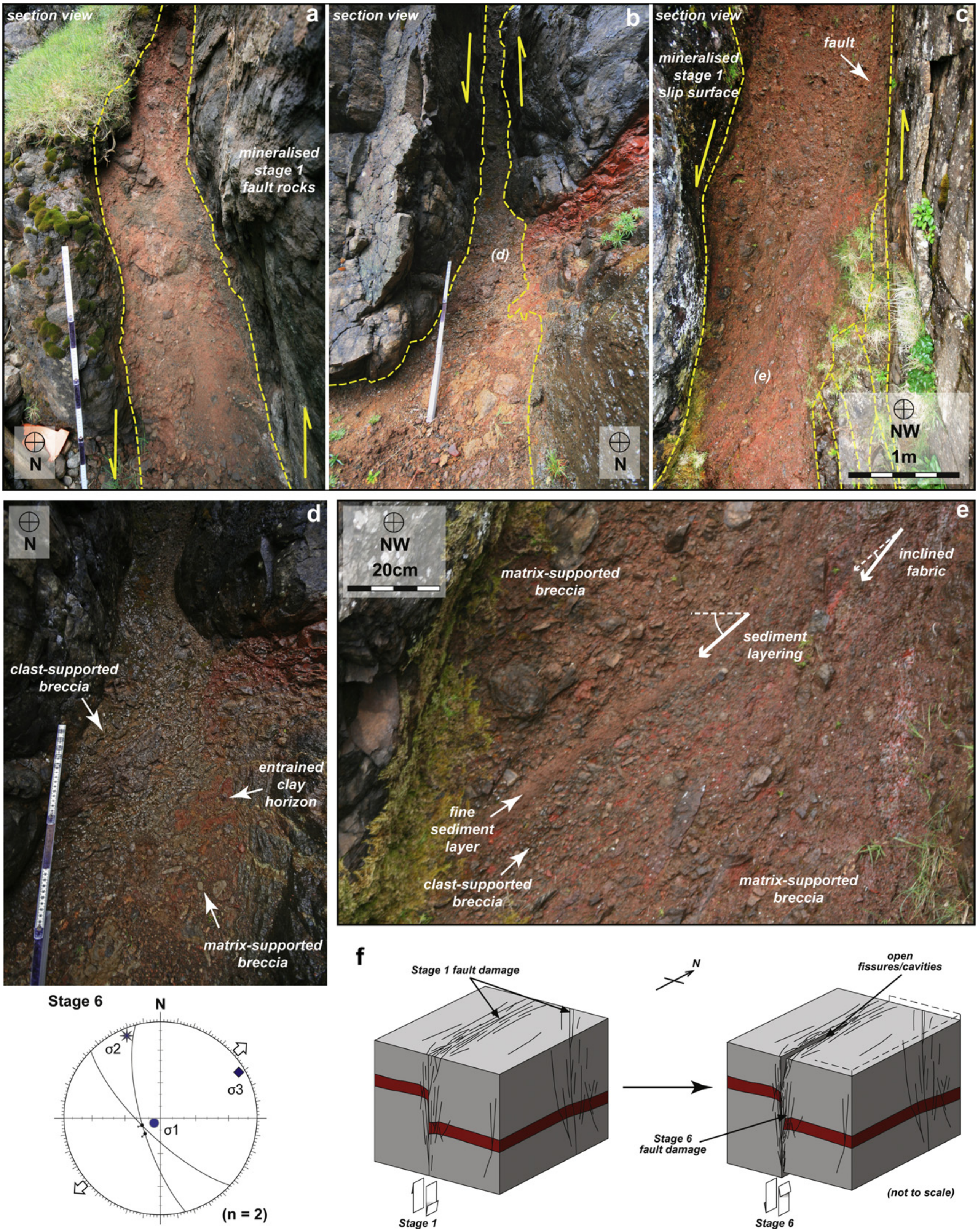


Fig. 4. (a–c) Overview of unmineralised matrix-supported clastic breccia lenses at Vagseiði (Location in Fig. 3). In (b) the clay horizon on the right has been entrained into the gravitationally deposited clastic sediments. (c) Chaotic breccia with an inclined grading and drag fabric again indicating a down to the west sense of motion. (d,e) Detail photos from *b* and *c* respectively – the shear sense (down to the west) within the sediments is opposite to the sense of motion of the host fault. (f) Summary model for the formation of persistent sub-surface cavities, based on the outcrops at Vagseiði, with lower hemisphere stereographic projection for fault-slip data, with idealised principal stress orientations and extension vector (calculated in MyFault™ v.1.03 using the simple-shear tensor average technique: Sperner et al., 1993).

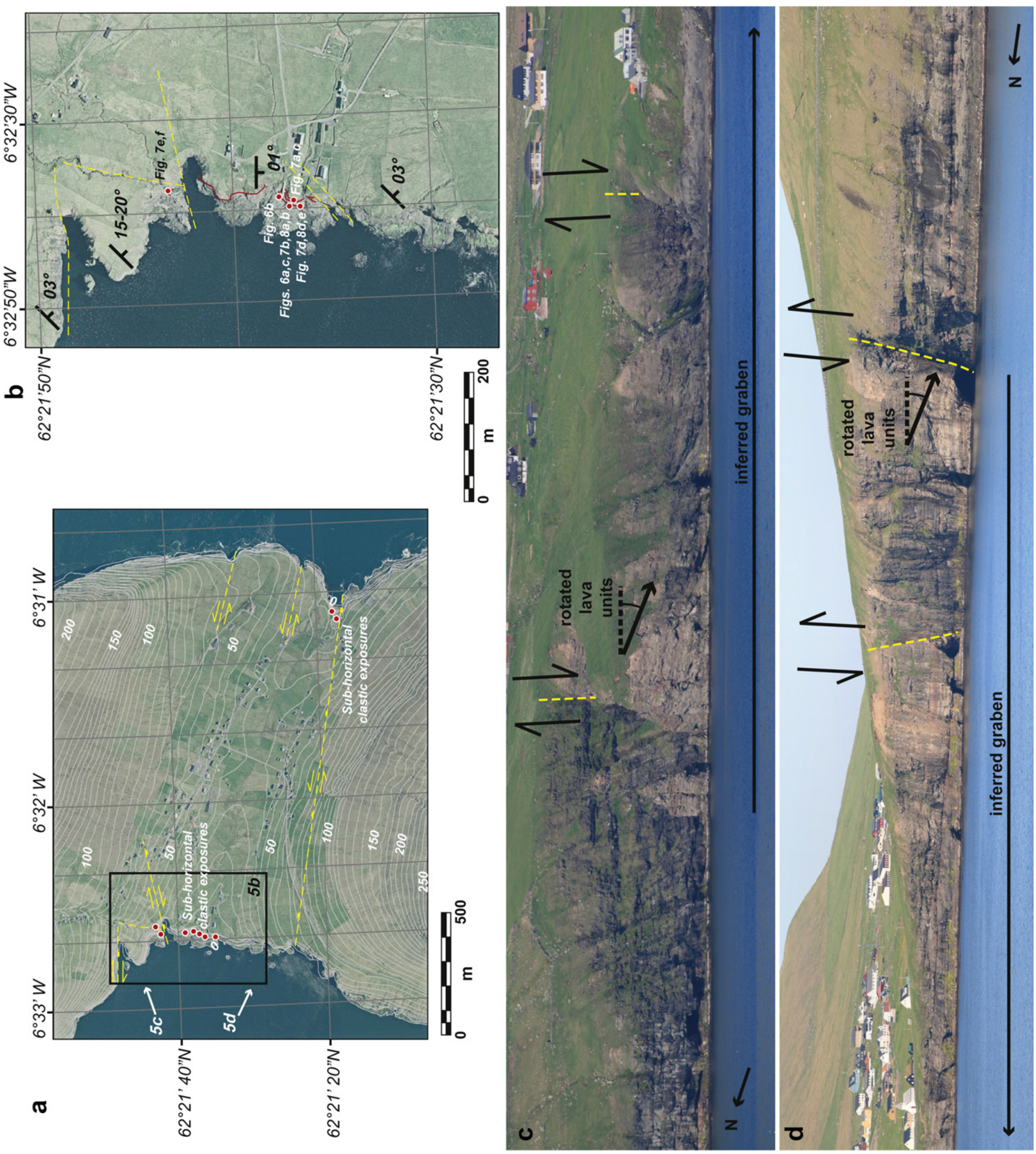


Fig. 5. (a) Contoured aerial photograph of Viðareiði showing the locations of major graben-forming faults in the area. (b) The Viðareiði coastal section detailing major faults and the location of the Viðareiði clastic horizons (outlined in dark red). (c,d) Overview of the west coast of Viðoy at Viðareiði. To the north of the village on the coast (c) a fault-bound section exhibits a much steeper dip than that of the surrounding units. (d) Units in the hanging-wall of the southern graben-bounding fault, are inferred to display a reverse drag geometry. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Walker et al., 2011). We therefore infer that these structures formed following emplacement of the FIBG. These post-magmatic structures lack mineralisation, and consistently show evidence for the existence of open cavities during their formation. The absence of a cement and the preservation of sedimentary structures in the infills suggests that these features formed in the near surface, perhaps at depths less than a couple of kilometres.

4. Discussion

4.1. The formation, filling and local collapse of sub-horizontal cavities at Viðareiði

Using the presence of sedimentary infills, we have shown that sub-horizontal to sub-vertical cavities existed in the sub-surface

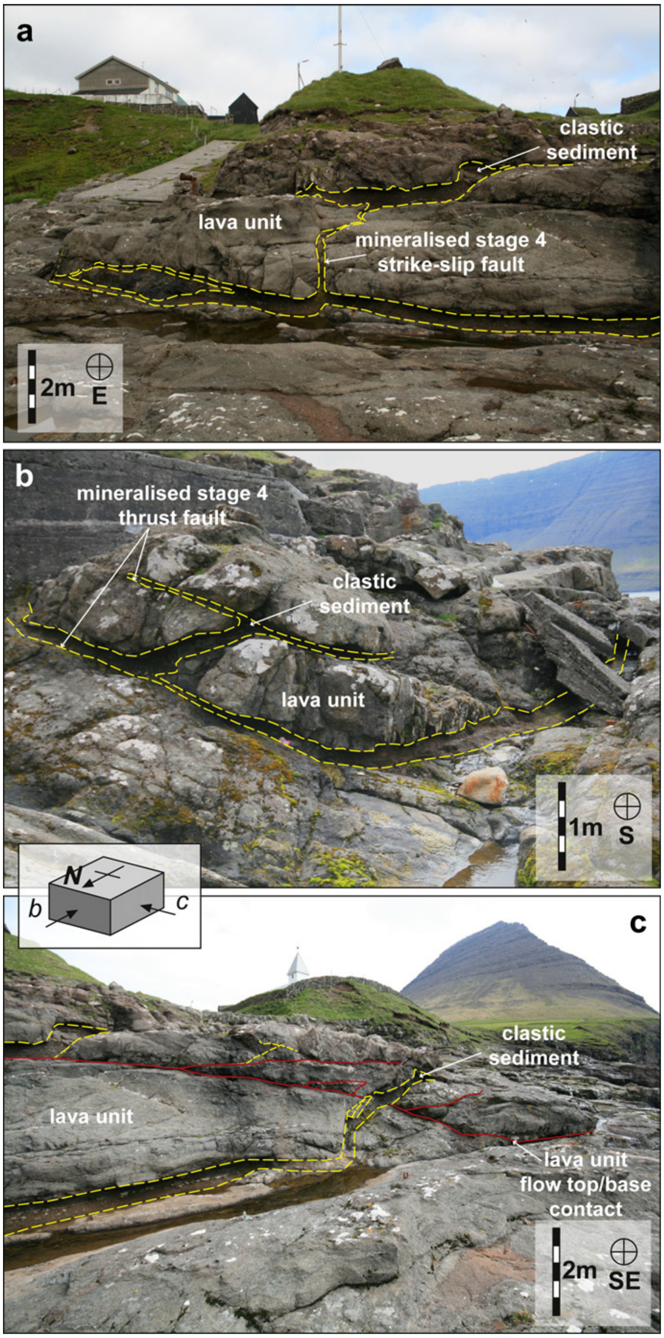


Fig. 6. (Locations shown in Fig. 5). (a) The Viðareiði coastal section (looking east) comprising overlapping, sub-horizontal lava units, separated by 0.3–0.6 m thick clastic horizons (delimited by dashed lines). In some instances the clastic horizons are linked by vertical injections along mineralised faults (detailed in Fig. 8); (e and f) Clastic horizons commonly display ramp sections that dip at about 45–75°, which cross-cut solid-state features within the surrounding basalt units.

as widespread post-magmatic features in the Faroe Islands. Sub-vertical cavities (e.g. Figs. 2 and 4) are developed along existing locally reactivated faults, and their formation could simply be attributed to late-stage, near-surface slip along irregular normal fault planes. The sub-horizontal (cave) fills and associated intrusions at Viðareiði have rather different geometries and internal textural characteristics, and have not developed along a single normal fault. This style of clastic infill is well-exposed in a number of coastal localities (the "coastal sections" henceforth) at Viðareiði, on the east and west coasts within an E–W trending graben (Fig. 5a). The formation of subterranean cavities in this area may therefore relate to conditions specific to the area. Here we propose two general mechanisms for the formation and opening of these features (Fig. 9), before discussing their infilling and closure.

The coastal sections at Viðareiði comprise lava units of the Malinstindur Formation. Within the E–W graben (Fig. 5), units are stacked as overlapping pahoehoe-type flow lobes that are individually thinner (<2 m thick) than the units to the north and south (individually >3 m thick). Holland et al. (2006) have shown that fault geometry differs between thick- and thin-layered basaltic sequences. Thin-layer sequences contain a greater abundance of discontinuity surfaces (i.e. interfaces between lavas) than thick-layer sequences. We suggest that the geometrically necessary wall rock strains during reactivation of, and slip along, pre-existing (mineralised) faults at Viðareiði were accommodated by dismemberment and rotation of the thinly-bedded, overlapping lava flow lobes of the Malinstindur Formation (Fig. 1). In a low confining pressure environment, such dismemberment is inferred to involve the opening of interlinked fissures and cavities of various sizes and orientations (Fig. 9).

Horizontal laminations in the uppermost parts of some clastic horizons are clearly the product of gravitational settling, which suggests that in some areas, the aperture of the cavity was originally larger than at present. Collapse of the overlying lava flow would also account for the undulating laminations seen at the tops of some cavity fills, which may have resulted from compaction and molding of the wet sediment against the lava roof as it descended. Periodic settling and partial collapse of the cave system may have occurred during ongoing fault slip or simply by gravitational collapse. In either case, roof collapse and wet-sediment compaction may have caused the development of localized fluid overpressures and remobilization of the clastic infills leading to the formation of clastic intrusions.

The clastic fills display planar cross-laminations, horizontal laminations, scour structures and gravel lenses (e.g. Fig. 7). These observations show that water flow rates through the system were highly variable with periods when the flow rate was sufficient to erode coarse-grained layers and carry basalt clasts (1–3 cm modal range), which were interspersed with more quiescent periods that allowed the settling of clay particles. It is not possible, based on the available geological observations, to determine accurately the timescales over which fluid flow and sedimentation were sustained. The lifespan of the cave system at Viðareiði would have depended on many factors, including the fault slip rate, nature of slip (seismic vs. aseismic), strength of the basalt, overburden thickness and anisotropy. Nevertheless, the volume of sediment preserved within the volcaniclastic layers and intrusions suggests that the network of cavities was a major fluid pathway, potentially connecting the surface with the interior of the lava pile during their formation and infilling. Their uncemented, porous nature suggests that the sediment fills have high permeabilities. Connected networks of horizontal clastic infills and clastic intrusions could therefore provide a high permeability pathway through what is otherwise a low permeability sequence of crystalline lava flows. Future research will aim to test this hypothesis using laboratory-based measurements of porosity and permeability.

4.2. *Regional significance of 'Stage 6' structures*

The Stage 6 structures demonstrably post-date mineralised fault rocks associated with Stages 1–5 and therefore formed following the Palaeocene. Most mid-Palaeogene to Neogene

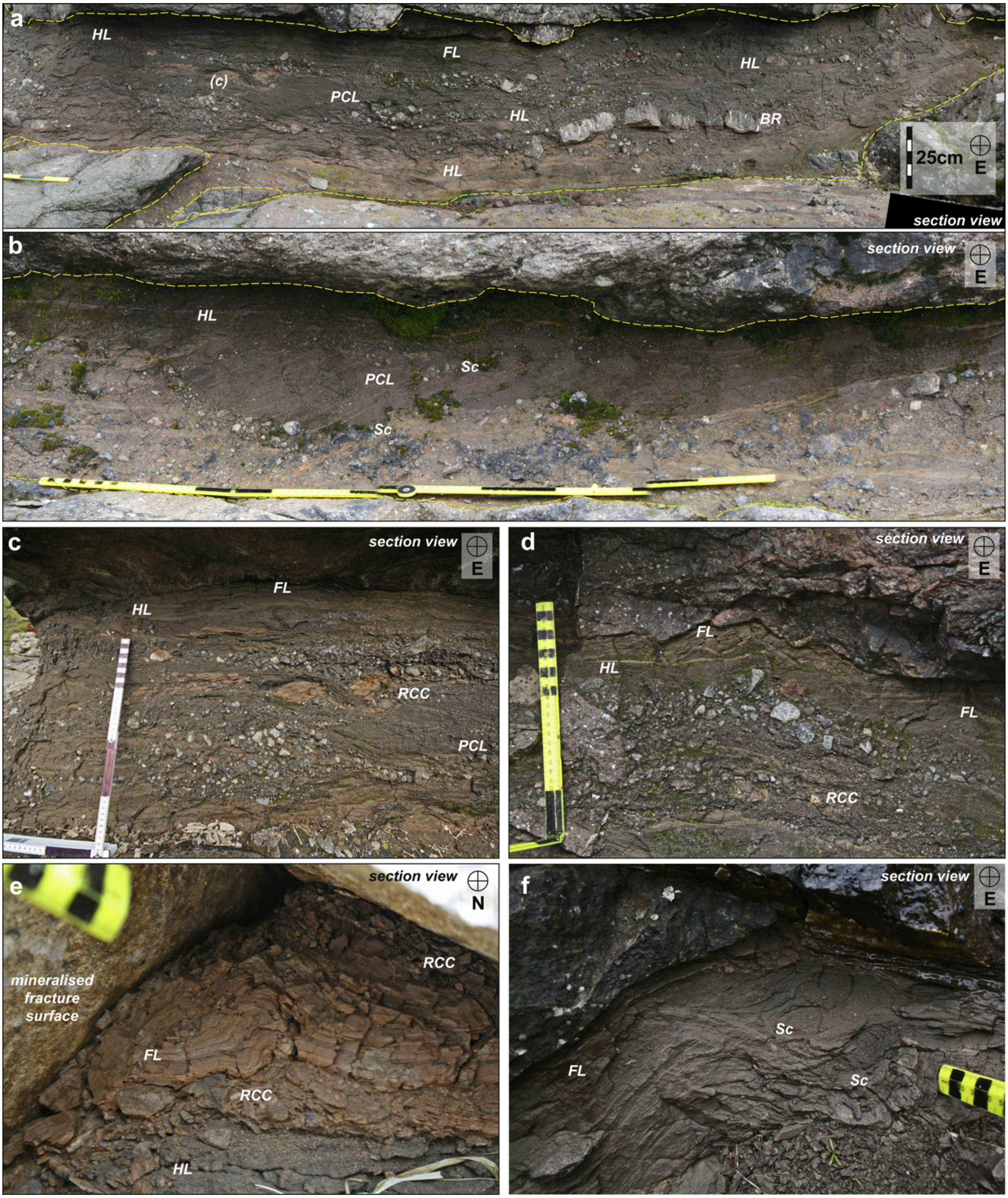


Fig. 7. (Locations shown in Fig. 5). (a–f) Examples of features of the clastic horizons at Viðareiði. *BR*: basalt raft; *HL*: horizontal laminations; *FL*: folded laminations; *PCL*: planar cross laminations; *RCC*: reworked clay clasts; *Sc*: Scours.

structures developed along the NE Atlantic Margin are attributed to the effects of compression and regional uplift. The nature and timings of compression and uplift in the Faroe-Shetland Basin (FSB) and adjacent regions is well documented (e.g. see Boldreel and Anderson, 1993, 1998; Andersen and Boldreel, 1995; Doré and Lundin, 1996; Ritchie et al., 2003; Sørensen, 2003; Smallwood, 2004; Johnson et al., 2005). Within the FSB, Cenozoic compression has generally resulted in the development of

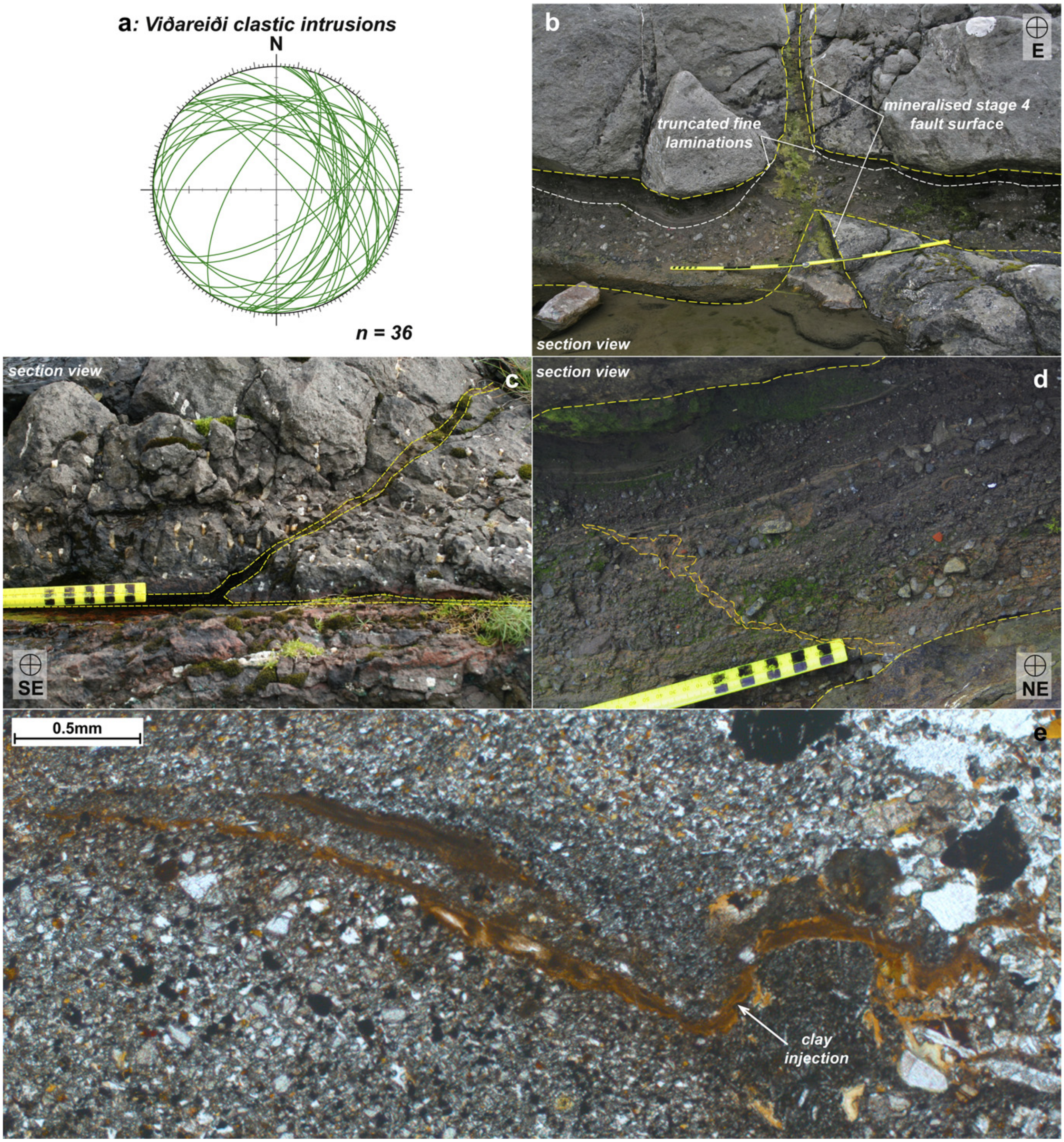


Fig. 8. (Locations shown in Fig. 5). Clastic intrusions that: (a–b) display various orientations and cut through lava solid-state features such as pipe amygdales (lower hemisphere stereographic projection showing plane orientations for anastamosing clastic veins); (c) exploit Stage 4 & 5 mineralised faults; and (c) cut through the original clastic horizons. (d–e) Micro-scale clay injections with in the Viðareiði sediments.

large but fairly gentle growth folds in various orientations (Ritchie et al., 2008). Whilst these folds represent low intensity deformation (e.g. a NE–SW-directed, post-basalt crustal shortening of <1% is typical for the Faroes Platform; Andersen et al., 2002), the substantial amplitudes and areal extents of the resultant folds and domes makes them potential hydrocarbon exploration targets (Doré et al., 2008). The Faroe Islands sit at the junction of three antiformal structures: the ENE–WSW trending Fugloy Ridge (to the east); the NNW–SSE trending Munkagrunnur Ridge (to the south); and the NW–SE trending Iceland-Faroe Ridge (to the NW) (Smallwood, 2008) (Fig. 10). The first two are anticlines that relate, at least in part, to compression along the margin with their location and orientation most likely controlled by basement structure (Doré et al., 1997). The Fugloy Ridge grew during several tectonic episodes in the Palaeocene, through to, perhaps, the mid-Miocene.

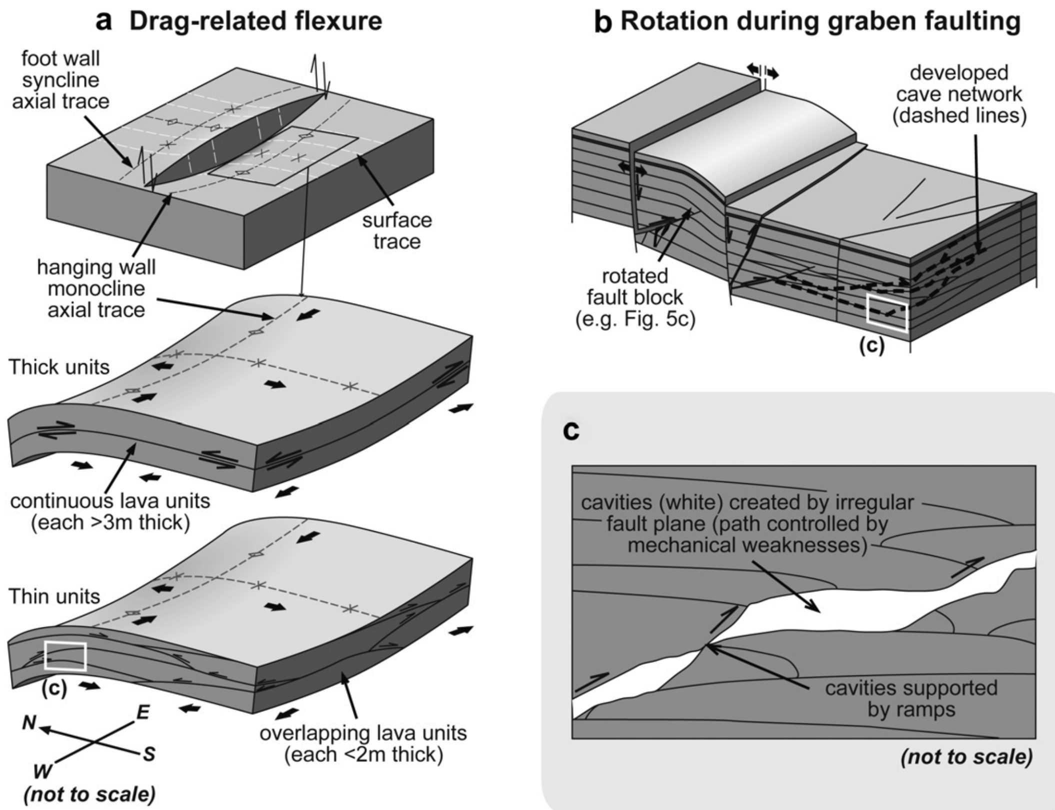


Fig. 9. (a–b) Potential mechanisms for formation of subterranean open cavities in thin lava units. (a) Drag-related flexure (e.g. Barnett et al., 1987; e.g. Fig. 5d). (b) Rotation during graben faulting (e.g. Holland et al., 2006; e.g. Fig. 5c). (c) Cavities are probably the result of dismemberment of relatively thin lava units along existing anisotropies and discontinuities in the pile during faulting.

Growth of the Munkagrunnur Ridge is more difficult to date as post-lava sediments are absent on the ridge. The Iceland-Faroe Ridge relates to interaction between the proto-Iceland plume and the Mid-Atlantic ridge, throughout continental break-up and sea-floor spreading (Bott and Gunnarsson, 1980).

Compression in this setting is typically attributed to a combination of gravitational forces, such as ridge-push and gravitational potential stresses related to lithospheric thickness and elevation variations in the continental interiors, coupled to additional horizontal compressive stresses relating to the development of Iceland and its insular margin (Cloetingh et al., 2008; Doré et al., 2008; Pascal and Cloetingh, 2008). Kilometre-scale uplift also affected a large area during emplacement of the North Atlantic Igneous Province, including the continental margins of NW Europe, Greenland and Canada (Maclennan and Jones, 2006; Saunders et al., 2007). Uplift was both transient, related to the regional, rapid emplacement of hot asthenosphere, and permanent, caused by addition of igneous material into and onto the crust, before and during continental break-up (Larsen and Saunders, 1998).

Most Stage 6 features on the Faroe Islands do not appear to directly result from shortening. On the contrary, they are typically extensional-shear or extensional features. In the absence of age dating for these infills, it is not yet possible to determine whether they formed during or after compression and uplift features found elsewhere along the NE Atlantic margin. It is worth pointing out, however, that *localised* extension and fracturing can certainly occur during regional shortening. Possible causes include collapse of a regional topographic high such as that represented by the Faroe Islands and its insular margin (e.g. Maclennan and Jones, 2006) or fractures related to tangential strain in the outer arcs of buckle folds (Ramsay and Huber, 1987; Price and Cosgrove, 1990; Cosgrove and Ameen, 2000). The inferred extension directions across the clastic infills are broadly consistent with tangential strain (Fig. 10). Inferred obliquity to the fold axes may simply be due to the orientation of the reactivated host fault.

With the exception of the sub-horizontal cavities at Viðareiði, Stage 6 structures are found throughout the available onshore exposures of the lavas, though rarely does this sequence exceed a thickness of a few hundred metres. It is unknown whether such sediment-filled fractures formed at greater depths. If these structures relate to the development of regional-scale Cenozoic folds (i.e. the Munkagrunnar and Fugloy ridges), then it is plausible that they would not be limited to the Faroes, and would be expected to be developed along the hinge zones of all such anticlinal folds along the margin, including in offshore regions. Further work in equivalent onshore settings could aim to test this hypothesis in areas such as East or West Greenland, or within the British Tertiary Igneous Province, or further afield in other volcanic passive margins (e.g. the South Atlantic). Where such clastic infills are present in the crestal regions of structural highs (e.g. potential anticlinal traps), they are potentially of major importance to hydrocarbon trapping and migration, since they may have remained as open cavities for a protracted period of time, and the uncemented nature of the fills means that they still represent significant potential fluid-flow pathways. A key test of this hypothesis would be to analyse core samples from offshore wells that intersect clastic infills for evidence of oil staining.

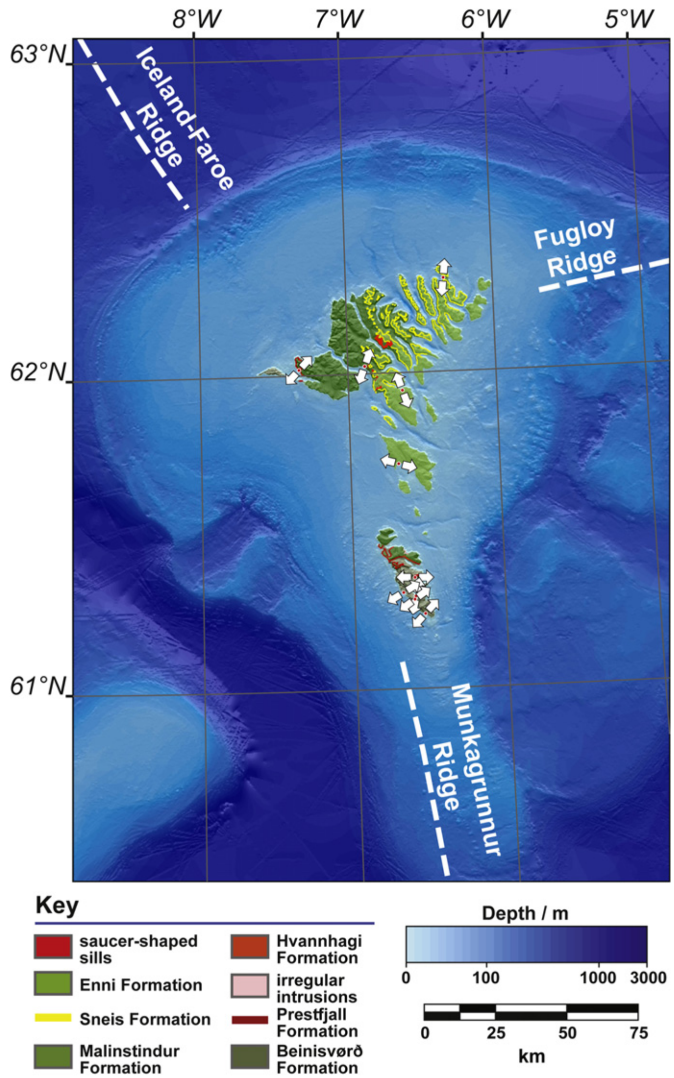


Fig. 10. Simplified hill-shaded geological map of the Faroe Islands, with hill-shaded bathymetric map of the Faroes shelf detailing axial-lines of the Munkagrunnur, Fugloy, and Iceland-Faroes ridges (after Boldreel and Anderson, 1998; Passey and Bell, 2007) and inferred horizontal extension directions of clastic-filled fractures on the Faroes. Extension directions for Viðareiði are based on the thick vertical clastic intrusions. Extension directions cannot be inferred from the clastic fills at Viðareiði as they are sub-horizontal, nor can a reliable direction be determined for the thinner clastic intrusions (there is too much variability, probably reflecting localized overpressure).

5. Conclusions

The fault-related features detailed in the present paper post-date, and commonly reactivate earlier, syn-magmatic faults, fault rocks and fractures. The lack of mineralisation within the clastic materials probably indicates post-burial, near-surface fault movements (<1–2 km depth?). Based on the relative timing, it is proposed that these late movements and infills are related to uplift during continental break-up and sea-floor spreading on the NE Atlantic. The kinematics indicated by offset markers and the localized development of clastic drag fabrics are typically the opposite sense to those of the host faults.

Clastic infills may be widespread offshore. The unmineralised nature of the clastics may mean that these faults present fluid-flow pathways, particularly at higher levels, but also potentially deeper, within the Faroe-Shetland Basin. The open cavities that originally formed would have introduced considerable localized permeability, potentially facilitating rapid cross-fault and cross-stratal migration of fluids, including hydrocarbons.

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