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1 **Complex circular subsidence structures in tephra deposited on large blocks of**
2 **ice: Varða tuff cone, Öräfajökull, Iceland**

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8 **Abstract**

9 Several broadly circular structures up to 16 m in diameter into which higher strata have
10 sagged and locally collapsed, are present in a tephra outcrop on southwest Öräfajökull,
11 southern Iceland. The tephra was sourced in a nearby basaltic tuff cone at Varða. The
12 structures have not previously been described in tuff cones and they were probably formed
13 by the melting out of large buried blocks of ice emplaced during a preceding jökulhlaup that
14 may have been triggered by a subglacial eruption within the Öräfajökull ice cap. They are
15 named ice-melt subsidence structures and they are analogous to kettle holes that are
16 commonly found in proglacial sandurs and some lahars sourced in ice-clad volcanoes. The
17 internal structure is better exposed in the Varða examples because of an absence of fluvial
18 infilling and reworking, and erosion of the outcrop to reveal the deeper geometry. The ice-
19 melt subsidence structures at Varða are a proxy for buried ice. They are the only known
20 evidence for a subglacial eruption and associated jökulhlaup that created the ice blocks. The
21 recognition of such structures elsewhere will be useful in reconstructing more complete

22 regional volcanic histories as well as for identifying ice-proximal settings during
23 palaeoenvironmental investigations.

24 **Keywords** ice-melt subsidence . lapilli tuff . tuff cone . Hofsfjall . subglacial . jökulhlaup .
25 kettle hole . Eemian . Holocene

26

27 **Introduction**

28 Öräfajökull is the largest active stratovolcano in Iceland. It is situated on the southern
29 margin of Vatnajökull and has a basal diameter of c. 23 km, rising to 2110 m a.s.l. at
30 Hvannadalshnúkur a rhyolite lava dome, which is the highest peak in Iceland (Fig. 1). The
31 volcano sustains a prominent summit ice cap that feeds several glaciers on its west, south
32 and east flanks, and it includes a caldera 4-5 km in diameter containing ice up to 550 m thick
33 (Magnússon et al., 2012; Roberts and Gudmundsson, 2015). Öräfajökull has erupted large
34 quantities of tholeiitic basaltic rocks together with rhyolites; rocks with intermediate
35 compositions are much less common (Prestvik, 1979, 1985). Many of the volcanic products
36 were erupted subglacially (Prestvik, 1979; Stevenson et al., 2006; Walker, 2011; Forbes et
37 al., 2014). Öräfajökull is known to have erupted twice in historical times: in 1362 and 1727-
38 28. The eruption in 1362 was the most notable, with ejection of large volumes of rhyolite
39 pumiceous tephra (Thorarinson, 1958; Sharma et al., 2008). It devastated a large settled
40 farmed region that was then deserted for more than 40 years and which became known as
41 Öräfi, or wasteland. Both historical eruptions were associated with significant glacier
42 outburst floods, or jökulhlaups (Thorarinson, 1958; Roberts and Gudmundsson, 2015).
43 Varða (called Hofsfjall in previous publications) is a small hill situated above 600 m a.s.l. on
44 the south flank of Öräfajökull. It is a basaltic tuff cone with a basal diameter of c. 1 km that

45 rises about 70 m above the surrounding landscape. The tuff cone has an associated tephra
46 apron with an outcrop that extends to the north (Figs 2, 3). Although the Varða tuff cone
47 has been known for some time (Thorarinson, 1958; Wadge et al., 1969; Prestvik, 1979), no
48 detailed description has been published. From its dissection and field relationships, it was
49 suggested that the Varða tuff cone was ‘many thousands of years old’ and erupted before
50 the last glaciation (Thorarinson, 1958; Wadge et al., 1969).

51 This paper describes distinctive features in the tephra apron, comprising broadly circular
52 structures up to 16 m in diameter in which higher strata have sagged and locally collapsed.
53 The structures appear to have formed as a result of collapsing into voids. They show
54 evidence for the soft-state deformation of tephra. Soft-state deformation features are
55 commonly observed in pyroclastic deposits of tuff cones, tuff rings and tephra aprons (e.g.
56 Russell and Brisbin, 1990; Branney and Kokelaar, 1994; Sohn and Park, 2005; Zanon et al.,
57 2009; Sohn et al., 2012; Okubo, 2014; Vitale and Isaia, 2014). When interpreted, they are
58 regarded as instabilities formed due to settling, slumping and subsidence in the edifice or
59 associated with caldera-related volcano-tectonism. However, the structures at Varða are
60 found hundreds of metres away from the coeval edifice and there is no possible association
61 with calderas. Structures comparable in size and geometry have not previously been
62 observed in tuff cone deposits. Our study suggests that they formed due to the melting out
63 of large buried masses, probably composed of ice. They are thus proxies for a glacial or
64 periglacial setting. Because many volcanoes across the world currently have some ice cover,
65 or had some once, the structures described in this paper are another useful reference tool
66 for inferring former glacial and glacial—proximal environments in volcanic settings.

67 **Composition, field relationships and deposits of the Varða tuff cone**

68 There are no published analyses of the Varða tephra or its constituents, but the abundance
69 of pale brown sideromelane with narrow palagonite-altered rims and phenocrysts of
70 labradorite—andesine and olivine indicate that it is basaltic. The tephra apron associated
71 with the tuff cone extends c. 1 km to the north where the topography rises slowly to merge
72 with the present-day ice cap on Öräfajökull. Despite significant post-eruption erosion, the
73 conical topographical shape of the tuff cone is still preserved, and the upper slopes, crater
74 and crater rim are recognizable. It is well bedded. The outward-dipping stratification wraps
75 around the two southeast-pointing topographically lower crater-rim ridges suggesting that
76 the cone had an original horseshoe shape 'open' to the south, and a significantly lower
77 southern rim when it was active, consistent with a predominantly southerly wind direction
78 during eruption. The rim to rim width of the crater is about 500 m and it is elongated slightly
79 in a WNW—SSE direction. Changes in the attitude of inward-dipping bedding on the west
80 side possibly define a smaller shallower subsidiary crater now largely back-filled with tephra.
81 Together with the slight northwest—southeast asymmetry of the cone edifice, at least two
82 coeval active craters may have been active. Other active vents are possible and may explain
83 the presence of an enigmatic outcrop of subaerial lava occupying the lower ground on the
84 south west flank of Varða, linked to one or more feeder dykes exposed in the crags
85 overlooking Bæjargil (Fig. 2, and [Supplementary Material Fig. 1](#)).

86 Thick deposits of the tuff cone are well exposed on the steep to subvertical sides of the
87 Bæjargil gorge and they also drape the steep face of a marine cliff on its south west side
88 ([Wadge et al., 1969](#); [Supplementary Material Fig. 1](#)). The deposits are overlain on the south
89 east side of Bæjargil by a younger lava and fluvial sediments; the lava has irregularly
90 intruded and baked the latter. Both the lava and sediments are overlain by boulder till from
91 the last glaciation and they are extensively eroded ([Thorarinson, 1958](#); [Wadge et al., 1969](#)).

92 The gorge of Bæjargil itself appears to be a postglacial feature that attests to significant
93 fluvial erosion of Varða tephra. The Varða tuff cone is also draped patchily by boulder till
94 almost to its summit and till boulders have accumulated preferentially in the crater bottom
95 (Fig. 2).

96 The Varða tephras are lapilli tuffs (classification of [White and Houghton, 2006](#)). The
97 abundant sideromelane ash grains and lapilli are generally ≤ 5 mm in diameter, pale brown
98 with mainly blocky angular shapes (less often cusped) and variably vesicular (mainly
99 incipient to moderate, rarely high; sensu [Houghton and Wilson, 1989](#)), with relatively few
100 small phenocrysts. The proportion of ash is high (typically c. 60%). Tachylite is also common
101 but less so than the sideromelane. It contains the same phenocryst phases as the
102 sideromelane and is thus petrologically similar and also juvenile. Accessory (lithic) clasts are
103 ubiquitous and comprise angular, non-vesicular petrologically variable lavas typically 1-4 cm
104 in diameter (up to 70 cm) that vary in their grain size (aphanitic to fine grained), colour
105 (shades of grey; rarely red), and phenocryst types and abundance; they are much less
106 common than sideromelane.

107 The deposits are diffusely stratified and less commonly thinly bedded (terminology after
108 [Branney and Kokelaar, 2002](#); Fig. 4). Thicker (up to 0.5 m) massive beds are more rarely
109 present, some showing coarse-fraction normal grading of lithic clasts. Beds are laterally
110 discontinuous and seldom extend laterally more than a few tens of metres down-dip
111 (typically < 30 m); the thinner stratification usually extends just a few metres before
112 wedging out. Armoured (ash-coated) lapilli (sensu [Ryane et al., 2011](#)) up to 4 cm in diameter
113 (usually 0.5-1 cm; Fig. 5) are common and conspicuous throughout. Black, highly vesicular
114 glassy juvenile bombs are uncommon and most outsize clasts are lithic blocks. Impact

115 structures are abundant (Fig. 4) and outsize clasts with ramps of fine tuff on the vent-side,
116 adhesion ripples and vesiculation in the fine ash matrix were also observed (Fig. 5). Impact
117 structures are rarely filled preferentially by coarser lapilli. A few dune and antidune
118 bedforms are present c. 800-900 m north-northeast of the crater (Fig. 5); they were not
119 observed in the main tuff cone. Evidence for edifice instability is relatively common
120 particularly on and close to the crater rim. It comprises normal and reverse faults of
121 uncertain but probably small displacement present both within the crater and on the outer
122 slopes, mainly close to the crater rim or cutting obliquely across it. Some are overlain by
123 younger beds. Steeply-dipping slipped beds are present within the crater, deformed into
124 small open folds with a wavelength of c. 0.5 m that verge downslope.

125 The lapilli tuffs are banked up steeply (65°) at the base of the southern flank of a small
126 pyroclastic cone 900 m to the north (Fig. 2) that is constructed of oxidised agglutinate and
127 they conformably overlie a thin 'a'ā lava that flowed south for a short distance out of the
128 agglutinate cone. The agglutinate cone shows poor glacial striations locally. Pristine clinkers
129 derived from the 'a'ā lava are dispersed within the basal beds of lapilli tuff nearby. The lapilli
130 tuffs also overlie two small mounds of grey agglutinate (probably representing the crater
131 rim of a second small agglutinate cone transected by the cliff) that are poorly exposed at the
132 base of the cliffs half way along the main north ridge (Fig. 6).

133 **Eruption character and palaeoenvironment of the Varða tuff cone**

134 The discontinuous stratification, abundance of ash (including fine ash), variably vesicular
135 juvenile lapilli with blocky shapes, abundant impact structures as well as clasts lacking
136 impact structures, together with the presence of dune and antidune bedforms and impact
137 structures filled by large lapilli are characteristic of deposits formed during

138 phreatomagmatic eruptions (e.g. Sohn, 1996; Cole et al., 2001; Branney and Kokelaar,
139 2002). They were probably deposited mainly from fully dilute pyroclastic density currents
140 but the poorly sorted massive beds may have been deposited from granular fluid-based
141 currents (cf. lithofacies dsLT, dbLT and mLT of Branney and Kokelaar, 2002). The presence of
142 numerous impact structures indicates a ballistic origin for many of the outsize blocks but no
143 evidence was observed for any of the beds having an origin solely by tephra fall. However,
144 the abundance of armoured lapilli, thought to form in a predominantly subaerial moist ash-
145 rich eruption column by processes similar to ash aggregates (e.g. Gilbert and Lane, 1994;
146 Brown et al., 2012), suggests that a high proportion of the clasts may have been
147 incorporated by falling into the moving density currents (Brown et al., 2010). Their
148 abundance and a lack of evidence for deposition in water (e.g. no ripples, fossils or sharply-
149 defined beds; and abundant impact structures at all levels in the cone) also suggest that the
150 eruption was substantially or entirely subaerial. In addition to the armoured lapilli, the
151 presence of abundant well-formed impact structures, bombs with ramps of fine tuff on the
152 vent-side (i.e. up-current), adhesion ripples and vesiculation in the fine ash matrix (Figs 4, 5)
153 all point to a wet, sticky, relatively cool eruptive and depositional environment. Beds
154 dipping at 65° (i.e. well beyond the angle of repose for cohesionless granular materials) at
155 the foot of the scoria cone to the north are further evidence for cohesiveness of the
156 deposits. The Varða tuff cone is thus a hydromagmatic centre in which eruptions were very
157 violent (to generate the large volume of ash observed) and involved magma interacting with
158 water.

159 There is a lack of any feasible topography that might have impounded a pluvial lake at
160 Varða, and the elevation is too high (> 600 m a.s.l.) for the area to have been flooded by the

161 sea. The tuff cone may have erupted either in a surface lake caused by melting through an
162 extensive ice cover or else the supply of water was from a free-flowing aquifer (e.g. highly
163 permeable ‘a’ā lava autobreccias; [Sohn, 1996](#)); a thick blanketing cover of snow would not,
164 in itself, be capable of supplying a sufficiently sustained supply of meltwater and would
165 soon become exhausted. An absence of any surrounding ice is suggested by the extensive
166 distribution of the Varða tephra outcrop, including on the relatively steep slopes on the
167 west side below the cone ([Fig. 2](#)); any tephra deposited on ice would either be advected
168 away by subsequent glacier flow or disrupted in situ and washed away when that ice
169 underwent static mass wasting and sapping (e.g. on a watershed with negligible ice flow;
170 see later). Furthermore, pristine-looking clinkers derived from the surface of the small ‘a’ā
171 lava sourced in the agglutinate cone c. 1 km north of Varða were detached and incorporated
172 as dispersed clasts locally in the basal deposits of the overlying lapilli tuffs. This signifies that
173 (1) they were not overridden and abraded by ice prior to the deposition of the Varða tephra
174 (whereas the agglutinate cone itself was, probably at the same time as the Varða cone was
175 overridden) and (2) a thick (several metres) overlying snow or ice cover was not present, as
176 it would have protected the ‘a’ā lava surface from the effects of the rapidly moving
177 pyroclastic density currents. There is also no evidence for deposition of the tephras in water
178 (e.g. ballistic impact structures are present at all levels in the cone). Thus, it is more likely
179 the water was supplied by an aquifer, consistent with the presence of accessory lithic clasts
180 which would have been derived by explosive detonations within the underlying bedrock.
181 The cone is also located on a high seaward-dipping platform above a cliff. The cliff (best
182 seen just to the east of Hof; [Wadge et al., 1969](#)) is draped by Varða tephra ([Supplementary](#)
183 [Material Fig. 1](#)) and was probably formed by a combination of glacial erosion and,
184 particularly, wave action during interglacial periods of raised sea level similar to the

185 formation of cliffs on the seaward side of Eyjafjallajökull and elsewhere in Iceland ([Wadge et](#)
186 [al., 1969](#); [Loughlin, 2002](#); [Thordarson and Hoskuldsson, 2002](#)). Therefore, it is suggested
187 that the magma interacted with groundwater derived from, and easily replenished by,
188 seawater that flowed into cracks within an aquifer. A lack of authigenic zeolites in the pore
189 spaces of the lapilli tuffs prevented the composition of the water (fresh or marine) from
190 being determined (cf. [Johnson and Smellie, 2007](#)).

191 **Description of collapse structures at Varða**

192 The low flat-topped ridge extending c. 1 km north of Varða (herein referred to as the main
193 ridge) contains most of the unusual features that are the focus of this study. The tephra
194 forming the ridge was deposited on a pre-existing broad topographical divide, or watershed,
195 as exposed today ([Fig. 3](#)). The ridge has an east-facing cliff up to 16 m high in which nine
196 collapse structures are exposed ([Fig. 6](#)). Similar but less well exposed structures are present
197 on its more subdued west flank and also on the west side of the small subsidiary outcrop to
198 the east of the main ridge ([Figs 2, 3](#)). Of the structures observed, most appear simply to be
199 parts of the margins of structures that have otherwise been completely eroded. They
200 include slab-like sections of stratified to massive fine lapilli tuff up to a few metres thick that
201 dip at c. 80° or greater and truncate bedding in the subjacent lapilli tuffs ([Fig. 7](#)). In some
202 cases, the contact with the adjacent lapilli tuffs is slightly overhanging and dips away from
203 the structure itself. The massive lapilli tuff is inhomogeneous, comprising poorly defined
204 domains rich in armoured lapilli or tuff matrix, respectively, together with ill-defined relicts
205 of impersistent stratification in a variety of attitudes. Bedding adjacent to (outside of) the
206 steep slabs is typically sharply truncated but the beds locally dip down within a few
207 decimetres of the contact.

208 Two of the structures (3 and 4 in Fig. 6) are more completely preserved than the others
209 (Figs 8, 9). The structures are of similar size, broadly circular and measuring c. 13-15 m N—S
210 and c. 12-16 m E—W but the east flanks are truncated by erosion and they may be elliptical
211 overall. Both are exhumed to c. 8 m in depth but their bases are unexposed. The upper beds
212 within each structure appear to have sagged down by c. 3 m or so. The structures are
213 asymmetrical internally, with inward-dipping downsagged strata on all sides but one side
214 (northern in both cases) that includes a fault-like discordance (Figs 8-10). In structure 3,
215 strata rapidly increase their centroclinal dip to 60° as they enter the structure, becoming
216 vertical and locally even slightly overturned further within the structure interior. In addition
217 to downsagged strata, the southern half of structure 3 includes polygonal blocks of stratified
218 lapilli tuff juxtaposed at all angles (Fig. 11). It also contains an approximately circular
219 present-day pit c. 3 m in diameter (called ‘the hole’ in Fig. 8) surrounded on three sides by
220 vertical beds (Figs 8, 12); the fourth (eastern) side is eroded. Structure 4 is dominated by
221 more gently downsagged strata with dips mainly increasing only to c. 20° but dipping more
222 steeply inward at the discordant northerly margin similar to structure 3 (Figs 9, 10). Its
223 surface therefore resembles a shallow asymmetrical depression rather than a steep-sided
224 pit. Beds outside both structures dip at 8-10° to the south, reflecting the regional gradient of
225 the pre-eruption landscape, which rises to the north (Fig. 2). The rare appearance in
226 structure 4 of a displaced metre-long block of strata with steep-dipping bedding suggests
227 that some beds have also been fragmented, similar to structure 3 but less well developed
228 (i.e. fewer blocks) at the level of exposure seen in structure 4. A thin (30-40 cm wide)
229 irregular zone of massive lapilli tuff is developed locally along the steeply inclined contact on
230 the northern margin of structure 4 (Fig. 10). The sharp contact is cross-cutting and fault-like
231 lower down where it truncates beds. Small normal and reverse faults with centimetre- to

232 decimetre-scale displacements are common in the overlying downsagged beds but without
233 consistent orientations. Faults are uncommonly present in the beds outside all of these
234 structures, but they show not obviously related geometrically to the concentric structures.
235 Folded and displaced bedding is also prominent enclosed in massive lapilli tuff in the smaller
236 structure 7 (c. 3 m in diameter).

237 **Discussion**

238 Origin of the Varða collapse structures

239 Important features of the structures include: (1) faulted steep-dipping (vertical to slightly
240 overturned) margins that sharply crosscut external lapilli tuff strata; (2) downbending of
241 some beds directly adjacent to the faulted margins ; (3) local presence of a marginal zone of
242 massive lapilli tuff with a semi-homogenized appearance, within which are indistinct blocks
243 of stratified beds; (4) the higher beds simply bend down into the structure (rather than
244 becoming thicker, e.g. infilling a depression), defining symmetrical and asymmetrical
245 concentric sag-like geometries; and (5) some structures contain breccia composed of
246 stratified blocks with bedding in various dips. A lack of burial by younger tephra suggests
247 that the structures formed after the eruption had ceased. Moreover, distinctive
248 sedimentary structures would have formed in pyroclastic density current deposits passing
249 over surface hollows, with variations in bed thickness and grain size.

250 The surfaces between adjacent blocks in the breccias are ill-defined (Fig. 11) and the
251 presence of narrow zones of homogenized lapilli tuff at the margins of several structures
252 (Figs 7a, 10), which contain poorly seen stratified blocks preserved in a massive matrix,
253 suggest that the lapilli tuff was still weakly lithified when it fragmented to form breccias and
254 underwent soft-state granular fragmentation when stressed. The absence of voids between

255 clasts probably indicates infilling by grains generated by disaggregation, and further
256 reduction in void space may have been caused by compression and ductile folding of some
257 clasts during compaction. The downward transfer of material, by tumbling, granular flow
258 and viscous creep, is called suffusion. It is well known in sinkholes and dolines, where it is
259 usually caused by rainwater gradually washing unconsolidated material into cavities
260 (Waltham et al., 2005). Some of the faulted margins are slightly overhanging, suggesting
261 that the adjacent ash-rich beds outside of the structures were cohesive enough to preserve
262 a vertical face. The overlying beds were also cohesive but reacted plastically, locally sagging
263 down into a void to rest against steep underlying marginal fault surfaces (Figs 10, 12c). In
264 some cases, beds may have become detached and slipped down as slabs, causing the
265 marginal shear effects observed (bending and bed homogenization). Detachment may have
266 been progressive and sequential rather than a single-stage process (as was also postulated
267 for the kettle holes in Mt Hudson lahars; Branney and Gilbert, 1995). This is suggested by
268 the observation that coarse breccias formed of stratified blocks are occasionally sandwiched
269 between tilted beds, implying a sequence of tilting, brecciation and further tilting (Fig. 12b).
270 Slabs of tephra, on a range of scales from metres to decimetres in thickness, may have
271 sagged down, with some breaking off and sliding intact whilst others were fragmented. The
272 polygonal slabs of lapilli tuff are thus interpreted as have accumulated by dropping into a
273 void, as the structure worked its way up to the surface (cf. Whittaker and Reddish, 1989).

274 Bed strength would have been greatly weakened by any coeval fractures caused by
275 settling in the tephra pile as it accumulated, and they are perhaps represented by the
276 intersecting tensile fractures, some with decimetre displacements, observed in the higher
277 downsagged tephra beds. Collapsing beds that remained intact as stratified slabs may have

278 been more cohesive or been deformed at lower strain rates, perhaps related to more
279 gradual mass withdrawal due to slower melting or the local geometry of the melting ice. The
280 ubiquitous evidence for sagging suggests that the overall circular structural features are
281 collapse structures. Analogue models suggest that collapse rates during subsidence vary
282 temporally and spatially, and are associated with incremental accelerations (e.g. [Poppe et](#)
283 [al, 2015](#)). Compared with the gentle dips elsewhere in the surrounding outcrop ([Fig. 2](#)), the
284 collapse structures at Varða were highly localised and suggest that large buried masses were
285 removed in situ from beneath the tephra pile at several locations. There is no preserved
286 material to show what the buried masses consisted of as the bases of the Varða structures
287 are unexposed.

288 Nature of the buried material

289 Options for the buried material that melted below the Varða tephra and caused its localised
290 collapse include (1) a thick snow cover, (2) snow drifts (sastrugi), (3) dirt cones, (4) deep
291 bedrock depressions filled by snow, and (5) ice blocks. These are examined further below.

292 How tephra subsides when it covers a thick layer of snow or firn is hard to predict.

293 Tephra fall deposits with grain sizes comparable to those at Varða are completely cold on
294 deposition (e.g. [Thomas and Sparks, 1992](#)) and any underlying snow will be effectively
295 protected by a tephra layer > 50 cm thick ([Manville et al., 2000](#); [Brock et al., 2007](#)). Under
296 such a thick layer, melting would be very slow. For example, snow > 0.5 m thick is still
297 preserved under tephra from the 1875 eruption of Askja ([Carey et al., 2010, fig. 3b](#), and
298 personal observation of M Branney). By contrast, deposits of pyroclastic density currents,
299 such as characterise the Varða outcrops, can have significant temperatures (up to c. 400°C;
300 [Sulpizio et al., 1998](#); [Zanella et al., 1998](#)), which might enhance the melting of any

301 underlying snow or ice. In some cases, phreatic explosion pits can be created in pyroclastic
302 density current deposits, as occurred following the 1980 Mt St Helens eruption (pits 5-100
303 m wide and 1-20 m deep; [Rowley et al., 1981](#)). However, the Varða structures lack evidence
304 for blast excavation and associated ejecta deposits and an explosive origin is highly unlikely.
305 This suggests that the Varða deposits were much cooler on deposition and unable to flash
306 water to steam. The temperature in these water-rich so-called 'wet surges' was less than
307 100°C and any steam present would be condensed to water droplets ([Druitt, 1996](#)).
308 Temperatures will be lowered further (to ambient) after deposition directly onto snow or ice
309 simply by the energy transferred to melt the snow or ice surface. The thermal conductivity
310 of lapilli ash is so low that further melting will be very slow, although the actual melting rate
311 is unknown. In the Askja example cited, ≥ 2 m of dilute density current deposits locally
312 overlie as little as 50 cm of tephra fall that rests directly on the coeval snow layer ([Carey et al., 2010](#)).
313 The heat from the density current deposits was clearly unable to pass through the
314 fall layer to melt the underlying snow.

315 The authors are unaware of published studies of the mechanical response of a thick layer
316 of tephra (of any kind) resting on a melting layer of snow but some localized circular
317 collapse structures with steeply tilted beds and pits have developed below the 1875 tephra
318 at Askja (although with smaller diameters than at Varða and forming prominent lines of pits;
319 personal observations of M Branney). However, there is evidence that thick snow (i.e. more
320 than a few metres) was probably absent at Varða when the tephra was deposited (see
321 above). If the melting layer was isotropic (i.e. had a constant thickness and uniform grain
322 size), we speculate that subsidence of an overlying thick tephra layer might be relatively
323 uniform, with pits restricted to anisotropic patches of snow, i.e. with a different crystal

324 structure or hardness. If the snow layer was highly anisotropic (e.g. uneven in thickness,
325 perhaps reworked by wind into hard-packed drifts (sastrugi) prior to tephra deposition),
326 then melting might over time lead to differential subsidence. However, sastrugi are typically
327 ridge-like with sharp, linear, wavy or otherwise sculpted crests and sloping often
328 asymmetrical flanks, and occur in fields of closely-spaced landforms. Sastrugi are also
329 generally smaller, seldom more than a few metres high and wide. Whether their melting
330 beneath a thick tephra layer might result in isolated concentric collapse pits with vertical to
331 slightly overhanging margins (as are typical for the Varða structures) is unclear as there are
332 no described examples.

333 Pits might also form by the melting of the snow cores of buried dirt cones. Dirt cones in
334 volcanic regions like Iceland commonly form by the differential melting of snow beneath a
335 surface ash layer of variable thickness; they are particularly common on glacier ice.
336 Although dirt cones are usually < 1-3 m high, exceptionally they can be much larger, up to 85
337 m ([Swithinbank, 1950](#); [Krenek, 1958](#); [Hauff, 1969](#)), thus overlapping in size with the Varða
338 structures. Dirt cones occur in close-spaced clusters or lines and are short lived, normally
339 lasting just a few weeks. Like melting buried sastrugi, there are no published examples of
340 structures resulting from melting of buried dirt cones and it is unclear whether large steep-
341 sided pits like those at Varða will be created. However, their natural occurrence in close-
342 spaced groups should probably result in moundy terrain rather than the isolated collapse
343 pits seen at Varða. Moreover, there is no evidence that the Varða eruption was
344 glaciovolcanic since ash deposited on glacier ice will be rapidly advected away. Undisturbed
345 tephra (lacking collapse structures) crop out in situ resting on bedrock on the relatively

346 steep western slope below the tuff cone, consistent with an absence of ice around Varða
347 during eruption.

348 Collapse into deep bedrock depressions, such as a concealed tectonic fissure, lava tubes
349 or tumuli, is also discounted. No such features were observed in the surrounding area (the
350 lavas are 'a'ā, not pāhoehoe) and, even if such features are unexposed, there would be
351 lithofacies evidence, such as bed thickening and preferential deposition of coarser clasts.
352 They are thus unlikely to be involved.

353 The collapse of sediment into voids created by the melting of buried ice is plausible and is
354 our favoured option. Similar surface structures on glacial outwash plains (sandurs) are
355 known as kettle holes. Kettle holes are hollows created in the sedimentary deposits when
356 partially to completely buried blocks of glacier ice melt out (e.g. [Maizels, 1977](#)). They are
357 common in the proglacial sandur areas of Iceland and their widespread presence and large
358 sizes are diagnostic of glacier outburst floods, or jökulhlaups ([McDonald and Shilts, 1975](#);
359 [Maizels, 1977, 1992](#); [Fay, 2002a,b](#); [Marren, 2005](#); [Russell et al., 2006](#); [Roberts and](#)
360 [Gudmundsson, 2015](#)). As such, they can be used to identify palaeojökulhlaups in the
361 geological record ([Marren, 2005](#)). The associated ice blocks can be a few tens of metres in
362 diameter and height (e.g. [Burke et al., 2010](#)), and the larger ones are usually not completely
363 buried ([Supplementary Material Fig. 2](#)). Kettle holes become filled mainly by stratified fluvial
364 sands and gravels ([Olszewski and Weckwerth, 1999](#)). The sedimentary layering in the infill is
365 centroclinal and it may be folded, faulted or partly fragmented. Vertical contacts between
366 the infill and exterior sediments are also rarely present. These features are distinct from the
367 Varða structures, which exhibit only deformation rather than sedimentation into a pit. The
368 internal features of kettles caused by subsidence are not commonly described but consist of

369 brittle fractures, which are mainly outward-dipping reverse ring fractures (McDonald and
370 Shilts, 1975; Maizels, 1977, 1992; Cocksedge, 1983; cf. Branney and Gilbert, 1995). A key
371 difference is the sequence of events envisaged for kettle holes versus the Varða structures,
372 i.e. 'conventional' sandur kettle holes are formed by ice block deposition during a sediment-
373 laden flood, whereas the scenario envisaged for the Varða structures comprises a discrete
374 phase of ice block deposition, followed by tephra deposition, and then ice block melting.

375 The dimensions of the Varða structures (c. 16 m in width) can be used to estimate the
376 approximate dimensions of the former buried ice blocks, taking into account that the
377 subsided volume will flare upwards at the angle of draw (θ), thus widening the diameter of
378 the structure at the surface (Whittaker and Reddish, 1989; Branney 1995). The angle of
379 draw is typically taken as c. 35° but it varies between c. 10 and 50° depending on the
380 rheology (strength) of the subsiding strata (Ren and Li, 2008). Weak strata such as
381 unconsolidated sands and clays, which are probably most comparable with ash-rich lapilli
382 tuffs, tend to have higher θ values (c. 35-40°). Using a mean value of 38° yields a possible
383 width of c. 8 m (range c. 7.5-9 m for $\theta = 35-40^\circ$) for an ice block with a horizontal upper
384 surface buried to a depth of c. 5 m; calculated diameters become greater at lower values of
385 θ (i.e. steeper angles of draw) whilst deeper burial will reduce the apparent width. A burial
386 depth of 5 m was used in the calculations because the observed surface sag of 3 m is
387 consistent with a total subsidence depth of 5 m (i.e. after bulking effects are removed; see
388 next section) and the observation that collapses over buried voids propagate vertically
389 upwards before flaring out near the surface at the angle of draw (e.g. Roche et al., 2000;
390 Acocella, 2007; Burchardt and Walter, 2009; Howard, 2010). Thus, at least some of the
391 buried blocks may have measured 8 m wide and 5 m high. An origin by melting of ice blocks

392 emplaced ballistically is unlikely. The collapse structures occur out to about 800 m from the
393 Varða crater, whereas ballistic lithic blocks 500 m from the crater only reach 1.1 m in
394 diameter; ice blocks of equivalent mass at that distance would have been less than 3 m in
395 width (based on differences in density).

396 There are also considerable similarities with structures known as ice-melt collapse pits
397 found in deposits of lahars sourced in snow- and ice-clad volcanoes and formed by melting
398 of ice blocks (as at Mt Hudson; [Branney and Gilbert, 1995](#); [Table 1](#)). Lahar deposits are often
399 relatively mud rich and therefore more cohesive than sandur sands and gravels. However,
400 although the ice-melt collapse pits at Mt Hudson are of comparable dimensions (up to 15 m
401 across) to those at Varða, they were preserved in plan view only and there was no erosional
402 dissection. We concur with the mode of origin described by [Branney and Gilbert \(1995\)](#) and
403 many of their interpretations are applicable to the structures which we describe here ([Table](#)
404 [1](#)). There are some differences, however. The Varða structures lack arcuate peripheral
405 extensional fractures at the surface and steeply outward-dipping subsurface fractures,
406 which implies that there may be rheological or cohesivity differences with the Mt Hudson
407 lahar deposits. However, the arcuate extensional crevasses surrounding the Mt Hudson ice-
408 melt collapse pits would probably have been temporary, in that their steep walls would
409 soon have crumbled/disaggregated and infilled, or become blurred by water oozing up
410 through the deposits and making the sediments 'quick'. A similar explanation might apply to
411 the structures at Varða. For example, the narrow zones of massive 'homogenized' lapilli tuff
412 adjacent to the faulted margins of the Varða structures ([Fig. 10](#)) might be escape zones
413 caused by upwelling displaced water disrupting, entraining and mixing material from poorly
414 consolidated strata, i.e. they represent 'quick' zones created as the surface sagged and

415 meltwater flowed up arcuate marginal faults. However, the common occurrence of beds
416 outside the structure that are deformed (i.e. physically downbent) and the absence of
417 evidence for surface venting (e.g. as 'sand volcanoes') strongly suggest that the massive
418 zones are more plausibly related to marginal shearing during downfaulting. The differences
419 between the ice-melt collapse pits described by [Branney and Gilbert \(1995\)](#) and the Varða
420 structures are probably minor and ascribable mainly to the different stage of evolution of
421 the two occurrences (i.e. more mature at Varða) and possibly greater cohesivity of the
422 Varða deposits. Although surface sagging was probably common, if not ubiquitous, in the
423 Varða examples, it is unclear how often a surface pit was formed (it probably occurred in
424 the case of Varða structure 3) and we prefer to call them ice-melt subsidence structures
425 rather than pits or cavities.

426 Comparison with other geological collapse structures

427 The collapse structures at Varða also show a resemblance to simple downsag structures
428 found in calderas, despite the differences in scale (cf. [Branney, 1995](#)). They form due to
429 subsidence involving inward tilting or rotation of strata with or without accompanying
430 faulting. There are numerous experimental and field-based studies of the formation of
431 calderas and they provide insights into the likely mode of formation of the Varða structures.

432 The most important factors governing subsidence mechanisms during caldera collapse
433 are the mechanical and geometrical properties of the overburden, in particular its strength
434 or cohesion, and the roof aspect ratio (AR, i.e. ratio of roof thickness to width of the
435 depression; e.g. [Whitaker and Reddish, 1989](#); [Roche et al., 2000, 2007](#); [Burchardt and
436 Walter, 2009](#); [Holohan et al., 2011](#); [Poppe et al., 2015](#)). Sagging is enhanced in low-strength
437 roof-rocks and at low AR; brittle piston-like subsidence along ring faults is favoured by

438 moderate roof-rock strengths and intermediate AR; and stoping by high roof-rock strengths
439 and at high AR (Roche et al., 2000, 2001; Holohan et al., 2011). Near-continuous collapse
440 (tilting) is associated with a gradually depleting subsurface mass, whereas near-
441 instantaneous collapse (fragmentation) occurs associated with a subsurface metastable
442 cavity (e.g. Poppe et al., 2015).

443 Experimental studies suggest that two types of ring fractures are generated: an inner set
444 of steeply-dipping, outward-inclined reverse ring faults and an outer set of inward-dipping
445 normal faults (e.g. Roche et al., 2000; Acocella, 2000, 2007; Walter and Troll, 2001; Geyer et
446 al., 2006; Marti et al., 2008; Burchardt and Walter, 2009; Supplementary Material Fig. 3).
447 Since the collapses are induced by a loss of support at depth, the ring faults nucleate there
448 and propagate vertically upwards without significant lateral expansion. As they approach
449 the surface they flare out and initiate surface tilting inward followed by faulting (normal or
450 reversed according to the fault geometry) when the faults reach the surface. Steep (vertical
451 to slightly overturned) strata (cf. Fig. 7) are often associated with the reverse ring faults (e.g.
452 Poppe et al., 2015). Brittle fragmentation of the roof by caving or stoping may occur during
453 the upward migration of sub-surface cavities formed at the apex of intersecting reverse ring
454 faults (Roche et al., 2001; Acocella, 2007). Volumetric expansion of the collapsing roof
455 material (known as 'bulking') occurs in both near-instantaneous and near-continuous
456 collapse and it is particularly well developed in roof rocks with high cohesion (Whittaker and
457 Reddish, 1989; Poppe et al., 2015). It occurs not only during the upward propagation of
458 reverse ring faults but also during the collapse of the roof rock, and it results in a surface
459 depression that is significantly smaller (by an average of c. 39 ± 11 %) than the space
460 vacated by removal of mass at depth. Asymmetry in the surface expression of subsidence is

461 explained in several ways. Low values of AR (< 1) cause asymmetrical ring fault
462 development. The associated collapse is also typically asymmetrical, with maximum
463 subsidence on the side of the first reverse fault (Roche et al., 2000). Subsidence above a
464 cavity with a sloping upper surface will also cause asymmetrical downsagging (Whittaker
465 and Reddish, 1989), because collapse will initiate preferentially on the side where the roof
466 thickness is greatest (Roche et al., 2000).

467 Cumulatively, these observations may help to explain some significant features of the
468 structures at Varða. AR values are unknown but, given the measured widths of c. 16 m and a
469 similar maximum thickness estimated from exposures in the main ridge, they are probably
470 close to 1. Some of the structures have asymmetrical surface depressions and normal-
471 faulted margins on one side only (structures 3 and 4; Figs 8, 9, 10, 12), implying an $AR \leq 1$ or
472 subsidence over a cavity with a sloping upper surface. Moreover, since the greatest void
473 depth will be below the highest point of a buried melting mass, the greatest void space will
474 be created there (assuming a level surface below the ice block) and subsidence will
475 therefore also be greatest, leading to asymmetry in the surface depression. The complicated
476 association of tilted beds and breccia in some structures (cf. Figs 12b, 13) is consistent with
477 a higher AR or caving and stoping during upward reverse ring fault propagation associated
478 with ephemeral cavity formation and piecemeal subsidence. The observed depths of
479 subsidence in Varða structures 3 and 4, approximately 3 m, are probably minima due to
480 bulking. A 'full' subsidence depth of at least 5 m is implied, corresponding empirically to the
481 thickness of the buried ice blocks at those localities. Finally, elongated depressions will form
482 due to structural coalescence caused by the melting of adjacent ice blocks, and this may be
483 an explanation for the 'figure of eight' surface morphology of structure number 3 at Varða
484 (cf. 'nested or dumbbell-shaped pits' of Branney and Gilbert, 1995; Fig. 12).

485 Age of the Varða tuff cone and sequence of events

486 It is noticeable that the 'a'ā lava and agglutinate surfaces directly beneath the Varða lapilli
487 tuffs are not glacially eroded but elsewhere they are modified and covered by till. They
488 show no evidence of water or ice interaction and they signify eruption under essentially dry
489 subaerial conditions, i.e. non-glacial and ice free or at least ice- or snow-poor. Moreover,
490 their pristine state suggests that they were erupted not long before the tuff cone (i.e.
491 perhaps by up to a few decades, though probably much less). Although relatively well
492 preserved, apart from the post-glacial carving out of the Bæjargil gorge, the Varða tuff cone
493 is also glacially eroded and it is draped by till from the last glaciation. The agglutinate cone
494 that fed the underlying 'a'ā lava also shows signs of overriding ice (local striations).
495 However, ice was not present at the site of either pyroclastic cone during their eruption. An
496 interglacial Eemian age (i.e. c. 132-116 Ka) is thus possible for eruption of both the
497 agglutinate cone and the Varða tuff cone (as suggested by [Thorarinson, 1958](#)), and the
498 inferred distribution of snow and ice was much reduced compared to that during glacial
499 periods when an ice sheet covered all of Iceland and may have extended out to the shelf
500 edge ([Hubbard, 2006](#)). However, the presence of ice-melt subsidence structures analogous
501 to fossil kettle holes indicates that ice was present on the landscape not far from Varða. The
502 simplest explanation is that there may have been an ice cap on Öräfajökull, similar to today.

503 An alternative scenario is for eruptions to have occurred in the Holocene followed by a
504 short-lived advance of the Öräfajökull ice cap to cover and erode the volcanic deposits and
505 leave behind a drape of till. To be viable, the advancing ice must have exceeded 70 m in
506 thickness at Varða (the height of Varða above its surroundings). It could have occurred
507 following the Allerød warm period, when the Icelandic ice sheet expanded greatly at least

508 twice (at c. 10.3 and 9.8 ka BP; e.g. [Norðdahl et al., 2008](#)). A Holocene age would be
509 consistent with the moderately well preserved morphologies of the Varða and agglutinate
510 cones.

511 The preservation of structures consistent with former buried ice blocks indicates that a
512 jökulhlaup occurred not long prior to the eruption at Varða (e.g. [Marren, 2005](#)). Varða is
513 situated high up on the flank of Örfajökull, a large volcano, and Iceland (generally, and
514 including Örfajökull) is well known for its many volcano-triggered jökulhlaups (e.g.
515 [Thorarinson, 1958](#); [Roberts and Gudmundsson, 2015](#)). It is unknown if the jökulhlaup event
516 that created the ice blocks was related to a subglacial eruption but it is plausible. Other
517 options for catastrophic floods, such as the sudden release of a glacier margin lake or
518 collapse of meltwater impounded by large terminal moraines (e.g. [Tweed and Russell,](#)
519 [1999](#)), do not fit well with the likely landscape inferred from the present topography. The
520 location of the vent is unknown other than it must have been upslope of Varða and
521 presumably beneath the present Örfajökull ice cap. The blocks were probably ripped off
522 the ice sheet terminus by the force of the rapidly exiting meltwater, as is commonly
523 observed during modern jökulhlaups, but a supraglacial derivation is also possible and is
524 recorded for historical jökulhlaups sourced on Örfajökull ([Jónsson, 1982](#); [Tómasson, 1996](#);
525 [Fay, 2002a,b](#); [Russell et al., 2006](#); [Roberts and Gudmundsson, 2015](#)). Ice blocks transported
526 in jökulhlaups are preferentially deposited on higher ground ([Maizels, 1992](#); [Fay, 2002a](#);
527 [Russell et al., 2006](#)), which may explain their preservation on the shallow watershed now
528 overlain by the tephra outcrop forming the main north ridge; they are absent in the
529 outcrops draping the steeper slopes to the west ([Figs 2, 3](#)). Ice blocks can survive on the
530 surface without melting typically for only for a few years although kettle holes (lacking ice)

531 may survive for decades (McDonald and Shilts, 1975; Roberts and Gudmundsson, 2015). The
532 duration of unmelted buried ice is unknown but it will be enhanced by the insulation caused
533 by the thick layer of Varða tephra, and the local elevation (c. 600 m) and consequent cool
534 ambient temperatures of the site (cf. snow preserved below tephra from Askja erupted in
535 1875; Carey et al., 2010, fig. 3b). If the ice blocks postulated by our study were sourced in a
536 subglacial eruption, as seems likely, the ice-melt subsidence structures preserved in the
537 Varða tephra are the only known evidence for that eruption. The glaciovolcanic centre and
538 its products may exist but are covered by the Örafajökull ice cap.

539 It has been suggested that the Varða tuff cone may be one of a series of small subaerial
540 basaltic pyroclastic cones erupted from a fissure-erupted chain with a NNE—SSW
541 orientation (Thorarinson, 1958). However, the northernmost feature included on the
542 putative fissure is a highly eroded lava outcrop not a cone, and no other volcanic fissures
543 have been reported on Örafajökull. Additionally, other than the alignment of the Varða tuff
544 cone with two small scoria cones situated c. 0.8 and 1.3 km to the NNE (Fig. 2), there are no
545 associated surface fractures or fault-related scarps that might confirm the presence of a
546 fissure. However, the suggestion from this study of a likely subglacial eruption upslope and
547 potentially along-trend of a line connecting the Varða tuff cone and the two small scoria
548 cones (Figs 2, 14) is consistent with the presence of a volcanic fissure. If present, the
549 eruptions did not take place simultaneously along the fissure but occurred on at least three
550 occasions, possibly during the same broad volcanic event but also possibly separated by
551 years (perhaps decades). If they are all related to the same eruptive episode, the slightly
552 different vent locations and different eruptive conditions along the same fissure could have
553 created a small early subaerial phase with agglutinate formed at the vent, followed by a

554 second and probably larger sub-ice event, and then a phreatomagmatic phase (at Varða)
555 where magma in part of the fissure intersected a free-flowing aquifer.

556 This study thus suggests the following sequence of events (summarized in [Fig. 14](#)): A.
557 Subaerial eruption of two agglutinate cones, probably on a fissure. B. Subglacial eruption
558 under an inferred Öräfajökull ice cap, possibly on a prolongation of the same fissure system
559 inferred in A. C. Jökulhaup associated with the subglacial eruption. D. Numerous large ice
560 blocks stranded preferentially on the local watershed by the drained jökulhaup. E. Subaerial
561 hydromagmatic eruption of Varða from another part of the same fissure system, with
562 magma interacting with groundwater or seawater in subsurface fractures. F. Erosion by an
563 ice advance and retreat, resulting in the present-day outcrops.

564 **Conclusions**

565 Unusual circular structures found in lapilli tuffs of a tuff cone tephra blanket were probably
566 formed by the melting of buried ice blocks, which caused the overlying tephra beds to
567 collapse into and fill the voids thus created. Other means of forming the structures (e.g.
568 melting of the snow cores of buried dirt cones) are possible but less plausible and
569 identification as former ice blocks is favoured. However, whatever their precise nature, the
570 buried objects melted to create voids and were thus glacial in origin. The ice blocks were
571 probably formed as a result of a preceding jökulhlaup that may have been triggered by a
572 subglacial eruption. Called ice-melt subsidence structures, they are the sole evidence for
573 that eruption which is preserved today. The location of the subglacial centre is unknown but
574 presumably was within an ice cap situated higher upslope on Öräfajökull. Thus, the
575 distribution of ice and snow-free ground implied by our study would have been broadly
576 similar to present, precluding eruption within a glacial period. For such structures to be

577 created relies on a tuff-forming eruption burying ice blocks generated by a preceding
578 jökulhlaup since ice blocks do not survive long on the surface (typically only a few years,
579 depending on local circumstances). The structures are analogous to kettle holes found much
580 more commonly on proglacial sandurs and in some lahars sourced in ice-capped volcanoes.
581 The ice-melt subsidence structures at Varða are another proxy for recognising an ice-
582 proximal setting for volcanism and their recognition will enhance our ability to reconstruct
583 palaeoenvironments more reliably, as well as for compiling more complete eruptive histories
584 of regions experiencing glaciovolcanic eruptions.

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592 **References**

- 593 Acocella, V., Cifelli, F. and Funiciello, R. 2000. Analogue models of collapse calderas and
594 resurgent domes. *Journal of Volcanology and Geothermal Research*, 104, 81-96.
- 595 Acocella, V. 2007. Understanding caldera structure and development: An overview of
596 analogue models compared to natural calderas. *Earth-Science Reviews*, 85, 125-160.
- 597 Branney, M.J. 1995. Downsag and extension at calderas: new perspectives on collapse
598 geometries from ice-melt, mining, and volcanic subsidence. *Bulletin of Volcanology*, 57,
599 303-318.
- 600 Branney, M.J. and Gilbert, J.S. (1995). Ice-melt collapse pits and associated features in the
601 1991 lahar deposits of Volcán Hudson, southern Chile: criteria to distinguish eruption-
602 induced glacier melt. *Bulletin of Volcanology*, 57, 293-302.

- 603 Branney, M.J. and Kokelaar, P. 1994. Volcanotectonic faulting, soft-state deformation, and
604 rheomorphism of tuffs during development of a piecemeal caldera, English Lake
605 District. *Geological Society of America Bulletin*, 106, 507-530.
- 606 Branney, M.J. and Kokelaar, P. 2002. Pyroclastic density currents and the sedimentation of
607 ignimbrites. *Geological Society, London, Memoir*, 27, 143 pp.
- 608 Brock, B., Rivera, A., Casassa, G., Bown, F. and Acuña, C. 2007. The surface energy balance of
609 an active ice-covered volcano: Villarrica Volcano, Southern Chile. *Annals of Glaciology*,
610 45, 104-114.
- 611 Brown, R.J., Branney, M.J., Maher, C. and Davila Harris, P. 2010. Origin of accretionary lapilli
612 within ground-hugging density currents: evidence from pyroclastic couplets on Tenerife.
613 *Geological Society of America Bulletin*, 122, 305-320.
- 614 Brown, R.J., Bonadonna, C. and Durant, A.J. 2012. A review of volcanic ash aggregation.
615 *Physics and Chemistry of the Earth*, 45-46, 65-78.
- 616 Burchardt, S. and Walter, T.R. 2009. Propagation, linkage, and interaction of caldera ring-
617 faults: comparison between analogue experiments and caldera collapse at Miyakejima,
618 Japan, in 2000. *Bulletin of Volcanology*, 72, 297-308.
- 619 Burke, M.J., Woodward, J. and Russell, A.J. 2010. Sedimentary architecture of large-scale,
620 jökulhlaup-generated, ice-block obstacle marks: Examples from Skeidarársandur, SE
621 Iceland. *Sedimentary Geology*, 227, 1-10.
- 622 Carey, R.J., Houghton, B.F. and Thordarson, T. 2010. Tephra dispersal and eruption dynamics
623 of wet and dry phases of the 1875 eruption of Askja Volcano, Iceland. *Bulletin of*
624 *Volcanology*, 72, 259-278.
- 625 Cocksedge, J.E. 1983. Road construction in glaciated terrain. In: Eyles, N. (ed.) *Glacial*
626 *geology. An introduction for engineers and Earth scientists*. Pergamon Press, Oxford,
627 pp. 302-317.
- 628 Cole, P.D., Guest, J.E., Duncan, A.M. and Pacheco, J.-M. 2001. Capelinhos 1957-1958, Faial,
629 Azores: deposits formed by an emergent surtseyan eruption. *Bulletin of Volcanology*,
630 63, 204-220.
- 631 Druitt, T.H. 1996. Pyroclastic density currents. *Geological Society, London, Special*
632 *Publications*, 45, pp. 145-182.
- 633 Fay, H. 2002a. Formation of kettle holes following a glacial outburst flood (jökulhlaup),
634 Skeidarársandur, southern Iceland. In: Snorrason, A., Finnsdóttir, H.P. and Moss, M.E.
635 (eds) *The extremes of the extremes: Extraordinary floods*. *Proceedings of the*
636 *International Association of Hydrological Sciences*, 271, 205-210.
- 637 Fay, H. 2002b. Formation of ice-block obstacle marks during the November 1996 glacier-
638 outburst flood (jökulhlaup), Skeidarársandur, southern Iceland. *Special Publications of*
639 *the International Association of Sedimentologists*, 32, 85-97.
- 640 Forbes, A.E.S., Blake, S., Tuffen, H. and Wilson, A. 2014. Fractures in a trachyandesite lava at
641 Öræfajökull, Iceland, used to infer subglacial emplacement in the 1727-28 eruption.
642 *Journal of Volcanology and Geothermal Research*, 288, 8-18.

- 643 Geyer, A., Folch, A. and Martí, J. 2006. Relationship between caldera collapse and magma
644 chamber withdrawal: An experimental approach. *Journal of Volcanology and*
645 *Geothermal Research*, 157, 375-386.
- 646 Gilbert, J.S. and Lane, S.J. 1994. The origin of accretionary lapilli. *Bulletin of Volcanology*, 56,
647 398-411.
- 648 Hauff, J. 1969. Ash mounds on Deception Island. *British Antarctic Survey Bulletin*, 22, 91-94.
- 649 Holohan, E.P., Schöpfer, M.P.J., and Walsh, J.J., 2011. Mechanical and geometric controls on
650 the structural evolution of pit crater and caldera subsidence. *Journal of Geophysical*
651 *Research*, 116, B07202, doi: 10.1029/2010JB008032.
- 652 Houghton, B.F. and Wilson, C.J.N. 1989. A vesicularity index for pyroclastic deposits. *Bulletin*
653 *of Volcanology*, 51, 451-462.
- 654 Howard, K.A. 2010. Caldera collapse: Perspectives from comparing Galápagos volcanoes,
655 nuclear-test sinks, sandbox models, and volcanoes on Mars. *GSA Today*, 20, no. 10, doi:
656 10.1130/GSATG82A.1.
- 657 Hubbard, A. 2006. The validation and sensitivity of a model of the Icelandic ice sheet.
658 *Quaternary Science Reviews*, 25, 2297-2313.
- 659 Johnson, J.S. and Smellie, J.L. 2007. Zeolite compositions as proxies for eruptive
660 paleoenvironment. *Geochemistry, Geophysics, Geosystems*, 8, Q03009,
661 doi:10.1029/2006GC001450.
- 662 Jónsson, J., 1982. Notes on the Katla volcanological debris flows. *Jökull* 32, 61-68.
- 663 Krenek, L.O. 1958. The formation of dirt cones on Mount Ruapehu, New Zealand. *Journal of*
664 *Glaciology*, 3, 312-314.
- 665 Loughlin, S.C. 2002. Facies analysis of proximal subglacial and proglacial volcanoclastic
666 successions at the Eyjafjallajökull central volcano, southern Iceland. *Geological Society,*
667 *London, Special Publications*, 202, 149-178.
- 668 Magnússon, E., Pálsson, F., Björnsson, H. and Gudmundsson, S. 2012. Removing the ice cap
669 of Öraefajökull central volcano, SE Iceland: Mapping and interpretation of bedrock
670 topography, ice volumes, subglacial troughs and implications for hazards assessments.
671 *Jökull*, 62, 131-150.
- 672 Maizels, J.K. 1977. Experiments on the origin of kettle holes. *Journal of Glaciology*, 18, 291-
673 303.
- 674 Maizels, J.K. 1992. Boulder ring structures produced during jokulhlaup flows. Origin and
675 hydraulic significance. *Geografiska Annaler, Series A*, 74, 21-33.
- 676 Major, J.J. and Newall, C.G. 1987. Snow and ice perturbation during historical volcanic
677 eruptions and the formation of lahars and floods. *Bulletin of Volcanology*, 52, 1027.
- 678 Manville, V., Hodgson, K.S., Houghton, B.F., Keys, J.R. and White, J.D.L. 2000. Tephra, snow
679 and water: complex sedimentary responses at an active snow-capped stratovolcano,
680 Ruapehu, New Zealand. *Bulletin of Volcanology*, 62, 278-293.
- 681 Marren, P.M. 2005. Magnitude and frequency in proglacial rivers: a geomorphological and
682 sedimentological perspective. *Earth-Science Reviews*, 70, 203-251.

- 683 Martí, J., Geyer, A., Folch, A. and Gottsmann, J. 2008. A review on collapse caldera
684 modelling. In: Gottsmann, J. and Martí, J. (eds) Caldera volcanism – Analysis, modelling
685 and response. *Developments in Volcanology*, vol. 10, Elsevier, Amsterdam, pp. 233-284.
- 686 McDonald, B.C. and Shilts, W.W. 1975. Interpretation of faults in glaciofluvial sediments. In
687 Jopling, A.V. and MacDonald, B.C. (eds) *Glaciofluvial and glaciolacustrine sedimentation*.
688 *SEPM Special Publication*, 23, 123-131.
- 689 Norðdahl, H., Ingólfsson, Ó., Pétursson, H.G. and Hallsdóttir, M. 2008. Late Weichselian and
690 Holocene environmental history of Iceland. *Jökull*, 58, 343-364.
- 691 Okubo, C.H. 2014. Brittle deformation and slope failure at the North Menan Butte tuff cone,
692 Eastern Snake River Plain, Idaho. *Journal of Volcanology and Geothermal Research*, 278-
693 279, 86-95.
- 694 Olszewski, A. and Weckwerth, P. 1999. The morphogenesis of kettles in the
695 Höfdabrekkujökull forefield, Mýrdalsandur, Iceland. *Jökull*, 47, 71-88.
- 696 Poppe, S., Holohan, E.P., Pauwels, E., Cnudde, V. and Kervyn, M. 2015. Sinkholes, pit craters,
697 and small calderas: Analog models of depletion-induced collapse analyzed by computed
698 X-ray microtomography. *Geological Society of America Bulletin*, 127, 281-296.
- 699 Prestvik, T. 1979. Geology of the Öraefi District, southeastern Iceland. *Nordic Volcanological*
700 *Institute Report*, No. 7901, 21 pp.
- 701 Prestvik, T. 1985. Petrology of Quaternary volcanic rocks from Öraefi, southeast Iceland. *The*
702 *University of Trondheim and Norwegian Institute of Technology, Department of*
703 *Geology, Report 21*, 81 pp.
- 704 Ren, G. and Li, J. 2008. A study of angle of draw in mining subsidence using numerical
705 modelling techniques. *Electronic Journal of Geotechnical Engineering*, 13F, 14 pp.
- 706 Roberts, M. J. and Gudmundsson, M. T. 2015. Öraefajökull volcano: geology and historical
707 floods. In: Pagneux, E., Gudmundsson, M.T., Karlsdóttir, S. and Roberts, M.J. (eds),
708 *Volcanogenic floods in Iceland: an assessment of hazards and risks at Öraefajökull and*
709 *on the Markarfljót outwash plain*. Reykjavík: IMO, IES-UI, NCIP-DCPEM, pp. 17-44.
- 710 Roche, O., Druitt, T.H. and Merle, O. 2000. Experimental study of caldera formation. *Journal*
711 *of Geophysical Research*, 105, 395-416.
- 712 Roche, O., van Wyk de Vries, B. and Druitt, T.H. 2001. Sub-surface structures and collapse
713 mechanisms of summit pit craters. *Journal of Volcanology and Geothermal Research*,
714 105, 1-18.
- 715 Rowley, P.D., Kuntz, M.A. and Macleod, N.S. 1981. Pyroclastic flow deposits. *U.S.G.S.*
716 *Professional Paper 1250*, pp. 489-512.
- 717 Russell, A.J., Roberts, M.J., Fay, H., Marren, P.M., Cassidy, N.J., Tweed, F.S. and Harris, T.
718 2006. Icelandic jökulhlaup impacts: Implications for ice-sheet hydrology, sediment
719 transfer and geomorphology. *Geomorphology*, 75, 33-64.
- 720 Russell, W.J. and Brisbin, W.C. 1990. Primary fractures within a tuff cone, North Menan
721 Butte, Idaho, U.S.A. *Journal of Volcanology and Geothermal Research*, 40, 11-22.

- 722 Ryane, C., Russell, K., Edwards, B.R. and Porritt, L.A. 2011. Armoured lapilli in glaciovolcanic
723 deposits: origins and implications. American Geophysical Union, Fall Meeting, abstract
724 #V51C-2531.
- 725 Sharma, K., Self, S., Blake, S., Thordarson, T. and Larsen, G. 2008. The AD 1362 Öraefajökull
726 eruption, S.E. Iceland: Physical volcanology and volatile release. *Journal of Volcanology
727 and Geothermal Research*, 178, 719-739.
- 728 Sohn, Y.K. 1996. Hydrovolcanic processes forming basaltic tuff rings and cones on Cheju
729 Island, Korea. *Bulletin of Volcanology*, 108, 1199-1211.
- 730 Sohn, Y.K. and Park, K.H. 2005. Composite tuff ring/cone complexes in Jeju Island, Korea:
731 possible consequences of substrate collapse and vent migration. *Journal of Volcanology
732 and Geothermal Research*, 141, 157-175.
- 733 Sohn, Y.K., Cronin, S.J. and seven authors. 2012. Ilchulbong tuff cone, Jeju Island, Korea,
734 revisited: A compound monogenetic volcano involving multiple magma pulses, shifting
735 vents, and discrete eruptive phases. *Geological Society of America Bulletin*, 124, 259-
736 274.
- 737 Stevenson, J.A., McGarvie, D.W., Smellie, J.L., Gilbert, J.S., 2006. Subglacial and ice-contact
738 volcanism at the Öraefajökull stratovolcano, Iceland. *Bulletin of Volcanology*, 68, 737–
739 752.
- 740 Sulpizio, R., Zanella, E., Macías, J.L. and Saucedo, R. 1998. Deposit temperature of
741 pyroclastic density currents emplaced during the El Chichón 1982 and Colima 1913
742 eruptions. *Geological Society, London, Special Publications*, 396, 35-49.
- 743 Swithinbank, C. 1950. The origin of dirt cones on glaciers. *Journal of Glaciology*, 1, 461-465.
- 744 Thomas, R.M.E. and Sparks, R.S.J. 1992. Cooling of tephra during fallout from eruption
745 columns. *Bulletin of Volcanology*, 54, 542-553.
- 746 Thorarinson, S. 1958. The Öraefajökull eruption of 1362. *Acta Naturalia Islandica*, 2, 100 pp.
- 747 Thordarson, T. and Hoskuldsson, A. 2002. *Classic geology in Europe 3. Iceland*. Terra
748 Publishing & Dunedin Academic Press, Edinburgh, 200 pp.
- 749 Tómasson, H. 1996. The jökulhlaup from Katla in 1918. *Annals of Glaciology*, 22, 249-254.
- 750 Tweed, F.S. and Russell, A.J. 1999. Controls on the formation and sudden drainage of
751 glacier-impounded lakes: implications for jökulhlaup characteristics. *Progress in Physical
752 Geography*, 23, 79-110.
- 753 Visale, S. and Isaia, R. 2014. Fractures and faults in volcanic rocks (Campi Flegrei, southern
754 Italy): insight into volcano-tectonic processes. *International Journal of Earth Sciences*,
755 103, 801-819.
- 756 Wadge, G., Boughton, I., Sparks, S. and Newall, C. 1969. Imperial College Volcanological
757 Expedition to Iceland 1969. Expedition and geological report, 22 p. [unpubl.]
- 758 Walker, A.J. 2011. Rhyolite volcanism at Öraefajökull volcano, S.E. Iceland – a window on
759 Quaternary climate change. University of Manchester PhD thesis, 325 p. [unpublished]
- 760 Walter, T.R. and Troll, V.R. 2001. Formation of caldera periphery faults: An experimental
761 study. *Bulletin of Volcanology*, 63, 191–203.

- 762 Waltham, T., Bell, T. and Culshaw, M. 2005. Sinkholes and subsidence. Karst and cavernous
763 rocks in engineering and construction. Springer-Verlag, Berlin, 382 pp.
- 764 White, J.D.L. and Houghton, B.F. 2006. Primary volcanoclastic rocks. *Geology*, 34, 677-680.
- 765 Whittaker, B.N. and Reddish, D.J. 1989. Subsidence. Occurrence, prediction and control.
766 *Developments in Geotechnical Engineering*, vol. 56, Elsevier, Amsterdam, 528 pp.
- 767 Zanella, E., Sulpizio, R., Gurioli, L. and Lanza, R. 1998. Temperatures of the pyroclastic
768 density currents deposits emplaced in the last 22 kyr at Somma—Vesuvius (Italy).
769 *Geological Society, London, Special Publications*, 396, 13-33.
- 770 Zanon, V., Pacheco, J. and Pimentel, A. 2009. Growth and evolution of an emergent tuff
771 cone: Considerations from structural geology, geomorphology and facies analysis of São
772 Roque volcano, São Miguel (Azores). *Journal of Volcanology and Geothermal Research*,
773 180, 277-291.
- 774

775 **Figure captions**

- 776 Figure 1. Sketch map of Öräfajökull with the location of Varða indicated. The inset shows
777 the location of Öräfajökull in SE Iceland. Modified after [Stevenson et al. \(2006\)](#).
- 778 Figure 2. Geological map of Varða. The lava depicted on the southwest flank of Varða
779 appears to be dyke-fed and may be associated with a subsidiary vent of the
780 Varða outcrop.
- 781 Figure 3. View of the Varða tuff cone looking south from the summit of the small
782 agglutinate cone c.1 km north of Varða. The shallow valley in the middle ground
783 is covered in pumice tephra from the 1362 eruption of Öräfajökull. Note the
784 topography of the middle ground overlain by Varða tephra. It forms a broad
785 watershed sloping down to right and left. The location of the 'main ridge'
786 described in the text is also indicated. Two seated persons in the foreground
787 (white rings) are present for scale.
- 788 Figure 4. Typical exposure of lapilli tuffs in the Varða tuff cone, showing prominent planar
789 diffuse stratification. Arrows mark the positions of outsize clasts with impact
790 structures; ballistic travel from upper right to lower left. The field notebook is 17
791 cm long.
- 792 Figure 5. Selected views of features of lapilli tuffs in the Varða tuff cone (a-d) and off-cone
793 outcrops to the north (e-f). (a) Abundant armoured (ash-coated) lapilli; (b) fine
794 tuff (below pencil) banked against bomb lapillus (dark grey) by a pyroclastic
795 density current travelling left to right; (c) block with impact structure; (d)
796 adhesion ripples; (e) dune bedform with low-angle foresets (transport left to
797 right); and (f) stacked antidunes (transport left to right).
- 798 Figure 6. View looking west at the east side of the main ridge extending north from Varða.
799 The locations of ice-melt subsidence structures are indicated and they are
800 numbered to link with descriptions in the text. Note also the two antiforms
801 created by tephra draping older agglutinate mounds (representing a bisected
802 crater rim). The pale scree is composed of 1362 tephra. The cliff face is up to 16
803 m high.
- 804 Figure 7. Views of the commonest ice-melt subsidence structures seen at Varða. A.
805 Steeply-dipping slab of massive lapilli tuff (white outline; structure number 6)
806 draped across a subvertical face that cuts across gently dipping stratified lapilli
807 tuff. The notebook is 17 cm in length. B. Poorly exposed structure on the west
808 flank of the detached Varða tephra outcrop east of the main ridge. The structure
809 comprises a subvertical slab of stratified lapilli tuff a few metres thick. The lapilli
810 tuffs outside (left) of the structure dip at 10° and are cut across by the structure
811 (not seen in the photograph). The green mapping case is c. 30 cm wide.
- 812 Figure 8. Photograph and annotated view of structure 3, showing steep inward-dipping
813 bedding, which varies to vertical and even slightly overturned, suggesting that a
814 surface pit may have formed as a result of the deformation. The northern
815 margin is faulted. See also [Figure 12](#).

- 816 Figure 9. Photograph and annotated view of structure 4. The downsagged strata form an
817 asymmetrical depression, with shallower bedding dips on the south side and
818 much steeper dips on the north side, where there is a prominent faulted margin
819 (shown in [Fig. 10](#)).
- 820 Figure 10. Annotated view of the northern margin of structure 4. The margin is a fault that
821 cuts across lapilli tuff beds that are slightly downbent close to the contact. The
822 relationships suggest that a large block of stratified lapilli tuffs has collapsed
823 along a normal fault and is not exposed at this level whilst the fault is draped by
824 downsagged higher beds. The three normal cross-faults shown (dashed white
825 lines) may be coeval with the subsidence structure, and possibly formed due to
826 tension at the axis of flexure for the downsagged beds. The notebook is 17 cm in
827 length.
- 828 Figure 11. Blocks of stratified lapilli tuff within structure 3. Note the ill-defined margins of
829 the blocks and lack of open pore spaces, which suggests that the blocks were
830 relatively weakly lithified when they were juxtaposed and partially
831 disaggregated during formation of the breccia. The notebook is 17 cm in length.
- 832 Figure 12. Field sketches of structure number 3. A. Plan view; B and C. Cross sections along
833 lines shown in A. Angle of draw (θ) is the angle at which the subsidence spreads
834 out; it defines the limit for subsidence effects ([Whittaker and Reddish, 1989](#); [Ren
835 and Li, 2008](#)). In A, 'centre 1' and 'centre 2' refer to the locations of two possible
836 buried ice blocks whose mutual melting caused the subsidence structure to have
837 an elongated, 'figure of eight' configuration (see text for details). Note the
838 presence of breccia sandwiched between tilted beds in B, suggesting that
839 subsidence was probably sequential (piecemeal).
- 840 Figure 13. Series of sketches showing internal structures observed in experimental
841 analogues for caldera collapses that are similar to those seen at Varða (based on
842 computed X-ray microtomographic images in [Poppe et al., 2015](#)). A. Breccia
843 development in a former cavity; B, C. Steep and slightly overturned beds
844 associated with marginal ring faults; D. folded beds within the collapsed mass.
- 845 Figure 14. Schematic depiction of the sequence of events envisaged leading to the
846 formation of the Varða ice-melt subsidence structures. The dashed grey line in
847 each figure indicates the approximate axis of the broad watershed; it may also
848 correspond to a volcanic fissure, now unexposed and inferred only by the
849 positions of the eruptive centres. The sequence of events may have taken place
850 during the Eemian interglacial or else in the Holocene, so long as a glacial
851 advance took place during the latter after the eruptions had ceased.

FIGURES FOR:

Complex circular subsidence structures in tephra deposited on large blocks of ice: Varða tuff cone, Öräfajökull, Iceland

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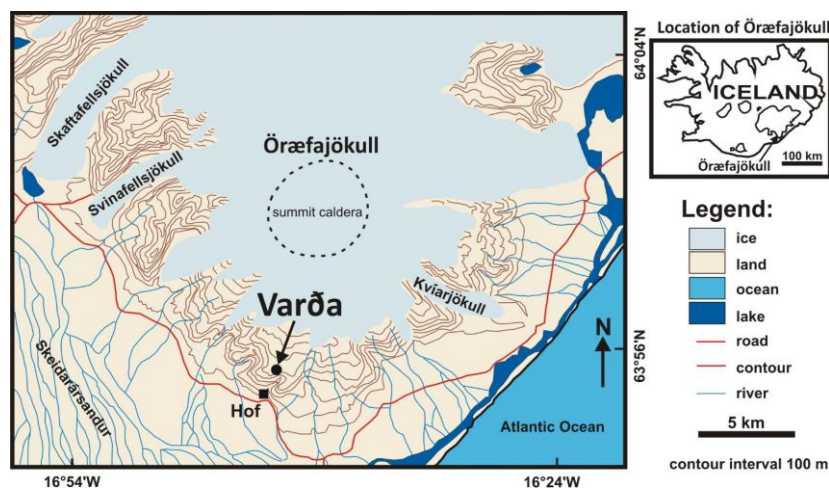


Fig. 1

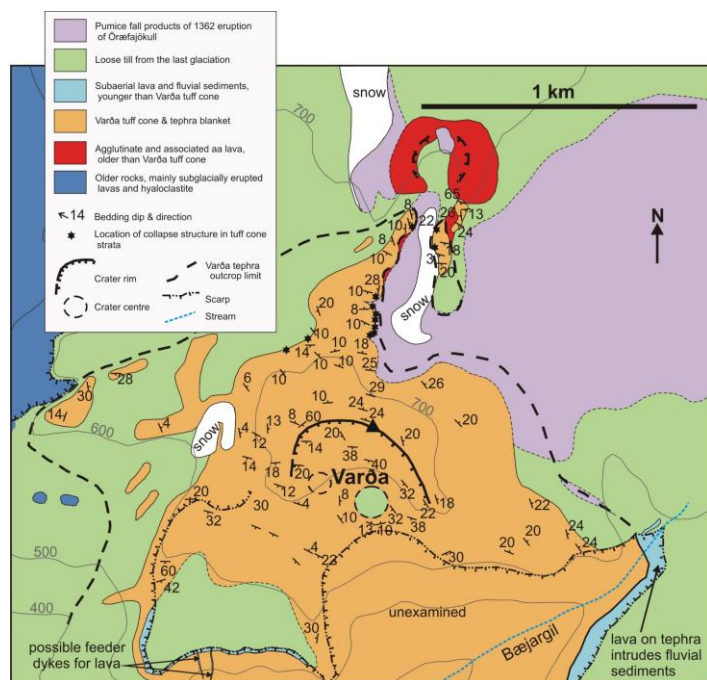


Fig. 2

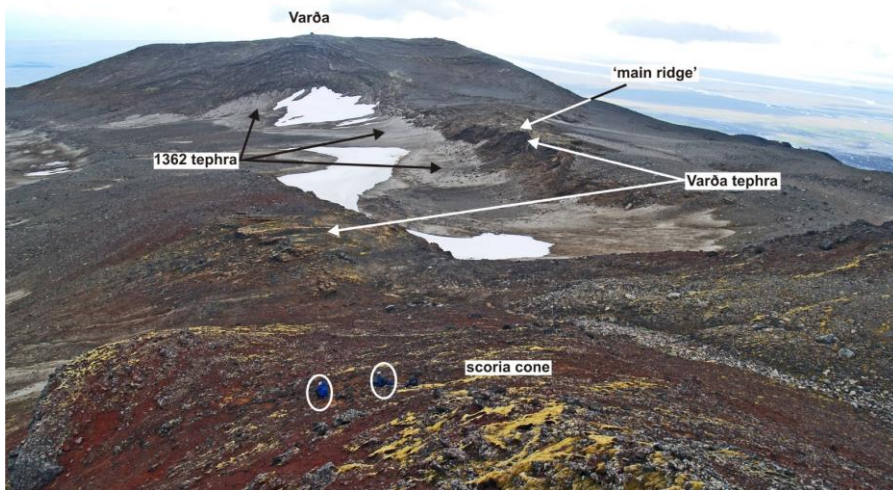


Fig. 3



Fig. 4



Fig. 5

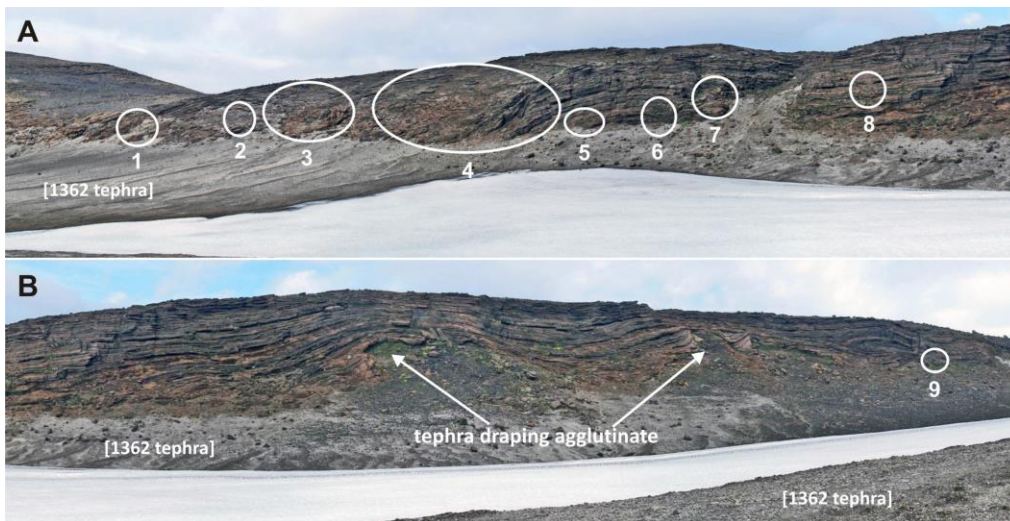


Fig. 6



Fig. 7a



Fig. 7b

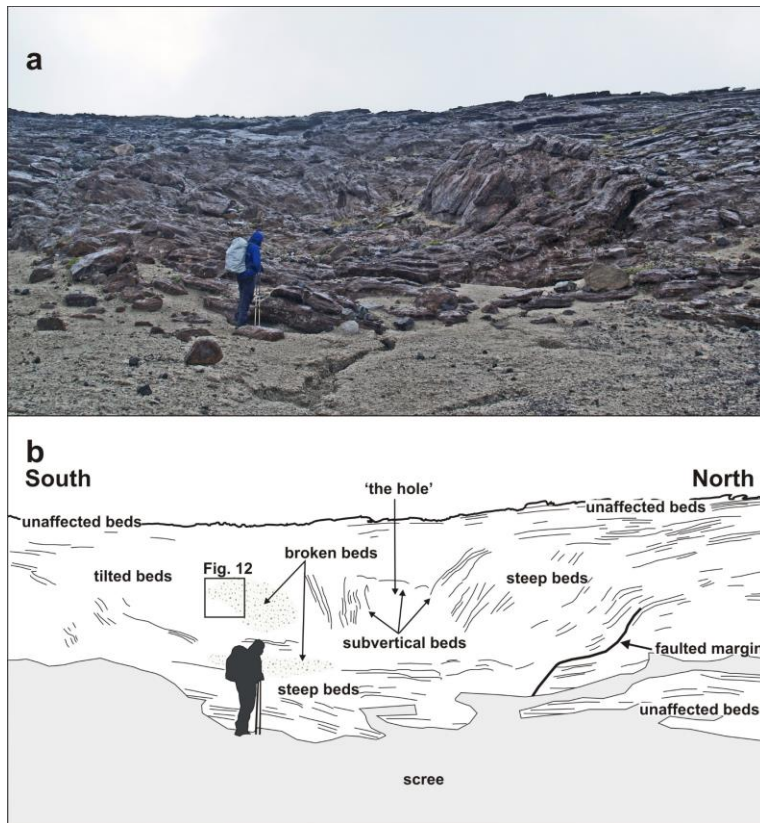


Fig. 8

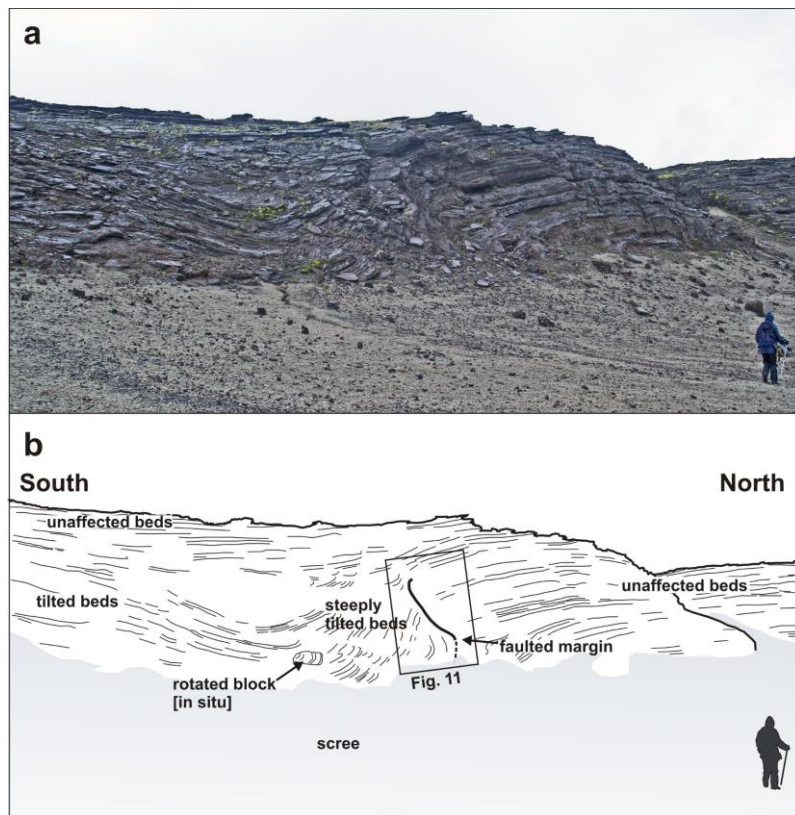


Fig. 9



Fig. 10



Fig. 11

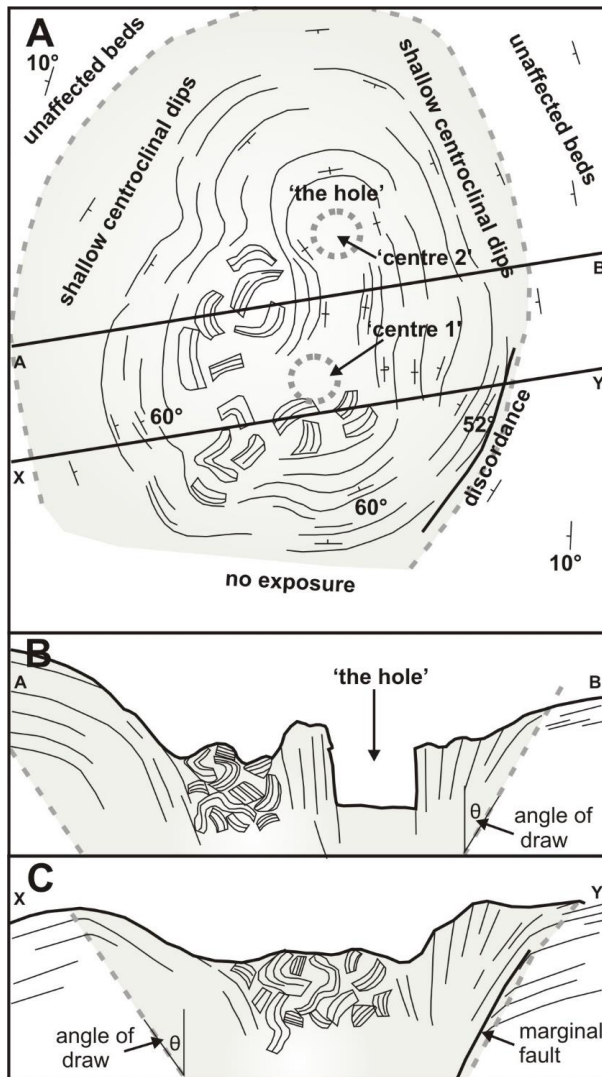


Fig. 12

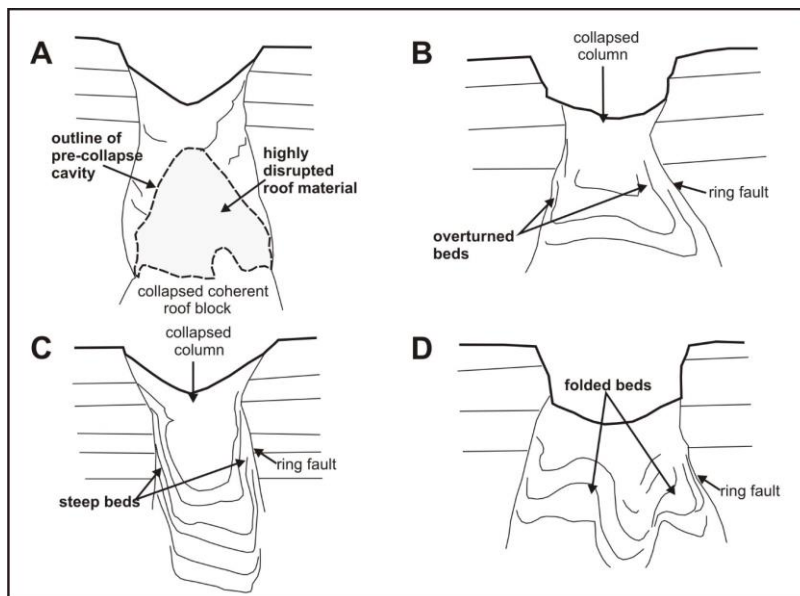


Fig. 13

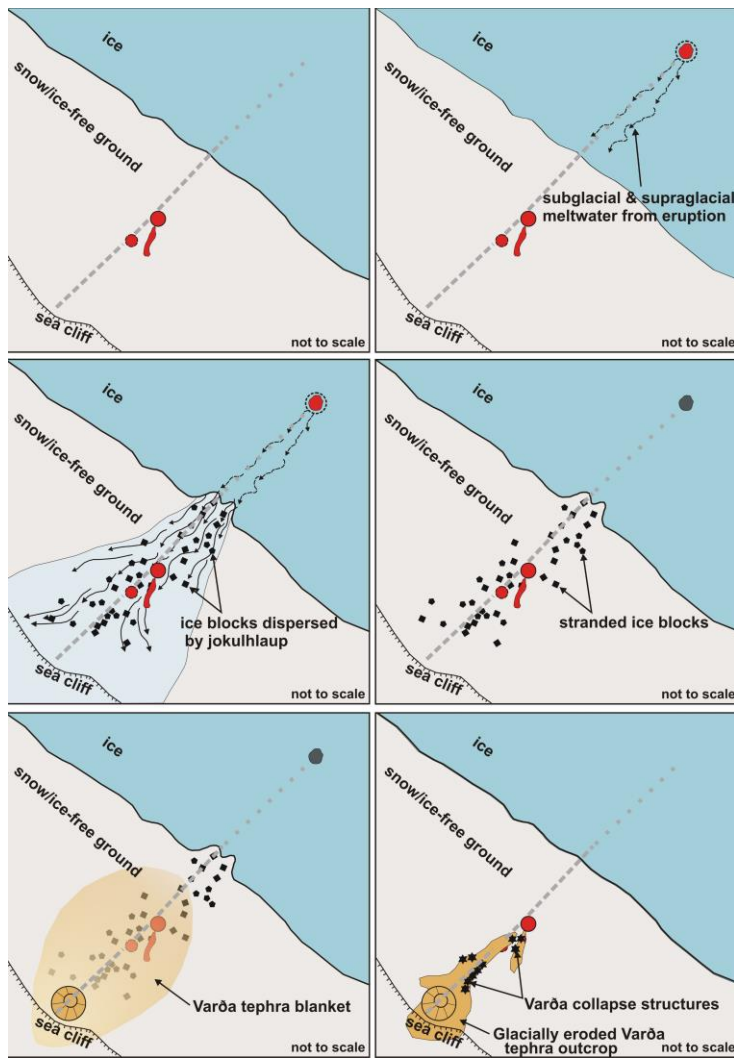


Fig. 14

SUPPLEMENTARY FILE

Complex circular subsidence structures in tephra deposited on large blocks of ice: Varða tuff cone, Öräfajökull, Iceland

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Figure 1. View looking northwest across the mouth of Bæjargil showing steeply dipping Varða tephra draped across an older cliff face.

Figure 2. A-C. Views showing numerous large ice blocks strewn across Skeidarársandur following the jökulhlaup associated with the 1996 eruption of Gjalp, Vatnajökull, photographed in 1997. Note the angular shapes of the individual blocks, their varied and often large sizes and steep sides. Although these ice blocks are exposed on the sandur, ice blocks also become completely buried during jökulhlaups (see D). D. Kettle hole developing above an ice block completely buried in a lahar deposited by a jökulhlaup from Gígjökull during the 2010 eruption of Eyjafjallajökull (cf. ice-melt collapse pits of [Branney and Gilbert, 1995](#)); photographed in July that year. The two steep-sided pits seen in the background are more fully developed kettle holes with vertical sides, also associated with completely buried ice. All images courtesy of Andy Russell.

Figure 3. Series of diagrams illustrating the evolution of subsidence in calderas (modified after [Acocella, 2007](#)). Four empirical stages are recognised, with different surface expression and development of internal structures. The subsidence may stop at any stage depending on the local circumstances. Note the development of surface sagging and the progressive upward growth of reverse and normal ring fractures. In stage 3, normal faults are depicted migrating upward draped by downsagged beds, a relationship broadly similar to that observed in Varða structures 3 and 4 (cf. [Figs 10, 12c](#)). The lack of a reverse ring fault cutting the surface at Varða may be due to a combination of a very slow strain rate and the ductility of the cohesive, mechanically weak lapilli tuffs, which reacted by downsagging. However, the presence of local breccias at Varða (e.g. in structure 3; [Figs 11, 12](#)) indicates that strain rates were variable.

