

# 1 **Impact of mechanical heterogeneity on joint density in a welded ignimbrite**

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5

## 6 **Abstract**

7 Joints are conduits for groundwater, hydrocarbons and hydrothermal fluids. Robust fluid flow models  
8 rely on accurate characterisation of joint networks, in particular joint density. It is generally assumed  
9 that the predominant factor controlling joint density in layered stratigraphy is the thickness of the  
10 mechanical layer where the joints occur. Mechanical heterogeneity within the layer is considered a  
11 lesser influence on joint formation. We analysed the frequency and distribution of joints within a  
12 single 12-meter thick ignimbrite layer to identify the controls on joint geometry and distribution. The  
13 observed joint distribution is not related to the thickness of the ignimbrite layer. Rather, joint initiation,  
14 propagation and termination are controlled by the shape, spatial distribution and mechanical properties  
15 of fiamme, which are present within the ignimbrite. The observations and analysis presented here  
16 demonstrate that models of joint distribution, particularly in thicker layers, that do not fully account for  
17 mechanical heterogeneity are likely to underestimate joint density, the spatial variability of joint  
18 distribution and the complex joint geometries that result. Consequently, we recommend that  
19 characterisation of a layer's compositional and material properties improves predictions of subsurface  
20 joint density in rock layers that are mechanically heterogeneous.

## 21 **1. Introduction**

22 The accurate characterisation of fracture attributes is essential for constraining fracture network  
23 models and, as a consequence, for improving predictions of fluid flow in fractured rocks. Such flow  
24 predictions can be key to assessing the viability of individual sites for industrial production, as for  
25 example, in assessing aquifer recharge for groundwater production schemes (Neuman, 2005; Jimenez-  
26 Martinez et al., 2013), determining the viability of enhanced geothermal systems (Fox et al., 2013;  
27 Hofmann et al., 2014) and determining hydrocarbon production prospects in tight reservoirs (Koning,  
28 2003). Stochastic or mechanical models that predict fracture distribution and geometry at depth are  
29 more reliable if they include information and interpretations about the manner in which fracture  
30 initiation, growth and arrest are affected by variables such as rock strength, anisotropy, stress state and  
31 fluid pressure (Cacas et al., 2001).

32 Predictive models of joint density generally focus on the thickness of the jointing layer, as commonly  
33 observed in layered sedimentary rocks where opening-mode joints occur as laterally persistent, layer-  
34 confined, parallel sets, with a positive correlation between median joint spacing and mechanical layer  
35 thickness. (Huang and Angelier, 1989, Narr and Suppe, 1991; Gross, 1993; Ji and Saruwatari, 1998; Ji  
36 et al., 1998; Fisher and Polansky, 2006). However, factors other than layer thickness also affect the  
37 number and geometry of joints within a layer. Principal among these is the mechanical heterogeneity  
38 of the layer, that is a factor overlooked in many numerical models of joint formation, which apply only  
39 to isotropic, homogeneous layers. In reality, rocks are spatially heterogeneous, varying in both  
40 composition and mechanical properties. Several workers have shown that mechanical heterogeneities  
41 in the form of flaws or inclusions are sites of joint initiation in rock. Inclusions such as fossils and  
42 intraclasts and flaws in the form of pores, bed forms and microcracks (Pollard and Aydin, 1988; Gross,  
43 1993; McConaughy and Engelder, 2001; Weinberger, 2001a) perturb the regional stress field and act  
44 to concentrate stress at the flaw until it exceeds the tensile strength of the rock, promoting joint  
45 initiation and propagation. When an inclusion is weaker than the surrounding rock, the stress  
46 concentration is tangential to the inclusion, for stronger inclusions the tensile stress is greater within  
47 the inclusion and the tangential stress less (Pollard and Aydin, 1988). Furthermore, inclusions can  
48 localise stress at the greatest point of curvature i.e. at 'corners' or 'tips' (Eshelby, 1957, 1959; Pollard  
49 and Aydin, 1988). Hence, flaw distribution, size, shape and material properties affect the density,  
50 average spacing and saturation of joints in a rock layer (Weinberger, 2001b; Tuckwell et al., 2003)

51 Mechanical heterogeneity not only controls joint initiation and propagation but also impacts joint  
52 geometry. In homogeneous material, joint propagation is proposed to occur by coalescing of  
53 microcracks in the process zone ahead of the joint tip (Scholz, 1993) resulting in planar joints. By  
54 contrast, observations of joints at sedimentary interfaces show that joints can step across, bifurcate or  
55 propagate straight through them (Cooke and Underwood, 2001; Larsen et al., 2010). Numerical  
56 modelling of this process demonstrates that as a fracture tip approaches an interface, two stress  
57 maxima occur ahead and either side of the fracture tip (Cooke and Underwood, 2001) resulting in a  
58 step-wise propagation of the joint, rather than a simple continuing coalescence for a migrating process  
59 zone.

60 In this study, we examine the manner in which the spatial distribution and geometry of joints in a 12-  
61 meter thick densely welded ignimbrite layer are affected by the geometrical and mechanical  
62 characteristics of heterogeneities in the form of flame, which create mechanical heterogeneities  
63 within the lithology. Although layering has been shown to play a significant role in the spatial  
64 distribution of joints; in the absence of strong layering, mechanical heterogeneity within, may exert a  
65 strong influence on joint network development. Our study is an example of how spatially

66 heterogeneous rock strength impacts joint development and the properties of the resultant joint  
67 network.

68 The observations and analysis presented here demonstrate that models of joint distribution, particularly  
69 in thicker layers, that do not fully account for mechanical heterogeneity are likely to underestimate  
70 joint density, the spatial variability of joint distribution and the complex joint geometries that result.  
71 Our observations may also serve as an analogue for understanding the affect mechanical  
72 heterogeneities can have on joint networks in layered sedimentary sequences.

## 73 **2. Formation and properties of ignimbrites**

74 The formation of ignimbrite deposits is a complex process that has significant impact on their  
75 mechanical properties. Key factors are ‘welding’; glass transition temperature; and syn- and post-  
76 cooling alteration processes. Welding refers to the syn- and post-depositional viscous deformation,  
77 fusion and compaction (‘flattening’) of glass shards, lapilli and pumice clasts, which post-compaction  
78 are known as fiamme (Grunder and Russell, 2005; Bull and McPhie, 2007). The welding process  
79 sinters and fuses particles together and decreases porosity, so that high degrees of welding (i.e. densely  
80 welded) correlate with increased unconfined compressive strength (Moon, 1993; Schultz and Li, 1995;  
81 Quane and Russell, 2005). The degree to which an ignimbrite is welded can be evaluated by measuring  
82 fiamme aspect ratio (Ragan and Sheridan, 1972; Kobberger and Schmincke, 1999). Fiamme in  
83 moderately-to-densely welded deposits have aspect ratios between 4 and 5 (Quane and Russell, 2005),  
84 these fiamme form a fabric of discontinuous layers, or eutaxitic texture, parallel or sub-parallel to the  
85 unit base. Poorly welded ignimbrites have fiamme aspect ratios less than 4 and a very poorly  
86 developed eutaxitic texture.

87 The base of an ignimbrite is commonly marked by a vitrophyre, a massive fine-grained glassy layer  
88 formed by rapid cooling of the pyroclastic material. Generally, the vitrophyre is devitrified to a yellow,  
89 brittle, fine-grained powder (Ross and Smith, 1961). An ignimbrite may be composed of one or  
90 multiple ash-flows. If each ash-flow has been emplaced in rapid succession then the whole body of  
91 material will cool as a single cooling unit or layer (Smith et al., 1994; Wilson et al., 2003). However, as  
92 the unit cools the level of welding compaction varies vertically and depends upon the duration over  
93 which the glassy shards and pumice remain viscous (Quane and Russell, 2005; Riehle et al., 2010).  
94 These vertical variations in welding describe the welding profile of an ignimbrite. The ideal welding  
95 profile for a ignimbrite unit comprises a poorly welded (i.e. low density and high porosity) base and  
96 top, formed by rapid cooling and thus limited compaction. In the lower half of the unit, slower cooling  
97 permits high degrees of welding compaction (i.e. high density and low porosity) (Quane and Russel,

98 2005 and references therein). In reality, a variety of ignimbrite welding profiles have been found  
99 including densely welded throughout (Henry and Wolff, 1992), densely welded lower half with a  
100 gradual decrease in compaction upward (Kobberger and Schmincke, 1999; Jutzeler et al., 2010) or  
101 multiple welding maxima and minima within the unit (Riehle et., 2010). The change between the  
102 welding facies is gradational. Commonly, the material at the top of the unit is increasingly ash rich and  
103 fiamme poor, recording the waning of the eruptive phase.

104 Deformation within an ignimbrite changes from ductile to brittle as cooling proceeds. Once welding  
105 compaction ceases, thermal stresses are relieved by the formation of columnar cooling joints (DeGraff  
106 and Aydin, 1993; Kobberger and Schmincke, 1999; Goehring and Morris, 2008; Sewell et al., 2012).  
107 The temperature at which this ductile-brittle transition occurs is known as the glass transition  
108 temperature ( $T_g$ ), (Giordano et al., 2005) and demarcates the cooling front within the layer. The time  
109 taken for a deposit to cool below  $T_g$  depends on several factors including the composition and initial  
110 temperature of the pyroclastic flow, flow layer thickness and substrate temperature (Ragan and  
111 Sheridan, 1972; Riehle, 1973; Miller and Riehle, 1994). For example, Riehle (1973) calculated that a  
112 10m-thick rhyolitic pyroclastic flow will cool to half its initial temperature within 2 years while a 40m-  
113 thick layer requires 20 years.

114 Cooling joints initiate at the top and bottom of the unit and follow the cooling front toward the unit  
115 interior, forming elongate, regularly and spaced, polygonal columns with  $\sim 120$  angles between joints  
116 (Goehring and Morris, 2008). Joint advancement is incremental, alternating between brittle joint  
117 propagation behind the cooling front and termination in the plastic medium beyond the cooling front.  
118 Consequently, the cooling joint surface is composed of sub-horizontal smooth (brittle) and rough  
119 (plastic) sections creating undulations or stria on the joint surface (Goehring and Morris, 2008).  
120 Mineralisation or alteration on or immediately around the cooling joint surface may also occur (Dunne  
121 et al., 2003).

122 Syn- and post-cooling secondary alteration processes can further alter the material properties of the  
123 ignimbrite. Vapour phase crystallisation precipitates minerals from hot gases, filling pore spaces in the  
124 ash matrix or pumice vesicles. Crystals grow discretely or as meshworks (McArthur et al., 1998), thus  
125 strengthening the matrix by reducing pore space and growth of interlocking crystals. Vapour phase  
126 alteration breaks down the glassy fiamme material to form either discrete acicular crystals growing  
127 inward from the fiamme rim or spherical intergrowths of elongate fibres called spherulites (Smith et  
128 al., 1994) within the fiamme.

129 The ignimbrite formation process significantly affects mechanical properties, and in particular, the  
130 spatial heterogeneity of rock strength. Welding has the capability to form discrete mechanical layers

131 within the ignimbrite unit, although the gradational changes between facies may inhibit this outcome.  
132 The presence of fiamme, as well as the positions of secondary alteration processes may result in  
133 isolated mechanical heterogeneities within the ignimbrite that may perturb the local stress field  
134 sufficiently to serve as the nucleation points (i.e., flaws) for joint initiation. Cooling may create  
135 additional joints that increases overall joint abundance in a unit, reducing median joint spacing, and  
136 locally altering the joint spacing distributions.

### 137 **3. Geological setting**

138 The study area is located in the southwest of the caldera island of Gran Canaria, Spain (Fig. 1a). Initial  
139 caldera collapse occurred at 14 Ma, forming the ca. 20 km in diameter Tejada caldera, and blanketing  
140 the island with at least 20 individual ignimbrite flows between 5 m to 40 m thick (Schminke, 2004;  
141 Jutzeler et al., 2010; Soden and Shipton, 2013). We focus on one of these ignimbrite units called  
142 ignimbrite B (Schminke, 1998), which was erupted during initial caldera collapse and forms part of  
143 the Upper Mogan Formation (Fig. 1b). Ignimbrite B is a densely welded, ash and fiamme rich  
144 ignimbrite, blanketing the west and south of the island and ranging in thickness from 10-30 m.

145 Coincident with caldera collapse and ignimbrite eruption was the formation of a system of extra-  
146 caldera faults (Troll et al., 2002) and fractures (Soden and Shipton, 2013). Faults accommodating  
147 extension during caldera collapse formed parallel to the caldera margin (Fig. 1a), inflation of the  
148 caldera during subsequent eruptive cycles reactivated these faults and formed an additional set of faults  
149 radial to the caldera margin (Branney 1995; Walter and Troll, 2001; Holohan et al, 2012). Joint sets  
150 observed by Soden and Shipton (2013), both associated and unassociated with faults, display the same  
151 parallel and radial orientations relative to the caldera margin.

### 152 **4. Study site and data collection**

153 Data were collected from a 12m thick cross-section of ignimbrite B exposed along a valley side at Los  
154 Frailes (Fig. 2a). Ignimbrite B is a single cooling unit with a basal vitrophyre marking the lower  
155 contact with ignimbrite A and the basal vitrophyre of ignimbrite C marking the top of the unit. Though  
156 fiamme rich throughout, the top 2 meters of Ignimbrite B is fiamme poor and ash rich, the long axes of  
157 fiamme are sub-parallel to the unit base. Along a path that runs from the base of ignimbrite B to 2  
158 meters below the top of the unit, we collected fiamme data from five clean vertical faces that are  
159 exposed along road cuts. We collected no fiamme data between the road cuts as rock surfaces are  
160 heavily weathered, obscuring the fiamme. Joint data were collected along the entire length of the path,  
161 with the exception of one section where the surface was completely scree-covered (Fig. 2a & b). Each

162 road-cut face is labelled F and numbered from 0 to 4, where 0 is at the base of the unit and 4 at the top  
163 (Fig.2a, b & c). No faults were observed at, or in the vicinity of the study site.

164 Joint data (spacing, orientation, height, and aperture) were recorded using one scanline starting at the  
165 base of the unit (RHS of Fig. 2a & c) and continuing upward along the path to 10.5m above the unit  
166 base (LHS of Fig. 2a & c). At the base of ignimbrite B, the scanline was positioned immediately above  
167 the basal vitrophyre (face F0, Fig. 2a) and continued along the path at the base of the outcrops. The  
168 scanline was parallel to the strike of the outcrop and, due to the gradual slope of the path, sub-  
169 horizontal. Data from every joint that touched or crossed the scanline was collected. All joints were  
170 observed to continue upward from the path, and the majority cut the entire height of the outcrop face,  
171 although some terminated within the face. For the total of 106 joints, the location and measured height  
172 of each was plotted against distance along the line (Fig. 2c). The use of a continuous scanline ensures  
173 the data are not biased by site selection on the best exposed faces, as would potentially be the case for  
174 discrete scanlines. Rather, our method provides a complete record from the exposed portions of the  
175 joint system along the scanline. Given the lack of horizontal variation in ignimbrite composition and  
176 the absence of faults in or near the sample line, we believe that the scanline captures the vertical  
177 variation in joint development through this one ignimbrite unit.

178 Joint spacing was recorded as the horizontal distance between all pairs of adjacent joints for which  
179 there was full exposure. The outcrop orientation changes along the path (Fig. 2b) and all joint spacing  
180 measurements have been corrected for strike using the Terzaghi correction. The mean strike values for  
181 the outcrop and the distance along the scanline along which they apply, starting at F0 and moving up  
182 along the path, are 075 (0 - 4.5m), 140 (4.5m - 14.5m), 014 (14.5m - 33m), 040 (33m - 52m), 035  
183 (65m - 76m), 077 (76m - 84m), 010 (84m - 97m) and 075 (100m - 106m). Joint dip ranges between  
184  $58^{\circ}$  and  $90^{\circ}$  with a mean of  $85^{\circ}$ . Joint height was measured from the base of the unit or path to the joint  
185 tip or the top of the exposure. Nowhere was both the lower and upper end of a joint observed, thus  
186 measurements only constrain the minimum joint length at the exposure and are censored. On Face F0,  
187 all joints met the base of the unit, whereas on faces F1-F4 the lower end of the joints were not  
188 observed. No joints were observed to continue from ignimbrite B into either ignimbrite A or C,  
189 therefore ignimbrite B is considered to be an independently fractured mechanical unit.

190 The fiamme within the layer were sampled using 25x25cm squares drawn on to the vertical road-cut  
191 faces, as these provided the best exposure. Since the mechanical controls on joint initiation,  
192 propagation and termination were the focus of this study, the sample areas at each face were located  
193 where joint(s) were present. An example of a sample square, showing an annotated joint and  
194 neighbouring fiamme is shown in Figure 3. The number of sample squares on each face depended on  
195 the quality of the exposure, whereas both the fiamme and joints cutting the face, had to be clearly

196 visible. Face 0, 1 and 2 have three sample squares and fiamme on Face 3 were sampled using two  
197 squares. Due to the poor quality of the exposure and small number of joints at Face 4, only one sample  
198 square was located on the face. The location of each sample square is shown in Figure 2a with white  
199 squares. Photographs of the sample areas were digitised, and using Image J freeware, the maximum  
200 and minimum axis of each fiamme and number of fiamme were recorded. The calculated fiamme  
201 aspect ratios were used to determine the degree of welding and any relative change in welding along a  
202 vertical profile through ignimbrite B. Fiamme that were totally or partially enclosed within the area of  
203 the sample square were measured in our analysis.

## 204 **5. Field data and analysis**

### 205 *5.1 Joint geometry*

206 The joints are steeply dipping having a mean dip of  $85^{\circ}$ , and orientated perpendicular to the unit base.  
207 Vertical trace length ranges from 2.5 cm to 3.8m (Fig. 2c), although the maximum observed trace  
208 length was limited by the tops of the outcrop faces at any sampling location. The majority of joints  
209 have apertures of 2-3 mm, and the maximum aperture recorded was 3.7 cm. No observed joints were  
210 mineralised. Joints are composed of planar sections that step where the joint intersects fiamme, as no  
211 joint surface was exposed, no plumose structures if present were observed. Consequently, we could not  
212 determine sites of joint initiation or the propagation paths.

213 Cluster analysis of the joint orientations (Stereonet 9.5, Allmendinger et al., 2012) reveals a well  
214 defined NW-SE joint set with an average strike of  $127^{\circ}$ , concentric to the caldera perimeter, and a less  
215 well defined NE-SW joint set with an average strike of  $046^{\circ}$ , radial to the caldera margin (Fig. 4). Small  
216 populations of other joints have even weaker N-S and ENE-WSW trends. As mentioned previously,  
217 caldera collapse formed a system of extra-caldera faults and joints parallel and concentric to the  
218 caldera margin. At Los Frailes, the abundant NW-SE joint set is essentially parallel to the caldera  
219 margin. While there is greater scatter in the NE-SW joints, the mean orientation is perpendicular to the  
220 caldera margin, with a number of joints that are oblique to the margin.

221 We believe that one of two mechanisms could be responsible for joint formation: cooling and layer-  
222 parallel extension related to caldera collapse. Distinguishing cooling joints from tectonic joints in  
223 ignimbrites is difficult in the absence of alteration products such as joint fill or bleached rims, which  
224 are attributes associated with cooling joints (Sweetkind et al., 2003). Furthermore, cooling joints can  
225 form decades after ignimbrite emplacement as the deposit cools to ambient temperatures (Dunne et al.,  
226 2003). None of the observed joints in ignimbrite B are mineralised, thus our assessment relies on joint  
227 geometrical properties. Several lines of evidence suggest that these joints formed in response to  
228 regional tectonic stresses after cooling. First, joint intersection angles and orientations are incompatible

229 with a cooling origin. Rather than the 120° that is common for intersecting cooling joints (Goehring  
230 and Morris, 2008), the intersection angle between the mean strike of the two sets we observed is 82°.   
231 Furthermore, the angle of intersections between adjacent joints is predominantly less than 50° (Fig. 5),  
232 as opposed to the expected intersection angles of around 120° or 60° for cooling joints. Second, many  
233 joints exhibit geometrical interactions with fiamme, where joints step across fiamme (Fig. 6a, b & d)  
234 and a number of joints terminate against horizontal or steeply dipping joints (Dunne et al., 2003).  
235 Hence, the joints interacted with these pre-existing features, rather than following a cooling front.  
236 Thirdly, joint spacing increases and correspondingly, joint abundance decreases toward the top of  
237 Ignimbrite B (Fig. 2d). This geometric pattern is contrary to the expectation for joints formed in  
238 response to thermal contraction, where joint spacing increases toward the layer centre (DeGraf and  
239 Aydin, 1993). Lastly, Soden and Shipton (2013) showed that joints in Ignimbrite B on the west coast  
240 of Gran Canaria are orientated NS and EW, radial and tangential to the caldera margin, respectively  
241 and formed in response to cycles of caldera inflation and collapse. In summary, evidence from analysis  
242 of the joint network geometry strongly suggests that the joints are not the result of cooling, but rather  
243 related to layer-parallel extension during caldera collapse and/or inflation..

## 244 *5.2 Joint intensity*

245 The scanlines record data obliquely upwards through the unit (Fig. 2c). We use these data to examine  
246 variation in joint characteristics from the base to the top of the layer, given the lack of nearby faults or  
247 lateral variation in ignimbrite composition to trigger changes in joint system attributes. To assess  
248 changes in joint frequency vertically within the unit, we plot the height within the unit against the  
249 horizontal spacing for each adjacent pair of joints with full exposure (Fig. 2d). Height is calculated as  
250 the height above the ignimbrite base mid-way between the pair of joints. This graph shows joints  
251 higher in the unit are more widely spaced and with greater variability in joint spacing, upward in the  
252 unit.

253 Joints in Ignimbrite B are layer confined and, given the relationship to the caldera margin, we suggest  
254 formed by layer extension during periods of caldera deflation and inflation. As previously stated,  
255 layer-confined, opening-mode joints commonly have a positive correlation between median joint  
256 spacing and mechanical layer thickness. The fundamental mechanism proposed to explain this  
257 relationship is the shear-lag model (Cox, 1952; Hobbs, 1967). Briefly the model involves the layer-  
258 parallel extension of a competent layer bounded between two less competent layers. Joints form when  
259 the tensile stress exceeds the tensile strength of the competent layer, with sequential joints forming  
260 midway between existing joints when the tensile stress again exceeds the layer tensile strength. The  
261 shear-lag model predicts that continued layer-parallel extension will ultimately result in the fracturing  
262 layer becoming joint saturated; at this point no new joints will form regardless of increasing strain (Wu

263 and Pollard, 1995; Bai et al., 2000; Bai and Pollard, 2000b; Dharani et al., 2003). Bai and Pollard  
264 (2000) proposed that a joint saturated layer will have a joint density (D) times layer thickness (T)  
265 between 0.8 and 1.2. If DT is approximately one, the layer is considered to be joint saturated, DT  
266 values >1.2 and <0.8 indicate the layer is over- and under-saturated respectively, and in the case of  
267 over-saturation new joints will not form by layer extension alone.

268 Already we have shown that joint spacing varies within the ignimbrite layer. To compare the joint  
269 intensity within the ignimbrite layer with studies in sedimentary rocks, we use the relationship between  
270 joint density (D) and layer thickness (T) (Ladeira and Price, 1981; Becker and Gross, 1996;  
271 Underwood et al., 2003). To estimate DT for the whole ignimbrite layer, we calculated the mean  
272 number of joints per meter, D, as 1.02 (Fig. 2d). This value yields a DT value for the whole 12m-thick  
273 ignimbrite B layer of 12.24. Indicating that, as a single mechanical layer, Ignimbrite B is highly joint  
274 over-saturated, which is contrary to Ladeira and Price (1981), who observed lower than expected joint  
275 intensity in thick layers.

### 276 *5.3 Fiamme mechanical properties*

277 Although the ignimbrite is densely welded throughout, a number of observations suggest that the  
278 fiamme are weaker than the ash matrix. Firstly, the ash matrix is pervasively jointed at the study site,  
279 whereas only one fiamme has joints that only occur in the fiamme without entering the adjacent  
280 welded ash. Secondly, SEM examination (Fig. 7) shows that the ignimbrite has undergone vapour  
281 phase alteration, producing meshworks of interlocking micro-crystals in the ash, thereby reducing  
282 porosity and strengthening the matrix (Fig. 7) (McArthur et al., 1998). Conversely, vapour phase  
283 alteration created porosity in fiamme, as well as producing discrete acicular crystals lining fiamme in  
284 the base of the unit and meshworks (sphaerulites) of crystals in fiamme toward the top of the unit (Fig.  
285 8). Although the exact timing of the secondary alteration relative to joint formation is uncertain,  
286 vapour-phase alteration occurs below the glass transition temperature when deformation changes from  
287 ductile to brittle (Giordano et al., 2005), thus the secondary alteration is either prior to or  
288 contemporaneous with jointing. The contrast in mechanical properties between the fiamme and ash  
289 will tend to promote joint initiation at the weaker fiamme, where a local tangential tensile stress is  
290 generated within the stiffer ash matrix (Pollard and Aydin, 1988).

### 291 *5.4 Distribution of fiamme*

292 Fiamme sampling squares 25x25cm were placed at heights of 0.25m, 1.5m, 5.5m, 8.5m and 10m  
293 above the ignimbrite base for each of faces F0 through to F4, respectively (Fig. 2a). The fiamme  
294 density (# fiamme/cm<sup>2</sup>) for each face is plotted against height above the unit base in figure 8a. A slight  
295 drop in fiamme abundance within the ignimbrite between station F1 and F2 is observed (Fig. 8a). The  
296 decrease in mean fiamme abundance (Fig. 8a) appears to coincide with the increase in mean joint

297 spacing (Fig. 2d), which we suggest indicates weaker fiamme are localising tensile stress and  
298 promoting joint initiation and propagation.

### 299 *5.5 Fiamme shape*

300 The welding profile of Ignimbrite B was examined by measuring the aspect ratio of each fiamme  
301 within the sample squares, from which the median aspect ratio for each face, as well as for the entire  
302 ignimbrite layer, were determined. The median fiamme aspect ratio for Ignimbrite B is 5.5, with values  
303 from each sample square ranging from 1.5 to 43 (Fig. 8b), thus Ignimbrite B is a densely welded  
304 ignimbrite (Quane and Russell, 2005). As with fiamme abundance, the fiamme aspect ratio decreases  
305 between station F1 and F2 (Fig. 8b), including the median, upper and lower quartiles of the aspect ratio  
306 distribution. Also, all but two of the measured fiamme with an aspect ratio greater than 20 are in the  
307 bottom 2 meters of the unit (Figure 8b). In section 2, we stated that a decrease in fiamme aspect ratio  
308 indicates a decrease in the degree of welding, hence welding intensity decreases toward the top of  
309 Ignimbrite B. The decrease in fiamme aspect ratio also coincides with the decrease in joint abundance  
310 (Fig. 2d). Lower aspect ratio fiamme are less oblate and, in cross-section, fiamme tips have a lower  
311 curvature. We suggest that the decrease in tip curvature diminishes the stress concentration tangential  
312 to the fiamme, thereby inhibiting joint propagation in the upper portion of Ignimbrite B.

### 313 *5.6 Joint-fiamme interaction*

314 From our analysis of the joint and fiamme data, we believe that the shape, material properties and  
315 distribution of the fiamme strongly influence joint initiation and propagation within Ignimbrite B. To  
316 investigate the potential role that fiamme shape had on joint propagation, we divided the fiamme data  
317 into two groups – jointed fiamme (i.e. those where a joint steps across, cross-cuts or terminates at the  
318 fiamme) and unjointed fiamme. A plot of these data shows that fiamme with greater aspect ratios are  
319 more commonly intersected by a joint (Fig. 8c). The results of a t-test demonstrate that at all  
320 stratigraphic positions, a highly significant difference exists between the mean aspect ratio of the  
321 jointed and unjointed fiamme, implying that joints intersect high-aspect ratio fiamme preferentially to  
322 lower aspect-ratio fiamme (Table 1).

### 323 **Insert Table 1**

324 Aspect ratio is a measure of fiamme compaction and hence potentially correlates with their mechanical  
325 properties. We must consider, however, the possibility that high aspect-ratio fiamme merely have a  
326 greater lateral extent, and consequently propagating joints have a greater probability of intersecting  
327 them. Data to discount this possibility are shown in Table 2, where the median lengths of jointed and  
328 unjointed fiamme differ by less than a millimetre but jointed fiamme aspect ratio is on average 40%  
329 greater than that of the unjointed fiamme. Hence, the observed preferential joint interaction with high

330 aspect ratio fiamme is not due to an increase in their average lateral extent. Thus, the presence of  
331 fiamme with greater aspect ratios was an important contributor to joint initiation and propagation, by  
332 localising stress at fiamme tips. To further test this hypothesis, we analysed the different joint-fiamme  
333 interaction geometries, and positions along the length of fiamme where the joint intersected. (Table 3,  
334 Figure 6).

### 335 **Insert Table 2**

336 Four types of joint-fiamme interaction are observed (Fig.6): unlinked stepping joints and linked  
337 stepping joints that step across fiamme (Fig. 6a & b), single joints that pass straight through fiamme  
338 (Fig. 6c), and single joint tips located at fiamme, i.e. joint initiation or termination (Fig. 6b). All joints  
339 are orthogonal to the fiamme long axis. Importantly, as joint surfaces are unexposed and initiation  
340 points and propagation paths unknown, joint geometries reflect joint interactions with fiamme.  
341 Consequently, the observed joint tips may be a 2D section through a joint tip-line rather than the actual  
342 joint initiation or termination point. The location of the joints along the fiamme long axis was defined  
343 as either occurring at the fiamme tip or non-tip, where we defined the tip area as the distance from the  
344 fiamme tip to one quarter way along the length of the fiamme.

345 The results of the joint-fiamme interaction analysis are shown in Table 3. For all faces, greater than  
346 50% of all joint types intersect the tip area of the fiamme - F0 57.7%; F1 55.5%; F2 56%; F3 60.2%;  
347 F4 76%. This supports our proposition that the high curvature fiamme tips localise tensile stress  
348 resulting in joint initiation and propagation. The remainder of the joints intersect the central portion of  
349 the fiamme, and hence, we infer that tangential stress resulting from a weak inclusion imbedded in a  
350 stronger matrix also has a role to play in joint propagation.

351 The joint geometries also reflect differences in material properties between the fiamme and ash matrix.  
352 The geometry of a joint is affected by the mechanical properties of the material through which it  
353 propagates. Work examining the propagation of joints in alternating shale and siltstone sequences  
354 (Hegelson and Aydin, 1991) demonstrates how the stress ahead of a joint tip is transmitted between  
355 stiff layers (higher modulus) across a weaker (lower modulus) interlayer. As the joint approaches the  
356 weaker interlayer, the transfer of the fracture tip stress across the layer produces two stress maxima in  
357 the unjointed stiff layer, which result in the joint stepping as it crosses the weaker layer. However,  
358 there is a critical weak layer thickness that impedes joint propagation, causing joints to terminate at the  
359 weak layer (Rijken and Cooke, 2001). When layers have similar Young's moduli the joint propagates  
360 straight through all layers.

361 In general, models of joint interaction with layer interfaces show joints often terminate at weak  
362 interfaces (Renshaw and Pollard, 1995; Cooke et al., 2006), propagate straight through strong

363 interfaces, and step at interfaces of moderate strength (Cooke et al., 2006). Hence, the observed joint  
364 geometries reflect the variation in the relative strength between the fiamme and ash matrix, as well as  
365 the different fiamme-ash interface mechanical strengths. Between 58% and 84% of joints cut straight  
366 through fiamme (Table 3), suggesting that either the fiamme and matrix are of the similar strength, or  
367 there is a strong fiamme-matrix interface. The greater proportion of these straight joints cut the fiamme  
368 tip, indicating a difference in material property between the fiamme and ash, as is shown by our SEM  
369 analysis. Further, the fiamme in this group have high aspect ratios indicating a strong degree of  
370 compaction and welding. Hence, the geometry is likely a result of a strong fiamme-ash interface. The  
371 next most frequently observed joint type are joint tips located at fiamme, however as we have stated,  
372 these may not be true joint tips and without seeing the joint surface we cannot say if these are joint  
373 initiation or termination points. It should be noted, however, that the lower tip of a joint is never  
374 observed (they all propagate down to the path or layer base). Hence, it seems likely that many  
375 observations of joint tips are terminations of upwardly propagating joints. In which case, given that the  
376 mean fiamme aspect ratios of this group do not differ greatly to fiamme in the other two groups, these  
377 fiamme must be much weaker than the ash matrix. As such, the weak fiamme are acting to terminate  
378 joints and hence reduce the joint intensity in the upper part of the ignimbrite. Stepping joints make up  
379 between 7% and 15% of all joint types and are approximately evenly split between joints intersecting  
380 fiamme at tips and non-tips. Joints stepping across fiamme indicate the fiamme are weaker than the  
381 matrix. We divided stepping joints into joints that are linked across fiamme via a horizontal section  
382 and those that are not linked (Table 3, Fig. 6b). The mean aspect ratio of fiamme in the unlinked  
383 stepping group is generally smaller than for fiamme cut by straight joints. Smaller aspect ratio  
384 indicates less compaction and welding and possibly a fiamme-ash interface of moderate strength.  
385 Fiamme in the linked stepping joint group have mean aspect ratios less than or similar to fiamme cut  
386 by straight joints. The latter case may reflect fiamme which having undergone vapour phase alteration  
387 and are weaker than the matrix.

### 388 **Insert Table 3**

389 The observations summarised in Table 3 support the proposition that fiamme perturbed the stress field  
390 during joint formation. The extent to which the stress field was perturbed, is a function of fiamme  
391 shape and the contrast in material properties between the fiamme and the surrounding matrix. For all  
392 joint geometry types, the greater proportion of joints interact with fiamme tips, thus the high curvature  
393 of the fiamme tips localise stress and are sites of joint initiation or propagation. The termination or  
394 stepping of joints is a result of the contrast in mechanical properties between fiamme and ash and the  
395 strength of the fiamme-ash interface. Given the competing effects of fiamme distribution, shape and  
396 material properties that influence the joint network, it is unlikely that small changes in any one

397 parameter can be directly correlated to changes in joint intensity. Rather changes across all fiamme  
398 characteristics act to produce a greater change in joint intensity.

## 399 **6. Model for joint network development**

400 Based on our analysis, we believe that the control on joint intensity within Ignimbrite B is the spatial  
401 distribution, geometry and mechanical properties of the fiamme in the unit rather than the thickness of  
402 the unit. Joint intensity is greatest where the fiamme aspect ratio is greatest at the unit base. We  
403 propose this relationship is due to larger stress concentrations at the tips of the more elongate fiamme,  
404 which are weaker than the surrounding ash matrix, and to stress tangential to the weaker fiamme  
405 embedded in the stiffer matrix; providing favourable sites for joint nucleation (Fig. 9). If a joint  
406 approaches a densely welded fiamme, propagation straight through or with a step across the fiamme is  
407 likely, depending on the fiamme-ash mechanical contrast and the fiamme-ash interface strength. If a  
408 joint encounters a less welded, low aspect ratio fiamme it is more likely to terminate. We propose that  
409 joints propagate upward, and as they propagate upward they, encounter progressively fewer and less  
410 welded fiamme, thereby inhibiting joint propagation. This proposed model of joint initiation and  
411 growth (Fig. 9) explains the observed spatial distribution of joints throughout ignimbrite B, as well as  
412 the apparent decrease in joint intensity with increasing elevation within the unit.

413 Our analysis shows that the mechanical heterogeneity within Ignimbrite B plays a significant role in  
414 controlling joint geometry and location. The spatial distribution, mechanical and geometric properties  
415 of fiamme influence joint initiation, propagation and termination, which in turn control the abundance  
416 of joints throughout the unit. These results suggest that greater attention should be paid to the spatial  
417 heterogeneity of rock strength when developing predictive models for fracture networks. The  
418 properties and distribution of flaws like fiamme may exert controls on fracture network properties that  
419 are equal to or greater than the well-known influences of variables such as layer thickness and  
420 interfacial shear strength..

## 421 **Conclusions**

422 We study joint frequency and orientation throughout the full thickness of an ignimbrite located on the  
423 island of Gran Canaria, Spain. Our observations show that joint spacing varies vertically within the  
424 unit, in tandem with subtle variations in the geometrical and mechanical properties of fiamme within  
425 the ash matrix. Propagating joints interact with fiamme and we propose that this interaction is  
426 responsible for the observed joint distribution and joint geometries. We propose a model whereby joint  
427 initiation, propagation and termination are governed by vertical variations in the geometrical and  
428 mechanical properties of the fiamme. We suggest that joints initiate near the base of the unit where the  
429 fiamme are more densely welded, due both to their high aspect ratio that causes larger stress

430 concentrations at their tips, and their lower strength, which contrasts with the stronger surrounding ash  
431 matrix. Once initiated, we propose that joints propagate predominantly upwards through the unit. As  
432 they encounter fiamme, they either step across them or terminate. Joints are more likely to terminate  
433 on fiamme with low aspect ratios, which are more common in the upper half of the ignimbrite unit. As  
434 a result joint intensity is very high at the base of the unit and decreases with increasing elevation.

435 Our research shows that in a mechanically heterogeneous lithology (i.e. with inclusions, lenses, clasts  
436 etc.) with weakly defined layering, joint intensity can be governed by the number and spatial  
437 distribution of heterogeneities with particular geometrical and mechanical properties. Consequently,  
438 joint spacing and location in siliciclastic or volcanoclastic lithologies at depth, may not be well  
439 described by models based only on the role of layer thickness. More accurate predictions may require  
440 characterisation of the composition and material properties within each layer.

441

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581

## 582 **Figure Captions**

583 Figure 1: a) Location map of the study area at Los Frailes, the caldera perimeter and an extracaldera  
584 fault concentric to the caldera perimeter, also shown are the outcropping Mogan and Fataga Group  
585 volcanics (light grey) and shield basalt (dark grey). b) Simplified stratigraphy of the Miocene and  
586 Pliocene and volcanic phases and detailed stratigraphy of the Mogan Group which contains Ignimbrite  
587 B, the focus of this study.

588 Figure 2: a) View of the exposure at Los Frailes which provides a complete cross-section through the  
589 12m thick Ignimbrite B unit. A path (grey line) runs from the base to the top of Ignimbrite B and five  
590 clean vertical faces (F0, F1, F2, F3 and F4) are accessible along the path. White square mark the  
591 location of the 25x25cm fiamme sample squares. b) The orientation of the vertical faces changes  
592 moving up through the unit, reducing any orientation sampling bias in the joint data. Start and end  
593 points of the scanline are marked X and X' respectively. c) Graph displays data for joint spacing and

594 joint height (vertical length of grey line) moving up through the unit. d) Joint spacing (cm) vs height  
595 above unit base, height is the height of the mid-point between joint pairs.

596 Figure 3: Example of 25x25cm square from F1 enclosing a joint. Fiamme long axes are sub-horizontal,  
597 some fiamme are highlighted in white.

598 Figure 4: Stereonet data plotted for all joints measure along the scanline (n=106). Great circles are for  
599 mean strike of NW-SE and NE-SW joint sets. Grey great circle is approximate caldera margin  
600 orientation relative to Los Frailes study site.

601 Figure 5: Angle of intersections between joints, and the frequency with which intersection angles  
602 occur.

603 Figure 6: Examples of the interaction between fiamme and joints from faces (F) at different heights in  
604 the ignimbrite. a & b) On intersecting high aspect ratio fiamme, joints step across the fiamme (ringed  
605 in red) forming composite joints composed of multiple segments. c) Where fiamme are less compacted  
606 joints pass through the fiamme tips. d) Stepping of a joint along multiple fiamme gives a curved  
607 geometry to the joint.

608 Figure 7: Fiamme (selection outlined in red) and ash matrix a) 1m and b) 6m above the ignimbrite  
609 base. Fiamme in the base of the unit are compacted and elongate. Secondary alteration processes have  
610 devitrified the glassy fiamme and formed acicular crystals in fiamme at the base (c) and spherulites in  
611 fiamme in the upper section of the unit (d), as well as crystal meshworks within the matrix (e). The  
612 meshworks reduce porosity in the ash matrix. f) Even at the micron level fiamme influence joint  
613 geometry causing a joint to step across fiamme.

614 Figure 8: Plots show for each face (F) number of fiamme per square centimetre (a) and aspect ratio for  
615 all fiamme sampled within each sample square (b) and fiamme divided into jointed (JF) and unjointed  
616 (UNJF) fiamme (c). Sample size at each face for JF and UNJF respectively are F0 n=380 & 220; F1  
617 n=311 & 232; F2 n=219 & 451; F3 n=151 & 118; F4 n=66 & 42. Note: Box plots in (c) are vertically  
618 offset for visual clarity but fiamme were sampled from the same squares on the outcrop, JF data are  
619 plotted at the actual sample heights.

620 Figure 9: Our model demonstrates how mechanical heterogeneities can have a significant impact on  
621 joint density within a layer, and that predictions of joint density based on layer thickness will differ  
622 greatly from the density and distribution of joints formed in a mechanically heterogeneous layer.  
623 Within the layer mechanical heterogeneities can i) localise tensile stress and initiate joints and ii) act as  
624 discontinuous mechanical sub-layers promoting or inhibiting joint propagation and influencing joint  
625 geometry.

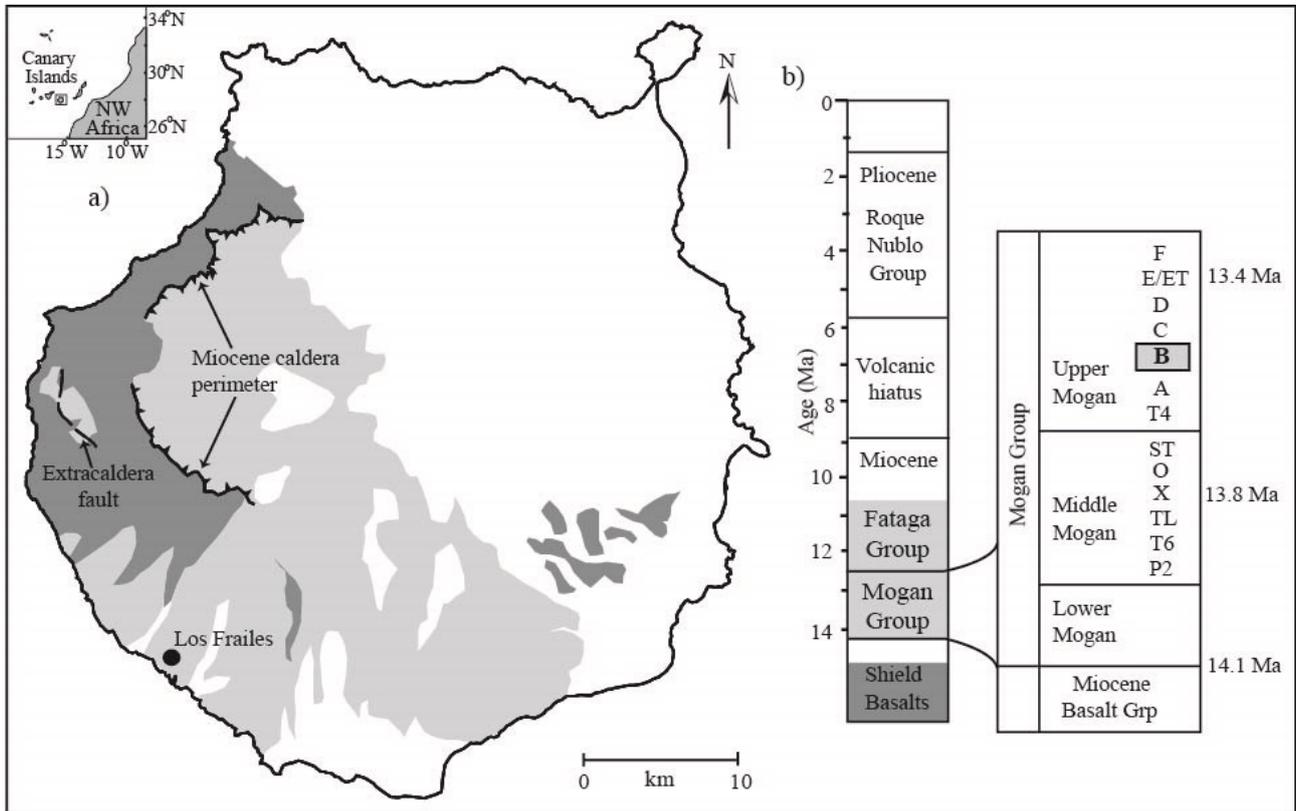
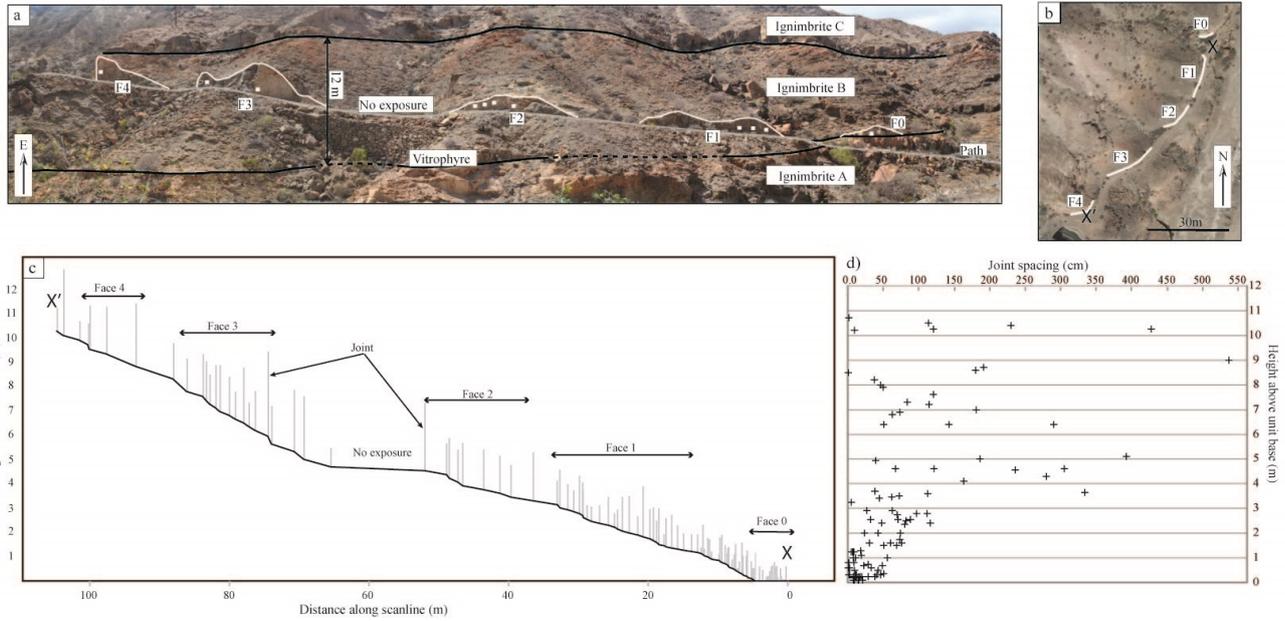


Figure 1: a) Location map of the study area at Los Frailes, the caldera perimeter and an extracaldera fault concentric to the caldera perimeter, also shown are the outcropping Mogan and Fataga Group volcanics (light grey) and shield basalt (dark grey). b) Simplified stratigraphy of the Miocene and Pliocene volcanic phases and detailed stratigraphy of the Mogan Group which contains Ignimbrite B, the focus of this study.

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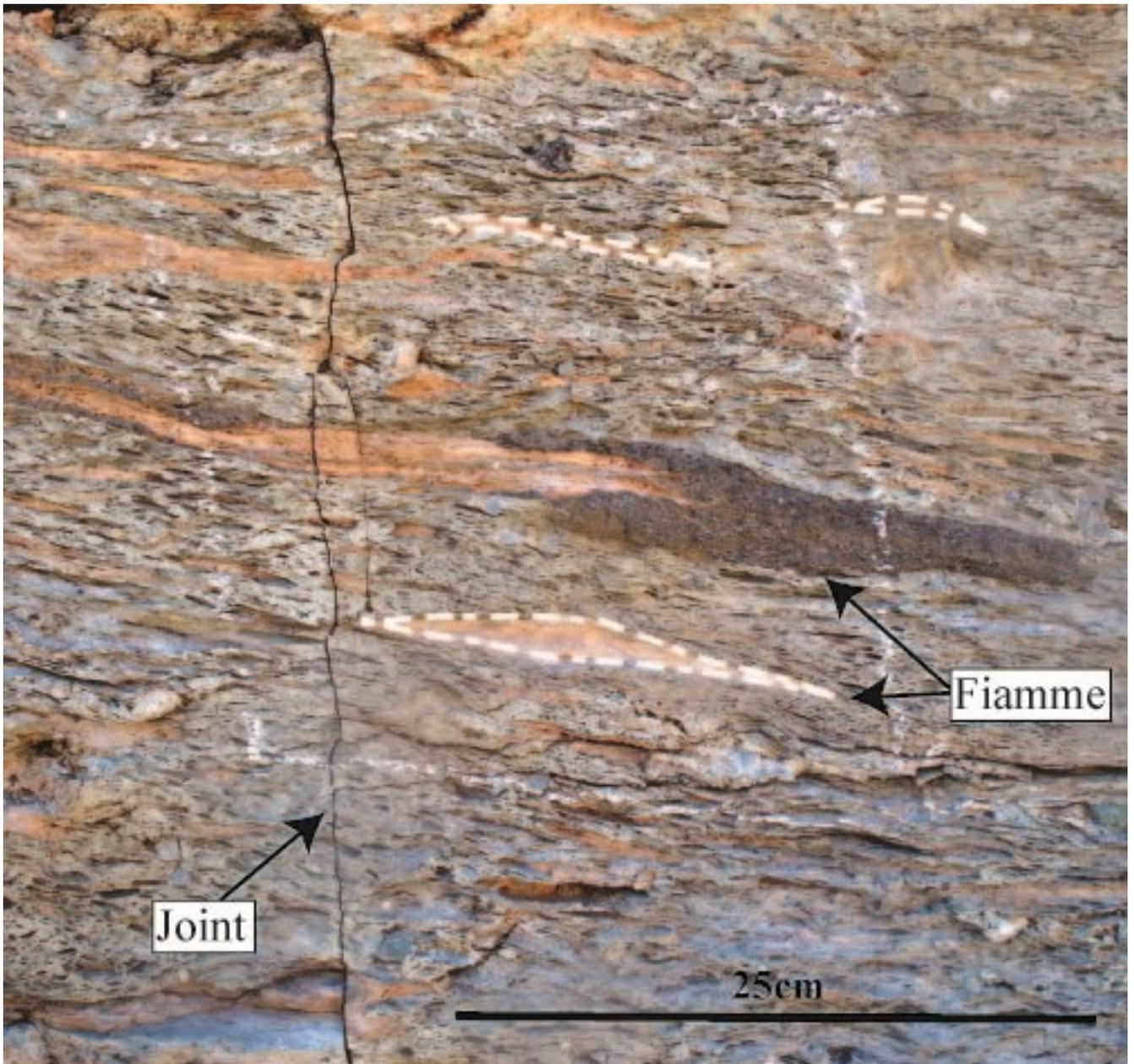
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630 Figure 2: a) View of the exposure at Los Frailes which provides a complete cross-section through the  
 631 12m thick Ignimbrite B unit. A path (grey line) runs from the base to the top of Ignimbrite B and five  
 632 clean vertical faces (F0, F1, F2, F3 and F4) are accessible along the path. White square mark the  
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 634 moving up through the unit, reducing any orientation sampling bias in the joint data. Start and end  
 635 points of the scanline are marked X and X' respectively. c) Graph displays data for joint spacing and  
 636 joint height (vertical length of grey line) moving up through the unit. d) Joint spacing (cm) vs height  
 637 above unit base, height is the height of the mid-point between joint pairs.

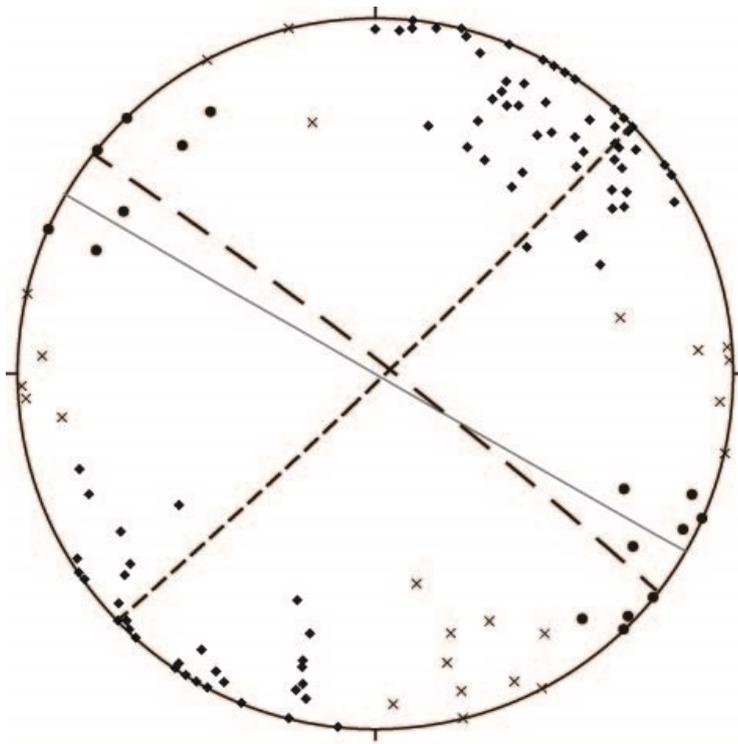
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641 Figure 3: Example of 25x25cm square from F1 enclosing a joint. Fiamme long axes are sub-horizontal,  
642 some fiamme are highlighted in white.

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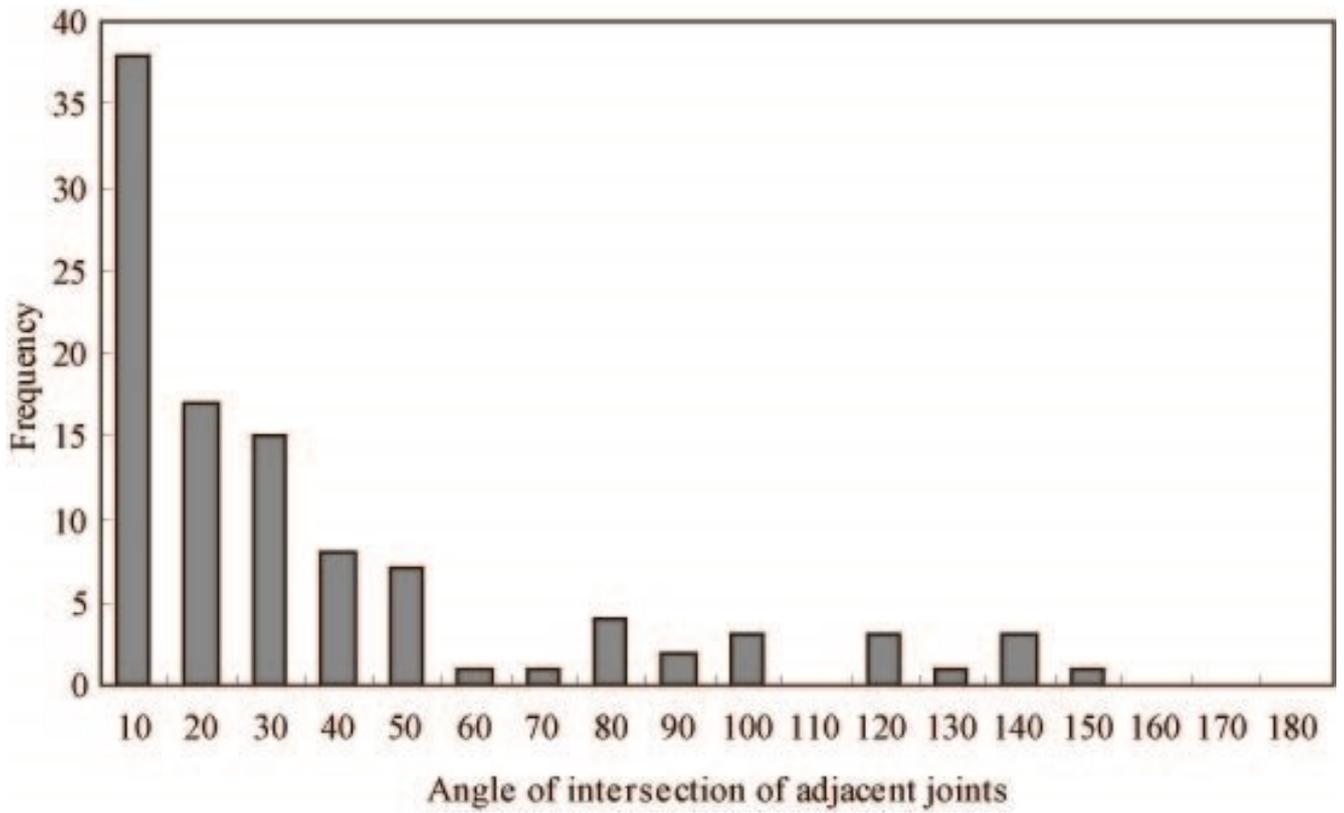


Fractures	Mean strike
● NE-SW n=13	-----
◆ NW-SE n=74	-----
Caldera margin	—————

645  
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647 Figure 4: Stereonet data plotted for all joints measure along the scanline (n=106). Great circles are for  
648 mean strike of NW-SE and NE-SW joint sets. Grey great circle is approximate caldera margin  
649 orientation relative to Los Frailes study site.

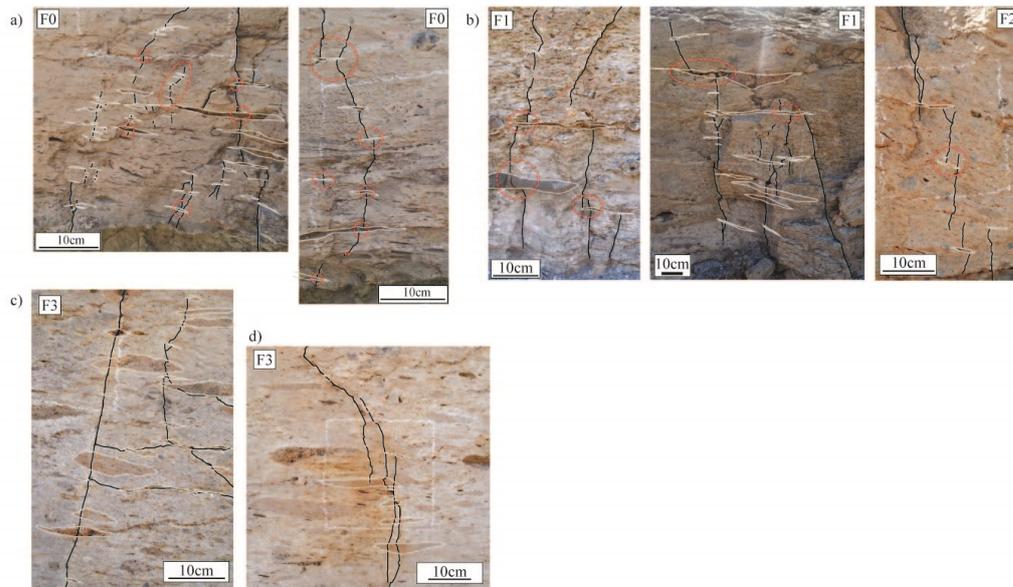
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653 Figure 5: Angle of intersections between joints, and the frequency with which intersection angles  
654 occur.

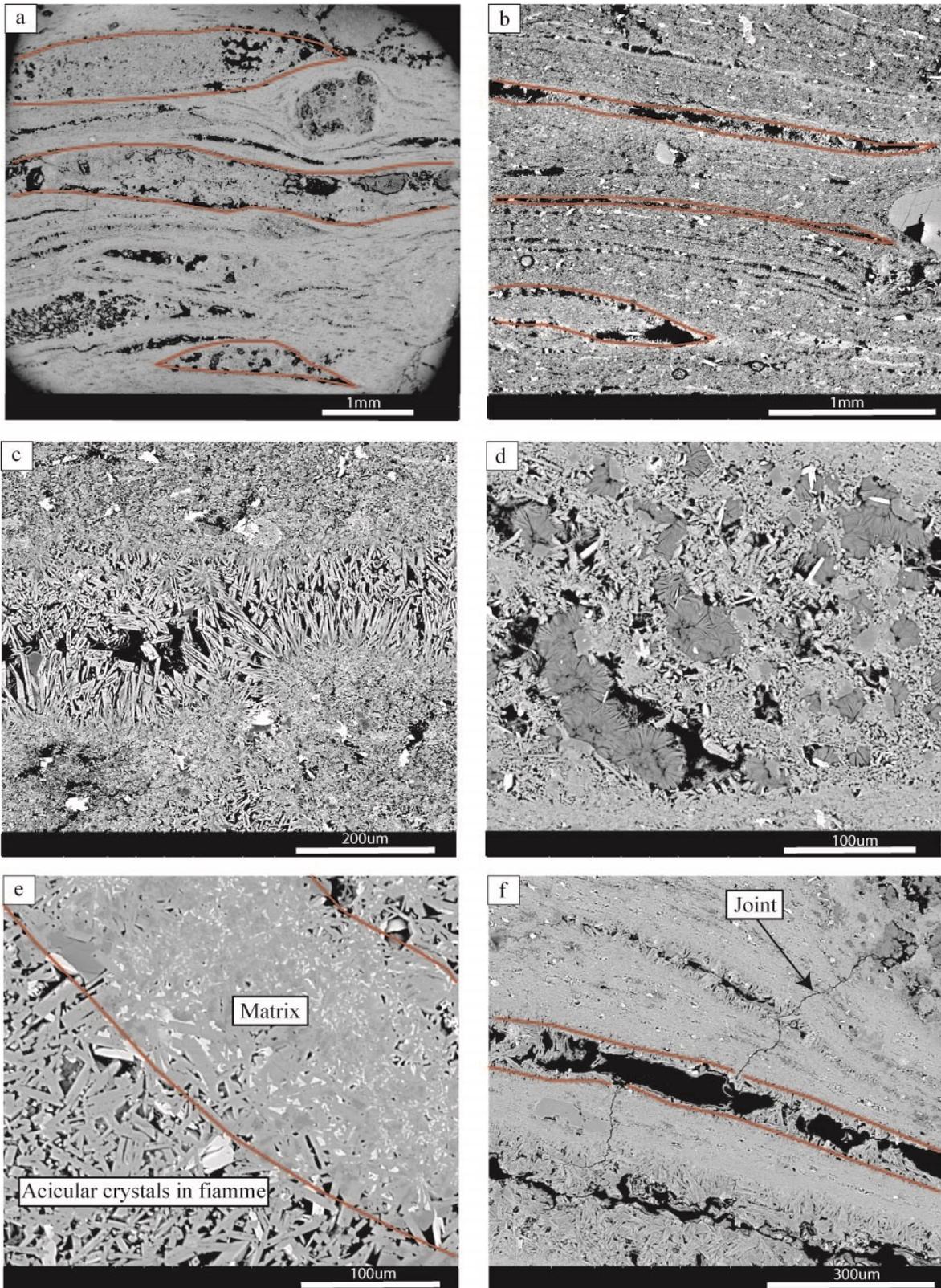
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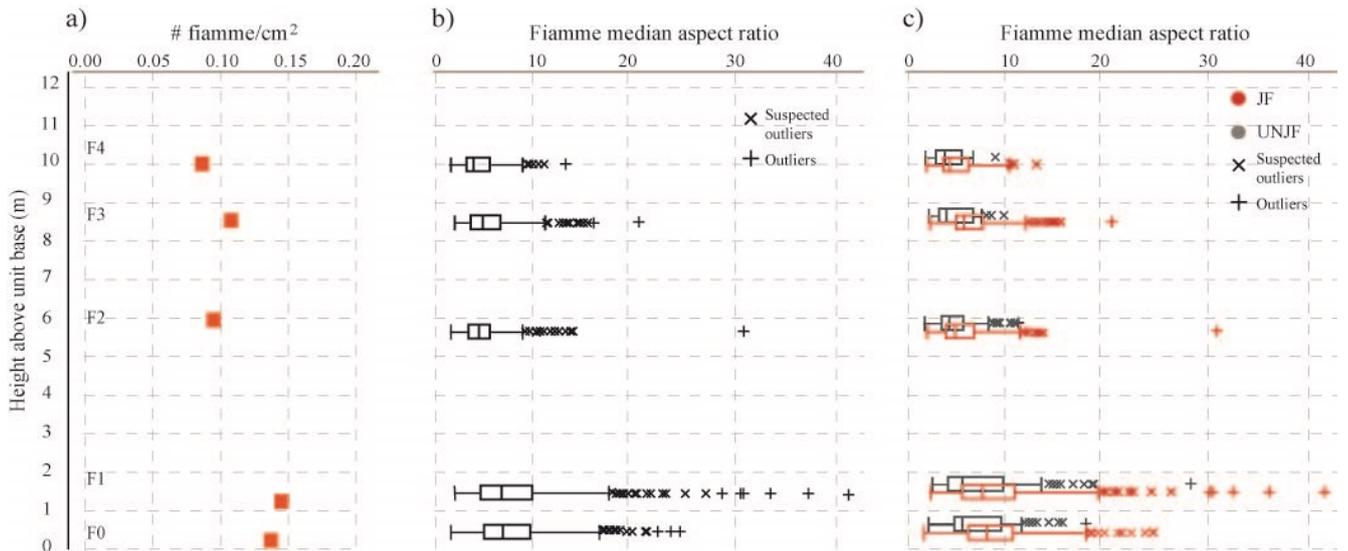
657 Figure 6: Examples of the interaction between fiamme and joints from faces (F) at different heights in  
 658 the ignimbrite. a & b) On intersecting high aspect ratio fiamme, joints step across the fiamme (ringed  
 659 in red) forming composite joints composed of multiple segments. c) Where fiamme are less compacted  
 660 joints pass through the fiamme tips. d) Stepping of a joint along multiple fiamme gives a curved  
 661 geometry to the joint.

662



663

664 Figure 7: Fiamme (selection outlined in red) and ash matrix a) 1m and b) 6m above the ignimbrite  
 665 base. Fiamme in the base of the unit are compacted and elongate. Secondary alteration processes have  
 666 devitrified the glassy fiamme and formed acicular crystals in fiamme at the base (c) and spherulites in  
 667 fiamme in the upper section of the unit (d), as well as crystal meshworks within the matrix (e). The  
 668 meshworks reduce porosity in the ash matrix. f) Even at the micron level fiamme influence joint  
 669 geometry causing a joint to step across fiamme.

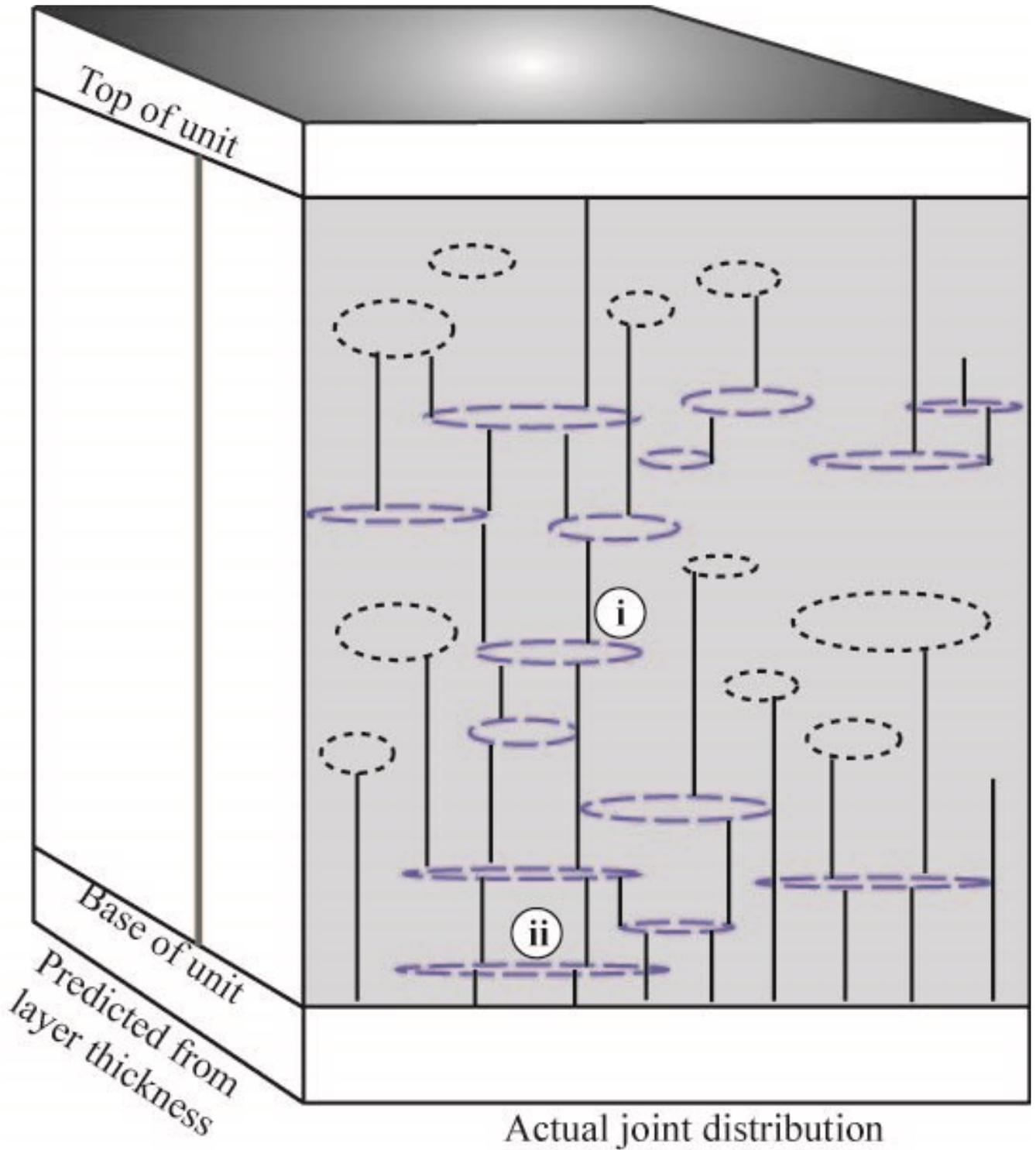


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672 Figure 8: Plots show for each face (F) number of fiamme per square centimetre (a) and aspect ratio for  
 673 all fiamme sampled within each sample square (b) and fiamme divided into jointed (JF) and unjointed  
 674 (UNJF) fiamme (c). Sample size at each face for JF and UNJF respectively are F0 n=380 & 220; F1  
 675 n=311 & 232; F2 n=219 & 451; F3 n=151 & 118; F4 n=66 & 42. Note: Box plots in (c) are vertically  
 676 offset for visual clarity but fiamme were sampled from the same squares on the outcrop, JF data are  
 677 plotted at the actual sample heights.

678



--- Densely welded fiamme  
 ..... Less welded fiamme

679

680 Figure 9: Our model demonstrates how mechanical heterogeneities can have a significant impact on  
 681 joint density within a layer, and that predictions of joint density based on layer thickness will differ  
 682 greatly from the density and distribution of joints formed in a mechanically heterogeneous layer.  
 683 Within the layer mechanical heterogeneities can i) localise tensile stress and initiate joints and ii) act as  
 684 discontinuous mechanical sub-layers promoting or inhibiting joint propagation and influencing joint  
 685 geometry.