

# The Vein Hosted Copper Deposits of the Allihies Mining Area, Southwest Ireland – A New Structural and Chronological Evaluation

Jürgen Lang<sup>1\*</sup>, Patrick A. Meere<sup>1</sup>, Richard P. Unitt<sup>1</sup>, Sean C. Johnson<sup>2</sup>, Giulio Solferino<sup>3</sup>,  
Koen Torremans<sup>2</sup>, David Selby<sup>4,5</sup> & Roisin Kyne<sup>6</sup>

<sup>1</sup> *Irish Centre for Research in Applied Geosciences (iCRAG), School of Biological, Earth and Environmental Sciences, University College Cork, Distillery Fields, North Mall, Cork, Ireland*

<sup>2</sup> *Irish Centre for Research in Applied Geosciences (iCRAG), University College Dublin, Belfield, Dublin 4, Ireland*

<sup>3</sup> *Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey, United Kingdom*

<sup>4</sup> *Department of Earth Sciences, University of Durham, Durham, United Kingdom*

<sup>5</sup> *State Key Laboratory of Geological Processes and Mineral Resources, School of Earth Resources, China University of Geoscience Wuhan, Hubei Province, 430074, China*

<sup>6</sup> *Teck Resources Limited, Suite 3300, Bentall 5. 550 Burrard Street, Vancouver, B.C., Canada, V6C 0B3*

*\*Corresponding author (e-mail: juergen.lang@icrag-centre.org)*

ORCIDiDs of authors preceded by their initials (optional):

J.L. <https://orcid.org/0000-0003-0086-0193>

P.M. <https://orcid.org/0000-0001-7686-2641>

R.U. <https://orcid.org/0000-0002-7504-1451>

K.T. <http://orcid.org/0000-0002-5127-5050>

**Abbreviated title:** The Copper Deposits of Allihies, SW Ireland

**Keywords:** quartz veins, Variscan Orogeny, copper mineralisation, drone mapping, Munster Basin & South Munster Basin, fluid inclusions, Re-Os geochronology

**Abstract:** This paper presents new data for historic vein-hosted copper sulphide deposits in the Upper Palaeozoic Munster and South Munster Basins of southwest Ireland. Detailed mapping, 3D modelling, fluid inclusion microthermometry and geochronology from the Allihies area of the Beara Peninsula, have led to a new interpretation of the timing and development of ore mineralisation. Macro- and microstructural studies reveal that the ore-bearing, mainly E-W striking quartz veins are directly related to early extensional, basal normal faults. Molybdenite Re-Os dating of the main-stage Cu lode yield ages from  $367.3 \pm 5.5$  to  $366.4 \pm 1.9$  Ma. This early vein system experienced subsequent late Carboniferous Variscan deformation, including cleavage development, sinistral SW-NE strike slip faulting, cataclastic deformation and recrystallization. The new timing of Cu mineralisation in SW Ireland has major implications for its relationship to the base metal deposits of the Irish Midlands. (*end of abstract*)

42

43 The mineral deposits of the Irish Variscan fold/thrust belt have been exploited for over 3500  
44 years (Williams 1991). In southwest Ireland copper has been mined as far back as the Bronze  
45 Age (O'Brien 1987). In 1812, malachite stained cliff faces at Dooneen on the Beara Peninsula  
46 (Fig. 1 and 2) led to the discovery of significant copper lodes (Blenkinsop 1902; Reilly 1986).  
47 As miners progressed further inland, they uncovered metal-rich, steeply dipping, E-W striking  
48 quartz veins in the vicinity of Allihies (Fig. 1 and 2). The biggest vein was worked at Mountain  
49 Mine which at the time became the largest copper mine in the region with a total estimated  
50 284,500 tonnes ore extracted (O'Brien 1959).

51 This paper focusses on the copper deposits of the Allihies mining district in West Cork (Fig.  
52 2) where previous authors studied the structure and chronology of the vein mineralisation  
53 (Sheridan 1964; Sanderson 1984; Spinks *et al.* 2016).

54

## 55 **Geological Setting**

56 Between the Middle and early Upper Devonian, north-south crustal extension led to the  
57 development of a half-graben structure in southern Ireland that comprises the Munster Basin  
58 (Naylor & Jones 1967). The northern bounding structure of this intracratonic basin has been  
59 described as the east-west trending, listric Coomnacronia-Killarney-Mallow Fault Zone (Fig.  
60 1; Naylor & Jones 1967; Capewell 1975; Price & Todd 1988; Meere 1995; Vermeulen *et al.*  
61 2000; Landes *et al.* 2003; MacCarthy 2007; Ennis *et al.* 2015) or the Dingle Bay-Galtee Fault  
62 Zone Williams (2000).

63 The lithostratigraphic nomenclature of the basin sediments is described in detail by MacCarthy  
64 1990, MacCarthy *et al.* 2002 and Pracht & Sleeman 2002. Late Middle to Upper Devonian  
65 alluvial and fluvial siliciclastic sediments derived mainly from the north were transported into  
66 the Munster Basin (MacCarthy 1990). These 'Upper Old Red Sandstone' sediments formed a  
67 basinal infill of over 6 km (Meere & Banks 1997). MacCarthy (1990) divided these siliciclastic  
68 sediments into 5 facies associations which evolved from early basin margin alluvial fans to  
69 floodplain-sheetfloods and ephemeral lakes.

70 Towards the end of the Devonian the formation of another east-west trending fault system,  
71 the Cork-Kenmare Fault Zone (Fig. 1) resulted in continuous subsidence of the South Munster  
72 Basin (MacCarthy 2007). This was accompanied by a marine transgression from the south  
73 with resulting accumulation of marine siliciclastics within the South Munster Basin and  
74 limestones on a more stable platform to the north (Fig. 1; MacCarthy 2007).

75 At the end of the Carboniferous NNW-directed compression terminated sedimentation in the  
76 region and marked the beginning of the Variscan Orogeny (Sanderson 1984; Ford 1987;  
77 Meere 1995; Quinn *et al.* 2005). Bulk shortening of over 52 % was achieved by pervasive  
78 cleavage development followed by kilometre scale buckling and faulting (Cooper & Trayner  
79 1986; Ford 1987). This resulted in the reactivation of high-angle basin-controlling faults (Price  
80 & Todd 1988). In the west of the Munster Basin, Meere (1995) identified NE-SW-trending  
81 reverse faults, as well as rarer NW-SE-trending strike slip faults. The sediments underwent  
82 metamorphism to sub-greenschist facies (Meere 1995).

83 E-W and ENE-WNW trending faults were interpreted by Wen *et al.* (1996) as late orogenic  
84 events. Daltry (1985) described a possible relationship of these fault systems with Post-  
85 Hercynian (Post-Variscan) wrench movements, associated with the North Atlantic opening in  
86 the Permian.

87 A series of minor sheet-like intrusions of mainly alkali basalts, trachytes and phonolites have  
88 been found along the northern coastline of Beara Peninsula (Pracht 2000; Fig. 1). These  
89 basalts are interpreted as surficial intrusions during the subsidence phase of the Munster



90 Basin. Pipe-like lamprophyric intrusions dated at  $314.44 \pm 1.00$  Ma (Ar/Ar phlogopite, Quinn  
91 *et al.* 2005) occur at Black Ball Head (5.6 km south of Allihies), which were formed during the  
92 early Variscan compression (Pracht & Kinnaird 1995; Pracht 2000).

93

94 The Allihies Mining District is located near the western end of the Beara Peninsula (Fig. 2).  
95 The predominant lithologies are purple and green siltstones and sandstones of the Caha  
96 Mountain Formation (MacCarthy *et al.* 2002). The Caha Mountain Formation can be  
97 subdivided into the Allihies Sandstone Member, which mainly outcrops north of Mountain Mine  
98 (Fig. 2) and has an approximate thickness of 1200 m, and the underlying Ballydonegan Slate  
99 Member (south of Mountain Mine) that has an approximate thickness of 1500 m (Reilly 1986).

100 The Allihies copper mines are positioned on the northern limb of the Beara Anticline (Sheridan  
101 1964). Around the mines, third-order open symmetrical folds with wavelengths of 90 to 150 m,  
102 trending SW-NE can be found associated with fault zones following similar strike (Reilly 1986;  
103 Fig. 2). Penetrative cleavage is sub-vertical and strikes SW-NE (Reilly 1986). The Cornish  
104 Village Fault is one of the rare NW-trending faults and was previously interpreted as a pre-  
105 mineralisation structure (Reilly 1986; Fig. 2).

106

107 There has been differing opinions about the timing of the vein structures and the copper  
108 mineralisation of the Allihies region. For example, mineralised veins were considered to post-  
109 date the barren veins and Variscan compression tectonics (Sheridan 1964). In direct contrast  
110 is the observation by Sanderson (1984) that mineralised (chalcopyrite and siderite) N-S  
111 trending quartz veins are both strongly folded and cleaved, suggesting a pre/syn-Variscan  
112 age. Sanderson (1984) also proposed that the east-west veins, which include the main lodes  
113 of the mining area, were formed in association with the cleavage development and the folding.  
114 Rogers (2002) divided the quartz veins of the Beara Peninsula into 3 different genetic events;  
115 early buckled veins, syn-buckled (syn-Variscan) and late stage extension. Wen *et al.* (1996)  
116 and Spinks *et al.* (2016) suggested remobilisation of sediment-hosted sulphides into late- or  
117 post-Variscan quartz veins.

118 At Mountain Mine Reilly (1986; Fig. 2) describes the major copper lodes, the E-W Lode, N-S  
119 Lode and New E-W Lode together defining a Z-shaped surficial outcrop. On the surface, these  
120 lodes are up to 18 m wide and 240 m long with bleached, altered, wall-rock zones up to 21 m  
121 in width. The mineralisation has been described in detail by Sheridan (1964) as consisting of  
122 mainly chalcopyrite, tetrahedrite and bornite within “compact silica” gangue (quartz) material.  
123 Reilly (1986) described the distribution of “molybdenum mineralisation” on the 1400 feet level  
124 of Mountain Mine, associated with high-grade copper mineralisation. Zones with a “cherty”  
125 appearance of quartz were identified as “dust-like” grains of molybdenite and pyrite (Fletcher  
126 1969). Selenium and tellurium minerals, as well as molybdenum and traces of gold, silver and  
127 mercury have been identified from the Allihies Mines (Reilly 1986; Spinks *et al.* 2016).

128 Previous microthermometry measurements of syn-Variscan quartz veins from Mizen  
129 Peninsula suggest peak-metamorphic conditions of between 300-400 °C (Wen *et al.* 1996).  
130 Detailed fluid inclusion studies from Allihies (near Mountain Mine) by Meere and Banks (1997)  
131 indicate medium to moderate salinities (4-16 wt% NaCl<sub>equiv</sub>) for syn-Variscan quartz veins and  
132 high salinities (22-27 wt% NaCl<sub>equiv</sub>) for post-orogenic extensional veins. At Hungry Hill (about  
133 19 km ENE of Allihies) Rogers (2002) compared early veins ( $T_h = 230$  °C) with the syn-buckling  
134 veins (syn-Variscan,  $T_h = 190$  °C) and late stage veins ( $T_h = 170$  °C). All 3 vein types have a  
135 moderate salinity of about 10 wt% NaCl<sub>equiv</sub>.

136

## 137 **Methodology**

138 Field mapping focussed primarily on the classification, measuring and sampling of quartz veins  
139 to establish a paragenesis and a structural chronology. Aerial drone mapping was utilised to  
140 investigate the area around the Allihies copper mines and to contextualise features identified  
141 in the field. A DJI Phantom 3 Professional with a 4K, 12.4-megapixel camera was flown at a  
142 vertical height of between 20 to 50 m, depending on the surface topography, over a defined  
143 area of approximately 30,000 m<sup>2</sup> per flight. Several flights were necessary to cover the entire  
144 mining area (Fig. 3a). The high-resolution images were captured with two thirds overlap. The  
145 geotagged images were processed with the photogrammetry software 3Dsurvey by Modri  
146 planet to calculate a 3-dimensional (3-D) digital terrain model (DTM) and a 2-D high-resolution  
147 orthorectified photograph, subsequently georeferenced in ArcGIS (Fig. 3a). The high-  
148 resolution drone orthophotography and aerial photography aided the field mapping of the  
149 faults and veins. The low capturing elevation facilitated the identification of veins and  
150 structures as small as 6 cm wide.

151 The 3-D DTM point cloud and historical mining maps (Wilson & Powell 1956) were used to  
152 create a 3-D model of Mountain Mine and its mineralised veins (see digital appendix). Data  
153 entry and 3-D modelling was done using SKUA-GoCAD (Emerson Paradigm) and the Mining  
154 Suite plugins of Mira Geoscience, using the discrete smooth interpolator to model the veins  
155 (Caumon *et al.* 2009). Data entry and georeferencing was performed in ArcMap (ESRI). Data  
156 validation and visualization were carried out with Leapfrog3DGeo (ARANZ Geo Ltd., now  
157 Seequent).

158 Sampling of mineralised and unmineralised quartz veins was conducted in the entire area  
159 around Allihies. Whenever possible, in-situ vein samples were taken, but in some cases the  
160 historic mine shafts were not accessible, collapsed or filled with water. This necessitated the  
161 collection and analysis of some samples from spoil material.

162 The samples were petrographically analysed as polished blocks and polished thin sections  
163 via reflected and transmitted light microscopy. Images were captured using a Leica  
164 (DVM2500) digital microscope with an attached VZ700C lens in the Geomicroscopy Facility  
165 at University College Cork.

166 Four spatially oriented samples from East-West striking mineralised quartz veins were  
167 collected and cut perpendicularly to cleavage  $S_{1,vein}$  (sample 418; Fig. 3a). Thin section images  
168 were captured and stitched for the entire width of the veins with the Leica DVM2500 digital  
169 microscope as false colour images to identify different generations and microstructures.

170 All vein types were prepared as doubly polished thin sections. Small chips of max. 1 cm<sup>2</sup> were  
171 examined with a Linkam (LMS600) temperature-controlled microscope stage, combined with  
172 an Olympus BX50 microscope, a x100 LWD objective and an attached 16 megapixels Nikon  
173 DS-Ri2 camera at the UCC Geomicroscopy Facility. Bi-phase (L+V) fluid inclusions, were  
174 analysed for their freezing temperature  $T_{ice}$ , the first melt temperature  $T_{fm}$  and the final melt  
175 temperatures  $T_m$ , as well as the homogenisation temperature  $T_h = liquid + vapour = liquid$ .  
176 Special care was taken to measure primary fluid inclusion assemblages. Secondary inclusion  
177 trails and healed areas were avoided. Within the mineralised veins, primary inclusions were  
178 selected, which are genetically related to the copper sulphides. The stage was calibrated using  
179 a CO<sub>2</sub> standard (-56.6 °C, Camperio) and a synthetic, doubly distilled H<sub>2</sub>O standard ( $T_m = 0.0$   
180 °C,  $T_h = L + V = L$ : 374.0 °C, Leoben). Salinity was calculated as wt% NaCl<sub>equiv</sub> by using the  
181 Excel macro HOKIEFLINCS\_H2O-NACL (Steele-MacInnis *et al.* 2012; Bodnar 1993; Atkinson  
182 2002; Bodnar *et al.* 1994; Bodnar 1983).

183 A historic molybdenite sample (BM.1964,R231) from Mountain Mine (Fig. 2) was provided by  
184 the National History Museum in London (NHM). The mineralised quartz-molybdenite  
185 specimen was collected by Sir Arthur Russell from the Mountain Mine dumps in 1918 (NHM  
186 Russell collection). A second molybdenite sample was discovered recently from spoil near  
187 Caminches Mine (Fig. 2). Small fragments (< 1 cm) were separated from the samples using a  
188 micro chisel to avoid major damage and potential rhenium contamination. The samples, which

189 both contain fine-grained molybdenite (< 2 mm), were analysed using reflected light  
190 microscopy and fluid inclusion microthermometry (quartz). The samples were used for Re-Os  
191 geochronology at Durham University Laboratory for Source Rock and Sulfide Geochemistry  
192 and Geochronology. Sample preparation and analysis was undertaken as described in detail  
193 by Selby & Creaser (2001) and Li *et al.* (2017). The molybdenite material was isolated from  
194 the vein quartz and other minerals with HF. Approximately 10mg of pure molybdenite was  
195 loaded into a carius tube with aqua regia (3 ml HCl + 6 ml HNO<sub>3</sub>) and a known amount of tracer  
196 solution (<sup>185</sup>Re + isotopically normal Os). The carius tube was then sealed and placed in an  
197 oven for 24 hrs at 220°C. The Os and Re isotopically equilibrated sample and tracer solution  
198 were extracted from the acid solution using solvent extraction, microdistillation and anion  
199 chromatography methods. The purified Re and Os fractions were measured for their isotopic  
200 compositions in static mode using a Thermo Scientific Triton mass spectrometer in the Arthur  
201 Holmes Laboratory at Durham University. The Re-Os molybdenite model age was calculated  
202 with the equation  $t = \ln (^{187}\text{Os}/^{187}\text{Re} + 1)/\lambda$  (Smoliar *et al.* 1996), where  $\lambda$  is the decay constant  
203 for <sup>187</sup>Re = 1.666 × 10<sup>-11</sup> a<sup>-1</sup> (Smoliar *et al.* 1996; Selby *et al.* 2007). Uncertainties were  
204 calculated with mass spectrometry uncertainty, all analytical sources uncertainties and the  
205 decay constant (Table 1).

206

## 207 **Results**

### 208 **Field Observations**

#### 209 **Host Lithologies**

210 The area north of Mountain Mine is dominated by micaceous siltstones and quartz arenites of  
211 the Allihies Sandstone Member (Caha Mountain Formation). The siltstones have a reddish to  
212 greyish colour and form beds from 10 cm to several metres thick. The sandstones are red to  
213 grey and are generally well sorted. Occasionally, siltstone clasts up to 2 cm were found within  
214 the sandstone. Ripple marks and mud cracks occur on the bedding planes. Grey mudstones  
215 of the Ballydonegan Slate Member are mainly observed in the southern part of the study area  
216 between Mountain Mine and Allihies village.

217 Both lithologies can display alteration zones adjacent to large (> 0.5 m width) mineralised  
218 quartz veins. The colour varies from yellowish-brown to pale yellowish-red, mainly due to the  
219 presence of iron hydroxides. These alteration zones are rarely wider than one metre around  
220 the mineralised veins but next to the smaller veins (< 10 cm width) they are often absent.

221

#### 222 **Early extensional structures and mineralisation**

223 East-West striking, normal faults with a strike-length of 60 to over 1000 m are present near,  
224 and at, the historic mine shafts (Fig. 3a). Their strike ranges in between 071 and 123 degrees.  
225 Due to surface weathering, these faults form natural depressions. Figure 3b shows a quartz  
226 vein following a steep dipping (70 degrees) normal E-W striking fault SW of Mountain Mine  
227 (Fig. 3a). This vein is deformed by a subsequent orogenic compression.

228 Sub-parallel to ESE-WNW striking quartz veins occur up to 35 m from the E-W faults (Fig. 3a  
229 and Fig. 4a). These veins are mineralised and range from centimetre to metre scale in  
230 diameter and have a maximum length of over 100 m. Only two vein sets have been observed  
231 striking North-South, including the N-S Lode at Mountain Mine (Fig. 3a).

232 Associated with larger quartz veins are a spatially concentrated series of smaller quartz  
233 veinlets with an average width of 0.5 to 10 cm and a maximum length of 108 m (Fig. 3a).  
234 Similar to the larger veins and lodes, these smaller veins have an ESE-WNW strike with a

235 nearly vertical dip (Fig. 4b). Major mineral constituents are quartz, fine disseminated chlorite  
236 and minor amounts of chalcopyrite.

237 Figure 5 (and Dig. App.) displays the extent of the underground workings at Mountain Mine,  
238 where it is evident that the E-W Lode and the New E-W Lode are connected by the N-S Lode.  
239 It is important to note that the E-W Lode extends to the West of N-S Lode while the New E-W  
240 Lode extends to the East of N-S Lode. Both extensions pinch out laterally.

241 In places, sets of multiple sub-parallel and closely spaced veins form lodes with a maximum  
242 surface outcrop of up to 18 m in width and up to 160 m in length (Fig. 6). The Marion Lode  
243 (Fig. 3a and Fig. 6) is formed by multiple generations (G1-G3) of E-W striking mineralised and  
244 brecciated quartz (G1), mineralised quartz (G2) and sub-horizontal unmineralised thinner  
245 quartz (G3). Corrugations on the vein wall of (G1) and rotated vein fragments indicate strike  
246 slip movement parallel to the vein orientation (Fig. 6).

247 Mineralisation of the large orebodies is dominated by chalcopyrite with minor amounts of  
248 bornite and late veinlets of tetrahedrite/tennantite. Aggregates of fine-grained chlorite and late  
249 cavity-fill siderite with minor calcite, associated with malachite were found on spoil material  
250 from Caminches Mine (Fig. 2). Pockets of clear, vuggy quartz crystals (up to 2 cm) are present  
251 in the outcrop of the massive Coom Lode.

252 At the surface, most of the lodes and the smaller E-W veins do not show any evidence of  
253 copper mineralisation. Malachite staining occurs only at fresh outcrops of the historical mines.  
254 Due to the lack of free carbonate within the sediments, malachite can be completely absent.  
255 Traces of reddish goethite staining, as well as extensively altered chalcopyrite can be found  
256 about 20 to 40 cm below the surface within the veins. Apparently barren, but mineralised veins  
257 were identified by the presence of epimorphs caused by weathered sulphides and the internal  
258 reddish staining from iron hydroxides, often visible through the partially translucent quartz as  
259 pale red staining.

260

## 261 **Syn-Compressional structures**

262 Large scale SW-NE trending faults cut the sedimentary succession into elongate blocks up to  
263 550 m lateral length, and result in predominantly sinistral offset of the E-W faults with a  
264 maximum dislocation of 17 m observed near the New E-W Lode (Fig. 7a). SE-NW to SSE-  
265 NNW striking faults (e.g. Cornish Village Fault, Fig. 2 and Fig. 7a) constrain northern and  
266 southern boundaries of the fault blocks. All ESE-WNW trending veins are affected by oblique  
267 faulting with lateral sinistral offsets of up to 83 m (Fig. 7b and Fig. 7c).

268 Thin beds (max. 30 cm) of the competent sandstones were found boudinaged in between  
269 layers of less competent siltstones. Penetrative cleavage is clearly visible within the siltstones,  
270 but less distinctive within the sandstones. The cleavage in the slates has a phyllitic texture  
271 and a high amount of sericitic, fine crystalline mica. Cleavage  $S_{1, \text{host}}$  has a general SW-NE  
272 strike with a sub-vertical dip (Fig. 4c). Some of the early quartz veins (e.g. at Great Mountain  
273 Mine North and Coom Mine, Fig. 7b and Fig. 7c) show clear evidence of syn-compressional  
274 cleavage development (Fig. 8a),  $S_1$  cleavage-refraction in the veins compared to the  
275 surrounding siltstones (Fig. 8b) and cataclastic deformation (Fig. 8c). Smaller E-W veins  
276 sometimes display asymmetric folding, cleavage and boudinage.

277 Second and third order step folds show bedding- $S_1$ -cleavage intersection lineations with a  
278 mean plunge of 47 degrees to the southwest (N = 55, Fig. 4d). These folds have an  
279 asymmetrical step geometry with limbs dipping from the northwest to the southeast with a  
280 shallow to vertical angle (Fig. 4e). Metre-scale joints observed are generally oriented SE-NW  
281 with a sub-vertical dip (Fig. 4f).

282 Other compressional structures (Fig. 3b) include saddle reef quartz veins up to one metre  
283 wide and 10 cm thick (Fig. 8d), and en echelon quartz tension gash arrays in semi-brittle shear  
284 zones ranging from 40 cm to several metres in length. These vein types host disseminated  
285 chlorite, as well as aggregates of chlorite. Subvertical extension related to subsequent tectonic  
286 compression led to the development of shallow dipping quartz veins within the earlier  
287 extensional lodes.

288

## 289 **Vein petrography and microstructures**

### 290 **Early extensional E-W veins**

291 Combined reflected and transmitted light microscopy show a coeval paragenesis of elongate  
292 blocky quartz and chalcopyrite mineralisation within veins (Mountain Mine, Fig. 9a). Quartz  
293 grains with cogenetic chalcopyrite and bornite with chalcopyrite exsolution lamellae were  
294 found in a sample from Mountain Mine spoil. Both minerals are partially surrounded by  
295 chalcocite of the same generation. Alteration seams with blue covellite and goethite occur  
296 around the sulphides as a result of supergene alteration. Parts of the mineralised veins are  
297 cross-cut by later quartz veinlets. Some specimens from Mountain Mine (Gunpowder Mine,  
298 Fig. 3a) contain quartz-chalcopyrite-tetrahedrite/tennantite veins, which are cross-cut by later  
299 tetrahedrite/tennantite-quartz-chalcopyrite veinlets. Minor amounts of specular hematite occur  
300 within a sample from Coom Lode (Fig. 2). Reflected light microscopy on the historic  
301 molybdenite material from Mountain Mine (BM.1964,R231) indicate a syngenetic intergrowth  
302 of quartz, molybdenite and minor chalcopyrite (Fig. 9b). Figure 9c shows the generalised  
303 paragenetic sequence of the E-W veins with all minerals observed in this study at the different  
304 mines of the Allihies District.

305

### 306 **Syn-Compressional veins**

307 The syn-compressional veins are mainly formed by stretched (Bons *et al.* 2012) to fibrous  
308 quartz crystals with sweeping type to no undulous extinction (Trouw *et al.* 2009). The fibrous  
309 quartz crystals are perpendicular to the vein walls but can be curved within the vein itself. As  
310 there are no clearly visible median zones, these veins are dominated by antitaxial crystal  
311 growth (Bons *et al.* 2012).

312

### 313 **Compressional deformation of E-W veins**

314 Microstructural examination of oriented, mineralised, E-W striking quartz veins (Sample 418,  
315 Fig. 3a) show a predominance of syntaxial elongate blocky quartz crystals (Fig. 9a and Fig.  
316 10, Sample 418\_A). The larger crystals in the vein centre have no or sweeping type undulous  
317 extinction with lobate contacts due to grain boundary migration (Trouw *et al.* 2009). The  
318 smaller crystals at the margin with the host-rock show patchy undulous extinction (Trouw *et al.*  
319 2009). WSW to ENE striking, intergranular secondary fluid inclusion trails occur in sample  
320 418\_B2 (Fig. 10). Vein samples 418\_B1 and 418\_B3 (Fig. 10) show centimetre wide, E-W  
321 striking cataclastic zones with anhedral and subhedral microcrystals in between the elongate  
322 blocky areas. In the case of vein B3, these cataclastic zones are associated with  
323 microfractures. Similar to vein A, the smaller crystals in vein B show a patchy undulous  
324 extinction, while the larger elongate blocky crystals show sweeping extinction and have lobate  
325 contacts. Sample 418\_B1 (Fig. 10) shows en echelon microveins with sinistral movement  
326 indicators along E-W strikes. In vein 418\_B3 intensive brecciation of the elongate blocky  
327 crystals is visible with fine grained zones of subhedral crystals and cataclastic seams around  
328 microfractures (Fig. 10, vein B3 magnified images).

329

330 **Fluid inclusion microthermometry**

331 Fluid inclusions were measured on mineralised lodes and smaller E-W veins, as well as syn-  
332 compressional (saddle reef and en echelon) vein samples.

333

334 **Extensional E-W veins**

335 Fluid inclusions in the mineralised, quartz veins, including the historic molybdenite sample,  
336 are generally oval shaped and consist of an undersaturated liquid-rich phase, and a vapour  
337 phase between 0.5 and 15 volume percent. Homogenisation temperatures  $T_h$  range between  
338 121 and 272 °C (Fig. 11a). The salinities vary between 3.2 and 25.4 wt% NaCl<sub>equiv</sub>. Fluid  
339 inclusions from the later tetrahedrite/tennantite-quartz-chalcopyrite veinlet show higher  
340 homogenisation temperatures with a maximum of 314 °C and a mean salinity of 15.5 wt%  
341 NaCl<sub>equiv</sub> (n = 9). Some of the fluid inclusions from this veinlet decrepitated at temperatures  
342 from around 259 °C. The pockets of vuggy, clear quartz from the Coom lode, which indicate a  
343 late formation of the early extensional veins contain unaltered, primary fluid inclusions up to  
344 60 µm and display a very high salinity of up to 28.5 wt% NaCl<sub>equiv</sub> and low homogenisation  
345 temperatures with a minimum of 74 °C (Fig. 11a).

346 Overall, the fluids of the E-W mineralised, quartz veins range from moderate salinity and high  
347 homogenisation temperatures to high salinities and very low homogenisation temperatures.  
348 Similar trends are observed in the small E-W veins which are associated with the mineralised  
349 veins (Fig. 3a, Fig. 8b and Fig. 11a).

350 The eutectic melting  $T_{\text{first melt}}$ , which indicates the salinity composition, shows a mode between  
351 -24 to -20 °C (Fig. 11b) for the extensional veins.

352

353 **Syn-compressional veins**

354 The fluid inclusions in the syn-compressional quartz veins are mainly elongate and consist of  
355 a liquid and a vapour phase (between 0.5 and 5 vol.%). They have an average size of 10 µm  
356 (max. 22 µm) and display homogenisation temperatures ranging between 121 and 243 °C  
357 (outlier: 309 °C), and low to moderate salinities between 8.2 and 19.1 wt% NaCl<sub>equiv</sub> (Fig. 11a).

358 The eutectic melting  $T_{\text{first melt}}$  of the compressional veins show a mode of temperatures between  
359 -18 and -14 °C (Fig. 11b).

360

361 **Re-Os molybdenite geochronology**

362 The fine grained (grain size < 2 mm) molybdenite sample from Mountain Mine spoil  
363 (BM.1964,R231, Fig. 9b) possesses  $43.9 \pm 0.2$  ppm Re,  $27.6 \pm 0.1$  ppm  $^{187}\text{Re}$  and  $169.1 \pm 0.8$   
364 ppb  $^{187}\text{Os}$ . The  $^{187}\text{Re}$ - $^{187}\text{Os}$  data yield to a model age of  $366.4 \pm 1.9$  Ma for the molybdenite  
365 mineralisation. The molybdenite sample from Caminches Mine spoil is also fine grained and  
366 has  $3.83 \pm 0.04$  ppm Re,  $2.41 \pm 0.03$  ppm  $^{187}\text{Re}$  and  $14.78 \pm 0.16$  ppb  $^{187}\text{Os}$ . The  $^{187}\text{Re}$ - $^{187}\text{Os}$   
367 model age is  $367.3 \pm 5.5$  Ma.

368

369 **Table 1.** *Re-Os isotope data and model ages for the molybdenite samples from Allihies*  
370 *Mountain Mine (BM.1964,R231) and Caminches Mine (Fig. 2).*

371

372 **Discussion**

373 Large E-W faults, such as the Coomnacronia-Killarney-Mallow Fault Zone and the Cork-  
374 Kenmare Fault Zone (Fig. 1, Naylor & Jones 1967; Capewell 1975; Price & Todd 1988; Meere  
375 1995; Vermeulen *et al.* 2000; Landes *et al.* 2003; MacCarthy 2007; Ennis *et al.* 2015) played  
376 an important role in the development of the Munster Basin. These major faults are part of a  
377 southwards progressing extensional fault system (Landes *et al.* 2003). Mineralised vein  
378 systems follow the same strike as these basin controlling structures (Fig. 12a). The E-W faults  
379 would have acted as pathways for the mineralising fluids.

380 Recent sulphur isotope studies on chalcopyrite from the Allihies Mining Area (Spinks *et al.*  
381 2016) show consistent negative  $\delta^{34}\text{S}$  values (-16.9 to -10.4 ‰). These values imply a biogenic  
382 sedimentary origin. This could indicate copper remobilisation from the host sediments into the  
383 quartz veins. Another possibility would be a more distant copper source. Meere & Banks  
384 (1997) described a basinal sediment infill of over 6 km. As the pre-Variscan, extensional E-W  
385 faults can be laterally extensive (e.g. Williams 2000; Landes *et al.* 2003; MacCarthy 2007;  
386 Ennis *et al.* 2015; Fig. 1), it is possible, that their extension to depth can reach the basement.  
387 According to seismic interpretation from Landes *et al.* (2003) a P-wave velocity change in 13  
388 – 14 km depth possibly indicates the termination of the basin controlling, E-W striking Cork-  
389 Kenmare Fault Zone (Fig. 1). This suggests that some of the major extensional fault zones  
390 extend below the basin infill.

391 The 3D model (Fig. 5) displaying the historic underground workings shows that the North-  
392 South Lode connects to the East-West Lode and the New East-West Lode at Mountain Mine.  
393 Previous workers described this arrangement as a Z-shaped structure of the Mountain Mine  
394 Lodes (e.g. Fletcher 1969; Reilly 1986). This is a misleading description, as both the E-W  
395 striking lodes extend laterally beyond the N-S Lode before pinching out (Fig. 3a and Fig. 5)  
396 This structure could be interpreted as a transfer fault or breached relay ramp (Walsh &  
397 Watterson 1991; Fossen & Rotevatn 2016) that developed during the early extensional phase.

398 The smaller E-W striking quartz veins appear to be barren at the surface. Their classification  
399 was only possible with the help of the drone and satellite imaging as it is clearly visible on  
400 Figure 3a, that the smaller E-W striking veins are always aligned parallel to the larger  
401 mineralised lodes. It seems that the smaller E-W veins are branches of larger lodes in their  
402 immediate proximity. According to this, the smaller E-W veins and the mineralised lodes can  
403 be classified together as pre-Variscan early extensional veins. Due to extensive surficial  
404 leaching processes mineralised quartz veins could be misinterpreted as barren. Reilly (1986)  
405 already mentioned this “apparently barren nature of the outer metre or so” at the Mountain  
406 Mine Lodes.

407 Meere & Banks (1997) sampled an extensional quartz vein (Fig. 3b) near Mountain Mine that  
408 showed high salinities (Vein 7, 22-27 wt%  $\text{NaCl}_{\text{equiv}}$ ) and was identified as a post-orogenic  
409 extensional vein. For this study, the identical vein from this locality was sampled again and is  
410 now classified as an early extensional vein (Fig. 11a). The pre-Variscan veins cover a quite  
411 large field of higher homogenisation temperatures (up to  $T_h = 271$  °C, Fig. 11a) and low  
412 salinities (as low as 3.2 wt%  $\text{NaCl}_{\text{equiv}}$ ), to very low homogenisation temperatures with a  
413 minimum of 74 °C and a high salinity of up to 28.5 wt%  $\text{NaCl}_{\text{equiv}}$ . The wide range in  $T_h$  and  
414 salinity, as well as the observed cross-cutting veins (Fig. 6) is interpreted to reflect the  
415 complexity of the mineralising fluids which occurred probably in several pulses with variable  
416 degrees of end-member fluids that show a spatial and temporal variability. A late cavity fill of  
417 vuggy quartz crystals at Coom Mine (Fig. 2 and Fig. 11a) was generated by progressive fluid  
418 cooling and an increase in salinity concentration at the end of the early vein filling processes.  
419 This development could be very localised, as the vuggy quartz occurs in small pockets within  
420 the massive Coom Lode.

421 The eutectic melting  $T_{\text{first melt}}$  of the early extensional veins is primarily between -24 and -20 °C  
422 (Fig. 11b). These measurements which are partially lower than the eutectic melting of -21.1  
423 °C in the  $\text{H}_2\text{O}$ - $\text{NaCl}$  system indicate an additional phase. As there is an occurrence of late  
424 siderite and minor calcite within the early extensional veins, it could be possible, that minor



425 amounts of  $\text{CaCl}_2$  was also present during the early mineralisation. This would define a ternary  
426 system of  $\text{H}_2\text{O}-\text{NaCl}-\text{CaCl}_2$  (e.g. Steele-MacInnis *et al.* 2011). Spinks *et al.* (2016) described  
427 barite as a further gangue mineral within the mineralised veins which could result as a  $\text{BaCl}_2$   
428 phase within the fluid system. Nevertheless, no significant amounts of barite were found at the  
429 Allihies region during this study. Meere & Banks 1997 showed a high Br/Cl ratio from the  
430 Allihies quartz veins, implying an early marine brine signature.

431 The early E-W veins contain mainly oval shaped inclusions, which is interpreted to  
432 demonstrate uniform crystal growth. The shape of the fluid inclusions can be a diagnostic  
433 feature in comparison to later compressional quartz veins which show a majority of elongated  
434 fluid inclusions. This elongation is probably caused by fibrous crystal growth in the Variscan  
435 quartz veins.

436 Due to their high competency, the East-West striking lodes and large quartz veins apparently  
437 cross-cut structures, such as bedding, folding and even faulting. These veins, with a width of  
438 at least 40 cm, show only very weak or no folding and the compressional features, caused by  
439 the Variscan Orogeny, such as tectonic cleavage and folding (e.g. Cooper & Trayner 1986;  
440 Ford 1987) can be easily missed and might be a reason why some previous workers (Sheridan  
441 1964; Halliday & Mitchell 1983; Wen *et al.* 1996; Meere & Banks 1997; Spinks *et al.* 2016)  
442 interpreted the timing of the mineralised lodes as a syn- to post-Variscan. Variscan  
443 compression (Ford 1987) affected the early mineralised veins and is clearly demonstrated by  
444 an intensely cleaved lode ( $S_{1, \text{vein}}$ ) at Great Mountain Mine (Fig. 8a), or the cataclastic  
445 deformation in the Coom Lode (Fig. 8c). Sanderson (1984) identified N-S trending veins on  
446 Beara Peninsula as early extension veins with cleavage and mineralisation. The early  
447 extensional N-S and NW-SE trending veins seem to be more affected by the syn-Variscan  
448 compression than the majority of the E-W trending veins due to the low angle of the vein's  
449 strike to the Variscan NNW-SSE maximum principle stress  $\sigma_1$  (Fig. 7b and Fig. 8a). Smaller  
450 E-W veins display a well-developed Variscan cleavage (Fig. 8b) and associated minor folding.

451 Sinistral faulting of the Great Mountain Mine Lode (Fig. 7b) and the Coom Lode (Fig. 7c) is  
452 also interpreted to be a result of NNW to SSE oriented Variscan compression. Minor sinistral  
453 faulting of the E-W Lode of Mountain Mine has been described by Matthews (1964) and Reilly  
454 (1986) on the 1400 level.

455 The saddle reef veins (Fig. 8d) are clearly syn-compressional structures and were already  
456 described by several authors as syn-Variscan features (e.g. Dolan 1984). A similar genesis is  
457 proposed for the en echelon tension gash arrays which are vertical and related to minor shears  
458 resulting from the main deformation (Coller 1984). The sub-horizontal veinlets (Fig. 6  
459 generation 3) which are present at Marion Lode and cross-cut all previous vein generations  
460 are similar to the sub-horizontal veins (from near Mountain Mine) described by Meere (1995)  
461 and are also related to ongoing Variscan compression and associated vertical extension.

462 Variscan deformation of the early E-W veins has also been identified in the microstructures  
463 (Fig. 10). The elongate blocky syntaxial veins, belonging to the early extensional structures  
464 (mineralising event, Fig. 10, vein 418\_A), were later deformed and developed cataclastic  
465 zones, microfractures (Fig. 10, vein 418\_B1 and 418\_B3) and micro en echelon veins (vein  
466 418\_B2). Sweeping undulosity in larger blocky crystals, with lobate contacts in the vein centre  
467 and patchy undulosity in the small grains along the vein rim, indicate a low temperature crystal-  
468 plastic deformation (Trouw *et al.* 2009). This is in agreement with Meere (1995) who identified  
469 a micro brecciated zone within a sample from nearby Mountain Mine as a result of Variscan  
470 compression normal to the vein wall. The micro fractures with the seams of cataclastic sub-  
471 hedral grains show patchy undulous extinction (Fig. 10 vein B3) and could be explained by  
472 deformation under low-grade sub-greenschist facies metamorphism during the Variscan  
473 Orogeny (Meere 1995). This provided conditions for a semi-brittle deformation, which caused  
474 partially recrystallization and fracturing.

475 Wen *et al.* (1996) collected syn-Variscan fluid inclusion measurements from Mizen Head with  
476 peak temperatures  $T_h$  of 300 to 400 °C. These are much higher than the results presented  
477 here with approximately 150 to 240 °C for the syn-Variscan quartz veins (Fig. 11a). A possible  
478 reason could be the different burial depths between the two locations. Meere & Banks' (1997)  
479 results of moderate salinities of 4 to 16 wt% NaCl<sub>equiv</sub> for syn-Variscan quartz veins fit very well  
480 with this study's results of about 8 to 19 wt% NaCl<sub>equiv</sub>.

481 The eutectic melting  $T_{\text{first melt}}$  of the Variscan veins (-18 to -14 °C, Fig. 11b) is above the eutectic  
482 point of the H<sub>2</sub>O-NaCl binary system (-21.1 °C). The H<sub>2</sub>O-NaCl phases are still the most  
483 possible components, as initial melting at the eutectic point of -21.1 °C are difficult to identify,  
484 especially at medium to low salinity concentrations. The characteristic shape of the syn-  
485 Variscan fluid inclusions is elongated with a high eccentricity.

486 Following the new vein classification of pre-Variscan early extensional veins and syn-Variscan  
487 veins, a simplified genetic model of mineralisation at Allihies is proposed (Figure 12). North-  
488 South extension during the development of the Munster Basin and South Munster Basin during  
489 the Middle Devonian to early Upper Devonian generated large scale E-W striking extensional  
490 faults which provided deep fluid pathways for medium to high saline copper-rich fluids (Fig.  
491 12a). These fluids formed the mineralised, mainly E-W striking, and steep dipping quartz veins  
492 seen in the Allihies region.

493 The relatively high homogenisation temperatures recorded from fluid inclusions during this  
494 study with  $T_h$  values of up to 314 °C confirm the identification of high geothermal gradients  
495 during basin formation (Meere 1995; Williams 2000). This is caused by extensive rifting  
496 processes with crustal thinning and resultant upwelling of the Moho (Williams 2000). According  
497 to seismic interpretations (Landes *et al.* 2003) the depth of the Moho can vary between 28 and  
498 33 km. The large amount of basinal infill (Meere & Banks 1997) probably provided an excess  
499 of pore fluids which could have led to the extensive quartz vein formation.

500 The end Carboniferous Variscan Orogeny folded and faulted the basin structures generating  
501 silica-rich fluids which precipitated quartz veins into tension gashes such as saddle reefs, en  
502 echelon veins and sub-horizontal veins (Fig. 12b).

503

#### 504 **Timing of the copper mineralisation**

505 Based on Pb/Pb model age measurements on vein hosted copper deposits from Ross Island  
506 (Killarney, Kerry), Kinnaird *et al.* (2002) assumed a syn-Variscan vein mineralisation between  
507 290 and 270 Ma for the Munster Basin deposits. K-Ar dates (Halliday and Mitchell 1983) from  
508 clay minerals which were sampled in Allihies from the wall rock next to the quartz veins  
509 produced ages of 290 to 261 Ma for the Mountain Mine Lode and an older age of 321 Ma for  
510 an apparently un-mineralised quartz vein. The post-Variscan dates from Allihies are probably  
511 caused by a younger alteration of the clay minerals.

512 The new model, presented in this paper, is supported by molybdenite Re-Os model ages of  
513  $367.3 \pm 5.5$  to  $366.4 \pm 1.9$  Ma (Table 1). It can be assumed that molybdenite formation was  
514 contemporaneous with the major copper mineralisation phase based on the petrographical  
515 association of molybdenite and chalcopyrite (Fig. 9b) and Reilly's (1986) description of  
516 "Molybdenum Mineralization" within the centre of the Main E-W Lode at Mountain Mine.

517 The Re-Os ages belong to the Famennian Stage (Cohen *et al.* 2019) of the Upper Devonian,  
518 suggesting that mineralisation was emplaced during basin development and sedimentation  
519 which occurred between the Upper Devonian and Lower Carboniferous (MacCarthy 2007). As  
520 no visible disseminated copper is known around the Allihies mining area, partial lithification  
521 may have already occurred in the adjacent host sediments to provide an impermeable, barrier  
522 to the mineralising fluids. On the other hand, all sedimentary copper could have been  
523 remobilised into the quartz veins and the sedimentary source was therefore older than the

524 vein mineralisation. This would explain the sedimentary sulphur isotope signature described  
525 by Spinks *et al.* (2016). The lamprophyric intrusions at Black Ball Head ( $314.44 \pm 1.00$  Ma,  
526 Quinn *et al.* 2005), dated as coinciding with the Variscan compression (Sanderson 1984; Ford  
527 1987; Meere 1995) postdate the mineralisation.

528 This new model puts the copper mineralisation at Allihies into a similar tectonic setting as the  
529 formation of large Zn-Pb deposits at Navan, Lisheen (pyrite Re-Os  $346.6 \pm 3.0$  Ma, Hnatyshin  
530 *et al.* 2015) in the Lower Carboniferous to the north. Similar to this study, the well investigated  
531 Zn-Pb deposits, such as Silvermines ( $334.0 \pm 6.1$  Ma, Hnatyshin *et al.* 2015) and Tynagh Mine  
532 (Irish Midlands, e.g. Kinnaird *et al.* 2002), are related to E-W striking faults, caused by a pre-  
533 Variscan North-South extensional phase (e.g. Hitzman 1999). Comparable to Allihies, the  
534 Variscan compression of the Irish Midlands deposits had only little effect on mineralisation  
535 related normal faults of these deposits (Hitzman 1999). Further similarities can be observed  
536 with fluid inclusion salinities and homogenisation temperatures (Fig. 11a). Comparable to the  
537 pre-Variscan extensional veins from the Allihies District, the Irish Type Deposits show a range  
538 of homogenisation temperatures  $T_h$  up to about  $240$  °C and low salinities (about 10 wt%  
539  $\text{NaCl}_{\text{equiv}}$ ), to very low homogenisation temperatures with a minimum of about  $55$  °C and a high  
540 salinity of up to 24 wt%  $\text{NaCl}_{\text{equiv}}$  (Wilkinson 2001; Wilkinson 2010; Gleeson & Yardley 2002).

541

## 542 **Conclusions**

543 The Allihies Mining District is dominated by two different quartz veining generations:

- 544 (1) Quartz veins with a general E-W strike are associated with early-extensional faults and  
545 branch out to smaller E-W striking veins. These veins bear the primary copper  
546 mineralisation as mainly chalcopyrite, bornite, tetrahedrite/tennantite and molybdenite.  
547 The timing of the mineralisation is dated by molybdenite Re-Os geochronology of  $367.3$   
548  $\pm 5.5$  to  $366.4 \pm 1.9$  Ma. The dates coincide with basin development and shortly post-  
549 date the early sedimentation sequences during the Upper Devonian. These appear to  
550 be directly related to large, basin controlling E-W faults.  
551 Fluid inclusion data suggest moderate to high salinity with homogenisation  
552 temperatures of up to  $314$  °C. Eutectic melting indicates a ternary fluid system.  
553 (2) Syn-Variscan veins occur as saddle reefs and en echelon tension gash shear  
554 structures. Sub-horizontal veins cross-cut early extensional structures.  
555 The homogenisation temperature is around  $200$  °C with moderate salinities.

556 Drone imaging and aerial photograph interpretation has proven to be very beneficial for the  
557 identification of pre-compressional features at the Allihies Mining District.

558

## 559 **Acknowledgements**

560 This publication has emanated from research supported in part by a research grant from  
561 Science Foundation Ireland (SFI) under Grant Number 13/RC/2092 and is co-funded under  
562 the European Regional Development Fund and by iCRAG industry partners.

563 SCJ is supported by iCRAG under the Science Foundation Ireland, EU Regional Development  
564 Fund and industry partners (13/RC/2092), as well as SFI research grant 16/RP/3849.

565 The work of KT was funded from the European Union's Horizon 2020 research and innovation  
566 program under Marie Skłodowska-Curie grant agreement no. 745945.

567 The authors are grateful for the assistance from Lingli Zhou (Trinity College Dublin) for the  
568 precise geochemical classification of the tennantite/tetrahedrite mineralisation. Many thanks  
569 to David van Acken (University College Dublin) for the initial geochronology on chalcopyrite  
570 which lead to the new perspective and finally to the new discoveries presented in this

571 publication. Thanks to Tadhg O'Sullivan and his colleagues from the Allihies Copper Mine  
572 Museum for the historical background knowledge and granting access to the underground  
573 workings of Allihies Mountain Mine. Many thanks to Geoff Long (University of Portsmouth) for  
574 his support with thin section preparation. Special thanks to the National History Museum in  
575 London (Simon Kocher and Robin Hansen) for providing molybdenite sample material  
576 (BM.1964,R231) from the historic Russell collection. Thanks to Kate Kiseeva for providing her  
577 recent finding of molybdenite from Caminches Mine.

578 The Geological Survey Ireland are acknowledged for providing regional data and background  
579 information for our 2-D mapping and 3-D modelling efforts. We also thank  
580 ARANZGeo/Seequent (Leapfrog3DGeo), Emerson Paradigm (SKUA-GoCAD), Microsoft  
581 (Bing Satellite Maps), Mira Geoscience (Mining Suite Plugins), Modri planet d.o.o. (3Dsurvey)  
582 and ESRI (ArcGIS) for providing support and academic licenses of software essential to this  
583 project.

584 DS acknowledges the technical support of Antonia Hoffman, Geoff Nowell and Chris Ottley,  
585 and the Total Endowment Fund and the CUG Wuhan Dida Fund.

586 Thanks also to the reviewers Samuel C. Spinks and Eddie Dempsey, as well as to the editor  
587 John MacDonald who commented on the earlier version of this manuscript and helped to  
588 improve this paper.

589

590

## 591 **References**

592 Allmendinger RW, Cardozo NC, Fisher D (2013) Structural Geology Algorithms: Vectors &  
593 Tensors: Cambridge, England. Cambridge University Press, 289 pp

594

595 Atkinson AB Jr. (2002) A Model for the PTX Properties of H<sub>2</sub>O-NaCl. Unpublished MSc  
596 Thesis, Dept. of Geosciences, Virginia Tech, Blacksburg VA, 133 pp

597

598 Blenkinsop HG (1902) Notes on the Berehaven copper mines. Trans. Inst. Mining and Metall  
599 12: 1-7

600

601 Bodnar RJ (1983) A method of calculating fluid inclusions volumes based on vapor bubble  
602 diameters and P-V-T-X properties of inclusion fluids. Economic Geology 78: 535-542

603

604 Bodnar RJ (1993) Revised equation and table for determining the freezing point depression  
605 of H<sub>2</sub>O-NaCl solutions. Geochimica et Cosmochimica Acta, 57: 683-684

606

607 Bodnar RJ, Vityk MO (1994) Interpretation of microthermometric data for H<sub>2</sub>O-NaCl fluid  
608 inclusions. In: De Vivo B, Frezzotti ML (eds) Fluid Inclusions in Minerals, Methods and  
609 Applications. Virginia Tech, Blacksburg, VA, pp 117-130

610

611 Bons PD, Elburg M, Gomez-Rivas E. (2012) A review of the formation of tectonic veins and  
612 their microstructures. Journal of Structural Geology 43: 33-62

613

614 Capewell J (1975) The Old Red Sandstone Group of Iveragh, Co. Kerry. Proceedings of the  
615 Royal Irish Academy. Section B: Biological, Geological, and Chemical Science 75: 155-171

616

617 Cardozo N, Allmendinger RW (2013) Spherical projections with OSXStereonet. Computers &  
618 Geosciences 51(0): 193-205

619

620 Caumon G, Collon-Drouaillet P, Le Carlier de Veslud C, Viseur S, Sausse J (2009) Surface-  
621 based 3-D modeling of geological structures. Mathematical Geosciences 41: 927–945.

622

623 Cohen KM, Harper DAT, Gibbard PL (2019) ICS International Chronostratigraphic Chart  
624 2019/05. International Commission on Stratigraphy, IUGS. [www.stratigraphy.org](http://www.stratigraphy.org). Accessed  
625 12 August 2019

626

627 Coller DW (1984) Variscan structures in the Upper Palaeozoic rocks of west central Ireland.  
628 Geological Society, London, Special Publications 14(1): 185-194

629

630 Cooper MA, Trayner PM (1986) Thrust-surface geometry: implications for thrust-belt evolution  
631 and section-balancing techniques. Journal of Structural Geology 8(3-4): 305-312

632

633 Daltry VDC (1985) A structural, geochemical and mineralogical appraisal of the stratabound  
634 ore deposits in western County Cork, Ireland. Thesis, University College Cardiff, Wales

635

636 Dolan JM (1984) A structural cross-section through the Carboniferous of northwest Kerry. Irish  
637 Journal of Earth Sciences, pp 95-108

638

639 Ennis M, Meere PA, Timmerman MJ, Sudo M (2015) Post-Acadian sediment recycling in the  
640 Devonian Old Red Sandstone of Southern Ireland. Gondwana Research 28(4): 1415-1433

641

642 Fletcher CI (1969) The sulphide mineralization in the Allihies region, County Cork, Eire.  
643 Dissertation, University of Leicester, pp 128-129

644

645 Ford M (1987) Practical application of the sequential balancing technique: an example from  
646 the Irish Variscides. Journal of the Geological Society 144(6): 885-891

647

648 Fossen H, Rotevatn A (2016) Fault linkage and relay structures in extensional settings - A  
649 review. Earth-Science Reviews 154: 14-28

650

651 Gleeson SA, Yardley BWD (2002) Extensional Veins and Pb-Zn Mineralisation in Basement  
652 Rocks: The Role of Penetration of Formation Brines. In: Stober I, Bucher K (eds) Water-Rock  
653 Interaction. Water Science and Technology Library, vol 40. Springer, Dordrecht

654

655 Halliday AN, Mitchell JG (1983) K–Ar ages of clay concentrates from Irish orebodies and their  
656 bearing on the timing of mineralisation. Earth and Environmental Science Transactions of the  
657 Royal Society of Edinburgh 74(1): 1-14

658

659 Hitzman MW (1999) Extensional faults that localize Irish syndiagenetic Zn-Pb deposits and  
660 their reactivation during Variscan compression. Geological Society, London, Special  
661 Publications 155(1): 233-245

662

663 Hnatyshin D, Creaser RA, Wilkinson JJ, Gleeson SA (2015) Re-Os dating of pyrite confirms  
664 an early diagenetic onset and extended duration of mineralization in the Irish Zn-Pb ore field.  
665 Geology 43 (2): 143-146

666

667 Jarvis A, Reuter HI, Nelson A, Guevara E (2008) Hole-filled SRTM for the globe Version 4.  
668 International Centre for Tropical Agriculture (CIAT).  
669 <http://srtm.csi.cgiar.org>. Accessed 25 July 2017

670

671 Kinnaird JA, Ixer RA, Barreiro B, Nex PA (2002) Contrasting sources for lead in Cu-  
672 polymetallic and Zn–Pb mineralisation in Ireland: constraints from lead isotopes. Mineral  
673 Deposita 37(5): 495-511

674

675 Landes M, O'Reilly BM, Readman PW, Shannon PM, Prodehl C (2003) VARNET-96: three-  
676 dimensional upper crustal velocity structure of SW Ireland. Geophysical Journal International  
677 153(2): 424-442

678

679 Li Y, Selby D, Condon D, Tapster S (2017) Cyclic Magmatic-Hydrothermal Evolution in  
680 Porphyry Systems: High-Precision U-Pb and Re-Os Geochronology Constraints on the  
681 Tibetan Qulong Porphyry Cu-Mo Deposit. Economic Geology 112 (6): 1419-1440

682

683 MacCarthy IAJ (1990) Alluvial sedimentation patterns in the Munster Basin, Ireland.  
684 Sedimentology 37: 685-712

685

686 MacCarthy IAJ (2007) The South Munster Basin of southwest Ireland. Journal of Maps 3:1:  
687 149-172

688

689 MacCarthy IAJ, Pracht M, Sleeman AG (2002) Geology of West Cork, Scale 1:100000, Sheet  
690 24. Geological Survey of Ireland

691

692 Matthews PFP (1964) The Copper Mineralization near Allihies, Co. Cork. Dissertation, Trinity  
693 College, Dublin

694

695 Meere PA (1995) High and low density fluids in a quartz vein from the Irish Variscides. *Journal*  
696 *of Structural Geology* 17(3): 435-446

697

698 Meere PA (1995) Sub-greenschist facies metamorphism from the Variscides of SW Ireland an  
699 early syn-extensional peak thermal event. *Journal of the Geological Society* 152(3): 511-521

700

701 Meere PA (1995) The structural evolution of the western Irish Variscides: an example of  
702 obstacle tectonics? *Tectonophysics* 246(1-3): 97-112

703

704 Meere PA, Banks DA (1997) Upper crustal fluid migration: an example from the Variscides of  
705 SW Ireland. *Journal of the Geological Society* 154(6): 975-985

706

707 Naylor D, Jones PC (1967) Sedimentation and tectonic setting of the Old Red Sandstone of  
708 southwest Ireland. In: Oswald D (ed) *International Symposium on the Devonian System*  
709 (Calgary), Alberta. *Soc. Petrol. Geol.* 2: 1089-1099

710

711 O'Brien MV (1959) The future of non-ferrous mining in Ireland. In: *The future of Non-Ferrous*  
712 *Mining in Great Britain and Ireland. Inst. Mining and Metallurgy Symposium*

713

714 O'Brien WF (1987) The dating of the Mt Gabriel-type copper mines of West Cork. *Journal of*  
715 *the Cork Historical and Archaeological Society* 92: 50-70

716

717 Pracht M (2000) Controls on magmatism in the Munster Basin, SW Ireland. *Geological*  
718 *Society, London, Special Publications* 180(1): 303-317

719

720 Pracht M, Sleeman AG (2002) A geological description of West Cork and adjacent parts of  
721 Kerry to accompany the Bedrock Geology, 1:100,000 Scale Map Series, Sheet 24, West Cork.  
722 With accompanying contributions by Wright G (Groundwater) and Cox W (Minerals),  
723 Geological Survey of Ireland, 79 pp

724

725 Pracht M, Kinnaird JA (1995) Mineral chemistry of megacrysts and ultramafic nodules from an  
726 undersaturated pipe at Black Ball Head, County Cork. *Irish Journal of Earth Sciences* 47-58

727

728 Price CA, Todd SP (1988) A model for the development of the Irish Variscides. *Journal of the*  
729 *Geological Society* 145(6): 935-939

730



731 Quinn D, Meere PA, Wartho JA (2005) A chronology of foreland deformation: Ultra-violet laser  
732  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of syn/late-orogenic intrusions from the Variscides of southwest Ireland.  
733 *Journal of Structural Geology* 27(8): 1413-1425

734

735 Reilly TA (1986) A review of vein mineralization in SW County Cork, Ireland. In: Andrew CJ,  
736 Crowe RWA, Finlay S, Pennell WM, Pyne JF (eds) *Geology and Genesis of Mineral Deposits*  
737 in Ireland. Irish Association for Economic Geology, Dublin, pp. 513–544

738

739 Rogers JG (2002) Regional veining in the Upper Palaeozoic Munster and South Munster  
740 Basins, Ireland; the evolution of palaeofluids and palaeofluid flow during basin inversion.  
741 Dissertation, University College Cork, Ireland, 283 pp

742

743 Sanderson DJ (1984) Structural variation across the northern margin of the Variscides in NW  
744 Europe. *Geological Society, London, Special Publications* 14(1): 149-165

745

746 Selby D, Creaser RA (2001) Re-Os geochronology and systematics in molybdenite from the  
747 Endako porphyry molybdenum deposit, British Columbia, Canada. *Economic Geology* 96:  
748 197-204

749

750 Selby D, Creaser RA, Stein HJ, Markey RJ, Hannah JL (2007) Assessment of the  $^{187}\text{Re}$   
751 decay constant by cross calibration of Re-Os molybdenite and U-Pb zircon chronometers in  
752 magmatic ore systems. *Geochimica et Cosmochimica Acta* 71: 1999-2013

753

754 Sheridan DJ (1964) The structure and mineralisation of the Mountain Mine area, Allihies, west  
755 Co. Cork, Ireland. *Royal Dublin Society, Series A*, 2: 21-27

756

757 Smoliar MI, Walker RJ, Morgan JW (1996) Re-Os ages of group IIA, IIIA, IVA, and IVB iron  
758 meteorites. *Science* 271: 1099-1102

759

760 Spinks SC, Parnell J, Bellis D, Still J (2016) Remobilization and mineralization of selenium–  
761 tellurium in metamorphosed red beds: Evidence from the Munster Basin, Ireland. *Ore Geology*  
762 *Reviews* 72: 114-127

763

764 Steele-MacInnis M, Bodnar RJ, Naden J (2011) Numerical model to determine the  
765 composition of  $\text{H}_2\text{O}\text{--}\text{NaCl}\text{--}\text{CaCl}_2$  fluid inclusions based on microthermometric and  
766 microanalytical data. *Geochimica et Cosmochimica Acta* 75(1): 21-40

767

768 Steele-MacInnis M, Lecumberri-Sanchez P, Bodnar RJ (2012) Short note: HokieFlincs\_  $\text{H}_2\text{O}\text{--}$   
769  $\text{NaCl}$ : A Microsoft Excel spreadsheet for interpreting microthermometric data from fluid  
770 inclusions based on the PVTX properties of  $\text{H}_2\text{O}\text{--}\text{NaCl}$ . *Computers & Geosciences* 49: 334-  
771 337

772

773 Stein HJ, Markey RJ, Morgan JW, Hannah JL, Schersten A (2001) The remarkable Re-Os  
774 chronometer in molybdenite: How and why it works. *Terra Nova* 13: 479-486

775

776 Trouw RAJ, Passchier CW, Wiersma DJ (2009) Crystal-Plastic Deformation, Recovery and  
777 Recrystallisation of Quartz. In: *Atlas of Mylonites- and Related Microstructures*. Springer,  
778 Berlin, Heidelberg: 241-262

779

780 Unknown Author (1919) Historic mining map, Allihies Copper Mines. Geological Survey of  
781 Ireland, GSI Goldmine.  
782 [https://secure.dccae.gov.ie/goldmine/docpage.html?id1=8260590&id2=9553634&id3=95569](https://secure.dccae.gov.ie/goldmine/docpage.html?id1=8260590&id2=9553634&id3=9556911)  
783 11. Accessed 16 July 2017

784

785 Vermeulen NJ, Shannon PM, Masson F, Landes M (2000) Wide-angle seismic control on the  
786 development of the Munster Basin, SW Ireland. In: Friend PF, Williams BPJ (eds) *New*  
787 *perspectives on the Old Red Sandstone*. Geological Society, London, Special Publication 180:  
788 223-237

789

790 Walsh JJ, Watterson J (1991) Geometric and kinematic coherence and scale effects in normal  
791 fault systems. In: Roberts AM, Yielding G, Freeman B (eds) *The Geometry of Normal Faults*.  
792 Geological Society, London, Special Publication 56: 193-203

793

794 Wen N, Boyce AJ, Fallick AE, Ashworth JR, Ixer RA (1996) The genesis of Cu-bearing quartz  
795 veins by metamorphic remobilization from stratiform red bed deposits, SW County Cork,  
796 Ireland. *Mineralogy and Petrology* 57(1-2): 73-89

797

798 Wilkinson JJ (2001) Fluid inclusions in hydrothermal ore deposits. *Lithos* 55(1-4): 229-272

799

800 Wilkinson JJ (2010) A Review of Fluid Inclusion Constraints on Mineralization in the Irish Ore  
801 Field and Implications for the Genesis of Sediment-Hosted Zn-Pb Deposits. *Economic*  
802 *Geology* 105: 417-442

803

804 Williams EA (2000) Flexural cantilever models of extensional subsidence in the Munster Basin  
805 (SW Ireland) and Old Red Sandstone fluvial dispersal systems. Geological Society, London,  
806 Special Publications 180(1): 239-268

807

808 Williams RA (1991) The Berehaven copper mines. *British Mining* No. 42, The Northern Mine  
809 Research Society, Sheffield U.K.

810

811 Wilson WH, Powell S (1956) Historic mining map, Allihies Copper Mines (Co. Cork),  
812 Mountain Mine. Geological Survey of Ireland, GSI Goldmine.

813 <https://secure.dccae.gov.ie/goldmine/docpage.html?id1=8264207&id2=24780680&id3=2478>  
814 0686. Accessed 8 May 2017

815

816

## 817 **Figure captions**

818 **Fig. 1.** Simplified map of the Munster Basin and the South Munster Basin in Southwest  
819 Ireland. The northern margin of the Munster Basin is defined by the Coomnacronia-Killarney-  
820 Mallow Fault Zone (CKMFZ) or alternatively by the Dingle Bay-Galtee Fault Zone (DB-GFZ).  
821 The Cork-Kenmare Fault Zone (CKFZ) indicates the rim to the South Munster Sub-Basin  
822 (modified from MacCarthy *et al.* (Geological Survey of Ireland) 2002; Williams 2000; Landes  
823 *et al.* 2003; MacCarthy 2007; Ennis *et al.* 2015).

824

825 **Fig. 2.** Left: Overview of the historic copper mines around Allihies Village on the western end  
826 of Beara Peninsula. Right: Zoom into the mining area at Mountain Mine, showing the  
827 bedrock geology, major structures, alteration zones and the traces of mapped underground  
828 workings (modified from Reilly 1986; historic mining map, Allihies Copper Mines 1919).

829

830 **Fig. 3. (a)** The major lodes and mineralised veins of the Mountain Mine Area with pre-  
831 deformation structures. High-resolution drone maps and Bing™ Satellite Maps (2016),  
832 including field analysis and modifications from Reilly (1986). **(b)** Outcrop of pre-Variscan,  
833 extensional faults (graben structure) at the western end of Mountain Mine E-W Lode. The  
834 southern fault is filled with a quartz-chlorite vein ( $V_{\text{extensional}} = 020/70$ ), which is deformed  
835 (syn-Variscan) by competent sandstone layers (Sst) and incompetent siltstones (Slst). Syn-  
836 Variscan, compressional veins ( $V_{\text{compressional}} = 033/79$ ) occur at the northern part of the  
837 outcrop.

838

839 **Fig. 4.** Equal angle stereoplots of structural features of the Allihies Mining District showing  
840 the poles according to the measured planar structures (Key: Kamb contours in standard  
841 deviation, interval 2, significance level 3; created with Stereonet (Allmendinger *et al.* 2013,  
842 Cardozo and Allmendinger 2013)). **(a)** Mineralised quartz veins. **(b)** Smaller E-W quartz  
843 veins. **(c)** Cleavage  $S_{1, \text{host}}$  of the host rock sediments. **(d)** Bedding-cleavage intersection  
844 lineations showing steep plunge. **(e)** Bedding of the host rock sediments (Caha Mountain  
845 Formation). **(f)** Jointing within the host rock sediments.

846

847 **Fig. 5.** 3D model of the major lodes and the underground workings at Mountain Mine. This  
848 model is a combination of a drone photogrammetry model, Bing™ Satellite Maps (2016),  
849 metadata for the SRTM digital terrain model (Jarvis *et al.* 2008) and historic mining plans  
850 (Wilkinson and Powell 1956).

851

852 **Fig. 6.** Photographs of pre-Variscan structures observed in the field of the Allihies Mining  
853 District: Outcrop at Marion Lode showing 3 different vein generations (G1-G3) in the  
854 siltstone (Slst). The dip direction of the lode is  $V = 015/78$ . The magnification inset (left)  
855 shows anticlockwise rotated vein clasts and corrugations (black arrows) on the vein surface,  
856 which indicate strike slip movement. The magnification (right) shows the 3<sup>rd</sup> vein generation  
857 (G3) cross-cutting the previous generations with a sub-horizontal orientation.

858

859 **Fig. 7.** Map with syn-Variscan structures affecting the pre-Variscan faults and veins (drone  
860 maps and Bing™ Satellite Maps (2016), including field analysis and modifications from Reilly  
861 (1986)). (a) The major lodes of the Mountain Mine Area with pre- and syn-deformation  
862 structures. (b) Is showing the sinistral faulted lode of Great Mountain Mine (NW of Mountain  
863 Mine Area, see Fig. 2). (c) Sinistral faulting of Coom Lode (ESE of Mountain Mine, see Fig.  
864 2).

865

866 **Fig. 8.** Field observations of the syn-Variscan structures at Allihies. (a) Cleavage (dip  
867 direction  $S_{1, vein} = 113/83$ ) within the Northern Lode of Great Mountain Mine. (b) Smaller E-W  
868 vein north of Mountain Mine displaying the cleavage within the vein ( $S_{1, vein} = 283/59$ ) and the  
869 cleavage of the hosting siltstone  $S_{1, host} = 324/79$  which aligns parallel to the vein orientation  
870  $V = 001/89$ . (c) Cataclastic deformation at the eastern end of Coom Lode. (d) Syn-  
871 compressional saddle reef quartz veins occurring at the fold axis of second order folds.

872

873 **Fig. 9.** Microphotographs of samples from the Allihies Mining District. (a) Mineralised quartz  
874 (Qz) veins within fine grained siltstone (Sltst) show syntaxial elongate blocky crystals with  
875 cogenetic chalcopyrite (Ccp) (xpl, Mountain Mine Underground). (b) Historic quartz (Qz) vein  
876 with molybdenite (Mol). The sample was collected by Sir Arthur Russell in 1918  
877 (BM.1964,R231; National History Museum of London). The smaller microscopic image (top  
878 right) shows the syngenetic intergrowth of molybdenite (Mol) with chalcopyrite (Ccp) within  
879 the quartz (Qz) vein. (c) Paragenetic sequence of the pre-Variscan minerals within the  
880 quartz veins at the Allihies Mining District.

881

882 **Fig. 10.** Mineralised E-W veins collected North of Mountain Mine (samples 418). The figure  
883 shows the E-W strike of the veins (dip direction  $V = 184/90$ ), their cleavage  $S_{1, vein} = 279/75$   
884 and the cleavage of the hosting, fine grained siltstone  $S_{1, host} = 321/80$ . The false colour  
885 microphotographs were captured (xpl) from thin sections ( $>30 \mu\text{m}$ ) cut perpendicular to the  
886 vein cleavage  $S_{1, vein} = 279/75$ . **Vein A** is a syntaxial quartz vein with elongate blocky  
887 crystals. **Vein B1** shows elongate blocky crystals with a cataclastic zone of smaller,  
888 subhedral crystals to the northern vein boundary (the colour change at the southern part of  
889 B1 is caused by image stitching effects). The magnification shows N-S striking intergranular  
890 secondary fluid inclusion trails. In **vein B2**, the elongate blocky crystals are cross-cut by a  
891 cataclastic zone to the northern grain boundary and one in the middle of the vein. The  
892 magnification shows a micro en echelon vein which indicates sinistral movement. **Vein B3**  
893 shows intensive brecciation of the elongate blocky crystals.

894

895 **Fig. 11.** Fluid inclusions from samples of the Allihies District. (a) Plot of the salinity wt%  
896  $\text{NaCl}_{\text{equiv}}$  versus the homogenisation temperatures  $T_h$  ( $^{\circ}\text{C}$ ). The points indicate early  
897 extensional vein samples and the triangles are measurements from syn-compressional  
898 veins. (b) Histogram of the eutectic melting  $T_{\text{first melt}}$  ( $^{\circ}\text{C}$ ) from early extensional veins and  
899 from syn-Variscan veins.

900

901 **Fig. 12.** Schematic model of the vein development, mineralisation and structural evolution of  
902 the Munster Basin and South Munster Basin (not to scale). (a) North-South extensional  
903 subsidence and alluvial sedimentation into the Munster and South Munster Basin. Active  
904 Extensional Faults, parallel aligned to the Cork-Kenmare Fault, provide fluid pathways for  
905 the precipitation of mineralised quartz veins. (b) Syn-Variscan compression causes  
906 cleavage, folding and faulting of the basin sediments. Cleavage development within early

907 extensional quartz veins and sinistral faulting. Formation of syn-compressional saddle reef  
908 and en echelon veins.

909

910 **Supplementary material:**

- 911 - Video file: 3D model of the major lodes and the underground workings at Mountain  
912 Mine (see Fig. 5). This model is a combination of a drone photogrammetry model,  
913 Bing™ Satellite Maps (2016), metadata for the SRTM digital terrain model (Jarvis *et*  
914 *al.* 2008) and historic mining plans (Wilkinson and Powell 1956).
- 915 - Excel spreadsheet: Fluid inclusions measurements of the Allihies Copper Mining  
916 District. Locations are as shown in Fig. 2 and 7.
- 917 - Excel spreadsheet: Sample locations of the Allihies Copper Mining District.

918

**Table 1.** Re-Os isotope data for the molybdenite sample (BM.1964,R231) from Allihies Mountain Mine (Fig. 3)

Sample	Sample wt (g)	Re (ppm)	$\pm 2\sigma$	$^{187}\text{Re}$ (ppm)	$\pm 2\sigma$	$^{187}\text{Os}$ (ppb)	$\pm 2\sigma$	Model age (Ma)*	$\pm 2\sigma^\dagger$	$\pm 2\sigma^\ddagger$	$\pm 2\sigma^\S$
BM.1964,R231, Mountain Mine	0.010	43.9	0.2	27.6	0.1	169.1	0.8	366.4	0.2	1.5	1.9
Caminches Mine	0.011	3.83	0.04	2.41	0.03	14.78	0.16	367.3	0.2	5.4	5.5

All data blank corrected (Re – 1.9 pg, Os – 0.8 pg with an  $^{187}\text{Os}/^{188}\text{Os}$  of  $0.201 \pm 0.03$ )

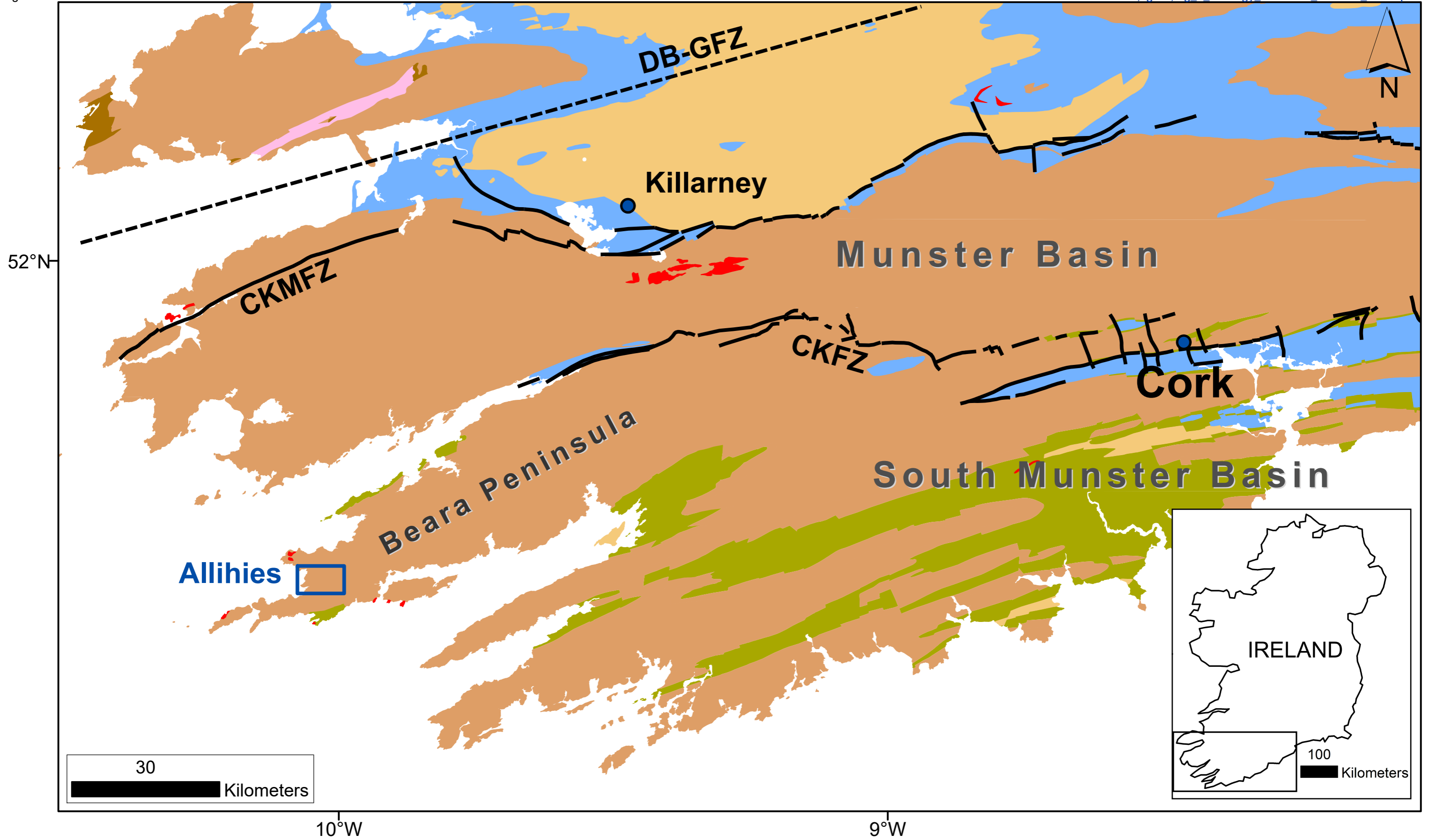
\*Model age calculated using the decay constant  $^{187}\text{Re} = 1.666 \times 10^{-11} \text{ a}^{-1}$  (Smoliar et al., 1996; Selby et al., 2007)

$^\dagger$ uncertainty including only mass spectrometry uncertainty

$^\ddagger$ uncertainty including all sources of analytical uncertainty

$^\S$ uncertainty including all sources of analytical uncertainty plus decay constant

figure 1





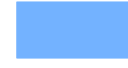




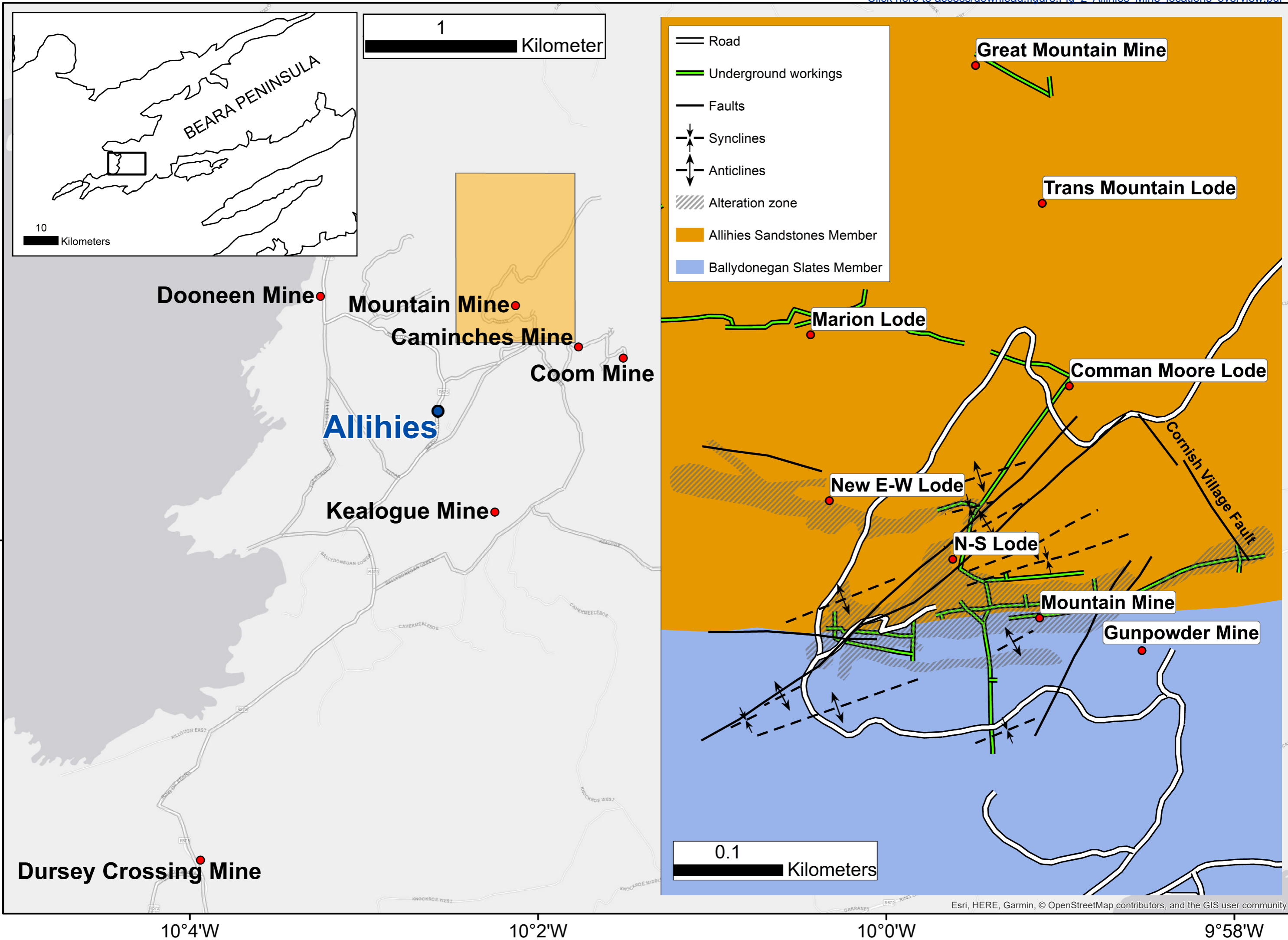
- |   |   |   |  |
|---|---|---|--|
|  | Upper Carboniferous (shale, sandstone, siltstone, coal) |  | Devonian/Carboniferous (volcanic rocks)                                |
|  | Lower Carboniferous (shallow marine limestone)          |  | Upper Devonian (Old Red Sandstone; sandstone, conglomerate, mudstone)  |
|  | Lower Carboniferous (sandstone, deep marine mudstone)   |  | Silurian (sandstone, siltstone, mudstone, greywacke, conglomerate)     |
|   |   |  | Lower to Middle Ordovician (slate, sandstone, greywacke, conglomerate) |



figure 2





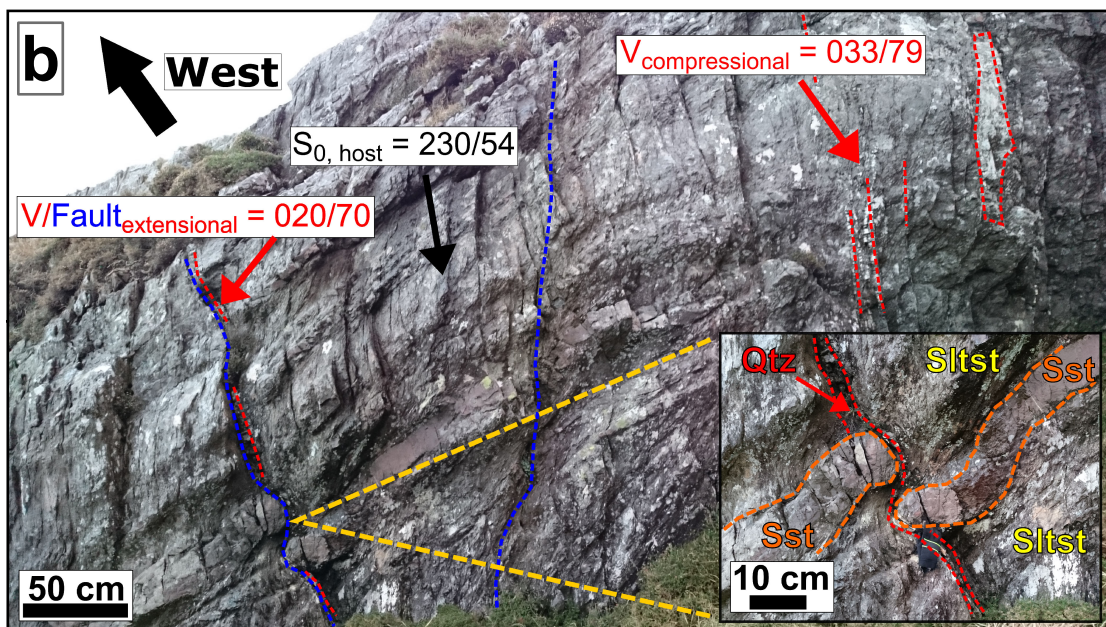
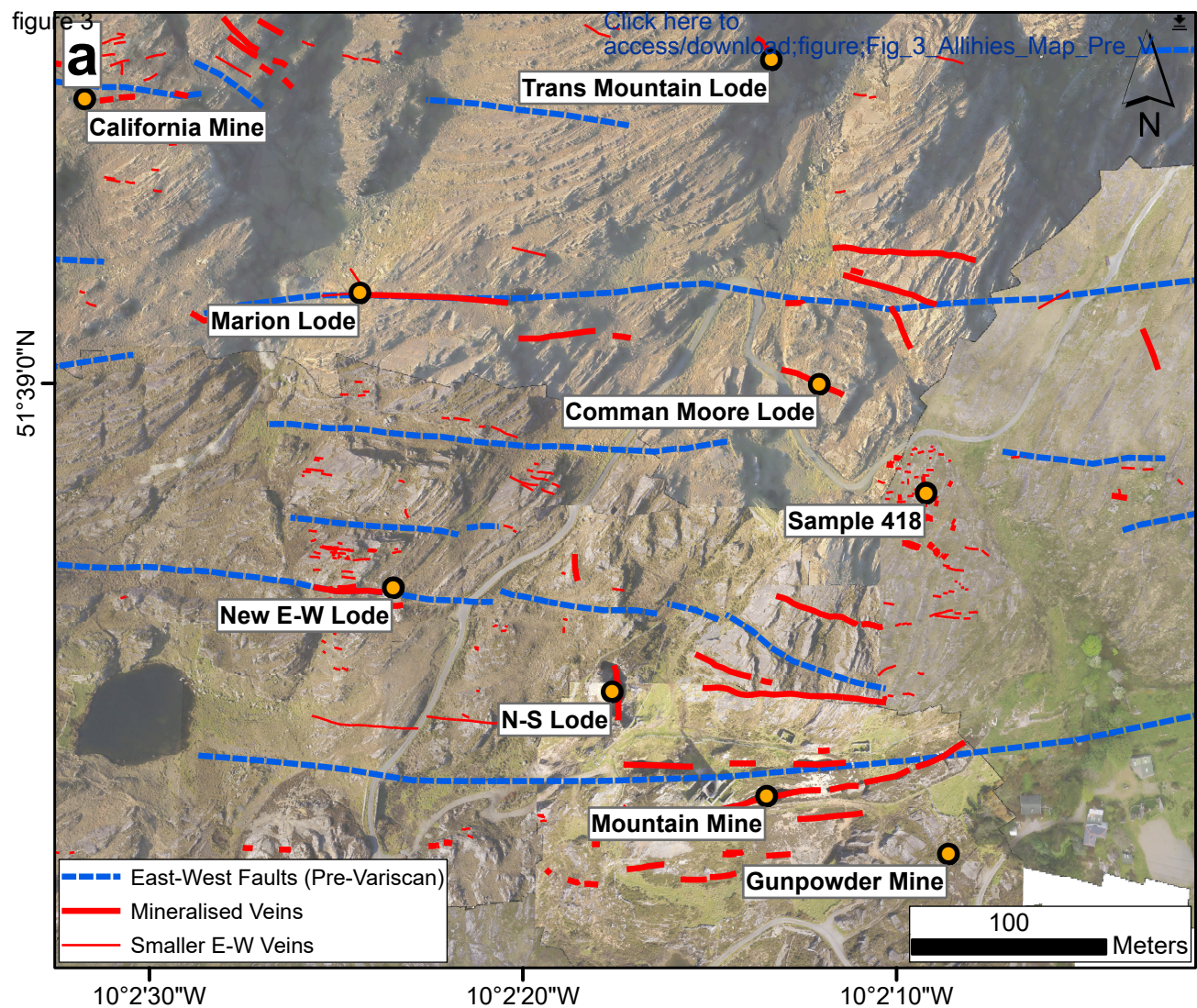
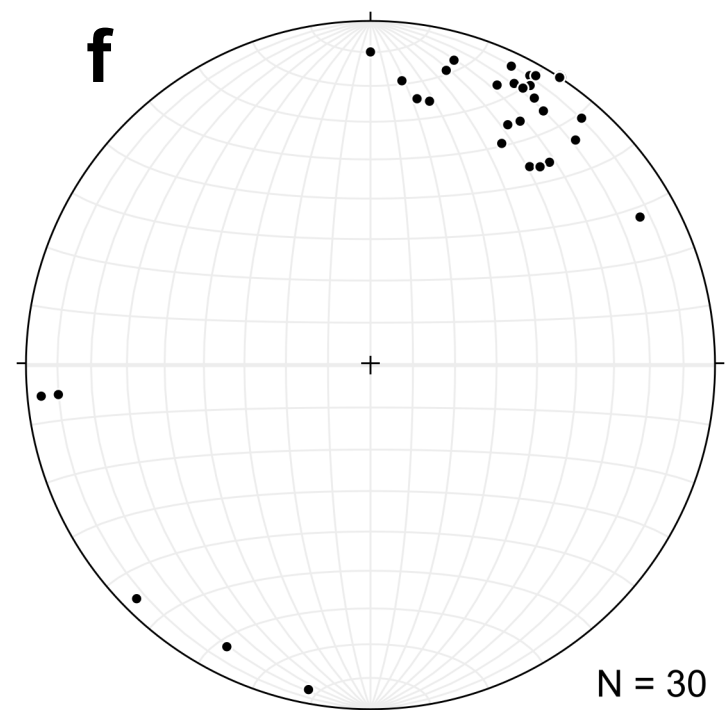
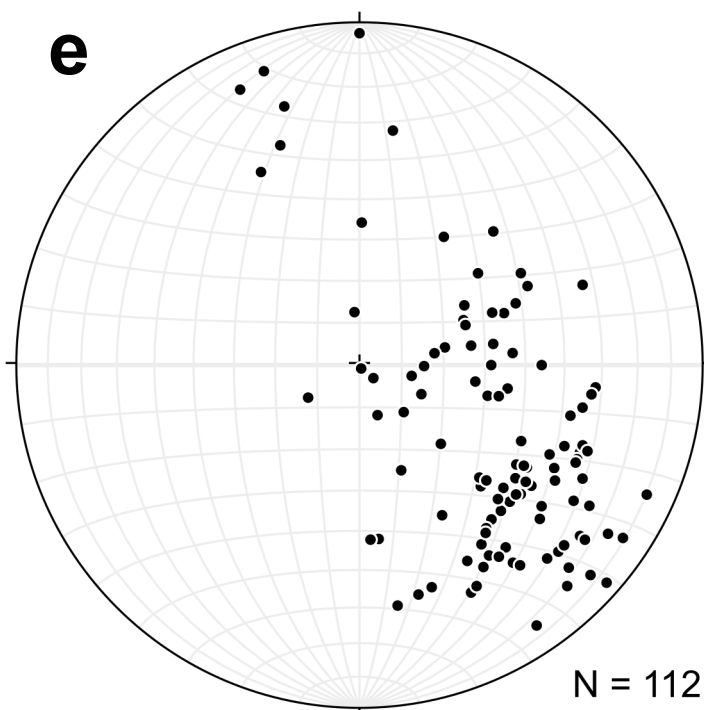
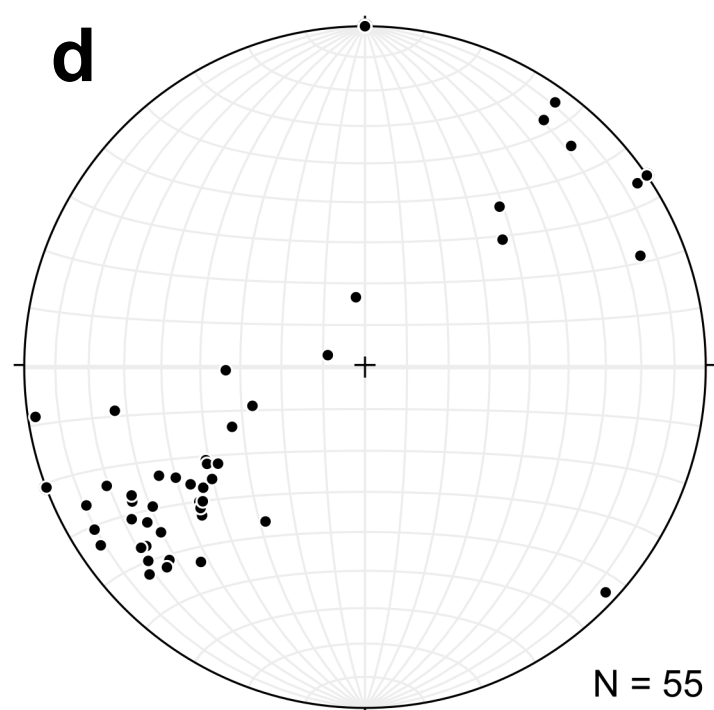
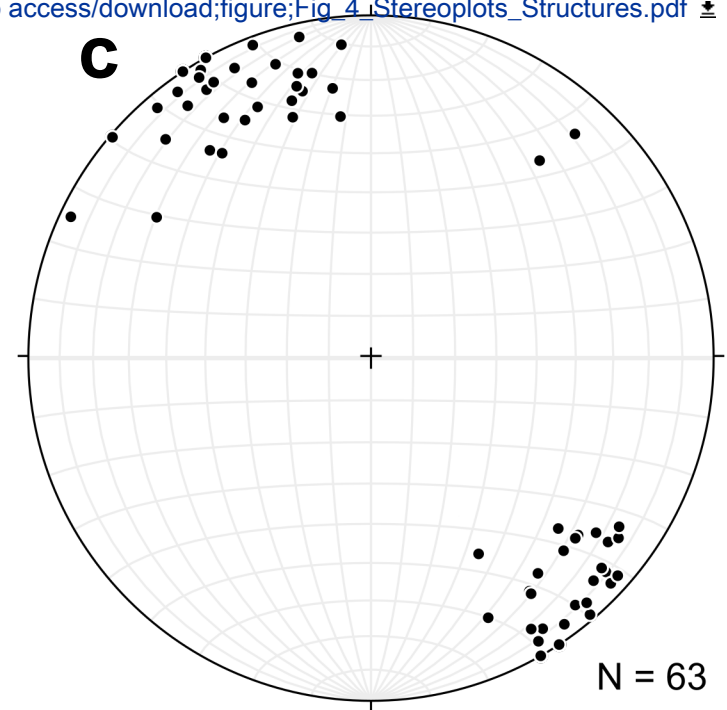
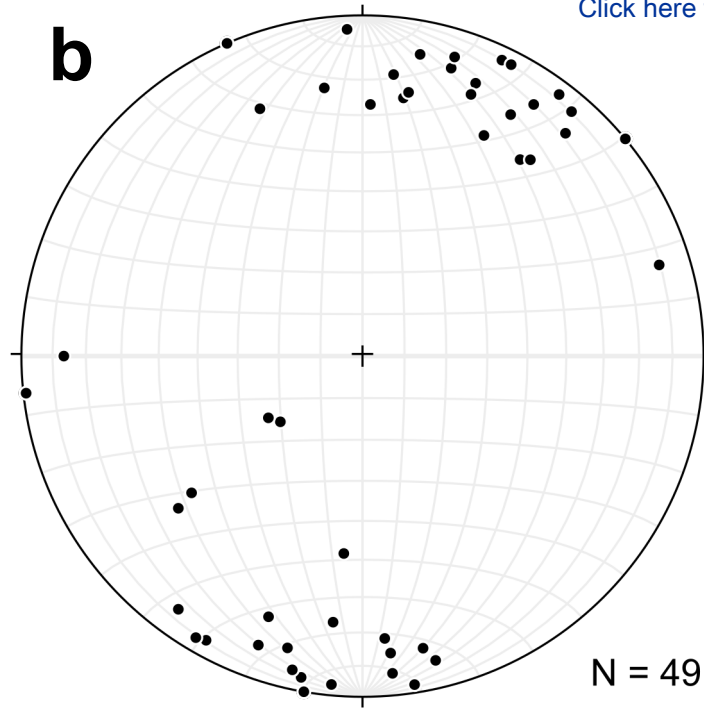
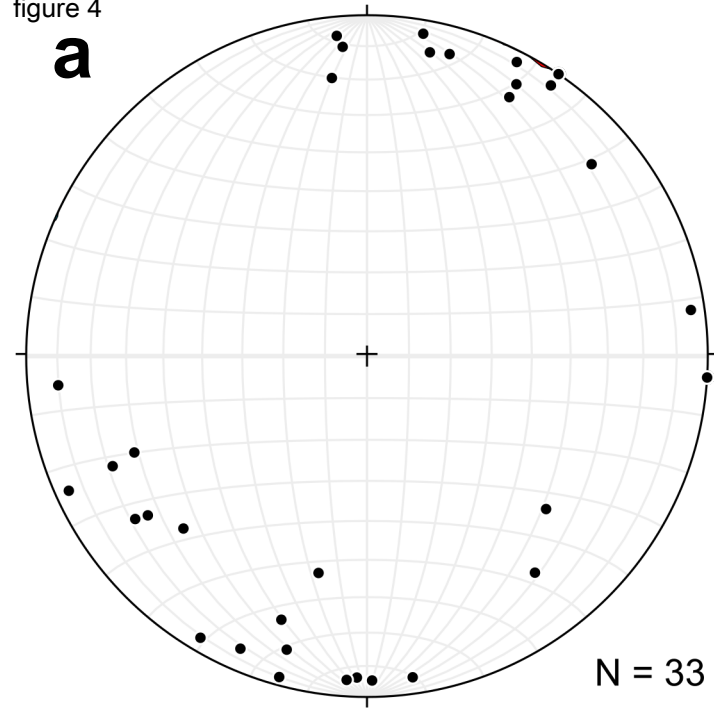
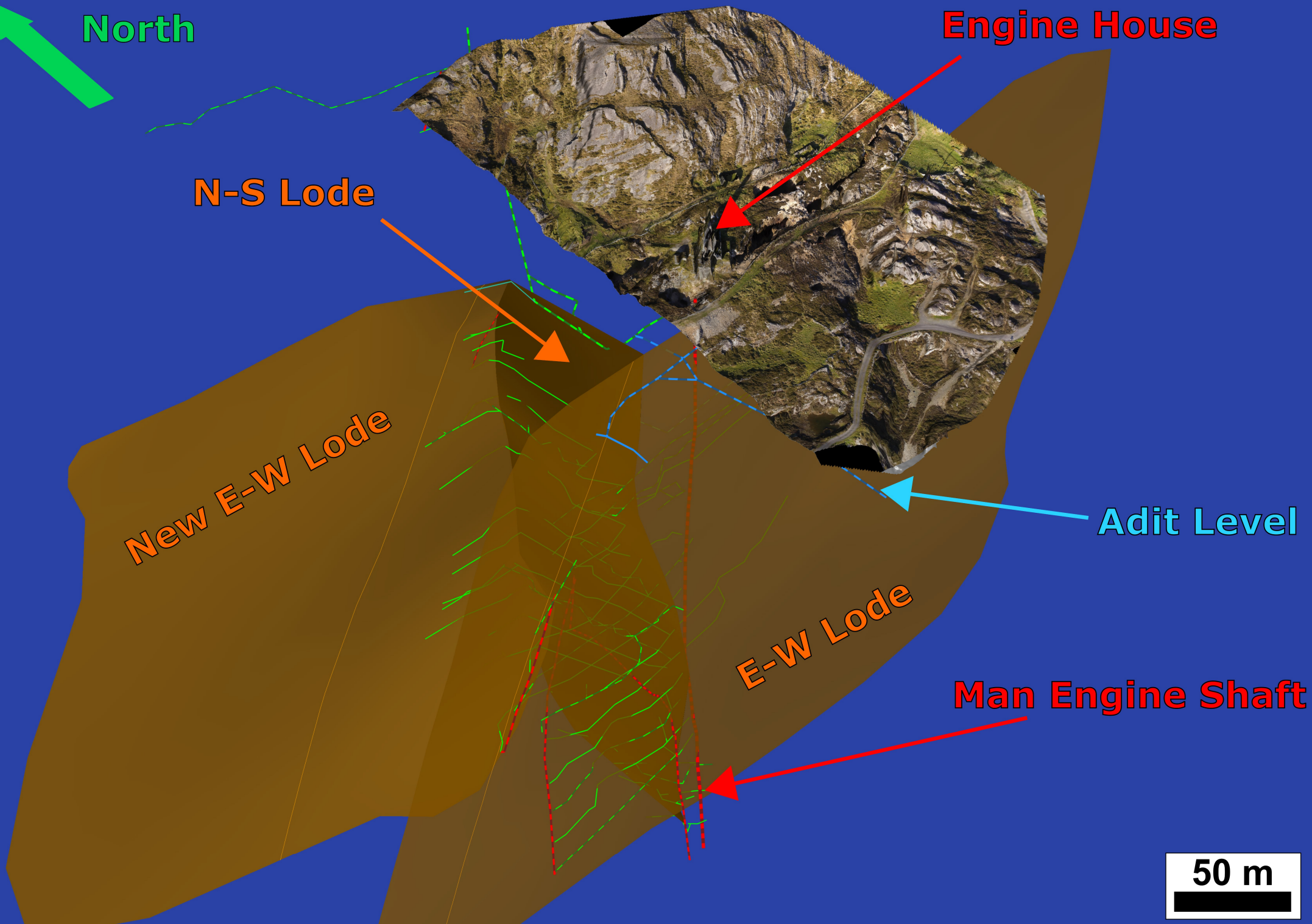




figure 4





50 m



10 cm

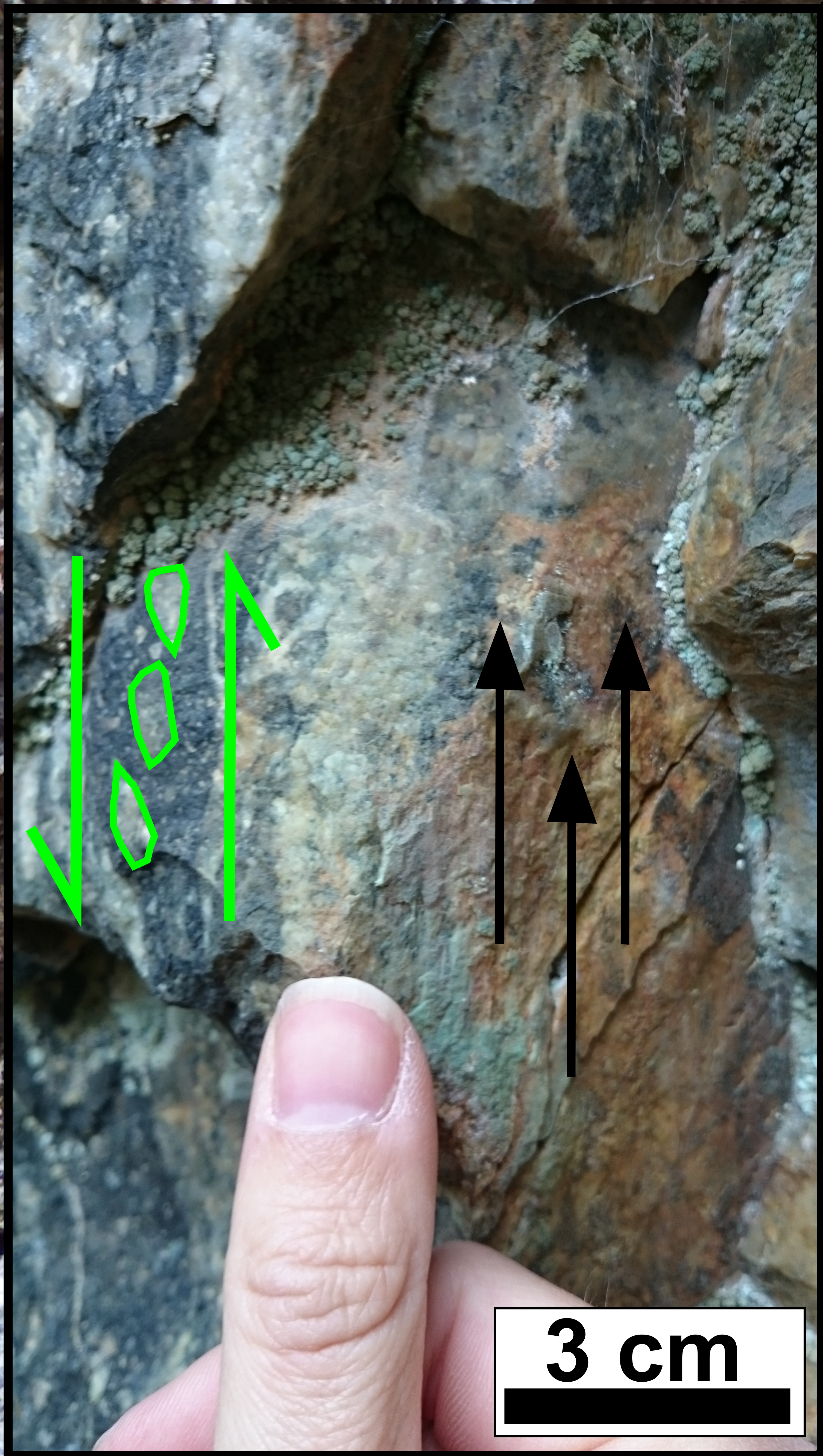
Sltst

V = 015/78

East



Sltst



3 cm

G1

G1

G1

G1

G1

G2

G2

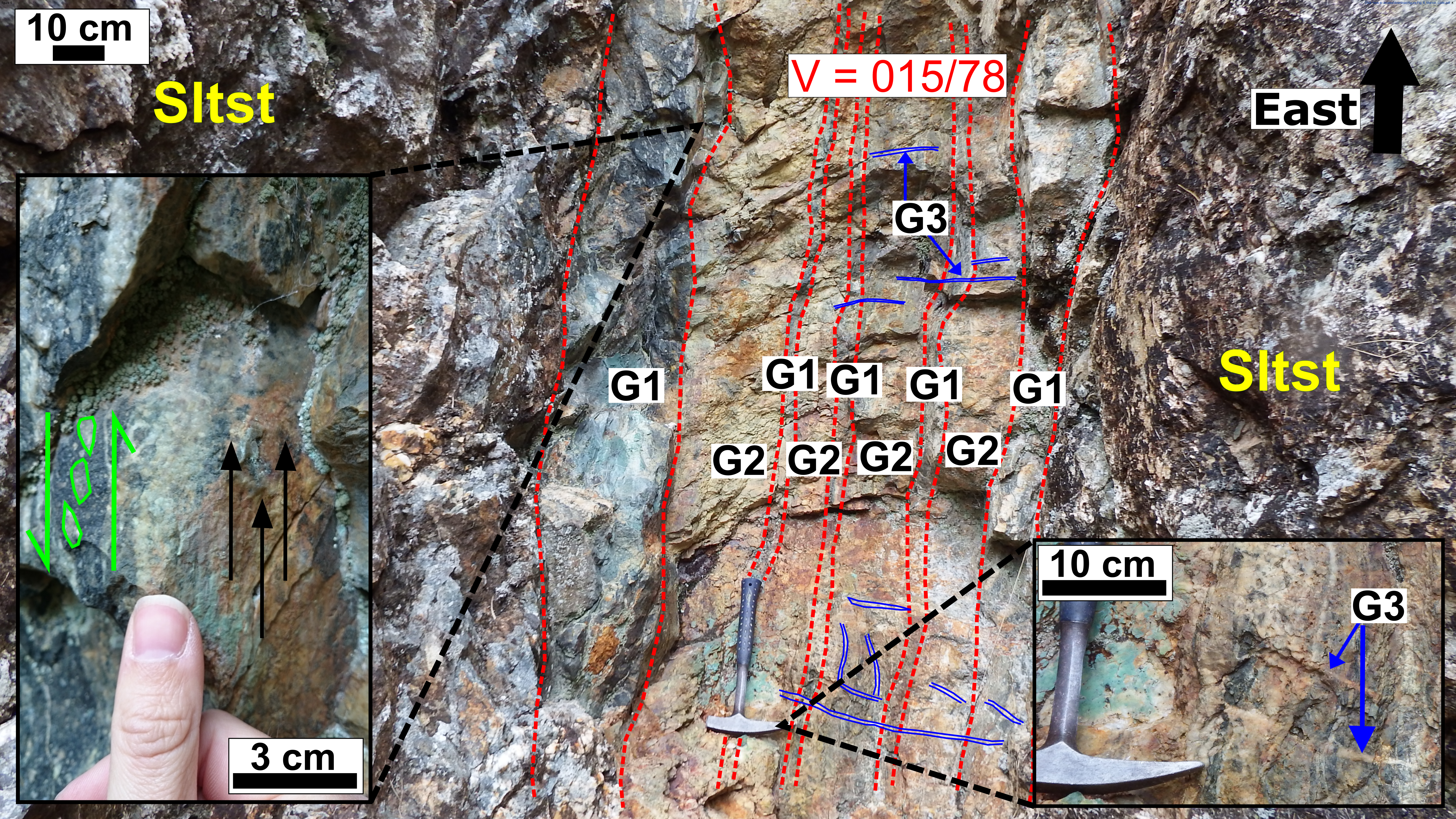
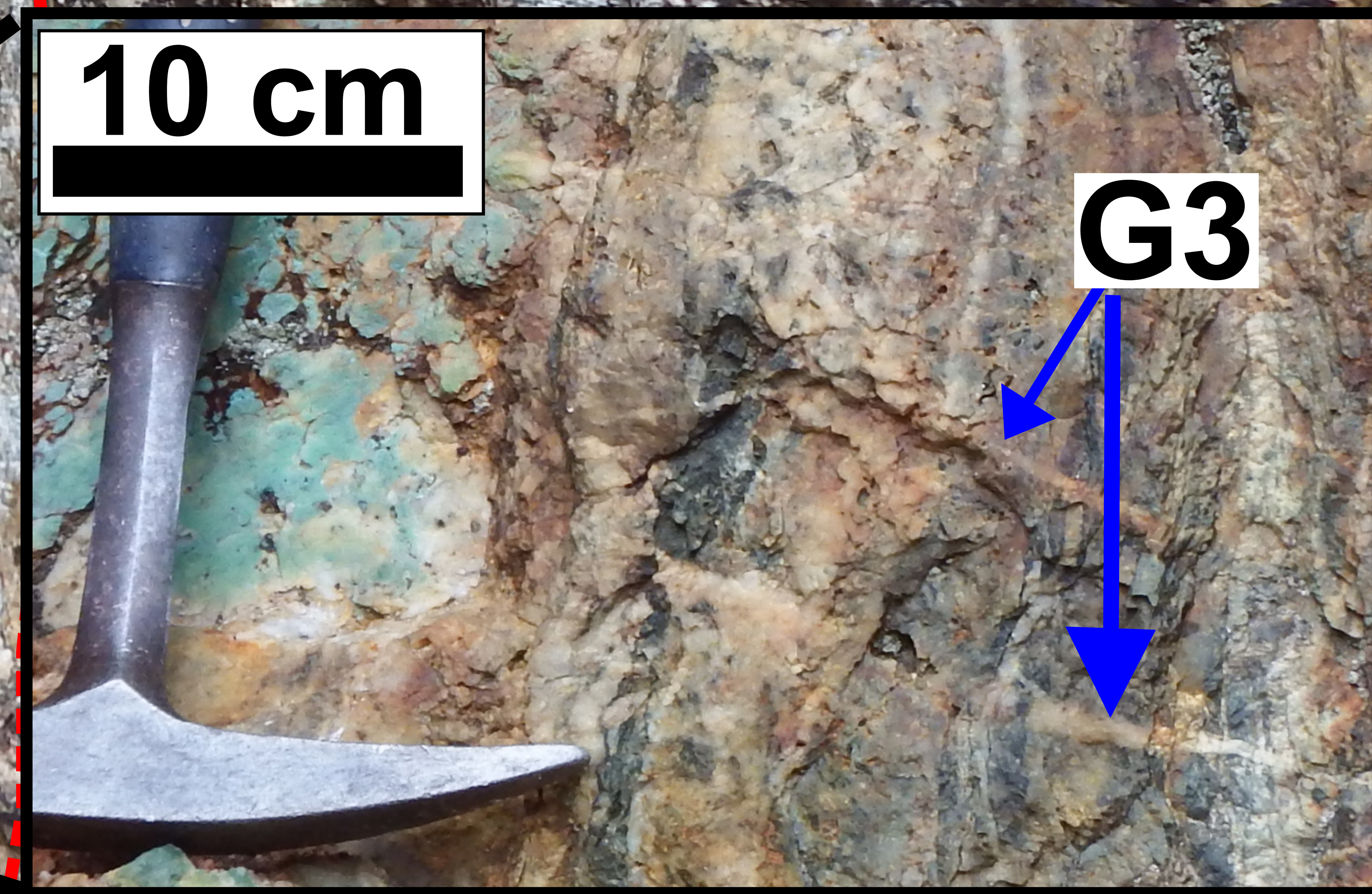
G2

G2

G3

10 cm

G3





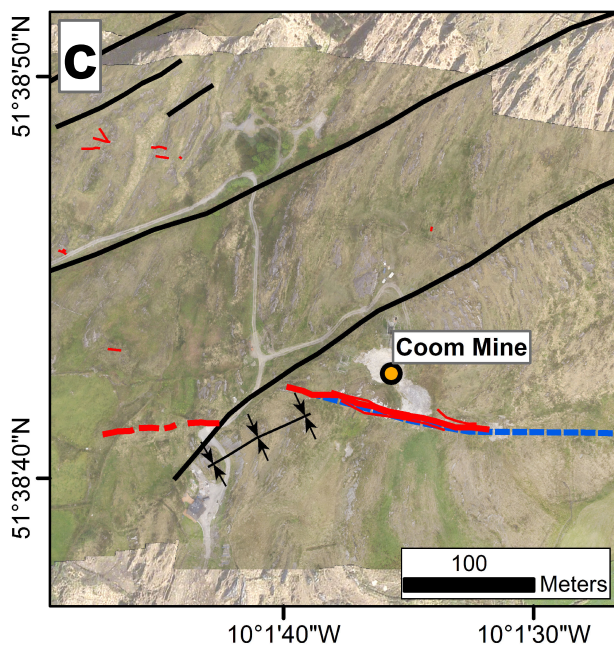
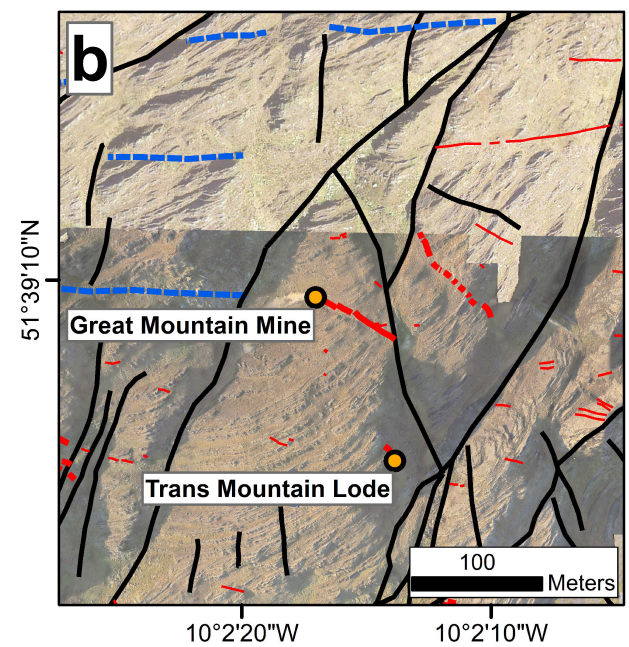
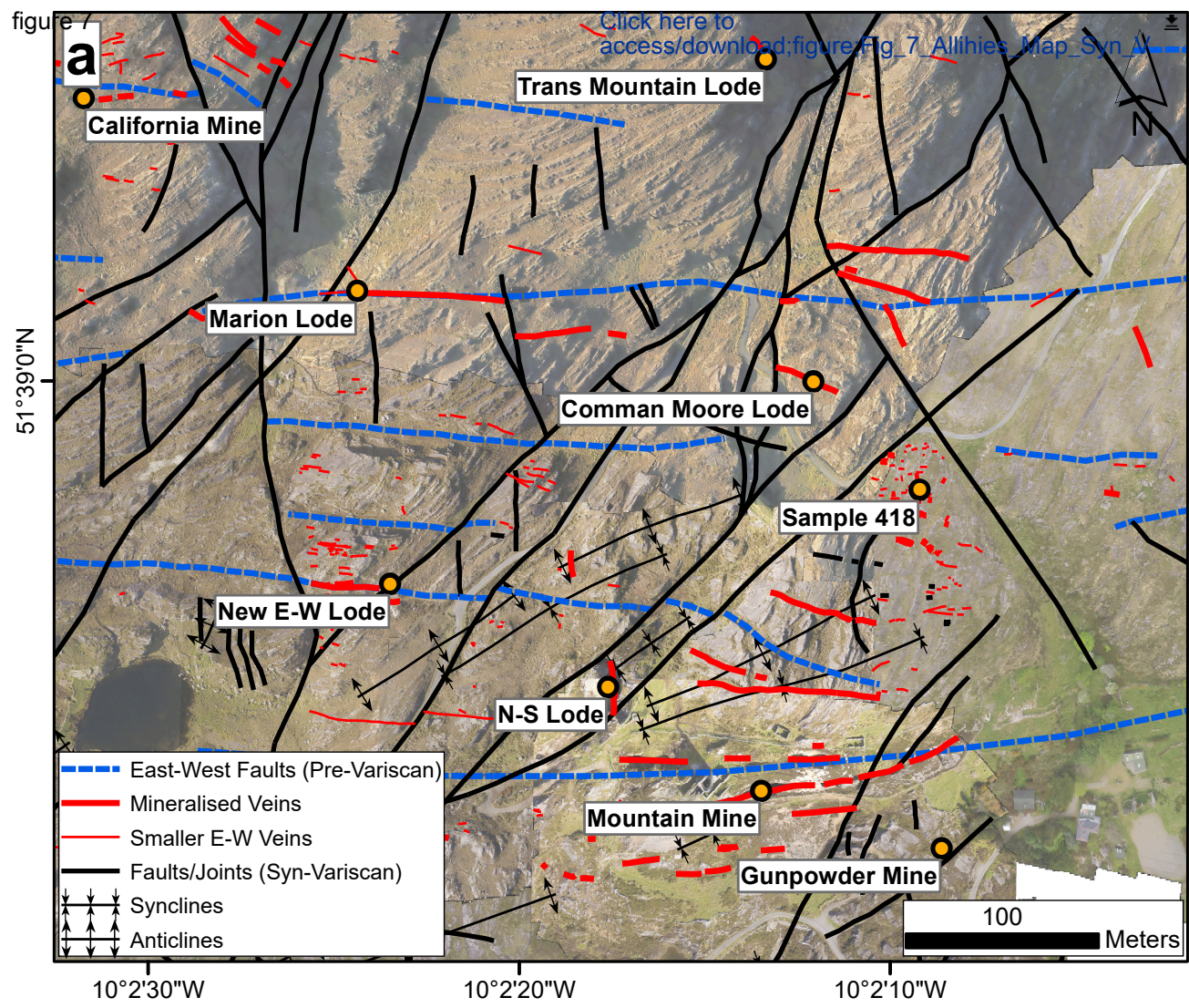
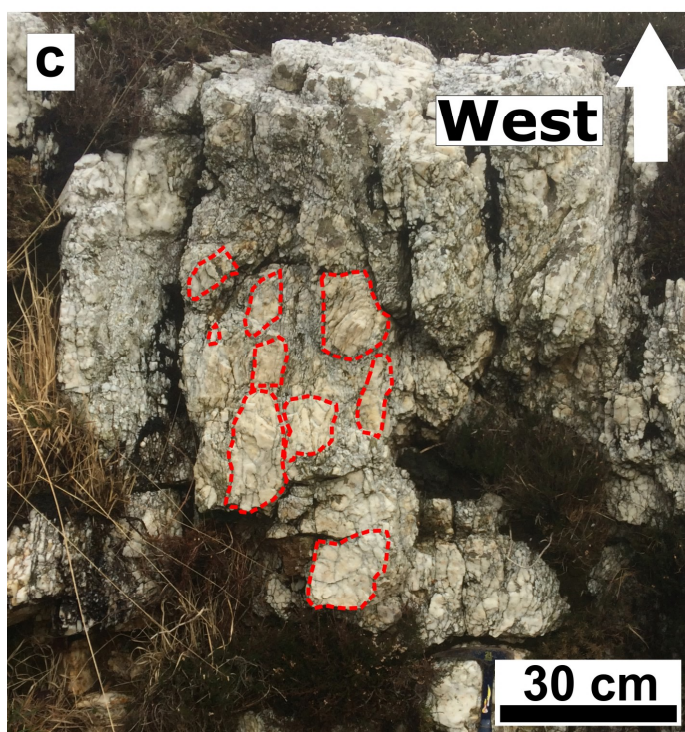
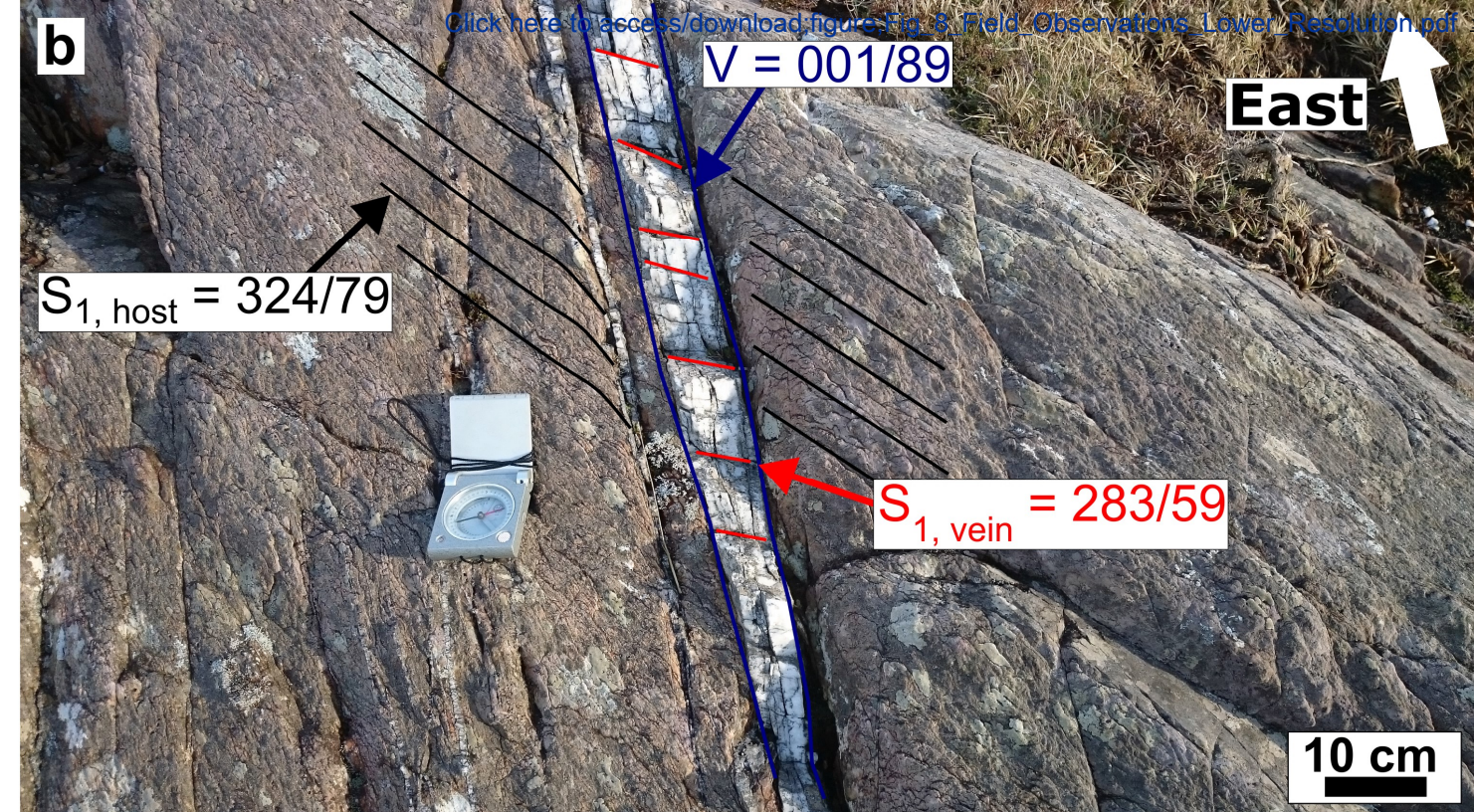
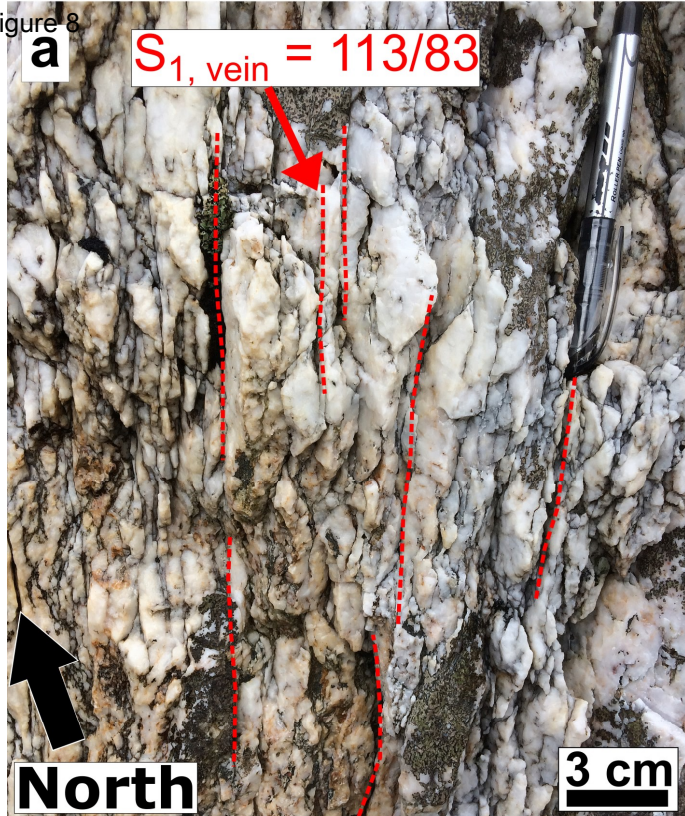




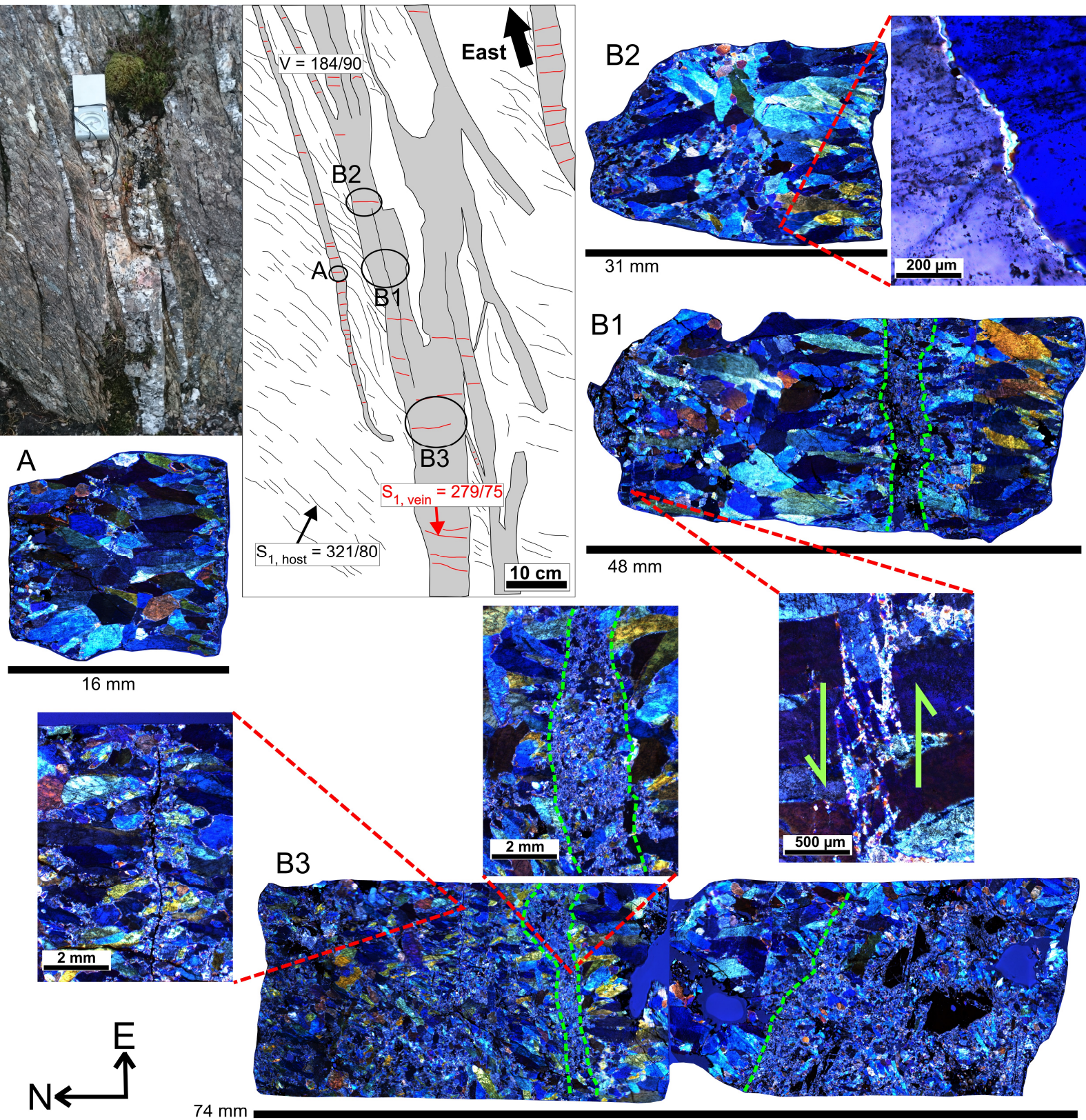
figure 8

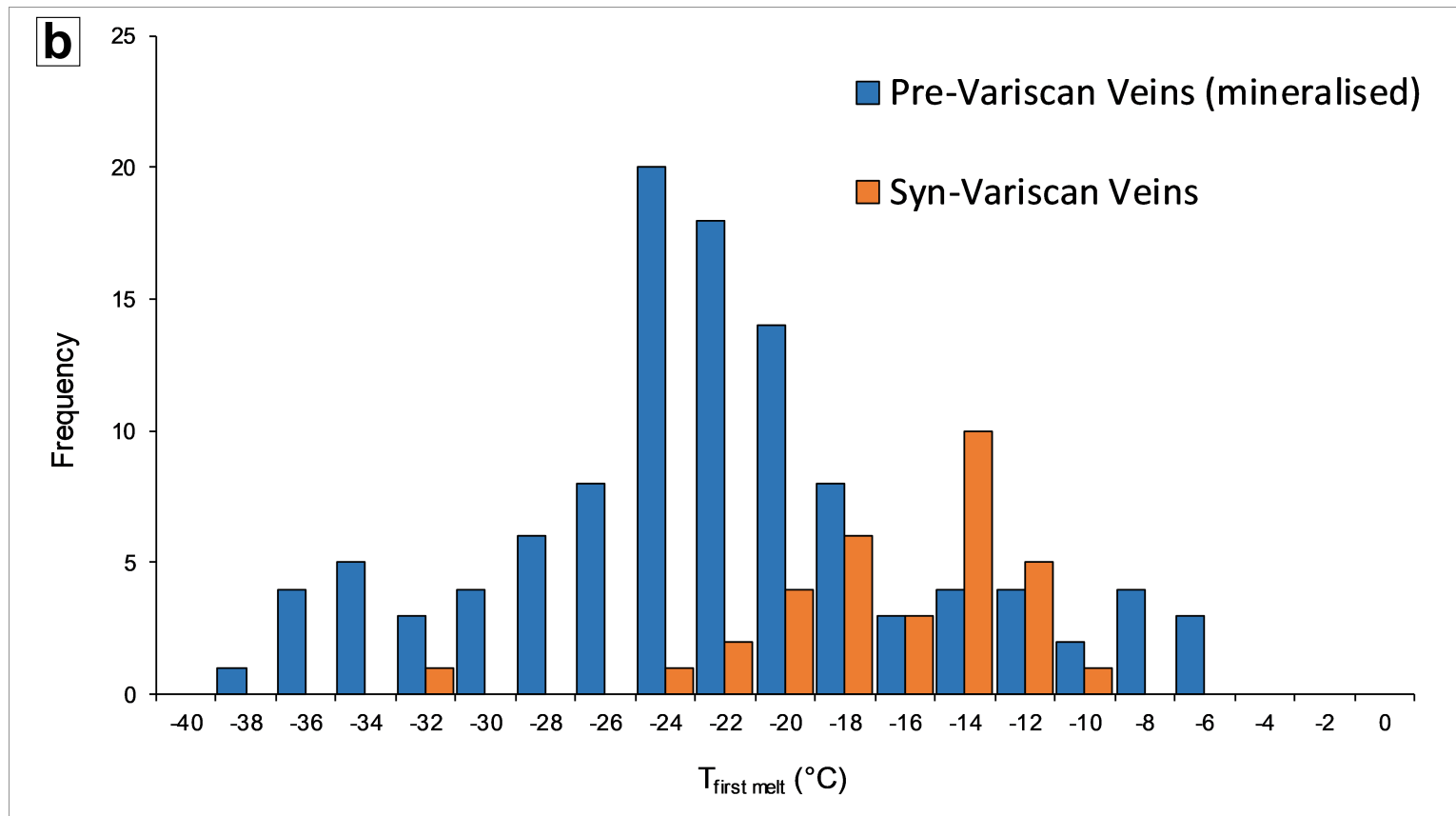
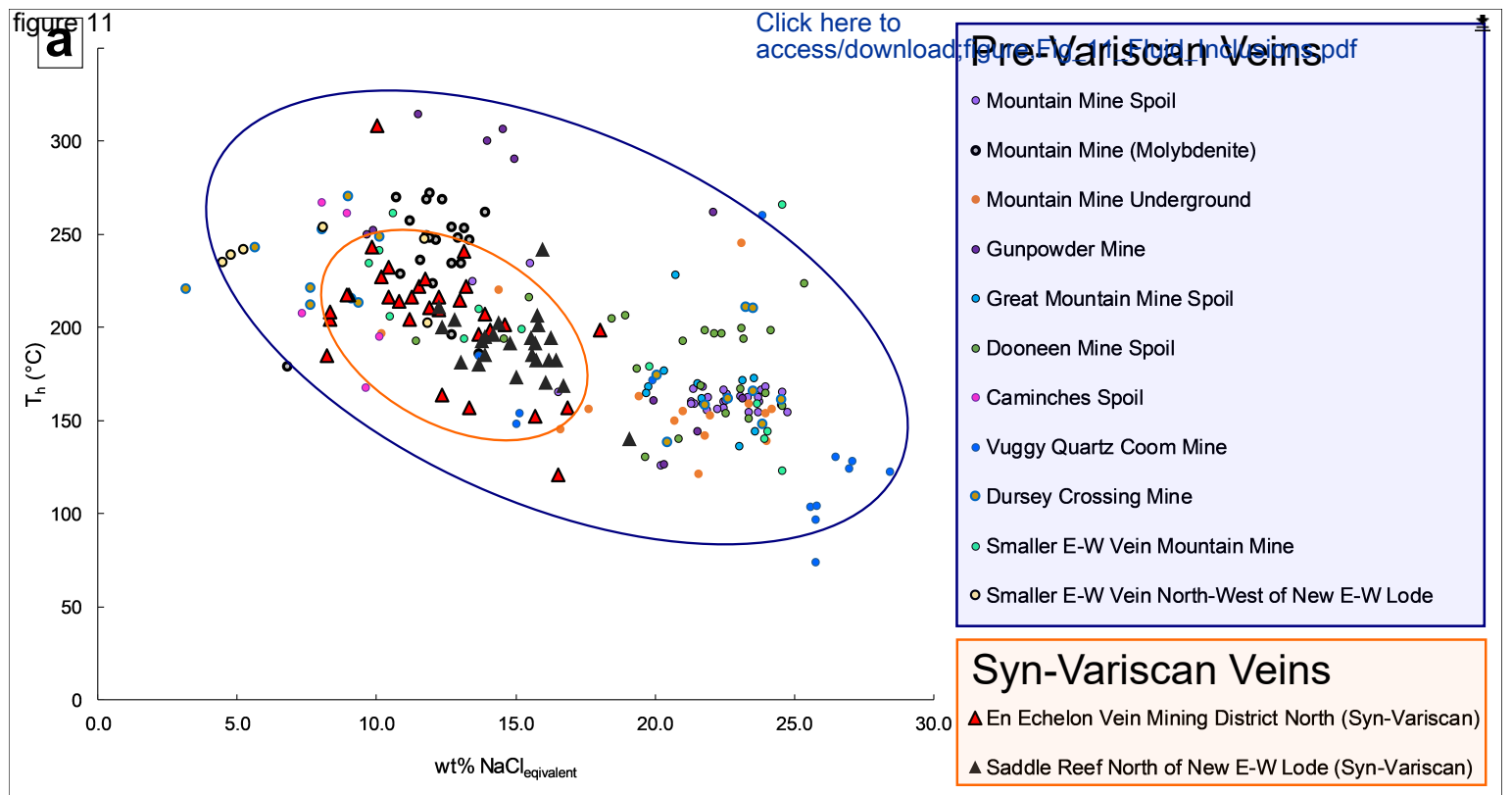




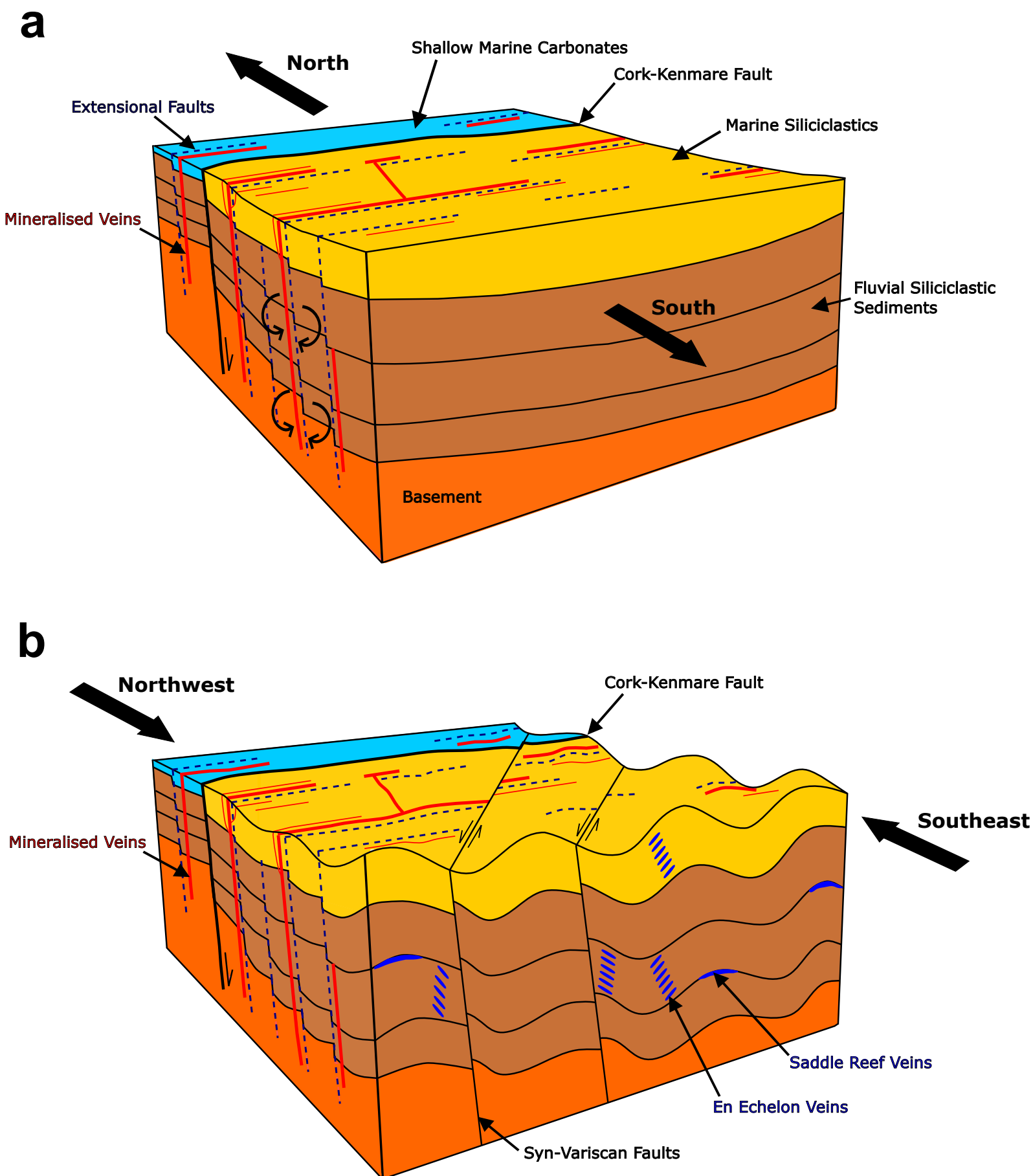














Click here to download supplementary material

<http://drive.google.com/drive/folders/1oCekq5EdrhQKTAWvL->





Click here to access/download  
**supplementary material**

Fluid\_Inclusions\_Allihies\_Lang\_et\_al\_supplementary\_data.xlsx



Click here to access/download  
**supplementary material**

Sample\_Locations\_Allihies\_Lang\_et\_al\_supplementary\_  
data.xlsx

