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1 **Syn-tectonic carbonation during syn-magmatic mantle**
2 **exhumation at an ocean-continent transition**

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10 **ABSTRACT**

11 A Jurassic extensional detachment associated with carbonated serpentinites and
12 basalts is preserved at Falotta (Platta nappe, southeastern Switzerland). Structural data
13 indicates that fluid circulation occurred during late increments of extension along the
14 detachment plane, separating serpentinites from basalts. The homogeneity of the isotopic
15 signatures ($\delta^{18}\text{O} \sim 16\%$ and $\delta^{13}\text{C}$ centered on 0–1‰) can be best explained by a single,
16 sudden seawater-derived carbonation event at temperatures of $\sim 100^\circ\text{C}$. Carbonation was
17 focused in the high permeability zone along the detachment. Our model yields new
18 insights for carbonation processes related to mantle exhumation.

19 **INTRODUCTION**

20 An important discovery in the study of passive margins was the recognition of
21 extensional detachments and mantle exhumation in the most distal parts of magma-poor
22 systems (Boillot et al., 1987). These structures resemble oceanic detachments that have

23 been observed at mid-ocean ridges (MacLeod et al., 2002; Cannat et al., 2009). MacLeod
24 et al. (2002) showed that large volumes of seawater interacted with the exhuming mantle
25 resulting in serpentinization of the uppermost 6 km of the exhumed mantle domain.
26 While hydrothermal cells lead to mineralization in the exhumed mantle (~1–3 km;
27 McCaig et al., 2007), ophicalcites develop within serpentinites close to the seafloor
28 (Weissert and Bernoulli, 1984). Characterizing such shallow fluid-rock interactions is
29 necessary to understand the chemical exchanges between the mantle and seawater
30 reservoirs and the mass budgets involved in metal deposition (Fe, Cu, Zn) close to or at
31 the seafloor.

32 In this paper, we present structural and geochemical data on the carbonation
33 associated with a well-preserved extensional detachment system exposed at Falotta in the
34 Platta nappe (southeastern Switzerland). We show that syn-tectonic carbonation occurred
35 during syn-magmatic mantle exhumation.

36 **GEOLOGICAL SETTING**

37 The Platta nappe, exposed in the southeastern Swiss Alps, hosts remnants of the
38 Jurassic Alpine Tethys Ocean Continent Transition (OCT; Fig. 1A). East-west-directed
39 regional extension, accommodated along mantle detachment faults (Desmurs et al.,
40 2001), was accompanied by mafic magmatism dated at 161 Ma (Schaltegger et al., 2002).
41 The Platta nappe is primarily composed of serpentinized mantle rocks and mafic rocks.
42 The serpentinites are carbonated at their paleo-surface, forming fracture-filling
43 ophicalcites (terminology of Bernoulli and Weissert, 1985). Tectono-sedimentary
44 carbonated mantle breccias (ophiolite breccias of Bernoulli and Weissert, 1985) occur
45 above the exhumed mantle. Mafic volcanic rocks (hyaloclastites, pillows, and lava flows)

46 overlie the opicalcites. The exhumed mantle rocks, breccias and basalts are capped by
47 the Radiolarian Chert Formation dated between 166 and 147 Ma (Bill et al., 2001).

48 **PETROGRAPHIC AND STRUCTURAL DATA**

49 At Falotta, three lithological units can be distinguished that are from bottom to
50 top: serpentinites, opicalcites, and basalts (Figs. 1B, 2A, and 3A). The serpentinites
51 consist of cataclasites with preserved serpentinite lenses crosscut by green serpentine
52 veins, gradually evolving upwards to a fault gouge (see also Picazo et al., 2013; Pinto et
53 al., 2015). The opicalcites consist of, from bottom to top, (1) fracture-filling opicalcites
54 with veins of fibrous calcite, and (2) foliated opicalcites. The latter consist of large
55 anastomosing and foliated carbonate shear bands (SBs) developed in serpentinite breccias
56 and around preserved lenses of various sizes (Fig. 2A). The sub-horizontal foliation,
57 broadly N°20 in strike, is defined by actinolite, carbonate, and minor talc and chlorite.
58 Carbonate veins mimic the foliation. The basalt unit contains foliated hyaloclastites,
59 foliated basalts, veined basalts and massive basalts further up-section (Figs. 2A and 3A).
60 The foliation is defined by amphibole and chlorite and displays the same strikes and dips
61 as those observed in the foliated opicalcites. The basalts are extensively epidotized and
62 chloritized along ribbons near the base.

63 Whereas carbonation may be locally massive and pervasive, replacing serpentinite
64 clasts and matrix, it is expressed throughout the whole section by veins and shear bands
65 (Fig. 3A). Only calcite, white to greyish in color, is observed. The extensional or hybrid
66 shear extensional character of the veins is indicated by fibrous habits of calcite filling and
67 wall rock offsets with calcite being the latest phase to crystallize (Figs. 2B–2E).
68 Extensional veins (EVs) in the serpentinites and opicalcites contain coarse calcite (up to

69 several millimeters) and minor amphibole and chlorite at their rims. The EVs crosscut the
70 serpentine veins (Fig. 2B). In the basalts, veins consisting of epidote, quartz, chlorite, and
71 albite, defining a greenschist paragenesis, are filled by late calcite (Fig. 2C). Hybrid shear
72 extensional veins (SVs) in the serpentinites and ophicalcites are filled with tiny calcite
73 (~10–50 μm) and actinolite. Close to the contact with the basalts talc and hydro-andradite
74 (garnet composition specified by scanning electron microscopy [SEM] analyses) are
75 found in veins. In the basalts, sparitic to micro-sparitic calcite is associated with
76 actinolite, iron oxides, talc, and hydro-andradite. Calcitic shear bands found in the
77 serpentinites and ophicalcites are composed of tiny calcite, actinolite, and minor chlorite,
78 leaving clasts made of serpentinite, serpentine, pyroxene, spinel, and magnetite. Within
79 the shear bands, the lack of dynamic recrystallization of the carbonate grains and the
80 cracks found in the grains argue for a cataclastic fabric (Fig. 2D). Locally, jogs between
81 calcitic shear veins form pull-apart structures filled with fibrous calcite (Fig. 2E).

82 Vein orientations and dips are plotted in Figure 3B. Throughout the section,
83 calcite fibers are sub-horizontal and oriented east-west. SVs dip ~40–50° either to the
84 east or to the west, whereas EVs steeply dip ~70–80°. At the base of the fracture-filling
85 ophicalcites, SVs strike N°160, whereas EVs have an N°0 orientation on average (Fig.
86 3B). EVs at the top of the fracture-filling ophicalcites trend N°160. In the foliated
87 ophicalcites, SVs and EVs roughly trend N°30 (Fig. 3B). In the basalts, EVs are N°30
88 and SVs trend N°40.

89 **STABLE ISOTOPE COMPOSITIONS**

90 The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of calcite are homogenous throughout the section with
91 no significant differences for the different types of veins and shear bands (Fig. 3C,

92 Appendix DR2 in the GSA Data Repository¹). The $\delta^{18}\text{O}$ values are centered at $\sim 16.0\text{‰} \pm$
93 0.3‰ (with a range of $15.4\text{--}17.0\text{‰}$). The $\delta^{13}\text{C}$ values are slightly more dispersed with
94 values between -0.44‰ and $+2.12\text{‰}$.

95 **DISCUSSION**

96 **Jurassic Carbonation from Seawater**

97 A recurring problem when dealing with Jurassic extensional events in the
98 European Alps is to assess the importance of the Alpine overprint (Weissert and
99 Bernoulli, 1984; Fröh-Green et al., 1990). There are several arguments for a Jurassic
100 carbonation from seawater, with no Alpine deformation and metamorphic overprint nor
101 isotopic resetting.

102 (1) Sub-vertical calcitic veins with east-west sub-horizontal fibers, together with
103 conjugate hybrid shear extensional veins with normal sense of shear, are indicative of
104 horizontal stretching/extension during carbonation. Normal shear bands in foliated
105 ophicalcites and conjugate hybrid shear extensional veins are symmetric systems
106 diagnostic of coaxial strain. These features, together with the lack of reverse shears
107 on the outcrop (Fig. 2A), are compatible with extensional deformation rather than
108 Alpine thrusting. Notably the structural pattern of veining is similar to veining
109 associated with slip along detachment faults (e.g., Mehl et al., 2005).

110 (2) The overall east-west extension during Jurassic exhumation is consistent with the
111 orientations of carbonate veins and fibers documented here (Froitzheim and
112 Manatschal, 1996).

- 113 (3) The presence of hydro-andradite suggests precipitation during oceanic
114 hydrothermalism rather than during regional Alpine metamorphism (Gutzmer et al.,
115 2001).
- 116 (4) One would expect that calcite crystals with variable habits (small versus large veins,
117 minute veins versus pluri-metric opicalcitized zones, veins hosted in basalts and
118 serpentinites) display variable $\delta^{18}\text{O}$ signatures, but they have identical $\delta^{18}\text{O}$ values.
119 This is inconsistent with recrystallization nor with isotopic exchange with host rocks
120 during a long-lived metamorphic event (see also Eppel and Abart, 1997).
- 121 (5) The $\delta^{13}\text{C}$ values centered at 0–1‰ are entirely consistent with typical marine
122 carbonates (Bach et al., 2011) and broadly fit with other Mesozoic, marine-related
123 opicalcite occurrences from the Alpine realm (Appendix DR2).

124 **Hydrothermal and Syn-Tectonic Carbonation**

125 Considering the large thickness (~10 m; Fig. 3A) and the large carbonate content
126 of the opicalcites, we can infer that seawater is an infinite isotopic reservoir in the fluid-
127 rock interaction system. Hence, we can evaluate the precipitation temperature of calcite
128 from seawater. Taking $\delta^{18}\text{O}_{\text{SW}} = 0\text{‰}$ and using the fractionation factor of Kim and
129 O'Neil (1997), we obtain 90–105 °C, a range considerably higher than the typical
130 temperatures of carbonate precipitation at present seafloor (~0–15 °C; Bach et al., 2011;
131 Alt and Shanks, 2003) or measured at the Iberian margin (~19–44 °C; Agrinier et al.,
132 1996; Schwarzenbach et al., 2013).

133 The remarkable isotopic homogeneity, i.e., homogeneous temperature,
134 documented in this study compared to other opicalcites (Appendix DR2) implies that
135 carbonation occurred as a dramatic, sudden event, the mechanism of precipitation being

136 unknown to date. Serpentinite breccias, formed during exhumation and subsequent
137 sedimentary reworking over exhumed mantle correspond to a high permeability zone
138 above which basalts were emplaced and underwent syn-emplacment greenschist
139 alteration (Fig. 4, stage I). Both the overlying massive and strongly altered basalts and the
140 underlying serpentinite gouges correspond to a low-permeability zone. The influx of
141 seawater-derived hydrothermal fluids in the high-permeability zone triggered
142 carbonation. The mechanisms of heating and downward circulation of seawater are likely
143 comparable to those described for ultramafic-hosted hydrothermal systems leading to
144 black smoker-type mineralizations or carbonate chimneys (e.g., McCaig et al., 2007; Alt
145 et al., 2018). In the regional context of mantle exhumation, a positive feedback occurred
146 between fluid flow and the extensional reactivation of the detachment plane. Indeed, even
147 if the amount of slip may have been limited, it enhanced dynamic permeability (stage II).
148 Epidote veins in the basalts were re-opened and calcite veins formed in the serpentinites,
149 all displaying orientations consistent with regional extension.

150 The present model contrasts with previous ones assuming that carbonation of
151 serpentinitized mantle occurs along the detachment plane during mantle exhumation or
152 under static conditions at the seafloor in the absence of magma (e.g. Lost City
153 hydrothermal field at MAR; Kelley et al., 2001). The coincidence of carbonation and
154 magmatism along present-day fault zones is poorly constrained due to the lack of access
155 to such outcrop. We propose that syn-tectonic carbonation along reactivated detachment
156 segment in relationship with overlying basalts may be an important contribution to
157 oceanic hydrothermal systems, including those leading to metal deposition, and may
158 likely be more widespread than previously thought.

159 **CONCLUSIONS**

160 Syn-tectonic carbonation along the Jurassic Falotta detachment (Swiss Alps)
161 resulted from the infiltration of hot seawater (~100 °C) into the high-permeability zone at
162 the top of exhumed serpentinites. The homogeneity of isotopic compositions pleads for a
163 sudden, short-lived fluid circulation. Extensional reactivation of the detachment plane,
164 with limited slip during magma emplacement, was favored by fluid-related weakening,
165 with a positive feedback between deformation-induced dynamic permeability and fluid
166 influx.

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262 **FIGURE CAPTIONS**

263 Figure 1. A: Map of the major paleogeographic and tectonic units in the Alps (after
264 Schaltegger et al., 2002). B: Simplified geological map (after Desmurs et al., 2001) of the
265 study area. C: Line-drawing photograph of the Falotta outcrop, southeastern Switzerland.
266 Two decametric blocks of serpentinite have slipped down-slope.

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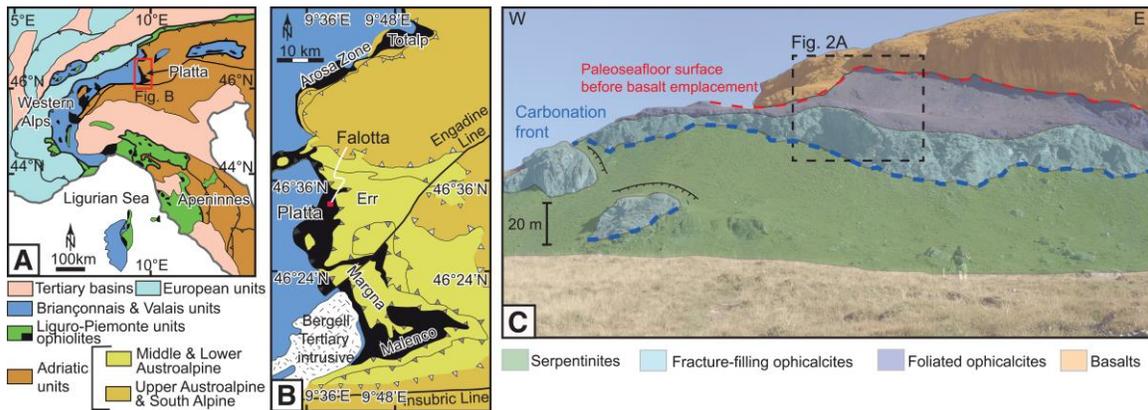
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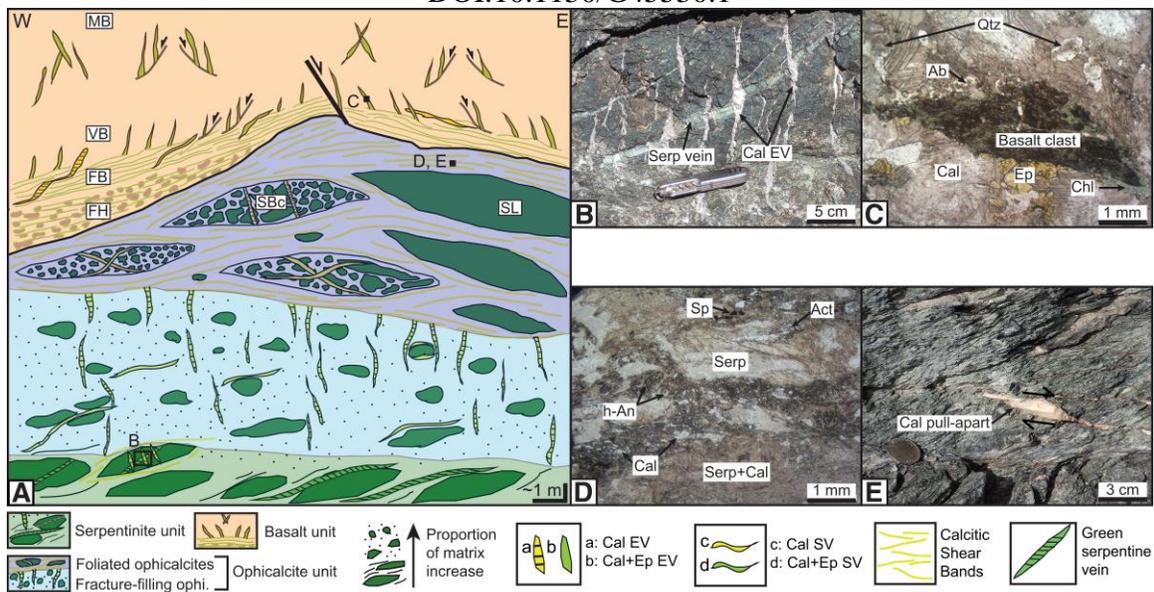


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275 Figure 2. A: Schematic diagram illustrating the encountered lithologies at Falotta,
276 southeastern Switzerland (not to scale). In the serpentinite and opicalcite units: SL—
277 serpentinite lenses; SB—serpentinite breccias. In the basalt unit: FH—foliated
278 hyaloclastites; FB—foliated basalts; VB—veined basalts; MB—massive basalts. See text
279 for details. B: Greenish serpentine vein crosscut by calcitic extensional veins (Cal EV) in
280 a serpentinite lens (photograph from a sliding block). C: Thin-section photograph
281 showing the greenschist alteration in the basalts [chlorite (Chl), epidote (Ep), quartz (Qtz)
282 and albite (Alb)] sealed by calcite (Cal) in a vein. D: Thin-section of a foliated
283 opicalcite. Serpentine (serp) is replaced by calcite during fluid-assisted deformation
284 forming a gouge (Serp+Cal). Spinel grains (Sp) are destabilized. Actinolite (Act) and
285 hydro-andradite (h-An) grains accompany the alteration. E: Calcite pull-apart in foliated
286 opicalcites.

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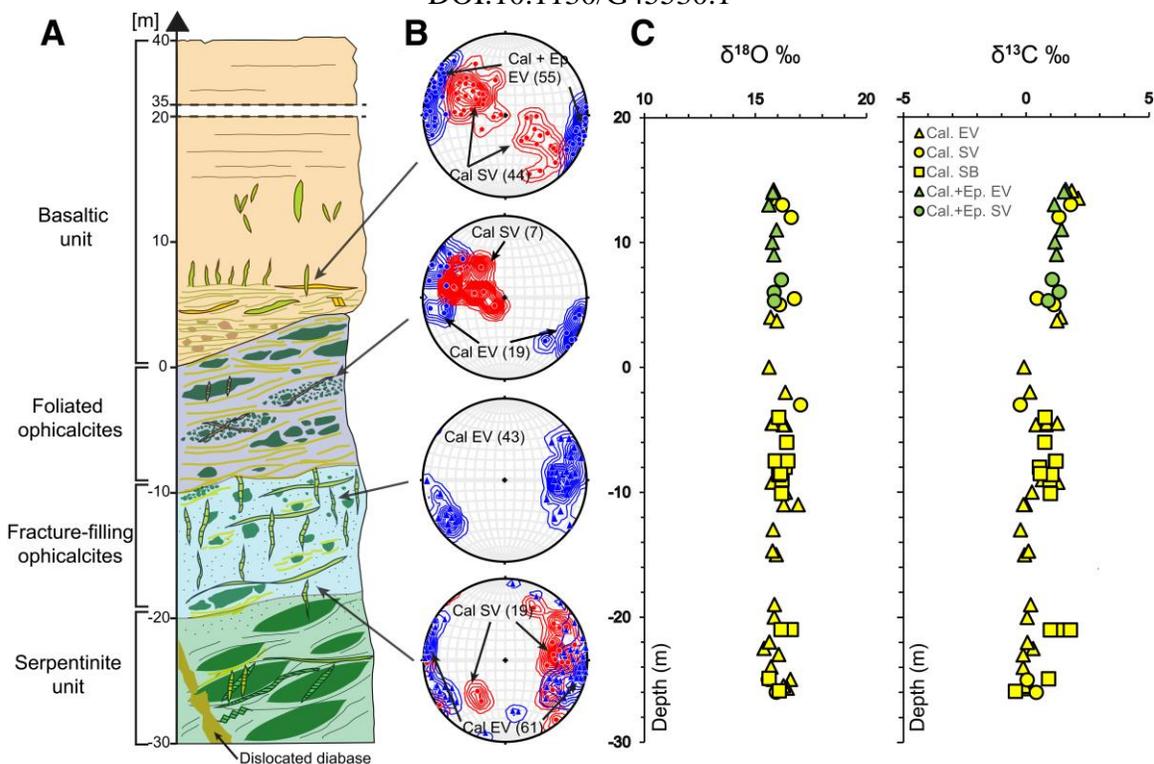
290 Figure 3. A: Synthetic log across the fossil detachment of Falotta, southeastern

291 Switzerland. B: Stereograms of vein poles (equal area, lower hemisphere, data number

292 N). See text for vein type abbreviations. C: $\delta^{18}\text{O}$ (VSMOW, Vienna Standard Mean

293 Ocean Water) and $\delta^{13}\text{C}$ (VPDB, Vienna Pee Dee Belemnite) versus depth.

294

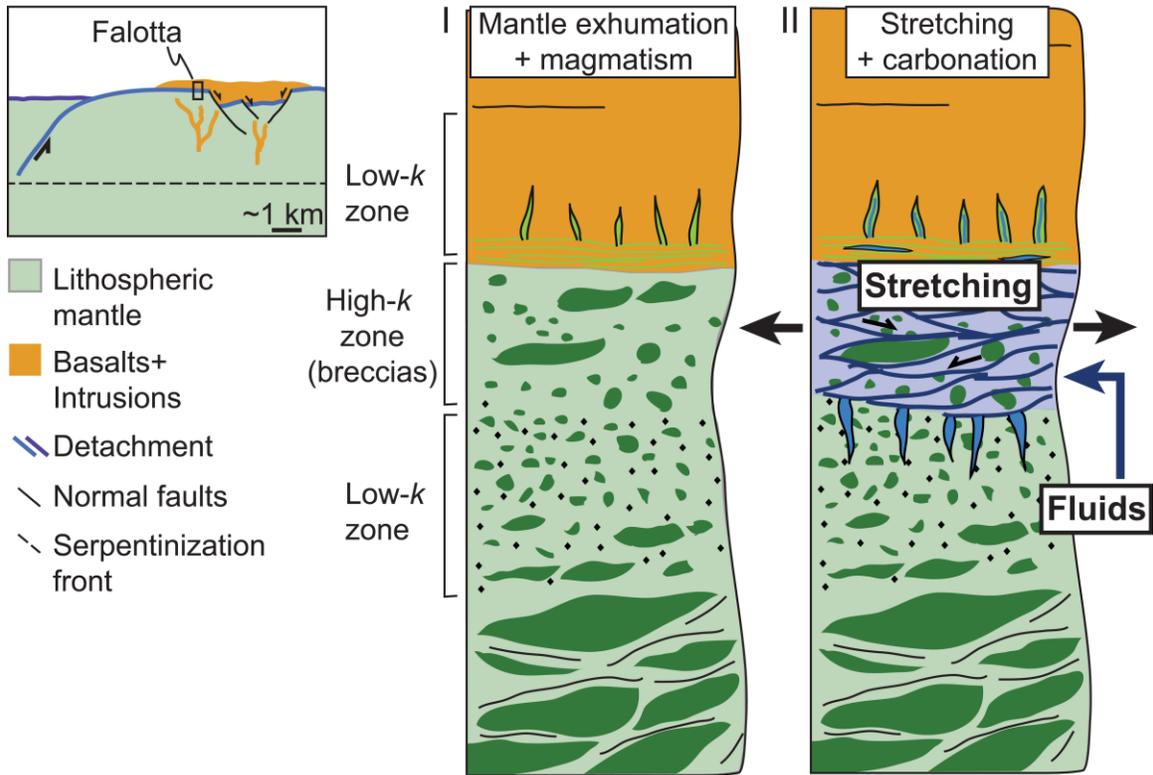


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296

297 Figure 4. Model of carbonation (right-side sketch, I and II) in the context of magma-
298 assisted mantle exhumation (left-side sketch). Carbonation is represented in blue (veins).
299 Log scale, symbols and colors as in Figure 2. k—permeability. Adapted from Decarlis et
300 al. (2018).

301



302

303 ¹GSA Data Repository item 2019xxx, xxxxxxxxxxxxxxxxxxxx, is available online at

304 <http://www.geosociety.org/datarepository/2019/>, or on request from

305 editing@geosociety.org.