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This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:

Vignaroli G., Rossetti F., Petracchini L., Argante V., Bernasconi S.M., Brilli M., et al. (2022). Middle Pleistocene fluid infiltration with 10–15 ka recurrence within the seismic cycle of the active Monte Morrone Fault System (central Apennines, Italy). *TECTONOPHYSICS*, 827, 1-18 [10.1016/j.tecto.2022.229269].

Availability:

This version is available at: <https://hdl.handle.net/11585/882461> since: 2022-04-18

Published:

DOI: <http://doi.org/10.1016/j.tecto.2022.229269>

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(Article begins on next page)

1 **Middle Pleistocene fluid infiltration with 10-15 ka recurrence**
2 **within the seismic cycle of the active Monte Morrone Fault**
3 **System (central Apennines, Italy)**

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31

32 **Abstract**

33 This study integrates field, geochronological and geochemical data to constrain fluid
34 circulation in the damage and core zone of the seismogenic Monte Morrone Fault System (MMFS),
35 central Apennines (Italy). Faulting along the MMFS evolved from a diffuse deformation at the
36 damage zone towards progressive localisation of a narrower fault core and, finally, to (re)activation
37 of discrete slip surfaces at shallower crustal conditions. Multiple generations of carbonate
38 mineralisations, including veins and slickfibers, occur along the main fault surfaces. Carbonate
39 mineralisations are locally fractured and incorporated in the surrounding cataclasites, documenting
40 repetitive structurally-controlled fluid infiltration during transient episodes of permeability creation
41 and destruction. Stable carbon and oxygen isotopes of the carbonate mineralisations document a
42 dominant meteoric water source probably mixed with deeper circulating waters having longer
43 residence time. Clumped-isotope yield formation temperatures of vein and slickenfibers in the range
44 between 23 and 40 °C. U-Th dating of carbonate mineralisations yield Middle Pleistocene ages (from
45 268 to 189 ka BP), with a 10-15-ka cyclicity that we link to the coseismic rejuvenation of the
46 structural permeability in the fault zone. We propose that fault-related mineralisations recorded the
47 interactions among tectonic deformation and climate during the Quaternary. Our study is the first
48 documentation of fault-controlled recurrence intervals in fluid infiltration in a seismically active fault
49 of central Apennines.

50

51 **Keywords:** Normal faulting, Mineralising fluid, Seismic cycle, U-Th carbonate dating, Monte
52 Morrone Fault, central Apennines.

53

54 **1. Introduction**

55 In the upper seismogenic crust, the growth of major faults includes creation/destruction of
56 secondary permeability involving deformation and fluid pressure fluctuations in response to a
57 continuous stress accumulation throughout the entire seismic cycle (e.g., Sibson, 1992; 2014;
58 Hickman et al., 1995; Miller et al., 2004; Smeraglia et al., 2016; Fig. 1). The relationship between
59 creation/destruction of secondary permeability in fault rocks and pulses of fluid ingress are sensitive
60 gauges of crustal deformation, with implication on location and recurrence intervals of earthquakes.
61 During the coseismic rupture, cataclastic processes and fracturing rejuvenate the internal
62 architecture of the fault in response to heterogeneous strain localisation during fault growth and
63 propagation (Sibson, 1992; Tesei et al., 2013; Delle Piane et al., 2017 and references therein).
64 Structural permeability increases depending on fracture persistency, interconnectivity, and
65 geometry, allowing enhanced fluid ingress in fault rocks (e.g., Caine et al., 1996; Rowland and
66 Sibson, 2004; Cox, 2010; Sibson, 2014; Williams et al., 2015). Fluids migrate through the
67 secondary permeability in hydrostatic condition if fault permeability is maintained by cycles of
68 coseismic failures (e.g., Sibson and Rowland, 2003). In the interseismic/postseismic stage, mineral
69 precipitation from circulating fluids progressively seals the fault zone permeability (e.g., Cox,
70 2010). This mechanism of permeability destruction sets the ground for the subsequent
71 suprahydrostatic pressure build up, which may enhance coseismic failure at seismogenic depths and
72 activation/reactivation of slip surfaces at shallower depths (e.g., Cox et al., 2001; Sibson, 2014;
73 Smeraglia et al., 2016). Consequently, cycles of permeability creation and destruction characterise
74 the fault zone evolution during the different stages of a seismic cycle, and the study of fluid
75 circulation is, therefore, key to reconstruct the space-time distribution and evolution of fault
76 permeability (Caine et al., 1996; Sibson and Rowland, 2003). In particular, the geochemical
77 properties of the fluids infiltrating along structurally controlled pathway (faults and fractures)
78 provide constraints on the scale and types of fluid circulation. The absolute ages of different
79 generations of sealing mineralisations provide the timing of the fault activation/reactivation
80 episodes. Reconstructing fault/host rock fluid interactions contributes to refine the recurrence model
81 of seismic failure during the geological history of major fault systems.

82 The seismotectonic framework of the central Apennines is controlled by distributed
83 extensional faulting (e.g., Cello et al., 1997; Galli et al., 2008; Faure Walker et al., 2010; Iezzi et al.,
84 2019). Fault activity is typified by a continuous interaction and feedback between fault
85 (re)activation and fluid migration during the complete seismic cycle (e.g., Smith et al., 2011;
86 Collettini et al., 2013; Doglioni et al., 2014; Smeraglia et al., 2016; 2018; Barberio et al., 2017).
87 Presently, instrumental (ISIDe database; <http://terremoti.ingv.it/en/iside>), historical (Rovida et al.,

88 2020; https://emidius.mi.ingv.it/CPTI15-DBMI15/index_en.htm) and paleoseismological (e.g.,
89 Galli et al., 2008 and references therein) datasets can help reconstruct activity and recurrence
90 intervals of seismogenic faults through the entire Holocene. Very few studies, however, provide
91 geological and geochronological constraints on the long-term tectonic activity of seismically active
92 normal faults. In this view, the occurrence of distinctive fabrics and mineralisations in faults has
93 been used to identify the relative chronological sequence of Quaternary deformation events during
94 the interseismic and the coseismic stages (Smeraglia et al., 2018; Vignaroli et al., 2020a).

95 In this study, we describe the structural relationships between tectonic structures and fluid
96 infiltration within the Monte Morrone Fault System (MMFS), an outstanding example of active
97 extensional faulting in the central Apennines (Fig. 2a,b). The MMFS consists of NW-SE-striking
98 normal fault strands, cutting across Pleistocene-to-Holocene continental deposits (Miccadei et al.,
99 1998; Galadini and Galli, 2000; Gori et al., 2011). The trace of the MMFS corresponds to a
100 regional-scale seismic gap with respect to the 2009 Mw 6.1 L'Aquila and the 2016-2017 Mw 6.0-
101 6.5 Amatrice-Norcia earthquakes, the last destructive seismic sequences in central Italy (e.g.,
102 Chiarabba et al., 2009; Chiaraluce et al., 2017). We document multiple generations of syn-tectonic
103 carbonate mineralisations within the damage and core zone of the MMFS. We constrained the
104 meso- and micro-scale structural properties, the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ and clumped isotope signature, and
105 the U-Th ages of these carbonate mineralisations to reconstruct the fault-fluid interplay and its
106 spatio-temporal evolution during the different stages of the seismic cycle. In particular, by dating
107 the fault-related mineralisations, we fixed the absolute ages of the MMFS activation episodes.
108 Finally, we propose a conceptual model of recurrence intervals of Middle Pleistocene fluid
109 infiltration and fault interaction during the seismic cycle of the MMFS. This study could set the
110 ground for establishing a seismic recurrence model on regional-scale faults within the seismically
111 active tectonic setting of the central Apennines.

112

113

114 **2. Geological Setting**

115 **2.1. The central Apennines**

116 The central Apennines (Fig. 2a,b) is a roughly NW-SE-trending orogenic segment originated
117 from the Cenozoic oceanic subduction and subsequent continental collision between the European
118 and the Adria plates (e.g., Dewey et al., 1989; Boccaletti et al., 1990; Faccenna et al., 2001;
119 Carminati et al., 2010). The resulting fold-and-thrust belt (Fig. 2b) deformed rocks belonging to

120 different paleogeographic domains, including (a) limestones and dolostones of Mesozoic platforms-
121 to-basin environments, and (b) flysch sediments of Tortonian-to-Pliocene foredeep basins (e.g.,
122 Vezzani et al., 2010; Cosentino et al., 2010). Crustal shortening operated through the activation of
123 west-dipping, regional-scale thrusts in a general eastward migration of compressive fronts toward
124 the Adriatic foreland (e.g., Barchi et al., 1998; Patacca et al., 2008).

125 The present-day structural setting of the central Apennines results from the progressive
126 uplift of the early stacked units followed by extensional tectonics since the Pliocene. This post-
127 orogenic phase has started from the hinterland (Tyrrhenian) side of the belt and migrated towards
128 the foreland, generating mainly NW-SE-striking normal faults and the formation of large
129 intermountain basins filled by transitional-to-continental Plio-Quaternary deposits (e.g., Malinverno
130 and Ryan, 1986; Dewey, 1988; Martini and Sagri, 1993; Faccenna et al., 1997; Cavinato and
131 DeCelles, 1999; Cavinato et al., 2002; Cosentino et al., 2017). Crustal thinning generated a complex
132 network of major extensional faults arranged in both en-echelon and collinear geometry (e.g.,
133 Ghisetti and Vezzani, 2002; Galadini and Messina, 2004; Roberts and Michetti, 2004; Pizzi et al.,
134 2017; Galli et al., 2019; Fig. 2b). The major normal faults extend to a depth of 10–15 km, with dip
135 $\geq 45^\circ$. Intermountain basins, mostly filled by continental deposits, often develop at the hanging wall
136 of the master faults, whereas Mesozoic carbonates are exposed at their footwall, indicating
137 kilometre-scale down-section stratigraphic displacements (e.g., Boncio et al., 2004; Roberts and
138 Michetti, 2004; Galli et al., 2008; Lanari et al., 2021). The estimated Holocene throw rate for the
139 major normal faults ranges from 0.3 to ~2 mm/yr (Roberts and Michetti, 2004; Cowie et al., 2017).

140 NW-SE-striking normal faults control the intense seismicity in the axial part of the central
141 Apennines, as testified by both the historical (Rovida et al., 2020) and the recent and destructive
142 events (the 1997 Colfiorito event, Mw 6.0; the 2009 L’Aquila event, Mw 6.1; the 2016-2017
143 Amatrice-Norcia sequence, Mw up to 6.5; Fig. 2b). Seismicity remains confined in the uppermost
144 10-12 km crustal section (Amato et al., 1998; Chiaraluce et al., 2017). Studies on fault slip rates
145 (Roberts and Michetti, 2004; Faure Walker et al., 2010), paleoseismology (Galli et al., 2008; Galli
146 et al., 2018; 2019) and global-positioning system (D’Agostino et al., 2011) confirm that the major
147 normal faults are the locus of active deformation localisation at short- and long-term scales (up to
148 10^4 years). For the active normal faults, a 1-2 ka recurrence time for Mw > 6.5 earthquakes has been
149 estimated based on paleoseimological constraints (Galli et al., 2008). Recent U-series ages for syn-
150 tectonic mineralisations constrained the long-term activity in potentially-seismogenic structures of
151 the central Apennines in the ~350-108 ka time interval (Smeraglia et al., 2018; Vignaroli et al.,
152 2020a).

153 The fluid-assisted deformation in the central Apennines has been documented in faulted
154 carbonate and siliciclastic units through the analysis of syn-tectonic mineralisations (e.g., Maiorani
155 et al., 1992; Conti et al., 2001; Ghisetti et al., 2001; Agosta et al., 2008; Smeraglia et al., 2016;
156 2018; Vignaroli et al., 2020a; Curzi et al., 2021; Coppola et al., 2021). Most syn-tectonic
157 mineralisations preserve the geochemical signature of cold-water circulation at shallow depths,
158 suggesting a dominant meteoric/groundwater fluid circulation. It is noteworthy, that earthquake-
159 related fluid circulation is characterised by the interplay between transient permeability at the fault
160 damage zones and mixing of fluids from different reservoirs, in part also of deeper origin
161 (Smeraglia et al., 2018).

162

163 ***2.2. The Monte Morrone Fault System***

164 The MMFS consists of NW-SE-striking fault segments with an along-strike cumulative
165 length of ~25 km (e.g., Miccadei et al., 2002; Gori et al., 2011; Fig. 2c). The MMFS runs sub-
166 parallel and cuts across the SW-dipping, back-limb of the NW-SE-trending Monte Morrone
167 anticline, developed at the hanging wall of E-verging thrust sheets (e.g., Vezzani et al., 2010).
168 Thrusting involved a Mesozoic-Cenozoic basinal succession of limestones and marls evolving to
169 platform carbonates. Seismic profiles suggest that the MMFS penetrates the crust to a depth of 10-
170 12 km, accommodating more than 2 km of cumulative movement during the Pleistocene-Holocene
171 (Patacca et al., 2008). Subsidence at the hanging wall of the MMFS provided the space for
172 sedimentation of several hundred metres of alluvial–fluvial–lacustrine sediments that fill the
173 intermountain Sulmona Basin (e.g., Miccadei et al., 1998; Giaccio et al., 2009; Fig. 2d). In the
174 Sulmona Basin, the eastward dip and the fan geometry of the strata attest for syn-tectonic deposition
175 during normal-sense movement of the MMFS (e.g., Miccadei et al., 1998; Gori et al., 2011). Based
176 on geomorphic expressions and geological correlations, the Holocene slip rate of the MMFS has
177 been estimated to be between 0.4 and 1.1 mm/yr (Roberts and Michetti, 2004; Gori et al., 2011).

178 The MMFS developed through propagation and interaction of two parallel west-dipping
179 fault strands: the western fault system (WFS) and the eastern fault system (EFS) (Galadini and
180 Messina, 2004; Boncio et al., 2012; Gori et al., 2014). The WFS runs through the Roccacasale
181 village and extends from the Popoli village in the NW to the Pacentro village in the SE (Fig. 2c).
182 This strand consists of a complex network of NW-SE-striking (SW-dipping) fault segments
183 arranged in collinear and, subordinate, right-stepping en-echelon geometry. The exposure of the
184 WFS fault scarps near Roccacasale reveals almost planar and striated surfaces (Boncio et al., 2012)
185 covering an up to half a metre-thick fault core developed through multiple events of fabric

186 formation and rejuvenation in response to cyclic stress accumulation and dissipation (Ferraro et al.,
187 2018; 2019; Coppola et al., 2021). Occurrence of different cemented fault rocks, from matrix-
188 supported to grain-supported (Ferraro et al., 2018), and multiple microcrystalline calcite cement in
189 cataclastic-to-ultracataclastic layers (Ferraro et al., 2019; Coppola et al., 2021) suggests a co-
190 seismic fabric reworking during fluid-assisted deformation.

191 No major (i.e. $M_w > 4$) historical earthquakes are associated with the MMFS (Rovida et al.,
192 2020). The seismic source of the catastrophic 1706 event that hit the Sulmona Basin is still debated
193 (Galli et al., 2015) and possibly located around the adjacent Majella ridge (Fig. 2b). However,
194 archaeoseismic and paleoseismic constraints set the elapsed time for the MMFS since the last event
195 at ~ 1850 yr ago, which is compatible with the average recurrence time of the Apennine
196 seismogenic faults (Galadini and Galli, 2001; Galli et al., 2015). Barberio et al. (2017) monitored
197 several springs located within the Sulmona Basin and associated their hydrochemical variation to
198 the mainshocks of the 2016-2017 Amatrice-Norcia sequence. This hydrogeological setting suggests
199 an active structural permeability in the Monte Morrone area, potentially sensitive to seismic inputs.

200

201

202 **3. Materials and Methods**

203 Through the study of fault strands exposed near the Roccacasale village, we focused on the
204 structural permeability of the WFS by characterising its brittle structural architecture and the
205 associated fault-related carbonate mineralisations (see structural stops in Fig. 2e). Field criteria for
206 fault rock classification (e.g., Sibson, 1977; Braathen et al., 2004) have been used to identify and
207 characterise the fault structural fabrics, whereas classic kinematic criteria have been used to
208 determine the sense of shear (e.g., Petit, 1987).

209 We collected hand samples of fault rocks and carbonate mineralisation (Table 1). Optical
210 and back-scattered electron (BSE) microscopy was performed on oriented thin sections to
211 characterise the overprinting relationships among different generations of structures and carbonate
212 mineralisations that took place during faulting. Cold cathodoluminescence (CL) imaging were
213 performed using a Cambridge Image Technology Limited luminoscope Leica DM2700P optical
214 microscope (model Mk5-2; operating system at 9.9 kV with a beam current of 256 μA) at the
215 Department of Chemistry, Life Sciences, and Environmental Sustainability of the University of
216 Parma.

217 U-Th dating was carried out on (1) a Thermo Electron Neptune multi-collector inductively
218 coupled mass spectrometer (MC-ICP-MS) (Shen et al., 2012) at the High-Precision Mass
219 Spectrometry and Environment Change Laboratory (HISPEC), National Taiwan University, and (2)
220 on α -spectrometer at the Laboratory of Environmental and Isotopic Geochemistry, Department of
221 Sciences, Roma Tre University, Italy. For MC-ICP-MS dating, we covered about 0.05 g of each
222 sample with H₂O and dissolved it gradually with double distilled 14 N HNO₃. After dissolution, we
223 added a ²²⁹Th–²³³U–²³⁶U spike (Shen et al., 2003) to the sample, followed by 10 drops of HClO₄ to
224 decompose organic matter. We followed the chemical procedure described in Shen et al. (2003) for
225 the separation of uranium and thorium. Detailed instrumental analysis is given in Shen et al. (2012).
226 Age correction was calculated using an estimated atomic ²³⁰Th/²³²Th ratio of $4 \pm 2 \times 10^{-6}$. The value
227 is the one typical for a material at secular equilibrium with the crustal ²³²Th/²³⁸U value of 3.8 and an
228 arbitrarily assumed 50% error. Half-lives of U-Th nuclides used for age calculation with 2-sigma
229 uncertainty are from Cheng et al. (2013). For α -spectrometry dating, samples were cut with a
230 diamond saw and ultrasonically washed in deionized water. About 60 g of each prepared sample
231 were thus dissolved in 7 N HNO₃ and filtered to separate leachates from insoluble residue. The
232 leachates were heated to 200 °C after adding a few millilitres of hydrogen peroxide to annihilate
233 organic matter, then spiked with a ²²⁸Th/²³²U tracer. U and Th were extracted according to Edwards
234 et al. (1987), then analysed through alpha-counting using high-resolution ion-implanted Ortec
235 silicon-surface barrier detectors. For samples with a ²³⁰Th/²³²Th activity ratio higher than 80 (with
236 insignificant non-radiogenic ²³⁰Th), ages were determined using the measured ²³⁰Th/²³⁴U and
237 ²³⁴U/²³⁸U activity ratio. Sample ages characterized by a ²³⁰Th/²³²Th activity ratio less than or equal
238 to 80 indicating the presence of non-radiogenic (detrital) ²³⁰Th required a correction based on the
239 assumption of an average ²³⁰Th/²³²Th activity ratio of 0.85 ± 0.36 for all detrital Th (Wedepohl,
240 1995). All ages were finally calculated using ISOPLOT (Ludwig, 2003) with errors expressed as
241 $\pm 1\sigma$.

242 Samples for geochemical analysis were obtained by micro-drilling. Carbon and oxygen
243 isotope analyses of 50 samples from the WFS (Table A1) were carried out at the Istituto di Geologia
244 Ambientale e Geoingegneria of the Consiglio Nazionale delle Ricerche (Rome, Italy), by acid
245 digestion at 72°C using a Thermo Fisher Scientific Gasbench II coupled to a Delta+ mass
246 spectrometer. Approximately 120 μ g of powder was weighted in duplicate. Standardisation to the
247 V-PDB scale was accomplished with three internal standards MC-200, CaCO₃ (Merck CCM) and
248 Solnhofen limestone (SLNF) calibrated against the international references NBS18 and NBS19.
249 Oxygen and carbon isotopes are reported with respect to the Vienna Pee Dee Belemnite standard
250 (V-PDB).

251 The clumped isotope compositions of the carbonates were determined at ETH Zürich using a
252 Thermo Fisher Scientific 253Plus mass spectrometer coupled to a Kiel IV carbonate preparation
253 device, following the method described in Schmid and Bernasconi (2010), Meckler et al. (2014),
254 and Müller et al. (2017). The Kiel IV device included a PoraPakQ trap kept at - 40°C to eliminate
255 potential organic contaminants. Prior to each sample run, the pressure-dependent backgrounds were
256 determined on all beams to correct for non-linearity effects in the mass spectrometer according to
257 Bernasconi et al. (2013). During each run, 20 replicates of 100-120 µg of different samples and 5
258 replicates of each of the two carbonate standards ETH-1, ETH-2, and 10 of ETH-3 were analysed in
259 LIDI mode. Data processing was carried out with the software Easotope (John and Bowen, 2016)
260 using the IUPAC parameters for 17O correction as suggested by Daeron et al. (2016). The data are
261 reported in the Intercarb Carbon dioxide equilibration scale (I-CDES) (Bernasconi et al. 2021) and
262 the temperatures of formation were calculated with the Anderson et al. (2021) calibration. The
263 oxygen isotopic composition ($\delta^{18}\text{O}_{\text{fluid}}$) of the fluids was calculated using the calibration of Kim and
264 O'Neil (1997).

265

266

267 **4. Results**

268 **4.1. Outcrop scale structures**

269 Near Roccacasale (Fig. 2e), the WFS cuts through a sequence of Sinemurian dolomitised
270 limestones. There, the WFS consists of multiple NW-SE-striking fault strands dipping moderately
271 (30°-50°) to SW, typically associated with dm-to-m-thick damage zones (Fig. 3a). The main slip
272 surface, which accommodates the most important offset, commonly show a planar morphology and
273 hosts slickenlines, provided by abrasion striae and rare calcite fibres (Fig. 3b). Slickenlines show
274 pitch values generally around 80° and 100° (Fig. 3b), indicative of nearly pure dip-slip kinematics.
275 Stratigraphic offset, synthetic shears, dragging of the bedding at the fault surfaces, and calcite
276 fibres indicate normal-sense movement.

277 The main slip surface is associated with a metre-thick damage zone and dm-thick fault core
278 at the footwall (Fig. 3c,d; see also Ferraro et al., 2018). The damage zone is characterised by dm-
279 thick lenses of either massive or foliated cataclasite (Fig. 3e). Cataclasites wrap around dm-to-half
280 metre-thick lithons of almost undeformed limestone. The boundaries between the cataclasite lenses
281 are commonly marked by mm-thick, subsidiary fault zones, synthetic to the main slip surface (Fig.
282 3e). Massive cataclasites are characterised by matrix-clast proportion >50% and clasts are sub-
283 angular to sub-rounded and up to 1 cm-wide. Foliated cataclasites are characterised by faint layers

284 with different grain size. Approaching the main slip surfaces, matrix becomes extremely dominant
285 and defines centimetre-thick layers of ultra-cataclasite (Fig. 3e; see also Coppola et al., 2021).

286 High angle (dip > 55°; insert in Fig. 3a) faults have been mostly observed at the hanging
287 wall of the main slip surface (Fig. 4a-c). These fault strands are characterised by roughly planar slip
288 surfaces (in section view) dipping to the W-WSW (Fig. 4a,b). The high-angle faults systematically
289 cut and displace the main slip surface, producing centimetre-to-decimetre down-dip offsets and
290 incipient rigid fault block rotation (Fig. 4b,c). They are commonly accompanied by sets of fault-
291 parallel joints and lenses of proto-cataclasites, defining centimetre-thick damage zones.

292 Carbonate mineralisations occur on the main slip surfaces and on the high-angle normal
293 faults (Fig. 4d-h). The main mineralisation is up to 10 cm-thick and consists of a layered calcite,
294 found in the immediate hanging wall of the main slip surface (Fig. 4c,d). In section view, layering is
295 dominantly plane-parallel, although thickness variations from few centimetres up to 15 cm, and
296 pinch-out geometry on older strata can be locally recognised (Fig. 4e,f). When associated with high-
297 angle faults, carbonate mineralisations consist of up to one cm-thick layers of fine grained calcite
298 lying atop striated surfaces (Fig. 4g,h). Layering in these mineralisations is mm-thick, dominantly
299 plane and parallel to the fault surfaces.

300

301 **4.2. Meso- to micro-scale structures**

302 The mineralisations consist of the rhythmic layering of mm-thick laminae and sparitic veins
303 (Figs. 5a,b and SM1a-e). The laminae, which often appears as alabaster-like translucent deposit of
304 fine-grained and massive calcite, are fault-parallel and often characterised by variation in thickness
305 and marked by change in colour from whitish to light brown (Figs. 5a and SM1a,d). Layers of fine-
306 grained calcite are locally intercalated by mm-to-cm-thick pockets of sedimentary breccias,
307 probably filling voids of karst origin. The fabric of the breccia consists of a chaotic distribution of
308 up to 1-cm large limestone clasts (i.e., protolith) mixed with other carbonate fragments deriving
309 from the previous cataclasite (Fig. 5a). The sparitic veins are up to one cm-thick, poorly- to non-
310 porous and are disposed parallel to the fault surface (Figs. 5a,b; SM1a,b,e). Macroscopically, veins
311 show fan-shaped morphology of elongated crystals, which provides unequivocal evidence on the
312 growth direction.

313 At the microscale, cataclasites show sub-rounded clasts, with increasing roundness
314 associated with decreasing particle size (Figs. 5d-f and 6a). The main structural characteristics are:
315 (i) sub-angular clasts fragmented at their edges and clasts showing internal set of polygonal

316 fractures (Fig. 5e,f, 6a,b,d, SM2a-c,g); (ii) truncated clasts by sharp slip surfaces (Fig. 6c); (iii)
317 traces of permeating fluid within the fine-grained matrix and mantling the carbonate clasts (Fig.
318 6d); (iv) sigmoidal foliation in proximity of the main slip surfaces (Figs. 5d; SM2d; SM3l,m).
319 Cathodoluminescence analysis reveals that the convolute structures are characterised by an overall
320 bright-purple colour, distinctively brighter than the calcite of both the fine-grained matrix and the
321 clasts (Fig. 6e).

322 Carbonate laminae and sparitic veins grew from a slip surface that truncates the cataclasite
323 (Figs. 6f, SM2a-f, SM3). While the laminae are characterised by fine-grained, dirty calcite mixed
324 with clay particles (Fig. 6j), the sparitic veins show an internal fibrous texture with crystal growth
325 direction roughly perpendicular to the vein wall (Fig. 6f). The calcite crystal tends to form vein-
326 normal elongated fan-shaped patterns, which are indicative of the vein growth direction and sense.
327 We observed both downward and upward growth patterns, with crystal that converge toward the
328 medial line of the veins, documenting a general syntaxial grow mechanism (Fig. 6f,k; SM3d,g).
329 Cathodoluminescence shows that this calcite is characterised by dull brown/black colour,
330 particularly darker than the calcite occurring within the cataclasite (Fig. 6g).

331 The mineralisations are locally reworked by fracturing and cataclasis to form new clasts
332 (Figs. 6h,i; SM2c-e; SM3h-m). They are affected by micro-joints producing micrometer
333 displacements or display deformation including sigmoidal foliation-like structure embedded in
334 minor slip surfaces (Fig. SM2d; SM3l,m). Reworked mineralisations are often surrounded by
335 secondary micro-crystalline calcite cements with a purple cathodoluminescence like the calcite in
336 the fine-grained matrix. Strips of protocataclasites are locally preserved or bracketed within
337 multiple generations of mineralisations (Fig. 6j,k). Bands parallel to the slip surface and formed by
338 cataclasites alternating with highly fractured mineralisations are observed within veins and laminae
339 (Fig. SM3). The boundaries between cataclasites and mineralisation are often represented by slip
340 surfaces or extensional fractures (Figs. 5a,c; SM2c-f) and some mineralisations are flattened and
341 truncated along the slip surface (Fig. SM3f,g).

342

343 ***4.3. U-Th geochronology***

344 We dated calcites from nine mineralisations (Table 2). Dated samples are characterised by a
345 roughly homogeneous $^{230}\text{Th}/^{238}\text{U}$ activity ratio (between 0.87 and 0.93) and a highly variable
346 $^{230}\text{Th}/^{232}\text{Th}$ activity ratio (between 243.2 ± 2.5 and 18969 ± 315) (Table 2). Collectively, samples
347 dated by the MC-ICP-MS method (samples M4G, M4H, M4H2, M4HW, M4F1, M4i) show ages

348 between 190 and 270 ka, with 2σ errors < 7 ka. The sample dated by α -spectrometry (sample M4e)
349 shows a mean age of 178 ka and larger 1σ error of +39 and -30 ka.

350 In the following, we detail the obtained ages with respect to the structural site of the
351 selected sample at the studied outcrop (Figs. 5, 7 and SM1). The oldest age (267.9 ± 6.1 ka) has
352 been obtained from sample M4H, which is a carbonate mineralisation collected from the main slip
353 surface. Three progressively younger ages (257.4 ± 4.3 ka; 246.6 ± 2.5 ka; 230.3 ± 2.0 ka) have
354 been obtained from three generations of calcite of sample M4G (bottom-to-top: M4G3, M4G2,
355 M4G1, respectively), a dm-thick mineralisation collected along the main slip surface (Fig. 5a).
356 Sample M4e ($178 +39/-30$ ka) has been also collected from the same main slip surface of M4G. A
357 cluster of similar ages have been obtained from samples M4H2 (218.3 ± 3.7 ka), M4HW ($215.8 \pm$
358 6.7 ka), and M4F1 (214.9 ± 2.1 ka). Sample M4H2 is from the lower part of the M4H
359 mineralisation; sample M4F1 are from the upward portion of the M4G mineralisation; sample
360 M4HW is from the top of the sample M4e. Finally, the youngest age (189.4 ± 2.5 ka) has been
361 obtained from sample M4i, from a high angle normal fault crosscutting the main fault plane (Fig.
362 7).

363

364 **4.4. Stable carbon and oxygen and clumped isotopes**

365 The analysed samples (carbonate clast in cataclasite, fine-grained matrix in cataclasite,
366 sedimentary breccias embedded within the mineralisation, and carbonate mineralisations deposited
367 on fault surfaces) can be grouped in different endmembers showing distinct isotope signatures (Fig.
368 8). The clasts in cataclasites are characterised by $\delta^{13}\text{C}$ ranging from 1.40‰ and 2.38‰ and $\delta^{18}\text{O}$
369 between -0.43‰ and -1.32‰ typical of marine limestones. Three samples of the fine-grained
370 cataclasite matrix are characterised by $\delta^{13}\text{C}$ between 0.61‰ and 0.19‰ and $\delta^{18}\text{O}$ between -1.83‰
371 and -2.08‰ whereas one has much more negative $\delta^{18}\text{O}$ (-9.04‰) and $\delta^{13}\text{C}$ (-8.67‰). Two samples
372 of sedimentary breccias are characterised by negative $\delta^{18}\text{O}$ between -3.04‰ and -3.33‰ and $\delta^{13}\text{C}$
373 between -1.13‰ and -1.35‰. Finally, the samples of carbonate mineralisations are characterised by
374 negative values of both $\delta^{18}\text{O}$ (between -7.37‰ and -11.65‰) and $\delta^{13}\text{C}$ (between -7.14‰ and -
375 10.46‰).

376 Clumped-isotope data from 6 carbonate mineralisations yield $\Delta 47$ values in a narrow range
377 between 0.552‰ and 0.600‰ (I-CDES) (Table A2). These values correspond to temperatures
378 between 40 ± 7 °C and 23 ± 4 °C. Calcite from M4G mineralisations dated between ~ 257 and ~ 230
379 ka (samples M4G_1b; M4G_1e; M4G_2a; M4G_2b; M4G_3c) precipitated at ~ 24 - 28 °C (95%
380 confidence level between ± 3 and ± 9 °C). Calcite from younger M4F1 mineralisation (dated at

381 ~215) precipitated at 40 ± 11 °C (sample M4F1_2). Finally, a cataclasite (samples M4G_5N) and the
382 host rock clast (M4HW_1N) yielded temperatures of 41-45 °C (± 7 °C, 95% confidence level).

383 The calculated $\delta^{18}\text{O}$ of the fluids from the 6 mineralisation samples range from -9.3 to -3 ‰
384 (VSMOW) reflecting a dominant meteoric water signal. The calculated fluids for the cataclasite and
385 host rock clast reflect a combination of the original marine carbonate components and the
386 composition of the fluids during burial diagenesis, and are not relevant for the further discussion of
387 the vein fluids.

388

389

390 **5. Discussion**

391 **5.1. Structural interpretation**

392 Previous structural studies of the MMFS documented fault rock heterogeneities (inner fault
393 core, outer fault core, damage zones, principal slip surfaces) developed via multiple deformation
394 phases of the Meso-Cenozoic carbonate bedrocks (Ferraro et al., 2018; 2019). Intense shear strain
395 localisation occurred along fluid-assisted co-seismic ultracataclastic layers (Coppola et al., 2021).
396 By integrating the insights from these studies with our data, we refine our understanding of the
397 structural permeability along the MMFS (Fig. 9a), which is governed by a continuous interplay
398 between tectonic deformation, fluid circulation and mineralisation. Our meso-to-microscale
399 observation can guide to a scenario of polyphasic permeability evolution from deep to shallow
400 conditions (Fig. 9b).

401 The early structural permeability formed in conditions of confined pressure corresponding to
402 the depth from which the main slip surface exhumed (< 3 km; Ghisetti and Vezzani, 2000; Coppola
403 et al., 2021). The early structural permeability (t_n in Fig. 9b) is controlled by the spatial distribution
404 of structures associated with formation of the damage zone and the fault core at the expense of
405 carbonate bedrock (Fig. 3c,d; Ferraro et al., 2018). The transition from the damage zone to the fault
406 core is attested by a strong grain size reduction and the occurrence of foliated cataclasites, which
407 progressively replace the massive ones in the damage zone proximal to the fault core (Figs. 3e, 4f).
408 Cataclasis is the main deformation mechanism steering significant deformation in the damage zone
409 and the fault core (Fig. 3c-e). Rock comminution and clast roundness in cataclasites is assisted by
410 chipping at the edges of the sub-angular clasts, as well as intergranular fracturing contributes to
411 grain size reduction in larger clasts (Figs. 5, 6a,d, SM2f; Billi, 2010 and references therein).
412 Carbonate clasts are commonly truncated by subsidiary slip surfaces and the fine cataclasite matrix

413 is permeated by fluidised ultra-fine material (Fig. 6c,e). As already argued by Coppola et al. (2021),
414 we consider these microstructural features as evidence for coseismic rupturing, comparable to
415 potential seismic markers documented from faulted carbonates within tectonic domains (Hadizadeh,
416 1994; Smith et al., 2011; Fondriest et al., 2012; Tesei et al., 2013; Smeraglia et al., 2016; Delle
417 Piane et al., 2017).

418 The subsequent structural permeability (t_{n+nx} in Fig. 9b) formed at shallower crustal
419 conditions and was connected to the development of sharp, discrete slip surfaces cutting through the
420 cataclastic fabric in both the damage zone and the fault core. Ferraro et al. (2018) document matrix-
421 supported textures for these slip surfaces, developed in the latest stages of fault exhumation. The
422 main slip surface occurs within the fault core and corresponds to the striated one atop the proximal
423 slip zone (of co-seismic origin) of Coppola et al. (2021) (Fig. 9c). This suggests a mechanical
424 scenario of progressive fault narrowing through multiple episodes of fabric reworking and shear
425 strain localisation (Smith et al., 2011; Smeraglia et al., 2018; Vignaroli et al., 2020b). The
426 mineralisations are exclusively localised along the main slip surfaces and on the slip surface of the
427 high-angle fault (Fig. 9a), not associated with a system of veins in the damage zone. We propose
428 that the fault surfaces acted as localised, fault-parallel conduits (Caine et al., 1996) and the fluid
429 circulation channelised within the fault core during reactivation and dilatancy of the slip surfaces
430 (Fig. 9b). The combination between faulting and dilatancy during creation of the structural
431 permeability is attested by: (i) carbonate mineralisation within cataclasite in dilatant jog (Fig. 4d);
432 (ii) fan-shaped crystals growth in veins documenting a general syntaxial grow mechanism (Figs.
433 6f,k; SM3); (iii) reworked carbonate mineralisations often fractured and cut by slip surfaces (Figs.
434 SM2a-f; SM3a); (iv) carbonate mineralisations incorporated within the underlying cataclasites or
435 embedded as pockets in protocataclasite or breccias (Figs. 5; 6; SM2; SM3); (v) bands parallel to the
436 slip surfaces made of protolith cataclasite alternating with highly fractured mineralisations (Fig.
437 SM3); and (vi) sigmoidal foliation-like structure embedded in minor slip surfaces within the
438 mineralisations (Figs. SM2d; SM3l,m). The (re)activation of main slip surfaces occurred during the
439 progressive exhumation of the fault core-damage zone formed at deeper structural levels.
440 Considering the U-Th age range (between 268 and 189 ka) and the Holocene slip rate estimated for
441 the MMFS (0.4-1.1 mm/yr Roberts and Michetti, 2004; Gori et al., 2011), we obtain depths between
442 60 and 300 m below the present-day outcrop elevation (~450 m a.s.l.) for the development of the
443 shallow structural permeability. In this time-dependent conceptual evolution of the structural
444 permeability, the development of the high-angle normal faults crosscutting the main fault core
445 represents the last increment of strain during fault growth and exhumation.

446

447 **5.2. Fluid circulation**

448 The structural interpretation can be integrated with the isotope data (Fig. 8; Table A1) to
449 propose a comprehensive time-dependent scenario for fluid circulation during the progressive
450 exhumation of the MMFS and concomitant subsidence of the Sulmona Basin at its hanging wall
451 (e.g., Miccadei et al., 2002; Gori et al., 2011; Galli et al., 2015; Fig. 9d). The protolith carbonate
452 clasts embedded in cataclasites have the highest isotope values, in the range of unaltered Mesozoic
453 marine carbonates from the central Apennines (e.g., Ghisetti et al. 2001; Agosta and Kirschner
454 2003; Smeraglia et al., 2016). The cataclasite matrix, representing the early structural permeability,
455 shows more negative isotope values consistent with mixing of marine carbonate particles with
456 calcite precipitated from meteoric waters. As observed in Figure 8, the cataclasites plot on a mixing
457 line between the host rock and the mineralisation.

458 The mineralisations formed within the shallowest structural permeability show typical
459 carbon and oxygen isotope signatures of calcite precipitated from meteoric waters that gained a
460 significant contribution of respired organic carbon in the soils. The calculated $\delta^{18}\text{O}$ of the fluids
461 ranges between -3 and -9‰ (VSMOW) and is like the average composition of rainfall (-7 and -9‰)
462 and slightly enriched with respect to the spring water (-8 and -11‰) in the central Apennines
463 (Minissale, 2004). Fluid temperatures (Table A2) range between 23 and 26° C. These temperatures
464 are, except for a mineralisation dated at 215 ka (Fig. SM1d), warmer than those of spring waters
465 found in the Sulmona Basin (6-15 °C; Barberio et al., 2017) and, in general, for cold springs
466 emerging in central Apennines (e.g., Minissale, 2004). Also, the calculated $\delta^{18}\text{O}$ of the fluids are
467 enriched in ^{18}O with respect to the spring waters in the Sulmona Basin (-10 to -11‰; Barberio et
468 al., 2017). We, therefore, infer that syn-tectonic mineralisations occurring along the MMFS could
469 preserve a minimal component of deeper flow, probably from the deeper circulating waters with
470 longer residence time, mixed with the dominant shallow meteoric water circulation. It is noteworthy
471 that the hottest sample at 40° C (M4F1-2; Table A2) yields the least negative calculated $\delta^{18}\text{O}$ of the
472 fluids, suggesting a contribution of warmer fluid with a higher oxygen isotope composition
473 resulting from more intense water-rock interaction as observe by Smeraglia et al. (2018) in the Val
474 Roveto Fault (see location in Fig. 2a). These temperatures are comparable with the coldest fluid
475 temperatures (between 32 and 75 °C) estimated for syn-tectonic mineralisations in potentially-
476 seismogenic structures (Smeraglia et al., 2016; 2018) and for tectonically controlled veins in
477 thermogene travertines in central Apennines (e.g., Berardi et al., 2016).

478

479 **5.3. Implications for long-term fault history**

480 The results from this and other studies (e.g., Ferrero et al., 2018; Coppola et al., 2021; Fig.
481 9c) confirm active coseismic rupturing during growing of the MMFS, creating secondary
482 permeability through major fracturing and cataclastic flow, which produced viable structural
483 network for fluid ingress. The U-Th ages spanning the Middle Pleistocene (between 268 and 189
484 ka) represent the first geochronological documentation of the long-term deformation history of the
485 MMFS, constraining the timing of cycles of permeability creation and destruction in response to
486 continuous interplay between brittle deformation and fluid ingress.

487 Our seismic scenario for the MMFS (Fig. 9e) proposes episodes of coseismic failure at
488 depth with faulting and tensile fracturing at shallower crustal levels, where the carbonate
489 mineralisations formed. Coseismic failure at seismogenic depths led to rejuvenation of the fault
490 permeability through the activation/reactivation of slip surfaces at shallower depths, favouring
491 channelised mineralising flow (e.g., Caine et al., 1996; Cox et al., 2001; Rowland and Sibson, 2004;
492 Sibson, 2014). Between successive failure events (interseismic/postseismic stage), shallow fault
493 permeability decreased ever more by carbonate precipitation and progressive sealing of the fault-
494 related structures. We propose that the syn-tectonic mineralisations within the MMFS constitute a
495 record of fault (re)activation and tensile episodes in response to the cyclic stress accumulation that
496 can be used to constrain the age of fluid ingress in response to the seismic failure. U-Th data
497 document activation of faulting/tensile failure in the periods 267, 257, 246, 230, and 215 ka. This
498 suggests a time recurrence in the range of 10-15 ka (Fig. 9e).

499 Our integrated geological model can help to reconstruct the activity of seismogenic master
500 faults of central Apennines, currently primarily constrained by seismic catalogues (e.g., Rovida et
501 al., 2020) and paleoseismological datasets (e.g., Galli et al., 2008), to much longer temporal and
502 spatial scales. Very few studies provided geochronological constraints on neotectonics by dating
503 syn-tectonic mineralisation related to major faults (Fig. 10). Smeraglia et al. (2018) dated four fault-
504 related mineralisations along the Val Roveto Fault (see location in Fig. 2a), which the authors used
505 to constrain fluid migration and mixing during Late Pleistocene multiple displacement episodes and
506 seismic slip along the fault. Vignaroli et al. (2020a) dated fault-related mineralisations along the
507 Amatrice Fault System (see location in Fig. 2a), used to constrain surface rupture and
508 hydrodynamic interconnection with the vadose zone during Middle-Late Pleistocene faulting. While
509 a cyclical reactivation of the MMFS occurred within the Middle Pleistocene between 268 and 189
510 ka, both the Val Roveto Fault and the Amatrice Fault System activated before 290 ka, followed by
511 reactivation in the Late Pleistocene-Early Holocene (Fig. 10).

512 All together, these fault-related mineralisations typify the time of multiple rupture events
513 along major NW-SE-striking normal faults, their reactivation and the recurrence interval connected
514 with their seismic cycle. Such an integrated geological model for seismogenic faults could play a
515 key role in seismic hazard assessment in those areas characterised by the absence of historical
516 seismicity and/or evidence of $M_w < 6$ paleoearthquakes. Additional studies on similar syn-tectonic
517 mineralisations could make possible to identify cyclical variations in the fluctuation of fluid ingress
518 at greater frequency and, therefore, to provide a viable contribution to the definition of a recurrence
519 pattern on a regional scale.

520

521 ***5.4. The paleoclimate influence***

522 To understand possible feedback relationships between paleoclimate changes and fault-
523 controlled circulation of mineralising fluids, we compared our ages for the MMFS carbonate
524 mineralisations with U-Th ages obtained for some Quaternary travertines and calcite veins located
525 on the Tyrrhenian margin of the Apennines (Semproniano-Saturnia travertines: Berardi et al., 2016;
526 Vignaroli et al., 2016; Radicofani and Val di Chiana travertines: Brogi et al., 2010; 2012; 2017; Fig.
527 10). We considered major Quaternary paleoclimate indicators determined at both local and regional
528 scale (Fig. 10), the pollen data set from Valle di Castiglione (Tzedakis et al., 2001) located ~100
529 km to the west of the MMFS and the atmospheric CO₂ concentration (Past Interglacial Working
530 Group of PAGES, 2016). We also considered the climate anomalies generated by periodic
531 oscillations of Earth's orbital parameters over the Cenozoic (Zachos et al., 2001; Past Interglacials
532 Working Group of PAGES, 2016).

533 The available U-Th data cover the time spanning from MIS 10 to MIS 5 (MIS: Marine
534 Isotope Stage; Fig. 10). There is a consensus in considering warm and wet (interglacial) conditions
535 as the most favourable for thermogene travertine deposition during late Quaternary time (e.g.,
536 Sturchio et al., 1994; Rihs et al., 2002; Faccenna et al., 2008; Uysal et al., 2009; De Filippis et al.,
537 2013; Priewisch et al., 2014). In this view, the ages obtained for the Semproniano-Saturnia
538 travertines fall within warm and humid climate periods that have been considered as triggers for
539 tectonically controlled fluid discharge along faults (Berardi et al., 2016; Vignaroli et al., 2016). On
540 the other hand, a different pattern has been proposed for the travertines in Radicofani Basin, Val di
541 Chiana Basin and Tiber Valley (Brogi et al., 2010; 2012; 2017; Giustini et al., 2018), suggesting the
542 importance of tectonic activity, rather than climate, to control travertine precipitation during low
543 stand conditions of the water table in dry glacial periods (e.g., Uysal et al., 2009; Özkul et al.,
544 2013). Moreover, some studies documented a correlation between growth phases of surficial

545 carbonate mineralisation (travertines and veins) and times of cyclical variations of the Earth's
546 orbital characteristics, including the c. 25 ka precessional component that controls high insolation
547 (e.g., Wang et al., 2004; Kampman et al., 2012; De Filippis et al., 2013).

548 Discarding the sample M4e, due to its rather large error bars, we note that five of MMFS U-
549 Th ages fall within the interglacial period, at 180-245 ka (MIS7 in Fig. 10), while three fall within
550 the glacial period MIS8. Noteworthy, ages within the MIS7 and MIS8 show a preferential
551 correlation with the interstadial events (humid times suggested by the high values of the pollen data
552 set from Valle di Castiglione). This correlation matches with paleoclimate conditions supplying the
553 deposition of the Semproniano-Saturnia thermogene travertines (Berardi et al., 2016; Vignaroli et
554 al., 2016). In addition, over the periods 100-150 and 300-350 ka there is a good correlation between
555 the mean ages of mineralisations from the Val Roveto Fault (s61, s129, s132, s149 in Fig. 10), the
556 Amatrice Fault System (Fven1/2, Fin8 in Fig. 10), and travertines with the rhythmical negative
557 peaks of precession (i.e., conditions of high insolation). Overall, this might suggest that carbonate
558 precipitation in active faults and travertines is sensitive to climate variation, being preferentially
559 facilitated by warm and humid climate conditions characterised by high-stands of the water table. In
560 dryer times, scarce meteoric water supply might not allow the formation of carbonate
561 mineralisations in active tectonic structures. Therefore, the variations in climate-controlled water
562 availability could bias the recorded periodicity of fault activity, as cycles of permeability creation
563 and destruction under dry conditions would not lead to significant mineral precipitation.

564

565

566 **6. Conclusions**

567 The structural evolution of the MMFS supports the general scenario of focussed,
568 structurally-controlled fluid flow and mineralisation at shallow depths during fault reactivation. We
569 document multiple events of permeability creation and destruction recording the long-term
570 evolution of the MMFS:

- 571 (i) The development of the secondary permeability in the MMFS evolved in space in
572 time from diffuse deformation (at the fault footwall) towards localisation of a
573 narrower fault core and to final (re)activation of discrete slip surfaces in the
574 shallower crustal levels. The latter correspond to a combination of faulting and
575 tensile fracturing, in response to the stress accumulation during its seismic cycle.

- 576 (ii) The hydrodynamic regime permeating the secondary permeability mineralising fluid
577 was dominated by meteoric water circulation at the shallower conditions, where
578 discrete slip surfaces (re)activated.
- 579 (iii) The polyphasic and syn-tectonic mineralisations on the fault surfaces reflect the
580 interaction and feedback among seismically active tectonics and transient circulation
581 of mineralising fluids, likely influenced by paleoclimate oscillations.
- 582 (iv) U-Th dating of the carbonate mineralisations defined the time lapse encompassed in
583 the fault permeability creation/destruction cycles, providing a pilot study to
584 reconstruct the seismic recurrence model at a regional scale.

585

586

587 **Acknowledgments**

588 This research did not receive any specific grant from funding agencies in the public, commercial, or
589 not-for-profit sectors. B. Giaccio is thanked for introducing some of us (G.V and L.P.) to some
590 outcrops studied in this work. F. Balsamo and M. Pizzati are thanked for assistance and advice
591 during the cathodoluminescence analysis at the Department of Chemistry, Life Sciences, and
592 Environmental Sustainability, Università di Parma. We also thank A. Billi for stimulating
593 discussion at the field. The Grant to Department of Science, Roma Tre University (MIUR-Italy
594 Dipartimenti di Eccellenza, Art. 1, comma 314–337, Legge 232/2016) is gratefully acknowledged.
595 U-Th dating at HISPEC was supported by grants from the Science Vanguard Research Program of
596 the Ministry of Science and Technology (MOST) (110-2123-M-002-009), the National Taiwan
597 University (109L8926 to C.-C.S.), the Higher Education Sprout Project of the Ministry of
598 Education, Taiwan ROC (110L901001 and 110L8907). The paper benefited from the helpful and
599 constructive comments by S. Mitterpergher and an anonymous reviewer. The Editor (P. Agard) is
600 acknowledged for an efficient editorial management.

601

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937 **Captions to Figures**

938 **Figure 1.** Structural scenario of the fault-valve mechanism framed within the seismic cycle. The creation of
939 fault permeability is here correlated to the tectonics, mineralisation, and fluid pressure cycling. EQ:
940 earthquake.

941 **Figure 2.** a) Schematic tectonic framework of the Apennines within the western Mediterranean region; b)
942 geological setting of the central Apennines, where the distribution of both the main thrust fronts and the
943 active normal faults is reported (modified and readapted after Cosentino et al., 2010). The map also shows
944 the localisation of both the main recent earthquakes (including their focal mechanisms) and the historical
945 earthquakes in the area surrounding the Monte Morrone. The seismic data are after Amato et al. (1998),
946 Chiarabba et al. (2009), Chiaraluce et al. (2017), and the Parametric Catalogue of Italian Earthquakes
947 (CPTI15 available at https://emidius.mi.ingv.it/CPTI15-DBMI15/index_en.htm). The location of two dated
948 faults (Val Roveto Fault: Smeraglia et al., 2018; Amatrice Fault System: Vignaroli et al., 2020a) and dated
949 Quaternary travertines (Semproniano-Saturnia travertines: Berardi et al., 2016; Vignaroli et al., 2016;
950 Radicofani and Val di Chiana travertines; Brogi et al., 2010; 2012; 2017) is also shown; c) geological setting
951 of the Monte Morrone area showing the orientation and distribution of the western (WFS) and eastern (EFS)
952 strands of the Monte Morrone Fault System (modified after Pizzi et al., 2015); d) schematic cross section
953 illustrating the main stratigraphic/structural setting of the Monte Morrone-Sulmona Basin system (modified
954 after Miccadei et al., 2002). The Monte Morrone Fault System cuts through the Meso-Cenozoic carbonate
955 bedrock and accommodates more than 400 m-thick Quaternary continental deposits filling the Sulmona
956 Basin; e) Google Earth © view of the study area around the Roccacasale village, showing the localisation of
957 structural sites along the western strand of the Monte Morrone Fault System. AFS: Amatrice fault System;
958 SeSa: Semproniano-Saturnia travertines; VRF: Val Roveto Fault.

959 **Figure 3.** Structural features of the western strand of the Monte Morrone Fault System observed at the
960 studied outcrops. a) Panoramic view of the main fault surface exposed southeast to the Roccacasale village
961 (structural stop M3.1 in Fig. 2e). In the insert: stereographic projection (Schmidt net, lower hemisphere) of
962 the measured main slip surfaces; b) dip-slip slickenlines (rock abrasion) exposed on the fault surface; c)
963 metre-thick damage zone, produced at the expense of Meso-Cenozoic carbonate bedrock, occurring at the
964 footwall of the main slip surface (structural stop M3.2 in Fig. 2e; compare with Fig. 4b of Ferraro et al.,
965 2018); d) outcrop view of the fault damage zone exposed northwest to the Roccacasale village (structural
966 stop M4.1 in Fig. 2e) where the carbonate mineralisations were collected; e) the damage zone is
967 characterised by lenses of foliated or massive cataclasites produced at the expense of the Mesozoic
968 limestone.

969 **Figure 4.** Mesoscopic properties of the WFS at the structural stop M4.1 (see Fig. 2e and Table 1 for
970 location). a) Damage zone around the main slip surface that is, in turn, cross cut by a set of high-angle
971 normal faults; b) detail of the crosscutting relationships between the main slip surface and the high-angle
972 normal faults, the latter producing decimetre-to-half metre offset; c) high-angle normal fault crosscutting the
973 main slip surface, the latter decorated by cm-thick carbonate mineralisation; d) detail of two separated cm-
974 thick carbonate mineralisation occurring atop the main slip surface; e) detail of the main slip surface
975 intervening between a massive cataclasite (at the footwall) and a dm-to-cm-thick mineralisation (at the
976 hanging wall); f) enlargement of the previous image (the broken mineralisation is here exposed) showing the
977 internal fabric of the carbonate mineralisation; g) and h) structural and petrographical details of high-angle
978 faults, where thin (a few mm) patina of carbonate mineralisation occurs on the slickensided surface. Samples
979 used for microstructural investigation and geochemical/geochronological purposes are indicated by red
980 labels.

981 **Figure 5.** Example of rock slab (sample M4G; Table 1) used for defining the main observed structural
982 fabrics. (a) Polished rock slab of sample M4G with the indication of micro-drilling sites for geochemical and
983 geochronological purposes. U-Th ages and temperatures deriving from clumped isotopes analysis are also
984 indicated; (b) scanned thin section of sample M4G showing, from bottom to top, the cataclasite, the main slip
985 surface, the sedimentary breccias (probably filling voids of karst origin) and three main mineralisations

986 characterised by a layering of thin laminae and sparitic veins; (c) line drawing of the main features observed
987 in the scanned thin section of sample M4G; (d) and (e) BSE images (see Fig. 5b for location) showing the
988 main slip surface, sub-rounded small clasts in the ultracataclasite, sub-angular clasts and clasts with
989 polygonal fractures; (f) enlargement of Fig 5e.

990 **Figure 6.** Microscale properties of the collected samples. a) Petrographic image (crossed polarised light) of
991 massive cataclasite consisting of a fine- to very fine-grained matrix embedding a few large clasts (up to 1.5
992 mm in width); (b) back-scattered electron (BSE) image showing the occurrence of polygonal fractures within
993 the cataclasite; (c) BSE image showing the occurrence of a slip surface that sharply truncate the carbonate
994 clasts; (d) petrographic image (plane polarised light) and (e) cathodoluminescence image showing traces of
995 permeating fluid (bright colour in cathodoluminescence) within the fine-grained cataclasite matrix; (f)
996 petrographic image (plane polarised light) and (g) cathodoluminescence image showing layered (and partly
997 folded) carbonate mineralisation atop a very fine-grained cataclasite. Note the general upward-convex fan-
998 shaped crystals grown during incremental layering. Cathodoluminescence imaging reveals that calcite
999 making the mineralisation is characterised by a dark violet colour, darker than the colour of the adjacent
1000 cataclasite; (h) petrographic image (plane polarised light) and (i) BSE image showing fractured mineralisation
1001 embedded within the fine-grained cataclasite; (j) petrographic image (crossed polarised light) showing
1002 polyphasic growth of mineralisation embedding lenses of protocataclasite. Note the different style of
1003 growing (including bedding-parallel layers, undulate layers, elongated crystals); (k) upward-convex fan-
1004 shaped crystals grown and downward-convex fan-shaped crystals grown in mineralisations separated by a
1005 thin layer of cataclasite.

1006 **Figure 7.** Line drawing of the studied outcrop (Fig. 3d) with indication of the selected mineralisation
1007 samples for U-Th ages. The insets indicate the mineralisation slabs, as well as the selected portion for U-Th
1008 analysis and the obtained results.

1009 **Figure 8.** Combined plot of $\delta^{13}\text{C}$ (‰V-PDB) and $\delta^{18}\text{O}$ (‰V-PDB) isotope values derived from the collected
1010 samples. V-PDB: Vienna Pee Dee Belemnite standard.

1011 **Figure 9.** a) simplified structural architecture of the MMFS as deduced from observation at the studied
1012 outcrops; b) schematic scenario of fault permeability development during the progressive exhumation of the
1013 of the fault core-damage zone formed at depth (at t_n) and reactivation of slip surfaces at shallower crustal
1014 conditions (at t_{n+nx}); (c) structural relationships between the analysed carbonate mineralisations and the fault
1015 domains as documented by previous work on the same fault strands (Ferraro et al., 2018; Coppola et al.,
1016 2021); (d) two-stage structural evolution for the MMFS according to fault cross-cutting relationships, pattern
1017 of fluid circulation during faulting as deduced from the isotopic analysis, and absolute ages provided by U-
1018 Th dating on carbonate mineralisations; (e) proposed scenario of cyclical fault-fluid interactions in the MMFS
1019 within a recurrence time of 10-15 ka between coseismic events as deduced from this study. fc: fault core; dz:
1020 damage zone. EFS and WFS are the eastern and western strands of the Monte Morrone Fault System,
1021 respectively.

1022 **Figure 10.** Comparison between U-Th ages of fault-related mineralisations from the MMFS (this study), the
1023 Amatrice fault System (AFS; Vignaroli et al., 2020a), the Val Roveto Fault (Smeraglia et al., 2018) and
1024 CaCO_3 samples (bedded and banded travertines, calcite-filled veins) from the northern part of the central
1025 Apennines (Sem-Sat: Semproniano-Saturnia travertines: Berardi et al., 2016; Vignaroli et al., 2016; Ra-VdC:
1026 travertines from the Radicofani and Val di Chiana basins: Brogi et al., 2010; 2012; 2017; see location in Fig.
1027 2b). Major paleoclimate indicators are represented by the deep-sea oxygen isotope trend (Zachos et al.,
1028 2001), the pollen data set from Valle di Castiglione (Tzedakis et al., 2001), and the atmospheric CO_2
1029 degassing (Past Interglacial Working Group of PAGES, 2016). Glacial-interglacial periods are redrawn and
1030 modified after Priewisch et al. (2014). Valle di Castiglione is located in central Italy (see location in Fig. 2b)
1031 only ~100 km west to the MMFS. MIS: Marine Isotope Stages. AP: arboreal pollen; NAP: non-arboreal
1032 pollen. Eccentricity/precession are redrawn and modified after Past Interglacial Working Group of PAGES
1033 (2016).

1034 **Table 1.** Summary of observed structures and collected samples during the structural survey along the
1035 western strand of the Monte Morrone Fault System (see Fig. 2e).

1036 **Table 2.** U-Th ages of the carbonate mineralisations from the Monte Morrone Fault System collected at the
1037 studied outcrop near Roccasale village (site M4.1; long.: 13.883°; lat.: 42.125°). Sample indicated with *
1038 was analysed through MC-ICP-MS at the HISPEC of the National Taiwan University (errors quoted as 2σ),
1039 whereas sample indicated with ** was analysed through α spectrometry done at the at the Laboratory of
1040 Environmental and Isotopic Geochemistry (Department of Sciences, Roma Tre University, Italy) (errors
1041 quoted as 1σ).

1042 **Table A1.** Stable oxygen and carbon isotope composition of the selected samples from the Monte Morrone
1043 Fault System collected at the studied outcrop near Roccasale village (long.: 13.883°; lat.: 42.125°). Isotope
1044 compositions are expressed in ‰ against Vienna Pee Dee Belemnite standard (VPDB).

1045 **Table A2.** Clumped isotopes analyses on the selected samples from the Monte Morrone Fault System.

1046 **Figure SM1.** Polished rock slabs of the analysed samples (sample M4G is reported in Fig. 5; Tables 1 and 2)
1047 with the indication of micro-drilling sites for geochemical (stable isotopes in black and clumped isotopes in
1048 red) and geochronological analysis (red-white circles). U-Th ages and temperatures deriving from clumped
1049 isotopes analysis are also indicated.

1050 **Figure SM2.** Polished slab, high-resolution scanned thin section, detailed petrographic and back-scattered
1051 electron (BSE) images showing the main observed structural fabrics of sample M4HW. a) Oriented polished
1052 rock slab showing the contact between the slip surface (here developed at the top of the carbonate
1053 mineralisation) and the hanging wall of the massive cataclasite; b) high-resolution scanned thin section of
1054 sample M4HW showing the carbonate mineralisations (at the bottom) and cataclasite (at the top); c)
1055 petrographic image (crossed polarised light) showing brecciated mineralisations partially embedded within
1056 the fine-grained cataclasite. Secondary cement made by calcite crystals occurs within the reworked carbonate
1057 mineralisations; d) petrographic image (plane polarized light) showing sigmoidal foliation within the
1058 carbonate mineralisations embedded in two minor slip surfaces; e) petrographic image (plane polarised light)
1059 showing fractured and brecciated carbonate mineralisations with several minor slip surfaces and embedding
1060 pockets of protocataclasites; f) BSE image showing the main slip surface at the top of the carbonate
1061 mineralisations and the fractured mineralisations partially embedded in the cataclasite. Note the two
1062 extensional fractures developed along the main slip surface; g) BSE image showing structures high angle to
1063 vertical slip surface, generally with undulating boundaries and characterised by tight cataclasite and calcite
1064 vein.

1065 **Figure SM3.** Petrographic images showing the microscale properties of M4H2 sample at different scale of
1066 observation. (a) Petrographic photomosaic (plane polarised light) of the lower part of M4H2 thin section
1067 showing (at the bottom) multiple generation of mineralisations (formed both by laminae and veins) and
1068 breccia (at the top). The upper edge of the mineralisation is characterized by a thin layer of ultracataclasite.
1069 At least one slip surface is observed within the mineralisation. (b) Petrographic image (plane polarised light)
1070 showing within the breccia clasts of former mineralisations mixed with other carbonate fragments deriving
1071 from previous cataclasite and calcite cement. (c-d) Petrographic images (plane and crossed polarised light,
1072 respectively) showing a series of bands of cataclasite and ultracataclasite within the mineralisation. (e)
1073 Petrographic image (plane polarised light) showing the upper edge of the mineralisation covered by a thin
1074 layer of ultracataclasite. (f-g) Petrographic images (plane and crossed polarised light, respectively) showing a
1075 series of bands parallel to the slip surface and formed by cataclasites alternating with highly fractured
1076 mineralisations. The upper portion of the mineralisation is flattened and truncated along the slip surface and
1077 some fragments of the mineralisation are partially embedded within the thin layer of ultracataclasite. (h-i)
1078 Petrographic images (plane and crossed polarised light, respectively) showing in detail a series of bands
1079 parallel to the slip surface and formed by cataclasites alternating with highly fractured mineralisations.
1080 Interposed between two bands of cataclasite, a thin level of mineralisation is highly fractured, and some
1081 carbonate clasts are partially dispersed in the cataclasite. (l-m) Petrographic images (plane and crossed

1082 polarised light, respectively) showing a highly fractured portion of the mineralisation with a shape miming a
1083 sigmoidal foliation. (n-o) Petrographic images (plane and crossed polarised light, respectively) showing in
1084 detail the upper portion of the mineralisation. A thin layer of ultracataclasite, with some synthetic shear zone,
1085 covers the edge of the mineralisation.

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TABLE 1. Summary of observed structures and collected samples during the structural survey along the western strand of the Monte Morrone Fault System (see Fig. 2e).

Structural stop	Lat.	Long.	Structural fabric	Sample for geochronology (Table 2)	Sample for isotope data (Table A1)
M1	42.124°	13.888°	<ul style="list-style-type: none"> • Damage zone (synthetic faults and extensional or hybrid fractures) 		
M3.1	42.121°	13.893°	<ul style="list-style-type: none"> • Fault core (main slip surface and cataclasite) • High-angle normal faults cutting the main slip surface 		
M3.2	42.121°	13.894°	<ul style="list-style-type: none"> • Fault core (main slip surface and cataclasite) 		
M4.1	42.125°	13.883°	<ul style="list-style-type: none"> • Fault core (main slip surface, cataclasite, fault breccias and veins made by calcite precipitation) • Damage zone (synthetic faults and extensional or hybrid fractures) • High-angle normal faults cutting the main slip surface 	M4G/1, M4G/2, M4G/3, M4H, M4H2, M4HW, M4F1, M4i, M4e	M4G/1, M4G/2, M4G/3, M4H, M4H2, M4HW, M4F1, M4i, M4e
M4.2	42.127°	13.882°	<ul style="list-style-type: none"> • Fault core (main slip surface and cataclasite) • High-angle normal faults cutting the main slip surface 		
M4.3	42.128°	13.881°	<ul style="list-style-type: none"> • Fault core (main slip surface and cataclasite) • High-angle normal faults cutting the main slip surface 		
M4.4	42.129°	13.879°	<ul style="list-style-type: none"> • Damage zone (synthetic faults and extensional or hybrid fractures) 		

Table 2. U-Th ages of the carbonate mineralisations from the Monte Morrone Fault System collected at the studied outcrop near Roccasale village (site M4.1; lat.: 42.125° N; long.: 13.883° E). Sample indicated with * was analysed through MC-ICP-MS at the HISPEC of the National Taiwan University (errors quoted as 2σ), whereas sample indicated with ** was analysed through α spectrometry done at the at the Laboratory of Environmental and Isotopic Geochemistry (Department of Sciences, Roma Tre University, Italy) (errors quoted as 1σ).

Sample ID	Weight g	^{238}U Ppb (a)	^{232}Th ppb	$\delta^{234}\text{U}$ measured (a)	$[\text{}^{230}\text{Th}/\text{}^{238}\text{U}]$ activity (c)	$^{230}\text{Th}/\text{}^{232}\text{Th}$ atomic ($\times 10^{-6}$)	Age (ka ago) uncorrected	Age (ka ago) corrected (c,d)	$\delta^{234}\text{U}_{\text{initial}}$ corrected (b)
M4G/1*	0.2311	154.95 \pm 0.16	0.1216 \pm 0.0020	21.6 \pm 1.4	0.9030 \pm 0.0018	18969 \pm 315	230.3 \pm 2.0	230.3 \pm 2.0	41.5 \pm 2.6
M4G/2*	0.21021	244.15 \pm 0.28	0.4809 \pm 0.0023	6.0 \pm 1.4	0.9027 \pm 0.0018	7556 \pm 38	246.6 \pm 2.5	246.6 \pm 2.5	12.1 \pm 2.8
M4G/3*	0.19458	198.01 \pm 0.27	2.5449 \pm 0.0055	7.7 \pm 1.6	0.9149 \pm 0.0033	1173.6 \pm 4.6	257.8 \pm 4.3	257.4 \pm 4.3	15.8 \pm 3.3
M4H*	0.20549	419.68 \pm 0.51	10.833 \pm 0.033	9.8 \pm 1.5	0.9264 \pm 0.0046	591.7 \pm 3.4	268.6 \pm 6.2	267.9 \pm 6.1	20.9 \pm 3.2
M4H2*	0.22826	429.58 \pm 0.55	11.059 \pm 0.036	17.6 \pm 1.8	0.8848 \pm 0.0043	566.7 \pm 3.3	219.0 \pm 3.7	218.3 \pm 3.7	32.6 \pm 3.3
M4HW*	0.21036	255.88 \pm 0.38	15.445 \pm 0.067	24.5 \pm 1.8	0.8902 \pm 0.0086	243.2 \pm 2.5	217.3 \pm 6.7	215.8 \pm 6.7	45.1 \pm 3.3
M4F1*	0.20277	323.87 \pm 0.38	0.2808 \pm 0.0023	8.9 \pm 1.7	0.8703 \pm 0.0020	16552 \pm 141	214.9 \pm 2.1	214.9 \pm 2.1	16.4 \pm 3.2
M4i*	0.2008	138.40 \pm 0.15	2.0115 \pm 0.0033	23.6 \pm 1.3	0.8483 \pm 0.0039	962.4 \pm 4.6	189.7 \pm 2.5	189.4 \pm 2.5	40.3 \pm 2.3

Sample ID	U (ppm)	$^{230}\text{Th}/\text{}^{232}\text{Th}$	$^{234}\text{U}/\text{}^{238}\text{U}$	$^{230}\text{Th}/\text{}^{234}\text{U}$	$(\text{}^{234}\text{U}/\text{}^{238}\text{U})$ initial	Age (ka)
M4e**	0.137 \pm 0.005	83.105 \pm 10.401	1.030 \pm 0.037	0.809 \pm 0.036	1.050 \pm 0.061	178 +39/-30

(a) $[\text{}^{238}\text{U}] = [\text{}^{235}\text{U}] \times 137.818$ ($\pm 0.65\%$) (Hiess et al., 2012); $\delta^{234}\text{U} = ([\text{}^{234}\text{U}/\text{}^{238}\text{U}]_{\text{activity}} - 1) \times 1000$.

(b) $\delta^{234}\text{U}_{\text{initial}}$ corrected was calculated based on ^{230}Th age (T), i.e., $\delta^{234}\text{U}_{\text{initial}} = \delta^{234}\text{U}_{\text{measured}} \times e^{\lambda^{234}T}$, and T is corrected age.

(c) $[\text{}^{230}\text{Th}/\text{}^{238}\text{U}]_{\text{activity}} = 1 - e^{-\lambda^{230}T} + (\delta^{234}\text{U}_{\text{measured}}/1000)[\lambda^{230}/(\lambda^{230} - \lambda^{234})](1 - e^{-(\lambda^{230} - \lambda^{234})T})$, where T is the age. Decay constants are $9.1705 \times 10^{-6} \text{ yr}^{-1}$ for ^{230}Th , $2.8221 \times 10^{-6} \text{ yr}^{-1}$ for ^{234}U (Cheng et al., 2013), and $1.55125 \times 10^{-10} \text{ yr}^{-1}$ for ^{238}U (Jaffey et al., 1971).

(d) Age corrections, relative to chemistry date on March 19th, 2019, were calculated using an estimated atomic $^{230}\text{Th}/\text{}^{232}\text{Th}$ ratio of $4 (\pm 2) \times 10^{-6}$.

Those are the values for a material at secular equilibrium, with the crustal $^{232}\text{Th}/\text{}^{238}\text{U}$ value of 3.8. The errors are arbitrarily assumed to be 50%.

Figure 1

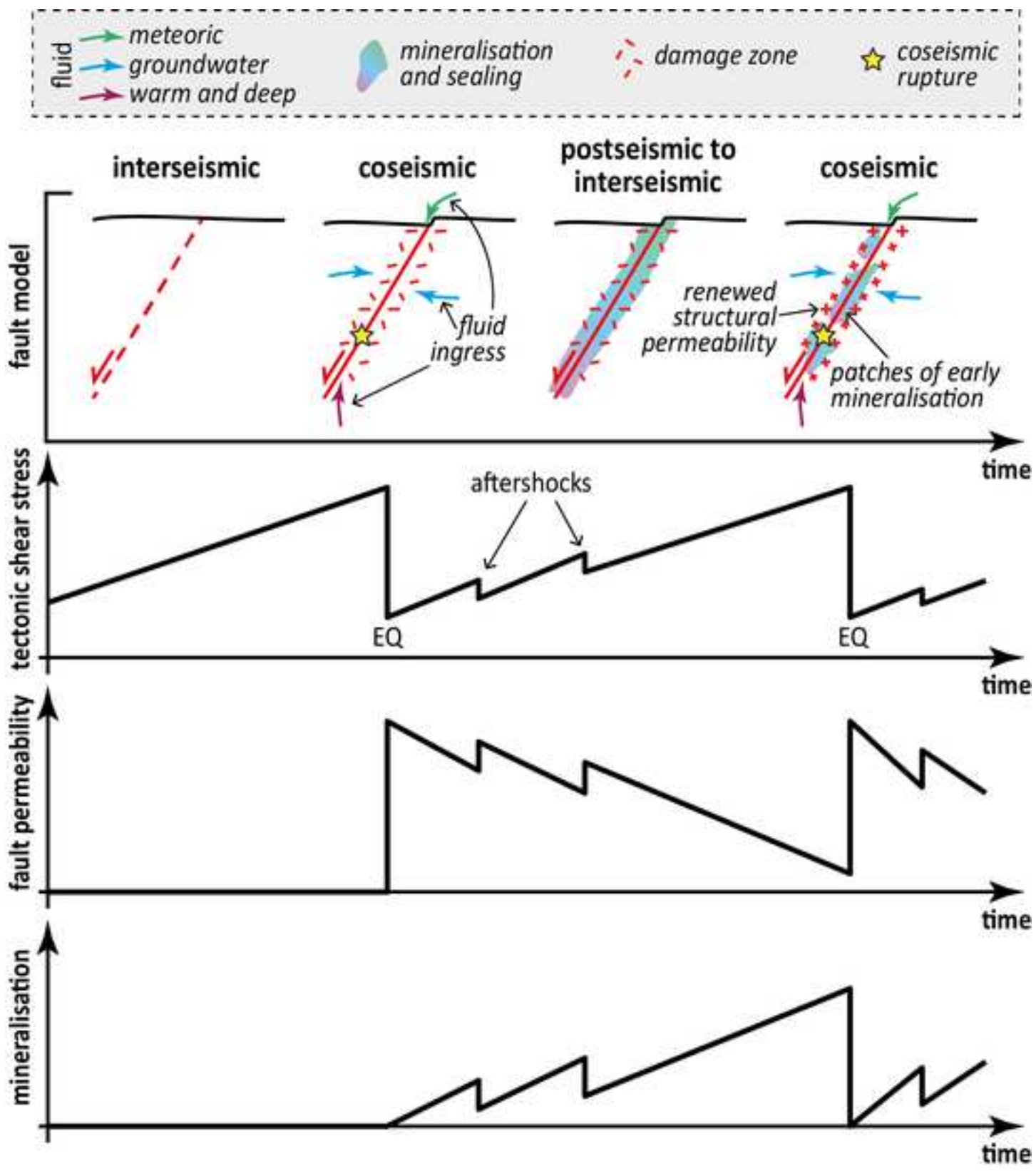


Figure 2

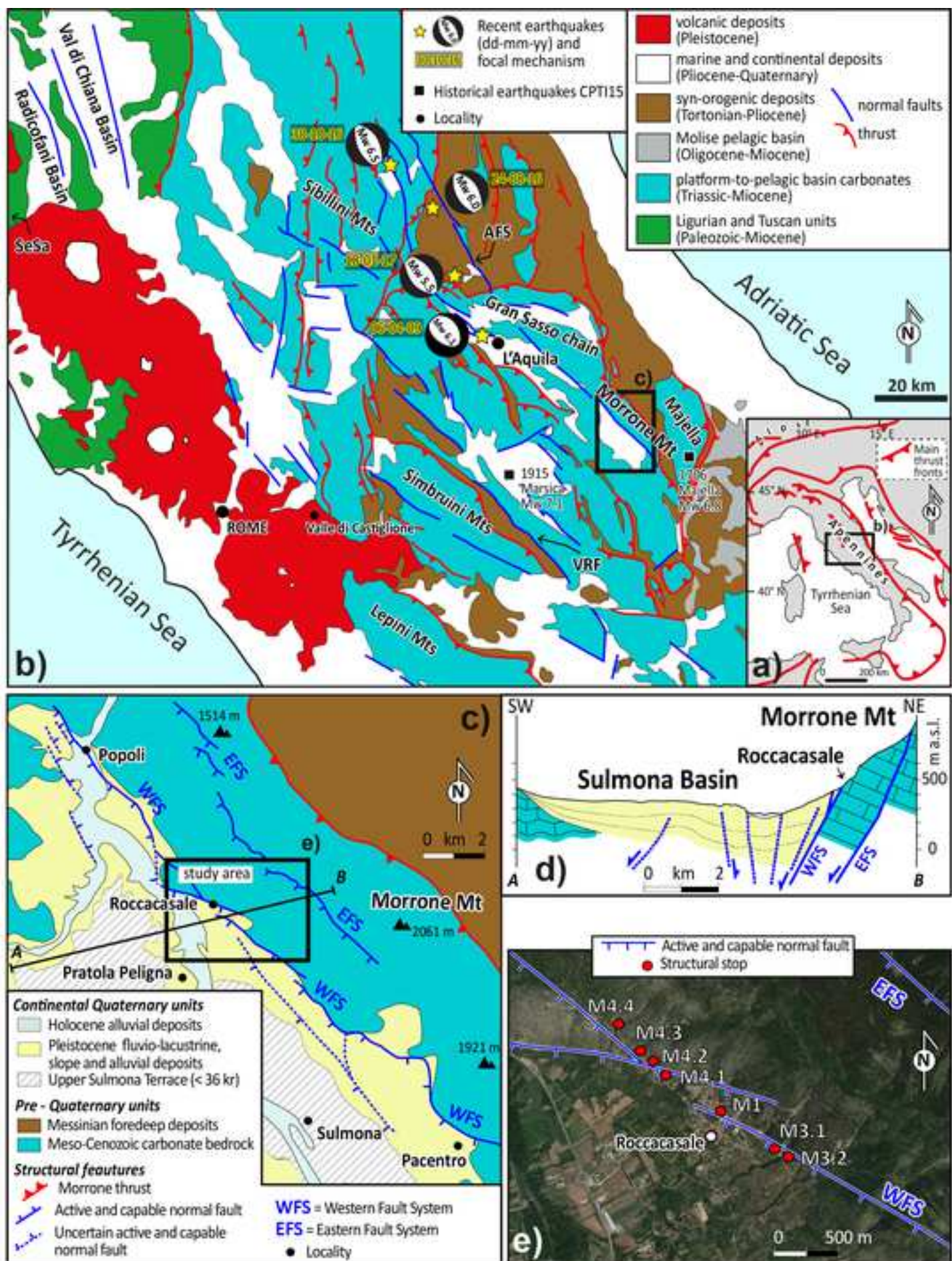


Figure 3

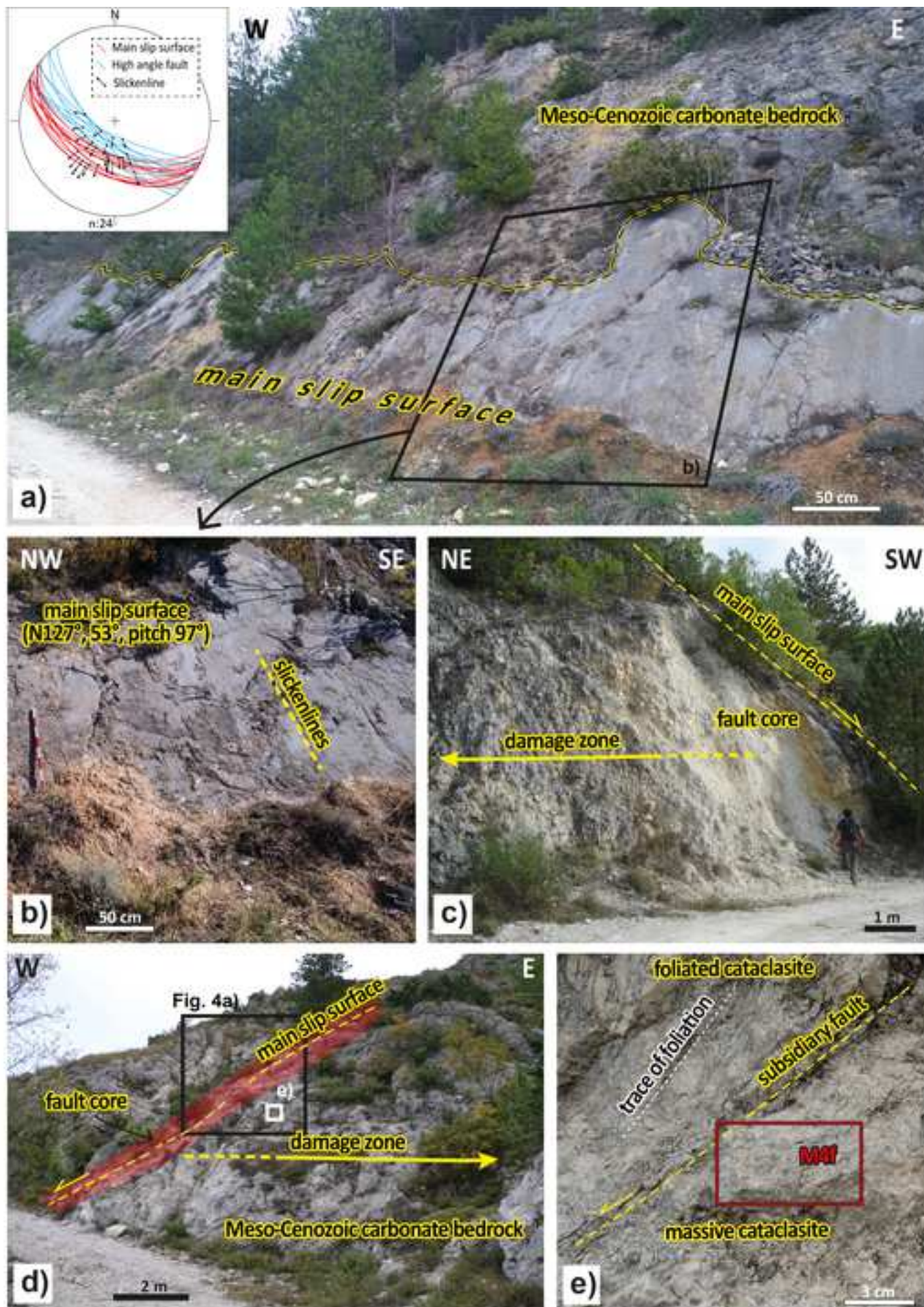


Figure 4

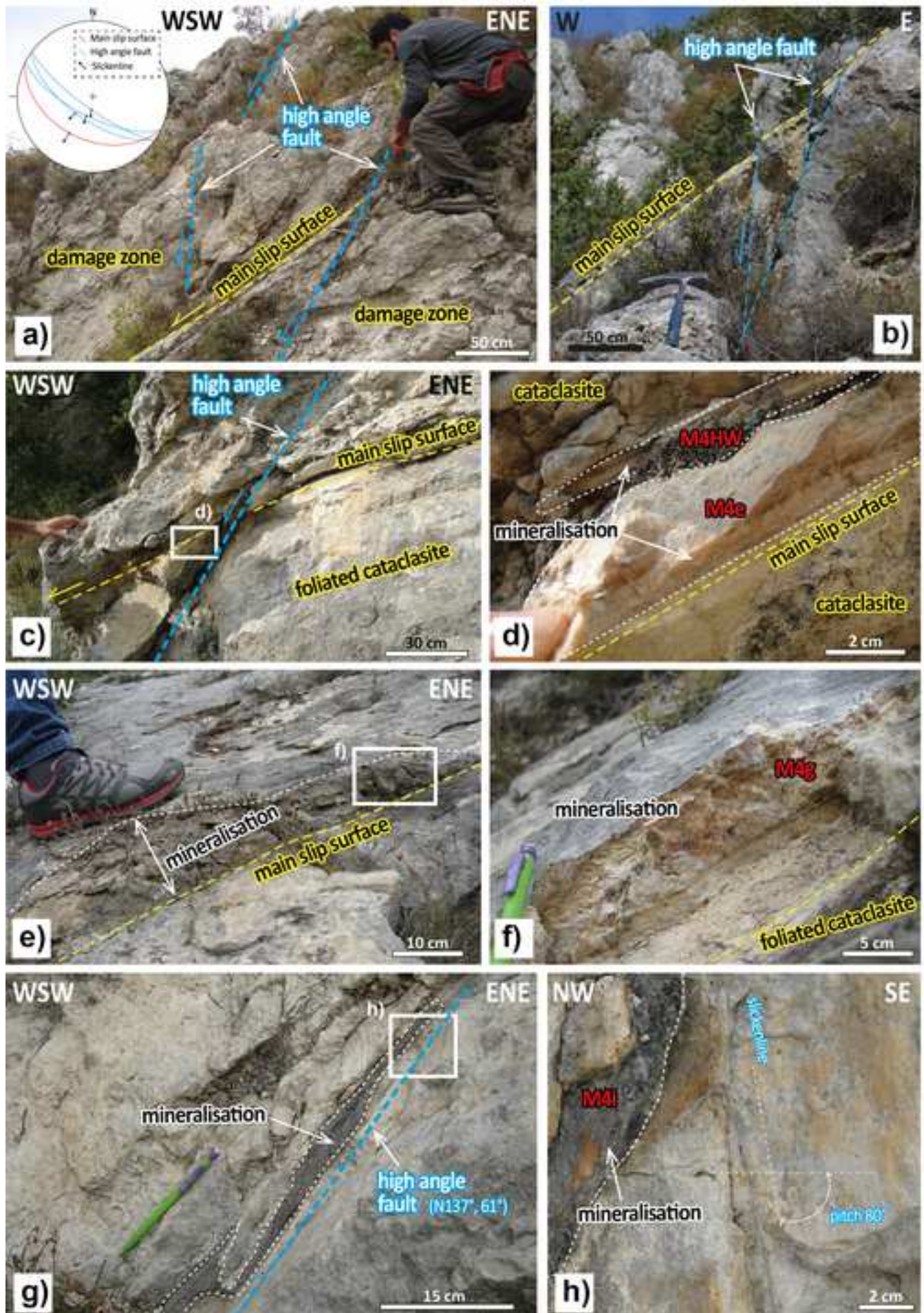


Figure 5

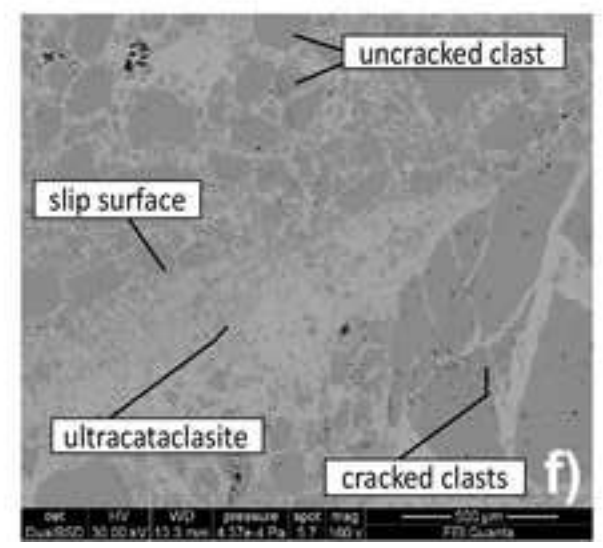
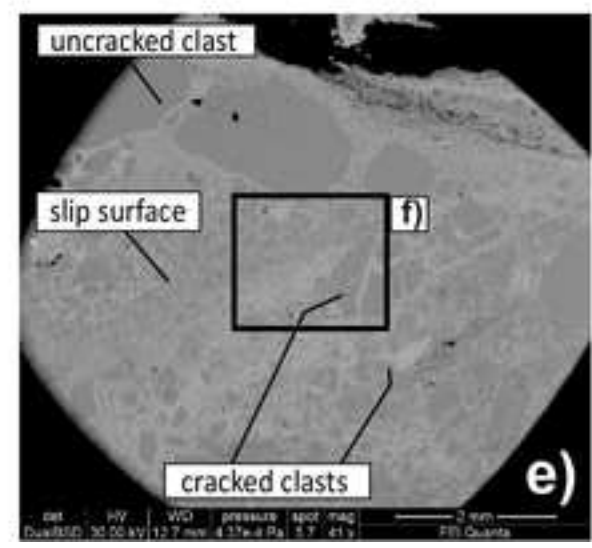
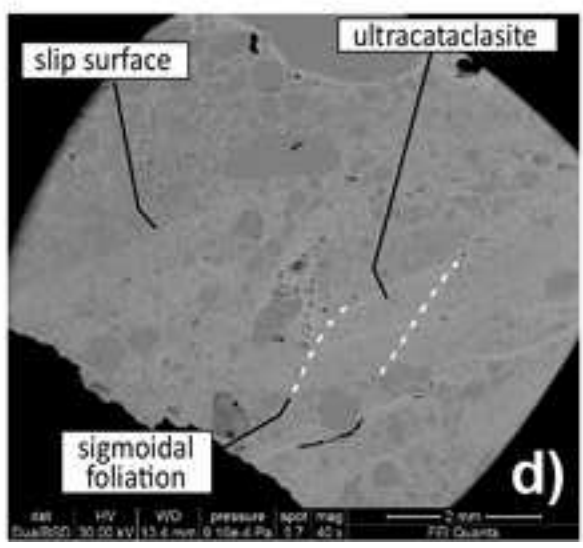
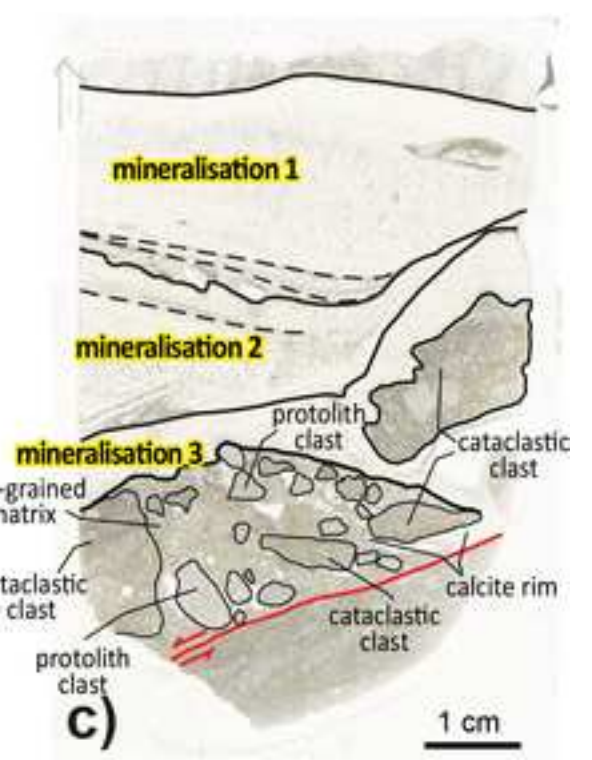
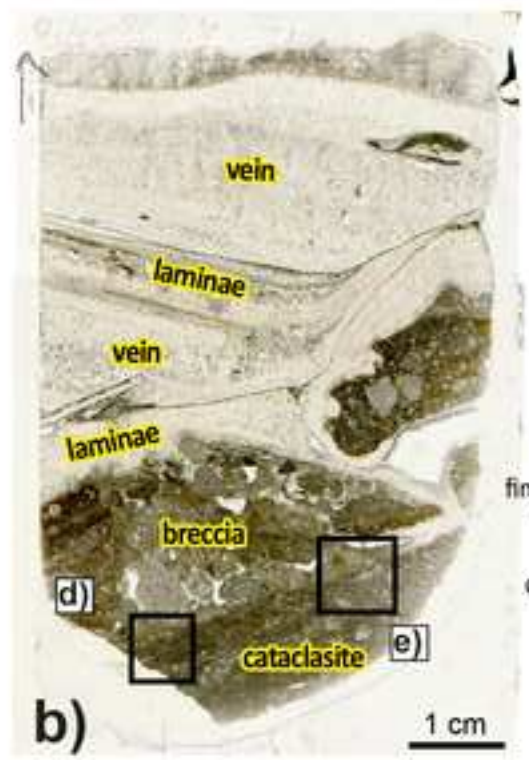
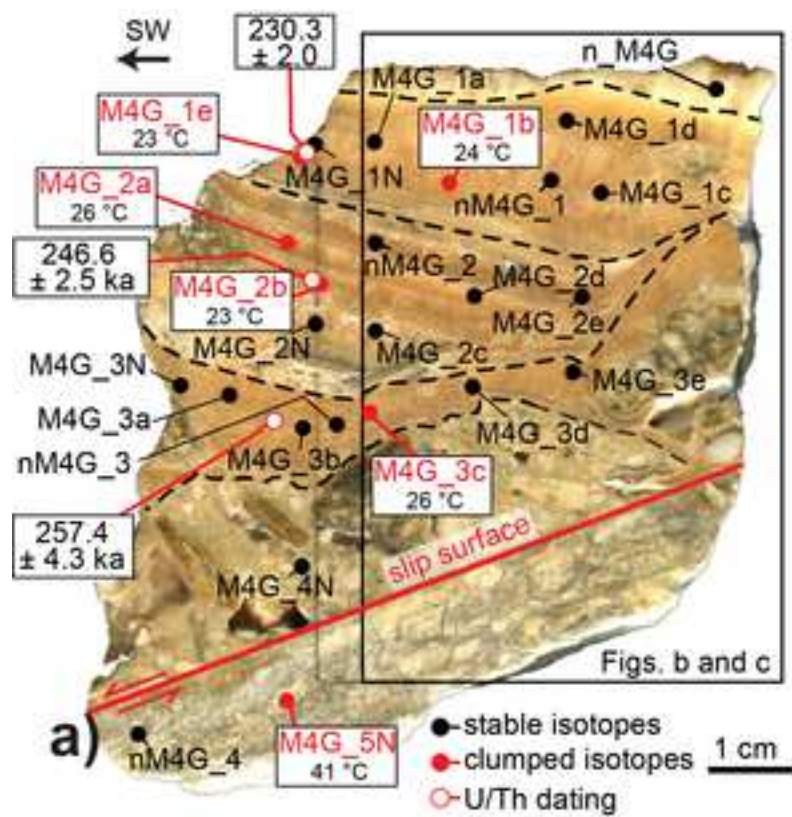


Figure 6

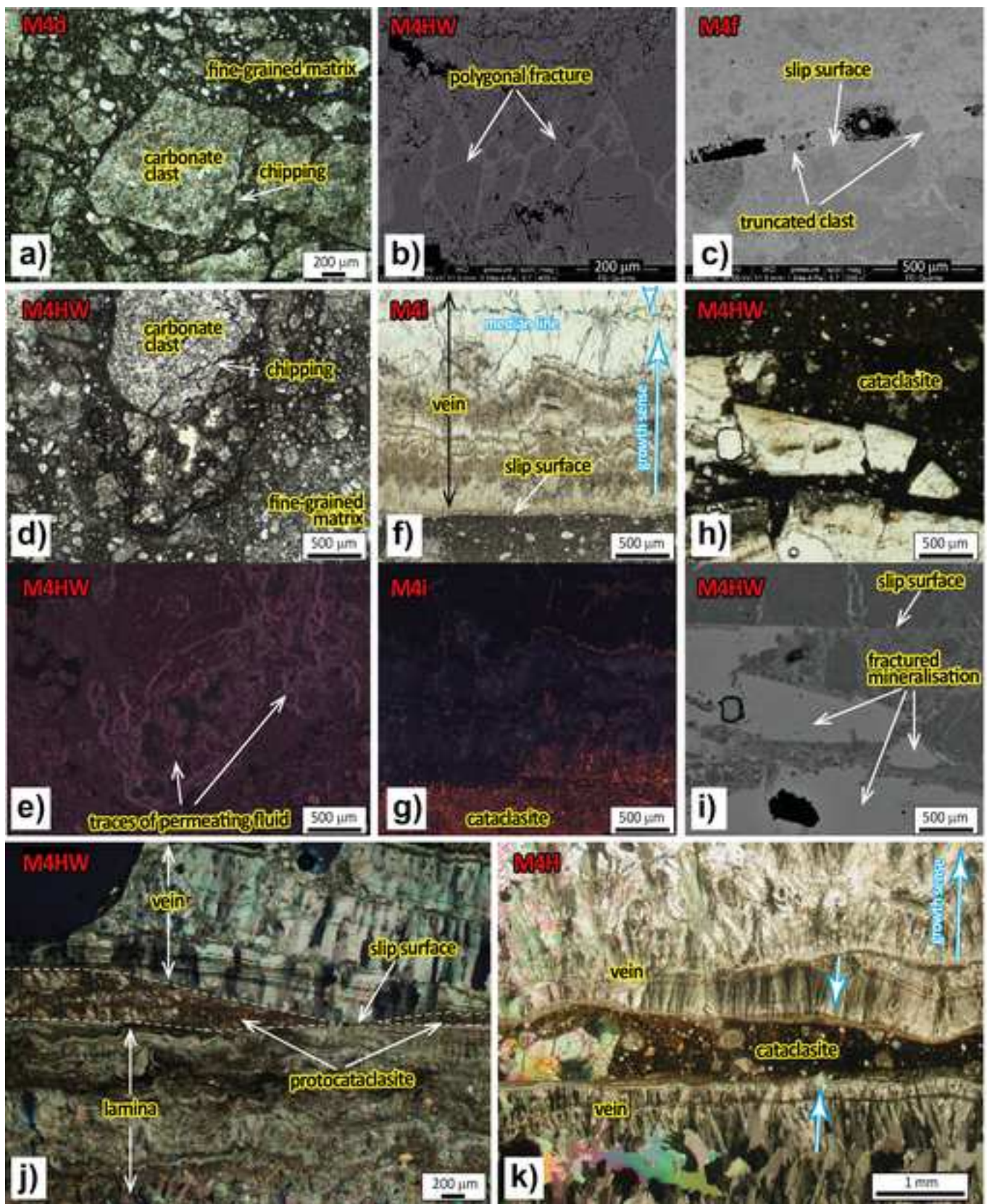


Figure 7

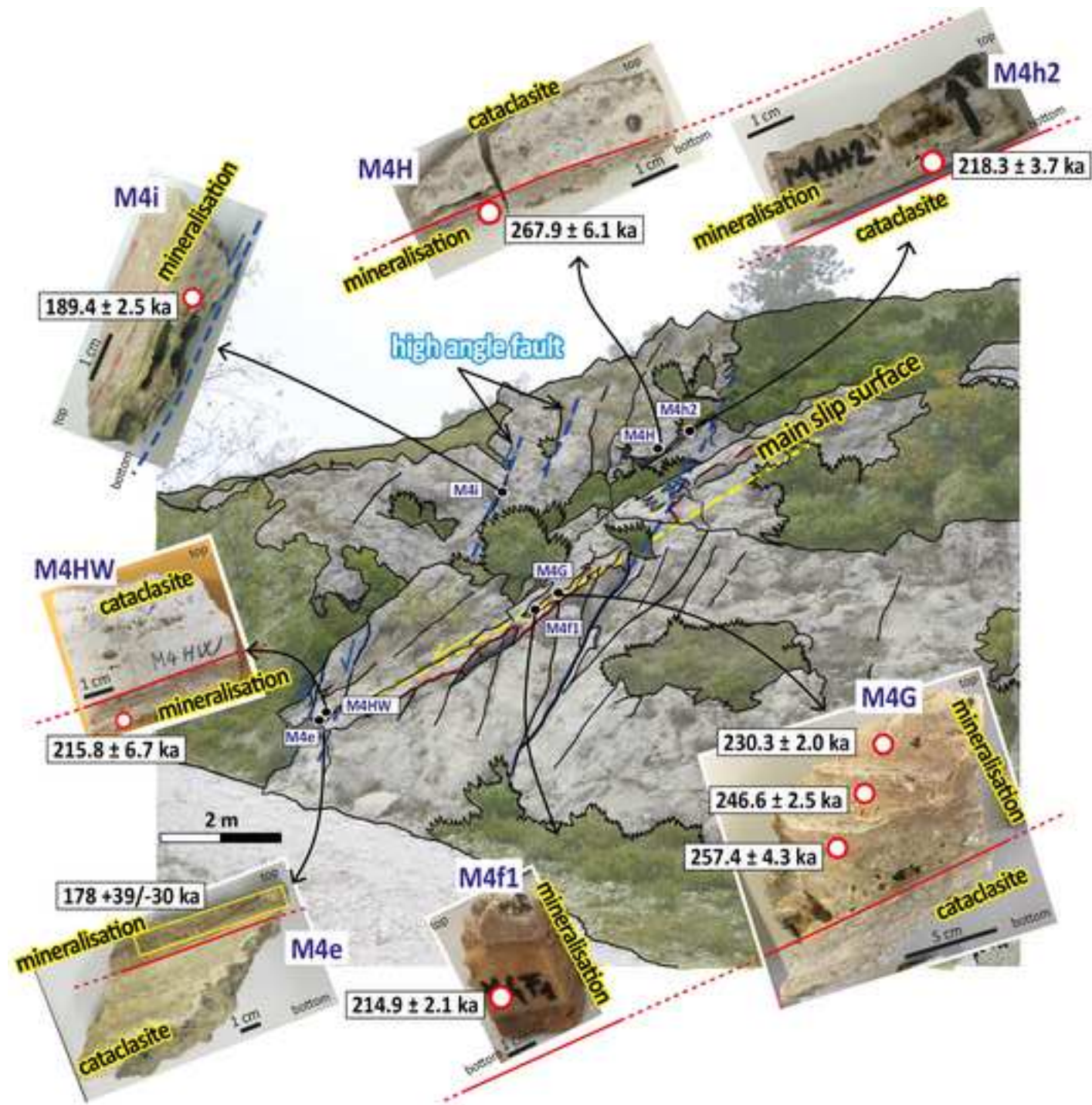


Figure 8

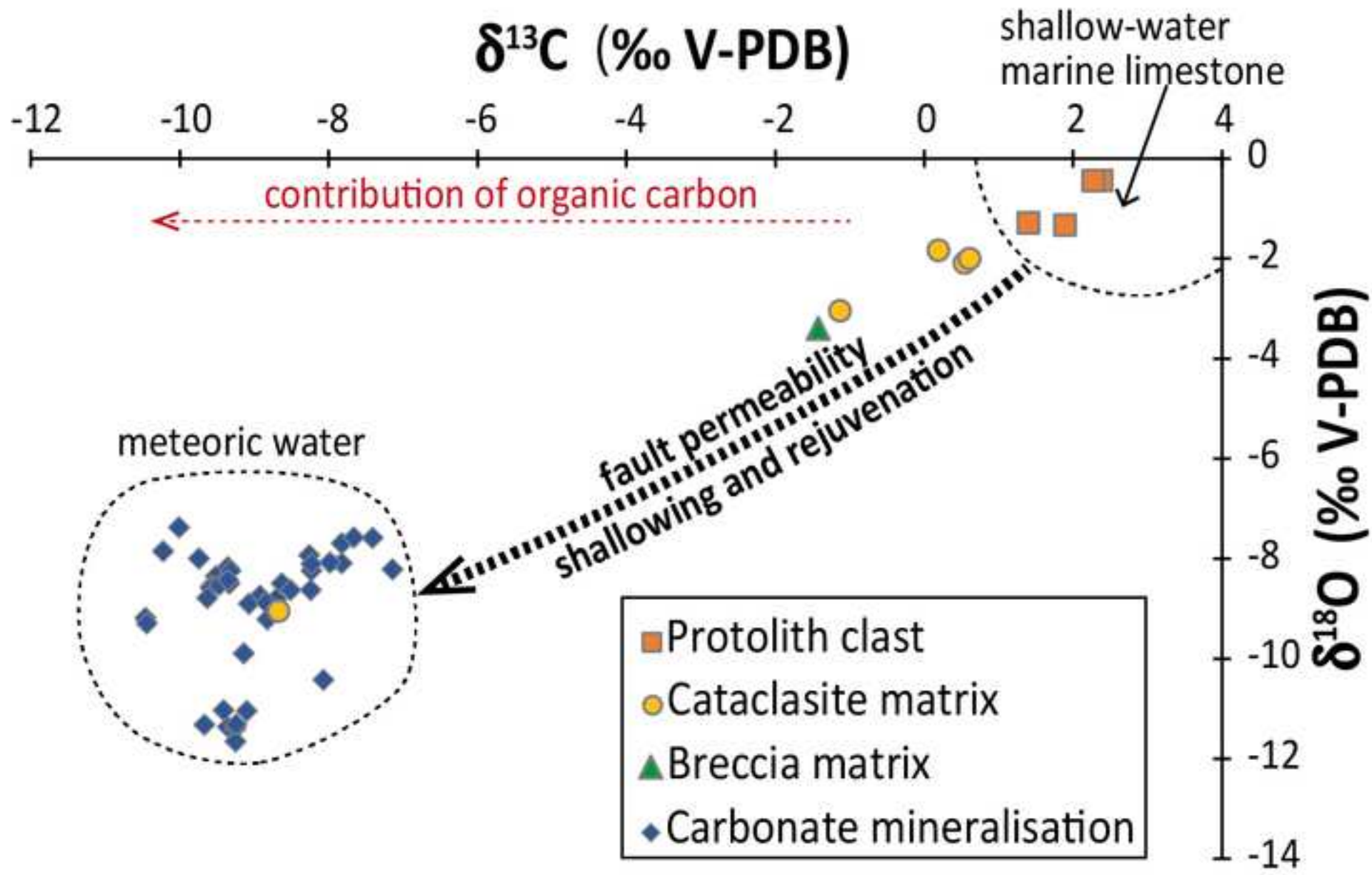


Figure 9

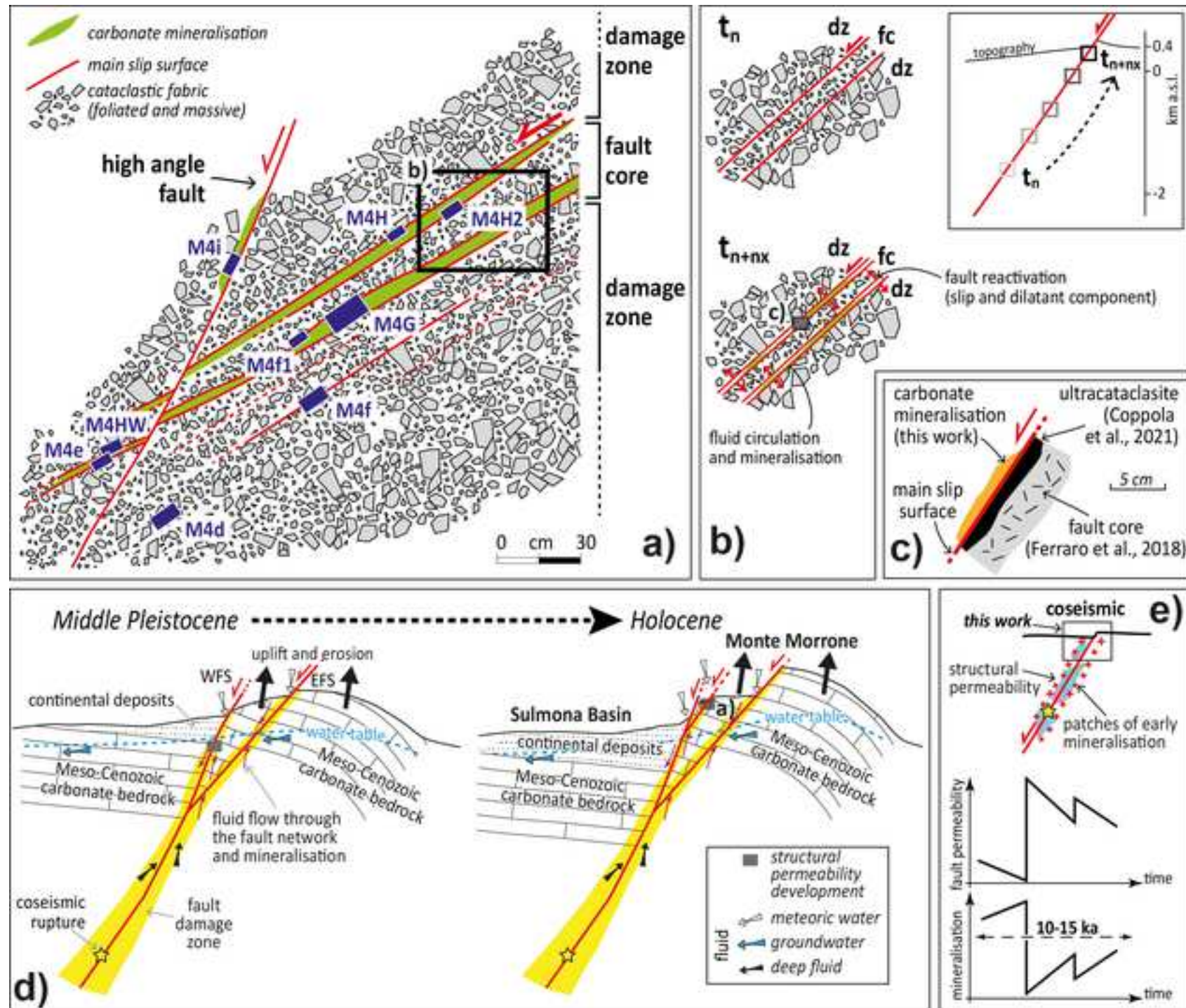
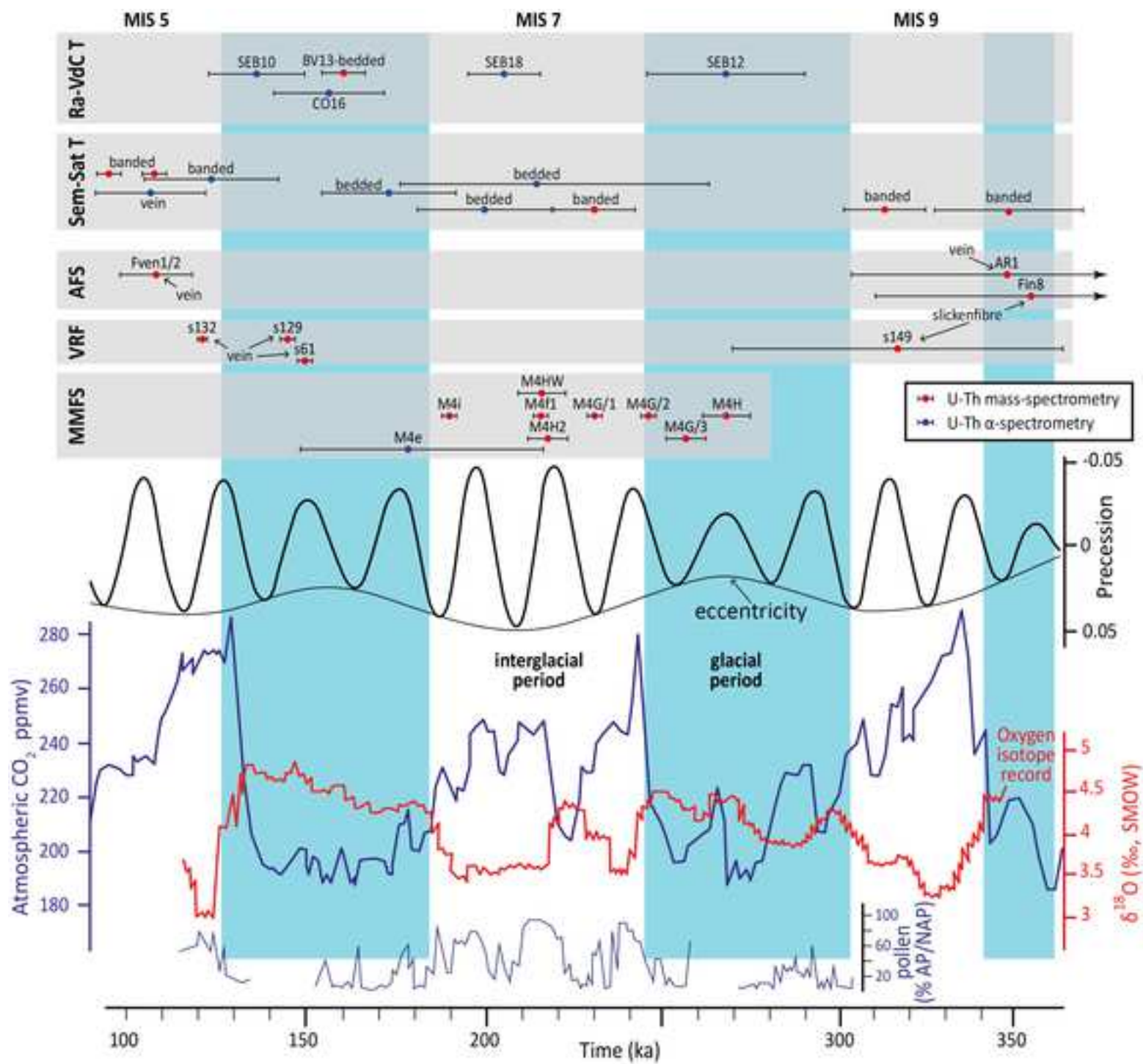


Figure 10



Credit author statement

Gianluca Vignaroli: Methodology, Investigation, Data curation, Visualisation, Writing - original draft, review & editing

Federico Rossetti: Validation, Investigation, Resources, Writing - review & editing, Supervision

Lorenzo Petracchini: Investigation, Data curation, Visualisation, Writing - review & editing

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