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Repeated seismic slips recorded in ultracataclastic veins along active faults of the Arima–Takatsuki Tectonic Line, southwest Japan

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ABSTRACT

Field investigations, combined with meso- and microstructural analyses, reveal that numerous ultracataclastic veins are widely developed within a fault zone (<150 m wide) as simple veins, complex lenses, and networks, along active faults of the Arima–Takatsuki Tectonic Line, southwest Japan. These veins comprise mainly pseudotachylyte-like vein and weakly consolidated to unconsolidated fault gouge that is black, dark-brown, brown, gray, and brownish-red in color. Meso- and microstructural features show that these pseudotachylyte-like and fault gouge veins and networks formed during multiple stages, as earlier veins are generally cut and overprinted by younger veins, indicating that the vein-forming events occurred repeatedly and that ultracataclastic material was injected into networks of faults and fractures in the fault zone. The pseudotachylyte-like and fault gouge veins are characterized by an ultrafine- to fine-grained matrix and angular to subangular fragments of host granitic rocks of various sizes, ranging from submicron to millimeters. SEM–EDS (Scanning Electronic Microscope-Energy Dispersive X-ray) and powder X-ray diffraction analyses show that all the ultracataclastic veins are characterized by crystalline materials composed mainly of quartz and feldspar, similar to the host granitic rocks.

The present results support the existing hypothesis that ultrafine- to fine-grained materials formed by comminution can be fluidized and injected rapidly into fracture networks located far from the source fault plane in a solid–fluid–gas system during seismic slip; therefore, such materials provide a record of paleoseismic faulting events that occurred repeatedly within the seismogenic fault zone.

Keywords: ultracataclastic veins, pseudotachylyte-like vein, fault gouge vein, fluidization, fossil earthquake, Arima–Takatsuki Tectonic Line (ATTL)

1. Introduction

It is well known that direct evidence of earthquakes within fault zones is limited to the presence of pseudotachylyte (e.g., Francis, 1972; Sibson, 1975; Passchier, 1982; Magloughlin, 1992; Lin, 1994, 2008a, b; Lin et al., 2003a, 2005). In addition to pseudotachylyte, previous studies have shown that the meso- and microstructural features of cataclastic veins [For avoiding the confusion, we use the cataclastic rock terminology of Lin (2008a) in this study] that lack the primary cohesion of the host rocks, including crush-origin pseudotachylyte (called pseudotachylyte-like vein in this study) (Lin, 1996, 2001; Wenk et al., 2000; Kano et al., 2004; Sagy and Brodsky, 2009; Janssen et al., 2010), fault gouge (Lin, 1996, 2001, 2011; Shigetomi and Lin, 1999; Otsuki and Monzawa, 2003), fault breccia (Sibson, 1986; Smith et al., 2008) and some calcite veins (Lin et al., 2003b; Lin, 2008a), may represent primary evidence of brittle deformation caused by recurrent seismic slip within seismogenic fault zones (Lin, 1996, 2001, 2008a, 2008b; Wenk et al., 2000; Kano et al., 2004; Sagy and Brodsky, 2009). It has also been reported that during the 2008 M_w 7.8 Wenchuan earthquake, ultracataclastic veins were produced along the seismic slip plane and injected into fractures within the seismogenic fault zone (Lin, 2011). Therefore, studies on cataclastic veins would provide new insights into the deformation process of seismic slip recorded in seismogenic fault zones. Although previous studies have investigated the structural modes of cataclastic veins (Lin, 1996, 2001, 2008a, 2011;

Shigetomi and Lin, 1999; Wenk et al., 2000; Kano et al., 2004; Sagy and Brodsky, 2009; Janssen et al., 2010, 2012), ultracataclastic veins are rarely found within fault zones, in contrast to the relatively common occurrence of melt-origin pseudotachylyte. Consequently, the lack of field and microstructural data hinders further assessments of the nature and formation mechanisms of ultracataclastic veins, and of the process of seismic slip within seismogenic fault zones.

In this study, we report on the structural mode of typical ultracataclastic veins including pseudotachylyte-like and fault gouge veins that formed repeatedly as simple veins and complex networks within a fault zone along active faults of the Arima–Takatsuki Tectonic Line (ATTL), southwest Japan. We also discuss the formation mechanisms of such veins and their tectonic significance in terms of seismic faulting events.

2. Geological setting

The study region is located in the marginal zone of the Eurasia plate, bounded by the Median Tectonic Line in southwest Japan (Fig. 1a). The ATTL is an active fault zone with a main strand oriented NNE–SSW, which consists mainly of the Kiyoshikojin, Rokko, and Ibayama faults. These faults record mainly dextral strike-slip movement, and are developed along the northern margin of the Osaka Basin, extending for about 60 km (Fig. 1b). Based on offsets of basement rocks and Tertiary peneplains, the total displacement along the ATTL is estimated to be about 17 km, with a long-term average slip rate of 1–3 mm/year horizontally and a vertical displacement of ~0.3 mm/year (Maruyama and Lin, 2002). Trench investigations indicate that the most recent seismic faulting event along the fault zone was the 1596 Keicho-Fushimi earthquake of M 7.25–7.5 (Sangawa, 1997; Maruyama and Lin, 2002).

Basement rocks in the study region consist mainly of Cretaceous granitic rocks (the Rokko granitic rocks) and welded rhyolitic tuff of the Arima Group, as well as Oligocene–Eocene sedimentary rocks of the Kobe Group and mid-Pleistocene sedimentary rocks of the Osaka Group (Fig. 1b). The Rokko granitic rocks are distributed mainly to the southwest of the ATTL, and the Arima Group occurs mainly to the north. The Kobe Group consists predominantly of mudstone, sandstone, and conglomerate, mainly northwest of the ATTL. The Osaka Group comprises weakly consolidated to unconsolidated alternating beds of silt, clay, and gravel, found mainly in the southeast part of the study region. Quaternary alluvial deposits are largely restricted to lowland areas in the southeast part of the study area, where terrace risers are widely developed (Fig. 1b).

3. Structural modes of ultracataclastic veins

3.1. Distribution of ultracataclastic rocks

Meso- and microstructural analyses reveal that the width of the fault-damage zone varies along the active faults of the ATTL, from ~50 m to ~1000 m (Lin et al., 2012a). Ultracataclastic veins are common within the fault-damage zone. To document the structural modes and distribution of the cataclastic veins, we mapped the rocks in two typical areas around Site 1 and Site 2 (see Fig. 1 for the site locations). At these sites, the basement rocks are well exposed due to strong erosion of the weak fault-damage zone and the damage zone is up to 500 m wide at Loc. 1 and 900 m wide at Loc. 2 (Lin et al., 2012a).

The mapping results indicate that the ultracataclastic veins are distributed mainly in a zone of <150 m wide bounded by the main fault trace of the ATTL (Fig. 2). This finding indicates that the ultracataclastic veins occur within the fault-damage zone, bounded by the main fault. The ultracataclastic veins occur as simple veins (herein called *fault vein*s) along the fault planes and as complex lens and networks in the country rocks (herein called *injection veins*) (Figs 3–6). The veins appear to be randomly oriented (Fig. 2b) and are black, brown, gray, dark-gray, bluish-gray, yellowish-gray, and brownish-red in color. Based on structural features, the veins can be divided into two types: hard and aphanitic pseudotachylyte-like veins (Figs 3 and 4) and weakly consolidated to unconsolidated fault gouge veins (Figs 5 and 6). The veins are described in detail below.

3.2. Pseudotachylyte-like vein

The pseudotachylyte-like vein is dark-brown, hard, and aphanitic, and generally occurs as thin films and simple veins along fault planes, and as complex injection veins, including lenses and networks of veins, in the country cataclastic rocks that originated from the granitic rocks (Figs 3 and 4). These apparent structural features of pseudotachylyte-like veins are similar with those of typical pseudotachylytes reported to date (e.g., Sibson, 1975; Passchier, 1982; Magloughlin, 1992; Lin, 1994, 2008a, b). Locally, fault veins can be traced along a single fault plane for >10 m intermittently (Figs 3a and 4a). The fault veins, which are bounded by fault planes, are generally developed in a narrow zone (<10 cm wide) and show irregular and uneven contacts with the country cataclastic rocks (Fig. 4b–d). Multi-stage fault veins are also observed, whereby older fault veins of pseudotachylyte-like

(Fig. 4b and d) and fault gouge veins (Fig. 4e) are cross-cut and overprinted by younger pseudotachylyte-like veins. The presence of multi-stage fault veins indicates that the pseudotachylyte-like-vein forming events occurred repeatedly along individual fault planes. Similar overprinting has been reported from both pseudotachylyte-like veins along many faults [e.g., the Iida–Matsukawa Fault (Lin, 1996) and the Itoigawa–Shizuoka Tectonic Line, Japan (Lin et al., 2012b)] and from pseudotachylyte veins along the Woodroffe Thrust, central Australia (Lin et al., 2005; Lin, 2008a, b).

The injection veins occur as isolated lenses, irregular chains of lenses, and networks that can be locally traced back to the source fault plane over distances of up to >10 m (Figs 3, 4c and f). These veins are relatively resistant to weathering and therefore protrude in outcrops, making them easily recognized (Fig. 3). Pseudotachylyte-like fragments (up to 20 cm in size) occur as talus breccias at the base of outcrop (Fig. 3a and c). The protruding nature of the veins and the occurrence of vein fragments as talus breccias indicate that the pseudotachylyte-like veins are consolidated and are harder than the country rocks, making them relatively resistant against erosion and weathering.

3.3. Fault gouge veins

Similarly to the pseudotachylyte-like veins described above, fault gouge also occurs along distinct fault planes as a thin film, as simple veins, and as lenses and complex networks in the fault-damage zone (Figs 5 and 6). The fault gouge veins are generally unconsolidated to weakly consolidated and are black, brown, dark-brown, yellowish-brown, brownish-red, gray, yellowish gray, bluish-gray, and dark-gray in color. Most of the fault gouge veins observed in this study are composed of ultrafine- to fine-grained materials that contain less than 10% clasts observable with the naked eye [i.e., less than 30%t in the terminology for fault gouge defined by Sibson (1977)].

The fault gouge veins are generally developed along distinct fault planes as tabular bodies with a simple geometry and are 1–15 cm wide, generally 1–3 cm (Figs 5 and 6a); in contrast, injection veins of fault gouge generally occur as complex networks and as irregular lenses with an uneven shape where they occur within the country cataclastic rocks (Figs 5 and 6). The fault gouge veins are commonly composed of at least four or five colored layers (including gray, brown-gray, bluish gray, and dark-gray), and are continuous along fault planes (Figs 5 and 6a). The fault gouge layers are bounded by the fault plane along a sharp and planar contact; in contrast, fault gouge layers located far from the fault plane generally have curved or uneven boundaries. The fault gouge veins overprint one another, as inferred from cross-cutting structures and contacts between different color veins (Figs 5 and 6a). These structural features indicate that the fault gouge veins formed in multiple stages, as with the pseudotachylyte-like veins described above.

In contrast to the fault veins, the injection veins of fault gouge generally occur as complex lenses and networks within the host cataclastic rocks, and are black, brown, yellowish-gray, gray, and brownish-red in color (Figs 5 and 6b–g). The black and brown veins are generally consolidated to weakly consolidated, and are hard and protrude in outcrop, t without aphanitic appearence as that of the pseudotachylyte-like veins (Fig. 6b and c). Fault gouge veins of other colors are generally unconsolidated and soft. Multi-stage injection veins of fault gouge are also observed, whereby older injection veins are overprinted by younger veins, as also observed for pseudotachylyte-like veins (Fig. 6b–g). The injection veins of fault gouge occur in a wide zone, far from the source fault plane, and terminate sharply within the country cataclastic rocks (Fig. 6b–g). Locally, injection veins located close to fault planes can be traced to fault veins by the color and continuity of veins (Figs 5a and 6a). Such an intrusive mode of origin for injection veins of fault gouge has been reported from some active faults in Japan (e.g., Lin, 1996, 2008a; Shiegetomi and Lin, 1999; Kano et al., 2004).

4. Microstructures

The pseudotachylyte-like and fault gouge veins were observed by optical microscope and scanning electronic microscope (SEM). All the ultracataclastic veins described above consist mainly of an ultrafine- to fine-grained matrix with the optical characteristics of glass (or glassy) materials that are generally too fine to observe under the optical microscope, as well as randomly oriented fragments of granitic rocks ranging in size from sub-micron to ~1 mm (Figs 7 and 8). In thin section, the boundaries between pseudotachylyte-like veins and fault gouge, and the country cataclastic rocks are generally sharp and planar, although locally they are gradational and irregular, as also observed in outcrops. SEM images reveal that the ultrafine- to fine-grained matrix of pseudotachylyte-like and fault gouge veins is composed mainly of angular to subangular fragments varying in size from sub-micron to several tens of microns, with most being ~1–10 μm (Figs 7b–c, g–h, 8g, h).

5. Grain-size distribution

To understand the distribution pattern of gain-size of the ultracataclastic veins, we measured two typical samples of black fault gouge and pseudotachylyte-like veins. The measurements were performed on the photomicrographs, using the measurement method described by Shimamoto and Nagahama (1992). The fragments of larger than 5 μm were measured as the fine-grained fragments of smaller than 5 μm are too fine to measure under optical microscope.

The measurement results were plotted as cumulative diagrams for the major diameter (r) in transversal axis and the total numbers of measured grains (N) in the vertical axis, using logarithmic scales on both axes (Fig. 9). The results show that there is a similar size-distribution pattern between the pseudotachulyte-like injection vein and fault gouge vein and that the fault gouge vein contains more small fragments of <10 μm than that of the pseudotachylyte-like vein.

6. Powder X-ray diffraction analysis

To identify the rock-forming minerals of fine-grained materials, 12 samples (including fault gouge veins, pseudotachylytelike-veins, and host granitic cataclasite) were selected for powder X-ray diffraction analysis. The measurements were performed on bulk veins and host rocks at Shizuoka University, Japan, using an RINT2000 X-ray Diffractometer under the following analytical conditions: filtered CuKα (1.54050Å) radiation, X-ray generator at accelerating voltage 40 kV and 20 mA, divergence slit 1.0°, receiving slit 0.15 mm, and scanning speed 2°/min.

Figure 10 shows six typical X-ray diffraction spectra. The default settings of the program were used to identify and remove background noise, and a peak correction was performed to shift sample spectra to the peak positions of the standard library spectra for synthetic quartz. All samples analyzed consist mainly of quartz, feldspar, and biotite, with minor accessory minerals. The results show that all the ultracataclastic veins are composed mainly of granitic rock-forming minerals such as quartz, feldspar, and biotite, which occur in the veins as ultrafine- to fine-grained materials derived from the host granitic rock (Fig. 9).

7. Discussion

7.1. Formation mechanism of the ultracataclastic veins

The meso- and microstructural observations, combined with the X-ray diffraction data, indicate that all the ultracataclastic veins described above are composed mainly of ultralfine- to fine-grained crystalline material derived from the country rock, with little or no glassy material. This result indicates that all of the pseudotachylyte-like and fault gouge veins described in this study were formed mainly by crushing rather than melting. Except for the hard and aphanitic nature of the pseudotachylyte-like veins, there is no distinct difference in mesostructure, microstructure, or petrologic features between the crush-origin pseudotachylyte-like veins and fault gouge veins. Pseudotachylyte and pseudotachylyte-like veins have been reported from many active faults in recent decades, and have been interpreted as fossil earthquakes, as for pseudotachylyte veins (Lin, 1996, 2001, 2008a, 2011; Wenk et al., 2000; Kano et al., 2004; Sagy and Brodsky, 2009).

The injection veins of fault gouge, as observed in the present study, share some of the features of pseudotachylyte-like veins: they consist of ultralfine- to fine-grained fragments of the host rock (nanometer to sub-millimeter in scale) and are injected into fractures with cross-cutting structures within the fault zone. In our previous studies, we proposed three possible formation mechanisms for injection veins and networks of ultracataclastic veins: (i) the rapid spray-like intrusion of ultrafine- to fine-grained material during seismic slip, (ii) the slow deposition of clay minerals and/or fine-grained materials transported by hydrothermal fluids, or (iii) slow intrusion of fined grained materials along fractures during aseismic periods (Lin, 1996, 2008a, 2011; Lin et al., 2012b). In the present case, on the basis of the microstructural features, combined with the lack of clay minerals and the unsorted nature of fine-grained fragments, we consider mechanisms (ii) and (iii) to be unlikely, and therefore favor mechanism (i) in terms of the formation of injection veins and networks of ultracataclastic veins (Lin, 2008a, 2011).

The structural modes and petrologic features of ultracataclastic veins described in this study are also consistent with formation mechanism (i). Firstly, if the injection veins formed by slow flow during a long aseismic period, it would be difficult to intrude fine-grained materials into sub-millimeter to millimeter-scale fractures over a distance of > tens of centimeters up to several meters in the strongly fractured and/or weak-consolidated fracture zone from the source fault plane without the presence of flowing water (Lin, 2011). If the injection veins formed via the slow flow of fine-grained materials within underground water, we would expect to find more fine-grained materials and rich clay minerals due to sorting within the fluid. As described in the text, microscopic and X-ray diffraction analysis shows that all the injection veins and fault veins described in this paper are dominated by a homogeneous mass of ultrafine to fine-grained materials with the same rock-forming minerals as that of the fault gouge, breccia and host rocks without distinct increase of clay minerals as reported in other pseudotachylyte-like veins (Lin, 2008a, 2011). The grain-size distribution pattern of fine-grained materials in the pseudotachylyte-like injection vein is consistent with that of the fault gouge vein described in this study as those reported in the pseudotachylyte-like veins and cataclastic veins within active fault zones in Japan (e.g., Lin, 1996, 2001, 2008a; Kano et al., 2004). This also suggests that the fine-grained materials are injected rapidly into the network fractures without sorting of fine-grained materials.

Secondly, the network fractures developed in the pseudotachylyte-like veins and fault gouge veins, which are considered to be formed by faulting and filled by the ultrafine- to fine-grained materials during a large earthquake because it is difficult to keep the irregular fracture spaces in the unconsolidated fault gouge and strongly fractured zones without filling in a long time after seismic faulting (Lin, 2008a; Lin et al., 2012b). Furthermore, it is also difficult to form the sharp contacts between the dark injection pseudotachylyte-like veins and different color fault gouge veins by slow flow without contamination of ultrafine- to fine-grained dark injection vein and gouge materials under unconsolidated conditions within the fault zone.

The structural and petrologic features documented above strongly support the idea that the dark, aphanitic injection pseudotachylyte-like veins and fault gouge veins described in this paper formed by rapid injection of ultrafine to fine-grained materials in a short period of seconds of seismic faulting but not formed by slow flow in a long aseismic period.

7.2. Tectonic implications

Lin et al. (2012b) proposed a fault dilatancy model to explain the formation of networks of ultracataclastic veins. Fault–fracture networks that form during seismic faulting represent void spaces that play a role in generating suction, leading to the rapid intrusion of superfine- to fine-grained material from the source fault zone. The presence of multi-stage veins indicates that the fracture networks are produced repeatedly by seismic faulting within the fault-damage zone of the ATTL.

The kinetic energy of comminution during seismic sliding is largely converted to heat (Rice, 2006), causing the thermal expansion of superfine- and fine-grained material, and fluid, including water and gas (thermal pressurization), along the principal slip zone, resulting in turn in the fluidization of ultrafine- to fine-grained granular material, which is then injected into the void spaces of fractures within a fault zone in a gas–solid–liquid system (Lin, 2008a, 2011). The presence of multi-stage veins indicates that vein-forming events occurred repeatedly in the wide fault–fracture zone (up to 150 m wide) along pre-existing active faults of the ATTL.

Incohesive cataclastic rocks, including fault gouge and fault breccia, generally form within shallow fault zones at <4 km depth (Sibson, 1975). The presence of multi-stage networks of ultracataclastic veins developed in a wide (~150 m) damage zone along active faults of the ATTL indicates that these veins formed repeatedly at shallow depths of <4 km.

The hard and aphanitic nature of the pseudotachylyte veins, combined with their petrologic features, indicates that they formed under high lithologic pressures without chemical reactions and that consolidation occurred at depths of <4 km.

The present study region is located in the margin of the Eurasia plate in southwest Japan, where the average rate of present-day uplift is 1–2 mm/yr (Yosikawa et al., 1981). Considering the present-day rates of erosion and uplift, we estimate that the networks of pseudotachylyte-like veins and fault gouge developed in the ATTL during the past 2–4 Ma. The geological and geomorphological features of active faults of the ATTL indicate that they formed in the period between the mid-Miocene and the Quaternary, and that they are presently active, with dextral slip rates of 1–3 mm/year and vertical displacement of >0.3 mm/year (Maruyama and Lin, 2002). Trench investigations reveal that the 1596 Keicho-Fushimi earthquake of M 7.25–7.5 probably ruptured the active faults of the ATTL (Sangawa, 1997; Maruyama and Lin, 2002). Therefore, it is inferred that the ultracataclastic veins were produced by recent seismic faulting along active faults of the ATTL from the late Pliocene to the Holocene.

8. Conclusions

Our analysis of ultracataclastic veins along active faults of the Arima–Takatsuki Tectonic Line (ATTL) yielded the following conclusions.

(1) Networks of ultracataclastic veins, including crush-origin pseudotachylyte-like veins and fault gouge, occur in a wide (up to 150 m) damage zone along the ATTL, southwest Japan.

(2) Both the pseudotachylyte-like veins and fault gouge veins consist of a ultrafine- to fine-grained matrix and angular to subangular fragments of granitic rocks that were generated by rapid comminution and injection during seismic faulting from the late Pliocene to the Holocene.

(3) Our results support the hypothesis that ultrafine- to fine-grained materials can be fluidized and injected rapidly into fault–fracture networks at sites located far from the source fault plane in a solid–fluid–gas system during seismic slip. Therefore, such materials represent a record of paleoseismic faulting events that occurred within the seismogenic fault zone.

Acknowledgements

We thank Professor J. Hadizadeh and an anonymous reviewer for their critical reviews and Professor T. Blenkinsop for editorial comments that helped to improve the manuscript. Thanks are also due to Dr. T. Mruyama for his assistance in the field and Professor K. Kano for discussion throughout the course of this study. This work was supported by the Grand-in-Aid Scientific Research (Science Project No. 23253002 for A. Lin) of the Ministry of Education, Culture, Sports, Science and Technology of Japan.

References

Francis, P. W., 1972. The pseudotachylyte problem. Comments on Earth Sciences. Geophysics 3, 35-53.

Huzita, K., Kasama, T., 1982. Geology of the Osaka–Seihokubu district. Quadrangle series, 1:50,000, Geological Survey of Japan, 112 pp. (in Japanese with English abstract).

Janssen, C., Wirth, R., Rybaoki, E., Naumann, R., Lemnitz, H., Wenk, H.-R., Dresen, G., 2010. Amorphous material in SAFOD core samples (San Andreas Fault): Evidence for crush-origin pseudotachylyte. Geophys. Res. Lett. 37, L01303, doi:10.1029/2009GL040993.

Janssen, C., Wirth, R., Lin, A., Dresen, G., 2012. TEM microstructural analysis in a fault gouge sample of the Nojima Fault Zone, Japan. Tectonophysics 583, 101-104.

Kano, K., Lin, A., Fukui, A., Tanaka, H., 2004. Pseudotachylytes of crushing origin from the Shimotsuburai fault of the Itoigawa-Shizuoka Tectonic Line active fault system, central Japan. J. Geol. Soc. Japan 110, 779–790 (in Japanese with English abstract).

Lin, A., 1994. Glassy pseudotachylyte veins from the Fuyun fault zone, northwest China. J. Struct. Geol. 102, 71–83.

Lin, A., 1996. Injection veins of crushing-originated pseudotachylyte and fault gouge formed during seismic faulting. Engineer. Geol. 43, 213–224.

Lin, A., 2001. S-C fabrics developed in cataclastic rocks from the Nojima fault zone, Japan and their implications for tectonic history. J. Struct. Geol. 23, 1,167-1,178 .

Lin, A., 2008a. Fossil earthquakes: the formation and preservation of pseudotachylytes. Springer, 348 pp.

Lin, A., 2008b. Seismic Slip in the Lower Crust Inferred from Granulite-related Pseudotachylyte in the Woodroffe Thrust, Central Australia. Pure Appl. Geophys. 113, 215-233, doi:10.1007/s00024-008-0301-4.

Lin, A., 2011. Seismic slip recorded in the fluidized ultractaclastic veins formed along the coseismic shear zone during the 2008 M_w7.9 Wenchuan earthquake, Geology 39, 547-550.

Lin. A., Sun, Z., Yang, Z., 2003a. Multiple generations of pseudotachylyte in the brittle to ductile regimes, Qinling-Dabie Shan ultrahigh-pressure metamorphic complex, central China. Island Arc 12, 423-435.

Lin, A., Tanaka, N., Uda, S., Satish-kumar, M., 2003b. Repeated coseismic infiltration of meteoric and sea water into deep fault zones: a case study of the Nojima fault zone, Japan. Chem. Geol. 202,139-153.

Lin, A., Maruyama, T., Stallard, A., Michibayashi, K., Camacho, A., Kano, K., 2005. Propagation of seismic slip from brittle to ductile crust: evidence from pseudotachylyte of the Woodroffe thrust, central Australia. Tectonophysics 402, 21–35.

Lin, A., Yamashita, K., Maruyama, T., 2012a. Spatial variations in fault zone structures along strike-slip faults: an example from active faults in southwest Japan. Journal of Asian Earth Sciences, submitted.

Lin, A., Shin, J., Kano, K., 2012b. Fluidized cataclastic veins along the Itoigawa–Shizuoka Tectonic Line active fault system, central Japan and its seismotectonic implications. The Journal of Geology, 120, 453-465. doi: 10.1086/665795

Magloughlin, J. F., 1992. Microstructural and chemical changes associated with cataclasis and frictional melting at shallow crust levels: the cataclasite-pseudotachylyte connection. Tectonophysics 204, 243-260.

Maruyama, T., Lin, A., 2002. Active strike-slip faulting history inferred from offsets of topographic features and basement rocks: a study of the Arima–Takatsuki Tectonic Line, southwest Japan. Tectonophysics 344, 81-101.

Otsuki, K., Monzawa, N., 2003. Fluidization and melting of fault gouge during seismic slip: Identification in the Nojika fault zone and implications for focal earthquake mechanisms. J. Geophys. Res. 108, doi:10.1029/2001JB001711.

Passchier, C.W., 1982. Pseudotachylyte and the development of ultramylonite bands in the Saint-Barthélemy Massif, French Pyrenees. J. Struct. Geol. 4, 69-79.

Rice, J.R., 2006. Heating and weakening of faults during earthquake slip. J. Geophys. Res. 111, B05311, doi 10.1029/2005JB004006.

Sagy, A., Brodsky, E.E., 2009. Geometric and rheological asperities in an exposed fault zone. J. Geophys. Res. 114, B02301, doi: 10.1029/2008JB005701.900.

Sangawa, A., 1997. Moving earth: earthquakes in Japan. Dohosha Ltd., Kyoto, 272 pp. (in Japanese).

Shigetomi, M., Lin, A., 1999. Seismic events inferred from the layering structures of fault gouge zone and pseudotachylytes in the Nojima fault zone, Japan. Struct. Geol. J. Tectonic Res. Group Jpn. 43, 38–42 (in Japanese with English abstract).

Sibson, R.H., 1975. Generation of pseudotachylite by ancient seismic faulting. Geophys. J. R. Astro. Soc. 43, 775–94.

Sibson, R.H., 1977. Fault rocks and fault mechanisms. J. Geol. Soc. London 133:191-213.

Sibson, R.H., 1986. Brecciation processes in fault zone: Inferences from earthquake rupturing. PAGEOPH 124, 159-175.

Smith, S.A.F., Collettini, C., Holdsworth, R.E., 2008. Recognizing the seismic cycle along ancient faults: CO2-induced fluidization of breccias in the footwall of a sealing low-angle normal fault. J. Struct. Geol. 30, 1034-1046.

Wenk, H. R., Johnson, L.R., Ratschbacher, L., 2000. Pseudotachylites in the Eastern Peninsula Ranges of California. Tectonophysics 321, 253–277.

Yoshikawa, T., Kaizuka, S., Ota, Y. (1981). The landfors of Japan. University of Tokyo Press, Tokyo, 222 pp.

Figure captions

Figure 1. Index maps of the study area, showing (a) the tectonic setting and (b) geology (modified from Huzita and Hasama, 1982). Locs. 1-3: Locations of typical outcrops of cataclastic veins. MTL: Median Tectonic Line; ISTL: Itoigawa–Shizuoka Tectonic Line.

Figure 2. Topographic map (a) and stereoplot (b) showing the distribution and orientation modes of ultracataclastic veins in the areas of Locs. 1 and 2 (see Figure 1 for outcrop localities). The veins occur within a <100-m-wide zone at Loc. 1 and within a <150-m-wide zone at Loc. 2.

Figure 3. Photographs showing the structural features of pseudotachylyte-like (Pt) veins (Loc. 1). (a) Pt veins are developed along a fault plane and in granitic cataclasite located far from the fault plane. Note that the pseudotachylyte-like fragments (up to 20 cm in size) occur as talus breccias at the base of outcrop (b) Close-up view of a Pt fault vein along the fault plane shown in (a). (c) Close-up view of Pt injection veins developed in the granitic cataclasite. Note that the veins protrude from the outcrop, similarly to dikes.

Figure 4. Photographs showing the structural modes of pseudotachylyte-like (Pt) veins developed in granitic cataclasite (Loc. 1). (a) Overview of an outcrop. The Pt veins are developed within a fault zone (<1 m wide) as simple veins and network injection veins within the country rocks. (b) Close-up view of Pt fault veins. Three stages of veins (Pt-1 to Pt-3) are observed, with irregular boundaries. (c) Close-up view of Pt injection veins. Note

that the veins terminate sharply against fractures. (d) Two stages of Pt veins (Pt-1 and Pt-2). The Pt-1 veins overprint the Pt-2 veins. Locally, the veins have a lumpy form (Pt-1). (e) Pt veins overprinting brown and yellow-gray unconsolidated fault gouge veins. (f) Pt injection veins with a planar geometry and with a complex curving geometry.

Figure 5. Photograph (a) and corresponding sketch (b) showing the structural modes of multi-stage fault gouge veins (Loc. 2). Fault gouge veins are developed along a fault plane (F) as a fault vein and occur as injection veins within the granitic cataclasite (Loc. 2). These veins have irregular boundaries.

Figure 6. Photographs showing the structural modes of fault gouge veins (Loc. 2). (a) Multi-stage fault veins that are dark-gray, gray, brown-gray, and blue-gray in color. (b–c) Two stages of fault gouge veins. Brown injection veins of fault gouge overprinted the yellowish-gray fault gouge. (d) Two stages of gray injection veins of fault gouge (vein-1 overprints vein-2). (e) Black injection veins terminate sharply against fractures. (f) Brown-red injection veins overprinting a brown-gray vein. (g) Two stages of fault gouge veins. The brown veins overprint the brown-red veins.

Figure 7. Photomicrographs showing the microstructural features of pseudotachylyte-like (Pt) and black fault gouge veins (Loc. 1). (a) Pseudotachylyte-like vein in granitic cataclasite. The vein consists of an ultrafine- to fine-grained matrix and angular to subangular fragments of granitic rocks. (b) Pt vein overprinting a fault gouge vein. (c) SEM

image of a pseudotachylyte-like vein bound within a microbreccia zone. Note that the boundary between the Pt vein and the microbreccia zone is sharp and irregular. (d) SEM image of a pseudotachylyte-like vein. The matrix is composed mainly of ultrafine-grained clasts (<1 μm). (e) Black fault gouge vein bound within a microbreccia zone. The black gouge vein is composed mainly of ultrafine- to fine-grained matrix and angular to subangular microfragments of granitic rocks. (f) SEM image of a black fault gouge vein bound within a microbreccia zone. (g–h): SEM images showing the microtextures of the fine-grained matrix of a black fault gouge injection vein. Note that the ultrafine- to fine-grained matrix is composed mainly of angular to subangular microfragments of granitic rocks (<5 μm). (a–b) Plane polarized light, (e) cross polarized light.

Figure 8. Photomicrographs showing the microstructural features of fault gouge veins (a–e, g–h) observed at Loc. 2 and (f) at Loc. 3. (a) Brown-red vein. (b) Brown vein. (c–d) Dark-gray vein overprinting a brown vein. The matrix is composed mainly of ultrafine-grained clasts (<1 μm). (e) Brown-gray vein. (f) Gray-green vein. (g) SEM images showing the microtextures of the fine-grained matrix of an injection vein of brownish-gray fault gouge bound within a microbreccia zone. The boundary between the fault gouge vein and the microbreccia zone is generally sharp. (h) SEM images showing the microtextures of the fine-grained matrix of an injection vein of gray-green fault gouge in rhyolitic tuff. Note that the ultrafine- to fine-grained matrix is composed mainly of angular to subangular microfragments of granitic rocks (<5 μm). (a–c, e) Plane polarized light, (d, f) cross polarized light.

Figure 9. Cumulative frequency plots of fragment sizes within the pseudotachylyte-like vein and black fault gouge vein from the ATTL. r: major diameter of fragment in the transversal axis; N: total numbers of measured fragments in the vertical axis.

Figure 10. Powder X-ray diffraction spectra of pseudotachylyte-like (Pt) and fault gouge veins. 01: black fault gouge; 02: pseudotachylyte-like injection vein (Pt); 03: gray fault gouge; 04: brown-red fault gouge; 05: host granitic rock. The same vertical scale (diffraction density) is used for all spectra. CPS: count points per second; Qz: quartz; Pl: plagioclase; Mi: mica (biotite).

Figure1
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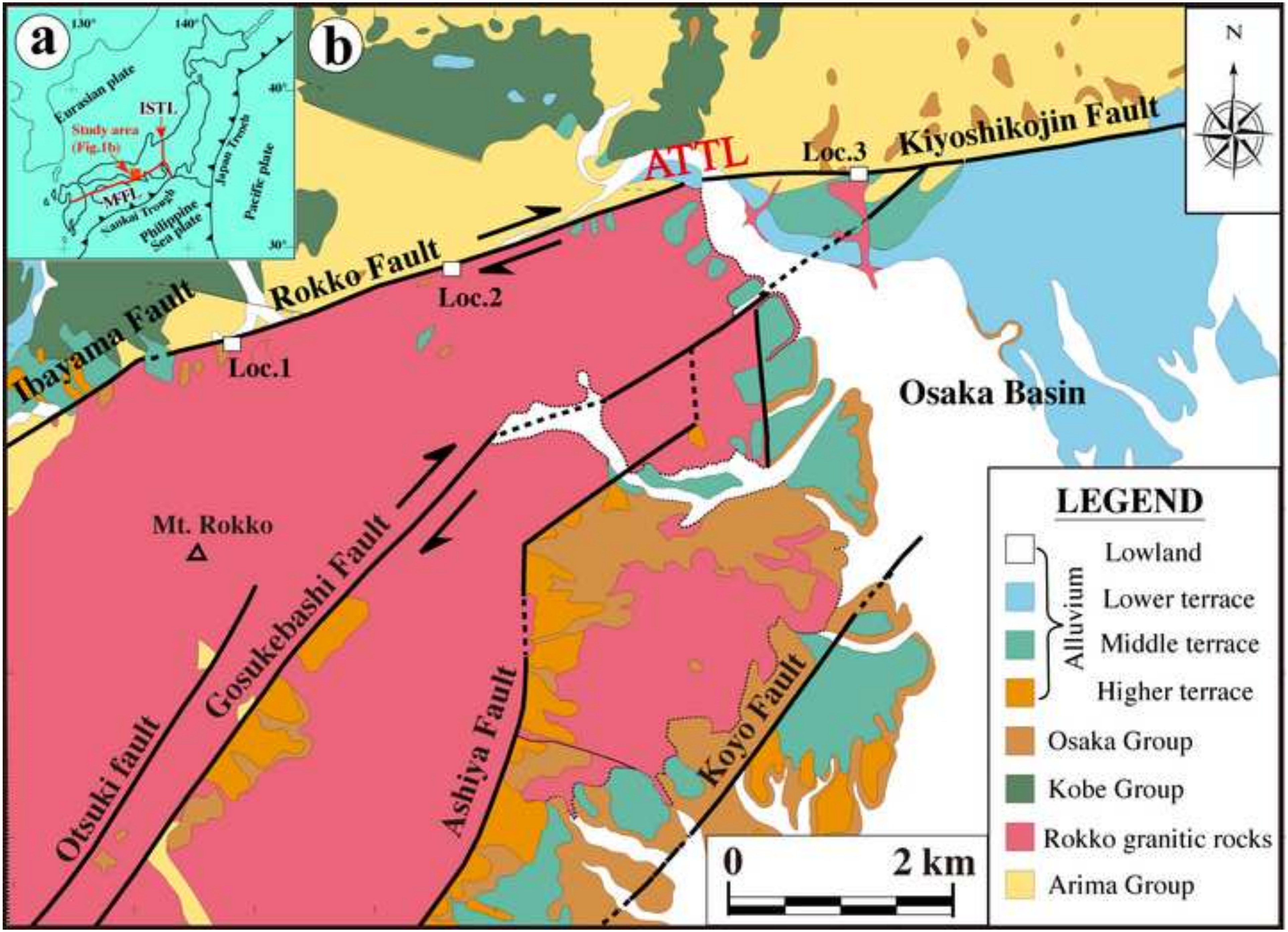

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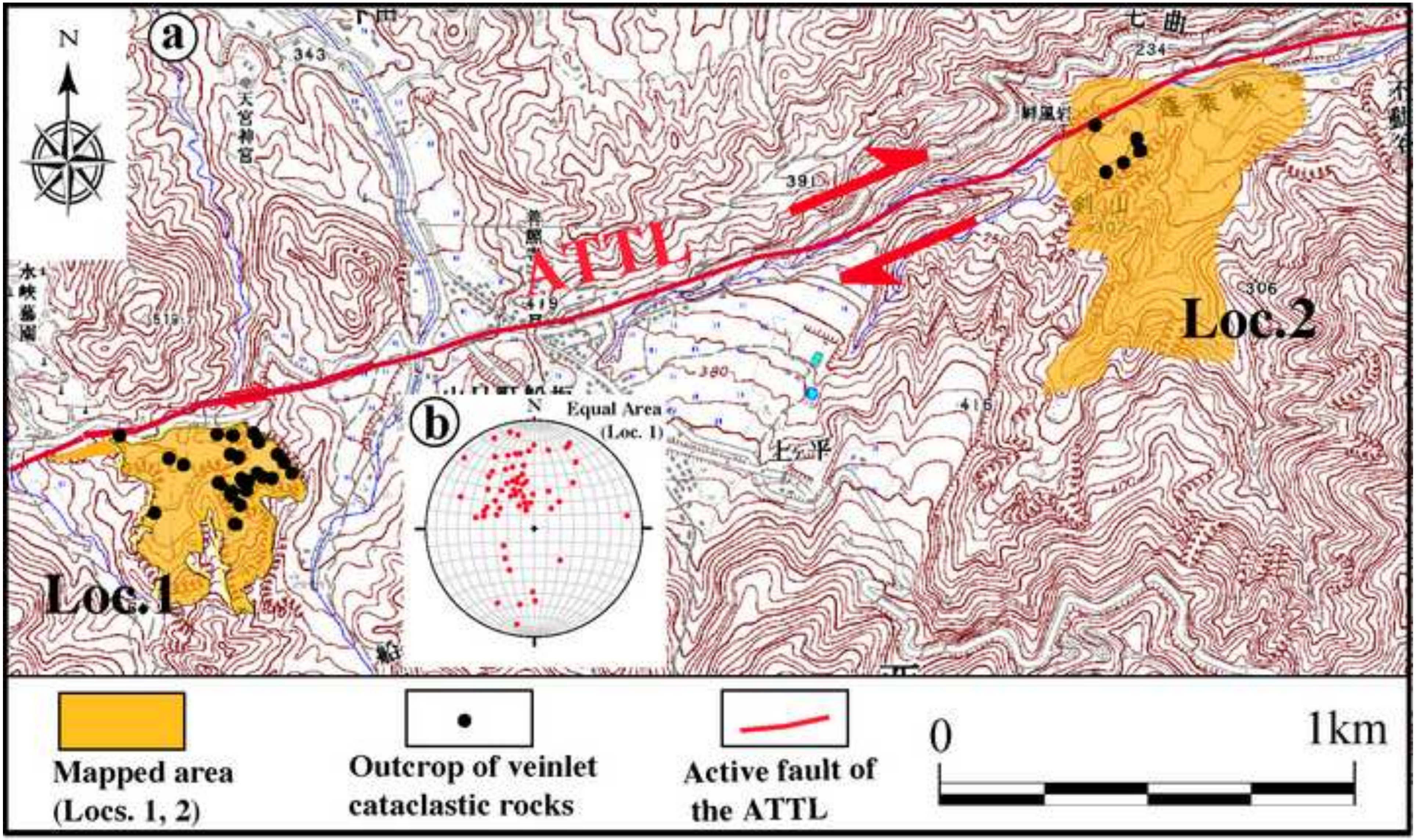

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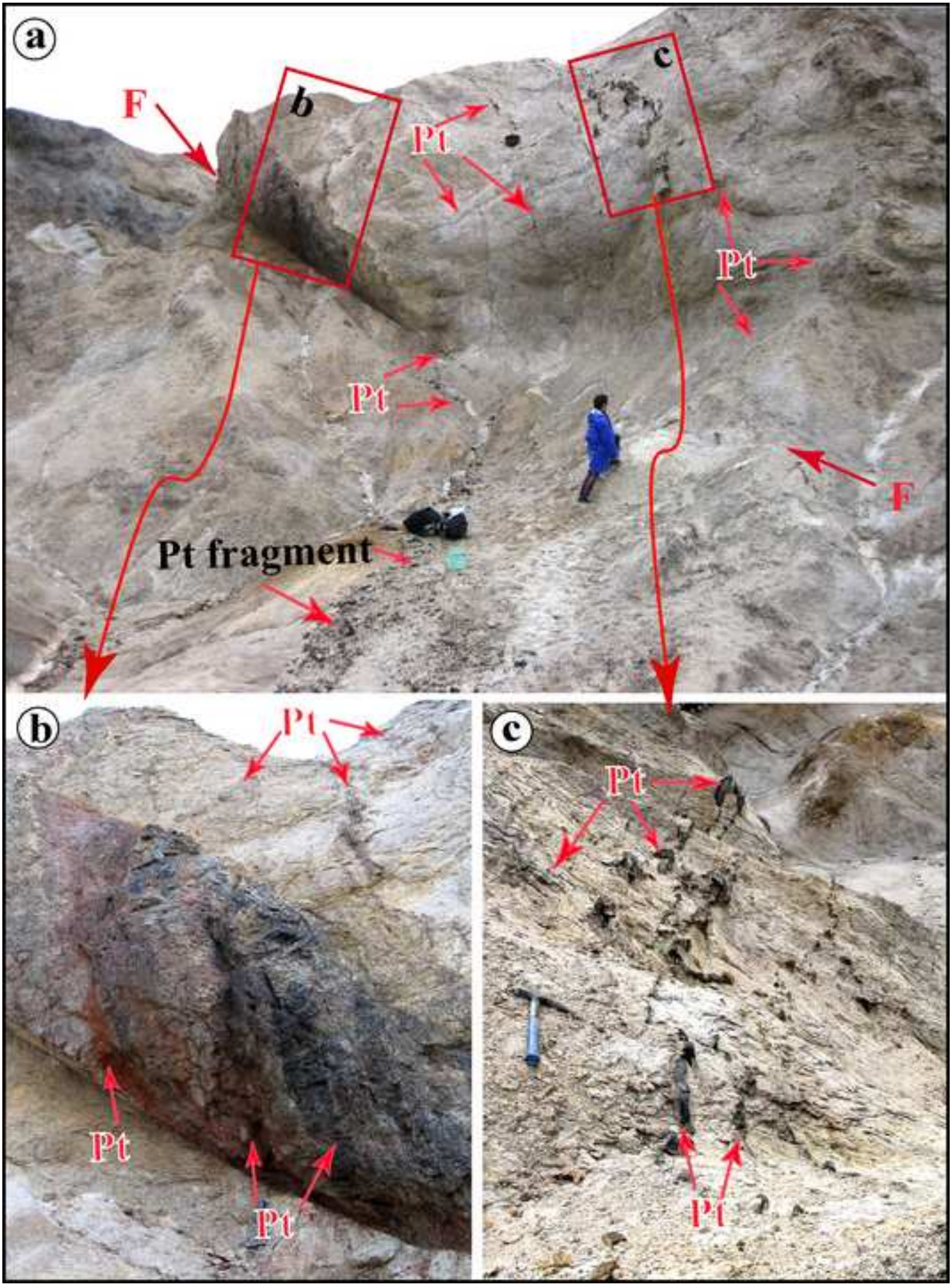

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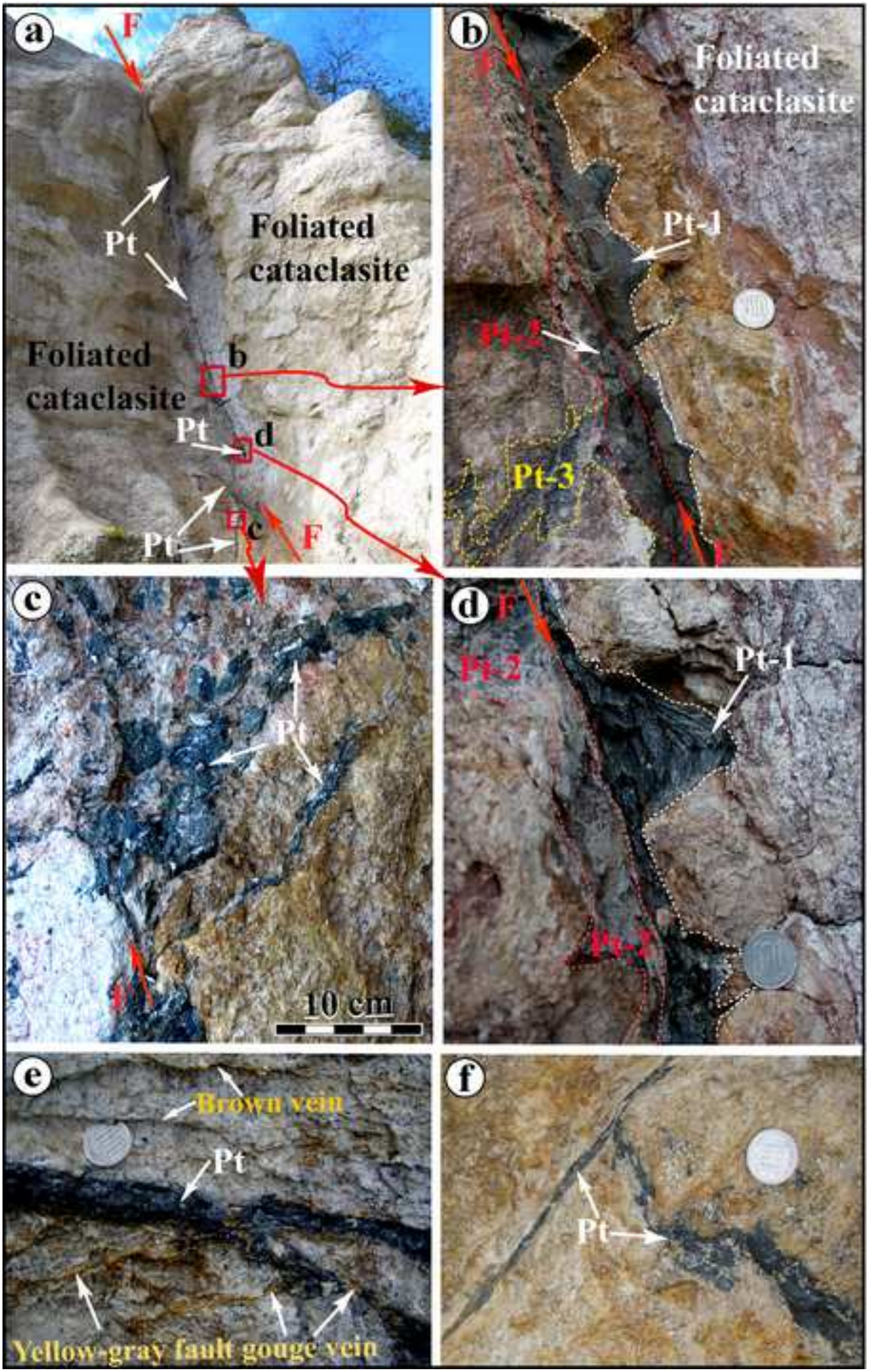

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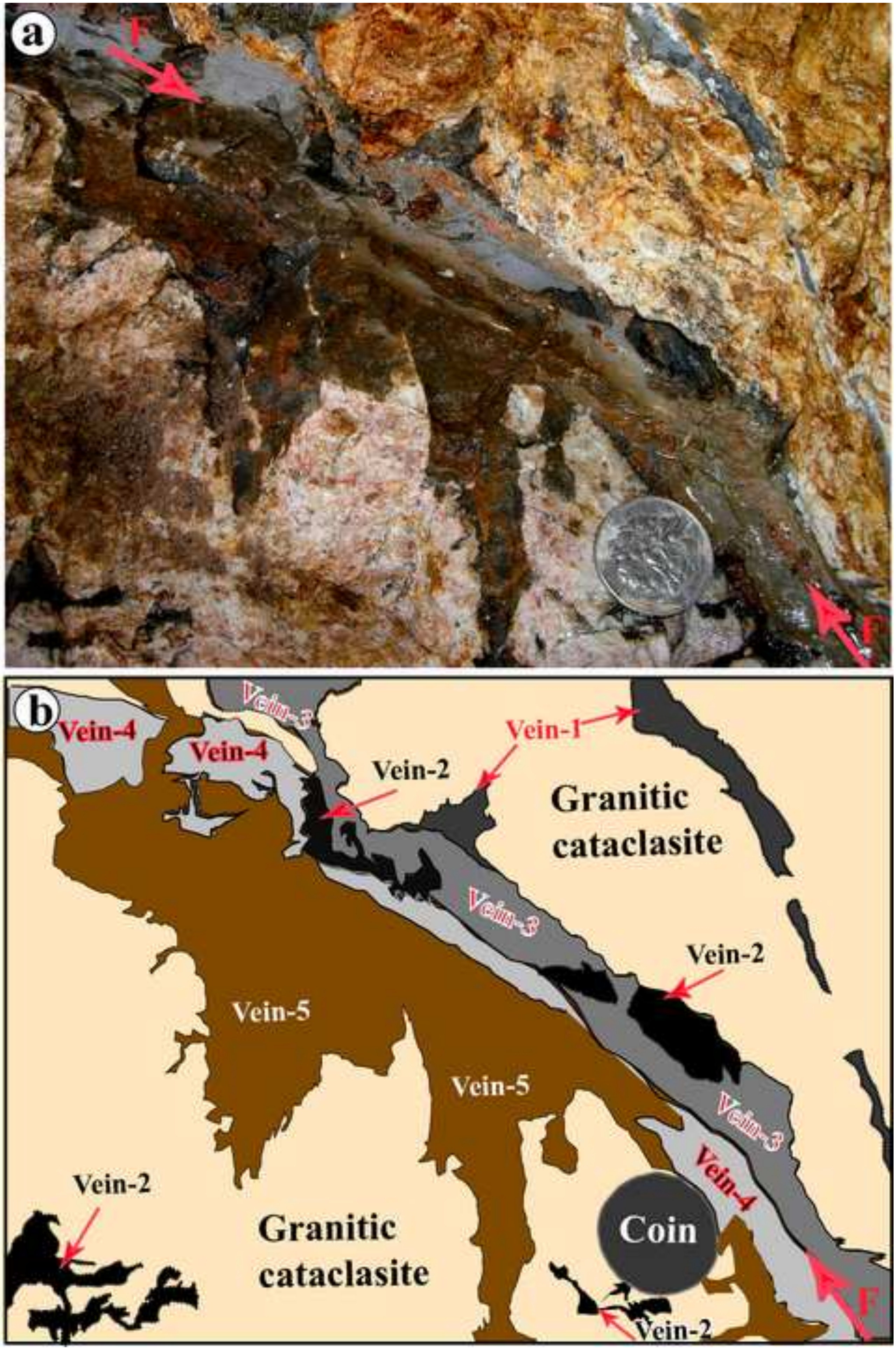

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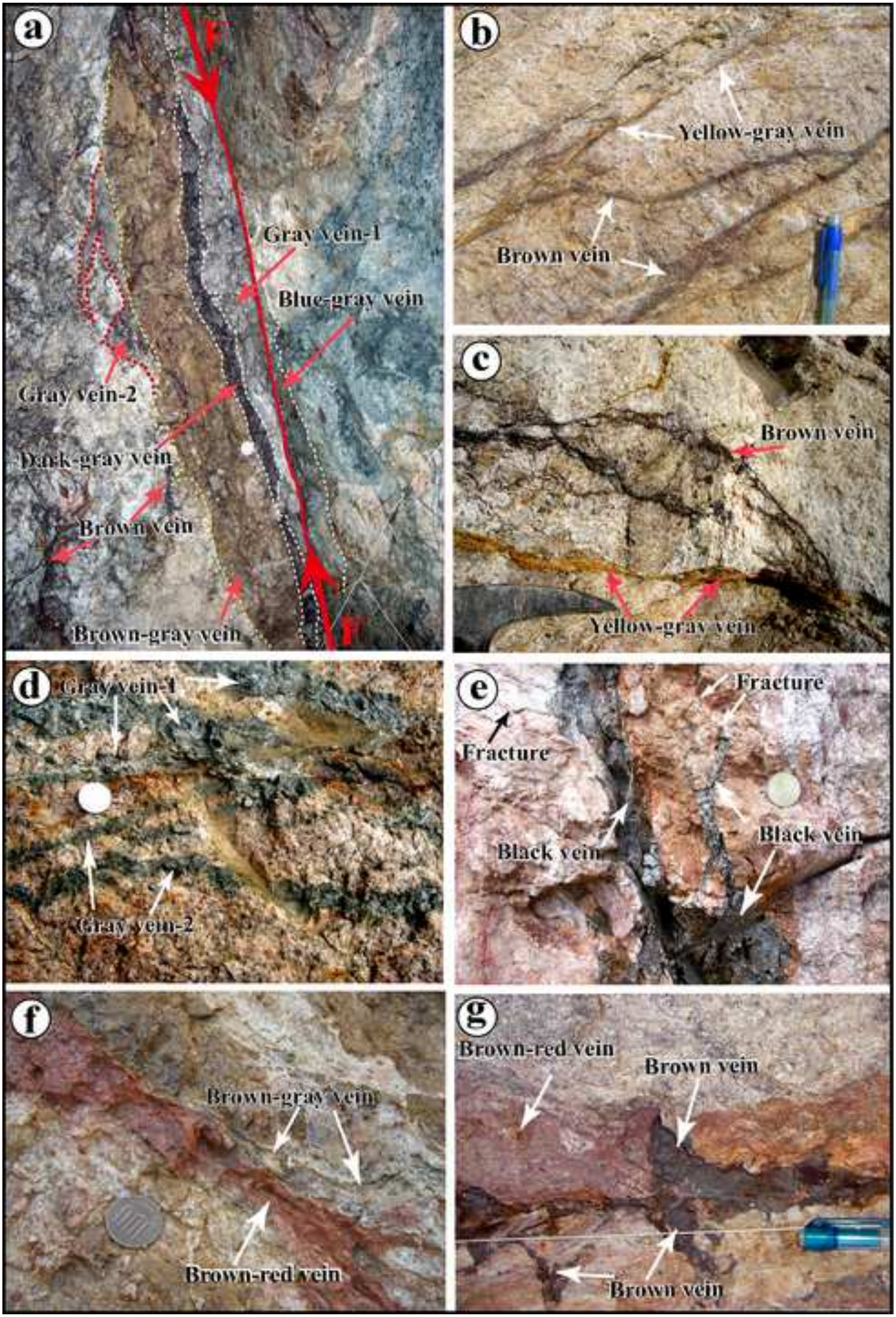

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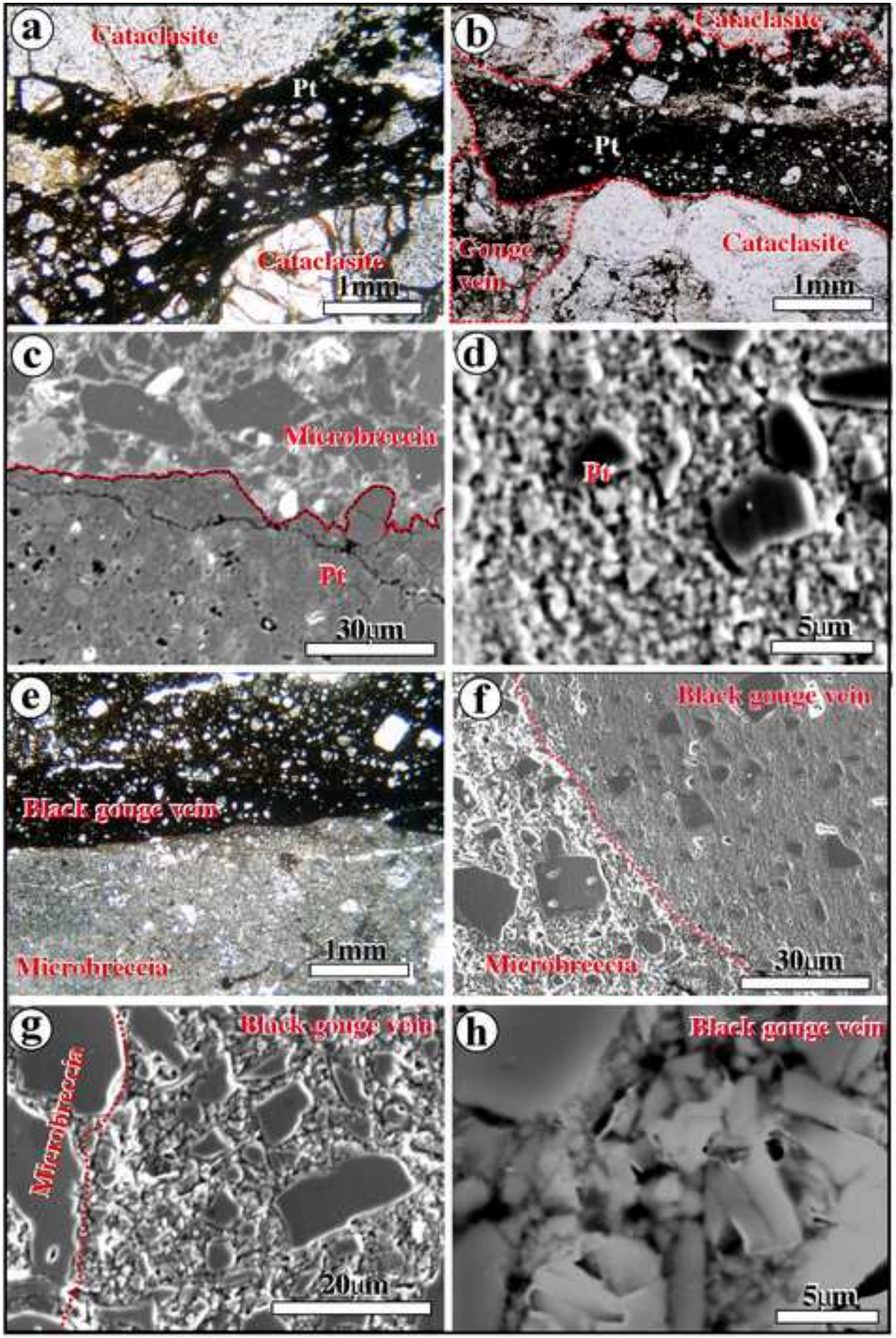

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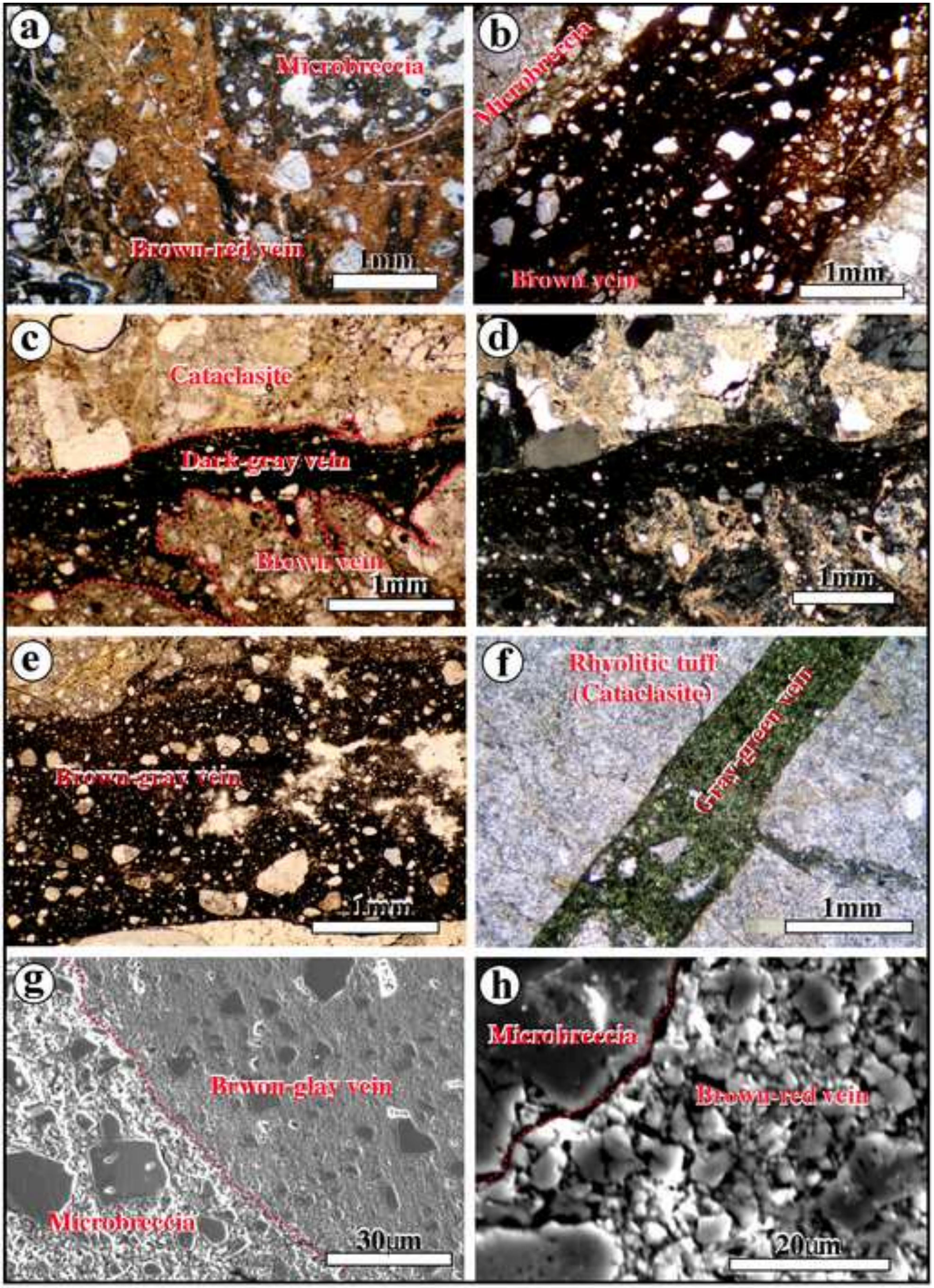

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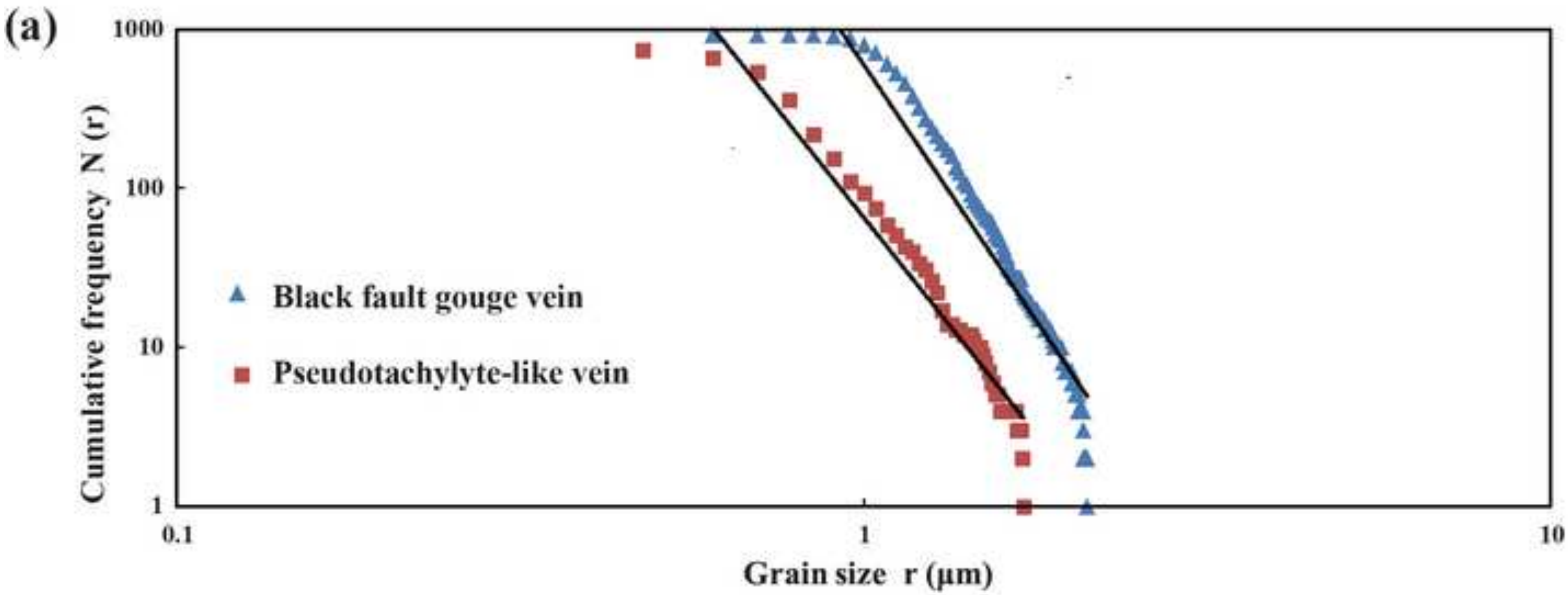

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