Repeated reactivation of clogged permeable pathways in epithermal gold deposits: Kestanelik epithermal vein system, NW Turkey

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Abstract: This study presents a detailed study of the dimensions, geometry, textures and breccias of a well-exposed epithermal vein system, the Kestanelik gold deposit in the Biga Peninsula, NW Turkey and investigates the permeability enhancement mechanisms in epithermal gold deposits. Here mineralisation is associated with quartz veins up to 13.6 m thick. Vein textures and breccia components indicate repeated sealing and subsequent brecciation of wall rock and pre-existing vein infill. Field and petrographic analyses characterize E-W trending veins as left lateral faults, whilst NE-SW trending veins are extensional (Mode I) fractures. Cataclasite and tectonic breccia of wall rocks and early quartz, hydrothermal crackle breccias, and matrix supported chaotic breccias of pre-existing vein infill, all of which are cemented by late iron-oxide-bearing quartz, indicate that co-seismic rupturing and hydraulic fracturing are two major permeability enhancement mechanisms. In addition, transient variations in local stress direction, caused by syn-mineralisation dyke intrusion, may have enhanced permeability on mis-oriented surfaces and at locations where the dip changes. This study emphasizes the importance of understanding structural geology and kinematics as controls on the location of boiling and mineralisation mechanisms in epithermal gold deposits.

Key words: epithermal, veins, permeability, kinematics, gold, earthquakes

Abbreviated title: Repeated reactivation of clogged permeable pathways

Epithermal deposits originate in the upper, brittle crust in regions with active magmatic and geothermal activity. Mineralisation in these deposits is dominantly hosted by veins or stockworks, confirming that brittle fault and fracture systems play a major role in the circulation of hydrothermal fluids (Buchanan 1981; Hedenquist & Lowenstern 1994; Curewitz & Karson 1997). The ore and gangue minerals in the veins are typically the result of multiphase precipitation (Spurr 1925; Hulin 1929; Buchanan 1981; Sibson 1987; Hedenquist *et al.* 2000), and associated with repeated and episodic fluid flow rather than a steady-state process (Sibson 1987; Micklethwaite & Cox 2004; Woodcock *et al.* 2007). Additionally, radiometric dating of some hydrothermal deposits indicates that permeability creation and hydrothermal fluid circulation could take place over thousands to tens of thousands of years (Fournier 1989; Lalou *et al.* 1993). This could be as long as millions of years in major porphyry systems (Sillitoe 2010). Understanding how subsequent permeability enhancement can be achieved after the deposition of minerals in fractures and faults chokes permeable pathways and restricts fluid flow is crucial.

Several precipitation mechanisms from the circulating hydrothermal solutions are invoked for both high and low sulphidation epithermal systems such as boiling, oxidation, fluid mixing, adiabatic boiling, pH change etc. The most favourable precipitation mechanism in low sulphidation epithermal systems is boiling. Epithermal fluids rise from depth along structural pathways at high temperatures under suitable pressure to prevent boiling. When the pressure drops suddenly (e.g. through faulting or fracturing-related dilation), boiling occurs. Even small magnitude earthquakes (Mw<2) can trigger boiling (Sanchez-Alfaro *et al.* 2016). Changes in the fluid chemistry by boiling result in precipitation of base metals at deeper levels, and precious ore and gangue minerals at relatively shallower depths until the open spaces are sealed, and fracture permeability is occluded or lost (Buchanan 1981; Henley 1985; Hedenquist *et al.* 2000).

The mineralogical and geochemical aspects of low sulphidation (LS) epithermal systems are well known (e.g. Buchanan 1981; White & Hedenquist 1990; Hedenquist & Lowenstern 1994; White & Hedenquist 1995; Hedenquist *et al.* 2000; Sillitoe & Hedenquist 2003; Simmons *et al.* 2005). However, limited studies exist on the fluid flow and permeability enhancement mechanisms in LS epithermal veins. The existing studies generally focus on the role and significance of geometric and mechanical aspects of the fault-fracture systems on the epithermal deposits. Terminations of individual faults and locations of multiple fault interaction are areas of high fracture density and connectivity and are therefore likely to localize high fluid flow (Curewitz & Karson 1997; Cox *et al.* 2001; Cox 2005). Observation from fossil epithermal deposits shows that epithermal mineralisation is often located in dilational jogs within fault systems (Sibson 1987). Major faults can be either important barriers or conduits to fluid flow (Caine *et al.* 1996; Rowland & Sibson 2004), while the permeability may be nonuniform along the fault depending on the relationship between the variable strike of the fault and the orientation of the local stress direction (Micklethwaite *et al.* 2010). Permeability can also be developed or maintained along individual fault segments because interconnected fractures and subsidiary faults form in the wall rocks where damage zone occurs adjacent to a fault core (Caine *et al.* 1996; Davatzes *et al.* 2005). The damage zone structures that are permeable may also change position over geological time (Woodcock *et al.* 2007; Burnside *et al.* 2013). Micklethwaite & Cox (2004, 2006) argued that if the event responsible for opening permeable pathways is an earthquake, although the permeability of the fault where the mainshock occurs may rapidly be lost due to the precipitation of hydrothermal minerals, enhanced fluid flow may occur along the structures where aftershock ruptures focus and the location of these structures are predictable based on stress transfer modelling.

Rather than focusing on structural controls at the fault system-scale, this study presents the dimensions, geometry, kinematics, textures and breccias of the individual veins. We examine the very shallowest levels of a well-exposed epithermal vein system at the Kestanelik gold deposit (Biga Peninsula, NW Turkey). Field and drill core data are used to understand the deformation mechanisms and kinematics of the vein system, specifically focussing on determining the origin of the fracture zones (a shear fracture or extensional fracture zone) along which the mineralisation has occurred. Implications for the vein-scale permeability enhancement mechanisms and effective prospect evaluation in epithermal gold deposits are explored.

This study has revealed significant new microstructural evidence for reactivation along the vein-wall rock contact and associated permeability development and fluid flow after the veins were clogged. These findings support the few earlier studies of the permeability enhancement mechanisms and fluid flow in epithermal systems (e.g. Sibson 1987; Cox *et al*. 2001; Micklethwaite & Cox 2004; Micklethwaite 2009) but are also the first detailed textural studies of the permeability enhancement mechanisms. It also emphasizes the importance of understanding structural controls and triggers for mineralisation that are evident from structures and textures during the exploration of epithermal gold deposits.

Kestanelik epithermal gold deposit

The Kestanelik gold deposit is located in the Biga Peninsula, NW Turkey approximately 45 km northeast of Çanakkale. Paleozoic metamorphic and ophiolitic basement rocks are cut by various Eocene to Miocene plutons and covered by Cenozoic volcanic and sedimentary rock units (Okay *et al.* 1996) (Fig. 1). Starting from the Middle Eocene, extensive magmatism prevailed in NW Turkey that changed in character from calc-alkaline to alkaline in the Middle Miocene (e.g. Altunkaynak & Genç 2008).

The gold mineralisation in the Kestanelik deposit is associated with quartz veins that crop out over an area of nearly 2 km^2 (Fig. 2). The veins are hosted by Paleozoic mica schist (Okay *et al.* 1990) and quartz-feldspar-hornblende (QFH) porphyry that yielded an age of 43.34±0.85 Ma (K-feldspar Ar-Ar age) at the Madendağ low sulphidation deposit (Ünal-İmer *et al.* 2013) ~45 km to the southwest of the Kestanelik deposit. The oldest sedimentary rock unconformably covering the mineralized veins is Priabonian limy sandstone, and the youngest host rock for the veins is the QFH porphyry. We therefore presume that the age of the mineralisation is Late Lutetian-Early Priabonian (Middle to Late Eocene), suggesting that the Kestanelik gold deposit has a genetic link with the Eocene calc-alkaline magmatism in the region.

The Kestanelik epithermal gold deposit is a LS epithermal type. Classification as a LS epithermal system is based on the vein-ore textures, and predominant ore and gangue mineralogy. Although we have not identified adularia, a common mineral in low sulphidation systems, pseudo-bladed quartz replacing bladed carbonate mineral is typical in LS systems. We also observed colloform to crustiform quartz, comb to cockade ore-vein textures, and hydrothermal breccias. Ore minerals are native gold and accessory silver. Quartz veins generally have moderate to high gold grades (Au range in 1-20 g/t) and the Au:Ag ratio is generally in the range of 2:1 to 1:1. Gangue minerals are principally quartz, amethyst and chalcedony with pyrite and accessory chalcopyrite, sphalerite and galena dissemination in the vein quartz.

Vein quartz textures observed in the field are types typically ascribed to open space filling (such as cockade and comb textures) and replacement (such as saccharoidal and pseudo-bladed textures). The most striking feature of the veins is brecciation. Quartz vein breccias are generally composed of monomictic to polymictic clasts of host rocks and/or earlier phase(s) cemented by quartz-iron-oxide. Clasts of earlier breccia within some breccias indicate that at least two phases of brecciation occurred in the area. The absence of silica sinter, a diagnostic paleosurface indicator in LS epithermal systems, suggests that the uppermost parts of the epithermal system have been eroded.

The QFH porphyry in the field area is always altered with some typical argillic alteration minerals (illite and smectite). These assemblages were also observed in initial PIMA analyses (Hedenquist 2011). Alteration is more intense around field exposure and drill core samples of the veins, suggesting that the veins were the source of the alteration fluids. In deeper drill cores the degree of alteration is lower. All of the observed porphyry outcrops are altered, the furthest is up to 500m away from the nearest observed vein. This is very wide for a vein-associated alteration halo (more typically a few tens of meters, Hedenquist *et al.* 2000).

A mafic dyke that cuts and contains fragments of altered QFH porphyry (xenoliths) is observed in a drill core. Adjacent to the dyke, a polymictic breccia contains clasts of the same dyke and vein quartz in turn cemented by quartz. This textural evidence indicates that the vein-related alteration was already present when the dkye was intruded, suggesting contemporaneous mineralisation and dyke intrusion (Fig. 3). This dyke is therefore likely to be related to Cenozoic magmatism in the Biga Penninsula (e.g. Altunkaynak & Genç 2008).

The field area is cut by the deeply incised Kestanelik River, providing a topographic exposure interval of ~150 m. The post-mineralisation limy sandstone records to the SW to a mean dip of 29° and direction of 110°. This tilting is exceeded by the effect of the river incision meaning that the NE flank of the valley is equivalent to a pseudo cross-section through the very shallowest part of the hydrothermal system with the paleo-depth of vein emplacement increasing slightly to the SW of the field area.

Characteristics of the epithermal vein system

The gold mineralisation in the area is hosted by major quartz veins, wall rock veins and sheeted veins in the river valley. Outcrop geometries of the veins were mapped using a Trimble GPS (±0.1 cm). Vein-related detailed structural data (attitude, thickness, infill type, length, and typology) were collected from surface exposures and outcrops along the creeks. The structural data were plotted using the software package Stereonet (Allmendinger *et al.* 2013; Cardonzo & Allmendinger 2013) and used to calculate the paleostress field at the time of gold mineralisation. In addition, observations were made of the host rock deformation around the veins both in the field and in diamond cut drill cores. Vein textures and breccias were examined both on exposed vein outcrops and in drill cores, with the help of petrographic analysis.

The 3D subsurface geometries of the vein-host rock boundaries were constructed by using mapped outcrop geometries, detailed field data, well-logs and geochemistry data from 396 drill holes (255 diamond cut and 141 reverse circulation holes) supplied by Chesser Resources, who, at the time of fieldwork, were the license holder company of the Kestanelik deposit. Modelling of the top and bottom surface of each vein was performed in MOVE Structural Modelling and Analysis Software granted by Midland Valley's Academic Software Initiative. In addition, vertical cross sections perpendicular to the vein strike were created for each vein in the MOVE Software. All veins were modelled except two (the K2 and Topyurt veins) which had insufficient drillhole data.

Major quartz veins

There are 9 major mineralized quartz veins that form a northwest trending corridor in the deposit area. These veins, from north to south include Karatepe, KK4, KK3, KK2, KK1, K1, K2, K3 and Topyurt veins (Fig. 2). The host rock, strike length, mean strike, mean dip angle, and minimum and maximum width of each vein from outcrop measurements are summarized in Table 1. There are two mineralized vein sets in the area based on strike orientation; the first set strikes NE-SW (KK1, KK2, KK3, KK4, K1, western end of K3, Topyurt) while the second one trends E-W (Karatepe, K2, eastern end of K3). All of the veins are continuous (not segmented) except the segmented K3 vein and Topyurt veins, however some veins have discontinuous outcrop traces due to the erosion. The NE-SW sets host the majority of gold mineralisation according to the average gold grade calculations of the modelled veins using the geochemical gold assay data of related drill cores (Table 2). We describe these veins in turn from north to south, representing veins emplaced at increasing paleo-depths.

The Karatepe vein is located in the northern part of the area and hosted entirely within the QFH porphyry. It is E-W oriented and extends for a strike length of 350 m. The vein dips to the south (Fig. 2) with an average dip of 69.8 degrees (from surface data, subsurface dips are given in Table 2). Vein orientation data collected from outcrop revealed that the vein has a very corrugated strike on a meter scale. The deepest drill intersection is around 160 m below surface.

The KK3 and KK4 veins are hosted by mica schist and strike almost NE-SW (Fig. 2). KK3 vein has a 52 m strike length and varies between 2 m and 8.7 m wide. The vein dips to the SE with an average dip of 70.2 degrees. The KK4 vein has a strike length of 47 m and dips to the SE with an average dip of 68.3 degrees. The deepest drill intersection of the KK3 and KK4 veins are around 120 m and 100 m below surface respectively.

The KK1 vein and KK2 vein are hosted by mica schist and trend approximately NE-SW (Fig. 2). The KK1 vein extends 150 m along strike and dips to the SE with an average dip of 76.7 degrees. Vein outcrop width varies between 1.2 m and 9 m. The KK2 vein outcrop extends for 185 m, with an average dip of 75.8 degrees to the SE. The deepest drill intersection of the KK1 and KK2 veins are around 125 m and 100 m below surface respectively.

The NE-SW trending K1 vein extends over a strike length of around 240 m and dips to the SE (Fig. 2) with an average dip of 75.1. The deepest drill intersection is around 90 m below surface.

The K2 vein, hosted by mica schist, has an E-W trending strike length of 86 m and dips gently to the north (Fig. 2) with an average dip of 43.5 degrees.

The K3 vein is composed of two segments and its strike extends over 510 m (Fig. 2). The western segment of the vein system (K3W vein) is hosted by mica schist and trends NE-SW with a strike length of 230 m (Fig. 2). It dips to the NW with an average angle of 62.3 degrees. The deepest drill intersection is around 215 m below surface. The eastern segment of the vein system (K3E vein), is hosted by the QFH porphyry, extends intermittently over an E-W oriented corrugated strike with a length of 280 m and dips to the north (Fig. 2) with an average angle of 71 degrees. The deepest drill intersection is around 140 m below surface. The western segment of the K3 vein is more persistent and thicker than its eastern part.

The Topyurt vein, hosted by QFH porphyry, is located in the southern part of the study area perpendicular to the valley and cuts the Kestanelik River. It has 3 sub-parallel NE-SW trending segments in an N-S trending zone (Fig. 2) with a total exposed strike length of 154 m and dips to NW with an average dip of 65.1 degrees.

The host rock, strike length, mean strike, mean dip , and minimum and maximum width of each vein are summarized in Table 1.

The top and bottom surfaces of major quartz veins modelled in 3D (Fig. 4a) indicate that the thickness of the veins decreases with depth and that the veins generally have a flaring upwards geometry (Fig. 4b). The attitude of the modeled vein surfaces is generally different from that observed in vein outcrops (compare Tables 1 and2) since the veins change geometry with depth (Fig.4b). Histograms of the subsurface dip data of the modeled veins show that the dominant subsurface dip angle of each vein is close to that measured at the surface. In addition, rose plots of the subsurface strike data indicate that the dominant subsurface strike of each vein is close to that at the surface (Table 1 and Fig. 4c), although there are not many measurements from the surface due to erosion along vein walls (Table 1). The mapped variable geometry along strike is mirrored at depth and most of the veins have multiple locations at depth where the dip changes (i.e. the veins have vertically segmented sections with differing dips) (Fig. 4b). E-W trending veins have more geometric irregularities than NE-SW trending ones both along strike and dip (Fig. 4c and Table 2: see standard deviation values).

In layered rocks such dip segmentation has been previously interpreted to be the result of the competency contrast within different host rocks (e.g. Schopfer *et al.* 2006, 2007). However at this site the dip segmentation appears to be independent of the host rock type. Segmentation in the dip direction may also be caused by the growth and coalescence of small planar segments of the structures (whether faults or open-mode fractures) (Cox 2005).

Wall rock veins

Detailed structural data (thickness, infill type, length, attitude, and typology) were collected from the wall rock structures surrounding two of the major mineralized quartz veins: the Karatepe vein and the Topyurt vein. Dense vegetation and thick soil cover around other vein-associated structures prevented the collection of structural data.

The E-W trending Karatepe vein is associated with an array of extensional veins in the wall rock which defines left-lateral kinematics (Fig. 5a). These veins have comb textured hydrothermal quartz crystals oriented perpendicular to the vein walls (Fig. 5b-c). Their width varies between 4 cm and 26 cm. Their orientations are given in Fig. 5d. The wall rock veins in drill core define a complex mesh of multiple fracture orientations with mutual cross-cutting relationships (Fig. 6a-b) indicating several episodes of fracturing in the damage zone to the main veins.

The Karatepe wall rock also contains veinlets that are too thin to be visible in hand specimen. The petrographical studies showed that the veinlets are filled by inequant granular hydrothermal quartz (Fig. 6c). This texture shows that the opening of the fracture was more rapid than the growth of the quartz crystals (Ramsay 1980; Woodcock *et al.* 2007).

The area surrounding the Topyurt vein system is also dominated by extensional veins (Fig. 7a). These veins are only observed in the FW of the Topyurt vein (the hangingwall is not exposed) (Fig. 7a) and their width varies between 3 cm and 20 cm on the surface. They are characterized by the same infill of hydrothermal quartz and have comb textured hydrothermal quartz crystals oriented perpendicular to the vein walls (Fig. 7b). A stereonet of their orientation data is presented in Fig. 7c. The NE-SW trending Topyurt vein components and its wall rock structures are consistent with a right-lateral en-echelon brittle shear zone.

Sheeted quartz veins

Sheeted quartz veins hosting epithermal mineralisation are present along the Kestanelik River valley in the southern part of the study area (Fig. 2). These closely–spaced, sub-vertical and sub-parallel veins are oriented almost perpendicular to the course of the river bed, hosted by QFH porphyry (Fig. 8a) and comprise up to 25% of the total rock volume. Their thicknesses vary between 0.5 cm and 15 cm (Fig. 8b-c). They therefore cannot be shown individually on the map, and the region where they crop out has been indicated by shading (Fig. 2). Although outcrop quality is variable across the area, similar veins are seen nowhere else, so they appear to be confined to the deep levels of the vein system where exposed in the deeply incised river valley.

These steeply dipping veins contain well-developed hydrothermal quartz crystals almost perpendicular to the vein walls (Fig. 8c), and there is no evidence of shearing along the vein walls; therefore they are very likely to be extensional veins. Attitude data recorded from these veins are shown on a stereonets (Fig. 8d).

Vein textures and breccias

The epithermal quartz veins at the Kestanelik deposit are dominated by the textures resulting from the boiling of hydrothermal fluids such as cockade (Fig. 9) and colloform (Fig. 10b) textures indicative of open space filling characteristics, and textures representing replacement such as pseudo-bladed and saccharoidal (e.g. Buchanan 1981; White & Hedenquist, 1990; Dong *et al.* 1995). Colloform texture at Kestanelik refers to fine rhythmic bands of chalcedony (Fig. 10b). Cockade texture forms when isolated fragments of wall rock or early vein material are rimmed by fine-grained rhythmic bands of quartz (Figs 9, 10b). Pseudo-bladed texture forms when quartz or chalcedony aggregates replace bladed or platy calcite along their original crystal outlines (Fig 11b-f-h) immediately after the boiling and removal of CO_2. Saccharoidal texture occurs when quartz replaces the massive granular carbonate along crystallographic defects, and in this texture, loosely packed vitreous to milky fine grained quartz aggregates show sugar appearance in hand specimen (Figs 11a-d-e, 12).

Although the Karatepe vein is dominated by chalcedony, other veins are characterized by quartz infill. The most striking feature of the veins is brecciation suggesting multiple generations of hydrothermal fluid flow and mineralisation. All the major veins are brecciated except the Karatepe vein (Table 1). The sheeted veins are not brecciated, though they can display two different generations of fills (Fig. 8c).

The Karatepe vein is dominated by breccias with cockade texture hosted by altered QFH porphyry. Wall rock clasts within the cockade breccia are sub-rounded to rounded and poorly sorted. This shows that the vein was emplaced along a zone that was already brecciated before the first phase of fluid flow. The clasts show neither normal nor reverse grading in any of the drill cores from all depths of the vein, (Fig. 9).

A cataclasite of feldspar (from the wall rock QFH porphyry) and early chalcedony (Fig. 10a) cemented by a relatively later (younger) phase of chalcedony was observed by the petrographic study of thin section from a drill core sample (Fig. 10b) taken from the FW of the Karatepe vein-wall rock contact. This cataclasite indicates that after the vein was sealed due to a first phase of fluid flow and associated mineralisation, further shearing occurred along vein FW-wall rock contact, producing cohesive cataclasite.

All veins except the Karatepe vein are cement supported, monomictic to polymictic breccias composed mostly of clasts derived from host rocks mainly schist and/or pre-existing quartz veins cemented by quartz or quartz-iron-oxide (hematite and/or goethite or both). Four different breccia types were recognized on the basis of macroscopic and microscopic observations from the vein outcrops and drill cores; **(1)** ***Cement-supported breccias***, comprising host rock clasts, most commonly schist, cemented either by saccharoidal or pseudobladed quartz, or by crystalline quartz. The poorly- to well-sorted clasts are angular to sub-angular, and the cement is more than 50% of the rock volume. These breccias are generally observed close to the vein margins and form semi-continuous domains on the exposed vein outcrops (Fig. 11a-b). Schist clasts commonly have silicification between foliation planes. In Fig. 11c, foliation-parallel silicification is synchronous with the silica forming the breccia cement: silica at the contact of the clast with the cement can be seen to be in optical continuity with the foliation-parallel silica. Conversely, in Fig. 11d, clasts containing foliation-parallel silicification are surrounded by a later quartz cement. **(2)** ***Crackle (jigsaw-fit) breccias***, consisting of clasts of pre-existing vein infill that generally match together and are cemented by quartz-hematite or quartz- goethite in a network of veinlets. Moderately- to well-sorted clasts are generally angular to sub-angular. In these cement-supported breccias, the cement is always less than 50% of the rock volume (Fig. 11e-f-g). ***(3) Chaotic breccias*** are composed of polymictic clasts of host rock and/or pre-existing vein infill with different quartz textures. The cement is quartz-hematite or quartz-goethite. Clasts are sub-angular to angular, poorly- to well-sorted, and range from mm to cm scale. These breccias are generally more frequent at the highest part of the vein outcrops (Fig. 11h-i). ***(4) Tectonic breccias*** with shear indicators were only seen in two different thin sections made from K3 vein and provides evidence that the E-W trending K3 vein was originally a fault. Deformed clasts and grains of saccharoidal quartz belonging to the previous phase have a cement of micro- to crystalline quartz-hematite. They were only observed in thin sections made from the samples taken from the margin of the K3W vein FW (Fig. 11j). Tectonic breccia has not been observed at the field scale – only in thin section. This may be because subsequent hydrothermal brecciation overprints any tectonic breccias formed during earlier shearing.

Host rock deformation

The Karatepe, K3E and Topyurt veins are hosted by QFH porphyry, while the other veins are hosted by schist. Deformation of the wall rock hosting each vein was studied in the field and drill core, and is summarized in Table 3. An important observation is that no shear indicator such as slickenlines was seen in the field at the Karatepe vein boundary.

Host rock schist around the NE-SW trending KK1, KK2, KK3, KK4 and K1 veins does not change foliation orientation adjacent to the veins and these veins have very sharp contacts with their host rock schist as observed in the field and drill cores (Fig. 12). In addition, drillcore and grab samples taken from the vein-wall rock contact do not return any shear indicator in petrographic analyses.

In contrast, the schist around the E-W trending K2 vein is highly fractured, contains hydrothermal quartz veins up to 6-7 cm wide that are discordant to the foliation planes, while the foliation can be observed to bend into the vein (Fig. 13a). In drill cores the wall rock schist of the K3 vein is also intensely fractured and brecciated (Fig. 13b-c). In addition, tectonic breccia with deformed clasts and grains of vein rock was observed at the vein footwall-wall rock contact (Fig. 11j) in the petrographic analyses.

The E-W striking Karatepe vein, hosted by porphyry, is surrounded by a domain of cemented extensional fractures and a small-scale post-mineralisation fault with small displacement (approximately 1 meter) on the Karatepe vein (Fig. 5). Cataclasite is also found at the vein footwall-wall rock contact (Fig. 10) in the petrographic analyses, which is an important shear indicator.

The wall rock zone of the Topyurt vein is also intensely deformed with many extensional veins and hard-silicified resistant porphyry screens (Fig. 7).

Discussion

Kinematics of the vein system

Cataclasite at the margin of the Karatepe vein (of feldspar from wall rock QFH, and chalcedony from first phase of mineralisation) contains asymmetric shear indicators (Fig. 10a), suggesting that the structure hosting the vein is a fault. Hydrothermal quartz forming the Karatepe vein (Fig. 9) and filling the comb fractures around it (Fig. 5c) shows that these structures are formed within the same deformation event. Infill of a comb quartz veinlet adjacent to the Karatepe vein has a granular texture and inequant fabric rather than a fibrous texture (Fig. 6c), which shows that the opening of the fracture was more rapid than the growth of the quartz crystals. We suggest that the brittle fracturing and dilation occurred during co-seismic or post-seismic aftershock phases of an earthquake, and then quartz cement was deposited progressively and sealed the fracture during the passive interseismic phase (e.g. Ramsay 1980; Woodcock *et al.* 2007). Furthermore, comb textured extension fractures around the Karatepe vein are proximal to the vein margin (Fig. 5b-c), and most of them curve towards the vein. This suggests that they are extensional fractures adjacent to the Karatepe fault that formed after slip on the irregular Karatepe fault plane.

The Karatepe fault-hosted vein is surrounded by extensional veins that have orientations consistent with left-lateral kinematics. We can infer a palaeostress for this subset of structures by assuming that the minor principal stress is perpendicular to the mean orientation of the Karatepe damage zone extensional veins, and their intersection with the fault plane is parallel to intermediate principal stress. The results of these calculations gives orientations of σ_1, σ_2 and σ_3 of **034°/02°, 124°/59° and 304°/31°** respectively (Fig. 14a-b). Hydrothermal macro crystalline quartz was also observed also in the extensional veins along the river valley similar to the ones around the Topyurt and Karatepe veins. The consistent textures and orientations of the main veins and sheeted veins suggest that all these veins are related to same hydrothermal mineralization event. Strikes of all these veins (Fig. 14c) suggest that the horizontal component of the minimum principal stress (σ_3) was ***N35°W***. The Karatepe inferred stress (Fig. 14a) compares well with the extention direction for all the measured extensional veins in the field area (Fig. 14c).

Similar analyses cannot be conducted for K2 and K3 veins. Although the drill cores show that K2 and K3 have extensional veins in the damage zone, they are not exposed at the surface, so their orientations cannot be measured. The K2 and K3 veins are dipping to the north, opposite to Karatepe, but if they were active in the same stress field they too would have a component of left-lateral slip. In the absence of a more complete dataset (for instance through oriented drill core) it is not possible to conduct a more sophisticated paleostress analysis, but the structures all seem consistent with subhorizontal NE-SW σ_1.

The tilt on the younger sediments means that the older veins must also have been tilted. However it is not straightforward to relate untilted stress orientations to tectonics because (1) as there may be unmapped faults which tilt different blocks in the younger sediments, (2) previous tilting may have affected the block of mineralized veins before the formation of the unconformity and (3) Late Miocene aged vertical axis rotations (Kaymakci *et al.* 2007) must also be considered for re-constructing the paleo-stresses responsible for the geothermal system, although the amount of such vertical axis rotations are very difficult to contrain because of the large error ranges in the palaeomagnetic measurements. Instead we want to establish if the vein sets are consistent with formation in a single stress regime.

The inferred directions of the principal stresses indicate that the E-W trending Karatepe, K3 and K2 veins can be characterized as left lateral strike-slip faults, while NE-SW trending KK1, KK2, KK3, KK4 and K1 veins are extensional (Mode I) fractures (Figs 14d-e, 15). In addition, the NE-SW trending Topyurt vein and associated N-S trending zone of wall rock veins correspond to a right lateral en-echelon brittle shear zone (Fig. 14d-e). Although kinematic indicators could not be found for the fault-hosted veins, sheared cataclasite, tectonic breccia and intensely deformed characteristics of the wall rocks suggest that they are developed as a result of shearing. However, the NE-SW trending KK1, KK2, KK3, KK4 and K1 veins do contain evidence of extensional fracturing (Mode I opening) and lack any shear indicators and wall rock deformation.

Permeability enhancement and fluid flow

Integration of the data from the Kestanelik epithermal vein system and the review of the literature suggest that three permeability enhancement and fluid flow mechanisms that could have been active in the Kestanelik epithermal gold deposit.

Co-seismic rupturing

Co-seismic rupturing generates permeable pathways, which are clogged progressively by interseismic hydrothermal sealing. Sibson (1987) suggested that episodic fault rupture causes co-seismic dilation at the rupture zones and an associated fluid pressure drop. The co-seismic fluid pressure drop drives boiling, which is evidenced by the common occurrence of pseudo-bladed quartz and crackle breccia in the Kestanelik veins. Rapid closure of permeability by hydrothermal precipitation clogs pathways and results in local pressure build-up. Quartz-iron oxide cement within the breccias shows that ascending boiled fluid may also have mixed with descending oxidized surface meteoric water in the shallower parts of the system (Fig. 15). Salinity and homogenization temperature data from fluid inclusion analyses along with the O- and H- stable isotope analyses of fluid inclusions could be used to further constrain boiling and mixing events.

Shear indicators such as cataclasite and tectonic breccia cemented by a later phase of silicification are observed at the footwall of the vein-wall rock contacts of the Kestanelik fault-hosted veins. These and the presence of angular wall rock clasts at the margins of extensional (Mode I) fractures suggest rupturing along the fault planes and extensional fractures (Fig. 15).

The inequigranular infill of a comb quartz veinlet at the wall rock of the Karatepe vein shows that the opening of the fracture was more rapid than the growing of the quartz crystals. This texture is more consistent with the brittle fracturing and dilation occurring during co-seismic or post-seismic aftershock phases of an earthquake, than with progressive silicification to seal the fracture during the passive interseismic phase (Woodcock *et al.* 2007). In addition, the absence of any grading in the clasts of the cockade breccias of the Karatepe vein (Fig. 9) may indicate that both shaking (where brecciation occurs due to seismic faulting and clasts are cemented during interseismic period) and fluidisation (see below) may have played a role in the formation of the cockade breccias (c.f. Frenzel & Woodcock 2014): These represent the first phase of fluid flow and formation of the Karatepe vein.

Hydraulic fracturing

Rapid hydrothermal sealing of the pathways by mineral deposition could cause an increase in hydrothermal fluid pressure. Increase in fluid pressure may promote extensional-shear failure of the vein walls at depth, which are subsequently propagated upwards into the shallowest part of the crust. Provided that the pore fluid factor increases at rates higher than the increase in stress difference (Cox 2005), when the hydrothermal fluid pressure exceeds the combined minimum principal stress (σ_3) and the tensile strength of the cap rock (T), then hydraulic fracturing occurs (Phillips 1972). This triggers boiling due to pressure release and creates permeable structural conduits for the input of fluids, and results in formation of hydrothermal crackle breccias without significant rotation of the fragments (Jebrak 1997). The cements have to be very rapidly deposited or the clasts would settle out causing grading and/or rotation. Crackle breccias with fragments of the early quartz infill without significant rotation cemented by later quartz or quartz iron-oxide-forming a network of veinlets observed at Kestanelik veins (Fig. 11e-f-g) indicate dilatant fracturing with a negligible shear component and suggest hydraulic fracturing may have occurred at the main vein conduits. As discussed above, the absence of any grading may indicate fluidisation, where brecciation occurs due to hydraulic fracturing and subsequent fluid flow cements the clasts (Frenzel & Woodcock 2014)

Transient local stress variation

Local stress orientation can change transiently, resulting in permeability enhancement. Intrusion of dykes coeval with the gold mineralisation at Kestanelik (Fig. 3), and the dynamic nature of the geothermal systems may explain the transient kinematic variation by disrupting the local stress field and triggering earthquakes (Fukuyama *et al.* 2001; Toda *et al.* 2002; Waite & Smith 2002; Micklethwaite 2009). Transient local stress variation might enhance permeability along the corrugated strike of the Kestanelik structures by facilitating slip on misoriented surfaces and influencing the kinematics of the structures. In addition, locations where the dip changes in the Kestanelik structures have potential to enhance permeability since they lead to stress concentrations and localize intense deformation compared to the smooth and planar segments (Cox 2005) during the earthquakes. It is important to note that permeability and fluid flow will be intermittent in both cases.

Conceptual model for the evolution of the Kestanelik veins

On the basis of field, drill hole and microstructural observations we suggest that the dominant mechanism for formation of the vein textures was co-seismic ruturing (Figure 15). When an earthquake occured, E-W trending fault-hosted veins reactivated and opened along their footwall-wall rock contacts. Conversely NE-SW trending mode I fracture-hosted veins reactivated and opened along either margin. Coseismic rupture and dilation resulted in rapid fluid pressure drop and drove boiling of hydrothermal fluids. Boiling fluid rose along the newly created permeable pathways and may have mixed with descending oxidized surface meteoric water at the shallower parts of the system. The evidence for rupture along the walls of the veins includes: shear indicators such as cataclasite and tectonic breccia of wall rock; pre-existing vein infill cemented by a later phase of silicification observed at the footwall of the vein-wall rock contacts of the two of the fault hosted veins (Karatepe and K3 veins), and the presence of angular wall rock clasts at the margins of extensional (Mode I) fractures. Evidence for multiple brecciation and sealing events is chaotic breccias with polymictic clasts from pre-existing vein infill and clasts of wall rock cemented by quartz-hematite or quartz-goethite. This evidence suggests repeated reactivation and opening in subsequent co-seismic events. Crackle breccias are evidence that hydraulic fracturing may also have taken place.

Although none of the fault rock textures that have been observed are definitely diagnostic of dynamic rupture, it is not possible to exclude dynamic slip (Cowan, 1999; Rowe & Griffith 2015). However it has been documented that earthquake rupturing can induce opening of faults and fractures off the plane of the main fault (Micklethwaite & Cox 2004, 2006). Kestanelik was likely to have been an earthquake prone region in the Late Eocene at the time of mineralisation because of the tectonic activity caused by further convergence after the closure of the northern branch of the Neo-Tethys Ocean (Late Cretaceous-Early Eocene: Şengor & Yılmaz 1981; Okay & Tüysüz, 1999; Sherlock *et al.* 1999; Önen & Hall 2000; Kaymakci *et al.* 2007, 2009). In addition, it is well known that geothermal regions are dynamic, and that pressure transfer due to hydrothermal flow and mineralisation can induce seismicity (e.g. Hill 1977).

As noted above, the altered porphyry zone is wider than usually expected for structurally-controlled alteration. It is possible that this wide halo is futher evidence for multiple recharge events of the altering fluids through repeated rupture of the main veins, and more protracted flow within the damage zone veins.

Implications for prospect evaluation

Mapping and study of veins, wall rock veins and collecting structural data on the veins are powerful tools to unravel the kinematics of the vein system. Correlation of the kinematics of the mineralized or high-grade vein system along with timing of the mineralisation may help to discover the areas or targets by defining the favourable orientation for structures to the mineralisation. Because repeated boiling results in multiple overprinting of textures, key features such as the shear textures may be missed if only a limited number of outcrop or drill cores are examined; therefore comprehensive petrographic investigation of vein material and delineating the ore-vein textures addressing multiple boiling and silicification phases (especially close to the vein margins) is strongly advised. The understanding of textures showing clogging and subsequent boiling of the hydrothermal systems in correlation with structural easement or enhancement of fluid flow along the conduits may contribute to the target assessment in epithermal systems as gold precipitation is triggered by boiling and oxidation in low sulphidation epithermal gold deposits. Thus mapping and petrographical analysis of the ore-vein textures both on the outcrops and in drillcores together with the geochemical analysis of gold assay data not only help to understand the likely gold deposition mechanism(s) but also the potential gold distribution within the deposits.

Conclusions

The Kestanelik fracture system is a LS epithermal gold deposit evident from pseudo-bladed quartz, colloform to crustiform quartz, comb to cockade ore-vein textures, and hydrothermal breccias. The mineralisation is hosted by major quartz veins up to 13.6 m thick, as well as sheeted extensional quartz veins in the valley and, extensional wall rock veins surrounding the major quartz veins. Vein textures and breccias are indicative of repeated sealing and subsequent brecciation of wall rock and the pre-existing vein infill. Boiling and fluid mixing are likely mechanisms of gold deposition. According to the field and petrographic data; the kinematics of the vein system is consistent with formation in a single regional stress field: E-W trending veins are characterized as left lateral faults, whilst NE-SW trending veins are characterized as extensional (Mode I) fractures. The gold grade is higher in the extensional veins; although further detailed analysis of the vein textures is required to unpick the mechanism(s) of gold deposition.

Cataclastic deformation and tectonic brecciation of wall rocks and early quartz, hydrothermal crackle breccias, and matrix supported chaotic breccias of pre-existing vein infill, all of which are cemented by late iron-oxide-bearing quartz indicate that co-seismic rupturing and hydraulic fracturing are two major permeability enhancement mechanisms which would have caused repeated reactivation of clogged permeable pathways at Kestanelik. Additionally, transient local stress variation, caused by syn-mineralisation dyke intrusion, has the potential to enhance permeability on mis-oriented surfaces and at locations where the dip changes on vein planes. These results indicate that a thorough understanding of structural geology and kinematics, when coupled with the examination of evidence for boiling and other mineralisation mechanisms should be an important tool in defining ore zones within areas of mineralisation in epithermal gold deposits.

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Figure captions

Fig. 1. (a) Major tectonic divisions of Turkey (simplified from Okay & Tuysuz 1999). **(b)** Simplified geological map of the Biga Peninsula with the location of the study area (modified from Türkecan & Yurtsever 2002).

Fig. 2. Geological map of the study area Kestanelik deposit.

Fig. 3. A drillcore (KED-6 65.5–65.7 m) photo showing a mafic dyke (upper right) and adjacent breccia with fragments of dyke and quartz vein cemented by quartz (upper left) on the margin of altered QFH porphyry intruded by the dyke (bottom) indicating contemporaneous mineralisation and dyke intrusion.

Fig. 4. (a) 3D view of modeled top and bottom surfaces of major quartz veins with DEM (Digital Elevation Model). **(b)** Representative cross section of each vein showing the flaring upwards geometry of the veins and their decreasing thickness with depth. **(c)** Rose plot of strike values and histogram of dip amount values of HW surfaces of each vein showing the strike and dip variability of modeled surfaces.

Fig. 5. (a) Detailed map of the Karatepe vein and its wall rock veins. **(b)** Photo showing one of the extension veins around the Karatepe vein. **(c)** Closer view of the extension vein having comb textured hydrothermal quartz. **(d)** Poles to the extensional veins around the Karatepe vein plotted on an equal-area stereonet with the arrows indicating the opening direction for the veins.

Fig. 6. (a) A core sample from KED-18 133.8-134 m showing mutual cross-cutting relationships of the wall rock veins close to the Karatepe vein footwall-wall rock contact (1.2 m from the vein wall down-hole equivalent to 0.9 m perpendicular distance) at the FW of the vein. n.b. the host porphyry here is not as altered as it is higher in the section where is has a strong yellow alteration (Fig. 5). **(b)** Sketch of the core sample. **(c)** A comb quartz veinlet filled by inequant granular hydrothermal quartz, and thinner quartz veinlets traversing the clay altered wall rock QFH porphyry close to the Karatepe vein footwall margin showing that opening rate of the fracture > precipitation rate of the cement (cmb qtz: comb quartz, wr: wall rock) (KED-16 124.4 m) (crossed polars image).

Fig. 7. (a) Detailed map of the Topyurt vein and its wall rock veins. **(b)** Photo showing one of the extension veins having comb textured hydrothermal quartz around the Topyurt vein. **(c)** Poles to the extensional veins around the Topyurt vein plotted on an equal-area stereonet with the arrows indicating the opening direction for the veins.

Fig. 8. (a) Photo showing the sub-vertical and sub-parallel sheeted quartz veins along the Kestanelik River valley**. (b)** Photo showing some of the sheeted quartz veins. **(c)** Closer view of one of the sheeted extensional veins having comb textured well developed hydrothermal quartz crystals oriented perpendicular to the vein walls. **(d)** Poles to the sheeted quartz veins plotted on an equal-area stereonet with the arrows indicating the opening direction for the veins.

Fig. 9. Cockade breccias composed of chalcedony enclosing sub-rounded to rounded and poorly sorted clay altered QFH porphyry clasts at different levels of the Karatepe vein. Size of individual cockade breccias neither decreases nor increases as elevation decreases (Note that the scale is same for each photo).

Fig. 10. (a) Cataclasite of feldspar (from the wall rock QFH porphyry) and early (phase 1) chalcedony (crossed polars image). n.b. drill cores are not oriented so it is not possible to derive sense of slip. **(b)** Photo of the drill core sample (KED-16 at 124.2-124.4 m) taken from the footwall of the Karatepe vein-wall rock contact showing the thin section location in which cataclasite observed and two different textures representing two different mineralization phases of the vein (fld: feldspar, ch: chalcedony, col ch: colloform chalcedony, coc ch: cockade chalcedony, wr: wall rock).

Fig. 11. (a) Breccia with the clasts of wall rock schist plus a cement of saccharoidal quartz close to the HW of the KK1 vein. **(b)** Breccia with the clasts of wall rock schist plus a cement of pseudo-bladed quartz close to the HW of the KK2 vein. **(c)** Breccia with schist clast (note the silicification is after brecciation, matrix and foliation planes are in optical continuity) (K3 vein) (crossed polars image). **(d)** Comb quartz matrix between two clasts of silicified schist. Silicification is parallel to foliation and before comb qtz formation. (KK1 vein) (crossed polars image). **(e)** Crackle breccia with the clasts of saccharoidal quartz separated by quartz-hematite cement observed close to the margin of KK1 vein. **(f)** Crackle breccia with the clasts of pseudo-bladed quartz separated by quartz-goethite cement

observed in a drillcore cutting the K3 vein (KED-14 70.5-70.65 m). (g) Crackle breccia with the clasts of saccharoidal quartz cemented by quartz-goethite in a drillcore cutting the KK1 vein (KED-7 13.1-13.2 m) **(h)** Chaotic breccia composed of polymictic clasts of pre-existing vein infill with different quartz textures cemented by quartz-hematite in a drillcore cutting the K3 vein (KED-20 30.1-30.2 m). **(i)** Chaotic breccia composed of polymictic clasts of pre-existing vein infill with different quartz textures cemented by quartz-hematite from the upper levels of K3 vein outcrop. **(j)** Tectonic breccia with deformed clasts and grains of early saccharoidal quartz which set in a microcrystalline quartz matrix observed in a thin section made from a hand sample taken from the outcrop of the K3 vein footwall margin (Note that the microcrystalline quartz replaces saccharoidal quartz fragments along the microfractures) (crossed polars image). (sac qtz: saccharoidal quartz, psbld: pseudo-bladed quartz, wr: wall rock, mqz: microcrystalline quartz, sil sch: silicified schist, cmb sac qtz: comb textured saccharoidal quartz, goet: goethite, qtz-hem: quartz-hematite, qtz-goet: quartz-goethite).

Fig. 12. (a) Sharp contact between the footwall of the KK1 vein and wall rock schist. **(b)** Photo of KED-105 74.5-82 m interval core boxes showing that the foliation of the schist does not change around the K1 vein. Note that the white veins around the K1 vein interval generally observed parallel to the foliation planes include meta-quartz. (Yellow dashed lines envelopes the vein interval).

Fig. 13. (a) Photo showing that the schist adjacent to the K2 vein is highly deformed and hosts hydrothermal quartz veins discordant to the foliation planes (Waved black lines represent the orientation of foliation surfaces; black dashed lines represent the boundaries of discordant veins.) Note that the foliation surfaces are not continuous and change their attitude. **(b)** Photo of KED-76 78.5-86.2 m interval core boxes showing that the host rock porphyry is fractured, brecciated and veined around the K3E vein. Note that porphyry includes the fragments of hydrothermal quartz veinlets around the HW of the vein (Yellow dashed lines envelopes the vein interval). **(c)** Photo of KED-20 24.9-33.4 m interval core boxes showing that the host rock schist is highly fractured and brecciated around the K3W vein. Note that the deformation is higher around the HW of the vein and schist includes the fragments of hydrothermal quartz veinlets around the HW of the vein (Yellow dashed lines envelopes the vein interval).

Fig. 14. (a) Determination of principal stress orientations based on Anderson’s theory of faulting by plotting the plane representing the mean orientation of the Karatepe vein and the mean plane of the

adjacent extensional veins on an equal area stereonet based on assumptions: (1) Minor principal stress (σ_3) is perpendicular to the extensional veins (2) Their intersection with the fault plane is parallel to intermediate principal stress (σ_2). **(b)** A hypothethic diagram showing the relationship between the principle stress directions and opening of the veins and movement along the fault plane (M plane is the movement plane). **(c)** Poles to the all extensional veins in the Kestanelik deposit plotted on an equal-area stereonet with the arrows indicating the opening direction for the veins. **(d)** A sketch model showing the kinematics of the major quartz veins at Kestanelik based on the determined principal stress directions. **(e)** A hypothethical model showing the opening of the structures hosting the Kestanelik major quartz veins.

Fig. 15. A conceptual model for the repeated reactivation and opening of clogged veins and associated fluid flow, mineralisation and resulting vein textures at Kestanelik. Note that K3 vein represents the fault hosted veins (except Karatepe vein), while K1 vein represents the extensional (Mode I) fracture hosted veins of the Kestanelik.

Tables

Table 1. *General characteristics of major quartz veins. All data are from measurements in outcrop.*

Vein	Host rock	No of data	Mean strike	Mean dip	Dip direction	Strike length	Min. width (m)	Max. width (m)
Karatepe	QFH porphyry	23	084,2	69,8	SSE	350	0,8	8
KK1	schist	11	047,3	76,7	SE	150	1,2	9
KK2	schist	13	044,5	75,8	SE	185	1	8,5
KK3	schist	5	046,9	70,2	SE	52	2	8,7
KK4	schist	4	042,4	68,3	SE	47	1	5,8
K1	schist	15	039,6	75,1	SE	240	0,9	13,6
K2	schist	8	268	43,5	NNW	86	0,6	12,9
K3E	QFH porphyry	18	274,5	71	NNE	280	0,6	7,8
K3W	schist	16	237,3	62,3	NW	230	2	12,5
Topyurt	QFH porphyry	10	224,5	65,1	NW	154	2	10

Table 2. *Descriptive statistics of modeled surfaces of each vein. All data are from the vertices of the subsurfaces).*

Vein	Subsurface*	No of vertices	Mean		Standard deviation		Median		Average gold grade (g/t) †
			strike	dip	strike	dip	strike	dip	
Karatepe	FW	110847	91.9	55.9	26.3	8.5	85.8	56.3	0.461
	HW	26048	92.7	55.8	25.1	10.9	85.8	57.3	
KK1	FW	7019	56.5	60.4	13.5	6.5	54.8	59.1	3.356
	HW	6202	55	62.6	6.4	5.1	54.9	61.8	
KK2	FW	444923	65.7	51.8	11.8	4.6	66.3	52.1	2.081
	HW	341583	67.5	53.2	16.4	8.6	65.8	55.8	
KK3	FW	45065	65.1	61.1	16.5	3.9	65.3	61.6	3.484
	HW	52235	55.7	66.2	9	4.1	55.7	66.2	
KK4	FW	231999	56.6	57.5	7.9	3.8	56.8	58.3	0.866
	HW	209578	58.3	59.9	5.2	3	58.4	60.5	
K1	FW	502776	52.9	63.6	22.8	6.8	50.3	64.7	2.921
	HW	384859	52.9	67.5	19.8	7.6	49	68.7	
K3E	FW	1048569	261.9	66.4	29	17	264.9	70.2	1.326
	HW	1042016	261	69	29.6	16.6	266.1	72.4	
K3W	FW	439652	225.9	63.3	31.9	8	232.3	64.4	6.943
	HW	317971	227.8	64.5	31.3	8.9	234.1	66.4	

*FW: Footwall, HW: Hangingwall. As is common in the mining literature we use these terms to refer to the wall below and above the vein respectively, and not to infer kinematics.

† Average gold grade values are calculated based on the geochemical gold assay data from the drill cores of the modeled veins.

Table 3. *Summary of host rock deformation observed around the major quartz veins.*

Vein	Host rock	Host rock deformation*
Karatepe	porphyry	F, V
KK1	schist	ND
KK2	schist	ND
KK3	schist	ND
KK4	schist	ND
K1	schist	ND
K2	schist	FC, V
K3E	porphyry	F, B, V
K3W	schist	F, B, V
Topyurt	porphyry	V

***B**: Brecciated, **F**: Fractured, **FC**: Foliation Changes, **ND**: Not Deformed, **V**: Veined

FIGURES

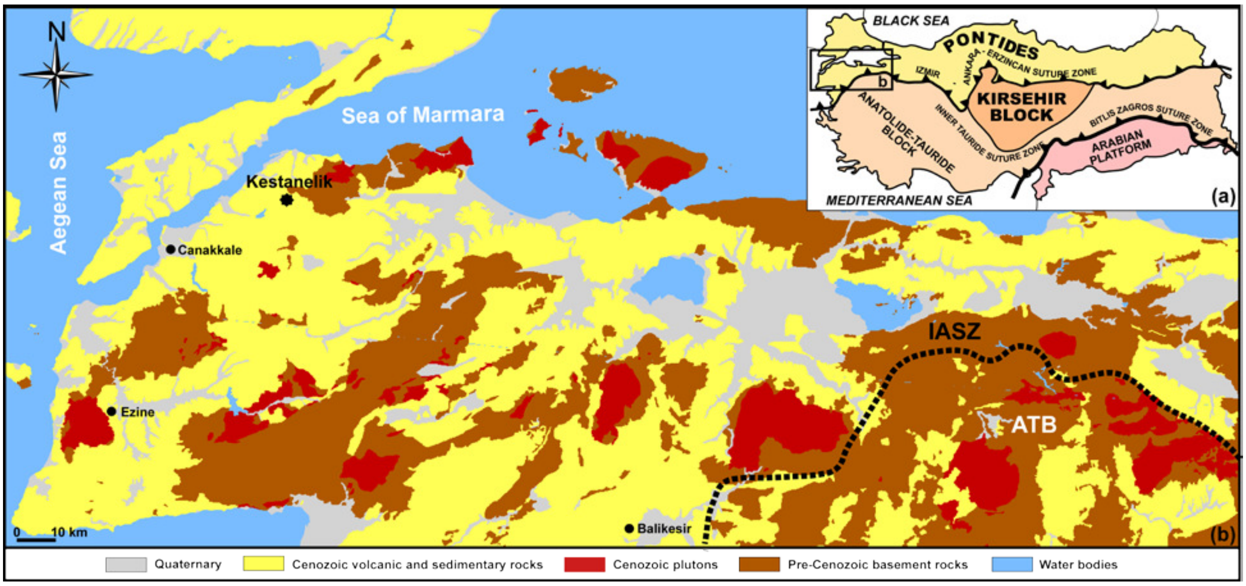


Figure 1

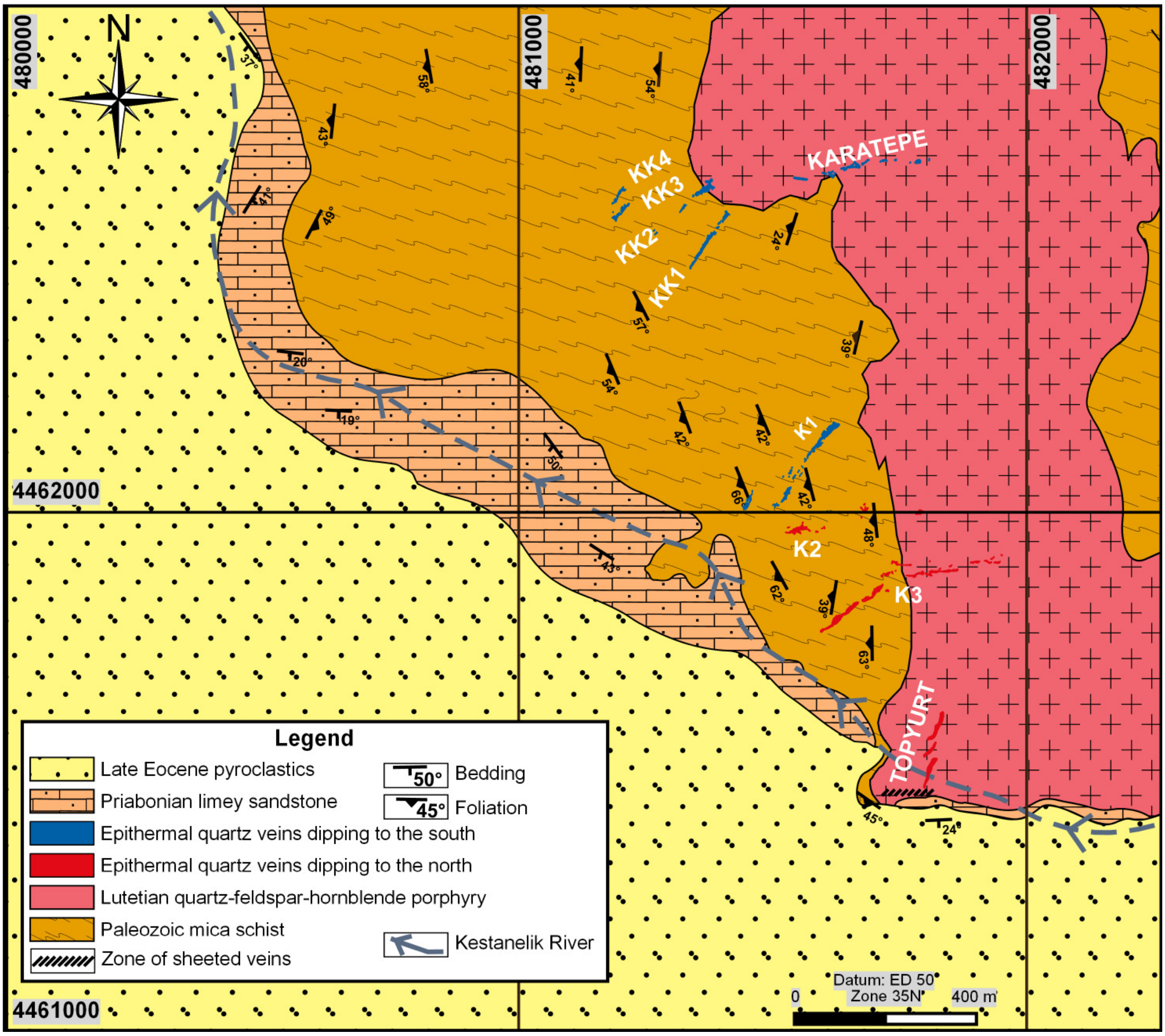

480000
481000
482000
4462000
4461000
N
KARATEPE
KK4
KK3
KK2
KK1
K1
K2
K3
TOPYURT
Legend
Late Eocene pyroclastics
Priabonian limey sandstone
Epithermal quartz veins dipping to the south
Epithermal quartz veins dipping to the north
Lutetian quartz-feldspar-hornblende porphyry
Paleozoic mica schist
Zone of sheeted veins
50° Bedding
45° Foliation
Kestanelik River
Datum: ED 50
Zone 35N
0
400 m

Figure 2

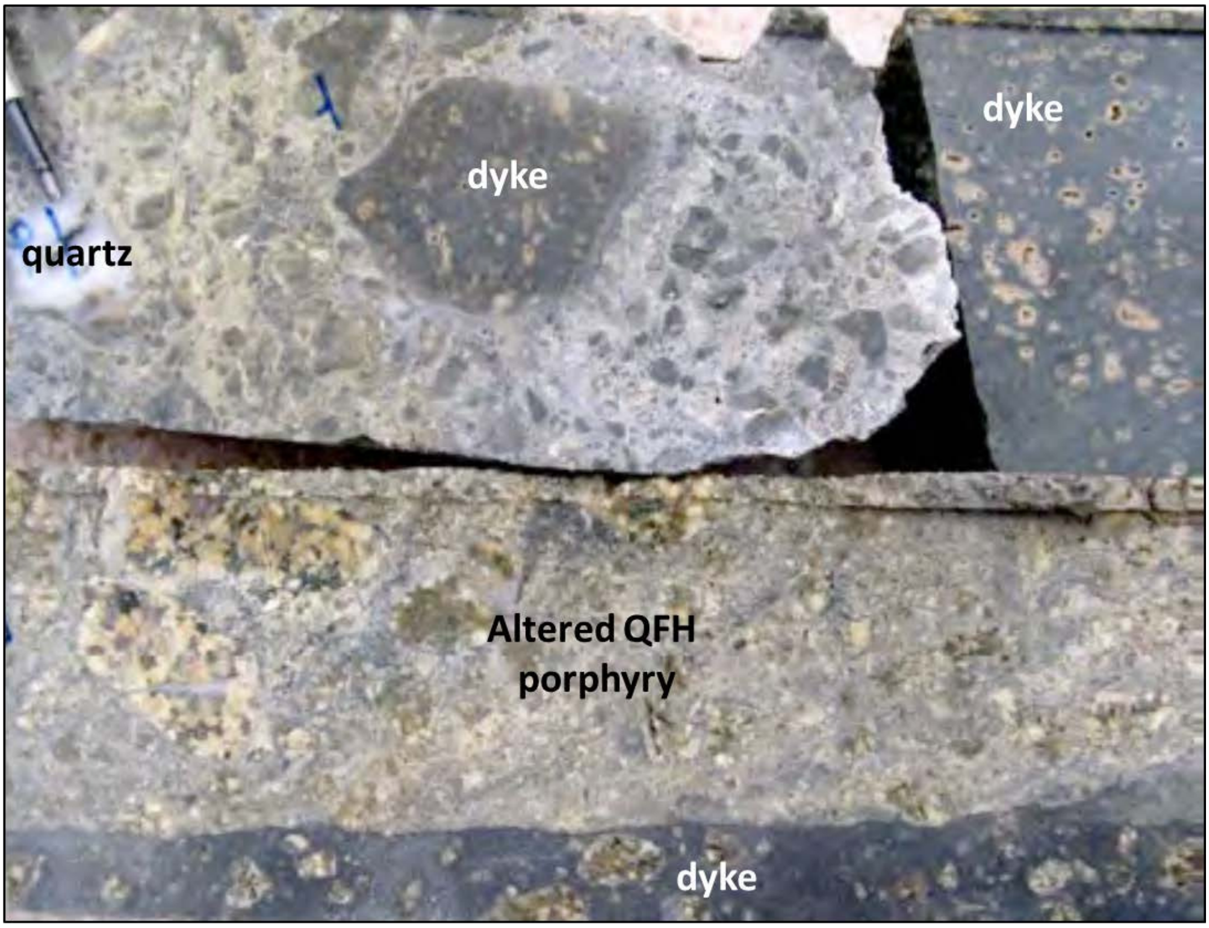
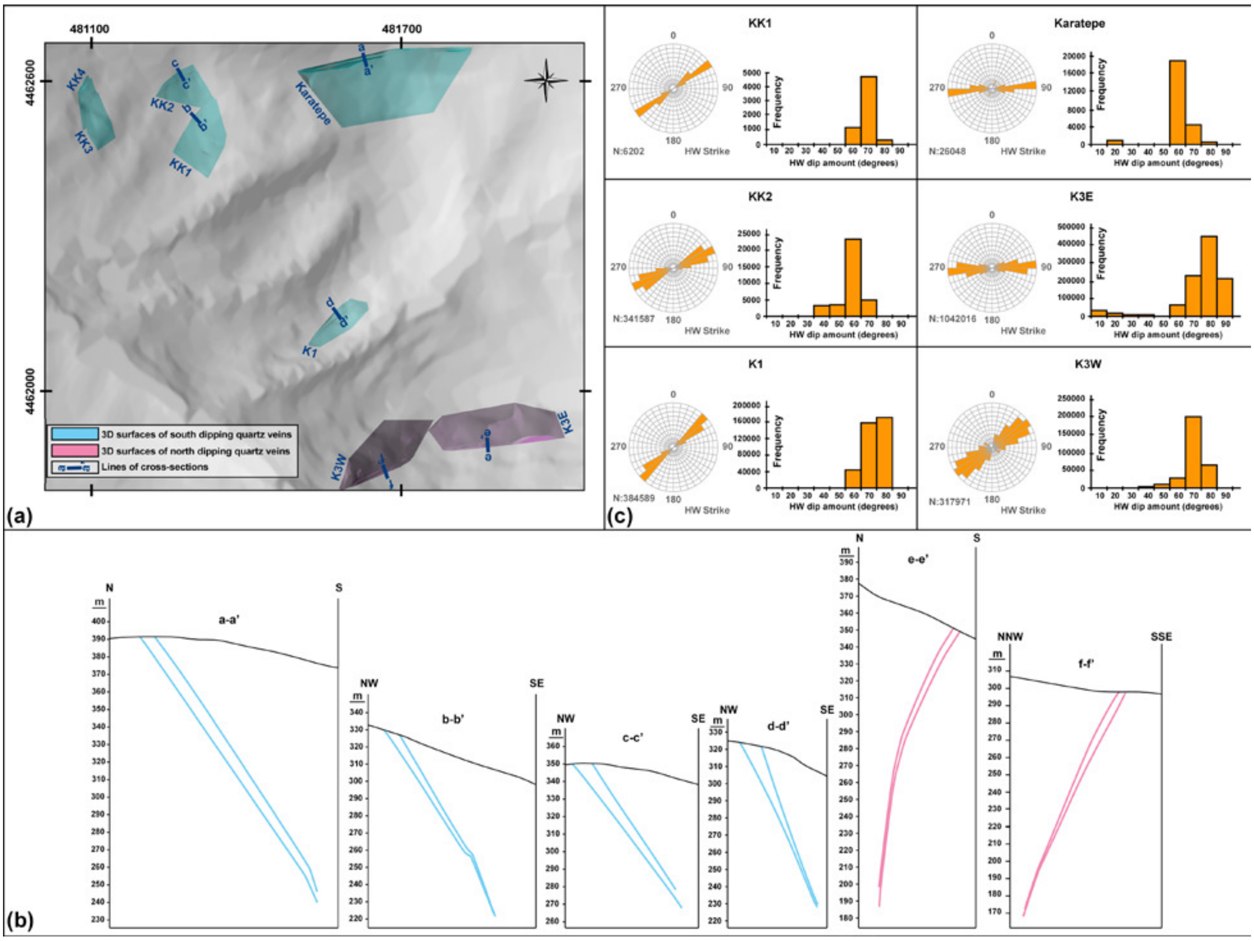


Figure 3



481100
481700
4462600
4462000
KK4
KK3
KK2
KK1
Karatepe
K1
K3W
K3E
3D surfaces of south dipping quartz veins
3D surfaces of north dipping quartz veins
Lines of cross-sections
(a)
KK1
Karatepe
KK2
K3E
K1
K3W
N:6202
N:26048
N:341587
N:1042016
N:384589
N:317971
HW Strike
Frequency
HW dip amount (degrees)
(c)
a-a'
b-b'
c-c'
d-d'
e-e'
f-f'
N
S
NW
SE
NNW
SSE
m
(b)

Figure 4

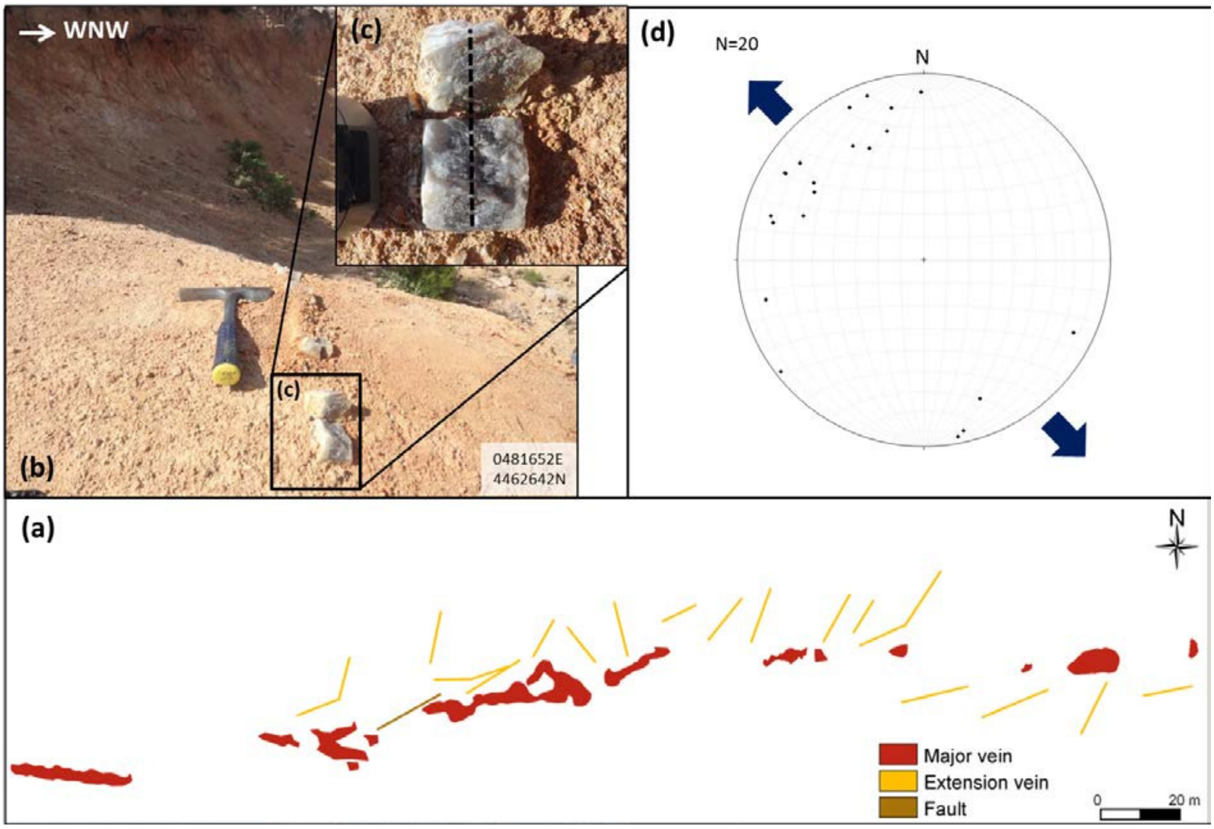


Figure 5

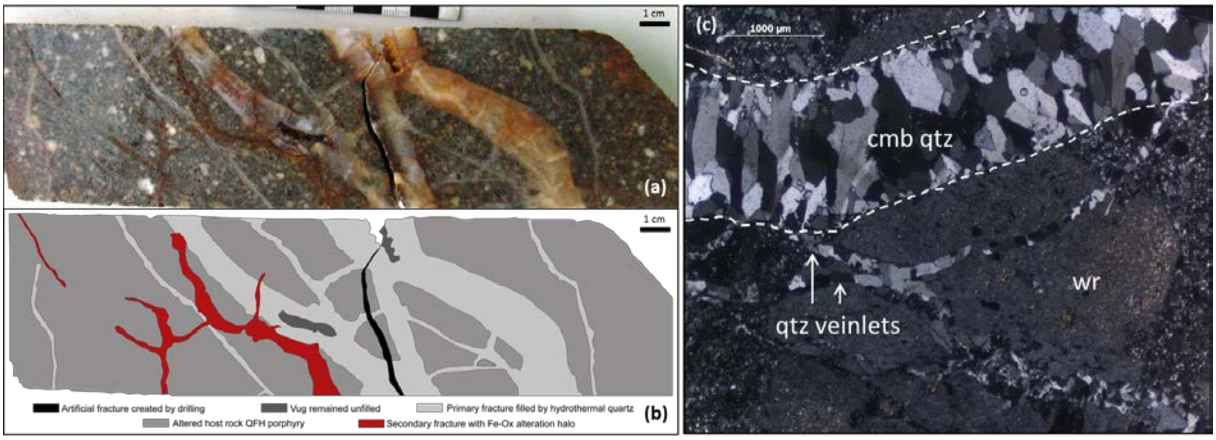
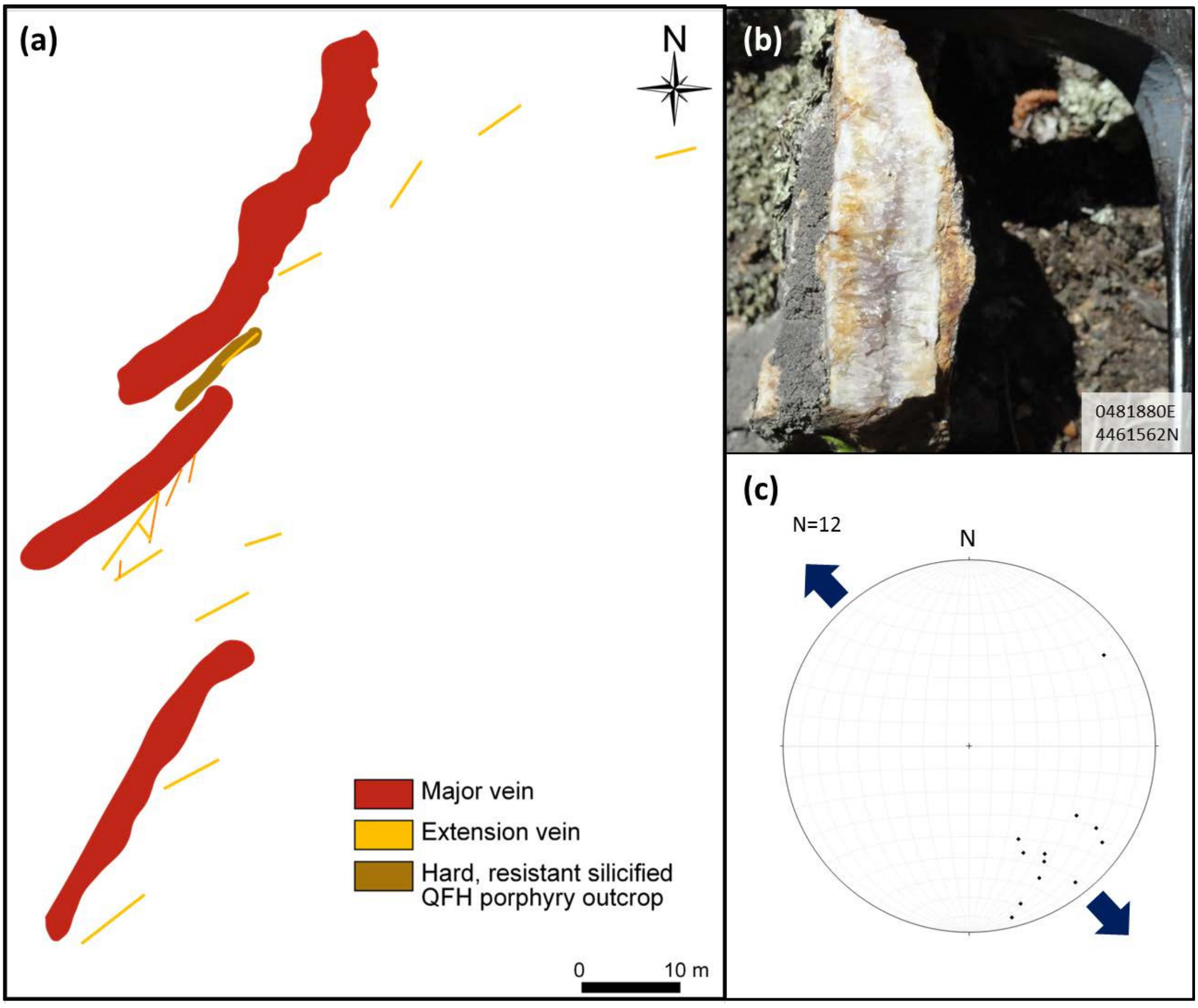


Figure 6



880

881 Figure 7

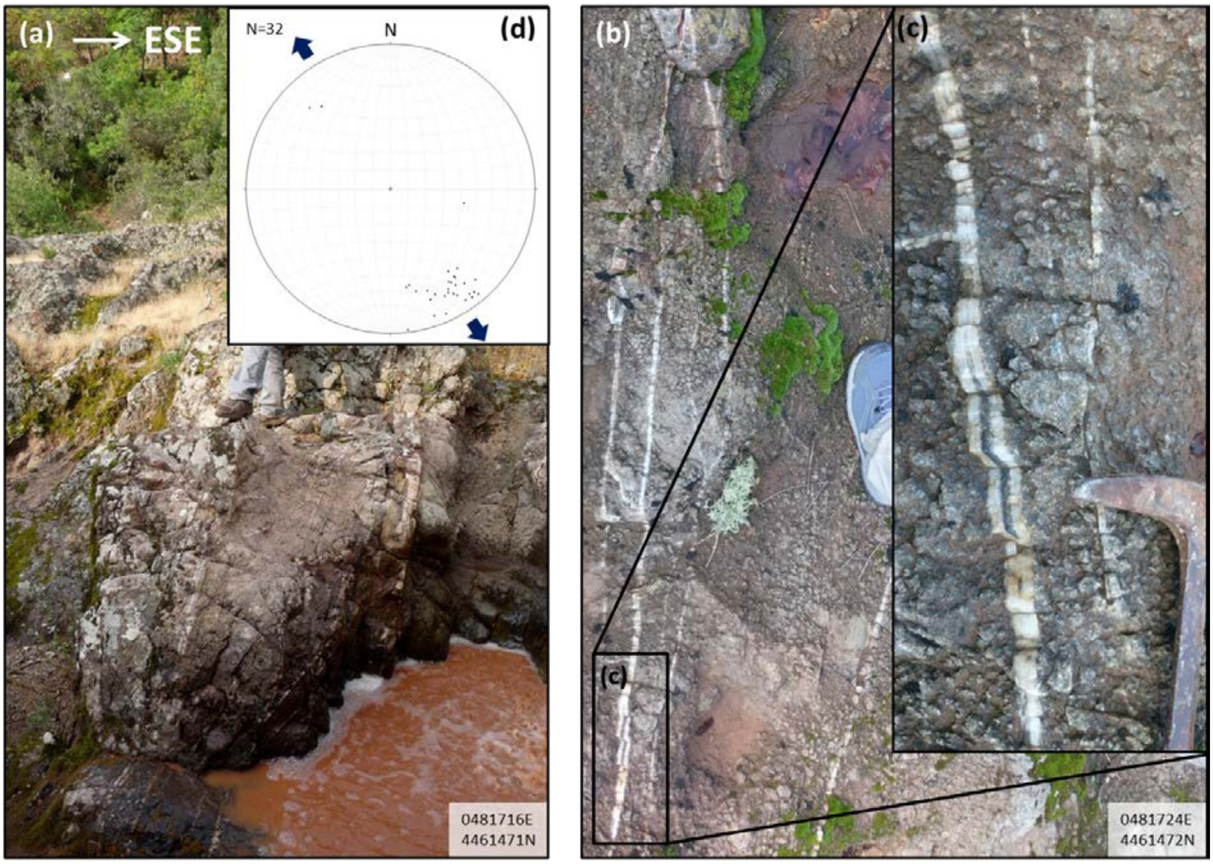


Figure 8

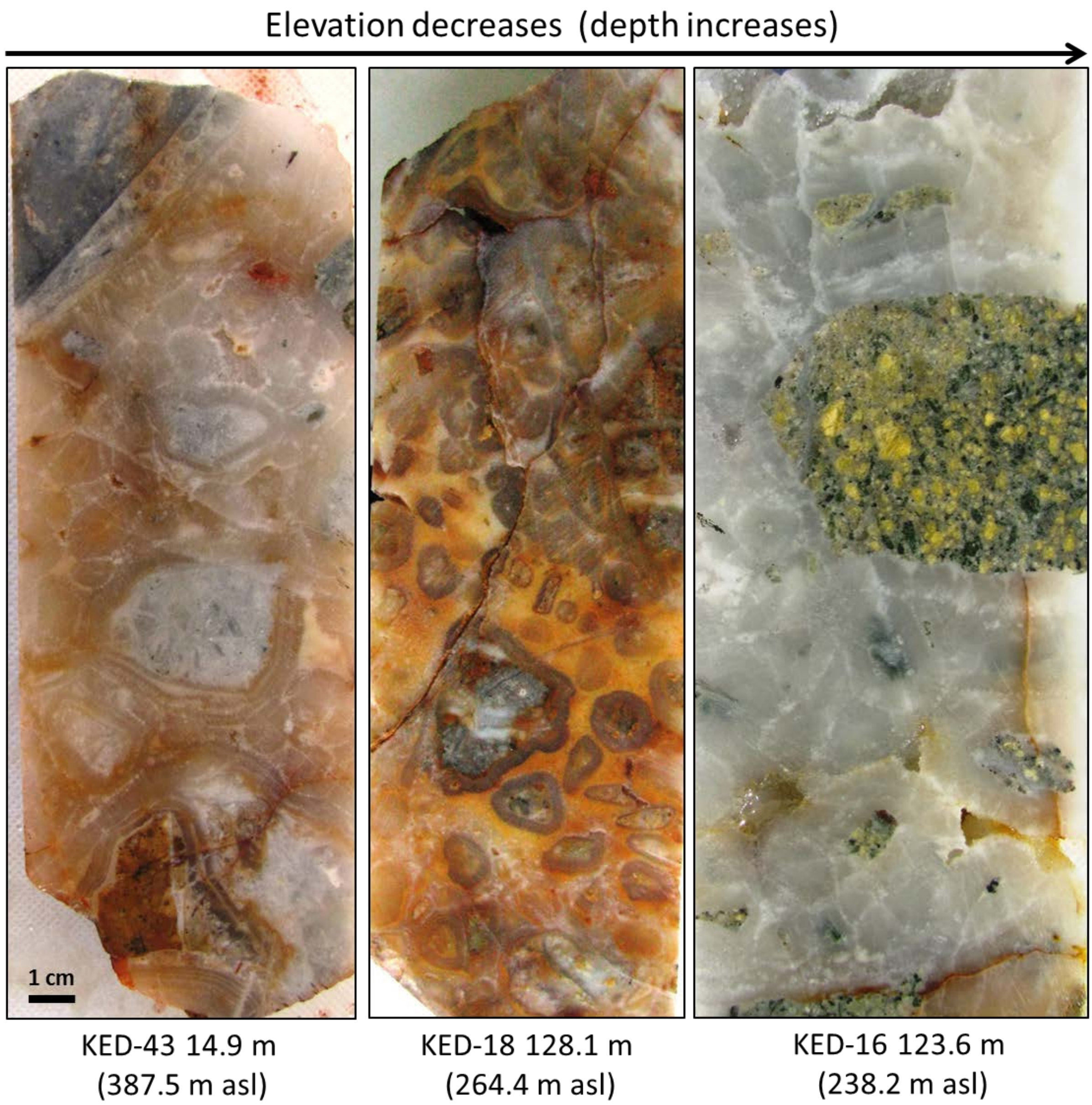
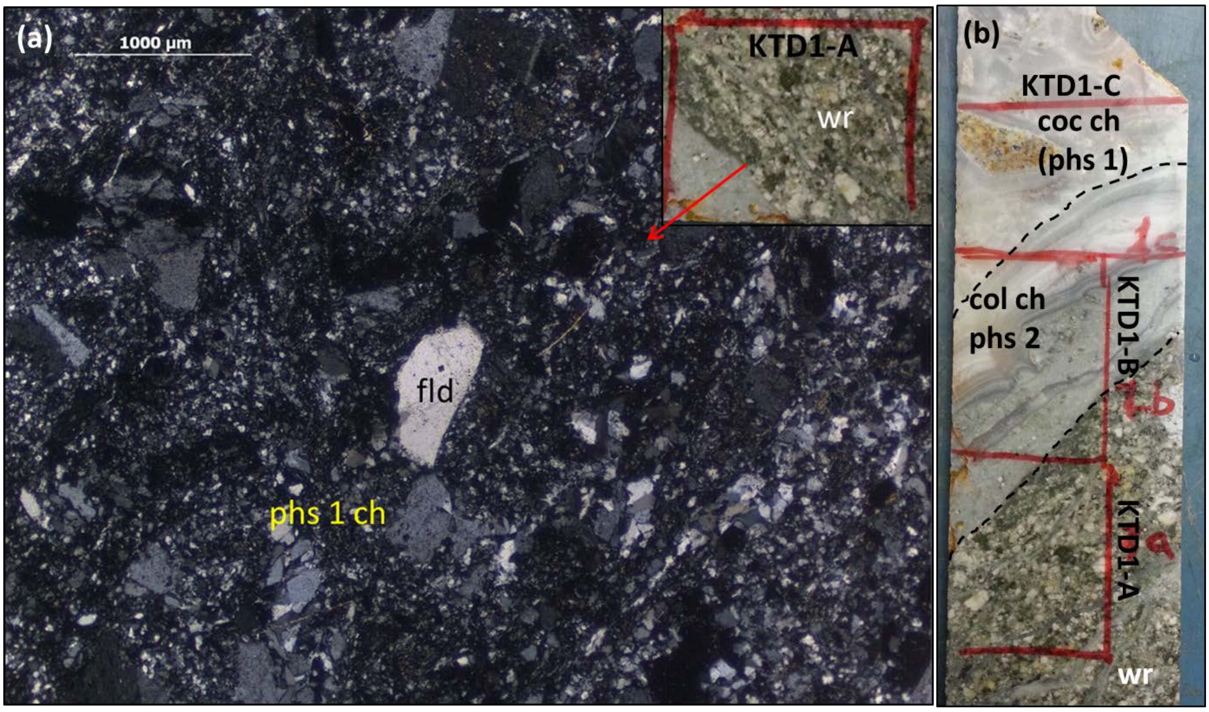
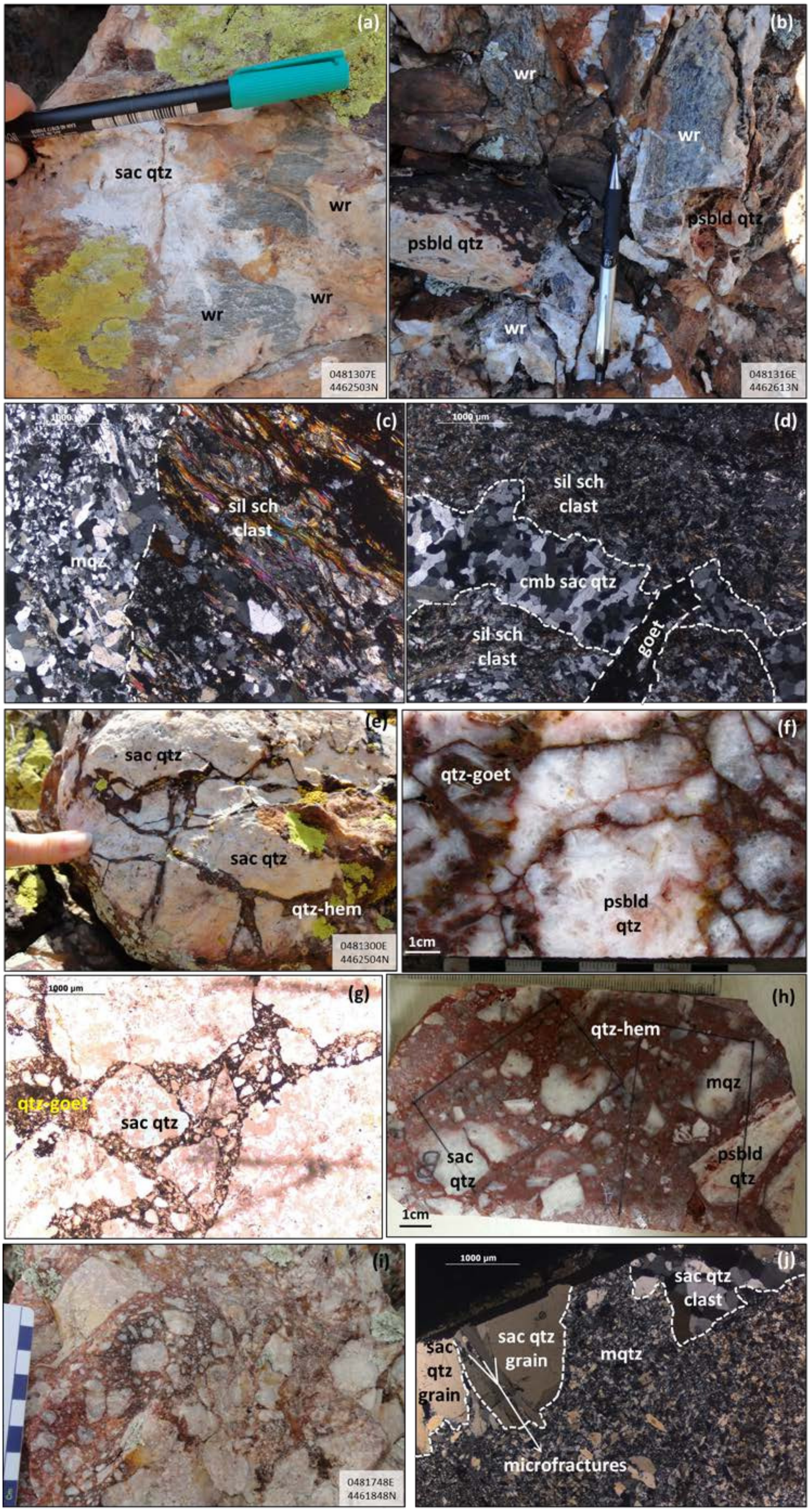

Elevation decreases (depth increases)
1 cm
KED-43 14.9 m
(387.5 m asl)
KED-18 128.1 m
(264.4 m asl)
KED-16 123.6 m
(238.2 m asl)

Figure 9

886



887 Figure 10



888

889 Figure 11

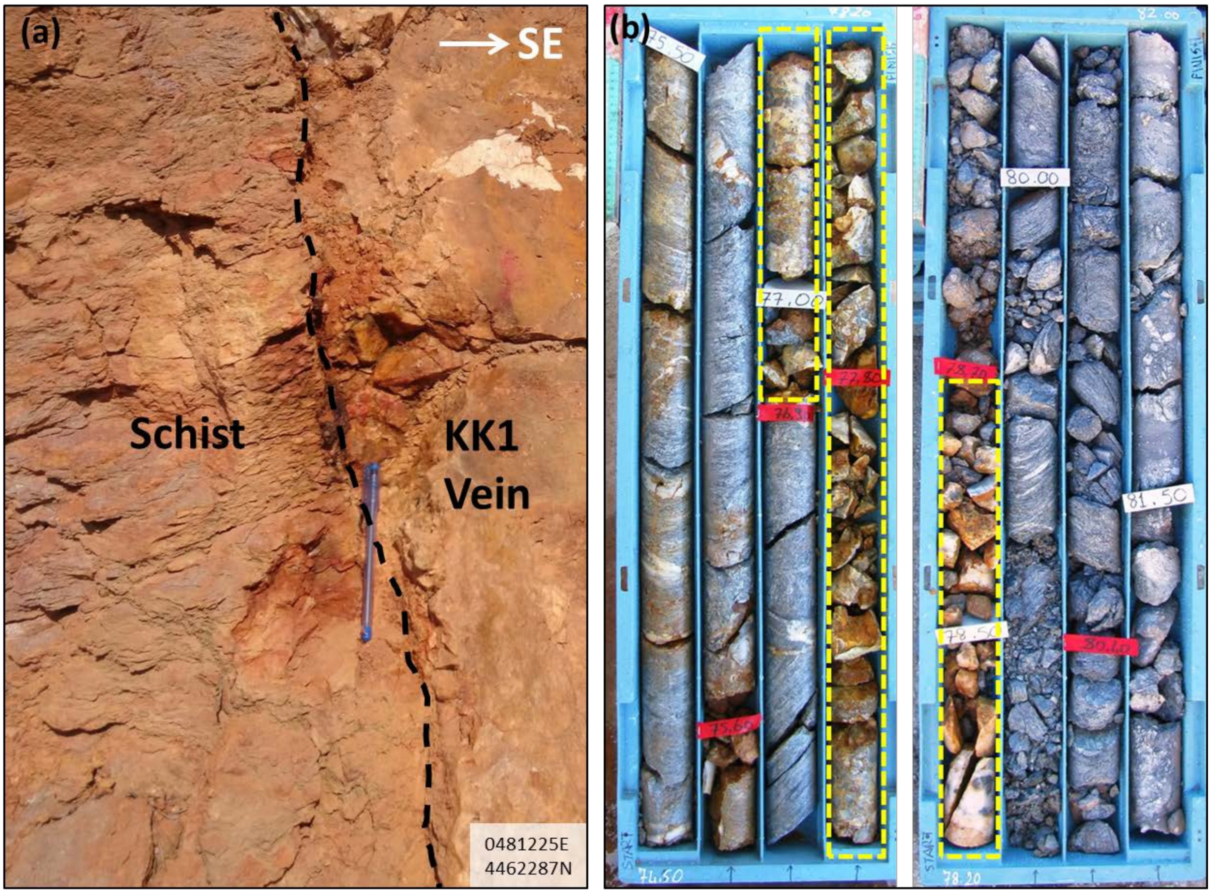


Figure 12

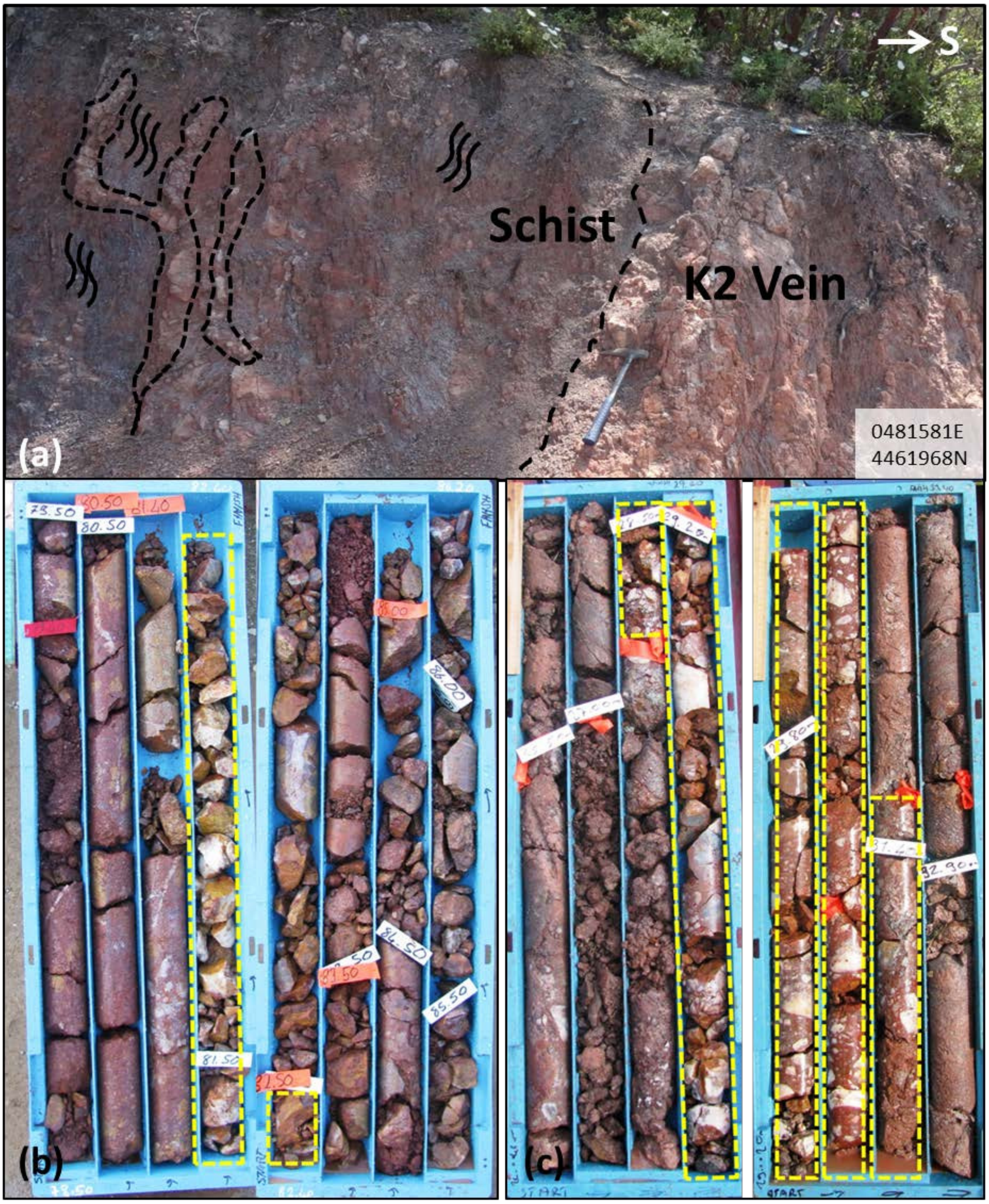
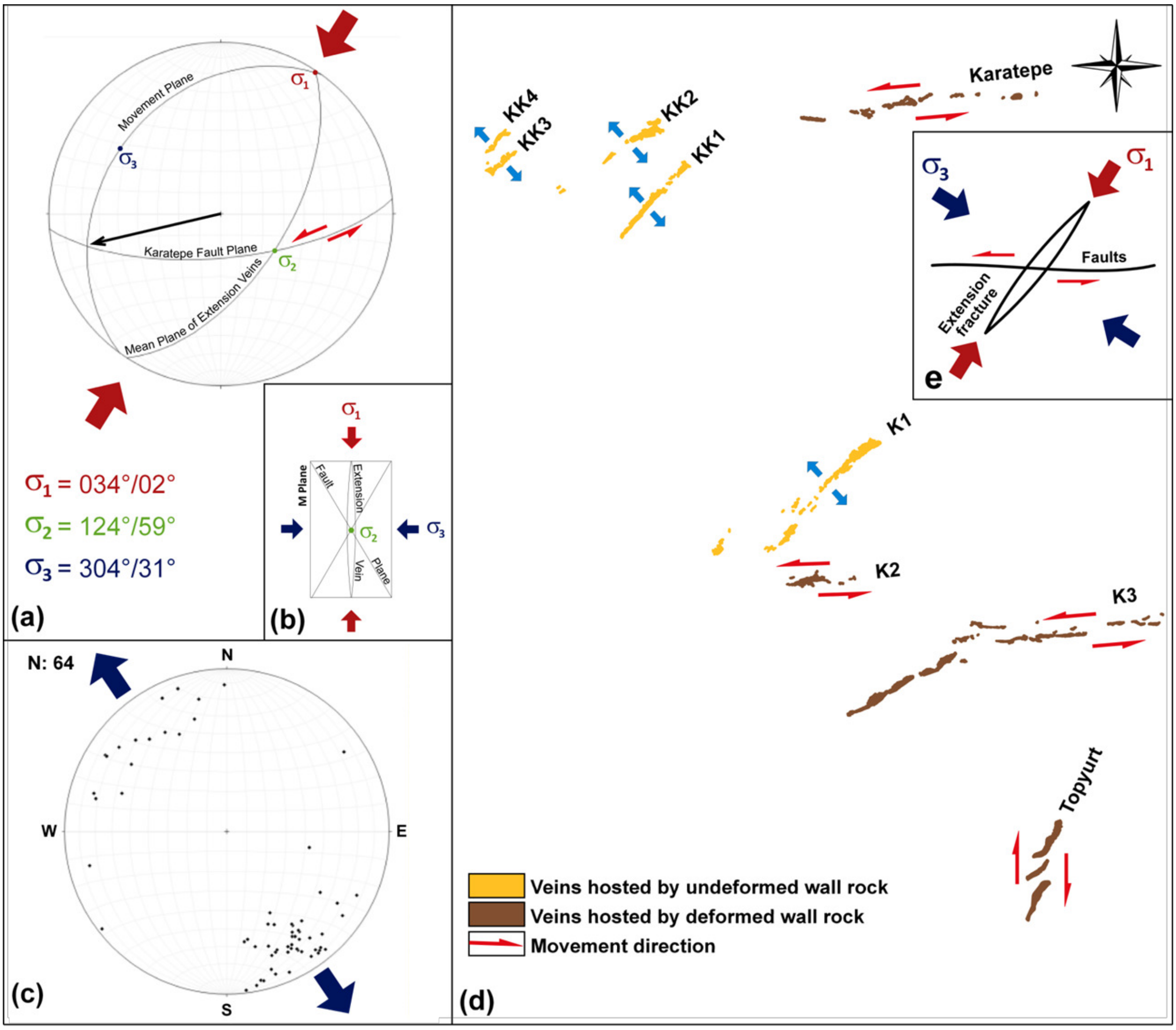
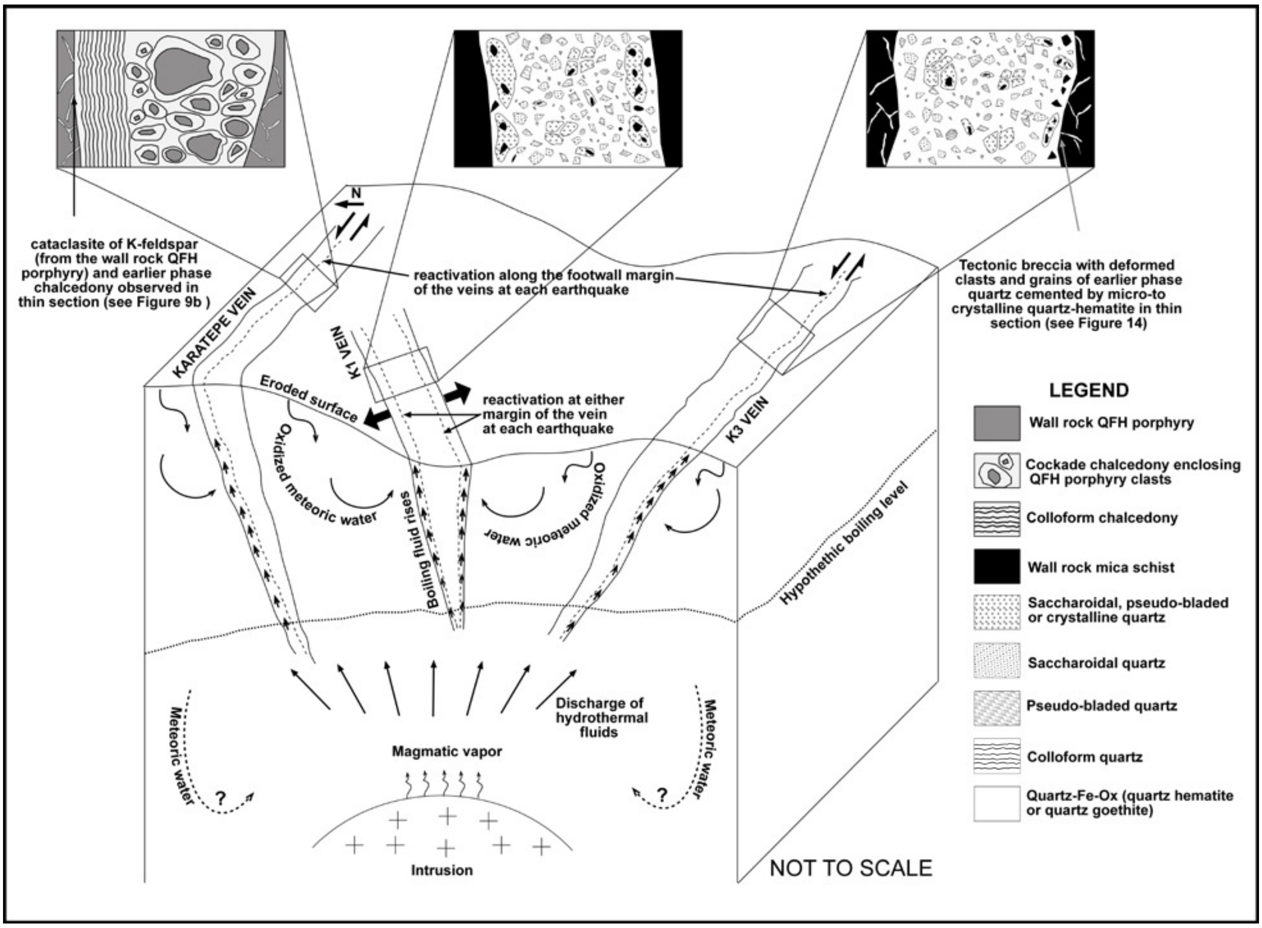


Figure 13

894



895 Figure 14



N
cataclasite of K-feldspar (from the wall rock QFH porphyry) and earlier phase chalcedony observed in thin section (see Figure 9b)
reactivation along the footwall margin of the veins at each earthquake
Tectonic breccia with deformed clasts and grains of earlier phase quartz cemented by micro-to crystalline quartz-hematite in thin section (see Figure 14)
KARATEPE VEIN
K1 VEIN
K3 VEIN
Eroded surface
reactivation at either margin of the vein at each earthquake
Oxidized meteoric water
Boiling fluid rises
Oxidized meteoric water
Hypothethic boiling level
Discharge of hydrothermal fluids
Meteoric water
Meteoric water
?
?
Magmatic vapor
Intrusion
NOT TO SCALE
LEGEND
Wall rock QFH porphyry
Cockade chalcedony enclosing QFH porphyry clasts
Colloform chalcedony
Wall rock mica schist
Saccharoidal, pseudo-bladed or crystalline quartz
Saccharoidal quartz
Pseudo-bladed quartz
Colloform quartz
Quartz-Fe-Ox (quartz hematite or quartz goethite)

Figure 15