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Fossil Versus Active Geothermal Systems: Reconstructing Fluid Pathways and Building a Bridge from the Past to the Present – Preliminary Results

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ABSTRACT

At Spiaggia Barbarossa on the Italian island of Elba, a hydraulic cataclastic shear zone produced by hydrothermal fluid overpressure was investigated in order to study anisotropic structures and fracture networks from macroscopic to microscopic scale. Fluid filled fractures and the degree of fracture networks that functioned as fluid pathways in a fossil hydrothermal system were also of interest. Tourmaline dykes and veins crosscut the oldest Tuscan units, the Calamita schists, parallel and oblique to the foliation and the Porto Azzurro pluton. Both metasomatic and hydrothermal tourmaline were identified in these veins. Metasomatic tourmaline exhibits reverse zoning with schoerl-rich cores and dravite-rich rims that indicate progressive replacement of biotite. Hydrothermal tourmaline forms the matrix fluid of cataclastic shear zones embedding quartz clasts within the range of ~ 100 – 2000 µm size. Fractal geometry analyses of the shear zones indicate the concentration of deformation during the regional extensional tectonic regime that was active from the Miocene to the Pliocene-Pleistocene. Quantification of fragmentation patterns by a modified Cantor-dust method (AMOCADO) indicates one process of fragmentation, whereas fragmentation of tourmaline-filled fragmentation zones at the western Barbarossa outcrop point to coeval processes of regional deformation and boron-rich fluid infiltration. The analysis of pattern anisotropy provides indication for two subsequent processes: hydraulic fracturing caused by fluid overpressure and shearing of the already fragmented rocks caused by a regional stress field. Both processes are regarded as roughly coeval.

1. INTRODUCTION

Exploring and exploiting deep geothermal energy for district heating and electricity generation is of growing interest. The increasing demand requires intensified investigation of basic geological processes and rock structures that control reservoir characteristics. Apart from underground temperatures, fluid circulation is one of the key parameters of the productivity of geothermal reservoirs. Circulation of geothermal fluids is decisively controlled by fracture networks and their connectivity at depth. Geothermal systems usually result from a combination of meteoric water and deep magmatic and/or metamorphic fluids. Deep fracture networks can be prospected by indirect methods, such as dedicated borehole logs and reflection seismology (Barbier, 2002, and references therein). The latter method serves to estimate the volume of fault-related damage zones where permeability is enhanced. The integration of data produced by indirect methods and numerical simulations (e.g., Kloditz and Clauser, 1998) can provide models that describe the relationship between the crustal structures and the geothermal resources. However, given the complexity of the natural systems, this approach does not allow detailed reconstruction of fluid pathways and fracture connectivity. This issue can be solved by studying fracture networks in the exhumed parts of fossil geothermal systems, best represented by epithermal systems (Hedenquist and Lowenstern, 1994). In these systems, palaeofluid pathways are observed as networks of mineral-filled, often ore bearing veins (Gudmundsson et al., 2002). A valuable prospection of a suitable present-day geothermal system requires a deeper understanding of fracture-forming processes in context with fluid overpressure. The latter is mostly marked by a transient behavior of hydrothermal pressure and chemical disequilibrium between matrix and fracture fluids, which results in pulsed transport through the fracture network (Matthäi, 2003), thus gradually sealing the fractures. It is necessary to understand the interacting processes that drive the formation, reservoir productivity, and the activity period of geothermal fields, all of which are dependent on geological setting..

The aim of the presented work is to study the behavior of fracture zones produced by hydrothermal fluid overpressure from a regional scale to the micro-scale. The study focuses on the development of an ancient fracture zone with anisotropic cataclastic structures and fracture networks acting as fluid pathways in a system that is geologically linked to an active geothermal field.

The Larderello geothermal field, located in southern Tuscany/Italy, is one of the few steam-controlled high-enthalpy systems worldwide. Intense research of this site during the last century delivered many results describing the geological development of the geothermal field (Batini et al., 2003), magmatic development of the underlying granitic batholith (Dini et al., 2005; Boyce et al., 2003), fluid inclusion composition (Boiron et al., 2007; Dallai et al., 2005), reservoir characteristics (Musumeci et al., 2005), etc. In this sense, the fossil geothermal precursor system of Elba

Island located 40 km westward provides the opportunity to study a direct "frozen" clipping of a hydrothermal system similar to the active Larderello geothermal field, thus providing useful information regarding the interaction of overpressure fluids and the wall rocks during the late granitic cooling phase.

2. GEOLOGICAL SETTING

2.1 Elba

A geological map of Elba and the study area is given in Figure 1. Elba is the biggest island of the Tuscan Archipelago. It is considered to be the westernmost exhumed part of the Northern Apennines chain. The area has been affected by extensional tectonics (Colletini et al., 2006a+b; Garfagnoli et al., 2005; Colletini & Holdsworth, 2004) and coeval magmatism since the late Miocene (Dini et al., 2008, 2002). Elba Island is made up of a complex pile of stacked tectonic nappes of the Tuscan and the Ligurian Domain. The evolution of Elba dates back to the Variscan Orogeny that affected the oldest lithological sequence of the Tuscan Domain (the Calamita schists), which was made up of deformed greenschist facies, quartzitic metasediments, and phyllites. From the upper Cretaceous to the Eocene, the closure of the Ligurian Ocean deformed the units of the Ligurian Domain. During the Miocene, development of extensional tectonics led to the thinning of the structural pile of nappes, thus favoring the ascent of magmatic bodies in Elba island, such as the Mt. Capanne (about 6.8 Ma, Garfagnoli et al., 2005, and references therein) and the Porto Azzurro (6.2-5.1 Ma, Garfagnoli et al., 2005, and references therein) granitoids. Linked to magmatic ascent, the formation of the characteristic predominantly low-angle Zuccale normal fault occurred (Colletini and Holdsworth, 2004; Keller and Pialli, 1990).

In the Northern Apennines, extensional tectonics and related magmatism migrated from west to east during the Miocene and Pliocene-Pleistocene. In view of this, the exhumed magmatic and geothermal system of eastern Elba represents a precursor system of the Larderello and Monte Amiata active geothermal fields. This analogy applies also to the metapelitic wall rocks of the buried Larderello pluton that showed marked similarities to the Calamita schists (Garfagnoli et al., 2005).

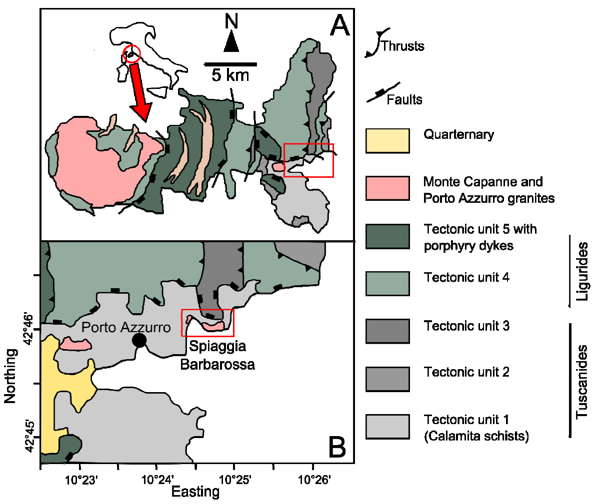

Figure 1: (A) Geological sketch of Elba island (modified after Dini et al., 2008); (B) Geological map of south-eastern Elba with study area (red box).

2.2 Study area

Pictured in Figure 2, the main study area is located at Spiaggia Barbarossa in eastern Elba, where parts of the Porto Azzurro monzogranite are exposed directly overlying the sequences of the deformed Calamita schist, thus forming a window below the directly overlying, meanwhile eroded Zuccale fault. The Calamita schist and the Porto Azzurro pluton are crosscut by microgranitic to pegmatitic dikes and by networks of hydrothermal veins. In particular, flow of boron-rich fluids indicated by the occurrence of tourmaline-rich veins occurs within the wall rocks and the Porto Azzurro monzogranite, crosscutting in different directions such as (sub)orthogonal and oblique systems. In the Calamita schists, vein systems dominantly follow the main foliation. Similar hydrothermal events are reported from other locations on Elba Island, such as the Calamita peninsula (Dini et al., 2008) or around the Mt. Capanne pluton (Tonarini et al., 1998).

Figure 2: Tourmaline shear zone (black) at Spiaggia Barbarossa, crosscutting the contact of Calamita schists (grey-brownish, below) and Porto Azzurro monzogranite (light-whitish, above).

The outcrop of Spiaggia Barbarossa is dominantly crosscut by swarms of tourmaline dykes and veins. A high concentration of quartz-filled extension gashes and veins occur locally. The main tourmaline dyke is related to a shear zone that forms the direct contact between the Calamita schist and the Porto Azzurro monzogranite, locally exceeding apertures of 20 to 30 cm and causing displacement within the Calamita schist. Fluid intrusion formed hydraulic cataclasites with fragments up to cm-scale sizes, as shown in Figure 3.

3. METHODS

The tourmaline dyke at Spiaggia Barbarossa was structurally and geochemically investigated to bridge a gap in the development history of eastward migration of magmatic and hydrothermal/geothermal activity. Thin sections of the dyke matrix were prepared to investigate and discriminate the fluid succession. One main question is whether the fluid intrusion can be considered to be one single event or if the filling is due to several injection pulses. Microprobe analyses of the vein filling are still in process and should classify the affiliation of the tourmaline minerals and give information about the fluid origin. Furthermore, the geochemical comparison between the hydrothermal systems on the Calamita peninsula and the composition of the Larderello fluids should give insight into the temporal development of the fluid system and into the propagation of magmatic activity.

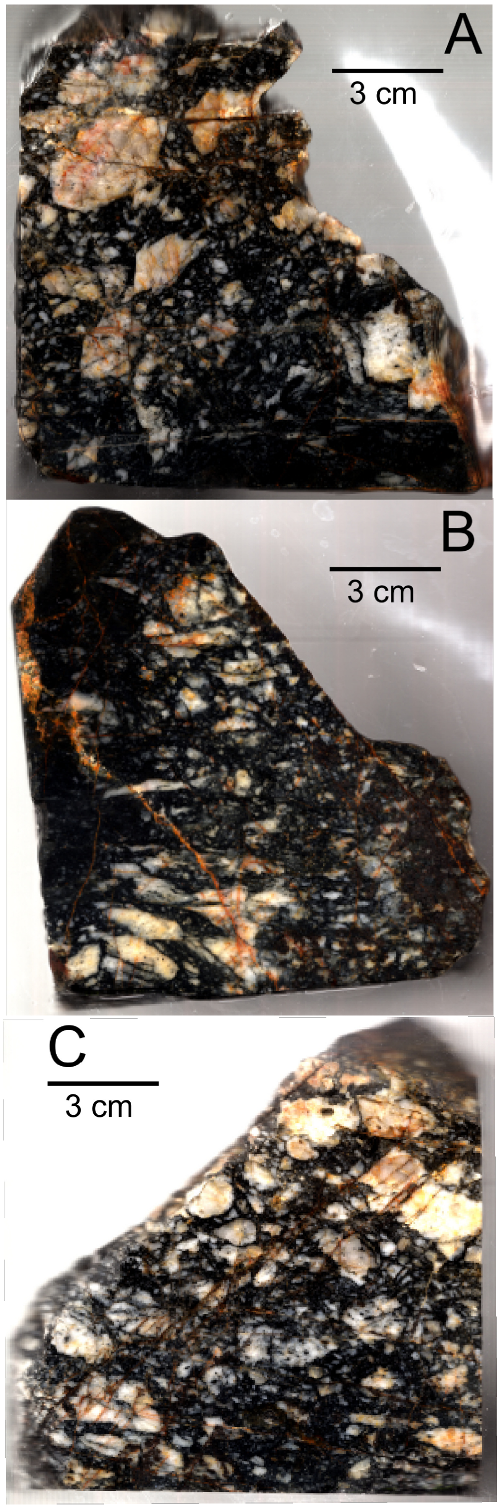

Figure 3: Specimen of the main tourmaline shear zone of the Barbarossa outcrop at the western shoreline (see Figure 2) forming hydraulic cataclasites with fabrics up to cm-sizes. Specimen was cut in three directions, (A) on top view into the shear zone, (B) parallel to the shear movement, and (C) perpendicular to the shear movement.

The cataclasites of the tourmaline shear zone were qualitatively and quantitatively analyzed in order to receive information about characteristics of fracture patterns (mainly anisotropy and heterogeneity) and fracture-forming processes. Moreover, fabric quantification is important insofar as it allows (i) more precise comparison of the ancient Elba and the active Larderello hydrothermal systems and (ii) forms a basis for modelling fragmentation leading to variable degrees of permeability. Fractal geometry offers powerful methods for quantifying complex patterns (Kaye, 1989), and specific methods are available for anisotropy and heterogeneity quantification (Kruhl et al., 2004).

4. RESULTS

Based on thin-section analyses, tourmaline fluids of different processes can be identified. Tourmaline composes the large shear zone that crosscuts the contact zone between the Calamita schists and the Porto Azzurro monzogranite at the western shoreline. The tourmaline most probably originated from hydrothermal fluids. Mineral aggregates are black to black-greenish and very small-grained (< 50 µm) to cryptocrystalline and belong to the schoerl group. A photograph of a section of the shear zone is given in Figure 4.

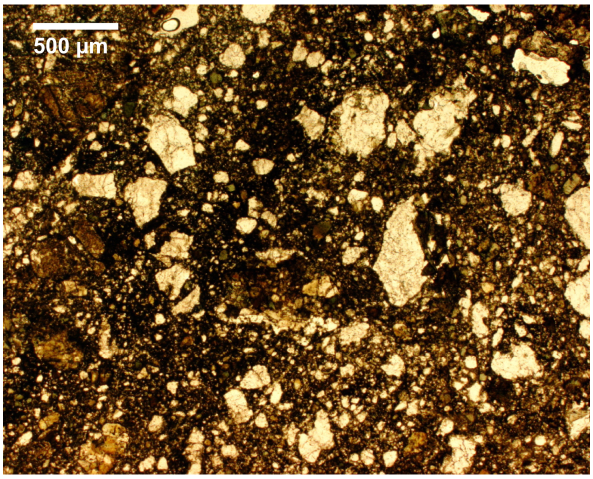

Figure 4: Thin section of the shear zone forming hydraulic cataclasites at the western shore of Spiaggia Barbarossa. The matrix is composed of tourmaline that originated from hydrothermal fluids.

In contrast, tourmaline injections at the eastern outcrop of the Porto Azzurro monzogranite exhibit at least three different generations, as shown in Figure 5. The first generation has relatively large crystals (150 to 500 µm), though fine-grained, but crystal size decreases in the second generation (50 to 100 µm).

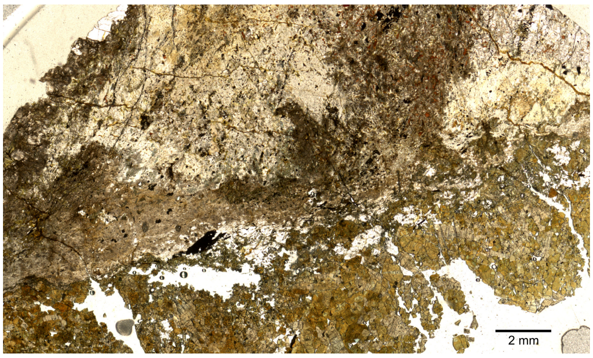

Figure 5: Three different tourmaline generations can be distinguished in some veins exposed in the outcrop of the Porto Azzurro monzogranite at the eastern shoreline.

Crystals of both generations are euhedral to subhedral and exhibit reverse zoning from a greenish schoerl-composed core in the center of the crystal to a dark-to light brownish dravite composition toward the crystal rim. The third generation is made up of cryptocrystalline to subhedral, grey-brownish to dark greenish tourmaline crystals that mark the direction of a later injection pulse of fluids. Subordinated single crystals of foitite were found. Elbaite was not yet identified. Locally, aggregates of fibrous schoerl form clusters or disperse with no preferred orientation. Biotite occurs in all generations of the tourmaline fluid. Epidote was not yet identified. Similar parageneses have been reported from the Larderello geothermal field (Boiron et al., 2007; Garfagnoli et al., 2005; Musumeci et al., 2005; Cavarretta, 1990).

The transformation of thin-section scans into black-and-white binary pixel patterns highlights the complex pattern of fragmentation and mineral infill, without a clearly visible anisotropy, as is pictured in Figure 6A. Box counting leads to the linear correlation seen in Figure 6B between box sizes and numbers of boxes occupied by the cataclasite matrix within the range of ~ 100 – 2000 µm. This supports the existence of a single process of fragmentation. The fractal dimension of 1.75 is considerably larger than values reported for fracture systems (e.g. Barton and Larson, 1990), as can be expected for such densely fractured material. However, because of the resolution limits of the pattern, the box-counting method cannot be used to analyze the fine-grained fragments in the matrix with sizes below ~ 5 pixels (roughly equivalent to 100 µm).

5. DISCUSSION

Quantification of the anisotropy of fragment and matrix patterns led to irregular point distributions, as illustrated in Figure 7. For the quartz-fragment pattern, the distribution is nearly isotropic, as indicated by the weak ellipticity of 1.09 shown in Figure 7A. In contrast, the matrix pattern shows a higher ellipticity of 1.16, as shown in Figure 7B. The local irregularity of point distributions is probably related to the orientation of major fragmentation zones. For example, the ‘neck’ of the point distribution in Figure 7B, which is roughly orientated ‘NW-SE’, can be related to the roughly ‘NE-SW’ oriented micro fragmentation zones pictured in Figure 6A. In general, the difference between the isotropy of the quartz fragmentation pattern and the anisotropy of the matrix pattern can be interpreted as resulting from two different processes. First, fluid overpressure led to an isotropic fragmentation of the quartzite host rock. Second, subsequent shearing resulted in weakly oriented micro-fragmentation zones. Shearing was possibly concentrated in the relatively weak fine-grained fragmentation matrix and, therefore, did not affect the coarsely fragmented parts of the rock.

The Barbarossa system indicates high-temperature circulation of boron-rich fluids forming centimeter- to meter-scale metasomatic veins. The injections could have been triggered by the intrusions of boron-rich monzogranitic magma that make up the Porto Azzurro pluton. The fluids at Spiaggia Barbarossa exhibit different hydrothermal and/or metasomatic imprints. This is manifested by repeated injections of voluminous black tourmaline dykes and veins. Tourmaline shows different compositions between the large shear zone at the western shoreline and the pulsed injections crosscutting the felsic Porto Azzurro monzogranite at the eastern shore outcrop. The latter can be identified as metasomatic veins exhibiting almost three generations of tourmaline. The first and second generation show concentric and reverse zoning from shoerl to dravite, thus indicating progressive biotite replacement. The third generation, which is more dark-greenish schoerl in composition, indicates hydrothermal pulsed injections of a late magmatic stage roughly corresponding to the large shear zone at the western outcrop at Spiaggia Barbarossa. This suggests a probable link between the metasomatic fluids and the fluids involved in the stage of hydrofracturing. For the production of such large amounts of tourmaline, a continuous supply of CO_2 is required. Such vapors could be generated within the Variscan Calamita schists and could also derive from a mantle source. Further, these vapors were trapped under lithostatic pressure. Such fluids and conditions are reported from the deepest parts of the Larderello geothermal field (Boiron et al., 2007)

The fracture deformation on the western Barbarossa outcrop is associated with fluid-overpressure combined with an extensional shear zone. Extensional fractures identified in the wall rocks should promote fluid circulation. But in areas of geothermal activity, fractures and veins can be sealed rapidly by mineral precipitation (Bellani et al., 2004), resulting in the re-opening and sealing of previous fractures and the formation of new ones. These processes, stress concentrations, and sealing of fractures in shear zones can trap fluids in supercritical reservoirs (Bellani et al., 2004) and finally result in an increase of fluid pressure, thus participating in the growth of fluid-overpressure zones.

6. CONCLUSIONS

Elba has been affected by extensional tectonics since the Miocene. Crustal thinning favored the ascent of magmatic bodies such as Mt. Capanne in the western island and the Porto Azzurro granitoids in the central and southeastern part of Elba. Magmatic ascent caused slope instability in the domed wall rocks and resulted in the formation of the characteristic low-angle Zuccale normal fault. Because magmatism migrated from west to east since the Miocene, the exhumed fossil magmatic and geothermal system of eastern Elba can be regarded as a precursor system of the Larderello and Monte Amiata active geothermal fields.

At Spiaggia Barbarossa, the Porto Azzurro monzogranite and the Calamita schists are crosscut by metasomatic and hydrothermal tourmaline dykes and veins. Reverse tourmaline zoning from schoerl-rich cores in the crystal center towards a dravite-rich rim indicates progressive biotite replacement. At the western outcrop, hydrothermal tourmaline dykes crosscut the contact between the Calamita schists and the Porto Azzurro granite during the late magmatic stage, locally forming cataclastic shear zones embedding medium-sized fabrics of quartz-clasts within the range of ~ 100 – 2000 µm. The occurrence of these shear zones indicates deformation concentration during a regional extensional stress field, active from the Miocene to Pliocene-Pleistocene. Fractal geometry methods allow the quantification of fragmentation patterns. Fractality of these patterns above fragment sizes of 0.1 mm indicates one process of fragmentation on this scale. The hydrothermal tourmaline-filled fragmentation zones at the western Barbarossa outcrop point to coeval processes of regional deformation and boron-rich fluid infiltration. However, analysis of pattern anisotropy indicates two subsequent processes: hydraulic fracturing caused by fluid overpressure and shearing of the already fragmented rocks caused by a regional stress field. Both processes are regarded as roughly coeval. In general, successful studies on fossil and active geothermal systems require multi-approach investigations, including mineralogical, petrologic and geochemical analyses and structural analyses in the field and on the micro-scale. Quantification of meso- and microstructures, which may form a basis for more precise comparison between different hydrothermal systems and for their modelling, appears to be significant in this context.

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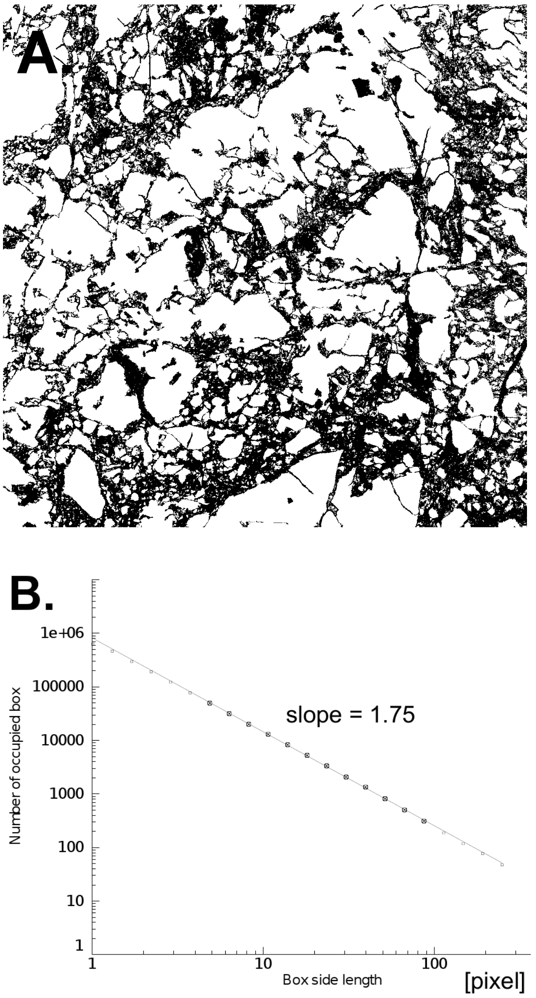

Figure 6: (A) Binary pattern of a tourmaline-filled cataclasite (Spiaggia Barbarossa, eastern Elba). A thin-section scan has been transformed to a black-and-white pixel pattern using an open-source image-analysis program with application of a threshold of 160 and subsequent 'cleaning' of the pattern. White = quartz fragments; black = fine-grained matrix + tourmaline. (B): Result of box counting applied to the quartz-fragment pattern (white) shown in (A). Box-side length is plotted versus number of boxes occupied by the cataclasite matrix. A linear regression, with a slope of 1.75 (= fractal dimension) and a standard deviation of 0.001, is received within the interval > 4 and < 90 pixel. One pixel is equivalent to ca. 20 µm. Data below 4 px have been ignored, in order to avoid back-ground noise of the pattern and above 90 px because the low number of large boxes is statistically not safe.

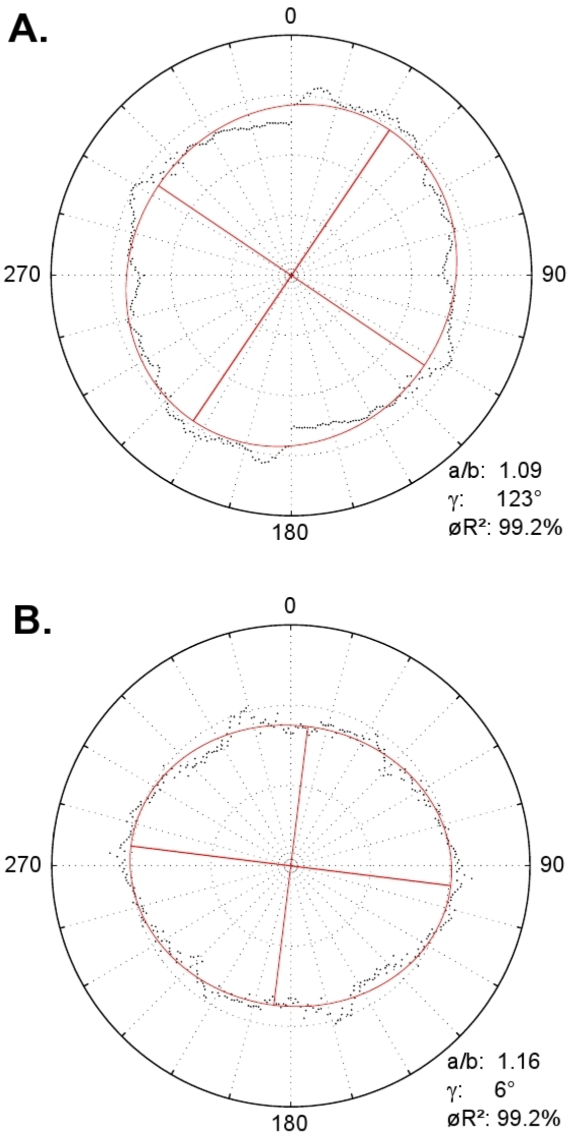

Figure 7: Anisotropy quantification of the tourmaline-filled cataclasite (binary pattern from figure 6A), performed using the modified Cantor-dust method (AMOCADO). Analysis leads to a slope of linear regression for 180 directions in 1° steps. These slope values are plotted from a central point toward the outside. The point distribution represents the anisotropy of complexity of the cataclasite pattern. The irregularity of point distribution is highlighted by a best-fit ellipse with an ellipticity a/b and a coefficient of determination R2. γ. is the angle of the short ellipse axis against the 0° reference line. (A) Quartz fragments – white in figure 6A; (B) tourmaline-filled matrix – black in figure 6A.

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