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Understanding of magmatic geothermal systems from studies of exhumed systems in continental and oceanic settings

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ABSTRACT

We contribute to the understanding of the relationships between geothermal fluid flow and geological structures studying analogous examples of exhumed geothermal systems developed in continental (Elba Island, Italy) and oceanic settings (Geitafell, Iceland). The adopted methodology follows the classical approach of structural geology, petrography and fluid inclusion studies. In both cases, field studies indicate that geothermal fluids-related hydrothermal mineralization is localized in fault damage zones which thickness is controlled by lithology and structural level. Permeable geological bodies, hydraulically connected to the main fault zones, can host hydrothermal ore deposits, indicating that fluids were channeled through the faults and were laterally stored. At Elba Island, fluid inclusion studies from veins collected at deep structural levels indicate a clear magmatic origin and P-T conditions compatible with supercritical conditions. At Geitafell, fluid inclusions studies from field and boreholes samples indicate that supercrital conditions might be occurred in the thermometamorphic aureole, close to the magmatic intrusion.

1. INTRODUCTION

The understanding of the relationships between geological structures and geothermal fluids migration through the upper crust represents a continuous task for a fruitful exploitation of geothermal resources. With this goal, several methodologies have been proposed, from numerical simulations of fluid circulation (e.g., Kloditz and Clauser 1998) to interpretation of geochemical (e.g., Magro et al. 2003), geophysical and structural data (e.g., Rowland and Sibson 2004). These models have a crucial role for planning exploration and defining exploitation targets (Barbier 2002, with ref.), however, given the complexity of the natural system, the resulting hydrological model almost always contains uncertainties on the fluid pathways. To contribute to fill the gap, the fluid flow path in geothermal areas can be reconstructed from field and laboratory studies on fossil geothermal systems whose expression is typically represented by epi- and meso-thermal mineralization (Hedenquist and Lowenstern 1994), particularly diffuse in extensional tectonic environments with coeval magmatism. .

We investigated two areas located in Italy (Eastern Elba Island) and Iceland (Geitafell area), as examples of exhumed geothermal systems, in oceanic and continental crust, respectively (Fig.1). These areas are considered as proxies of the active geothermal systems, respectively named as Larderello and Krafla.



Figure 1: Location of the study areas. Left: Elba Island is the main Island of the Northern Tyrrhenian sea where a Miocene magmatic and hydrothermal system is exposed. Right: Geitafell is a Miocene central volcano widely outcropping together with its thermometamorphic aureole.

2. EASTERN ELBA ISLAND

Eastern Elba Island (Fig. 2) consists of a completely exposed fossil geothermal system: from the heat source, represented by the Porto Azzurro monzogranite (5.9 Ma), to the main conduits and reservoirs, marked by the location

of ore deposits. The aim is to get information on the relationships between structures and mineralization from the heat source, through the main conduits, to the shallow parts of the geothermal system.

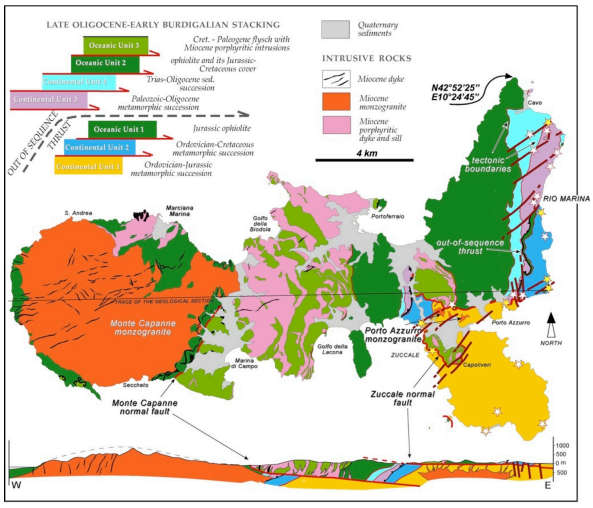


Figure 2: Schematic geological map of Elba Island and related geological cross section. Stars indicate the main ore deposits location. The study area has been the Eastern Elba Island from Capoliveri and Rio Marina localities, mainly.

Extensional tectonics was dominated by Miocene-Pliocene low-angle normal faults, and favoured the emplacement of the Porto Azzurro (eastern Elba Island, 5.9 Ma) monzogranite. The damage zones of these low-angle faults are characterized by hydrothermal mineralization mainly represented by quartz-tourmaline and Fe-oxides and sulphides. The same mineralization characterized high-angle left-lateral transtensional faults, interpreted as transfer zones active during the extensional tectonics, and hydrothermal fluids circulation. The conceptual model showing the relationships among the geological structures and tectonic units is displayed in Fig. 3.

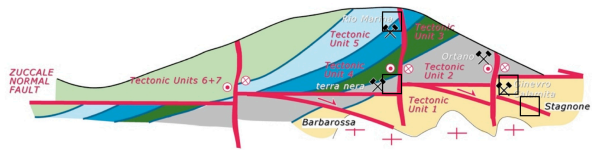


Figure 3: W-E oriented sketch (not to scale) illustrating the relationships between tectonic units and geological structures in eastern Elba Island. The structural location of the key-areas is also indicated (squares)

As it concerns the ore deposits and the areas of hydrothermal alteration and metasomatism, these are diffuse within tectonic units originally located at different structural levels (squares in Fig. 3). The deepest mineralized level, characterized by quartz-tourmaline veins, occurs within the crystalline rocks (micaschist) hosting the Porto Azzurro monzogranite; the intermediate mineralized level is characterized by almost vertical brittle shear zones affecting metasedimentary rocks and the cataclasite of the intersected low-angle normal faults; the mineralization is mainly composed of Fe-oxides, and Fe-sulphides; the shallowest level is instead connected to the permeable rock-levels belonging to the Tuscan domain, where Fe-oxides and Fe-sulphides ore deposits occur.

The heat source is represented by the Porto Azzurro monzogranite (5.9 Ma) and its hosting rocks. Both are affected by SW-NE trending transtensional faults, mineralized by quartz-tourmaline and and Fe-hydroxides, clearly indicating that these structures strictly controlled the circulation of the B-rich geothermal fluids. Similar mineralization is in the damage zone of the low-angle normal faults affecting the same area, thus indicating that geothermal fluids circulation was also controlled by the permeability associated to the low-angle faults. The tectonic features of faults that played as main conduits, have been studied through field mapping and collection of structural and kinematic data. The results indicate that the mineralized structures can be explained in the framework of a SW-NE trending transfer zone contemporaneously active together with the low-angle normal faults (Fig.4).

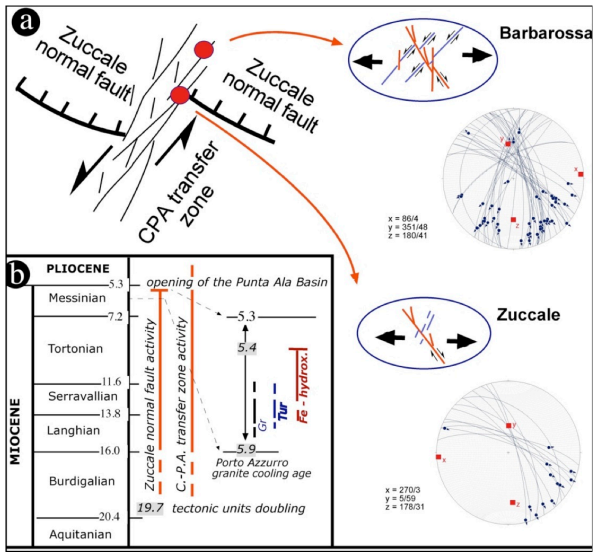


Figure 4: (a) Structural sketch illustrating the relationships between quartz-tourmaline (blue lines) and Fe-sulphide and/or Fe-oxy/hydroxides (red lines) mineralized faults in the study areas. (b) Time relationships among tectonic, magmatic and hydrothermal events, summarized on the basis of available age determinations and

crosscutting relationships between mineralized faults.

Fluid inclusions (FIs) were studied in quartz-tourmaline veins of Mt. Calamita (Fig.2) and in hydrothermal quartz, adularia and calcite from Fe-ore deposits of Rio Marina (Fig.2) and Porto Azzurro (Fig.2) to derive: i) the chemical characteristics and PT conditions of fluids circulating in a paleogeothermal system similar to the Larderello ones, and ii) the origin and evolution of the fluids. Specifically, in quartz of quartz-tourmaline veins we found: a) hypersaline multiphase FIs (29-49 wt.% NaCl eq.) with moderate total Th (<400°C) and b) saline two-phase FIs (16-29 wt.% NaCl eq.) with moderate to high Th (up to 600°C) (Fig.5).

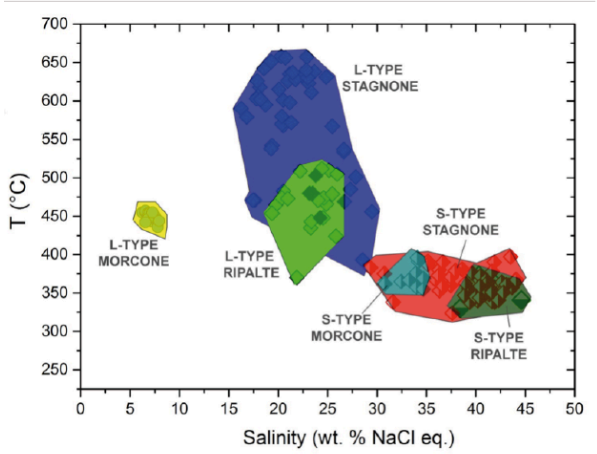


Figure 5: Salinity vs. calculated trapping temperature of fluid inclusions from quartz-tourmaline veins

The composition of both FIs types is dominated by Na, Cl, Fe, K and characterized by the occurrence of B. P-T reconstruction suggests that two-phase FIs were trapped at mean pressure around 130 MPa and that they cooled from about 650 to 400°C (Fig.5), whereas multi-phase FIs were trapped between 320 and 400°C (Fig. 5), at pressure fluctuating between 100 and 200 MPa. Fluid inclusion salinity and compositional data as well and isotopic data of tourmaline indicate that the fluids circulating in quartz-tourmaline veins were of magmatic derivation. In the hydrothermal minerals (quartz, calcite and adularia) of Fe deposits FIs are mainly two-phases with variable salinities (1-33 wt.% NaCl eq.) and Th (170 350°C) although sporadic multiphase FIs with high-salinity (31-33 wt.% NaCl eq.) and Th (up to ca. 400°C) were also found (Fig. 6). Similarly to FIs in quartz-tourmaline veins the composition of the two-phase FIs Fe-deposits is characterized by high concentration of Na, Fe, K, Cl, and by the occurrence of Li and B. P-T reconstruction based on fluid inclusion data and isotopic geothermometer suggest that the fluids in these areas circulated at a pressure of about 110 MPa and in temperature range from 250 to 450°C (Fig. 6). The most saline and hot fluid was a fluid of magmatic derivation, (similar to that recorded in quartz-tourmaline veins) that undergone cooling and dilution before entering in the hydrothermal systems of Fe-mineralization (Fig. 6).

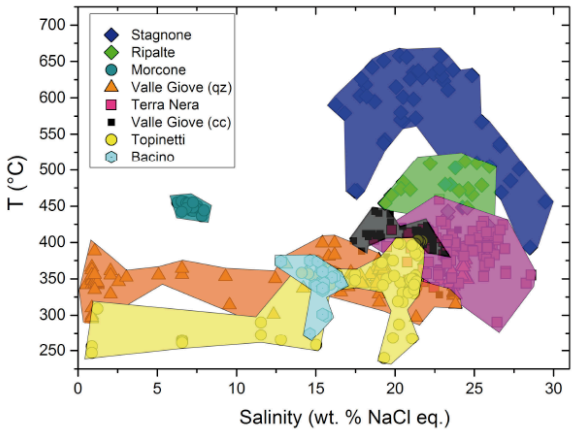


Fig. 6 - Salinity vs. calculated trapping temperature of fluid inclusions from quartz-tourmaline veins

Finally, permeability of the structural conduits have been studied by collecting width, length and frequency of mineralized veins along selected scan lines. Data were considered applying the relationships proposed by Gale (1982), Zimmerman and Bodvarsson (1996) and Nicholl (1999). The results indicate values between 10^{-12} and 10^{-17}, with a maximum around 10^{-14} and 10^{-13} m^2.

3. GEITAFELL

The Neogene Geitafell central volcano, located in the south-eastern Iceland, provides a rare opportunity to study the evolution of volcano-hydrothermal systems that is parallel those of the active rifting neo-volcanic zone of Iceland, like the Krafla geothermal system. The study area is characterized by a Tertiary gabbro representing the inner part of the Geitafell Centralvolcano (Freidleifsson 1983a,b; 1984; 1986). This is a Miocene-Pliocene gabbro emplaced at shallow depth (2-4 km) and intruded in Late Miocene flood-basalts beds. The Geitafell Volcano is believed to be located in the rift valley during Miocene and, later on, in the framework of the crustal accretionary process affecting the divergent margins, has been migrating south-

eastwards up to the present location, about 20km far from the Icelandic cost (Fig.7). Contact metamorphism is reduced to few meters within the hosting rocks in the surroundings of the gabbro, and it is clearly marked by the occurrence of mm-size hornblende and augite. The structural and geochemical study was carried out close to the eastern side of the gabbro intrusion where seven boreholes were drilled into

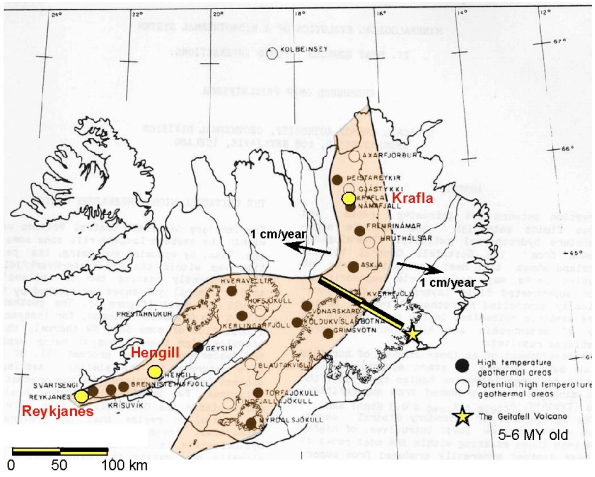


Figure 7: Structural location of the Geitafell volcano with respect to the icelandic oceanic ridge (from Freidleifsson 1983a).

the contact aureole (Fig.8). The distribution of faults and shear veins and associated hydrothermal mineralization were analyzed in order to get information on the reservoirs and feeding channels. Data from fieldwork are integrated with the drill-cores and geochemical data.

Gabbro and its hosting rocks are affected by two significant sets of faults, SW-NE and NW-SE oriented. Fault slip surfaces and damage zones (up to 50m thick) of both systems are characterized by shear veins, filled with hydrothermal minerals, such andradite, epidote, quartz and calcite (+zeolith). Very often the faults zones are affected by hydraulic breccias, testified by regular and symmetric clasts cemented by hydrothermal minerals. Basalt levels hydraulically connected to main fault zones were, in some cases, deeply alterated and characterized by centimenter to decimenter sized vesicles filled by hydrothermal minerals (chlorite, actinolite, andradite, quartz, calcite, zeolith).

The results of the kinematic and structural study indicate two main structural trends: the SW-NE system is mainly typified by a dominant normal movement with a minor right-lateral component; the NW-SE system is characterized by dominant oblique-slip movements.

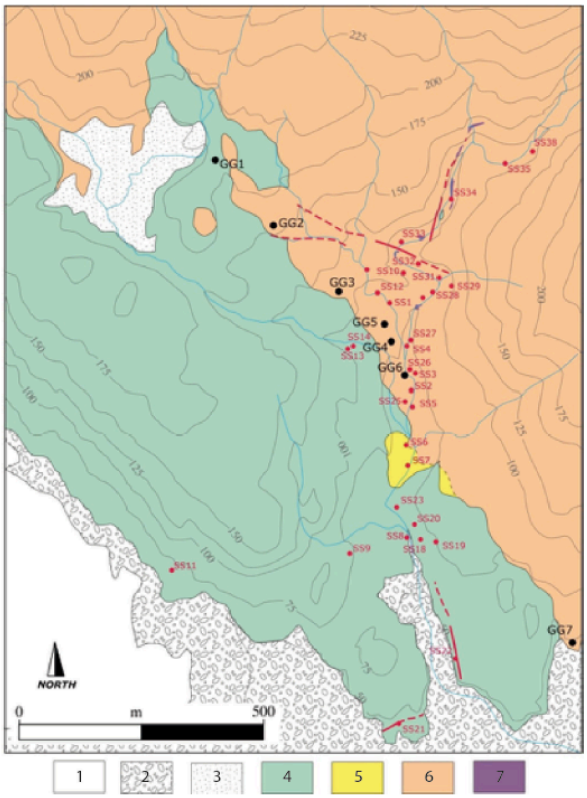


Figure 8: Geological map of the study area and location of boreholes (GG1-GG7) and structural stations (SSG1-SSG38). Symbols: 1) glacier; 2) alluvial plane; 3) detritum; 4) Miocene-Pliocene gabbro; 5) horneblende-bearing host-rock; 6) Miocene tholeitic lava; 7) epidote-bearing shear zone.

The throw of each structure appears in the order of some meters, as a maximum; the damage zone is defined by comminution of mafic rocks, resulting in breccias and matrix, often cemented by hydrothermal minerals such as epidote, calcite, quartz and chlorite. Rarely zeolite and andradite can occur. Usually, andradite has been found within fault zones and hydrothermally alterated vesicular basalt close to the gabbro, whereas epidote, quartz, calcite and zeolite have been found far from it, although the gabbro itself is dissected by faults with the same hydrothermal parageneses. Finally, permeability of the structural conduits was estimated in about 10^{-14} and 10^{-13} m^2.

Within the central volcano, evidence for up to seven periods of hydrothermal activity is preserved in the crosscutting relationships of alteration veins. The earliest veins predate metamorphic activity and are composed of limonite and clays. Upon the emplacement of a central gabbro, at paleo-depth of 1 to 1.5 km, a high-temperature system was active and

produced a contact metamorphic aureole consisting of an inner aureole of sanidinite facies basaltic lava hornfels (formed by secondary augite-andesine- ore) enveloped by an outer aureole of skarn deposits (Fridleifsson, 1984). In the inner aureole, veins composed by andesine and pyroxene also occur; a change of secondary pyroxene is observed going from wall-rock that is characterized by salitic pyroxenes to the vein center characterized by hedenbergite. The skarn is constituted by amygdales partly infilled by hedenbergite and garnet. The lava amygdales were earlier partly infilled by low-temperature minerals such as limonite, opaline silica, clays and possibly calcite, which reacted with metamorphic fluid to produce hedenbergite and garnet assemblages. Upon retrograde conditions hedenbergite was partly replaced by andradite containing inclusions of calcite. An actinolite-sphene vein mineral system occurring within the gabbro, partly replacing augite and ilmenite in the vein-wall-rock zones, was the first hydrothermal mineral assemblage to invade the gabbro heat source during cooling. Fridleifsson (1984) suggested that the skarn minerals were produced from supercritical fluid (T≥400°C, P≤0.3 kbar), whereas, the actinolite-sphene assemblage developed from superheated steam (T T≥300°C, P≤0.1 kbar). Later hydrothermal events superimposed the high-temperature assemblages, producing a widespread mineral alteration that includes: actinolite, epidote, chlorite, quartz, calcite and sulfides. Andradite garnet is also a common mineral in amygdale fillings, stratigraphically below the gabbro exposure at Geitafell. Epidote is present in veins, amygdale fillings and as groundmass replacement in the actinolite, andradite and epidote zones. Finally, zeolite mineralization related to regional low-temperature hydrothermal system overprints the exposed high temperature mineralization of the central volcano, postdating the volcanic activity in the area.

Fluid inclusions (Fig.9) were investigated through thermometric and isotopic analyses. The studied mineralogical phases were hydrothermal quartz, calcite and minor in garnet. These phases are considered as the hydrothermal mineralogical assemblage resulting of the intense hydrothermal circulation affecting the Geitafell area. Mineralogical, isotopic and fluid inclusion studies on core- and surface samples indicated that the Geitafell fossil hydrothermal system was

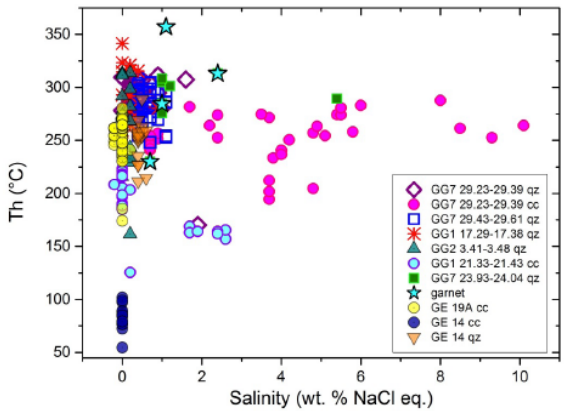


Figure 9: Th vs salinity data for all the dataset.

characterized by a fluid circulation that caused the precipitation of typical secondary minerals (i.e. quartz, calcite, garnet, epidote, actinolite, albite, zeolites, etc.) found in many Icelandic geothermal systems. These phases replace previous high temperature skarn minerals (i.e. hedenbergite and wollanstonite) that occur as relict in the examined samples. The paleo-geothermal aqueous phase was usually low-salinity (0-1.5 wt.% NaCl equiv.), had meteoric origin and showed interaction with the host magmatic rocks. The occurrence significant S, probably ascribed to SO_4, detected by SEM-EDS in some salt mounds resulted from decrepitated fluid inclusions, may be ascribed by magmatic input of S species in the fluid. The hydrothermal fluid circulated at boiling conditions, in some cases prolonged non-adiabatic boiling caused significant salinity increase (from 1.5 to 10 wt.% NaCl equiv.). Temperature during quartz crystallization ranged from 240°C to 320°C. During calcite deposition temperature was lower: mostly between 150°C and 270°C, in some cases down to about 80°C. The occurrence of few vapour-rich inclusions in garnet, not trapped under boiling conditions, could record super-heated steam trapped at relatively low pressure. Whereas, supercritical conditions at Geitafell could be only hypothesized for a liquid-rich inclusions, if trapping pressure was at a least 350 bars.

3. CONCLUSIONS

The integration among the geological survey, the structural and kinematic study in eastern Elba Island and the results of geochemical analyses, suggest the following main points: a) the geothermal fluids circulation occurred with fluids having high temperature (650°C) down to lower

temperatures (about 200-300°C); this circulation was coeval with the brittle deformation, represented by the activity of the low angle normal faults and almost vertical oblique slip fault systems. b) Circulation of fluids is mostly controlled by the almost vertical structures from which fluids laterally migrated into the hydraulically connected structural traps (Fig.10).

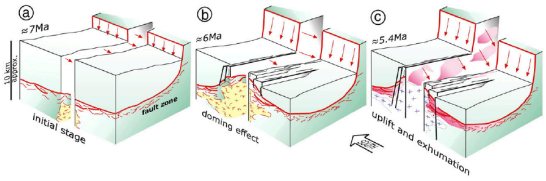


Figure 10 - conceptual model illustrating the relationships among low-angle normal fault, transfer zone, magmatism and hydrothermalism during late Miocene–early Pliocene time span. (a) During the Messinian, the Porto Azzurro monzogranite emplaced at the intersection between normal and transfer fault, where permeability increased. (b) During the Late Messinian, a doming effect on the geological bodies and structures above the roof of the magmatic body was induced. (c) Cooling of the monzogranite and hydrothermal stage, during which the damage zones associated to the transfer fault provided the main up-flow channels for fluids, permeating the cataclasite of the low-anlge normal fault during its activity (from Liotta et al. 2015).

c) At shallower levels, the geometry of the structural traps is defined by the interplay between lithology (impervious vs. permeable) and previous deformational events. d) At deeper levels the circulation of fluids is controlled by fractures, mostly. e) Supercritical conditions can be reached where fluid temperature is very high (above 600°C) and Pressure is significant (>0.4 kbar). f) Fluids are of magmatic origin progressively mixed with meteoric water, from deeper to shallower levels g) Tectonic evolution and structural setting of the eastern Elba Island appears to be comparable with that of the Larderello geothermal field (Bellani et al., 2004; Liotta et al., 2010).

As it regards the Geitafell study area, the integration among field studies, borehole logs and fluid inclusion analyses brought to a conceptual model as sketched in Fig.11. This was based on the following points: a) the fluid inclusions data indicate that the origin of the fluid is meteoric; b) the geological field study indicates that circulation of hydrothermal fluids was mostly controlled by the fault zones

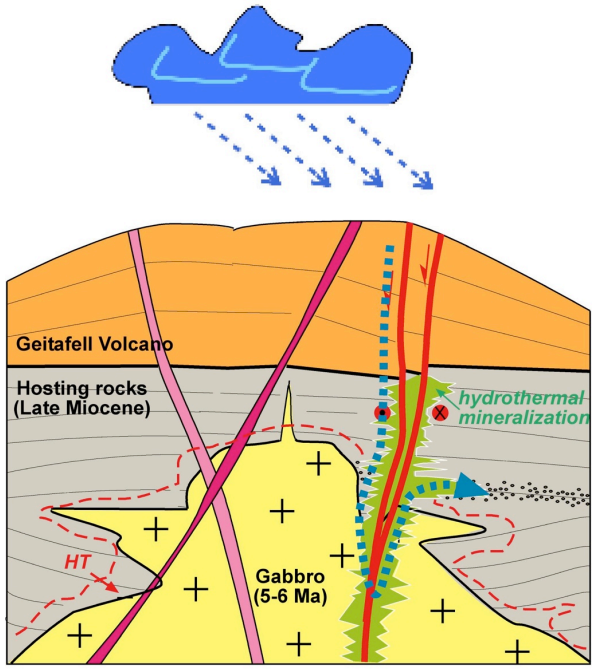


Figure 11: conceptual model illustrating the meteoric fluid path during magma cooling and producing hydrothermal mineralization in fault damage zones and into hydraulically connected permeable lava-levels.

independently by their orientation. c) The occurrence of the same hydrothermal mineralogical phases in SW-NE and NW-SE oriented fault systems indicate that the activity of both systems of faults is contemporaneous. d) The permeable geological levels that are hydraulically connected with the main shear zones can represent reservoirs where hydrothermal fluids were stored. e) Fluid inclusions in garnet may suggest the occurrence of super-heated steam at relatively pressure in the fossil system whereas supercritical conditions need a strong contribution by increasing pressure on fault zones. The only reasonable way to get it, it would be in terms of fault-valve behaviour (Sibson, 1992), if other general conditions have been satisfied (e.g.: hydraulic head, Temperature, depth of the structural level). Finally, we underline that the data deriving from the exhumed geothermal systems are in agreement with the present knowledge on the fluid circulation as it is defined at the Krafla active geothermal field.

The main conclusion indicates that the study of fossil geothermal systems represents a powerful approach in order to get information about the properties of the fluids and on the relationships between geological structures and fluid flow. The information so far obtained, can effectively drive

the exploration of the active geothermal systems.

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