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Development and Fast Exhumation of a Geothermal System in a Resurgent Caldera Environment. the Example of Ischia Island (Italy)

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ABSTRACT

An integrated approach (melt and fluid inclusions, mineralogy, stable isotopes) was used on the pumices, tuffs and syenitic xenoliths of Ischia volcanic system to provide strong physico-chemical constraints on the shallow magmatic reservoir and the hydrothermal system. The latter is partially exposed on the surface due to the rapid uplift of the Mt. Epomeo resurgent block. The engine of the hydrothermal system of Ischia Island can be identified in the shallow (top at around 2 km of depth) and wide magmatic system that hosts hot (around 1000°C) trachytic melts. The hydrothermal system developed within thick intracaldera ignimbrite deposits, and the most external portions of the subvolcanic bodies, to a depth of at least 1 km defining a secondary mineralogical distribution typical of high temperature geothermal systems dominated by seawater.

1. INTRODUCTION

Ischia Island represents a rare case of well-exposed, young, and ongoing caldera resurgence. Resurgence is a quite common feature in large caldera depressions, with an increase in pressure in the magmatic system and the inflation of the magma chamber generally being considered as the triggering mechanism for the doming of the caldera floor. The depressions formed by caldera structures typically host active high temperature geothermal systems, which are exploited for electrical energy production all around the world. Furthermore, caldera structures are often associated with epithermal precious and base metal mineralization that represent the "fossil" equivalent of the active geothermal systems (Hedenquist and Lowenstern, 1994). Ischia Island offers an unique opportunity to examine the hydrothermal system's 3-dimensional anatomy because of its exposure related to Mt Epomeo uplift. This work fills a gap in the knowledge of the magmatic-hydrothermal system of Ischia and, more generally, offers an important contribution to the knowledge of the magmatic-hydrothermal processes that occur inside a resurgent caldera environment characterized by shallow and active magmatic system.

2. RESULTS

Ischia Island is located in the northern part of the Gulf of Naples (Fig. 1), and, with the Campi Flegrei and Mt. Vesuvius, constitutes a most important Quaternary volcanic area of Mediterranean region. The volcanic activity on Ischia started before 150 kyr ago with the emplacement of lava flows, domes, tuff and scoria cones that formed a huge volcanic field, the 1302 Arso eruption ended the volcanic activity on the island. Between 73 and 56 kyr ago Ischia experienced a period of intense explosive volcanic activity characterized by numerous trachytic Plinian and ignimbritic high-magnitude eruptions (including "Green Tuff) that provoked the formation of a poly-phase caldera depression. This was followed by the resurgence of Mt. Epomeo block, the major uppermost relief of the island (787 m a.s.l).

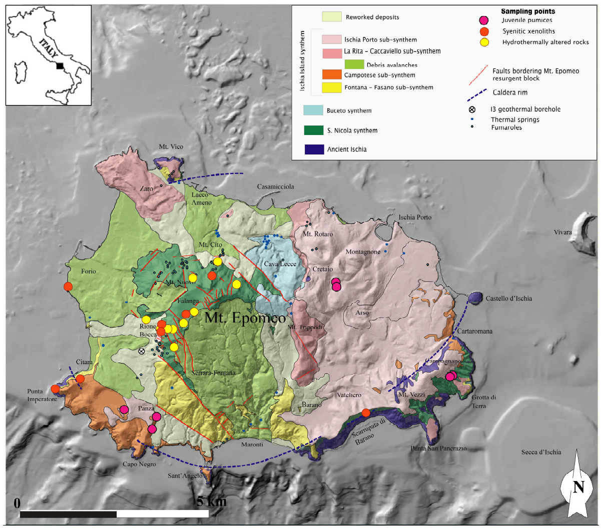

Figure 1: Schematic geological map of Ischia (Sbrana et al., 2009 modified) with the location of sampling points

For our study, juvenile fractions of Ischia volcanic deposits were selected to provide samples suitable for melt inclusion studies. Melt inclusion studies provide a fundamental tool for the reconstruction of the P-T-X conditions of the magmatic reservoir. Sample collection was therefore restricted to pumice from fallout deposits. Selected pumices shows variable vesicularity and crystal content (~1 to 15 vol. %). Their mineralogical assemblage is formed by K-feldspar, plagioclase, clinopyroxene biotite, oxides, apatite and titanite in varying proportions. Holocrystalline, non-equigranular xenoliths of syenitic subvolcanic rocks are composed of primary K-feldspar, plagioclase, clinopyroxene, K-pargasitic amphibole, biotite and accessory titanite and apatite. Samples from the intracaldera tuff units, forming the Mt. Epomeo uplifted block, reveal the occurrence of different hydrothermal mineralogical assemblages that substitute the original primary phases and glasses (Fig. 2).

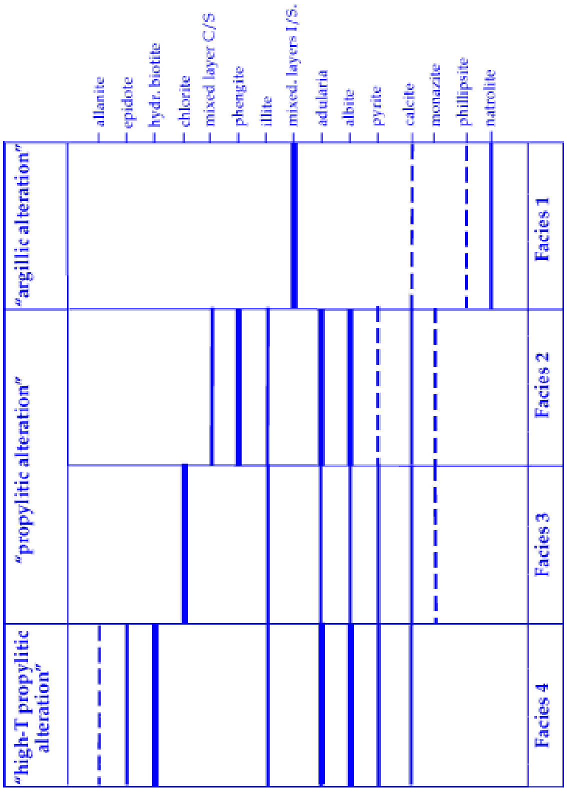

Figure 2: Distribution of authigenic minerals and hydrothermal Facies of Ischia hydrothermal system, as deduced from the investigation of the hydrothermally altered tuffs and syenitic xenoliths

They span (from top to bottom of the sequence) from mixed layer illite/smectite (I/S) ± zeolites (natrolite and phillipsite) (Facies 1, related to the argillic alteration facies that characterizes the upper impermeable cover of geothermal systems) to phengite + illite + albite + adularia ± mixed layers chlorite/smectite (C/S) (Facies 2). This suggests that the tuff sequence was affected by hydrothermal alteration zoning typical of geothermal systems (Browne, 1978). Furthermore, several syenitic xenoliths are pervasively altered by hydrothermal mineralogical assemblages different from those observed in the hydrothermally altered intracaldera tuff units (Fig. 2). The mineralogical assemblages that characterize these samples are: chlorite + albite + adularia + illite (Facies 3), and hydrothermal biotite + epidote + adularia + albite + illite (Facies 4; this Facies coupled with Facies 2 and 3 correspond to propylitic alteration that characterizes geothermal reservoirs). To better constrain the origin of the fluids involved in the hydrothermal alteration, authigenic minerals (phyllosilicates and adularia) were analysed for $\delta^{18}O$ and δD . The samples come from alteration Facies 2 where it has been possible to obtain an accurate separation of the authigenic minerals. Adularia has an oxygen isotope composition around 7.5‰. The $\delta^{18}O$ values of phengite range between 10.5‰ and 8.5‰, while mixed layer C/S has a $\delta^{18}O$ of 7.8‰. Mixed layer C/S and phengites have relatively high δD values (phengites are around -8‰ and mixed layer C/S is -15‰). Oxygen and hydrogen isotope composition of the water in equilibrium with secondary minerals were calculated assuming an equilibrium temperature of 230°C on the basis of mineralogical geothermometric calculations and hydrothermal mineralogical paragenesis. $\delta^{18}O$ values of water in equilibrium with phengite and mixed layer C/S range from 2.8 to 4.8 ‰, whereas δD composition of water is in the range -1 to 2‰. These data suggest the occurrence of a significant seawater component in the hydrothermal fluids.

Well-quenched primary glassy melt inclusions (MIs) (20–60 µm in size) are found in clinopyroxene of pumices of the juvenile fraction. Most clinopyroxene hosted MIs are two phase with brown glass and a shrinkage bubble, or are glassy and bubble free. The lack of shrinkage bubble(s), is due to the high quenching rate of the analyzed samples. The characteristics of MIs thus probably closely reflect the pre-eruptive conditions of the magma chamber. The MIs are all of similar trachytic composition and FT-IR investigation revealed that their dissolved water content ranges from 1.6 and 3.1 wt.% with a strong mode between 2 and 3 wt.%. Microthermometry of the MIs provided a range homogenization temperatures between 960 °C and 1050 °C, with a mode of 1010°C.

Fluid inclusions (FIs) in K-feldspar were examined in both hydrothermally altered and fresh xenoliths. The size of the analyzed FIs is in the range 10-50µm. Three main types of FIs are observed at room temperature:

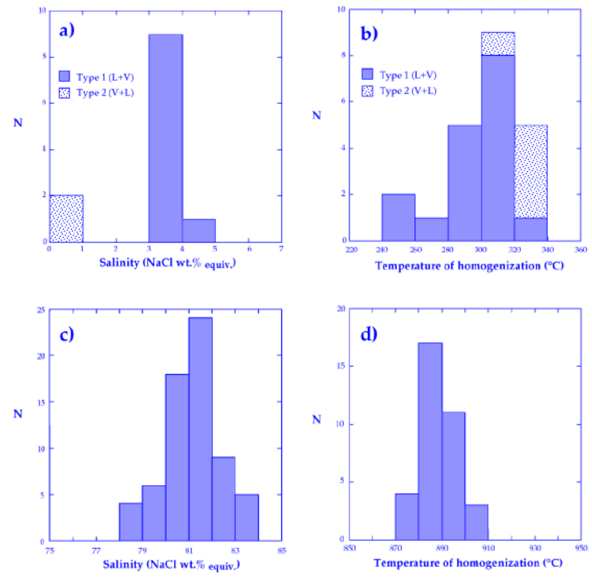

Figure 3: a) Salinity and b) Temperature of homogenization of Type 1 and 2 two phase fluid inclusions; c) Salinity and d) Temperature of homogenization of Type 3 multiphase fluid inclusions

Type 1 FIs are two phase liquid-rich FIs (L+V) found in hydrothermally altered xenoliths. They exhibit a temperature of first ice melting (T_e) around -21/-22°C suggesting Na^+ as the predominant cation. The temperature of final ice melting (T_{mi}) is in the range –1.8/-2.4°C with a mode about –2.1°C. This corresponds to salinities in the range 3.1-4.0 wt.% $NaCl_{equivalent}$ (using the equation of Bodnar, 1993), with the mode around 3.5 wt.% (Fig. 3a). Total homogenization (in the liquid phase) temperature (T_h) occurs in the range 250-325°C with a mode around 315°C (Fig. 3b).

Type 2 are two phase vapor-rich FIs (V+L) found in hydrothermally altered xenoliths. The T_{mi} of Type 2 inclusions was measured in a couple of inclusions to be around -0.1°C corresponding to salinity of 0.2 wt.%

$NaCl_{equivalent}$ (Fig. 3a). FIs exhibit T_h in the range 315-330°C (Fig. 3b). No T_e could be clearly established.

Type 3 multiphase liquid-rich FIs (L+V+many daughter minerals) are found either in hydrothermally altered and fresh syenitic xenoliths. In Type 3 FIs the last cubic daughter mineral (halite) dissolves at temperatures from 630°C to 670°C (T_s) corresponding to salinity of 78-84 wt.% $NaCl_{equivalent}$ (Sterner et al., 1988) with a mode at 82 wt.% $NaCl_{equivalent}$ (Fig. 3c) and the T_h of the vapor bubble in the liquid phase occurs in the interval 878°C - 910°C with a mode of 885°C (Fig. 3d). SEM-EDS studies on opened fluid inclusions revealed the occurrence of a complex daughter mineral assemblage in which the most abundant phases are halite and sylvite; other phases include sulfates (anhydrite, glaserite, glauberite and arcanite) and fluorides (NaF and Ca-Rare Earth Elements-F).

3. DISCUSSION

Melt inclusions of trachytic composition occur within crystals of investigated juvenile samples. As the major element composition of most MIs is similar to that of the bulk pumice and the glassy matrix, this could indicate that only minor differentiation of melts occurred between entrapment and eruption. Therefore the dissolved water content of melt inclusions (2.5 ± 0.5 wt.%) can be assumed as representative of the pre-eruptive volatile content of melts. The H_2O solubility model of Di Matteo et al. (2004) for trachytic melts was applied to calculate saturation pressure for these MI and a pressure of 40 ± 7 MPa was obtained. According to the hypothesis of water saturation conditions for the trapped melts, 40 MPa was assumed to be the mean trapping pressure of MIs. This pressure was converted to depth via a model, based on measured densities of the rocks (from 1.5 to 2.0 g/cm3 for tuffs and hydrothermally altered tuffs, 2.4 to 2.5 g/cm3 for trachytes and syenites), indicating that melt inclusions formed within a magmatic storage region located at about 2 km. Our data, highlighting the occurrence of a trachytic magma chamber located at about 2 km, agree well with the model proposed by Paoletti et al. (2009) that hypothesizes the occurrence of a trachytic intrusion having the top at about 1250-1750m of depth. This shallow magmatic system can be considered responsible of the resurgence of Mt Epomeo block in accordance with Rittmann (1944), Vezzoli (1988), Orsi et al. (1991), Carlino et al. (2006) and others. Assuming that the pressure correction is negligible, the homogenization temperature of MI around 1000°C corresponds to the crystallization temperature of magma. Crystallization temperatures were also estimated using another independent method: a two-feldspar geothermometry. The two-feldspar temperatures were calculated for pairs of plagioclase and K-feldspar using the calibration of Elkins and Grove (1990) and considering a pressure of 40 MPa. Differences in T_{Or}, T_{Ab} and T_{An} were minimized by adjusting the two given feldspar compositions within a 2 mol% uncertainty, based on the algorithm developed by Fuhrman and Lindsley (1988): the calculations were carried out using SOLVCALC 2.0 software by Wen and Nekvasil (1994). The obtained temperatures are in the range 970-1025°C, which is considered in very good agreement with the measured temperatures of homogenization of melt inclusions. The occurrence of primary multiphase fluid inclusions in syenitic xenoliths indicates that a hypersaline aqueous fluid phase has been locally exsolved from subvolcanic bodies representative of the peripheral portions of the magma chamber, or of the associated intrusions. Microthermometry of these fluid inclusions suggests that the fluids exsolved at a temperature of about 880°C. This value is in good agreement with two-feldspar geothermometry temperatures that furnish a range of 850-870°C using the calibration of Elkins and Grove (1990) and considering a pressure of 40 MPa. The lower temperatures found for syenites are coherent with the different compositions observed in K-feldspar, plagioclase, and clinopyroxene from juveniles and xenoliths (Fig. 4).

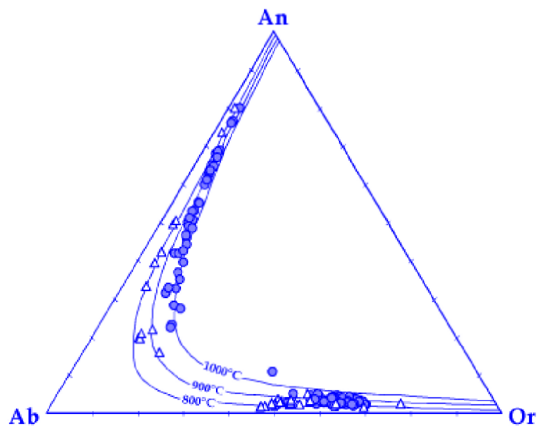

Figure 4: Composition of primary plagioclase, K-feldspar of investigated pumices and xenoliths. Dots = crystals in juvenile pumices, triangle = crystals in syenitic xenoliths. Isotherms in feldspar diagram have been calculated according to Elkins and Grove (1990)

The mixture of non-silicate daughter minerals observed in these inclusions is suggestive of a complex composition of the entrapped fluid, in which anions such as sulfate and fluoride are present in significant amounts in addition to chlorides.

The pile of the hydrothermally altered intracaldera sequence was involved in a rapid uplift process occurred in several steps (with a mean uplift rate in the order of 10-2 m/y), forming the Mt Epomeo block. Chlorite, illite and phengite composition can be used to estimate formation temperature using suitable geothermometers. The average temperatures calculated from chlorite geothermometers are between 260 and 320°C for the Facies (3) whereas illite geothermometer gave a range of 220°-265°C for Facies (2), 280-315°C for Facies (3) and ~340°C for Facies (4). Hydrothermal mineral assemblages, mineralogical geothermometry and fluid inclusion data on the Ischia island hydrothermal system are in good agreement and indicate temperatures of the hydrothermal fluids ranging from 120-140°C to about 340°C. On the basis of the characterizing authigenic minerals, we identified a prograde zonation of the hydrothermal alteration that reflects temperatures that increase from top to bottom of the altered units (Fig. 2). It is interesting to remark that within the outcropping propylitically altered ash flow tuff units (Facies 2) the estimated alteration temperature (around 230-240°) does not significantly change with depth indicating a nearly constant thermal gradient over a drop of about 500m. This suggests the predominance of a convective heat transfer for this zone that can be considered the geothermal reservoir of the hydrothermal system of Ischia. The highest temperatures (315-340°C) of the hydrothermal fluids were found in the hydrothermally altered syenitic xenoliths, indicating that the deepest and hottest portions of the hydrothermal system penetrated trachytic subvolcanics. Fluid inclusion investigation (salinity of fluid inclusions around 3.5 wt.%$NaCl_{equivalent}$) and particularly the stable isotope compositions of water in equilibrium with authigenic minerals indicate that the hydrothermal fluids were dominated by seawater that invaded caldera area after the collapse. In some hydrothermally altered syenitic xenoliths, the coexistence of liquid-rich and vapor-rich fluid inclusions and their similar range of temperature of homogenization (~315°C) suggest that boiling may have occurred during deposition of hydrothermal alteration mineral assemblage. The mode of Th of Type 2 FIs is slightly higher than that of the coexisting Type 1 FIs. The pressure estimated for the boiling zone is about 10 MPa at 315°C, corresponding to a depth of about 1 km, assuming hydrostatic pressure and that the fluid can be represented by the H_2O-NaCl system (the hydrostatic boiling curve was reconstructed considering the salinity of Type 1 fluid inclusions of 3.5 wt.% $NaCl_{equiv}$.). It is interesting to remark that these results are comparable to those reported in Chiodini et al. (2004) for the active hydrothermal system present in the stable (not uplifted) sectors of the caldera (Fig. 1). The occurrence of an active geothermal system in this area is confirmed by deep geothermal wells drilled between 1939 and 1955 (Penta 1954) that found high-T hydrothermal fluids (I3 well found ~250°C at 1051m of depth) that were used to feed a little geothermal power plant (300 kW) for a few years. The hydrothermal alteration paragenesis described for these wells (Penta, 1954) are very similar to those found in the uplifted successions that have been investigated in the present work.

4. CONCLUSIONS

The multidisciplinary approach of investigation carried out in this study led to the development of an integrated model concerning the evolution of the magmatic-hydrothermal system of Ischia island. At Ischia volcanic field, after high volume caldera forming eruptions (60-56 kyr ago), a very important resurgence affected the center of the caldera floor exposing a thick pile of caldera filling deposits. The investigation of these thick ignimbrite deposits highlighted that these rocks were subjected to strong hydrothermal circulation mainly carried out by fluids of marine origin. This allowed the development of a geothermal system with argillized units forming the impermeable cover of the system and the underlying propylitized units that can be considered the geothermal reservoir (Fig. 5).

The high uplift rate of Mt Epomeo block induced negligible effects of superimposition of lower temperature hydrothermal alteration processes. We have clear evidence that fluids of the deepest part of the hydrothermal system penetrated the most external parts of subvolcanic bodies, present in the deeper parts of the island, to a depth of at least 1 km. The engine of the high-T hydrothermal system of Ischia can be identified in the shallow (top at around 2 km of depth) and wide magmatic system that hosted hot (around 1000°C) trachytic melts. The results of this work fill a gap in the knowledge of Ischia volcanic system and can therefore be used as a dissected analog for the architecture of active hydrothermal systems that are inaccessible at present.

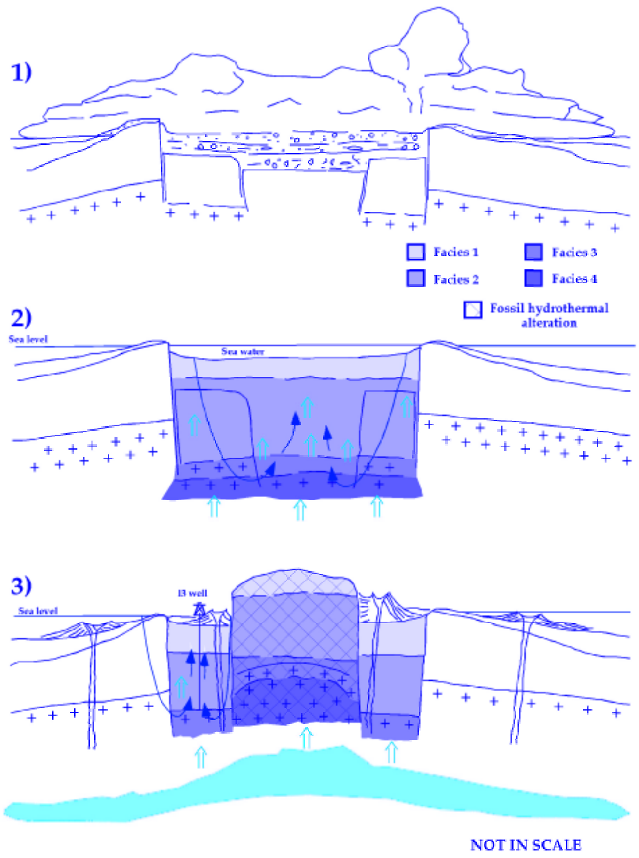

Figure 5: Schematic sequence summarizing the evolution of Ischia magmatic-hydrothermal system. 1) Caldera filling eruptions (60-56 kyr); 2) Development of seawater-dominated hydrothermal system inside cauldron; heat energy was supplied by the shallow (~ 2km of depth) magmatic system; 3) Resurgence and exhumation of part of the hydrothermal system, which remains active today in the footwall sectors of the caldera. Red arrows = hydrothermal fluids; blue arrows = surficial waters

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