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THE USE OF FLUID INCLUSIONS FOR TEMPERATURE ESTIMATIONS IN THE LARDERELLO GEOTHERMAL FIELD (ITALY)

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ABSTRACT

In-hole temperature measurements can cause problems during geothermal drilling. Direct in-hole temperature measurements are relatively expensive, time-consuming and, in some cases, could be affected by errors due to thermal disequilibrium after drilling. In particular, the vapor-static nature of the Larderello geothermal system makes temperature estimations particularly difficult in this field, as in-hole thermal conditions can be strongly influenced by the pressure of the water introduced during drilling operations. Direct temperature measurements may also be a problem in deep wells characterized by high-temperatures (>375°C), as in the case of some Larderello wells. Local temperature information can be obtained from fluid inclusions trapped in minerals if they contain hydrothermal fluids representative of the recent thermal conditions. In this work we compare present-day estimated temperatures with the homogenization temperatures of recent fluid inclusions in order to evaluate whether the latter can be used for temperature evaluations at Larderello.

In the Larderello geothermal field, early fluid circulation was characterized by the presence of magmatic-derived and contact-metamorphic fluids trapped at high temperature (425-690°C) and under lithostatic pressure. At this stage, contact-metamorphic minerals (cordierite, biotite, corundum) and high-temperature hydrothermal minerals (tourmaline, biotite, plagioclase) crystallized. Early fluid circulation was replaced by a late hydrothermal activity characterized by the presence of meteoric fluids of lower temperature (usually <400°C) under hydrostatic pressure. This hydrothermal activity was responsible for the precipitation of relatively low-temperature, late mineral assemblages (chlorite, epidote, carbonates, anhydrite, etc.). Finally, the Larderello system evolved to present-day vapor-static conditions.

The relatively young maximum ages (20 and 270 ka) of late hydrothermal minerals suggest that the fluid inclusions trapped in these minerals may contain fluids representative of the recent thermal conditions at Larderello. Comparison of present-day temperature with average and minimum homogenization temperatures of late-stage inclusions found in 23 core samples indicates that these homogenization temperatures cannot precisely estimate the present-day temperature at the depth of core sampling. In general, both the average homogenization temperature and minimum homogenization temperatures approximate the present-day temperature with an error of ±30°C in most (≥ 65%) of the samples. Within this error, the average homogenization temperatures predict the present-day temperature in more cases than the minimum homogenization temperatures. Therefore, the average homogenization temperatures can be used for a broad evaluation of present-day temperature, when in-hole measurements are missing or dubious.

1. INTRODUCTION

One of the main tasks during geothermal exploration is the reconstruction of the thermal gradient of the prospect area. In fact, a correct utilization of the geothermal resources implies a quantitative evaluation of all their physico-chemical characteristics. However, direct temperature measurements could prove difficult to obtain in geothermal wells as the thermal state of the wells is usually perturbed during drilling operations. In some wells, thermal equilibrium after drilling is reached after several days. Consequently, direct temperature measurements can be relatively expensive and time-consuming. It is particularly difficult to obtain direct temperature evaluations in high-temperature deep geothermal areas using conventional logging tools, as they cannot accurately detect temperature over 375°C at depths below 3000 m (Sawaki et al., 1997). High temperatures could be estimated using metals with known melting temperatures. This method gives only a range of temperatures or minimum values.

Qualitative estimates of temperature in well-defined zones of the geothermal field can be obtained from the hydrothermal mineral assemblage precipitated or equilibrated with the geothermal fluid. In this case, however, it may be difficult to establish whether the hydrothermal mineral assemblages are in equilibrium with the present-day fluid (Cathelineau et al., 1989a). The trapping temperatures of the fluid inclusions trapped in minerals can also provide local temperature values if the inclusions contain fluids recording the modern fluids (Cathelineau et al., 1989a). A new promising method for temperature logging in high-temperature geothermal areas based on synthetic fluid inclusions was recently proposed by Sawaki et al. (1997).

Difficulties in direct in-hole temperature measurements are also experienced in the vapor-dominated Larderello geothermal field. A problem peculiar to vapor-dominated fields is the water that can be introduced during drilling, and the concurrent presence of fractures above the site of temperature measurements. If this water is boiling, in-hole temperature is controlled by the temperature-pressure relation for liquid water. In this case, the actual temperature before drilling could be higher than the temperature under the new conditions. If the water level in the well is depressed by the presence of fractures above the measurement site, the pressure may be so low that the temperature cannot reach its original values before drilling. Accurate temperature data can also be difficult to achieve in many deep Larderello wells with temperatures in excess of 375°C.

In this paper we test the possibility of using fluid inclusion microthermometric data for local temperature estimates at Larderello. We have revised the fluid inclusion homogenization temperature data published over the last two decades for core samples from this geothermal area and compared them with present-day temperature values. Most of the studied fluid inclusions probably record the fluid circulation before the present-day vapor-dominated condition. Thus, on the basis of the thermal evolution of the Larderello geothermal fluids, we can select the fluid inclusion data that are most representative of the present-day temperatures.

2. THERMAL EVOLUTION IN THE LARDERELLO GEOTHERMAL SYSTEM

Studies on contact-metamorphic and hydrothermal minerals (Cavarretta et al., 1980, 1982; Bertini et al., 1985; Cavarretta and Puxeddu 1990; Gianelli and Ruggieri, 1999) and fluid inclusions (Belkin et al., 1985; Cathelineau et al., 1989b; 1994; Valori et al., 1992; Petrucci et al., 1993; Ruggieri and Gianelli, 1995; 1999; Gianelli et al., 1997; Ruggieri et al., 1999) have described the complex history of the geothermal fluids at Larderello. These studies documented two main stages of hydrothermal activity at Larderello.

2.1 Early Stage Fluid Circulation

The first stage is related to the emplacement of an S-type granite intrusion at > 2000 m depth below ground level (b.g.l.) that promoted thermometamorphic and metasomatic phenomena in the surrounding metamorphic rocks (gneiss, micaschist and phyllite). Thermometamorphism gave origin to crystallization of biotite, andalusite, cordierite, quartz and muscovite and, in places, to corundum and K-feldspar. Metasomatic processes are evidenced by the widespread occurrence of veins with biotite, tourmaline, quartz and plagioclase (Gianelli and Ruggieri, 1999). Granite and contact metamorphic rocks are characterized by K/Ar and $^{40}Ar/^{39}Ar$ ages between 3.8 and 1.6 Ma (Villa and Puxeddu, 1994). Fluid inclusion studies showed that during this stage two main types of fluids circulated at depth: 1) magmatic-derived Li+Na-rich brines, and 2) $H_2O+CO_2\pm CH_4\pm N_2$ vapors and liquids produced during contact metamorphism (Valori et al., 1992; Cathelineau et al., 1994; Ruggieri and Gianelli, 1995). Both these fluids were trapped in inclusions in quartz of granite dykes and of high-temperature mineral assemblages (biotite, tourmaline, plagioclase, etc.) found in the deepest part (>2500 m b.g.l.) of the geothermal field. These early fluids are sub-contemporaneous and were trapped under temperatures of 690 to 425°C and lithostatic pressures of approximately 100-130 MPa.

2.2 Late Stage Fluid Circulation

The second stage of hydrothermal activity was characterized by the precipitation of lower temperature hydrothermal minerals: quartz, chlorite, epidote, adularia, calcite, anhydrite, muscovite and sphene. Late hydrothermal minerals are commonly found at shallow-intermediate depth (≤ 2500 m b.g.l.) and sometimes as replacement of the deep high-temperature assemblage and granites. Quartz and calcite, in late veins, exhibit $^{230}Th/^{234}U$ maximum ages between 20 and 270 ka (Bertini et al., 1996). During this stage several fluids with different compositions were present: 1) $H_2O+NaCl\pm CO_2$ liquids with low to moderate salinity (<10 wt. % NaCl eq.), 2) $H_2O+NaCl+CaCl_2$ relatively high salinity (up to 22 wt. % NaCl eq.) liquids, 3) $H_2O+NaCl$ high salinity (up to 40 wt % NaCl eq.) liquids produced by local boiling with steam loss, 4) $H_2O\pm CO_2$ low-density vapors derived from boiling and 5) nearly pure H_2O resulting from the condensation of the vapors produced by boiling (Cathelineau et al., 1989b; Valori et al., 1992; Ruggieri et al., 1999; Ruggieri and Gianelli, 1999). These fluids were usually found in late quartz, carbonates, K-feldspar, albite, anhydrite, and in early quartz as late secondary inclusions. Late hydrothermal fluids were trapped at variable temperatures, between 150 and 400°C, under hydrostatic pressures (<35 MPa). They are interpreted to be meteoric-derived fluids that changed their composition, salinity and temperature through water-rock interaction (in particular with evaporite layers), fluid boiling, mixing and cooling.

The final evolution of the hydrothermal fluids resulted in the development of the present-day vapor-dominated condition of the geothermal field.

3. SELECTION OF FLUID INCLUSION DATA FOR TEMPERATURE ESTIMATES AT LARDERELLO

The latest trapped fluids are contained in the inclusions of the recent hydrothermal minerals, and in the late secondary inclusions of the early minerals. However, as stated above, these inclusions may contain several types of fluids characterized by different compositions and, in some examples, by different homogenization temperatures. The most represented fluids in these inclusions are the $H_2O+NaCl\pm CO_2$ liquids with low to moderate salinity. These liquids were found in most of the studied samples and they are also relatively abundant. We usually selected the data of these fluid inclusions for the temperature evaluations. Where these fluid inclusions were not available we used the data of the $H_2O+NaCl+CaCl_2$ inclusions.

When we were able to determine that the $H_2O+NaCl\pm CO_2$ fluids were trapped during different trapping events, we chose the data of the latest trapped fluids. For example, the data of the secondary inclusions were preferred when these inclusions were clearly distinguishable from the primary or pseudosecondary inclusions. When fluid inclusion data were obtained for different minerals of the same sample we chose the data of the inclusion contained in the last minerals to precipitate.

Table 1 shows the homogenization temperature values (maximum, minimum and average) of the selected inclusions from previous studies and new data from well Sesta 6bis. The estimated present-day temperature at the depth of the core-sample collection is also reported (Table 1). The homogenization temperature actually corresponds to the fluid trapping temperature only when the fluid was trapped during boiling processes. Boiling phenomena were evidenced in many samples (Belkin et al., 1985; Gianelli et al., 1997; Ruggieri and Gianelli, 1999; Ruggieri et al., 1999). In other samples, however, boiling processes could not be demonstrated (although they were sometimes suggested by the widespread presence of vapor-rich inclusions). The formation temperature of a fluid inclusion not formed during boiling can be calculated from its trapping pressure, from the isochore of the trapped fluid. However, for a fluid inclusion formed at relatively low pressure, as in the case of the late inclusions at Larderello, probably trapped under hydrostatic pressure, the original temperature exceeds the homogenization temperature by only a few degrees (usually ≤10°C at Larderello). Thus, in first approximation, the homogenization temperatures of the late fluid inclusions can be considered close to their trapping temperatures. The instrumental errors on homogenization temperature are usually considered ±2°C.

Present-day temperatures were mostly estimated on the basis of direct in-hole measurements at the site of core-sampling or extrapolated from measurements carried out at different depths in the same well. In some occurrences, when direct in-hole temperature measurements were not available,the temperatures were evaluated from the thermal regime of neighbouring wells. In the case of Sesta 6bis the temperature was obtained from the temperature of the fluid produced by a fracture located near to the core-sampling site. The maximum error on the estimated present-day temperature is considered to be ±10°C.

4. DISCUSSION

The relatively young ages of late calcite and quartz suggest that the fluids trapped in these minerals can give reliable information on recent thermal conditions at their trapping depth.

As shown in Table 1, the selected fluid inclusions usually show a wide range of homogenization temperatures, so that it is difficult to choose the homogenization temperature that is most similar to present-day thermal conditions. Figure 1 shows the plot of present-day temperature vs. the average and minimum homogenization temperatures.

The average homogenization temperature should be the temperature of the most represented fluids in the sample, if the fluid inclusions mostly belong to a homogeneous population with relatively similar microthermometric data. In this case, the average homogenization temperature also minimizes the possible errors related to data coming from fluid inclusions affected by necking-down, stretching or the heterogeneous trapping of some vapor together with the liquid during boiling processes. From Fig. 1 it can be observed that the average homogenization temperatures of numerous samples are relatively similar to the present-day temperature. However, there are also some average homogenization temperatures that are consistently higher than present-day temperatures (Table 1, Fig. 1). This can be imputed to the variation of the fluid temperature during inclusion formation, as suggested by the large homogenization temperature ranges of some samples. In particular, the presence of distinct groups of fluid inclusions characterized by different homogenization temperature ranges (and variable trapping conditions) was evidenced by Ruggieri et al. (1999). In these cases, the average homogenization temperatures cannot be representative of the temperature of the last trapped fluid.

The Larderello geothermal field has been affected by a quasi-monotonous cooling since its beginning (Cathelineau et al., 1994). Thus, for the samples that contain inclusions trapped at different temperatures, the last trapped fluid inclusions should be those characterized by lower (minimum) homogenization temperatures. Cooling processes were revealed, in particular, by studies on inclusions found in late hydrothermal minerals from Larderello (Ruggieri et al., 1999; Ruggieri and Gianelli, 1999). Table 1 and Figure 1 show, however, that the minimum homogenization temperatures of fluid inclusions cannot precisely estimate the present-day temperature. This may be imputed to different factors, such as: 1) a cooling process occurred after the last trapped fluids; 2) some of the minimum homogenization temperatures underestimate the true trapping temperature since the trapping pressure was not considered; and 3) non-representative homogenization temperature data were collected from fluid inclusions affected by necking-down.

Generally the whole of the data indicate that the difference between the average homogenization temperature and present-day temperature is within ±20°C in 57% of the samples, and within ±30°C in 70% of them, while the difference between the minimum homogenization temperature and the present-day temperature is within ±20°C in 52% and within ±30 in 65% of the cases. These differences should be even lower if we consider that the estimated present-day temperatures are affected by an error of up ±10°C. Thus, the average homogenization temperatures probably better predict the present-day temperatures.

5. CONCLUSIONS

In the Larderello geothermal field, the average and minimum homogenization temperatures of late fluid inclusions found in core samples differ from present-day temperatures by less than ±30°C in most of the samples. Within this range, the average homogenization temperatures more often approximate the present-day temperatures. The average homogenization temperatures could be used for the evaluation of present-day temperatures of the Larderello geothermal field when direct in-hole measurements are not available or are affected by large uncertainties.

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Table 1. Comparison between the present-day estimated temperature at the depth of core sampling and minimum, average and maximum homogenization temperatures of late fluid inclusions found in core samples. The maximum error on the estimated present-day temperatures is ±10°C; instrumental error on homogenization temperature is ±2°C.All fluid inclusion data except those of well Sesta 6bis are from Belkin et al. (1985), Petrucci et al., (1993); Gianelli et al., (1997), Ruggieri and Gianelli (1999), Ruggieri et al., (1999).

Well	Depth (b.g.l.)	Estimated present-day temperature (°C)	Minimum homogenization temperature (°C)	Average homogenization temperature (°C)	Maximum homogenization temperature (°C)
Secolo 1R	480	240	224	238	251
Radicondoli 16	1165	175	224	267	296
Carboli 11A	1515	150	161	174	182
Badia 1B	964	160	156	163	169
Larderello Profondo	789	250	240	249	350
Lago Puntone 3	1448	230	310	330	370
Val Pavone	673	130	187	256	285
Serrazzano Sperimentale	1824	280	285	287	291
Sasso 22	1480	300	283	310	375
Sasso 22	1600	305	274	290	331
Sasso 22	2163	315	303	324	341
Sasso 22	2636	325	300	325	339
Sasso 22	2767	330	293	297	302
Capannoli 2B	2380	340	328	344	367
Monteverdi 1	2227	295	309	368	377
Monteverdi 2A	1781	285	254	302	343
Monteverdi 2	886	150	279	308	315
Monteverdi 2	1933	290	303	314	328
Monteverdi 2	2298	320	291	324	344
Monteverdi 5A	1088	135	139	150	171
Monteverdi 7	3438	335	332	362	422
S. Giovanni 1bis	1780	320	287	304	322
Sesta 6bis	2733	310	346	353	358

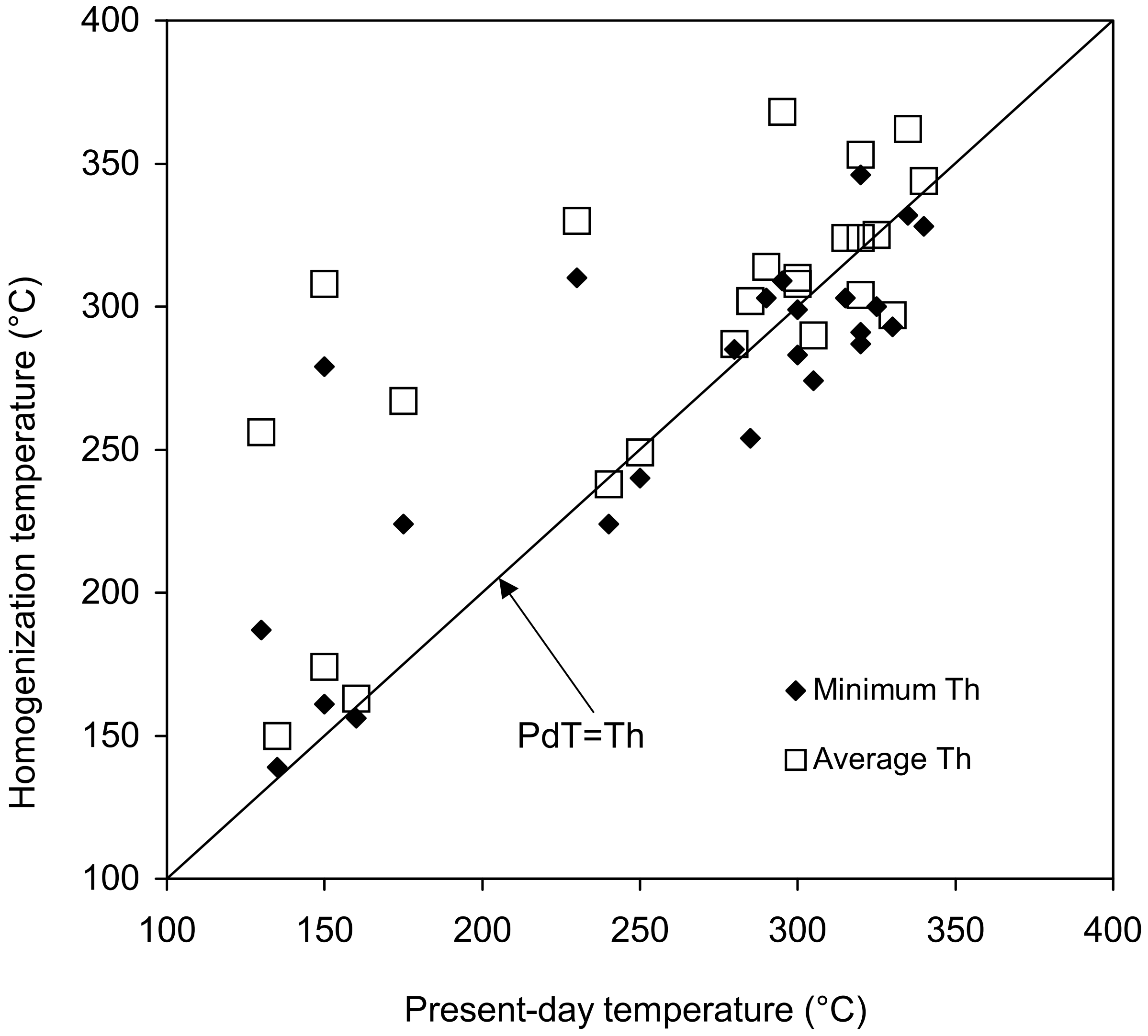

Figure 1. Plot of the estimated present-day temperature vs. the average and minimum homogenization temperature. Abbreviations: Th=homogenization temperature, PdT=present-day estimated temperature.