Insight into the fluids occurring in the super-hot reservoir of the Los Humeros geothermal system from fluid inclusions and isotopic data of the Las Minas exhumed system (Mexico)

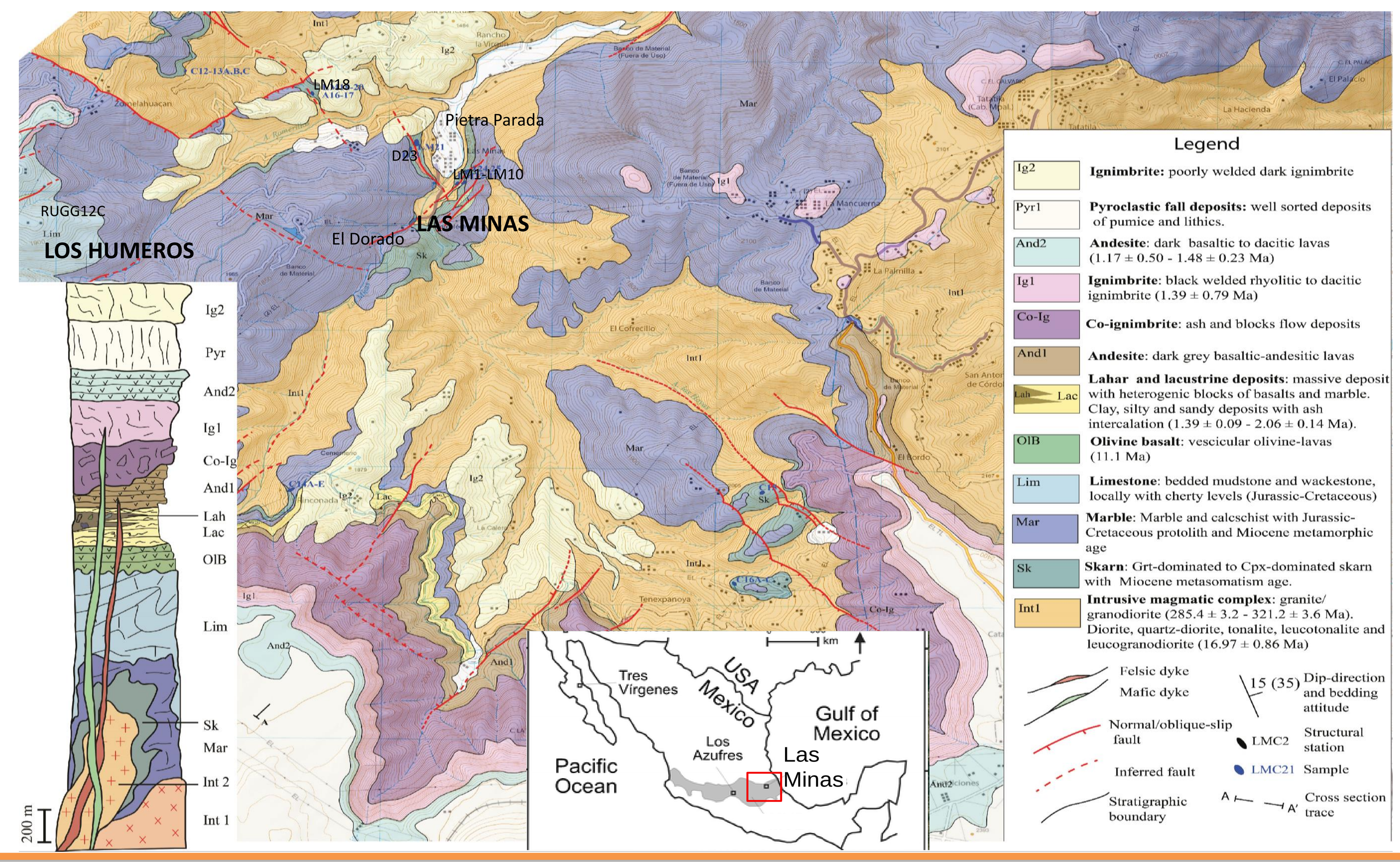
G. Ruggieri (CNR), G. Morelli (CNR), M. Zucchi (UNIBA), E. Braschi (CNR), S. Agostini S. (CNR), G. Ventruti (UNIBA), A. Brogi (UNIBA), D. Liotta (UNIBA), C. Boschi (CNR), E. González-Partida (UNAM)

1. AIMS AND ANALYTICAL METHODS

The skarn-hydrothermal exhumed system of Las Minas is thought to be analogue of the super-hot system located below the present exploited zones of the Los Humeros geothermal system. Structural studies coupled with minero-petrographic, fluid inclusion and isotope analyses have been carried out on skarn-hydrothermal mineral assemblages collected in the Las Minas area in order to: i) obtain information on the physico-chemical features and the origin of the fluids which circulated in the paleo-super-hot reservoir; ii) define the fluid-rock interaction processes promoted by the fluids circulating through the paleo-reservoir; iii) characterize the structural control on the fluids circulation in the exhumed system. This information was used to predict the features of the deep fluids in the active system of Los Humeros.

2. STUDY AREA AND STRUCTURAL FEATURES

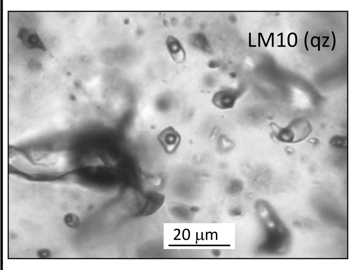
The Las Minas area (Veracruz, Mexico) is characterized by the occurrence of skarn-hydrothermal mineralization related to Miocene magmatism. Structural data showed that the two main fault systems NNW- and SW-trending acted as main conduits favoring the uprising of fluids from deep to shallow structural levels.



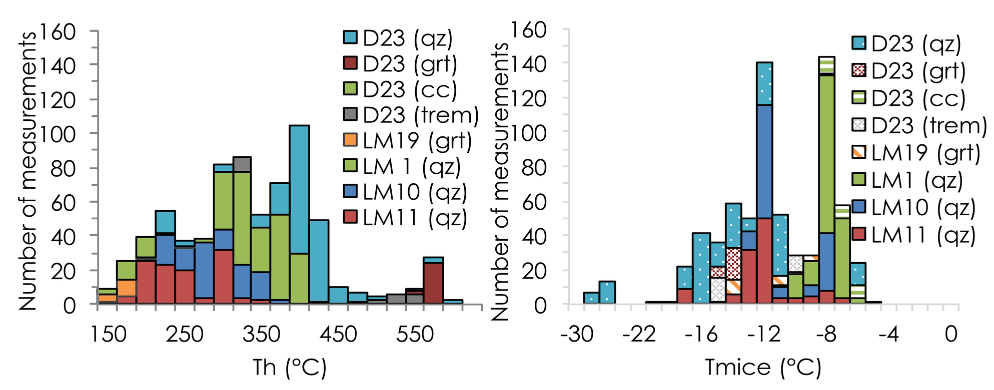
3. FLUID INCLUSIONS DATA AND INTERPRETATION

Fluid inclusions analyses revealed that at least four main fluid-types were trapped into the inclusions

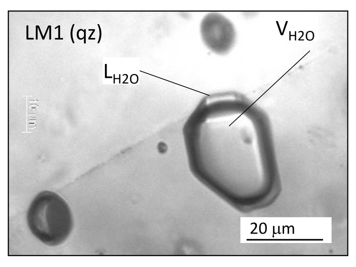
L-type: two phases aqueous (liquid+vapour) liquid-rich



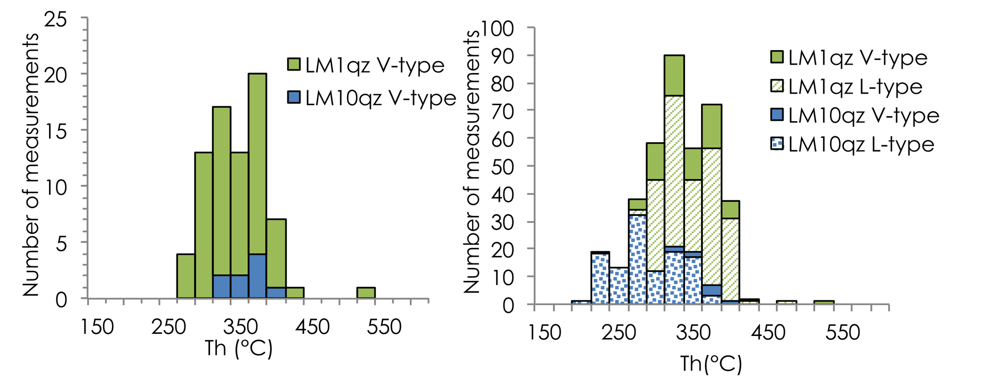
L-type are present in all the examined samples and minerals. In hydrothermal quartz, L inclusions are often associated to growth zones of the crystal. Within skarn quartz, garnet, calcite and tremolite usually occur along trails of secondary or pseudosecondary origin.



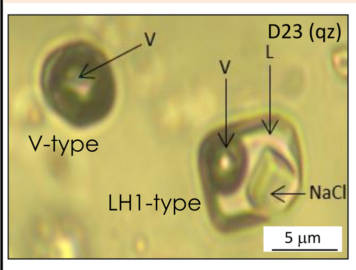
V-type: two phases aqueous (liquid+vapour) vapour-rich



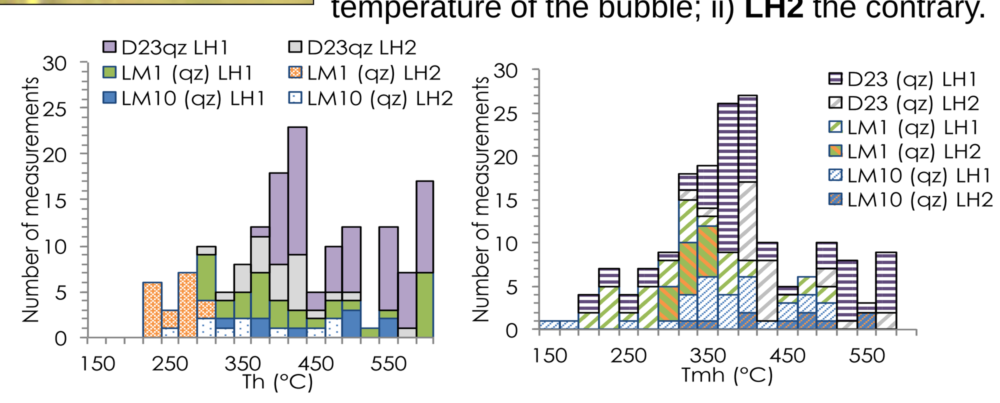
V-type occur both in hydrothermal quartz and in quartz associated to skarn minerals. As for L inclusions, V inclusions in hydrothermal quartz often show primary features, whereas in skarn quartz they occur along trails or, more rarely, form groups with an apparently three dimensional distribution. Some V inclusions contain a halite crystal (Vs-inclusions).



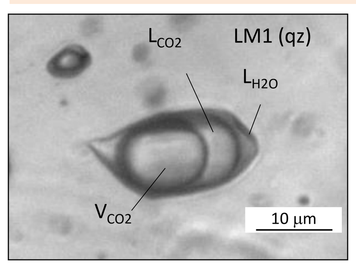
LH-type: multi-phases aqueous (liquid + vapor + halite +/- solids)



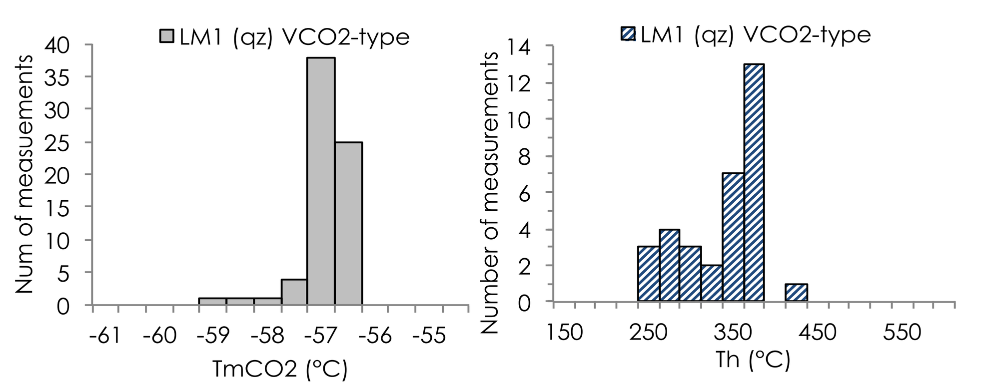
LH-type occur in groups of inclusions with a three dimensional distribution in quartz of the skarn assemblage. Two sub-types of LH inclusions are distinguished on the basis of microthermometry: i) **LH1** showing halite melting temperature < homogenization temperature of the bubble; ii) **LH2** the contrary.



V_{CO_2}-type: three-phases (liquid H_2O + liquid CO_2 + vapour CO_2) or two phases (liquid H_2O + vapour CO_2)



V_{CO_2}-type occurs along trails or in clusters. In few V_{CO_2} inclusions H_2S, N_2, and O_2 were detected as minor component in the volatile phases by Raman analyses.

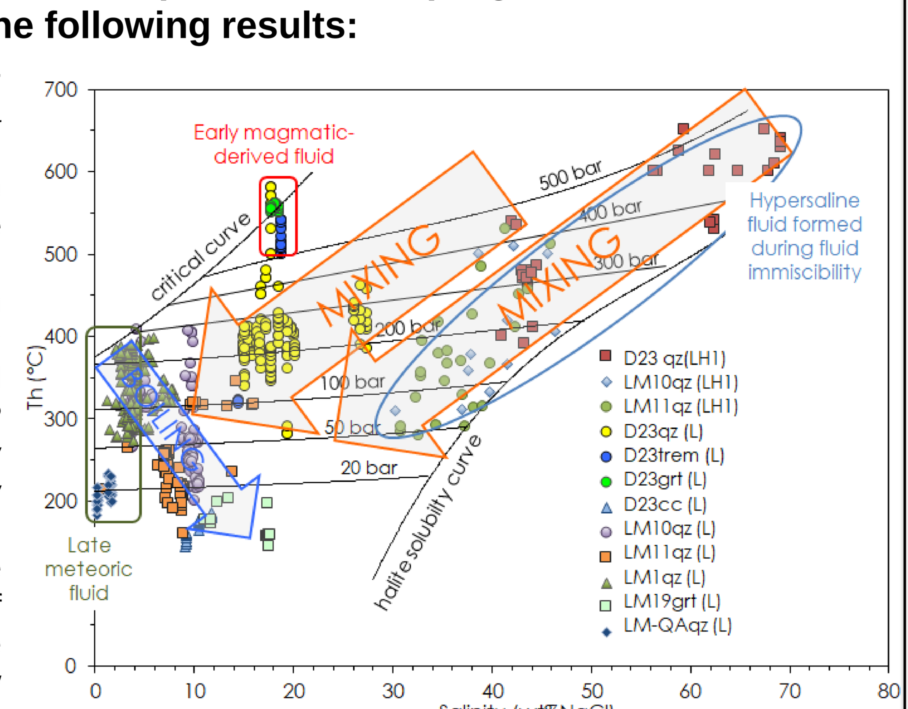


Frequency histograms of fluid inclusions microthermometric data. Th: homogenization temperature (i.e. disappearance of the vapour phase), Tmice: ice melting temperature, Tmh: halite dissolution temperature, Tm_{CO_2}: CO_2 melting temperature, qz: quartz, grt: garnet, trem: tremolite, cc: calcite.

- ❑ **LH1 and LH2-type** inclusions are characterized by high to very high-salinity (30.3-68.6 wt% NaCl eq. for LH1 and 34.7-72.5 wt% NaCl eq. for LH2 inclusions) and variable final homogenization temperature (279-650°C for LH1 and 275-600°C for LH2 inclusions).
- ❑ Coexistence of **LH1 + V** inclusions and the **LH1 + Vs** inclusions (i.e. V-rich inclusions containing halite) testify fluid immiscibility processes that interested a magmatic-derived saline fluid subject to decompression.
- ❑ **V_{CO_2}–type** inclusions are characterized by x_{CO_2}: 0.194-0.490 and salinity of 0.0-9.3 wt% NaCl eq., H_2S was also detected within the volatile phase by Raman analyses in few V_{CO_2}.
- ❑ **L-type** inclusions are characterized by a wide range of Th (144-580°C) and salinities (0.2-27.4 wt% NaCl eq.) suggesting variations of the physical-chemical parameters during their trapping.

Interpretation of fluid inclusion data combined with isochores computation, isotope geothermometer (see right) and inspection of Th vs. salinity diagrams led to the following results:

- ➢ **V_{CO_2}** inclusions record an early aqueous-carbonic fluid issued during contact-metamorphism related to an intrusion emplacement. P was around 1-1.6 kbar at a maximum temperature of 650°C.
- ➢ **L** inclusions in garnets and tremolite testify the earliest saline (18-20 wt% NaCl eq.) fluid exsolved from the magma at P-T of 0.5-1.5 kbar and 500-650°C that formed the endoskarn.
- ➢ **LH1** (hypersaline) and coexisting **V** inclusions formed as consequence of an immiscibility processes, which likely affected early saline fluid, due to decompression of the system. Whereas, **LH2** inclusions could derive from a hypersaline fluid trapped at relatively high pressure. During this stage the system was characterized by large P oscillation (from 0.05 to >1.8 kbars) and T variation (290-650°C). The T vs. salinity trend of **LH1** inclusions suggests that the fluid was progressively diluted and cooled by lower T-salinity fluid.
- ➢ **L** inclusions with moderate Th (i.e. <450°C) are characterized by large salinity range (0.0-27 wt% NaCl eq.). These features, the Th vs. salinity relation and the presence of coexisting L and V inclusions can be interpreted considering mixing between saline magmatic-derived fluid with meteoric fluid and fluid boiling. L inclusions with very low salinity testify ingress of meteoric fluid in the skarn system.

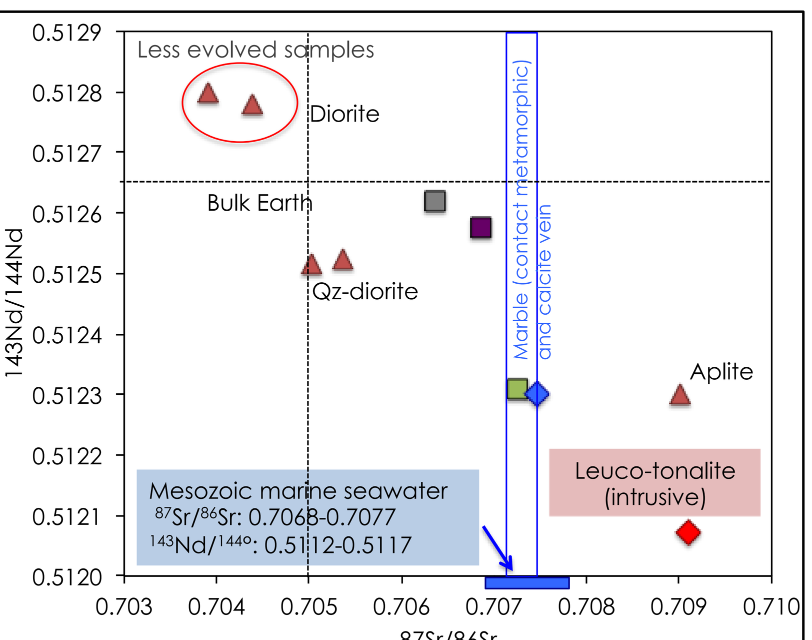


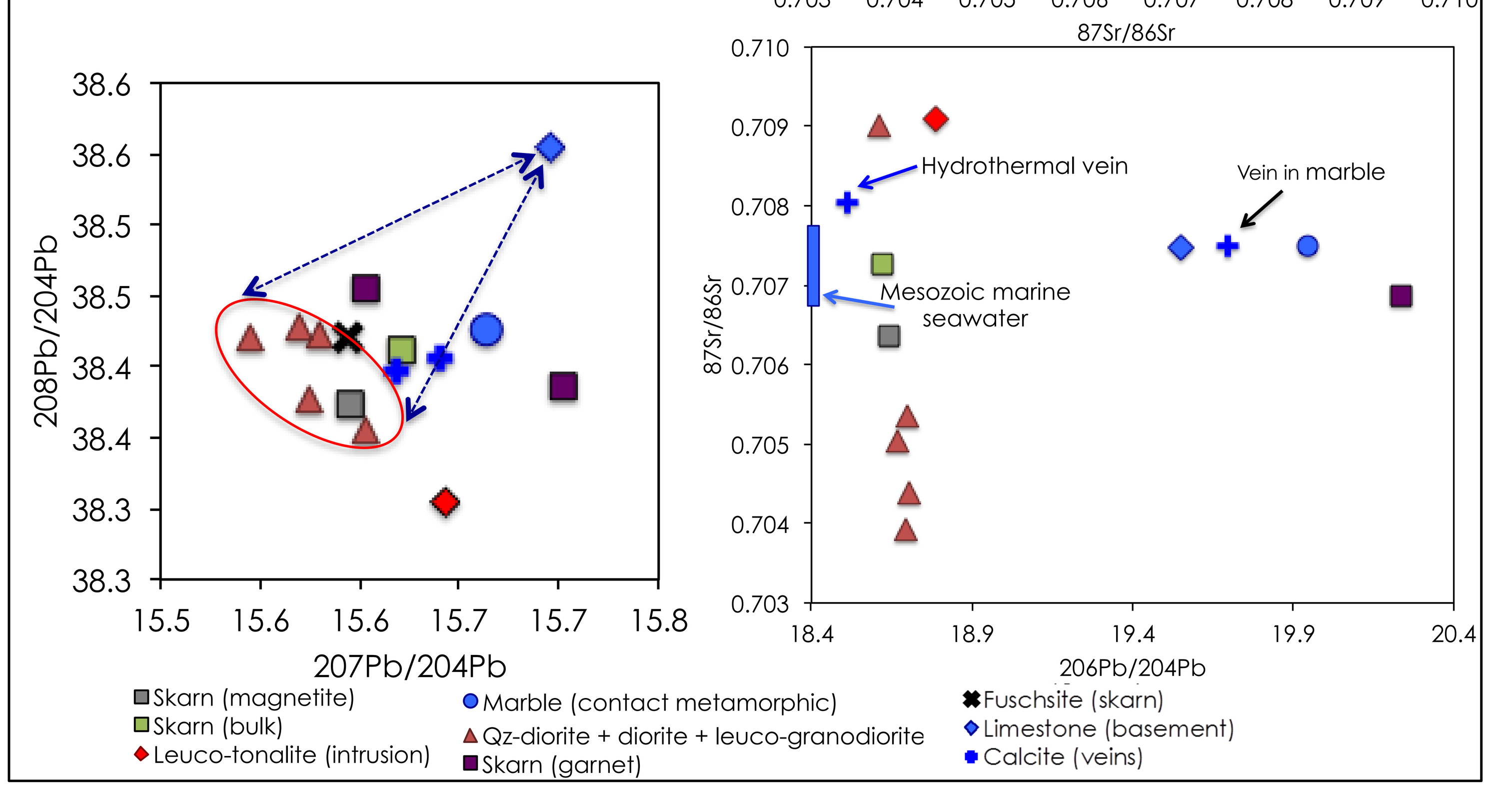
4. ISOTOPIC DATA AND INTERPRETATION

Radiogenic isotope (Sr, Nd, Pb)

Skarn samples show variable isotopic ratios, spanning from "carbonatic dominated" signature from **Nd-Sr isotopes** to a "magmatic dominated" signature especially combining Pb and Sr isotopes.

Pb isotopes show that three skarn samples cluster within diorite and qz-diorite dikes representing the most suitable source of magmatic derived components for the skarn and skarn minerals (magnetite, fuchsite, garnet).





Stable isotope (O)

Temperatures computed from **oxygen isotopic** data on skarn minerals range between 570-650°C in agreement with maximum trapping temperature derived from fluid inclusions.

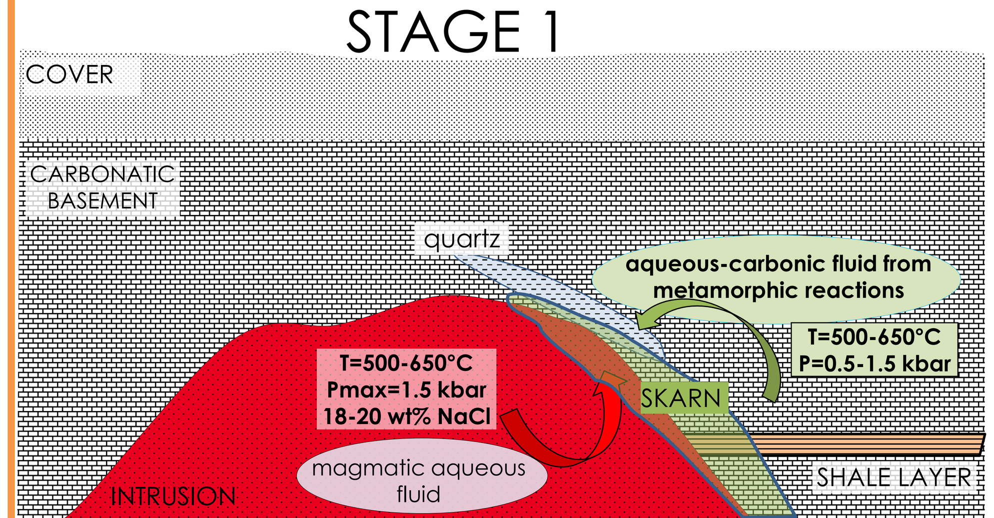
Sample	Mineral	$\delta^{18}O_{mineral}$ (‰)	$\delta^{18}O_{H_2O}$ (‰)	T(°C)
LM1	quartz	10.61	8.54	570
LM10	quartz	10.1	8.83	635
LM10	magnetite	3.34	8.83	635
LM14	magnetite	2.95	8.59	600
LM14	garnet	6.49	8.59	600
LM15	garnet	2.21	7.63	650
LM15	garnet	5.36	7.63	650
LM18	garnet	6.91	9.01	600

Main results

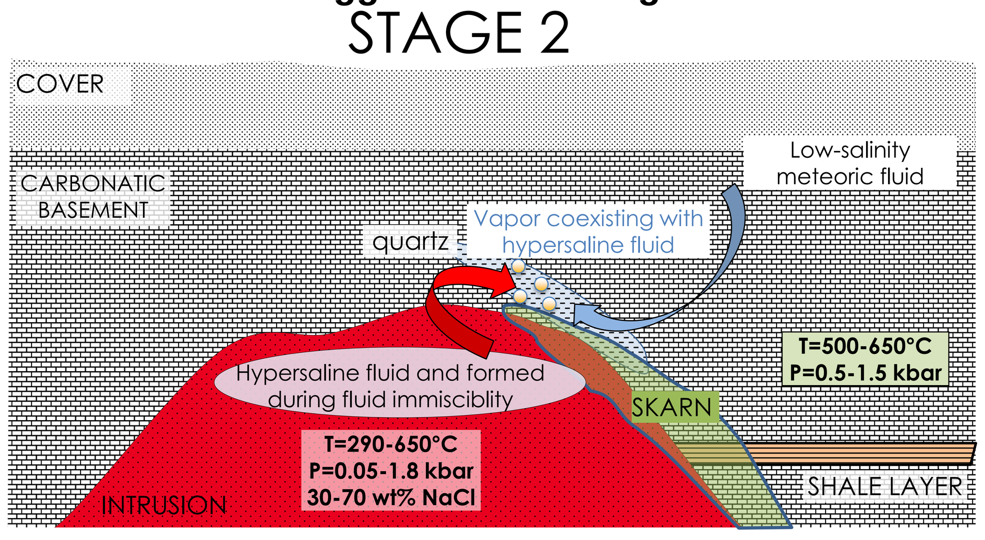
- ➢ Mixing between hydrothermal fluids from the two reservoirs ("magmatic" and "carbonatic") representing the principal end-member of the hydrothermal exhumed system of Las Minas explains the variation of skarn isotopic signature.
- ➢ The temperatures and isotopic compositions of the fluid in equilibrium with the skarn minerals are coherent with a magmatic derivation of the fluid.

5. EVOLUTION OF THE SKARN-HYDROTHERMAL SYSTEM

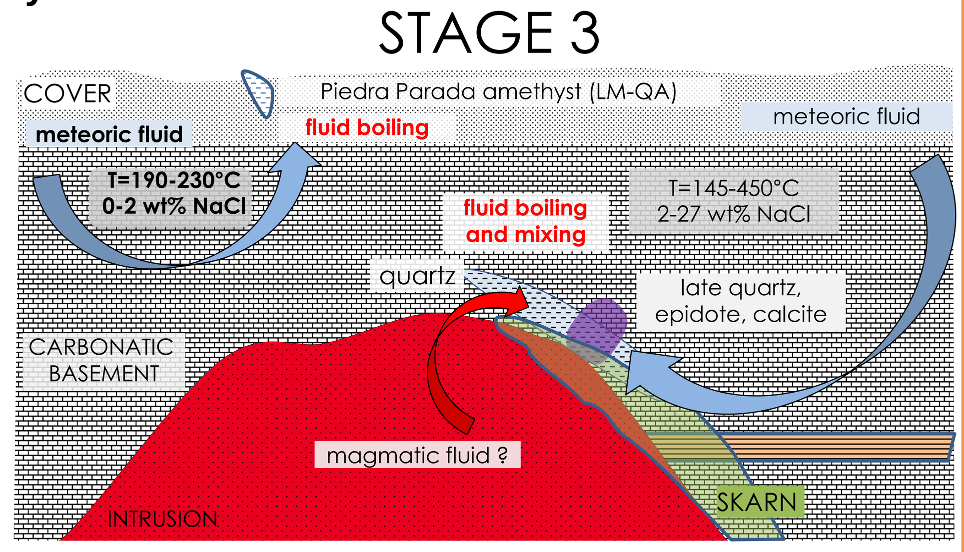
The integration of all data suggest a three-stage evolution of the system



1. High-temperature (up to 650°C), saline (up to 20 wt% NaCl eq.) fluid exsolved from a siliceous melt reacted with carbonatic rocks and formed skarn assemblage at P up to 1.6 kbar. Nearly contemporaneous aqueous-carbonic fluid issued during contact-metamorphism were trapped in quartz veins. These fluids eventually mixed during skarn formation.



2. Decompression (to hydrostatic P) of the system triggered fluid immiscibility which produced a **hypersaline fluid** (up to 70 wt% NaCl) and **low-salinity vapor.** However, self-sealing processes can close the system at time causing the trapping of portions of the hypersaline fluid at relatively high P (> 1.8 kbar). The ingress of meteroric fluid was responsible of the salinity decrease (down to 30 wt% NaCl) and cooling (down to 290°C).



3. Progressive input of low-salinity (up to 2 wt% NaCl equiv.) fluid of **meteoric fluid** in the deep system caused the dilution and cooling of the residual magmatic derived fluid. However, during the early phase of the third stage T could be still relatively high (up to 450°C). Throughout the third phase, besides fluid mixing, also fluid boiling occurred and influenced the salinity of the fluid.

6. CONCLUSIONS

- ❑ Fluid inclusion and isotopic data of skarn and hydrothermal minerals showed different stages of fluid flow in the system related to the emplacement of intrusive rocks and their interaction with the andesitic and carbonatic reservoirs. The two main fault systems NNW- and SW-trending, recognised in the study area. played the role of main conduits favouring the uprising of the geothermal fluids from deep to shallower structural levels.
- ❑ Present-day exploited geothermal reservoirs in **Los Humeros** have T of 300-400°C and are mostly recharged by meteoric water. Thus, it could be expected that the T conditions of the deeper super-hot system in Los Humeros can be comparable to those during the STAGE 3 of Las Minas (i.e. up to 450°C). In this case the fluid expected in the super-hot system is a mixture of low-salinity meteoric water and high-salinity magmatic derived fluid. Less probably, the conditions are similar to those of STAGE 2.

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Contact:
giovanni.ruggieri@igg.cnr.it
guia.morelli@igg.cnr.it
martina.zucchi85@gmail.com
edgopa@gmail.com

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