Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Analogue Geothermal Systems In Mexico: Insights Into The Deep Part Of Los Humeros Geothermal Field From The Las Minas Mining Area (Eastern Mexico)

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Keywords: Interdisciplinary approach, structural geology, geochronology, fluid inclusions, petrology, analogue geothermal system.

ABSTRACT

This study is part of the H2020-GEMex Project, a collaboration between Europe and Mexico for investigating super-hot geothermal systems. The novelty of this work is in its integrated methodological approach which bridges the past to the present and contributes to the reconstruction of conceptual models of deep geothermal systems, thus favoring appropriate strategies for deep exploration. The Las Minas mining area (Veracruz State) where Cu-Fe-Au ore-deposits have been historically exploited, is considered as an exhumed Neogene geothermal system analogous to the deeper part of the Los Humeros geothermal field (Puebla State). We used an integrated approach, which involved structural and kinematic, petrological, geochemical, geochronological and fluid inclusion analyses of the pre-volcanic Paleozoic-Cretaceous succession, intruded by Miocene-Pliocene granitoids and mafic dykes. Our emphasis was on the (paleo) fluid-rocks interaction and the related structural control. The results indicate that saline and hypersaline fluids (up to 70 wt. % NaCl equiv.) of magmatic derivation and aqueous-carbonic fluids issued during metamorphic or metasomatic reactions with T up to 600-650°C were channeled along and in the intersection between the NW- and NE-trending faults and their damage zones. The faults are characterized by strike-slip to oblique-slip/normal movements. Fluids were also stored in carbonate rock-volumes at the contact with the granitoids. The distribution of the ore-deposits and hydrothermal alteration related to the interaction of geothermal fluids and hosting rocks indicates the importance of conduits (such as fractures and faults) in the reservoirs. Hence, understanding the relationships between ore-deposits, hydrothermal alteration and structures can increase our knowledge of the present geothermal fluids' deep circulation in the Los Humeros geothermal field.

1. INTRODUCTION

The understanding of geothermal fluid pathways in the upper crust represents a continuous task for any successful exploration for hot to super-hot geothermal fluids in active geothermal systems, as is the case for the Los Humeros geothermal field (Figure1). To contribute to this issue, deep geothermal fluid flow paths can be derived from field and laboratory studies of fossil geothermal systems, that are considered analogous to the deep parts of the active systems of the exploration target. With this aim, we investigated the Las Minas fossil geothermal system (i.e. mineralized system) as an analogue of the Los Humeros active geothermal system, within the framework of the collaborative EU-Mexican joint program, named GEMex. The methodology is based on the integration of stratigraphic, structural, petrological, geochemical and geochronological data. The results shed light on fluid paths and the relation between geological structures and fluid flow, providing a key for the deep investigation in Los Humeros.

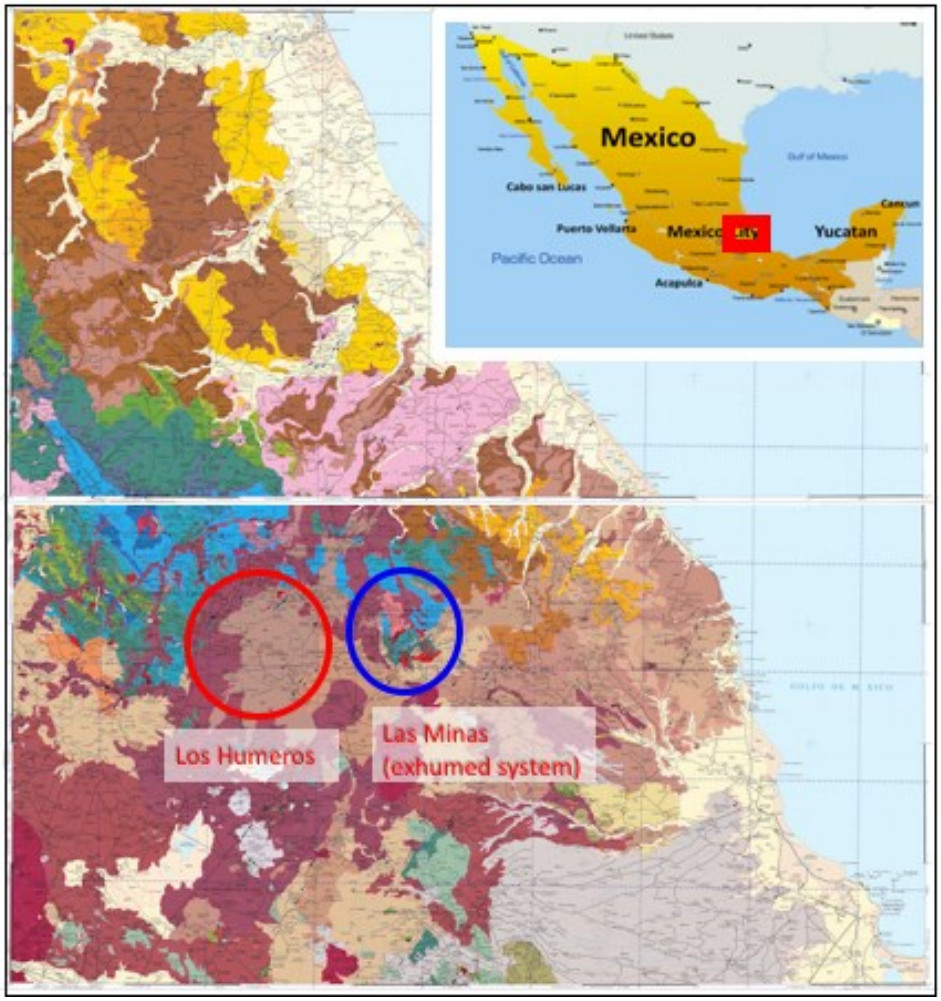


Figure 1: Location map of the Las Minas exhumed system with respect to the active Los Humeros geothermal field. The base is from the official geological map of Mexico (https://mapasims.sgm.gob.mx/CartasDisponibles/).

2. DATA

Several datasets were merged together for assessing the geothermal fluid paths at depth. These are briefly described in the following, highlighting the main results from each methodological approach.

2.1 Stratigraphic Succession

The succession of rocks (Figure 2) of the Las Minas mineralized district is made up of a basement composed of a Paleozoic granodiorite covered by a thick succession of Mesozoic limestones (Cretaceous), intruded by Tertiary (Miocene) dioritic to granitic rocks, and passing upwards to a Quaternary basalt and to dacitic to rhyolitic pyroclastites (andesite). The Miocene intrusions, at the contact with limestones, caused the development of a thick metamorphic aureole with the formation of skarns and marble. Noteworthy, in the study area and in particular above the olivine basaltic lava, are lacustrine deposits which have been recognized for the first time. The stratigraphic succession up to the andesite is crosscut by a system of mafic to felsic dykes emplaced after the hydrothermal mineral formation. Eolian sands (Quaternary) can unconformably overlap the described succession, locally. The analysed intrusive rocks from the Las Minas area are represented by diorite, dolerite, leucotonalite and leucogranodiorite. The level of emplacement was determined by using the Al-in-horneblende method of Anderson and Smith (1995) coupled with the amphibole-plagioclase thermometry by Holland and Blundy (1994). The results indicate a depth of emplacement at 4.4$\pm$0.7 km.

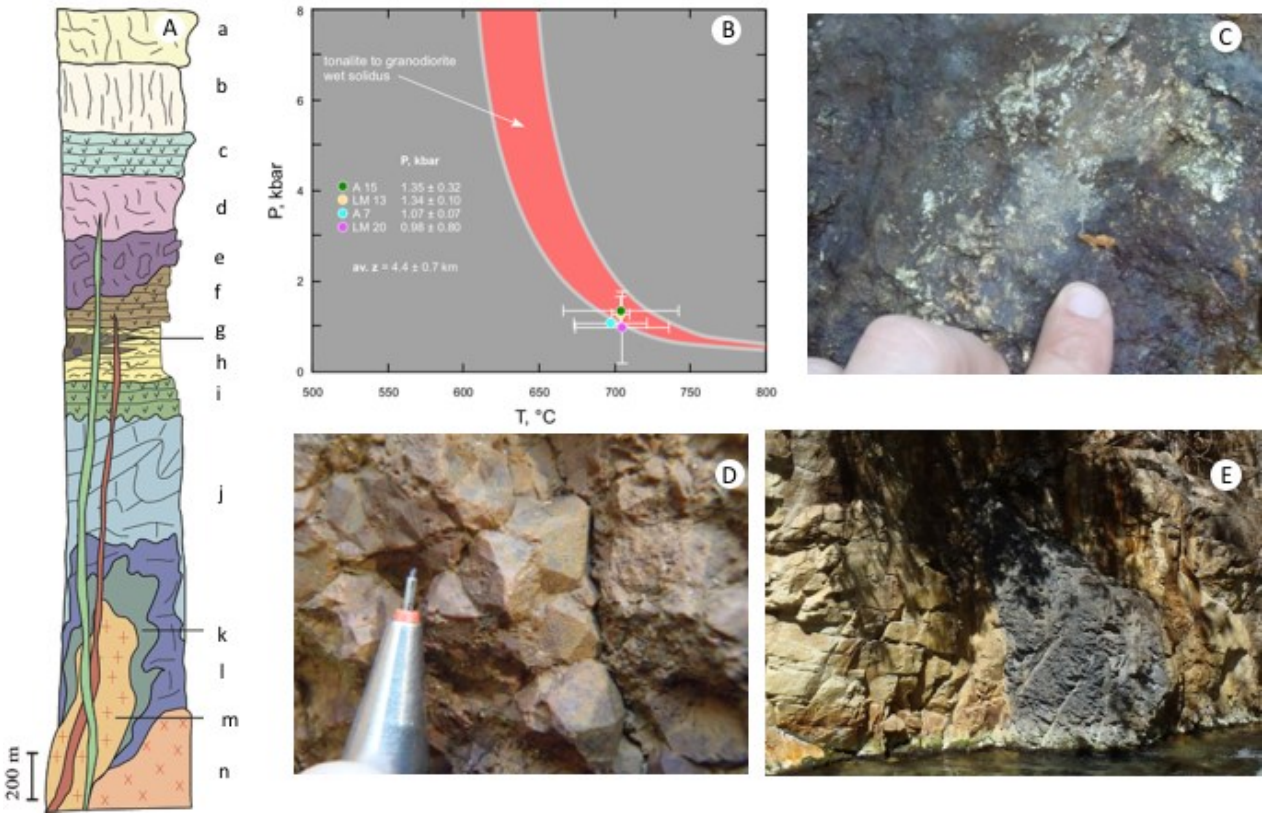


Figure 2: Succession of rocks in Las Minas. (A) - stratigraphic log of the outcropping geological bodies: a =ignimbrite; b = pyroclastic fall deposits; c = andesite; d =ignimbrite; e=co-ignimbrite; f= andesite; g=lahar deposit; h=lacustrine sediments; i=olivine- basalt; j=limestone; k=skarn; l=marble; m= main Miocene intrusive rock body; n= main Paleozoic intrusive rock body. (B) – P-T diagram illustrating the results of thermobarometry on quartz-dioritic to tonalitic samples. Examples of outcropping rocks: (C)–(D) skarn with Fe-hydroxides and oxide and Ca-garnet, respectively. (E) mafic dyke crosscutting quartz-diorite.

2.2 Geochronology by Zircon Dating

The geochronology of volcanic rocks, mafic dykes, diorites and granites of the regional basement from the Las Minas exhumed system was studied using U-Pb isotope zircon dating (SHRIMP IIe) and magnetostratigraphy. The andesites and dacites cropping out in the upper part of the Las Minas section were emplaced during the Matuyama reversed polarity chron. The concordia/model ages of these rocks constrain the exact time of their emplacement as constrained to 1.26–1.40 Ma. The granites from the basement of the Las Minas succession contained zircon grains with Late Carboniferous and Early Permian U-Pb ages, thus proving their Late Paleozoic origin. The concordia U-Pb ages calculated for the mafic dyke (15.41 Ma) and diorite (16.97 Ma) speak for their Miocene age (Figure 3).

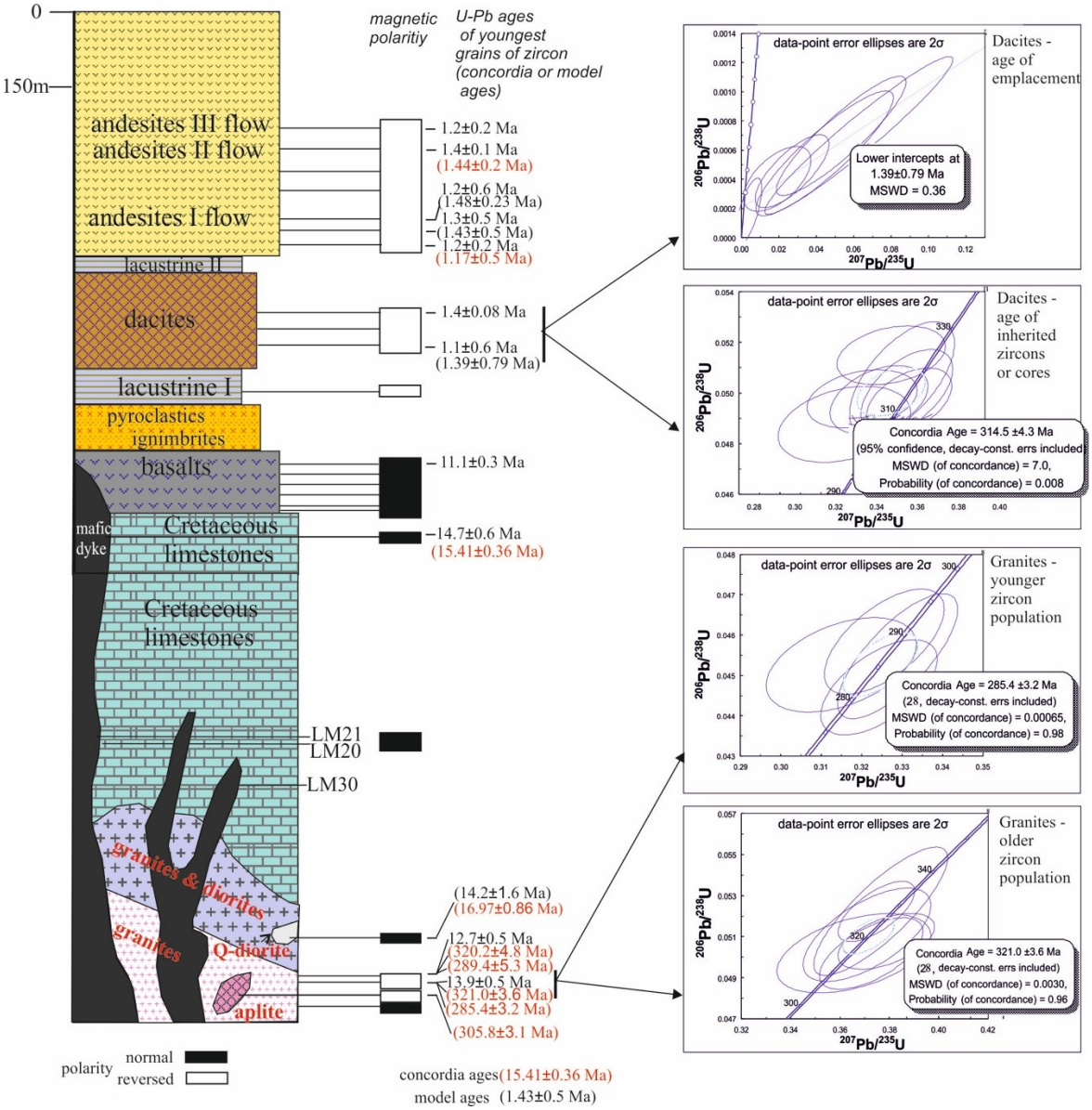


Figure 3: Magnetic polarity and U-Pb isotope ages of selected crystalline rocks from the Las Minas exhumed system. On the right examples of results of U-Pb isotope studies are presented as concordia plots.

2.3 Structures and Kinematics

The main goal of this study is to reconstruct the geometry, orientation and kinematics of the main brittle structures in the study area. Particular emphasis is given to the relationships between structures and skarn (Figure 4) since skarn is the expression of fluid circulation at a deep structural level. In the Las Minas valley, the largest outcrops of skarn are present where faults crosscut each other. A clear example is close to the Las Minas village (Figure 4). Minor skarn deposits are located along bedding in limestone and at the boundary between limestone and granitoids. Two main fault systems have been recognized, both at map- and outcrop-scale. These are defined by NNW-SSE and SW-NE striking faults, respectively (Figure 4). Both families are characterized by strike-slip to oblique to normal movements. However, their kinematics are different. The SW-NE trend is mainly defined by normal movements, whereas the NNW-SSE trending is mostly defined by right-lateral movements. Their activity is coeval, on the basis of the relationships between the faulting and the lacustrine sediments cropping out in the area. Thus, considering their mutual relations, and their coeval activities, the NNW-SSE fault system is interpreted as a transfer fault system, active together with the SW-NE faults, in the frame of regional NNW-trending extension.

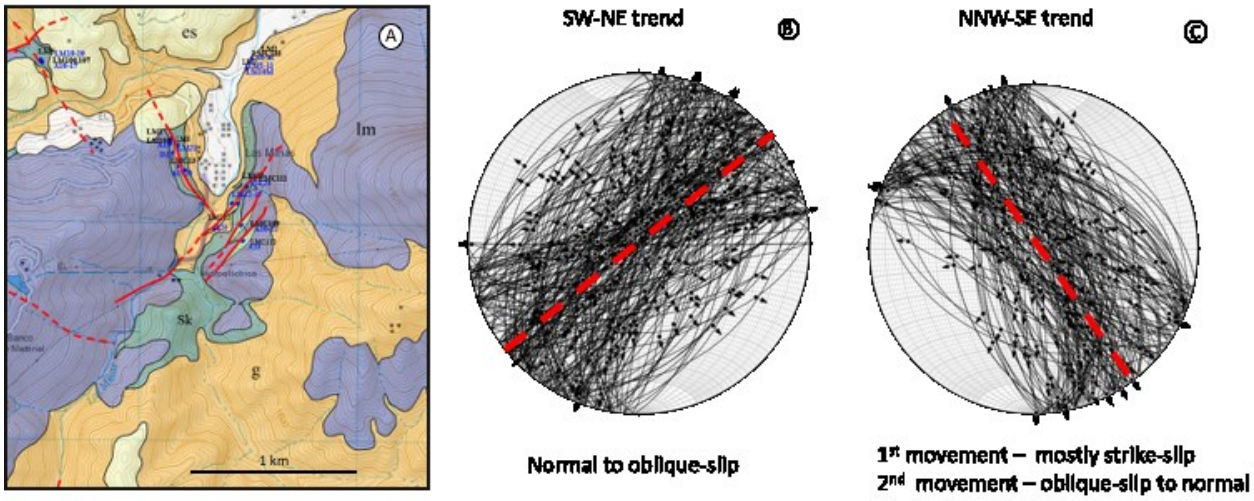


Figure 4: (A) – part of the Las Minas geological map, focussed on the Las Minas village where the two main fault trends crosscut; Symbols: g – granitoids; lm – limestone and marble; sk- skarn; es- eolian sands. B and C: stereonets (lower hemisphere, equiareal distribution) showing the two main orientations of the meso-faults in the study area. The kinematics are also indicated. In the NNW-SSE striking faults, two kinematic events have been recognized.

In order to better predict fracture architectures relevant to the Los Humeros reservoir, detailed (meter-scale) structural studies were made on selected outcropping fracture systems representative of the Los Humeros reservoir lithologies and structures. For applying these analog studies to exploration and production fluid-flow models, the spatial and tectonic relation of the outcrop analog to the regional and reservoir-scale structural framework system is particularly important. Considerations in choosing analogs included representing fracture systems both within and outside significant fault damage zones, locations where deep fluid circulation (e.g. skarn) was demonstrated, active fault systems, and older faults with indications of recent fluid flow (e.g. mineralization or karst). Figure 5 shows three outcrop-based examples for the carbonate reservoir section; models were also created for lacustrine, lava and welded tuff.

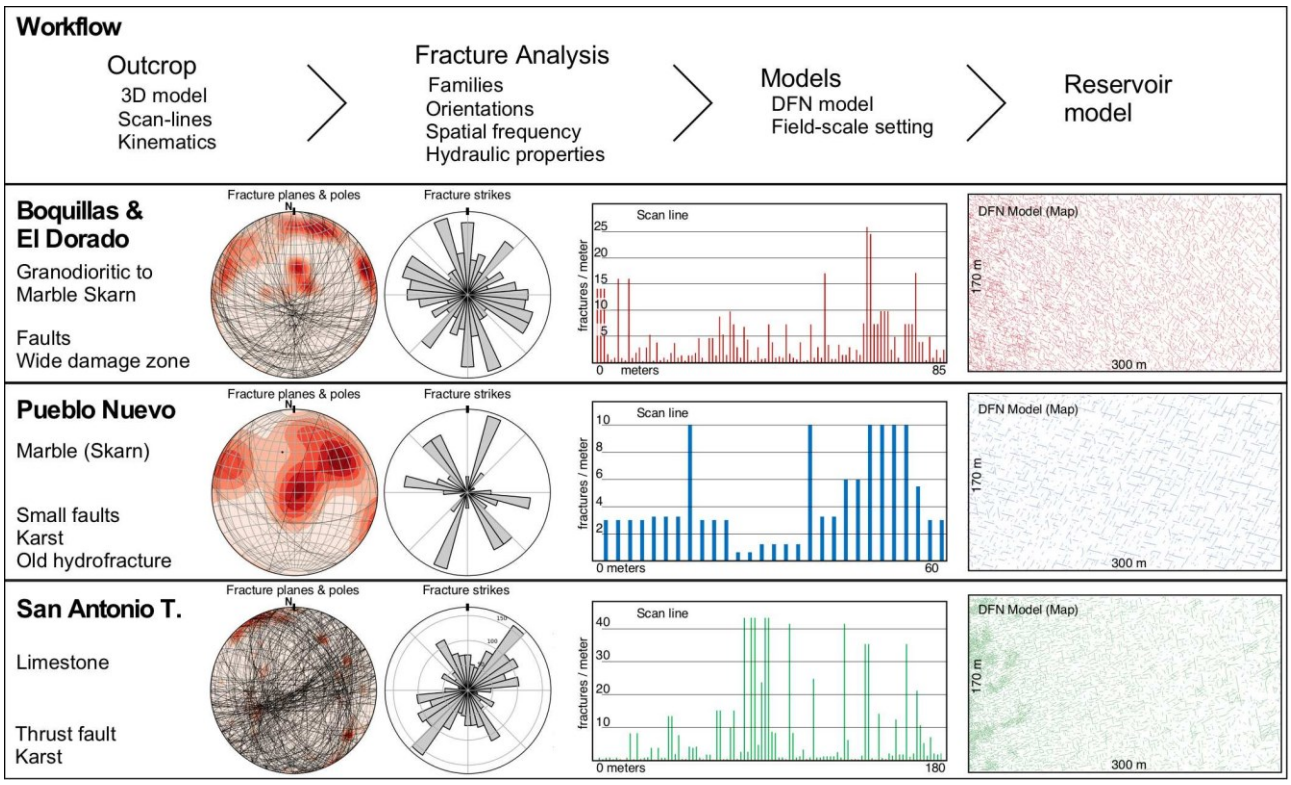


Figure 5: Three outcrop-based fracture models applicable to the carbonate section of the Los Humeros reservoir. The workflow begins with data collected from outcrops, followed by an analysis of conductive and non-conductive fracture systems, and ends with model building appropriate to flow simulation. For each outcrop fracture planes are plotted on a stereonet with superimposed on contoured pole densities. The rose diagram shows fracture strikes. The scan-line example shows fracture spatial frequency indicating corridors and faults. The DFN based map shows predicted spatial variability in fracture strike, length and spacing.

The Boquillas and El Dorado example is built from two outcrops 400 meters apart, in the area of crossing faults near the Las Minas town (Figure 4). Both are inferred to lie within the damage zone of the main NW-trending faults, consistent with the high fracture frequencies. Both outcrops lie in the skarn-rich contact zone between the granodioritic intrusive and the limestone host and are heavily mineralized. In Figure 5, the fracture data and scan line are from the Boquillas outcrop, while the DFN model shows a transition between the Boquillas and El Dorado architectures.

The outcrop at Pueblo Nuevo lies on the north side of the Las Minas valley, in a relatively un-mineralized grey to locally white marble, several hundred meters from the nearest skarn and granodiorite. The outcrop is cut by joints and small faults; the low fracture frequency indicates it is not in the damage zone of a significant fault. Older fractures and breccias, now overprinted (cemented) by diagenesis, indicate an episode of hydrofracturing inferred to have occurred at substantial burial and to be related to the nearby intrusion. There is recent, open karstification. The cemented breccias are cut by narrow open fractures with predominantly normal kinematic indicators. These show little sign of mineralization by thermal fluids.

The outcrop at San Antonio Tenextepec exposes a thrust fault. Although this outcrop lies outside the Las Minas valley it is included here because thrust faults, typically attributed to Laramide shortening, are a ubiquitous feature of the limestone basement. Thrust faults were not documented in Las Minas. The exposure includes the thrust fault and steep fractures in the footwall and hanging-wall damage zones. Unlike the steeply-dipping fracture systems of the Boquillas and Pueblo Nuevo outcrops, the San Antonio thrust fault represents a 50-m-thick damage zone that dips 30°-50° NE. The damage zone, represented in the stereonet and rose diagram, shown in Figure 5, consists primarily of steep, NE-trending, fractures. These steep fractures are characterized by long (15 m) trace lengths and are connected (crosscut) by shorter fractures and the main faults. The vertical NE-trending fractures and fracture corridors (fracture frequency >30/m), including strike slip faults, are continuous structures in outcrop, kinematically related to the thrust. They are locally karstified and brecciated, attributed to (near) surface diagenesis. Some fracture families are cemented with calcite. Such regional structures, typically attributed to Laramide shortening, are likely to have been locally deformed during later tectonic events.

2.4 Fluid Inclusions

The main goals of fluid inclusion studies are to characterize the paleo-fluids stored in the exhumed reservoir of Las Minas and to obtain from this characterization information on the physical-chemical conditions of the fluids which could be present in the deep part of the present-day Los Humeros system. To this end, four samples from skarn-hydrothermal mineralization from the Las Minas area and one sample of hydrothermal mineralization from the Piedra Parada were selected for fluid inclusion studies. Fluid inclusions were examined in quartz, garnet, tremolite and calcite. On the basis of the phases (i.e. liquid, vapor, solid(s)) present at room temperature, the relative volumetric proportion and microthermometric data, four fluid inclusion types have been distinguished:

- Two-phase (aqueous liquid+vapor) liquid-rich, aqueous fluid inclusions (L-type) (Figure 6a). This inclusion type is present in all the examined samples. In quartz, L inclusions are often associated with vapor-rich inclusions (V-inclusions, see below) (Figure 6a). Total homogenization temperature of these inclusions varies from 144 to 580°C, whereas salinity is comprised between about 0.0 to 27% NaCl equiv. Low-salinity L inclusions trapped meteoric derived fluid, whereas L inclusions with higher salinities and higher temperature likely recorded the mixing between meteoric and magmatic-derived fluid.
- Three-phase (aqueous liquid+vapour+halite) and multi-phase (aqueous liquid+vapour+halite + one or more solids) inclusions (LH-type) (Figure 6b). LH inclusions usually occur in quartz of the skarn assemblage. These inclusions trapped high-temperature (homogenization temperatures are up to 650°C), hypersaline fluid (i.e. up to about 70 % NaCl equiv.) of magmatic derivation. LH inclusions are sometimes associated with vapor-rich inclusions or aqueous-carbonic inclusions (V and V_{CO2} inclusions, see below).
- Two-phase (aqueous liquid+vapor) vapor-rich fluid inclusions (V-type) (Figure 6c). V inclusions occur in both hydrothermal quartz and in quartz associated with skarn minerals. Some V inclusions can coexist with L inclusions (Figure 6a) or LH inclusions. Total homogenization temperatures of V inclusions are up to 520°C.
- Two-phase (aqueous liquid+carbonic vapour) and three-phase (aqueous liquid+carbonic liquid+carbonic vapour) fluid inclusions (V_{CO2}-type) (Figure 6d). This inclusion type was found only within quartz from skarn and trapped fluid formed during contact-metamorphic and/or metasomatic reactions. V_{CO2} inclusions occur along trails or in clusters and are in some cases associated with LH1 inclusions. The carbonic phase of these inclusions homogenized to vapor phase or critically between 12.3 and 31.1°C, whereas total homogenization temperatures into the vapor phase occurred between 240 and 421°C. Raman analysis confirmed that the carbonic phase is essentially composed of CO_2 although a small amount of H_2S was detected in a few inclusions.

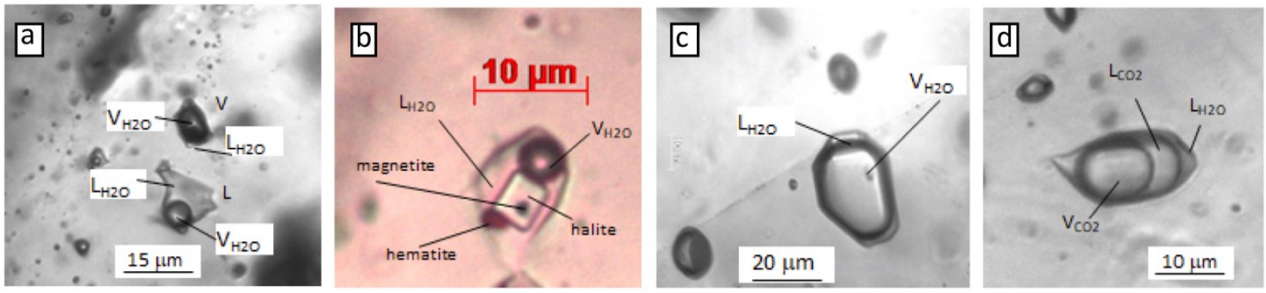


Figure 6: Main fluid inclusion types found in the skarn-hydrothermal minerals at Las Minas. a) Two-phase liquid-rich (L) inclusions coexisting with two-phase vapor-rich (V) inclusions in quartz. b) Multi-phase (LH) inclusions in quartz. c)

Two-phase vapor-rich inclusions in quartz. d) Three-phase inclusions (V_{CO2}). Abbreviations: L_{H2O}: aqueous liquid, V_{H2O}: aqueous vapor, L_{CO2}: carbonic liquid, V_{CO2}: carbonic vapor.

Fluid inclusion data highlighted the typical evolution of a magmatic-hydrothermal system characterized by an early fluid circulation of high-temperature (up to 650°C) saline and hypersaline fluid exsolved from a crystalizing melt and by the presence of a vapor phase produced by immiscibility processes at sub-lithostatic or hydrostatic pressure. During this stage, aqueous-carbonic fluid issued during high-temperature metamorphic reaction of carbonate rocks was also present. The skarn-hydrothermal system then evolved toward a lower temperature and lower salinity, and the residual saline fluid mixed with low-salinity meteoric fluid. Fluid boiling also occurred during this stage. The final stage was dominated by low-temperature (down to 200°C). These data can be useful to predict the P-T conditions in the super-hot system that could be present below the geothermal system of Los Humeros. In particular, the physical-chemical conditions of the Las Minas fossil hydrothermal system could be similar to those occurring within the super-hot system below the present-day geothermal exploited reservoirs at Los Humeros. Thus, fluid inclusions could predict some of the features of the super-hot system. However, due to the uncertainty of the physical conditions of the magmatic system present below Los Humeros, the following different scenarios are proposed:

- If a partially crystallized intrusive body is present below Los Humeros (geophysical data can help to identify the state of the intrusion) the P-T conditions of the super-hot system can be comparable to those during the circulation of high-temperature saline or hypersaline fluids. If P is sufficiently low a vapor phase coexists with the hypersaline fluid within the super-hot reservoir. The presence of saline fluids would favor the production of HCl due to brine/plagioclase reaction: anorthite + 5quartz + 2NaCl + H_2O → 2 albite + wollanstonite + 2HCl0. This process could explain the presence of HCl (and low-pH fluid) in some parts of the Los Humeros system. In fact, low-pH fluids at Los Humeros were interpreted to be related to the migration of deep magmatic volatile species (including Cl) induced by the extraction of fluids from the reservoir (Izquíerdo et al., 2009). Moreover, a CO_2 phase issued during metamorphic reactions involving carbonate rocks could also be present in the deep system and eventually rise to shallower depths together with aqueous vapor.
- If the intrusive body is almost totally crystallized the P-T conditions at Los Humeros would more likely reflect those present during the circulations of moderate too low-salinity fluids, during which meteoric fluids infiltrated at depth and residual saline magmatic-derived fluid could be contemporaneously present and mixed. The presence of residual saline fluid can also produce HCl as in the previous scenario.
- If the intrusion is totally crystallized, meteoric waters also likely dominate the deep fluid circulation and the T is lower compared to those of the second scenario. The third scenario is, however, unlikely as it is characterized by T comparable to those encountered in some wells at Los Humeros (up to 400°C), whereas it is expected that T increases with depth below the present-day system. Moreover, a completely crystallized intrusion cannot explain the production of deep HCl.

2.5 Fluid-Limestone Interaction

Fluid-rock reactions observed within the limestone are complex, reflecting a long history of initially high temperature reactions followed by progressively cooler and wetter retrograde reactions. A key control on reactions is the protolith, which varies from relatively pure limestone to dolomite. Where rocks are closer to the granitic intrusion these have become calcite marble, dolomite marble, and even periclase marble with sufficient heating. Hydration of periclase marble also led to brucite marble.

High temperature fluids rich in Si(±Al) migrating through fractures in the Ca-rich carbonates produced typical skarn assemblages typified by wollastonite, grossular-andradite garnet (with the addition of Al), and locally also subordinate diopside (where some Mg was also added). Reaction of Si-rich fluids with Mg-rich carbonates led to the formation of forsteritic olivine and diopside (±spinel), plus also calcite (Figure 7). Later-stage circulation of cooler hydrothermal fluids resulted in retrograde reactions (back reactions), with conversion of anhydrous Mg-rich silicates to serpentine and talk. A range of metallic minerals (e.g. magnetite, pyrite, tellurides) are also associated with these vein fills. Some veins show evidence of leaching of wallrocks around them (notably in brucite marble, Figure 7). Significant solid volume changes were associated with fluid-rock reaction, and mineral formation appears to have sealed the fractures. We speculate, therefore, that continued advection of fluids through the rock would likely have required multiple fracture events, feasible in this tectonically active region, consistently with the regional and local observations described in section 2.2. A more detailed summary of these reactions can be found in Lacinska and Rochelle (2020).

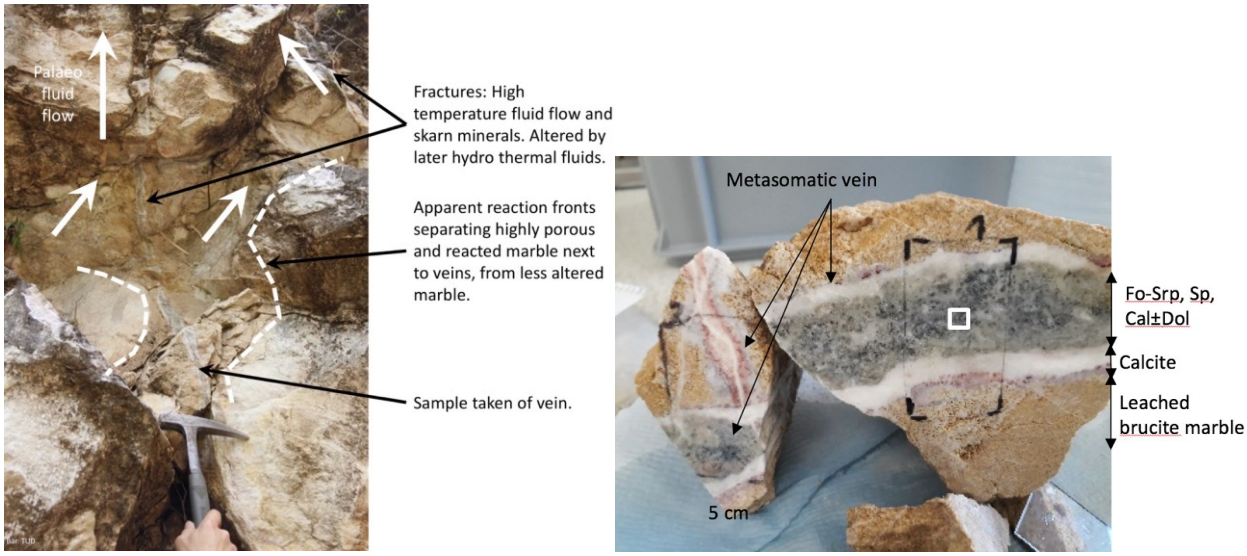


Figure 7: Left image: Exposed face of altered Mg-rich marble at Las Minas. Note the metasomatic vein surrounded by a zone of porous and weakened carbonate wallrock. Right image: Detail of (hydrated) crosscutting metasomatic veins within leached brucite marble (Fo: forsterite, Srp: serpentine, Sp: spinel, Cal: calcite, Dol: dolomite).

3. CONCLUSIONS

The new geological survey of the Las Minas fossil geothermal area allowed us to improve the previous knowledge on its stratigraphic and structural setting. In particular, elements of novelties are the discovery of lacustrine sediments in the volcanic succession and the occurrence of Palaeozoic rocks at the base of the succession. Two main systems of regional faults NNW-SSE and WSW-ENE striking fault systems have been recognized: on the basis of their kinematics and activity, these are interpreted as transfer and normal faults, respectively, in the frame of the regional NW-SE striking extension. Finally, the study on fracture distribution in key outcrops indicated significant fracture corridors corresponding to the NNW-SSE striking fracture system, suggesting an increase of permeability and a preferential hydrothermal fluid pathway through them. From this viewpoint, the dominant lateral kinematics in the NNW-SSE structures suggest the occurrence of preferential vertical or close-to-vertical structural pipelines (Sibson, 2000), channelling deep fluids from depth. Information from fluid inclusions indicates that an original hypersaline fluid, exsolved from a cooling magma, migrated through the fracture systems, interacting with the hosting rocks. During this process, the hosting rocks might be weakened through the fluid-rock interaction, thus concentrating in a relatively narrow zone of the fluid path. The conceptual model on the relationships between geological structures and fluid flow is summarized in Figure 8: deep fluids are, therefore, channelled into the NNW-SSE striking fractures and laterally migrating in the cataclasite of the intersecting normal faults and, along the limestone bedding, as it is clearly indicated by the skarn location.

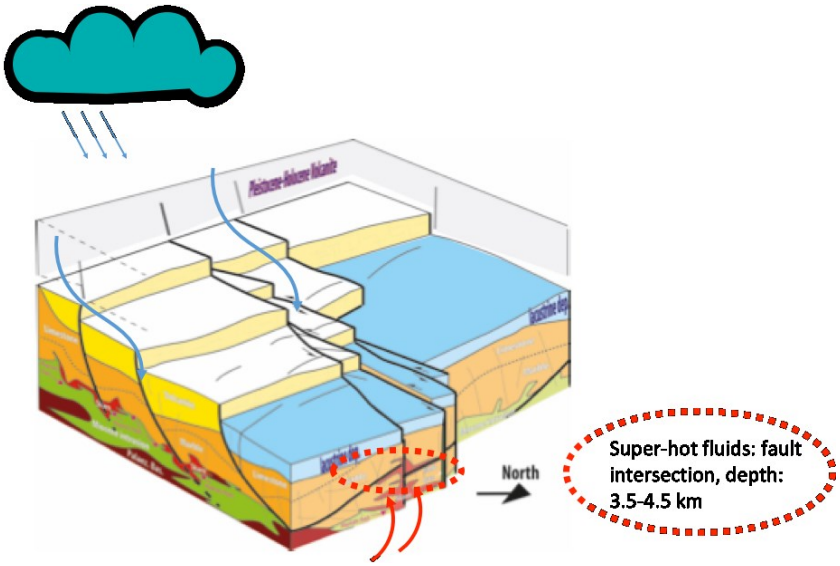


Figure 8: Conceptual model of the relationships between geothermal fluid flow and geological structures in the Las Minas exhumed system. Meteoric water represents the main recharge at shallower structural levels. Differently, the contribution of saline fluids of magmatic origin is dominant at depth; these are mainly located at the intersection between NNW-SSE and SW-NE structures.

ACKNOWLEDGMENTS

The GEMex project is supported by the European Union's Horizon 2020 programme for Research and Innovation under grant agreement No 727550. AL and CR publish with the permission of the Executive Director of the British Geological Survey (UKRI).

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