Mineral textures and fluid inclusion petrography of the epithermal Ag–Au deposits at Guanajuato, Mexico: Application to exploration

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A B S T R A C T

Fluid inclusion petrography and vein mineral textures indicative of boiling have been characterized in 855 samples from epithermal precious metals deposits along the Veta Madre at Guanajuato, Mexico. Mineral textures and fluid inclusions characteristic of fluid immiscibility or boiling, including colloform quartz, plumose/feathery/amboyant quartz, lattice-bladed calcite and lattice-bladed calcite replaced by quartz, as well as coexisting liquid-rich and vapor-rich fluid inclusions and assemblages of vapor-rich only inclusions, have been identified in mineralized samples from the Veta Madre. Most samples studied were assayed for Au, Ag, Cu, Pb, Zn, As and Sb, and were divided into ore grade and sub-economic samples based on the gold and silver concentrations. For silver, samples containing > 100 ppm were classified as ore grade, and ore grade gold samples contained > 1 ppm Au. The feature that is most closely associated with ore grades of both gold and silver is colloform quartz that was originally precipitated as amorphous silica, and this feature also shows the largest difference in average grade between samples that show colloform texture (178.8 ppm Ag and 1.1 ppm Au) and those that do not exhibit this texture (17.2 ppm Ag and 0.2 ppm Au). Statistical analysis of the data confirmed the petrographic observations that indicated that colloform quartz is the feature that has the greatest predictive power for distinguishing between ore grade and sub-economic samples. For both Ag and Au, there is no significant difference in average grade of samples containing coexisting liquid-rich and vapor-rich fluid inclusions or assemblages of vapor-only inclusions and those that do not, suggesting that fluid inclusion evidence for boiling is not correlative with ore grades. This result is consistent with the fact that most forms of silica that are precipitated during boiling do not trap useful fluid inclusions. The results of this study suggest that mineral textures and fluid inclusions provide complementary information that should both be used in exploration for epithermal precious metal deposits. Metal grades and boiling intensity of samples collected along a traverse perpendicular to the Veta Madre and above known economic mineralization are both low at relatively short distances away from the vein and increase as the vein is approached. This suggests that mineralogical and fluid inclusion evidence for boiling are restricted to the immediate vicinity of, and increase in the direction of, mineralized veins and may be used in exploration to establish vectors towards vein systems that may host precious metal mineralization. Previous studies of epithermal systems show that the Ag and Au mineralization zone is most often located at or above the bottom of the boiling zone. In this regard, the presence of abundant evidence for boiling that is observed in the deepest levels of the Veta Madre that have been sampled suggests that additional precious metal mineralization may be present beneath the deepest levels that have been explored.

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1. Introduction

Over the past several decades there have been numerous studies of fluids and fluid inclusions in both active terrestrial geothermal systems and their fossil equivalents, the epithermal precious metal deposits (Albinson et al., 2001; Bodnar et al., 1985; Camprubí and Albinson, 2007; Hedenquist et al., 2000; Kamilli and Ohmoto, 1977; Roedder, 1984; Simmons et al., 2005; Vikre, 1985). There is now a large database of fluid characteristics in these systems that documents the close association between boiling and mineral deposition in the epithermal environment (c.f., Brown, 1986). In this paper we use the term “boiling” to indicate the presence of two immiscible fluids, even though we recognize that “boiling” refers sensu stricto to one-component systems in which the compositions of the liquid and vapor phases are identical, and that “effervescence” or “immiscibility” are more appropriate for multi-component systems in which
the compositions of the liquid and vapor phases are different. Once boiling begins at depth, the fluid will usually continue to boil all the way to the surface (Fig. 1) if the system is composed of interconnected open fractures that are open to the surface (Cline et al., 1992; Fournier, 1985; Henley and Brown, 1985; Vikre, 1985). Above the boiling horizon low to moderate salinity liquid and a low-density vapor coexist. Fluid inclusion assemblages trapped from the boiling horizon to the surface are characterized by coexisting liquid-rich and vapor-rich inclusions that generally homogenize at \( \leq 300 ^\circ C \) near the base of the boiling zone (Bodnar et al., 1985; Simmons and Christenson, 1994), to \( < 220 ^\circ C \) near the top of the system (Albinson et al., 2001), and provide a valuable tool in exploration for epithermal deposits (Roeder and Bodnar, 1997). At depths beneath the boiling horizon, fluid inclusion assemblages consist of a mono-modal assemblage of liquid-rich inclusions with consistent liquid to vapor ratios (Bodnar et al., 1985) (Fig. 1). Note, however, that hydrothermal systems associated with the formation of epithermal deposits are dynamic systems, and the bottom of the boiling zone likely shifts upward and downward over time as the fluid temperature, flow rate, fracture apertures, etc., vary through time. As a result, at a given depth “boiling assemblages” and “non-boiling assemblages” may alternate through time as the hydrothermal system evolves.

The “intensity” of boiling may also vary in time and space within the hydrothermal system as the fluid PTX characteristics of the system vary. Fig. 1 shows schematically two end-member scenarios, one in which a small portion of the original liquid is converted to vapor during boiling (path \( B_0 \rightarrow B_1 \rightarrow B_2 \)), and another in which 100% of the liquid is converted to vapor (path \( F_0 \rightarrow F_1 \rightarrow F_2 \)). The exact proportion of the liquid that will vaporize depends on the P-T conditions of the system as well as on the ability of the fluid to extract “excess heat” from the surrounding wallrock (Henley and Hughes, 2000). In some cases, especially in an open hydrothermal system in which the fluid pressure is controlled by the weight of the overlying hydrothermal fluid column that extends from depth to the surface, a one-phase liquid may migrate upwards and intersect the liquid–vapor curve and remain on the liquid–vapor curve all the way to the surface (Fig. 1). In such cases, a relatively small portion of the original liquid mass may be transferred to the vapor phase — in this paper we refer to this as “gentle boiling”, for lack of a better term, and to distinguish between this style of boiling and more intense boiling described below. In other cases, the liquid hydrothermal fluid at depth may be present in numerous poorly connected and/or highly cemented fractures, resulting in fluid pressures that exceed hydrostatic and may approach lithostatic (Fig. 1). If the rock fractures, perhaps as a result of seismic activity or increased fluid pressure, a pressure decrease to less than hydrostatic pressure might occur instantaneously, resulting in conversion of essentially 100% of the original liquid into a low density vapor phase. This type of boiling is referred to as “flushing”, and has been observed to occur in active geothermal systems as the high temperature geothermal fluids (liquids) pass through a pressure plate into a low pressure environment and all of the liquid is instantaneously converted to steam (Brown, 1986). As discussed in more detail below, euhedral quartz with coexisting liquid-rich and vapor-rich inclusions will be precipitated during less intense boiling. Conversely, flushing is likely to deposit amorphous silica with a colloform texture and does not result in trapping of primary fluid inclusions, although secondary fluid inclusion assemblages containing vapor-only (or vapor-rich) inclusions may be trapped in earlier-formed minerals in the vein (Fig. 1). The presence or absence of boiling determines the fluid inclusion types that are trapped at a given location in then system, and may also control ore metal distribution in the system. Beneath the boiling horizon many systems are characterized by higher base metal and lower (or absent) precious metal grades, whereas above the boiling horizon precious metals are more common. The highest gold grades are often found immediately above the boiling horizon (Buchanan, 1981; Cline et al., 1992; Hedenquist et al., 2000). In systems in which flushing occurs, a high grade (bonanza) zone is more likely at the base of the boiling zone (Fig. 1), whereas in systems characterized by more gentle boiling precious metal grades may be lower and distributed over a greater vertical distance above the bottom of the boiling zone, and the highest grades may occur at some distance above the bottom of the boiling zone (Simmons and Browne, 2000).

Albinson et al. (2001) note that ore zones in boiling epithermal systems often show an economic bottom that is characterized by a dramatic change from high-grade ore to barren rock over a depth range of a few tens of meters to about a hundred meters (see Fig. 1), whereas in the less common non-boiling (or gently boiling?) epithermal deposits the economic bottom of the deposit occurs due to a gradual decrease in ore grade with depth and/or increased mining costs that make the deeper mineralization uneconomic to mine.
The spatial relationship between boiling, fluid inclusion and gangue mineral characteristics and precious metal mineralization provides a potentially valuable tool in exploration for epithermal precious metals deposits. Thus, the presence of fluid inclusions or mineral textures indicative of boiling (or flashing) in surface outcrops suggests that the base of the boiling zone is below, and that deeper levels in the hydrothermal system may contain precious metal mineralization. Moreover, the presence of modest precious metals grades that decrease gradually with depth in the vein system without evidence of boiling suggests that boiling was not the cause of metal deposition and that a high-grade bonanza-type deposit is unlikely at depth.

1.1. Previous fluid inclusion studies in the Guanajuato Mining District

During the past half-century numerous fluid inclusion studies have been conducted in the Guanajuato Mining District (GMD) (Table 1). One of the earliest studies, by Wilson et al. (1950), focused on the Rayas and Cata mines in the central part of GMD (Fig. 2). Thirty samples containing quartz crystals from these deposits showed homogenization temperatures ranging from 215 to 299 °C, with an average of 254 °C. These workers did not comment on whether the samples contained boiling assemblages with both liquid-rich and vapor-rich inclusions.

Gross (1975) reported fluid inclusion homogenization temperatures from several samples collected along the Veta Madre and adjacent Sierra vein systems (Fig. 2). Homogenization temperatures ranged from about 260 to 330 °C and showed a systematic increase with depth. For example, the homogenization temperature at an elevation of 1700 m above sea level was 320 °C and dropped to 260 °C at 2400 m elevation along the Veta Madre. As with the earlier work by Wilson et al. (1950), Gross (1975) did not comment on whether the samples contained both liquid-rich and vapor-rich inclusions.

The most detailed fluid inclusion study in the GMD, and one of the first to relate boiling and precipitation of precious metals in the district, was conducted by Buchanan (1979), whose research focused on the Las Torres mine and the deepest levels of the Rayas mine (1705 meter level) (Fig. 2). In both mines, coexisting liquid-rich and vapor-rich inclusions indicated that boiling occurred during precious metal mineralization. In the Las Torres mine, a correlation was observed between silver sulfide deposition, high abundance of fluid inclusions with homogenization temperatures ranging from 231 to over 360 °C, and deposition of adularia and sericite. In addition, a sample from the Rayas mine collected at an elevation of 1705 m showed evidence of boiling and homogenization temperatures from 290 to 385 °C. Twelve other samples from the Rayas mine contained vapor-rich inclusions but these were interpreted to have formed by necking down (Buchanan, 1979). Two boiling horizons were observed in the Las Torres Mine. The shallow horizon was interpreted to represent “normal” hydrostatic boiling, whereas the deeper horizon was thought to represent flashing of the hydrothermal fluids when the impermeable seal fractured. The boundary between the boiling zone (above) and the non-boiling zone (below) was located at an elevation of about 1800 m (Buchanan, 1979).

In contrast to the observations of Buchanan (1979, 1980), Mango (1988) and Mango et al. (1991) found no evidence of boiling in fluid inclusions in quartz, calcite, and sphalerite from the Rayas Mine, and stable isotope analyses indicated that the precious and base-metals were deposited from meteoric water (Mango, 1988). Homogenization temperatures of fluid inclusions ranged from 230 to 305 °C and salinity ranged from 0.5 to 3.3 wt.% NaCl equivalent. Results from gas analysis showed 0.3 to 2.1 mole % CO₂, 0.06 to 0.8 mole % H₂S, and less than 1 mole % CH₄, H₂ and CO in the inclusions (Mango et al., 1991). Mango et al. (1991) reported that boiling did not occur at any of the levels studied at Rayas, and suggested that if boiling of the hydrothermal fluids did occur it was at higher stratigraphic levels which have since been eroded. These workers also report that up to 850 m of erosion may have occurred above the Rayas ore body. This result disagrees with Buchanan (1981), who indicated that boiling only occurred to a depth of 650 m below the paleosurface during mineralization. It should be noted that Rayas contains more base metal sulfides than most other mines in the GMD (i.e., Las Torres), and less gold than others (i.e., El Cubo).

In this study, the relationship between fluid inclusion and mineral textural evidence for boiling and precious metal grades in the classic epithermal Ag-Au deposits at Guanajuato, Mexico, have been investigated to test for systematic correlations that may be used in exploration for similar deposits. Eight hundred and fifty-five (855) samples were collected from surface outcrops, underground workings, and recent drill core over a strike length of 4 km and to depths of 750 m beneath the surface in four active mines and one closed mine along the Veta Madre. Each sample was assayed for Au, Ag, Cu, Pb, Zn, As, Sb. The goal of this study was to develop a method to target and prioritize areas for future exploration based only on data obtained during petrographic examination of thin sections. The method does not involve microthermometry or microanalysis of the inclusions.

2. Geological setting

The Guanajuato Mining District (GMD) is located at the southern end of the Sierra Madre Occidental Eocene-Oligocene volcanic province and between the Sierra Madre Oriental and the Trans-Mexican volcanic belt (Clark et al., 1982). The GMD is part of a large northwest trending belt of silver-lead-zinc deposits that parallels the eastern flanks of the Sierra Madre Occidental (Randall et al., 1994). Aranda-Gómez et al. (2003) divide the rocks in this area into a “basal complex” and “cover rocks”. The basal complex consists of metamorphosed marine sediments of Mesozoic to early Tertiary age, while the Cenozoic cover rocks are composed of continental sediments and subaerial volcanic rocks. The Cenozoic volcanism has been divided into seven pulses (Aranda-Gómez et al., 2003), ranging in age from about 51 Ma to 8 Ma. Felsic to intermediate volcanism that occurred from 37 to 27 Ma produced the rock units and structures that host the mineral deposits at Guanajuato (Godchaux et al., 2003).

The regional geology in the GMD has been studied in detail by Edwards (1955), Echegoyen-Sanchez (1964), Taylor (1971), Gross (1975), Buchanan (1979) and Randall et al. (1994). The lowermost unit present in the area is the Esperanza Formation composed of

Table 1

<table>
<thead>
<tr>
<th>Location</th>
<th>Homogenization temperature (°C)</th>
<th>Salinity (wt.% NaCl)</th>
<th>Maximum sample depth (meters above sea level)</th>
<th>Evidence for boiling observed?</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rayas Mine, Cata Mine</td>
<td>215–299</td>
<td>Not reported</td>
<td>1820</td>
<td>Not reported</td>
<td>Wilson et al. (1950)</td>
</tr>
<tr>
<td>Rayas Mine</td>
<td>230–305</td>
<td>0.5–3.4</td>
<td>1675</td>
<td>No</td>
<td>Mango (1988)</td>
</tr>
<tr>
<td>Las Torres, Veta Madre, Rayas Mine</td>
<td>231–360</td>
<td>Not reported</td>
<td>1705</td>
<td>Yes</td>
<td>Mango et al. (1991)</td>
</tr>
<tr>
<td>Veta Madre, Sierra System</td>
<td>260–320</td>
<td>Not reported</td>
<td>1700</td>
<td>Not reported</td>
<td>Buchanan (1979)</td>
</tr>
<tr>
<td>Cuatro Mine</td>
<td>220–235</td>
<td>1.6–5</td>
<td>2270</td>
<td>Yes</td>
<td>Gross (1975)</td>
</tr>
<tr>
<td>Cuatro Mine (San Nicolas)</td>
<td>172–282</td>
<td>0–2.95</td>
<td>2100</td>
<td>Yes</td>
<td>Girnius (1993)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Abeyta (2003)</td>
</tr>
</tbody>
</table>
carbonaceous and calcareous mudstones, shales, limestones and andesitic to basaltic flows that have all been metamorphosed to phyllite, slate and marble (Randall et al., 1994; Stewart, 2006; Wandke and Martinez, 1928). The thickness of this unit exceeds 600 m in the GMD and it has been assigned a Cretaceous age based on radiolaria (Dávila and Martínez Reyes, 1987).

The next youngest unit in the GMD is the La Luz andesite (Randall et al., 1994), but this unit is absent in the vicinity of the city of Guanajuato and along the portion of the Veta Madre that is the focus of this study (Buchanan, 1979). In this area, the Guanajuato Formation lies unconformably on the Esperanza Formation. The Guanajuato Fm. is composed of red, poor- to well-sorted conglomerate, sandstone and shale (Buchanan, 1979). The Guanajuato Fm. ranges from 1500 to 2000 m in thickness and is Eocene to early Oligocene in age based on vertebrate fossils (Edwards, 1955).

The Guanajuato Fm. is conformably overlain by the Loseros Fm., which is a 10 to 52 m thick, green andesitic volcaniclastic sandstone (Buchanan, 1979; Echegoyen-Sanchez, 1964). While no ages have been determined for the Loseros Fm., it is assumed to be early Oligocene based on its conformable location between the underlying Guanajuato Fm. and overlying Oligocene Bufa Fm.

The Bufa Formation conformably overlies the Loseros Fm. The Bufa Fm. represents a 350 m thick distal volcano-sedimentary unit with white, yellow and pink rhyolitic lapilli air-fall ash that has been dated at $37 +/− 3.0$ Ma using K–Ar (Gross, 1975). The Bufa Fm. is separated from the overlying Calderones Fm. by a disconformity (Buchanan, 1979). The Calderones Formation consists of chloritized, crystal-rich andesitic tuff, except at the base. Here, andesitic volcaniclastic shale and sandstone lie unconformably on the Bufa Fm. The Calderones Fm. is $200–250$ m thick (Gross, 1975; Stewart, 2006) and has been assigned a late Oligocene age based on cross-cutting relationships (Gross, 1975).

Overlying the Calderones Fm. is the Cedros Fm., which consists of grey to black andesitic flows interbedded with grey to green andesitic
tuffs (Buchanan, 1979). The thickness of this unit is highly variable and ranges from 100 to 240 m in the district (Gross, 1975; Stewart, 2006).

The Chichindaro Fm. is the youngest formation in the area and has been dated at 32 ±/− 1 Ma by K–Ar (Gross, 1975; Randall et al., 1994). It unconformably overlies the Cedros Formation and is composed of felsic ash and flow breccias (Taylor, 1971). Buchanan (1979) reports that the Chichindaro Fm. is pre-mineralization.

Mineralization in the GMD is associated with three parallel, north-west trending fault systems. The La Luz system is to the north and west of the city of Guanajuato, the Sierra system is to the east and south of the city of Guanajuato, and the intermediate Veta Madre system passes through the city of Guanajuato (Fig. 2). All samples studied here were collected from the Veta Madre and along a traverse perpendicular to the vein.

In the study area the Veta Madre dips 35–55° to the SW and varies from hairline to several tens of meters in thickness (Buchanan, 1979). The Esperanza Fm., composed of dull-black carbonateous and calcareous mudstones, shales, limestones and andesitic to basaltic flows that have all been metamorphosed to phyllite, slate and marble, serves as the footwall of the Veta Madre (Cornelius, 1964; Edwards 1955; Guiza, 1949). The Guanajuato Fm., composed of red, poor- to well-sorted conglomerate, sandstone and shale, forms the hanging wall of the Veta Madre (Edwards, 1955).

The Veta Madre mineralization consists mostly of quartz with various textures and less abundant calcite, fluorite, barite and adularia. The Veta Madre shows multiple generations of silica and carbonate deposition and brecciation to produce a complex system of veins and stockworks (Wandke and Martinez, 1928). The banding structures in the veins are closely associated with mineralization and were an indication to early miners of high grades of ore (Wandke and Martinez, 1928). The stockworks are present in the hanging wall of the main vein and can have stope dimensions of more than 200 m×100 m (Wandke and Martinez, 1928).

Cambrú and Albinson (2007) summarized data for epithermal deposits in Mexico and classified the deposits at Guanajuato as Type “B” deposits that show characteristics of both intermediate-sulfidation and low-sulfidation end members. According to these workers, the deposits become richer in base metals with depth and formed during multiple hydrothermal events. They also report that fluids responsible for the formation of low sulfidation mineralization are generally ~240 °C with salinities of 3.5–7.5 wt.% NaCl. On the other hand, the intermediate sulfidation mineralization fluids vary from 230 to 300 °C and show higher salinities of 7.5–23 wt.% NaCl. These values are consistent with results of previous fluid inclusion studies in the district summarized above.

3. Methodology

3.1. Sample collection and preparation

In collaboration with the staff of Great Panther Silver, 855 samples were collected along a 4 km strike length of the Veta Madre from both surface outcrops (Fig. 3, top) and underground locations, including drill core (Fig. 3, bottom). The accessibility of underground workings in the San Vicente, Cata, Valenciana, Rayas and Guanajuatito Mines offered good three-dimensional geological controls. The northern part of the Valenciana Mine was not accessible because this area was flooded and access was prohibited. Collection of samples from surface outcrops and underground and drill cores focused on samples that contained transparent minerals that could be examined for fluid inclusions, especially quartz and calcite.

Surface samples were collected at each location where veins were encountered outcropping on the surface (Fig. 3, top), including along a 400 m traverse perpendicular to the Veta Madre in the vicinity of the San Vicente Mine. In the underground mines, samples were collected at regular intervals along drifts. Sample locations were determined using mine maps and survey marks. Samples were collected from the hanging wall and footwall of the vein where access permitted. Underground areas sampled included the following mines and levels: Rayas Mine (345 and 390 levels), Cata Mine (390 and 414 levels), south Valenciana Mine (320 level), Guanajuatito Mine and San Vicente Mine (190, 220, 270, 275 and 345 levels) (Fig. 3, bottom). Levels for all mines indicate depth beneath the surface in meters, relative to the elevation at the top of the Rayas shaft, which is at an elevation of 1,999 m above sea level. Drill core samples were obtained from the underground and surface drilling program and historical drilling (Fig. 3, bottom). At each location one sample representing the dominant style of mineralization and/or vein texture at that location was collected, although it should be noted that recognizable heterogeneity often occurred over short distances along each level. In some cases, two or more samples were collected at a given location to better capture the diversity of mineralization styles.

The hand samples were cut perpendicular to the vein to produce a section that extended from the vein wall towards the center of the vein. Then, a thin-section-sized billet approximately 13/16 in.×1 inch (21 mm×35 mm) was cut from the larger slab and a “thick” section approximately 75 μm thick was prepared. If the vein thickness was greater than twice the long dimension of the billet, the billet was cut to include one of the vein walls. The logic of this approach is that the material closest to the vein wall is the oldest material in the vein, because these are open-space filling veins and not crack-seal type veins that often re-fracture at the wallrock-vein contact and make determination of mineral and fluid inclusion paragenesis problematic (see Becker et al., 2010). Our logic for using this sample preparation protocol was that even if mineralization at that location occurred later than the time represented by the sample, the sample is still likely to contain secondary fluid inclusions containing fluids responsible for precipitating later material. This approach increases the likelihood of sampling all fluid events associated with vein formation while at the same time minimizing the size and/or number of thick sections needed.

Thick section preparation was done by an outside vendor and at Virginia Tech. This study involved only petrographic examination of the samples, thus doubly polished sections were not required. “Quick plates” were prepared (Goldstein and Reynolds, 1994) by grinding the cut surface with 320 micron grit to eliminate the macroscopic imperfections produced by cutting the sample. Next, the sample was mounted to a glass slide with epoxy adhesive. The final process consisted of cutting and grinding the sections to 75–100 micron thickness (Van den Kerkhof and Hein, 2001) in order to study the fluid inclusions and mineral textures.

In addition to preparing thick sections from the samples, one half of each cut sample was assayed for gold (Au), silver (Ag), copper (Cu), lead (Pb), zinc (Zn), arsenic (As) and antimony (Sb).

4. Petrography

Goldstein and Reynolds (1994) describe the technique for observing unpolished thick sections (“quick sections”) under the microscope that involves covering the surface with immersion oil to improve the optical properties of the sample for viewing fluid inclusions. The immersion oil with an index of refraction close to that of the mineral fills all cracks and imperfections. Because our samples consisted mostly of quartz we used oil with an index of refraction of 1.515.

Samples were examined using a petrographic microscope, starting at low magnification and proceeding to higher magnification. The first task for each sample was to identify the mineral phases and to classify the textures of quartz and calcite if present (every sample contained quartz and about one-quarter also contained calcite). Next, the
sample was examined systematically to identify fluid inclusion assemblages (FIAs) and the types of fluid inclusions in each FIA were noted. An FIA represents a group of fluid inclusions that were all trapped at the same time (Bodnar, 2003a; Goldstein and Reynolds, 1994) and thus represent the physical and chemical conditions in the system at the time of trapping (assuming that the inclusions have not reequilibrated; Bodnar, 2003b). FIAs may be composed of primary inclusions trapped during precipitation of the host phase, or may contain secondary inclusions that are trapped along fractures in the host phase at some time after the mineral has formed. FIAs in samples from the Veta Madre were further classified as containing either only liquid-rich inclusions with consistent liquid-to-vapor ratios, or containing coexisting liquid-rich and vapor-rich inclusions with a broad range in liquid to vapor ratios, or only vapor-rich inclusions (Fig. 4).

Fluid inclusions in the Veta Madre, and in most epithermal deposits, must be interpreted with caution because much of the host material may have been deposited as an amorphous silica phase or chalcedony and has since (re-)crystallized to produce coarse-grained quartz. Primary appearing inclusions in such samples are unlikely to record the original formation conditions (Bodnar et al., 1985; Sander and Black, 1988). In this study, only secondary inclusions that

![Consistent phase ratios "non-boiling"](image)

![Coexisting liquid-rich and vapor-rich inclusions "Boiling"](image)

![Only vapor-rich inclusions (no liquid-rich) "Flashing"](image)

Fig. 4. Fluid inclusion types observed in samples from the Veta Madre at Guanajuato, Mexico. The top row shows schematic drawings of the phase ratios of the inclusions, and the bottom row shows photomicrographs of the same inclusion type in samples from the Veta Madre. Fluid inclusion assemblages (FIAs) containing liquid-rich inclusions only with consistent liquid-to-vapor ratios are indicative of non-boiling conditions (left); FIAs consisting of coexisting liquid-rich and vapor-rich inclusions are indicative of boiling conditions (center); and FIAs containing only vapor-rich inclusions indicate flashing of the system (right).
clearly crosscut quartz crystal boundaries, and therefore were trapped after the quartz (re-)crystallized, were studied in quartz that showed textures indicative of original precipitation as an amorphous or fine-grained phase, as described below. Similar arguments apply to fluid inclusions in replacement minerals, such as quartz replacing lattice-bladed calcite.

4.1. Quartz and calcite textures

Previous workers have shown that silica and carbonate phases in the epithermal environment often show highly variable and sometimes diagnostic textures (Figs. 5 and 6) that identify the physical conditions associated with mineralization (Adams, 1920; Bodnar et al., 1985; Camprubí and Albinson, 2007; Dong et al., 1995; Henley and Hughes, 2000; Sander and Black, 1988; Simmons and Christenson, 1994). These various textures can be divided into those that are produced during the original deposition of the phase, those that represent recrystallization textures, and those that represent replacement of originally precipitated material. Further, some of these textures are readily apparent in hand samples, others require microscopic observation, and some textures are only revealed under crossed-polars. Finally, some of these phases contain fluid inclusions that may be used to infer the paleo-environment in the hydrothermal system, whereas others rarely contain useful fluid inclusions (Bodnar et al., 1985). In this study, we have characterized the mineralogy and mineral textures observable in hand samples and under the microscope, and these are summarized below.

The most common mineral texture observed in 752 out of 855 samples (Fig. 7) from the Veta Madre is mosaic or jigsaw-textured quartz (Figs. 5 and 6A, B). Camprubí and Albinson (2007) report that this texture is the one most commonly associated with ore minerals in the Mexican epithermal deposits. This texture is characterized by aggregates of microcrystalline to crystalline quartz crystals with interpenetrating grain boundaries (Camprubí and Albinson, 2007; Dong et al., 1995). Fournier (1985; see also Saunders, 1994) reports that the presence of jigsaw texture quartz indicates a recrystallization temperature >180 °C, which is approximately the upper stability limit for chalcedony. In some cases the original colloform texture is readily apparent in plain polarized light. As noted by Sander and Black (1988), primary fluid inclusions in this type of quartz do not record the original depositional conditions. However, in this study we observed many trails of secondary fluid inclusions in jigsaw quartz that record fluid conditions in the Veta Madre after recrystallization of the original chalcedony or amorphous silica. As such, these fluid inclusions are useful monitors of the fluid conditions during the later
Fig. 6. Photomicrographs of mineral textures observed in samples from the Veta Madre at Guanajuato. Jigsaw texture quartz observed in plane-polarized light (A) and under crossed polars (B). Plumose texture quartz in plane polarized light (C) and under crossed polars (D). Lattice bladed calcite in plane polarized light (E) and under crossed polars (F). Lattice bladed calcite replaced by quartz in plane polarized light (G) and under crossed polars (H). Acicular calcite replaced by quartz in plane polarized light (I). Colloform texture silica (now quartz) under crossed polars (J).
stages of the hydrothermal history of the system, including later stages of Ag–Au mineralization.

The next most abundant texture (549 samples; Fig. 7) is plumose quartz texture (Sander and Black, 1988) that shows variable extinction positions when observed under crossed polars (Fig. 6C, D). This quartz texture has also been referred to as “feathery” (Fig. 5B) or “flamboyant” (Fig. 5C) by Adams (1920) and Dong et al. (1995), respectively. This recrystallization texture is thought to develop from aggregates of fibrous chalcedony with rounded external surfaces, and originated as silica gel (Dong et al., 1995). The silica gel is precipitated when supersaturation occurs in response to rapid pressure decrease associated with fracturing and the concomitant temperature decrease, leading to precipitation of amorphous silica (Henley and Hughes, 2000). Depending on the initial temperature and pressure (enthalpy) of the fluid before fracturing, the fluid may flash with 100% of the liquid converted to vapor (see Brown, 1986), or P–T conditions may remain on the liquid–vapor curve as the fluid continues to boil along its upward flow path. Camprubí and Albinson (2007) report that this type of silica is a transitional phase in the silica precipitation cycle that precipitates after the amorphous silica phase and before the later crystalline quartz phase. As with the jigsaw texture described earlier, primary fluid inclusions in this type of quartz do not record the original depositional conditions, but secondary inclusions may provide useful information concerning later conditions.

Rhombic or massive calcite (Fig. 5N) is observed in 190 out 855 samples from the Veta Madre (Fig. 7). While bladed calcite is thought to be characteristic of deposition from a boiling solution (see below), an association between rhombic calcite and boiling is less clear. Camprubí and Albinson (2007) report that this type of “blocky” calcite is not associated with mineralization in the Mexican epithermal deposits but, rather, represents the collapse of shallow steam-heated carbonate waters late in a given hydrothermal cycle. Dong and Zhou (1996) also note that massive calcite is late and not associated with mineralization in the Cracow epithermal vein system in Australia.

Quartz with colloform texture is observed in 193 out of 855 samples from the Veta Madre (Fig. 7). Rogers (1918) introduced the term “colloform” to describe quartz with a rounded or botryoidal form that occurs in continuous bands (Fig. 6L). When observed under crossed-polars, the colloform texture sometimes shows an evolution from fine-grained to more coarse-grained quartz with a plumose texture (Fig. 5C) along a traverse from the vein wall to the center of the vein. Similarly, colloform texture sometimes shows a jigsaw texture characterized by banding of fine-grained quartz near the wallrock contact, with the grain size increasing towards the vein center, and

is most easily recognized when the sample is viewed under crossed polars (Fig. 5H). This type of quartz contains no useful primary fluid inclusions (Bodnar et al., 1985). Colloform texture is a primary depositional texture that has been interpreted to indicate rapid deposition of chalcedonic quartz in open space in shallow epithermal systems to produce the rhythmic banding (Bodnar et al., 1985; Fournier, 1985; Roedder, 1984). Henley and Hughes (2000) suggest that this texture is generated during rapid opening of a fracture that produces a pressure drop and rapid cooling associated with boiling or flashing (Fig. 1). Saunders (1990) notes that eutectic at the Sleeper deposit in Nevada is associated with alternating colloform bands of fine-grained quartz and opaline silica. He suggests that the gold and silica in the opaline bands originally precipitated as colloidal particles in the deeper parts of the system and were then remobilized and transported upwards by later fluids.

Lattice bladed calcite, including lattice bladed calcite replaced by quartz, is observed in 120 out of 855 samples from the Veta Madre (Fig. 7). This classification includes bladed calcite that is still compositionally calcite today (Figs. 5F and 6E, F), as well as bladed calcite that has been replaced by quartz (Figs. 5K and 6G), and calcite with an acicular texture that has been replaced by quartz (Fig. 5L). Albinson (personal communication, 2011) notes that acicular textures similar to those shown in Fig. 5L may be produced when quartz replaces barite, zeolites or laumontite. Barite and zeolites do occur in the Veta Madre, and the possibility that some of the pseudo-acicular replacement textures interpreted to be pseudomorphs after calcite may in fact be replacements of these other phases.

Simmons and Christenson (1994) described the close association between bladed (platy) calcite and boiling in geothermal systems and attribute this morphology to the rapid growth of calcite as carbon dioxide is lost to the vapor phase during boiling. Camprubí and Albinson (2007) note that bladed calcite is common in Mexican low-sulfidation deposits but is usually not closely associated with ore minerals. The presence of coexisting liquid-rich and vapor-rich inclusions in the calcite often confirms that the fluids were boiling during bladed calcite formation (Simmons and Christenson, 1994; Simmons et al., 2005). Often quartz completely replaces the bladed calcite and this type of replacement texture contains no useful primary fluid inclusions, but secondary inclusions may provide information concerning later conditions. The pseudo-acicular replacement texture (Fig. 5L) is produced when bladed calcite is replaced by quartz, but has also been observed in bands of chalcedony (Albinson, personal communication, 2011). An aggregate of fine-grained quartz phases with anhedral to rectangular shape replace the calcite to produce an acicular morphology (Adams, 1920; Dong et al., 1995). This type of
replacement texture contains no useful fluid inclusions. The next most abundant texture observed in 52 samples from the Veta Madre is massive quartz (Fig. 5Q). This term refers to quartz veins that have a homogeneous texture, show no banding or deformation features (Dong et al., 1995). The massive texture represents an original growth feature and can form during slow precipitation in open space, and is generally not associated with boiling.

The remaining mineral textures are observed in less than five percent of the samples. The zonal quartz texture was observed in 23 samples. This primary depositional texture is similar to comb texture, but with euhedral quartz crystals that show growth zoning and which are oriented perpendicular to the vein wall (Fig. 5P, R). The growth zones often contain primary fluid inclusions that record the original depositional conditions. The crustiform texture is a primary depositional texture that has been described by Adams (1920), Lindgren (1933), Bodnar et al. (1985), and Dong et al. (1995). The banding is often symmetrically distributed with respect to both walls (Fig. 5M) and is formed as a result of rapid, episodic fluctuations in temperature, pressure or fluid conditions during boiling. The original quartz and chalcedony banding is sometimes partially destroyed by recrystallization (Adams, 1920). This type of quartz can contain useful primary and secondary fluid inclusions. Cockade texture is a primary depositional feature that is confined to breccia zones, where rock fragments are surrounded by concentric crusts of quartz (Fig. 5Q) (Adams, 1920; Dong et al., 1995). This occurrence of quartz, which is uncommon in the Veta Madre, can contain useful primary and secondary fluid inclusions. Comb texture quartz (Fig. 5R) is a primary depositional texture that was observed in a few samples. This texture is characterized by coarse, imperfect, euhedral crystals growing into open space perpendicular to the vein walls (Adams, 1920). This type of quartz often contains numerous microfractures that contain secondary fluid inclusions (Bodnar et al., 1985). The ghost-sphere and moss textures are deposited from colloidal amorphous silica. Under crossed polars these types of quartz show a jigsaw texture resulting from recrystallization (Fig. 5I). Ghost-sphere and moss texture quartz contain no useful primary fluid inclusions.

While the goal of this study was not to develop a mineral paragenesis, some generalities concerning the paragenesis of the vein minerals and textures can be summarized. Within a given sequence, colloform quartz is earliest, followed by jigsaw or plumose texture, and finally by coarse euhedral quartz, some of which is amethyst. This sequence may be repeated several times at a given location. Bladed calcite may appear along with any of the quartz textures that are indicative of boiling, but rhombic calcite is always late.

As noted previously, boiling has been linked to metal deposition in precious metal systems (Andre-Mayer et al., 2002; Bodnar et al., 1985; Brown, 1986; Buchanan, 1979; Etoh et al., 2002; Roedder, 1984; Simmons and Christenson, 1994), and many of the textures described above are thought to be produced as a result of boiling (or, at least, rapid temperature and/or pressure drop that leads to oversaturation and rapid precipitation). Shallow hydrothermal systems such as those associated with epithermal deposits often experience repeated episodes of sealing and fracturing during the lifetime of the system, as evidenced by abundant brecciation and broken crystals in epithermal systems. Hydraulic fracturing and the concomitant pressure drop may cause the fluid to boil (or “flash” to steam) (Fig. 1). When this occurs the temperature decreases owing to the large heat of vaporization of water. At temperatures ≤340 °C, the solubility of quartz decreases with both decreasing pressure and decreasing temperature (Fournier, 1985). As a result, the fluid that was originally in equilibrium with quartz may achieve a high degree of supersaturation, leading to the precipitation of amorphous silica with a colloform texture. With time, the amorphous silica may recrystallize to chalcedony and/or quartz (Fournier, 1985). This interpretation is consistent with the general quartz paragenesis observed in Mexican epithermal deposits, which includes early amorphous silica, followed by chalcedony and plumose quartz, and finally by coarse crystalline quartz (Camprubi and Albinson, 2007).

We note that this sequence relates to a single episode of fracturing, and that this process repeats itself many times during the history of the system. Thus, at any one location up to several tens of fracturing and boiling episodes may be observed.

Those textures observed here that are thought to be produced directly by precipitation from supersaturated solutions, or by crystallization of chalcedony or quartz from original amorphous silica, include jigsaw (Fig. 5A), feathery (Fig. 5B), flamboyant (Fig. 5C), plumose (Fig. 5D), colloform (Fig. 5E), colloform banded plumose (Fig. 5G), colloform banded jigsaw (Fig. 5H), crustiform quartz (Fig. 5M), moss (Fig. 5J) and ghost-sphere (Fig. 5I). Similarly, lattice bladed calcite (Fig. 5F), lattice-bladed calcite replaced by quartz (Fig. 5K) and pseudo-acicular quartz after calcite (Fig. 5L) are also textures associated with boiling fluids. In each sample, the presence of these textures has been noted and used to infer whether boiling occurred at the sample location at some time during or after deposition of the original material. The number of samples containing each of the textures described above is summarized in Fig. 7.

4.2. Fluid inclusions

Petrographic examination of Fluid Inclusion Assemblages (FIAs; Goldstein and Reynolds, 1994) can provide evidence concerning the chemical and physical environment of formation of epithermal precious metals deposits (Bodnar et al., 1985). As noted by previous workers (Bodnar et al., 1985; Dong et al., 1985; Sander and Black, 1988), some types of quartz (either originally precipitated or recrystallized amorphous silica) from the epithermal environment contain no useful fluid inclusions. Thus, primary-appearing fluid inclusions in colloform banded plumose, colloform banded jigsaw, jigsaw and plumose texture quartz do not record the conditions of formation because these phases were originally precipitated as amorphous silica or chalcedony and have subsequently recrystallized. On the other hand, secondary fluid inclusions trapped along healed fractures in quartz that has recrystallized from amorphous silica or fine-grained chalcedony do record the conditions of this later fracture-healing event. In each sample containing these textures, secondary FIAs were monitored to determine if the inclusions showed evidence of boiling. While these secondary fluid inclusions do not record boiling during precipitation of the material immediately surrounding the inclusions, they are thought to reflect boiling conditions nearby in the vein at some later time in the evolution of the system (Fig. 1).

When fluid inclusions are trapped in a single-phase fluid system, all of the inclusions will show the same phase behavior when observed under the microscope at room temperature. However, if the inclusions are trapped in a boiling or immiscible fluid system, some inclusions will trap the liquid phase, some will trap the vapor, and some will trap mixtures of the two phases (Bodnar et al., 1985). In each FIA identified as described above, the phase relations of individual inclusions were examined, petrographically to determine if all the inclusions appeared to have the same liquid-to-vapor ratio, or if the inclusions in the FIA showed variable ratios (Fig. 4). While variable liquid-to-vapor ratios may be produced by trapping mixtures of liquid and vapor in a boiling system, they may also be produced by necking down of the inclusions after a vapor bubble has nucleated in the inclusions. Following Goldstein and Reynolds (1994), we have assumed that if the FIA includes vapor-rich inclusions and liquid-rich inclusions with variable liquid-to-vapor ratios, as well as all-liquid inclusions, that the inclusion phase ratios are the result of necking down or, possibly, recrystallization of amorphous silica or chalcedony (Sander and Black, 1988), and are not the result of boiling.
5. Results and interpretation

The goal of this study was to examine possible correlations between precious metal mineralization and mineralogical and fluid inclusion evidence for boiling along the Veta Madre at Guanajuato, Mexico, and to develop a tool that could be used in exploration for epithermal systems. As noted above, many of the textures described for quartz might have formed as a result of rapid precipitation from hydrothermal fluids, likely as a result of boiling. In addition, the presence of coexisting liquid-rich and vapor-rich fluid inclusions in the same FIA (with no single-phase, all-liquid inclusions present, which would suggest necking, rather than boiling) indicates that the inclusions were trapped in a boiling fluid. Importantly, Camprubí and Albinson (2007) report that boiling is the most important depositional mechanism in the Mexican epithermal deposits based on the close temporal and spatial association of mineralogical and fluid inclusion evidence for boiling and ore mineralization. Thus, textual and fluid inclusion evidence can help the explorationist to identify systems that have experienced boiling and may be suitable hosts for precious metal mineralization.

For each of the 855 samples examined, a numerical value was assigned for each mineral texture and fluid inclusion feature described above. A value of 0 (zero) was assigned if a given feature was not observed during petrographic examination of the sample, and a value of 1 (one) was assigned if the feature was observed. The number of observations for each of the boiling features is summarized in Fig. 7. Jigsaw texture quartz was observed in 88% of the samples (752 of 855). Plumose texture quartz, also referred to as feathery or flamboyant texture quartz in the literature, occurs in 64% (549 samples). Colloform textures, including colloform banded plumose and colloform banded jigsaw textures, were observed in 23% (193 samples). Lattice bladed calcite and/or lattice bladed calcite replaced by quartz and/or acicular calcite replaced by quartz was observed in 14% (120 samples). Fluid inclusion assemblages containing coexisting liquid-rich and vapor-rich fluid inclusions were observed in 193 samples (Fig. 7).

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Fig. 8. Relationship between the average Au grade of samples and the presence or absence of each mineral or fluid inclusion feature in samples from the Veta Madre, Guanajuato, Mexico. Features listed above the horizontal solid line are those that characterize boiling environments, whereas those below the line are characteristic of non-boiling environments.

Fig. 9. Relationship between the average Ag grade of samples and the presence or absence of each mineral or fluid inclusion feature in samples from the Veta Madre, Guanajuato, Mexico. Features listed above the horizontal solid line are those that characterize boiling environments, whereas those below the line are characteristic of non-boiling environments.
For each of the textures described above, the average Au and Ag grade of samples in which the feature is present, and the average Au and Ag grade for samples in which that feature is absent, have been calculated and the results are shown on Figs. 8 and 9, respectively. The average grade of Au is higher in samples in which the boiling feature is present, compared to samples for which it is absent, for all features except for cockade texture quartz (Fig. 8). Also, the largest difference in grade between samples showing the presence or absence of a feature is for colloform texture quartz (1.1 ppm Au versus 0.2 ppm Au). The average Au grade is lower in samples dominated by non-boiling textures, including massive, zonal and comb texture quartz and rhombic calcite, consistent with the assumption that boiling is the depositional mechanism in these deposits.

The average grade of silver is higher in samples in which a boiling feature is present for all features except for jigsaw texture quartz. This observation is consistent with observations of Camprubí and Albinson (2007), who report that the silica phase that is most closely associated with ore-bearing minerals is colloform-textured jigsaw quartz. Based on these results, we suggest that the jigsaw texture quartz is an indicator of boiling, which may or may not be associated with mineralization, depending on the metal content of the fluid. As noted by Camprubí and Albinson (2007), “the occurrence of boiling does not necessarily lead to the occurrence of metallic-bearing associations (Camprubí et al., 2001) if the boiling fluids are not endowed with dissolved metals.”

The average Ag grade is lower in samples that show mineral textures that are indicative of slow crystal growth (non-boiling), including massive, zonal, cockade and comb texture quartz – the lone exception is rhombic calcite, which is not thought to be associated with boiling but may indicate effervescence of CO₂ or descent of steam-heated waters that precipitate calcite as the temperature increases (Simmons et al., 1988; Simpson et al., 2001). Features that show the most dramatic difference in Ag grade when comparing samples that show the presence or absence of that feature are colloform texture quartz (178.8 ppm Ag versus 17.2 ppm Ag) and bladed/platy calcite (128.4 ppm Ag versus 47.5 ppm Ag).

There is no significant difference in average grade of samples containing both liquid-rich and vapor-rich fluid inclusions, compared to those in which fluid inclusion evidence for boiling is absent. The Au grades are essentially identical (∼0.4 ppm Au) in samples containing boiling FIAs and those in which they are absent (Fig. 8). The Ag grade is slightly elevated in samples containing coexisting liquid-rich and vapor-rich fluid inclusions, compared to those in which fluid inclusion evidence for boiling is absent (67.1 ppm Ag versus 49.4 ppm Ag; Fig. 9). This lack of correlation likely reflects the fact that the phases being precipitated as a result of boiling (dominantly amorphous silica and chalcedony) are not amenable to the trapping of fluid inclusions that reflect the original trapping conditions, and thus the metal deposition stage and the secondary fluid inclusion trapping events were not concurrent.

Data shown on Figs. 8 and 9 were evaluated using the t-test to assess whether the average grades (means) for samples in which a feature is present are statistically different from those in which the feature is absent. Differences between the presence or absence of a feature indicative for boiling are statistically different at the 95% confidence level (p < 0.05) for all features except jigsaw texture silica (p < 0.10) and fluid inclusions (p < 0.25) for silver, and for fluid inclusions (p < 0.10) for gold (Fig. 10). For comparison, the distribution of grades for samples in which massive quartz (a non-boiling texture) is present and absent are also shown on Fig. 10.

The textural and fluid inclusion data obtained in this study were analyzed using the binary classifier within the statistical software package SPSS Clementine. The binary classifier builds 10 different statistical models and evaluates the performance of each model. The Au and Ag grades show a log normal distribution based on application of the Shapiro-Wilks test for normality (Fig. 11A, B). Our goal was to determine if the statistical models could distinguish between samples with ore grades (≥1 ppm Au or ≥100 ppm Ag) and those that were sub-economic. Each sample was assigned a label that identified whether the concentration was above or below these thresholds. Of the 694 samples for which we had Au and Ag assay data, only about 6% of the samples had concentrations that classified them as ore grade (≥1 ppm Au or ≥100 ppm Ag) for either gold or silver.

**Fig. 10.** Distribution of Au (left) and Ag (right) grades (in log ppm) plotted as a function of whether a particular mineralogical or fluid inclusion feature was present or absent. Also shown by the vertical line on each histogram is the mean metal grade for samples in which the feature is present (solid) or absent (dashed). A t-test was applied to each pair of data to assess whether the mean values were statistically different and the results are shown as the probability (i.e., P < 0.05 indicates that there is less than a 5% chance that the difference is due to chance).
In order to build an unbiased statistical model, the number of observations was balanced via random sampling to contain an approximately equal number of ore grade and sub-economic samples. If an equal number of ore grade and sub-economic samples was not selected to develop the model, the model would tend to over-predict the grade with a higher frequency in the sample population. For Au, after balancing, 78 samples were selected to build the models (36 had Au ≤1 ppm and 42 >1 ppm). Similarly, for Ag, 77 samples were selected to build the models, and 38 samples had >100 ppm Ag and 39 <100 ppm Ag.

After balancing the number of ore grade and sub-economic samples, the dataset was split into a training dataset (70% of the observations) and testing dataset (30% of the observations). The software iteratively builds and evaluates the predictive models and ranks the resulting models based on accuracy, i.e., the proportion of correct predictions. The models that showed the highest “profit” or greatest predictive capability for both Au and Ag were the neural network, the C5 decision tree and Quest decision tree models, all of which predicted the correct results in about 70–75% of the tests. For both Ag and Au, most other models showed significantly poorer predictive capability.

The binary classifier model building and testing software also provides information on the relative importance of each of the variables included in the model. For both Au and Ag, the colloform texture was the variable with the greatest importance, i.e., colloform quartz has the greatest predictive power to distinguish between ore grade samples and sub-economic samples (Fig. 12). This is consistent with the fact that amorphous silica with colloform texture is precipitated as a result of intense boiling (or flashing), and Camprubí and Albinson (2007) have noted that boiling or fluid immiscibility is temporally and spatially associated with ore mineralization in the Mexican epithermal deposits. For Au, the second most important variable was bladed/platy calcite replaced by quartz (Fig. 12A), and for Ag, fluid inclusion evidence for boiling (coexisting liquid-rich and vapor-rich fluid inclusions or FIAs containing only vapor-rich inclusions) showed the second highest importance (Fig. 12B). Note that Camprubí and Albinson (2007) report that bladed calcite is usually not associated with ore minerals in the Mexican deposits. The association with bladed calcite may therefore not reflect conditions during deposition of the original calcite but, rather, conditions during replacement of that calcite by quartz.

6. Application in exploration for epithermal precious metal deposits

The goal of this study was to develop a methodology that could be used in exploration for epithermal precious metal deposits. The method is based on the assumption that precious metal mineralization and boiling are genetically related and that systems with strong evidence for boiling have greater potential to host ore than those that do not show this evidence. In practice, the method identifies systems in which boiling has occurred, and it must be emphasized that not all hydrothermal fluids in the epithermal environment contain Au and/or Ag. Thus, some systems may show significant evidence of boiling but contain no Au or Ag mineralization, as also emphasized by Camprubí and Albinson (2007).

The feature that is most closely related to higher Au and Ag grades in the Veta Madre is colloform quartz. This texture is often easily

Fig. 11. Log-normal distribution of Au (top) and Ag (bottom) grades in samples from Guanajuato, Mexico.

Fig. 12. Relative importance of variables used to build models to predict Au (top) and Ag (bottom) grades at Guanajuato, Mexico.
recognizable in outcrop and hand sample, as well as during normal petrography. Lattice bladed or platy calcite and plumose texture quartz are also closely associated with higher grade samples in the Veta Madre. While lattice bladed calcite is recognizable in hand sample, it may be necessary to examine samples under crossed polars to recognize plumose texture quartz. Contemporaneous liquid-rich and vapor-rich fluid inclusions show only a poor correlation with higher Au and Ag grades at Guanajuato. This lack of correlation reflects the fact that inclusions are not trapped during precipitation of amorphous silica that later crystallizes to produce colloform quartz, and inclusions that are trapped during precipitation of lattice bladed calcite are often destroyed when the calcite is replaced by quartz. These observations suggest that mineral textures may be better indicators of mineralization in the epithermal precious metal deposits in the Guanajuato Mining District compared to fluid inclusions showing evidence of boiling, but that the two tools are complementary.

Most samples collected from the Veta Madre for this study show some evidence of boiling (>750 out of 855 samples). Most of the samples that do not show evidence of boiling contain only rhombic calcite, and this form of calcite is not thought to be precipitated during boiling but, rather, is precipitated as steam-heated waters descend (Simmons et al., 1988; Simpson et al., 2001).

To test whether the methods developed in this study might be used to establish vectors pointing towards a mineralized vein system that was formed from boiling fluids, four samples were collected along a traverse perpendicular to the Veta Madre. The samples were collected by starting at the Veta Madre outcrop on the surface and walking perpendicular to the vein, collecting a sample everywhere that a vein oriented approximately parallel to the Veta Madre, or a stockwork outcrop, was encountered. Most of the veins away from the Veta Madre were less than about 10 cm wide.

With distance away from the Veta Madre, the Ag and Au grades quickly drop to subeconomic values (Fig. 13B, C). The only feature indicative of boiling that is recognized in 4 samples collected along a traverse perpendicular to the vein is jigsaw quartz (Fig. 13A). The rapid drop-off in boiling intensity indicators (and Ag and Au grades) with distance from the mineralized vein has both advantages and disadvantages for exploration. The disadvantage is that samples collected at a relatively short distance laterally away from a well-mineralized vein may show no evidence of boiling and/or mineralization. Conversely, if a sample collected from a surface outcrop contains

![Diagram](image-url)
good evidence for boiling, it is likely that this represents the surface expression of a vein that has potential to host precious metal mineralization.

As noted earlier, and as observed in modern geothermal systems, once boiling begins at depth it usually continues to the surface. Additionally, the best gold grades would be expected to occur at or above the base of the boiling zone. Therefore, good evidence of boiling in surface samples indicates that the base of the boiling zone where precious metal mineralization is mostly likely to occur is beneath the present surface. Such an area might be given higher priority for drilling to explore the subsurface, even if precious metal grades in the surface samples are poor. At Guanajuato, an angled drill hole from the surface into the Veta Madre showed a systematic increase in boiling intensity indicators as the vein was approached (Fig. 13D), even though the metal grades in the drill core were well below economic values. From an exploration perspective, boiling evidence suggests that drilling should be continued, even though metal grades are subeconomic.

Results of this study can also be applied during mining to explore deeper or peripheral parts of a mineralized vein system. For example, at Guanajuato evidence of boiling is present in samples from the surface to the deepest levels of current mining activities (Fig. 14), including drill core samples that extend beneath the deepest levels that have been mined at Cata (Fig. 3). This suggests that the bottom of the boiling horizon is at some depth greater than that explored by mining, and that additional precious metal resources might be encountered as deeper levels of the Veta Madre system are explored and developed. This hypothesis was tested and found to be correct when Great Panther Silver explored the deep levels between the Rayas and Cata Mines (Fig. 3) and discovered mineralization on the Santa Margarita vein. Mineralization on the Santa Margarita changes from Au-rich (a zone 52 meters long, 3.4 meters wide, with assays averaging 5.06 g/t gold and 20 g/t silver) to Ag-rich with depth (26 meters long, 3.45 meters wide, with assays averaging 5.23 g/t gold and 359 g/t silver). The Santa Margarita vein has a total mineralized length of over 300 meters (Great Panther Silver, 2009), and its presence beneath the deepest explored levels at Rayas was suggested in part by the strong evidence for boiling observed in subsurface samples.

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