A preliminary fluid inclusion study of a quartz-sulphide-chlorite vein at the Anio Creek prospect, northwest Tasmania

by J. Taheri

INTRODUCTION

The Anio Creek prospect area is located inside the Cradle Mountain–Lake St Clair National Park in northwest Tasmania. The geology of the area is characterised by two isolated closed anomalies which are different to those of the surrounding area (Richardson, 1994). The source of the anomalies is not yet known, but the anomalies are associated with mineralisation and may indicate the potential for discovery of new mineral deposits within the area.

The objects of this preliminary investigation were to:–

(a) identify the possible ore-forming environment through fluid inclusion study; and

(b) propose a genetic model for the mineralisation based on geophysical, geological, fluid inclusion and petrological investigations.

FLUID INCLUSION STUDIES

During processes of crystal growth or fracture healing, small portions of the fluid medium are commonly trapped as fluid inclusions. If the fluid contains solid phases these may also be trapped as solid inclusions. However these solid inclusions are different from "daughter minerals", as the latter crystallise out of fluid upon cooling after trapping. Fluid(s) and solid(s) may be trapped either during the growth of the crystal by any process which interferes with a perfect growth, yielding primary fluid inclusions, or at some later time by recrystallisation along fractures from different fluids to form secondary fluid inclusions. Pseudo-secondary fluid inclusions are those formed along the fractures during the growth of a crystal.

Fluid inclusions normally have a vapour or gas bubble which may move constantly under the effects of a thermal gradient or of gravity. The volume coefficients of thermal expansion for minerals are less than water by up to three times. Therefore upon cooling, a fluid inclusion which has been formed from an homogeneous fluid at elevated temperatures will shrink more than the host mineral, and when the total vapour pressure in the fluid is more than the pressure in the inclusion a bubble will nucleate and grow. The process can be reversed simply by heating the inclusion to the temperature at which the bubble disappears (i.e. homogenisation temperature). This was first suggested by Sorby (1858).

Fluid inclusions are rarely larger than one millimetre. However museum specimens with fluid inclusions containing hundreds of millilitres of fluid are known (e.g. Rankin and Greenaway, 1978).

Fluid inclusions which have been formed in a heterogeneous system of two or even more immiscible phases (e.g. droplets of oil in an aqueous liquid) may contain one to all of the fluids, with different ratios. A similar phenomenon may result from phase separation during boiling of a fluid. If the fluid consists of water with very low salinity, there will be coexisting vapour-rich and liquid-rich fluid inclusions which may homogenise to vapour or liquid upon heating. Fluid inclusions formed from the boiling of compositionally more complex fluids (e.g. CO_2-H_2O-$NaCl$) exhibit wide variations in phase ratios, compositions and homogenisation temperatures.

The composition of fluid inclusions varies widely. In general the major solvents are H_2O and less commonly CO_2, and the major solute ions include Na, K, Mg, Ca, Cl, SO_4, and HCO_3, with lesser amounts of Li, B, Fe, Mn, F, and P. Major constituents in inclusions with organic liquid or gas include H_2, CH_4 and C_2H_6, as well as a variety of high molecular weight compounds.

The salinity of fluid inclusions (wt% NaCl equivalent) can be estimated by freezing the fluid inclusions and measuring the depression of their freezing points. This is just an estimate, as other solute ions such as Mg, Ca etc. may also be present in the fluid. There are many microbeam techniques, both non-destructive and destructive, to determine the compositions of the fluid inclusions (e.g. electron, ion, and X-ray probes, Laser-Raman spectroscopy).

Fluid inclusions may be subject to different physical changes after trapping, some of which may cause erroneous results in composition and homogenisation temperature measurements. There are mainly two physical changes which have been of great concern in fluid inclusion studies.

(1) Movement of fluid into or out of the inclusions after trapping (i.e. leakage). Many factors, including overheating of primary fluid inclusions above their homogenisation temperatures, deformation of host rocks in metamorphic terranes, microfractures, and cleavages may all cause leakage in fluid inclusions.

(2) Necking down, which occurs in fluid inclusions with a large surface area. In order to minimise the high surface energy of the system a process of recrystallisation (i.e. necking down) may occur immediately after trapping if the host mineral has any finite solubility in the fluid. The final result of the necking down is the formation of several smaller fluid inclusions with the same total volume as the original flat fluid inclusion but with less surface energy. If there is no phase change before necking down, the composition of the fluid will stay the same. However if any phase changes occur before necking down, the inclusions resulting from this process may have different compositions or homogenisation temperatures. Therefore great care must be taken in order to identify the fluid inclusions which have suffered from leakage or necking down processes.

In general, fluid inclusions can be effectively utilised in the studies of ore deposits, either in problems of mineral exploration or in studies of ore-forming environments. They can also be used in igneous and metamorphic terranes, in oil exploration, in active geothermal systems, and in many other fields.

The following terms and observations are used in this report:–

L — Liquid

V — Vapour

H — Halite

S — Sylvite

Th — homogenisation temperature of fluid phases:

ThL = L + VL$\Rightarrow$L (i.e. fluid inclusion homogenises to liquid phase);

ThV = L + V$\Rightarrow$V (i.e. fluid inclusion homogenises to vapour phase);

U — Unknown solid inclusion

Immiscibility — Immiscibility is defined as a system containing several homogeneous phases in equilibrium with each other.

FLUID INCLUSIONS AT THE ANIO CREEK PROSPECT

The following descriptions and results are based on the study of fluid inclusions in quartz from one quartz-chlorite-sulphide vein (sample AC12). Therefore any interpretations and conclusions drawn from this study must be considered cautiously.

The sample was collected from a massive white quartz containing pyrite and chlorite as the main minerals, with minor carbonates, galena, chalcopyrite, pyrrhotite and possibly cassiterite. The occurrence of cassiterite must be verified by microprobe analysis.

Fluid inclusions in quartz have a variety of shapes including rounded, oval, negative crystal or irregular, and range in size from <4 to >20 μm. The section is characterised by having myriads of tiny fluid inclusions along healed microfractures, cutting across the grain boundaries. This texture is known to be indicative of a deep environment, greater than 4 km in depth (Reynold, 1990).

The fluid inclusions may be classified as follows:–

Type A: Two-phase (LH$_2$O + VH$_2$O) fluid inclusions which can be divided into two sub-types, viz:

Type A-1: Fluid inclusions with low vapour-liquid ratios (10–20%) by volume. These fluid inclusions are commonly secondary and show relatively low homogenisation temperatures (less than 200°C).

Type A-2: Fluid inclusions with high vapour-liquid ratios (70%) by volume. The vapour-liquid ratios are variable (fig. 1 and 3). The fluid inclusions appear to be mostly primary in origin, as they are not associated with fractures and mainly occur as isolated individuals or as small groups, and are commonly found in growth zones.

Type B: CO$_2$-bearing fluid inclusions consisting of LCO$_2$ + VCO$_2$ (B-1), LCO$_2$ + LH$_2$O + VCO$_2$ (B-2) and LH$_2$O + V(H$_2$O + CO$_2$) (B-3). In general these fluid inclusions are rounded in shape, although negative crystal shape can also be seen (fig. 1 to 3).

Type B-1 inclusions commonly contain a single liquid phase at room temperature, and vapour CO$_2$ only nucleates upon cooling (i.e. higher density and internal pressure). These inclusions can easily be mistaken for type A-2 inclusions at room temperature.

Type B-2 inclusions consist of aqueous solution and a CO$_2$ vapour phase ringed by CO$_2$ liquid (fig. 2). The CO$_2$ vapour bubbles in some inclusions appear only on cooling (i.e. LCO$_2$ + LH$_2$O at room temperature).

Type B-3 inclusions consist of aqueous solution + liquid CO$_2$ with a dark meniscus around the vapour bubble . The occurrence of CO$_2$ can only be positively identified by freezing experiments. All type B inclusions are closely associated with each other on a microscopic scale.

Type C: Fluid inclusions containing one solid phase. Fluid inclusions types A (H$_2$O only) and B (H$_2$O + CO$_2$) may also contain a solid inclusion. Halite inclusions are by far the most common solid phase (fig. 3). Another relatively common solid phase is a rounded to angular anisotropic mineral. Halite-bearing fluid inclusions may coexist with type A-2 or type B fluid inclusions or they are in groups which lack any relationships with fractures. However fluid inclusions containing the unknown mineral mostly occur in isolation and show no relationships with other fluid inclusion types. The phase ratios may vary, particularly for the unknown solid phase which may constitute more than 90% of some fluid inclusions (fig. 4).

Type D: Fluid inclusions containing more than one solid phase (fig. 5 to 7). These fluid inclusions are less common and contain up to eight solid inclusions. The solid inclusions vary in size and shape and may almost fill the
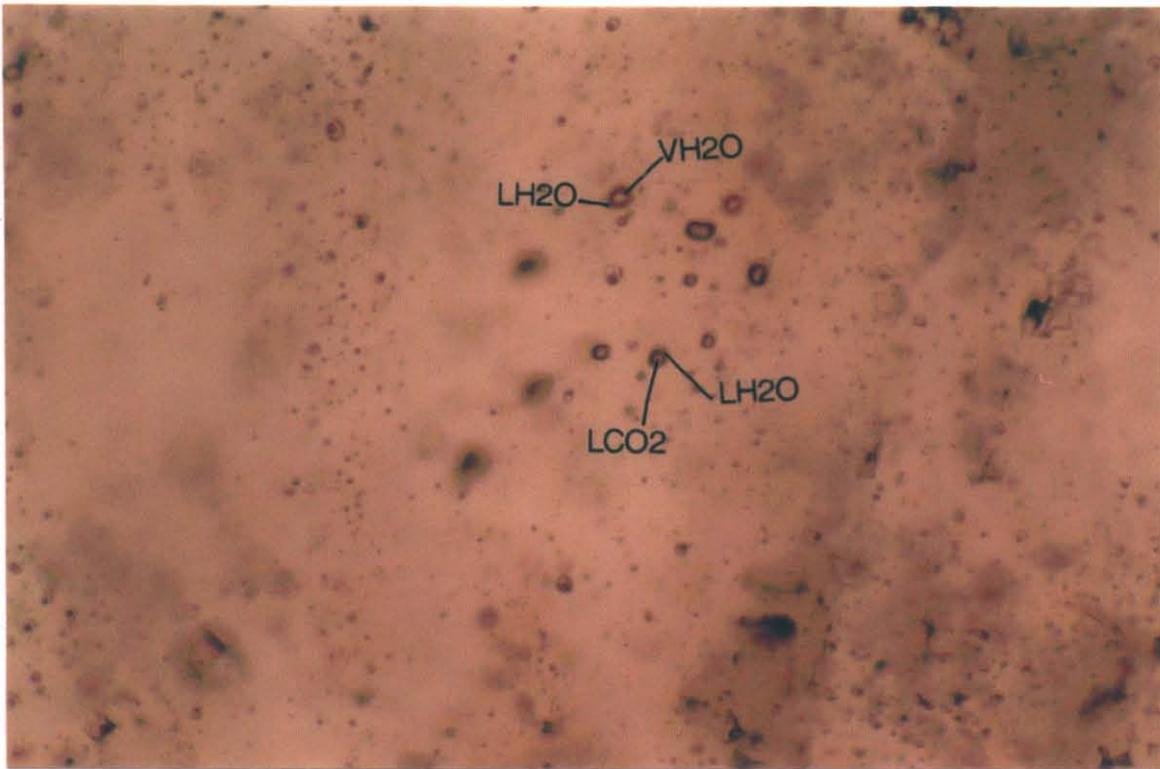
Figure 1
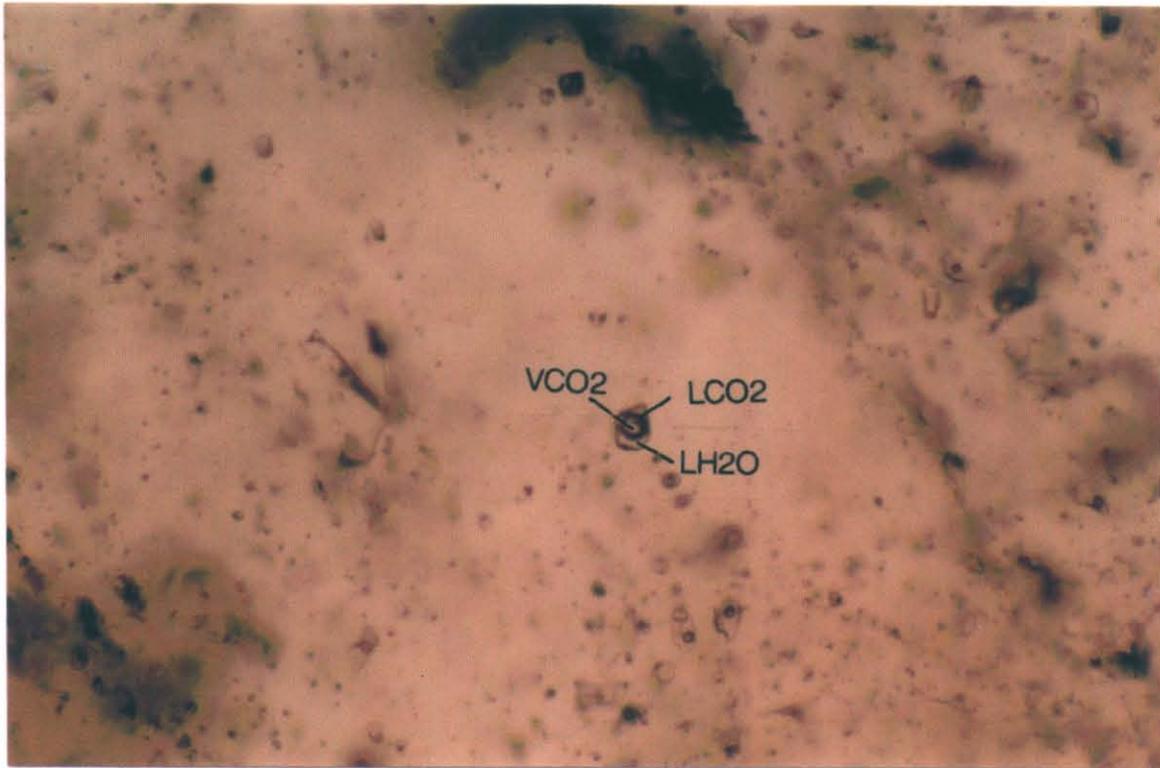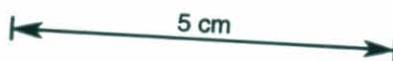Types A-2 and B fluid inclusions. Note the coexistence of the two types of the inclusions.

Figure 2
Type B-2 fluid inclusion. Note the occurrence of the fluid inclusion along the growth zone.
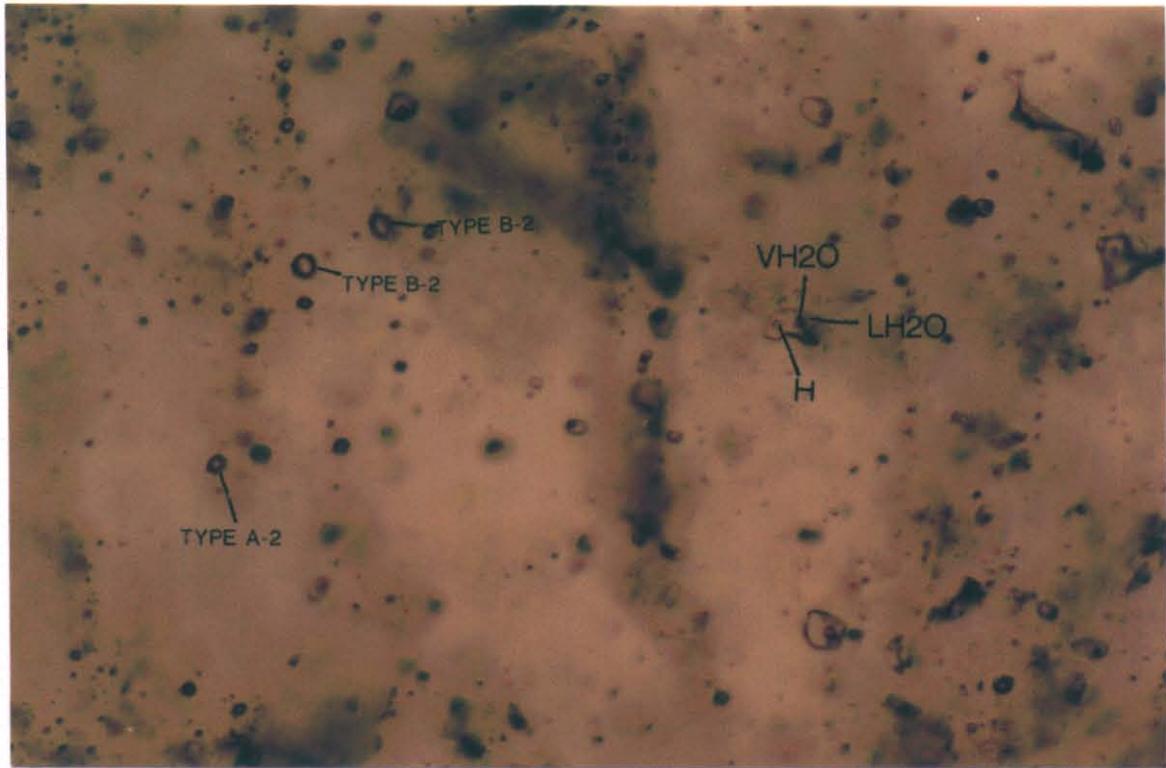
5 cm

Figure 3
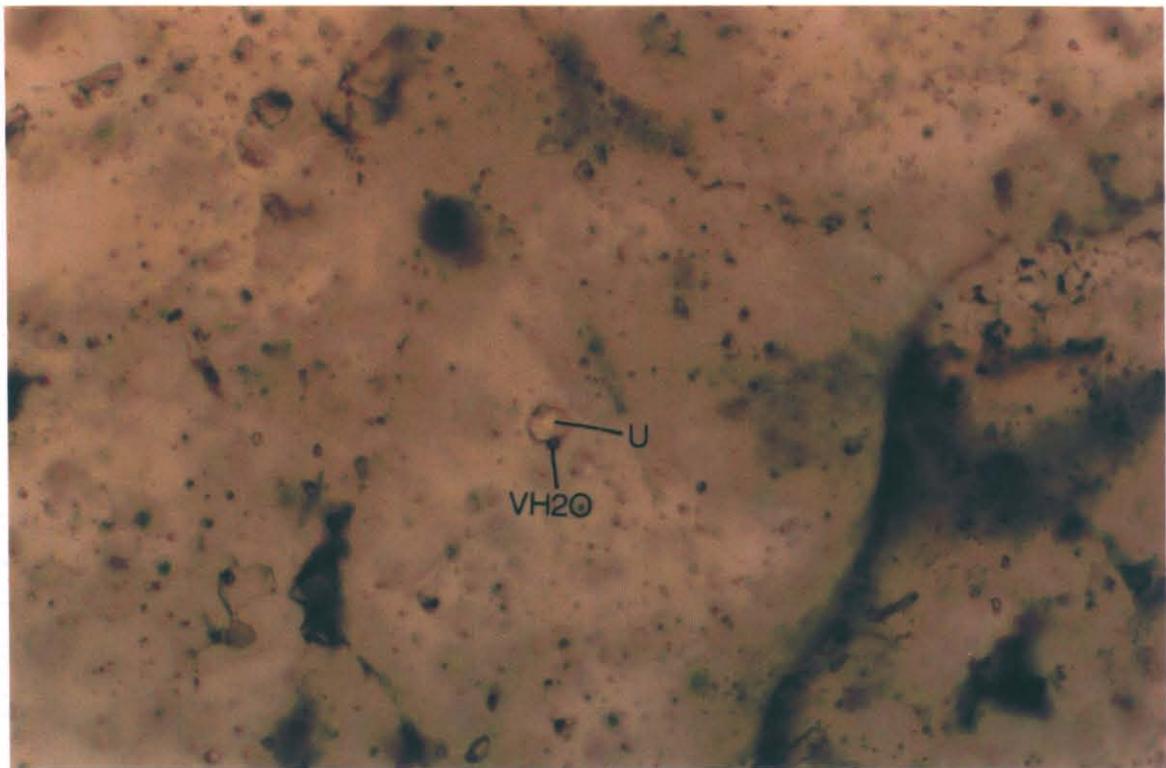Type C fluid inclusions containing halite (H). Types B and A-2 can also be seen.

Figure 4
Type C fluid inclusion containing unknown anisotropic solid inclusion. Note that the
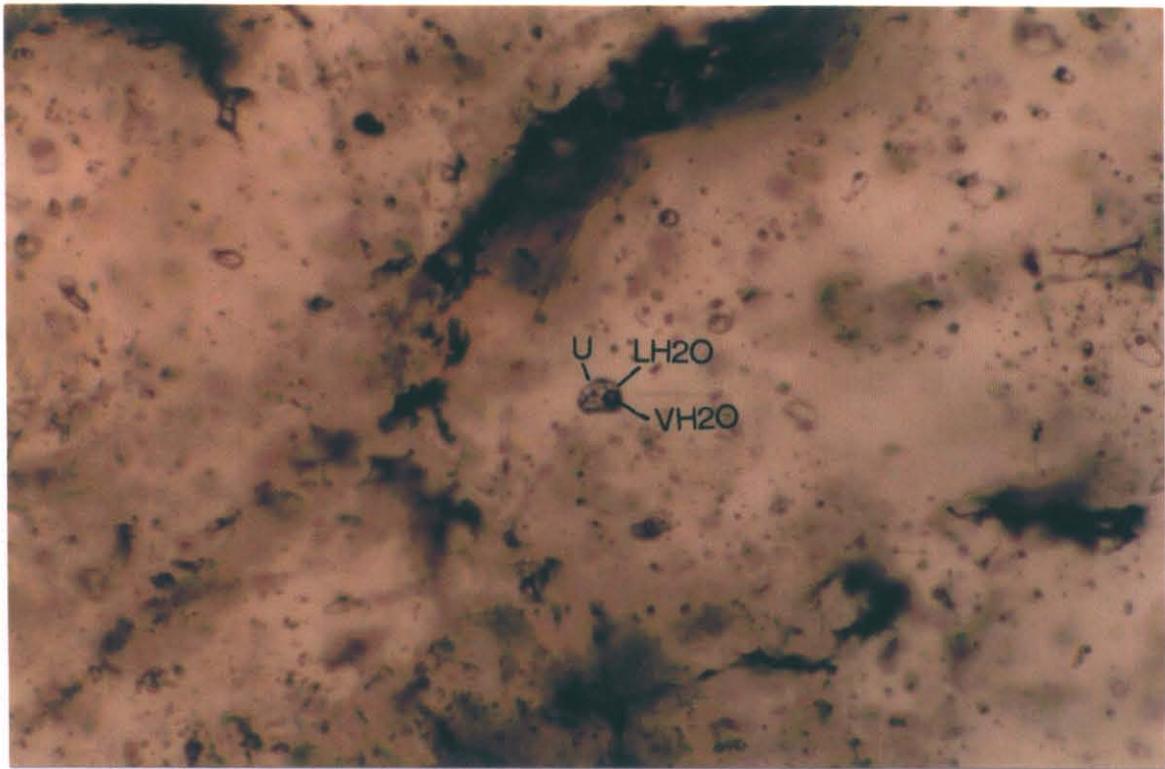inclusion is almost filled with the solid inclusion.

5 cm

Figure 5a
Type D fluid inclusion containing up to 8 solid inclusions.
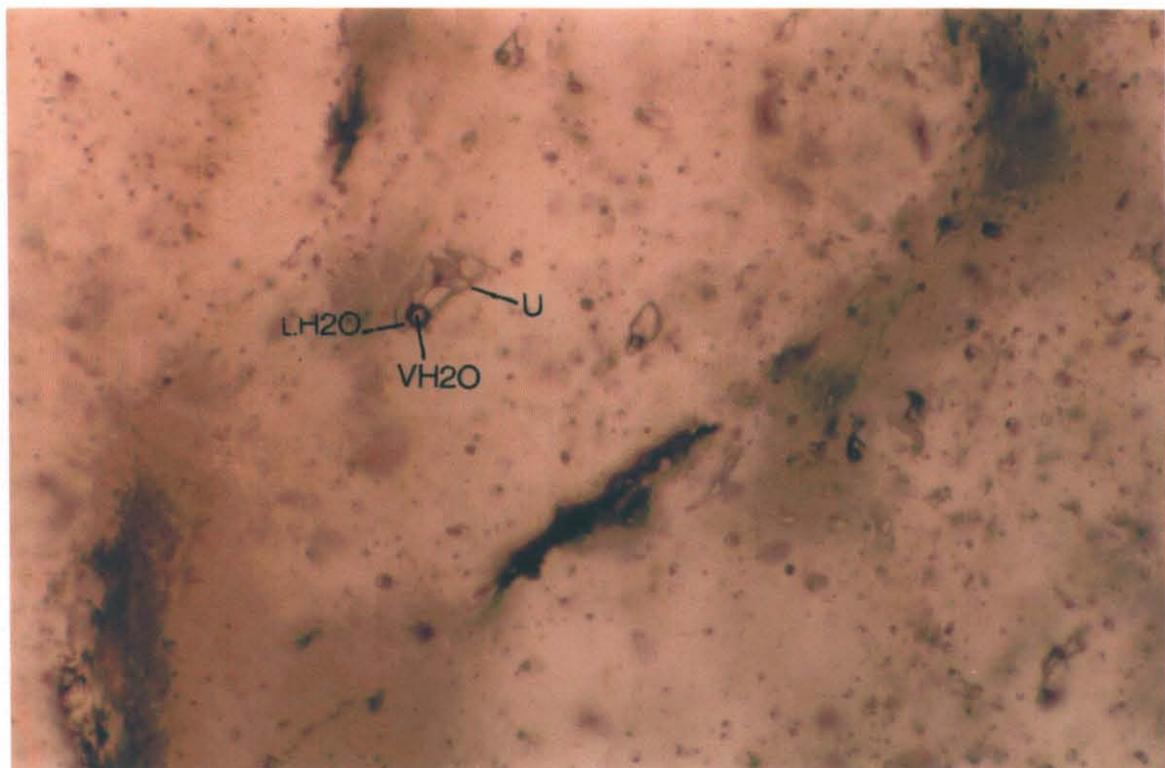

Figure 5b
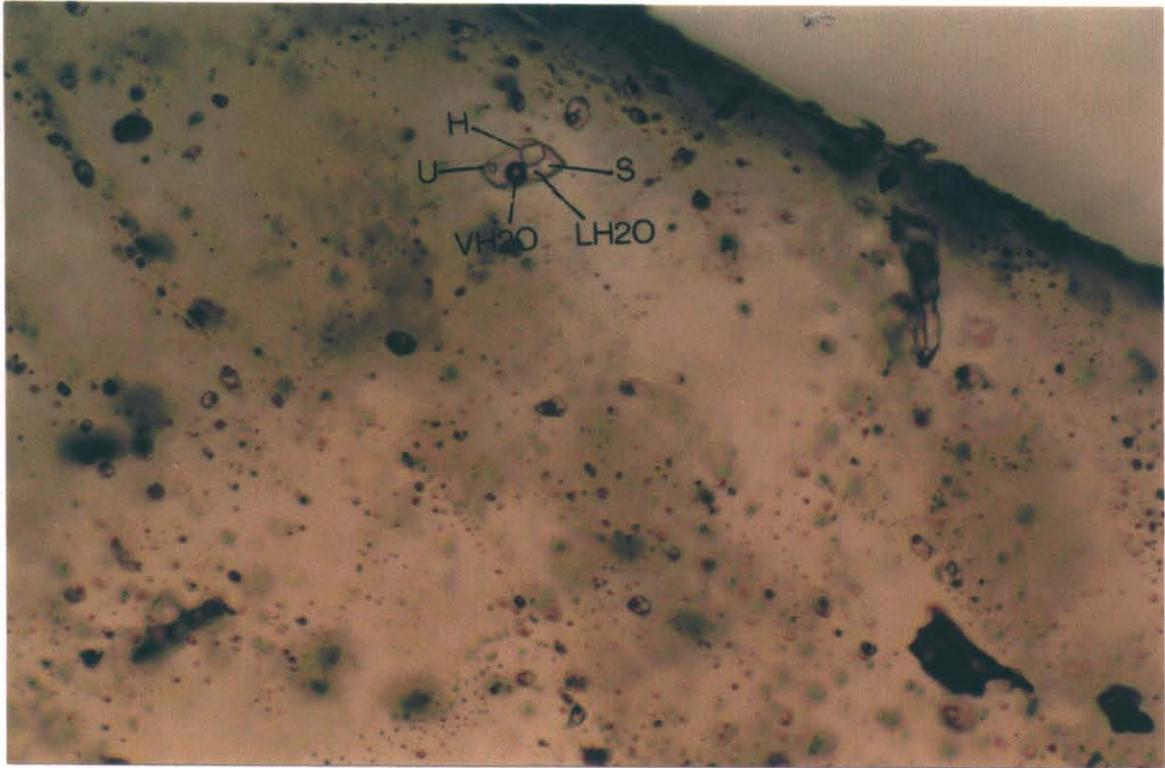Type D fluid inclusion containing up to 8 solid inclusions.

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Figure 6
Type D fluid inclusion containing halite (H), sylvite (S) and unknown (U) solid inclusion.
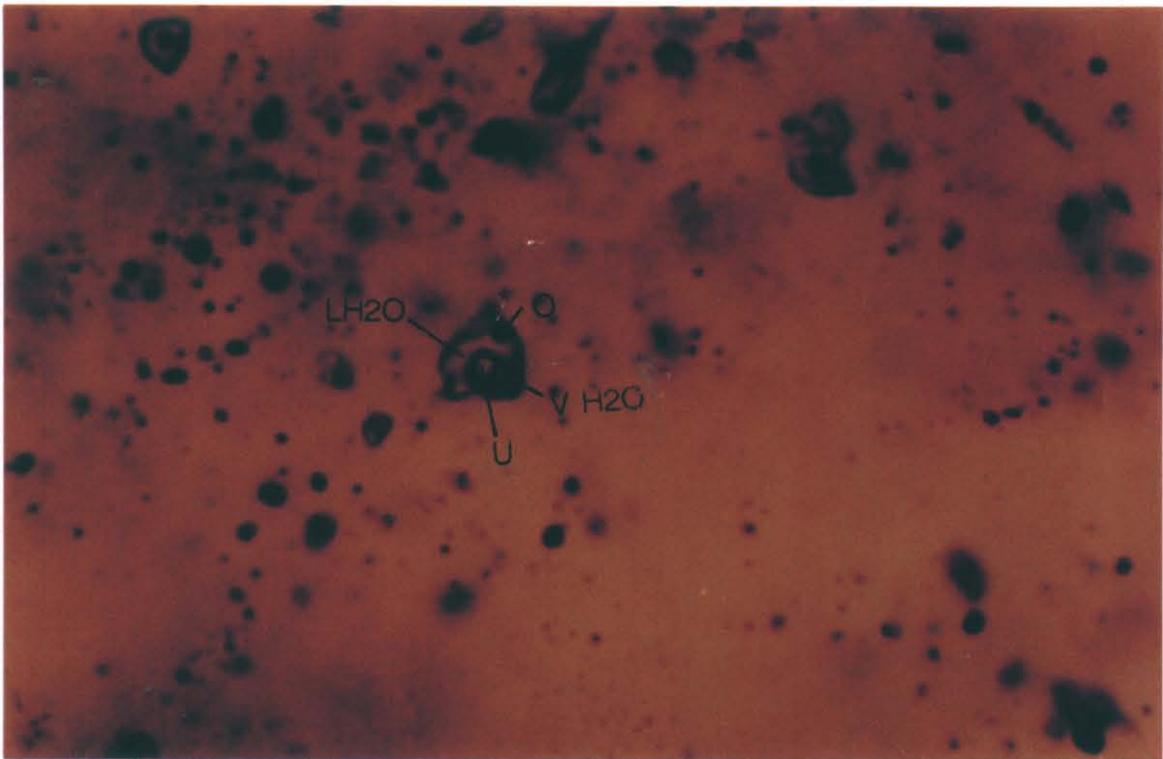

Figure 7
Type D fluid inclusion containing two opaque (O) and
one unknown anisotropic solid inclusions.

|← 5 cm →|

inclusions (fig. 5). They are all anisotropic with the exception of halite and sylvite inclusions. The most abundant solid inclusions include halite, a rounded anisotropic mineral, and an opaque mineral (hematite?).

FLUID INCLUSION HOMOGENISATION TEMPERATURE

Because of insufficient time and the reconnaissance nature of this study, only a very limited number of homogenisation temperature measurements were made on different fluid inclusion types (Table 1). More samples and measurements are essential in order to establish statistically reliable data. In general the fluid inclusion types show a relatively wide range of homogenisation temperatures, and many decrepitated before being homogenised.

Type A-1 fluid inclusions are of a secondary nature and show different homogenisation temperatures. Two sets of secondary fluid inclusions along fractures show homogenisation temperatures of around 150 and 210°C.

Type A-2 fluid inclusions appear to provide relatively consistent homogenisation temperatures ranging from 300 to 380°C, with an average and standard deviation of 323 ± 26°C. It should be mentioned that fluid inclusions of type A-2 were not frozen for CO_2 determinations. Therefore, there is every chance that some of the fluid inclusions were possibly CO_2-bearing inclusions (i.e. Type B-3). The significance of the variations in the homogenisation temperatures will be discussed in the next section. The majority of the inclusions were homogenised to liquid phase with only a few being homogenised to a vapour phase.

Many CO_2-bearing fluid inclusions decrepitated before the final homogenisation temperature. This could be due to high internal pressures during heating and possibly indicates heterogeneous trapping (i.e. trapping more than one phase) at the time of their formation. Only a few homogenisation temperatures were measured and these ranged from 290 to 323°C. However many did not homogenise at temperatures higher than 400°C.

The final homogenisation temperatures (bubble disappearance or halite melting point) for type C inclusions ranged from 155 to 235°C. A halite daughter mineral in one inclusion dissolved at 268°C but the vapour bubble did not homogenise even at 450°C. Two fluid inclusions containing anisotropic minerals homogenised to liquid at 215°C without the solid inclusion being dissolved, even at temperatures greater than 450°C.

Most of the type D fluid inclusions decrepitated upon heating before the dissolution of solid phases. In one fluid inclusion a halite crystal dissolved at about 420°C and the vapour bubble disappeared at 315°C, whereas the total homogenisation temperature (to liquid) for another fluid inclusion was 215°C and the halite crystal dissolved at 171°C. None of the anisotropic solid crystals dissolved or showed any decrease in size upon heating up to 400°C. Fluid inclusions containing CO_2 and a solid phase decrepitated before reaching homogenisation temperatures or complete dissolution of solid phases. This is, however, based on heating of only few fluid inclusions.

DISCUSSION

Despite the lack of sufficient samples, the freezing and heating experiments, the petrography of the fluid inclusions, and the limited microthermometric data appear to provide very important information with regard to the evolution and nature of the ore-forming solution. The fluid inclusions are distinctly characterised by a wide range of homogenisation temperatures, different behaviour upon heating, and different compositions. The wide range of homogenisation temperatures and fluid compositions between and within different fluid inclusions types may have resulted from:–

(a) Necking down;

(b) Crystallisation at high pressure;

(c) Trapping of solid NaCl from saturated fluid;

(d) Mixing of fluids;

(e) Immiscibility of fluids;

(f) Heterogeneous trapping.

Necking down

Necking down of fluid inclusions after trapping can be an important factor in causing a wide range of salinity and homogenisation temperatures and has been described in detail by Ahmad and Rose (1980) and Wilkins and Ewald (1984). Although necking down was common among fluid inclusions, every attempt was made to select only primary-looking fluid inclusions showing no evidence of necking down, and those formed along growth zones. Therefore it is unlikely that necking down was an important factor in creating the wide range of homogenisation temperatures and compositions.

Crystallisation at high pressure

A possible explanation, other than necking down, for halite-bearing fluid inclusions showing homogenisation temperatures less than the melting temperature of halite is that of trapping at high pressures (fig. 8). If a fluid containing say 40 wt% NaCl is trapped at point A and follows the isochore until point B, halite will precipitate as the liquid moves into the 2-phase region (liquid + halite) and then vapour will form on the vapour + halite curve. Based on the few microthermometric data on type C fluid inclusions, there is very little difference between the homogenisation temperatures and halite melting points. This indicates a low trapping pressure, and the inclusions may even have been formed on the immiscibility curve (i.e. may represent a boiling halite-saturated solution).

Trapping of solid NaCl from saturated fluid

The salinity of halite-bearing fluid inclusions may be estimated using the dissolution temperatures of halite (Keevil, 1942; Sterner et al., 1988). Based on data obtained from halite-bearing fluid inclusions, the salinity of fluid inclusions ranges from about 30 to 47 wt% NaCl. Because of insufficient data it is not statistically reliable to draw any conclusions in regard to the saturation of hydrothermal fluid with NaCl prior to trapping. However it is worth mentioning that eight out of nine fluid inclusion compositions plot above the NaCl saturation curve. This may suggest that the hydrothermal fluid was, at least at one
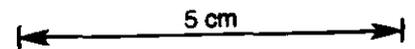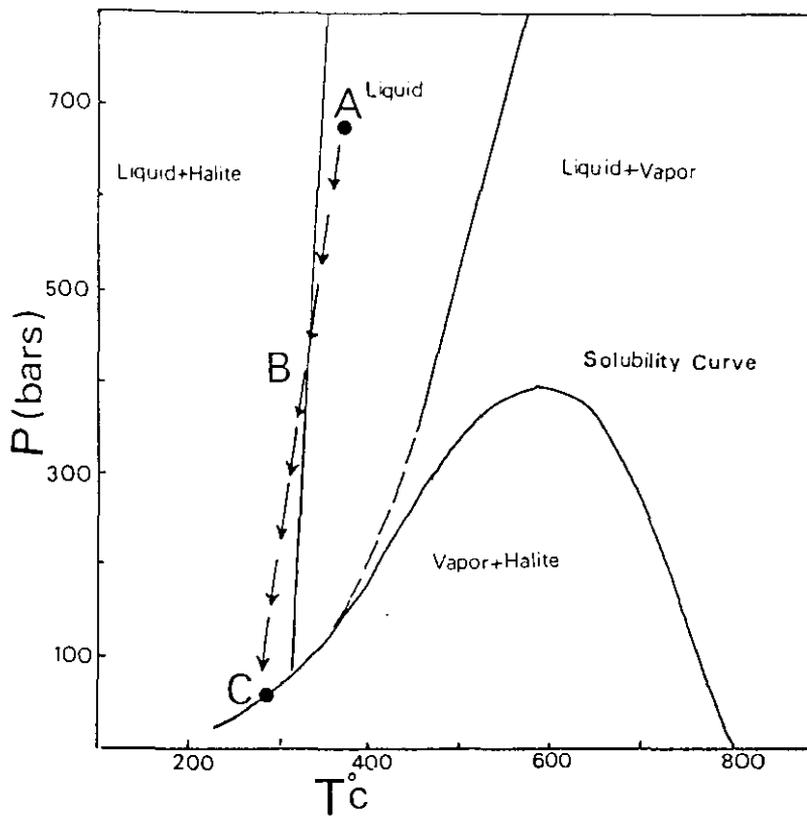
Figure 8

Diagram showing the possible path for inclusions showing $Tm_{NaCl}>Th$. Data from Sourirjan and Kennedy (1962) for $NaCl-H_2O$ system.

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stage, saturated with NaCl prior to trapping. This needs to be substantiated with more detailed studies.

Mixing of fluids

There is insufficient data from the different types of fluid inclusion to discuss the effect of fluid mixing on the observed variations in the fluid inclusion compositions. Heterogeneous trapping and immiscibility (see below) appear to be much more important in forming the wide range of fluid inclusion compositions.

Immiscibility

The complexity of the fluid inclusions and their behaviour upon heating is best explained by fluid immiscibility in the H_2O-CO_2-NaCl system. The criteria used for this interpretation are:-

(a) Co-existence of CO_2-poor and CO_2-rich fluid inclusions in the same field of view without showing any associations with fractures.

(b) Lack of any evidence for necking down processes or leakage.

(c) Variability in vapour-liquid ratios, water-CO_2 ratios, and salinities for co-existing fluid inclusions.

(d) Homogenisation of fluid inclusions to either vapour or liquid phase.

Fluid immiscibility has been considered to be the main control on deposition of many ore deposits in different geological environments (e.g. Eastoe, 1978; Wilson *et al.* 1980; Spooner, 1980; Halley, 1982; Ahmad, 1989; Taheri, 1985). This process appears to have played the main role in precipitating the sulphides in the Anio Creek prospect area, as will be further discussed below.

Heterogeneous trapping

Heterogeneous trapping occurs when two fluids are trapped in the same inclusion. Heterogeneous trapping is very reliable evidence for fluid immiscibility as it indicates that the two fluids were in contact with each other at the time of trapping (fig. 9 and 10). Heterogeneous trapping is clearly indicated in Figure 10, where fluid inclusions of different compositions are closely associated with each other. The relative amount of each phase, or the number of phases in one fluid inclusion, may vary considerably. This will result in scattered densities, homogenisation temperatures and compositions. The homogenisation temperatures will be generally shifted towards higher values and some fluid inclusions may decrepitate before their homogenisation temperatures. Heterogeneous trapping appears to have been an important factor in creating variable compositions and phase ratios, and also in creating different behaviours for the fluid inclusions of the same type upon heating in sample AC12.

It should be emphasised that not all the fluid inclusions have been formed by the process of heterogeneous trapping. For example the majority of the low density fluid inclusions (i.e. vapour-rich) exhibit relatively consistent homogenisation temperatures ($323 \pm 26°C$) and may homogenise to vapour or liquid phase. This is a clear indication of fluid immiscibility (boiling) rather than heterogeneous trapping.

No pressure correction is needed for fluid inclusions showing immiscibility relationships, as both fluids are saturated with respect to each other. Therefore a temperature range of $300°C$ to about $350°C$ may be considered for the formation of the quartz-chlorite-sulphide vein in the Anio Creek area. This is based on the
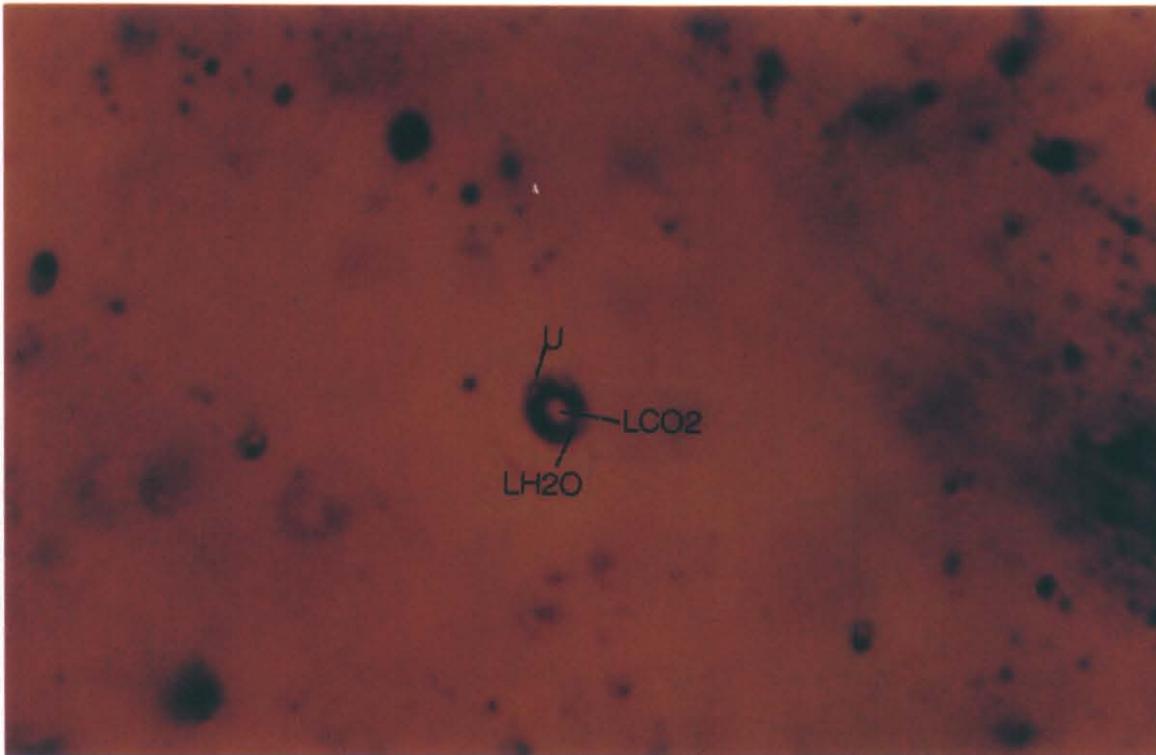
Figure 9
CO_2-rich fluid inclusions containing two anisotropic solid inclusions
(heterogeneous trapping).
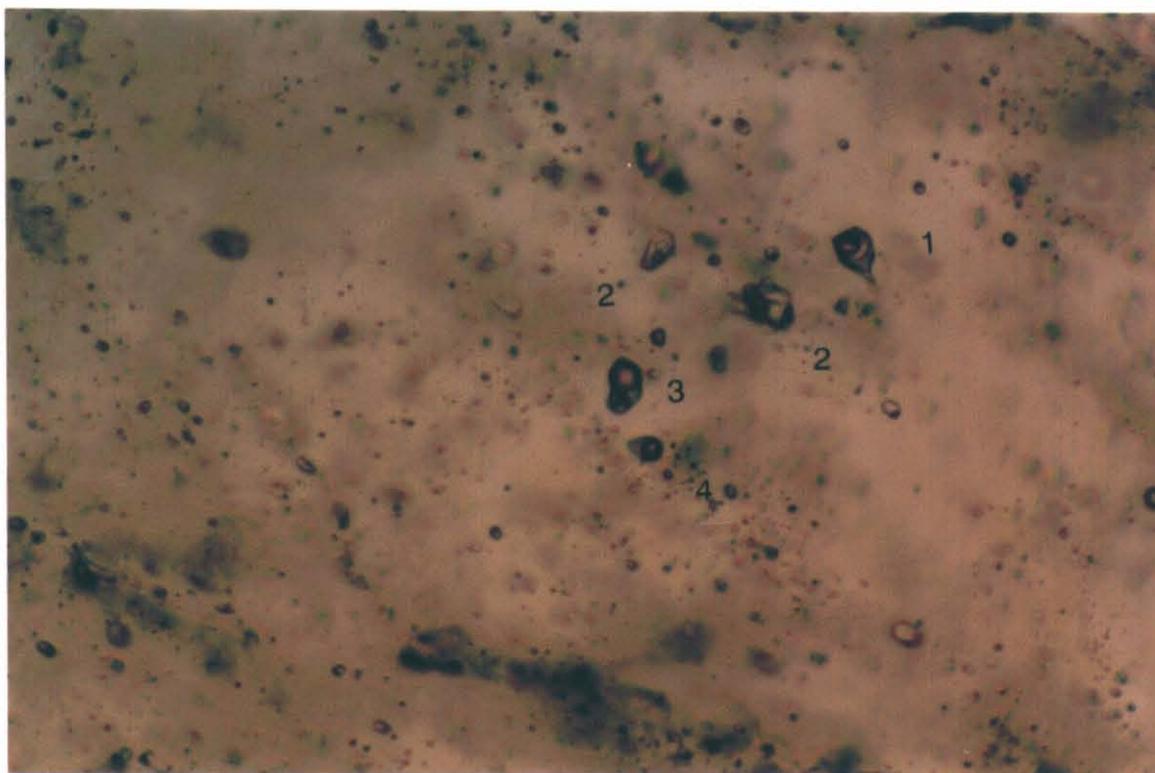
Figure 10
Heterogeneous trapping in type D fluid inclusions. This photo clearly demonstrates the
complex compositions of the fluid inclusions which have undergone different processes of
boiling and heterogeneous trapping. Note that fluid inclusion (1) appears to have suffered
from necking down.

(1) CO_2-rich (type B-2) fluid inclusion.
(2)   Halite-bearing fluid inclusions.
(3) CO_2-rich fluid inclusion + opaque solid inclusion.
(4)   Vapour-rich fluid inclusion (type A-2).

5 cm

assumption that the temperature range has not resulted from a later, post-mineralisation phase separation event. Detailed petrographical and fluid inclusion studies are required to establish the formation temperature of minerals belonging to a particular paragenetic stage.

CONCLUSIONS

It is almost impossible to make a reliable conclusion as to the source and evolution of the hydrothermal fluid based on fluid inclusion petrography and limited microthermometric data of one sample. However this preliminary study has provided some useful information with regard to the possible origin of the fluid and the likely mechanism for the deposition of quartz and sulphide veining at the Anio Creek prospect.

It is suggested that the complexity of fluid inclusions and their behaviour upon heating has resulted from phase separation of a saline fluid and low density vapour phase in a H_2O-CO_2-NaCl system from a magmatic aqueous phase. It is possible that the low density fluid inclusions (types A-2 and B) represent the low density vapour phase. However no saline inclusions with equivalent homogenisation temperatures were observed to coexist with these fluid inclusions to substantiate this hypothesis. This may indicate that low density fluid inclusions have been formed as a result of a later phase separation during the evolution of the hydrothermal fluid. Intermittent changes of pressure from lithostatic to hydrostatic may occur by episodic emission of fluid from a magma.

The relatively low temperature, saline fluid inclusions (type C) may have formed from the condensation of a low density fluid as it rose and cooled, and itself became saturated with NaCl. The low density fluid would have possibly been derived from the separation of an early, higher temperature aqueous phase into brine and a vapour phase. Type C fluid inclusions could have also been formed as a result of mixing of magmatic-dominated fluid with externally-derived saline fluids.

The formation temperature of the mineralisation is estimated to be at least in the range of 300 to 350°C. This temperature range can be a minimum formation temperature because few saline fluid inclusions show filling temperatures of above 400°C. Detailed study of more samples must be undertaken to understand the evolution of the hydrothermal fluid, and to investigate whether the higher homogenisation temperatures are related to other factors, such as heterogeneous trapping, or truly represent a higher temperature of formation.

The occurrence of tourmaline, Mo and pyrrhotite, and of a breccia outcrop characterised by a matrix of fine-grained tourmaline and quartz (Bottrill, 1994) are indicative of granite-related mineralisation in the area. Fluid inclusions derived from a granitic source are also commonly characterised by having a wide range of compositions and homogenisation temperatures, as they have undergone different processes of boiling, heterogeneous trapping and condensation (e.g. Ahmad, 1989; Eadington, 1983; Taheri, 1985). The fluid inclusions in the quartz sample from the Anio Creek area also exhibit similar features to those which are related to the evolution of granitic fluids. Assuming that the mineralisation is related to a granitic body, then the mechanical energy released by the exsolution of the magmatic fluid during the emplacement and crystallisation of the underlying granite would have been sufficient to cause brecciation and the fracturing of the country rocks. A magma with 2.7 wt% H_2O will expand by nearly 50% at a shallow depth of around 2 km (Burnham and Ohmoto, 1980). A sudden drop in pressure from lithostatic to hydrostatic, due to either above mechanism or the movement of fluid along a pre-existing fault or shear zone, caused boiling (as evidenced by fluid inclusions) resulting in lowering the temperature of ore-bearing fluid and precipitation of sulphides along fractures.

Systematic sampling of the area and all the surrounding prospects, together with detailed petrographical, oxygen and sulphur isotope, and fluid inclusion studies are needed in order to test the above genetic model.

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Table 1
Fluid inclusion microthermometry data, sample AC12, Anio Creek Prospect

Fluid inclusion type	Thv (°C)	ThL (°C)	TmH (°C)	ThCO2L (°C)	ThCO2V (°C)	Decrepitation (°C)
A-1		185				
		170				
		190				
A-2 or B-3		312				
		357				
		342				
		340				
		300				
		325				
		302				
		300				
		300				
		315				
		415				
	350					
	292					
	330					
	300					
		366				
		376–384				
	301					
	303					
					421	
					451	
A-2	Vapour bubble started to decrease in volume above 450°C but heating was stopped at 480°C.					
B-2				18		
				17.5		
C*		215				
		215				
C		?	210			
		155	218			
		166	210			
		220	231			
		218	235			
		207	211			
		223	225?			
D		195	162			
		315	420			
	402		275			
		?	178			
	300		?			
		215	171			
D*						300–320

C*   containing anisotropic inclusion
D* CO_2-bearing fluid inclusions with more than one inclusion. Similar results for several inclusions.