PETROLOGY OF THE EARLY FORMED HYDROTHERMAL VEINS WITHIN THE CENTRAL POTASSIC ALTERATION ZONE OF LOS PELAMBRES PORPHYRY COPPER DEPOSIT, CHILE

MILKA ALEXANDRA SKEWES
WILLIAM ATKINSON Jr.

University of Colorado, Department of Geological Sciences
Boulder, Colorado 80309, U.S.A.

ABSTRACT

Alteration and mineralization in the Los Pelambres porphyry copper deposit, located in the Central Andes of Chile, are associated with various types of veins. The earliest formed veins associated with copper mineralization have been termed "Intermediate Potassic" and "Type 4" by local geologists. Intermediate Potassic veins are characterized by a mica-rich central veinlet and a narrow vein halo containing quartz and K-feldspar and are better referred to descriptively as Green Mica Veins. The first micas formed in the central veinlet of Green Mica Veins are biotite with a high TiO_2/Al_2O_3 ratio, similar to magmatic biotites. The coexistence of andalusite, K-feldspar, and sericite, along with quartz, in the central veinlet of some Green Mica Veins indicates that the temperatures at which the materials in the central veinlets of these veins were precipitated may have exceeded 550° C. Type 4 veins are characterized by a narrow quartz and K-feldspar-rich central veinlet surrounded by a wide mica-rich halo containing the assemblage andalusite, K-feldspar, sericite and quartz, indicating temperatures of more than 550° C in the host rock at the times of formation of these vein halos. Both Green Mica and Type 4 veins contain highly saline halite-bearing fluid inclusions as well as halite-free vapor-rich inclusions, indicating boiling of saline magmatic fluids at the time these veins formed, similar to conditions inferred for the early stages of development of other porphyry copper deposits.

Later quartz-molybdenite veins, responsible for molybdenum mineralization, consist of a central fracture filled with quartz and an intermittant halo of K-feldspar or sericite. Fluid inclusions in these veins suggest both boiling of highly saline fluids and the presence of a fluid of lower salinity, perhaps related to the first influx ot meteoric water into the system.

The Los Pelambres porphyry system is typical of many porphyry systems in that the first episodes of alteration and mineralization are related to magmatic fluids, and as the system evolved, meteoric fluids entered the system. In Los Pelambres, it appears that the early high-temperature magmatic fluids initially invaded a cool host, resulting in Green Mica veins with narrow alteration halos. As the host rock became heated, Type 4 veins with wider halos developed. Although the relation between the time of intrusion and crystallization of the host rock at Los Pelambres and the subsequent alteration and mineralization event is uncertain, this conclusion is supported by the similarity of the veins at Los Pelambres with those observed at Butte, Montana, where alteration occurred 10 million years after the intrusion of the host rock, and different from the veins at El Salvador, Chile, where intrusion and alteration of the host rock were nearly contemporaneous processes.

RESUMEN

La alteración y mineralización en el depósito de cobre porfídico Los Pelambres, se encuentra estrechamente ligada a varios tipos de vetillas. Las vetillas mas tempranas asociadas a la mineralización de cobre han sido denominada en trabajos previos como "Vetillas Intermedia Potásica" y "Tipo 4". Las Vetillas Intermedia Potásica poseen una zona central rica en micas y rodeada de un pequeño halo con feldespato potásico y cuarzo. En este trabajo se prefiere describirlas bajo el nombre de Vetillas Micáceas Verdes. Las primeras micas formadas en la zona central de las Vetillas Micáceas Verdes son biotitas con una alta razón de TiO_2/Al_2O_3, similar al de las biotitas magmáticas. La coexistencia de andalucita, feldespato potásico y sericita junto a cuarzo, en esta zona central de las Vetillas Micáceas Verdes, indica que la temperatura bajo la cual se precipitaron estos minerales excedió los 550° C. Las vetas Tipo 4 se caracterizan por poseer una zona central angosta, constituida por cuarzo

Revista Geológica de Chile No. 25-26, p. 39 - 56, 10 figs., 5 tablas, 1985.

y feldespato potásico y bordeado de un ancho halo micáceo, que contiene la asociación andalucita, feldespato patásico, sericita y cuarzo, indicando temperaturas de, por lo menos, 550°C, en la roca de caja al formarse estos halos. Tanto las Vetillas Micáceas Verdes como las Tipo 4 contienen inclusiones fluidas de alta salinidad, con "hijas" de halita que coexisten con inclusiones fluidas ricas en vapor, sin halita, indicativa de fluidos magmáticos en ebullición, a partir de los cuales se precipitaron estas vetillas. Esta situación es similar a la inferida para las etapas iniciales de otros sistemas de cobres porfídicos.

Vetillas posteriores de cuarzo-molibdeno, son responsables de gran parte de las mineralización de molibdeno, y están formadas por una fractura central rellena con cuarzo y bordeda de un halo intermitente de feldespato potásico y/o sericita. Las inclusiones fluidas presentes en estas vetillas sugieren tanto la ebullición de fluidos salinos, como la presencia de fluidos de más baja salinidad, estos últimos, quizás, relacionados con el primer influjo de aguas meteóricas dentro del sistema.

La evolución del yacimiento Los Pelambres es muy similar a la de otros depósitos de cobre porfídico cuyas primeras etapas de alteración y mineralización se encuentran ligadas a la acción de fluidos magmáticos. A medida que el sistema evoluciona, entran en él fluido meteóricos. En Los Pelambres, fluidos magmáticos iniciales de alta temperatura parecen haber invadido rocas de caja frías, produciendo las Vetillas Micáceas Verdes, con halos de alteración muy pequeños. A medida que aumentó la temperatura de la roca de caja, se desarrollaron las vetillas Tipo 4, con anchos halos de alteración. Aun cuando el intervalo de tiempo entre la intrusión y cristalización de la roca de caja y el posterior evento de la alteración y mineralización es desconocido, las vetas de Los Pelambres se pueden comparar con las de Butte, Montana, donde la alteración ocurrió 10 Ma después de la intrusión de la roca de caja. Las vetas de ambos yacimientos son diferentes a las vetas de El Salvador, donde la intrusión y alteración de la roca de caja fueron fenómenos casi contemporáneos.

INTRODUCTION

A ubiquitous feature of porphyry deposits is the presence of veins, which commonly consist of two parts: a central veinlet deposited from hydrothermal solutions circulating through fractures in the host rock, and an alteration halo formed by penetration of fluids from the fractures into the host surrounding the veinlet. The same hydrothermal processes responsible for vein formation also cause alteration and mineralization in porphyry deposits. This is especially clear when vein density is low and fresh unaltered rock may be observed between the veins. When vein density in porphyry deposits is high the direct genetic relations between veins, alteration, and mineralization may be obscured. In this case it is not possible to observe the overlapping alteration halos, and alteration and mineralization associated with veins appears to be pervasive and disseminated through the host rock.

Porphyry deposits are characterized by spatially zoned variations in alteration and mineralization, and associated vein types (Lowell and Gilbert, 1970). Porphyry deposits typically consist of an early-formed central zone of potassic alteration surrounded by a probably contemporaneously developed propylitic alteration zone. The early potassic alteration, which normally occurs near the center of porphyry deposits, is interpreted to have developed at high temperature (Gustafson and Hunt, 1975). The fluids responsible for this alteration are believed to be of magmatic origin. Later sericitic alteration and supergene effects are superimposed on the early-formed potassic and propylitic alteration. Isotopic studies indicate that the fluids responsible for sericitic alteration are low temperature fluids of meteoric origin (Sheppard and Gustafson, 1976). Potassic and sericitic alteration thus represent different stages in the evolution of porphyry deposits, in which the high-temperature post-magmatic hydrothermal conditions which prevail initially are followed by a regime in which low-temperature meteoric water becomes predominant.

Study of the mineral assemblages in veinlets and their associated alteration envelopes, where definable, may provide information concerning the physico-chemical conditions under which the varying alteration and mineralization zones observed in porphyry deposits form. Moreover, because the relative chronology of petrologically different vein types can often be established by crosscutting relationships, veins record information about the complex temporal changes in the physico-chemical conditions that prevailed during the formation of porphyry deposits.

This work presents a petrologic study of early-formed vein types occurring within and near the central zone of the porphyry copper deposit at Los Pelambres, Chile (Fig. 1). The deposit is a

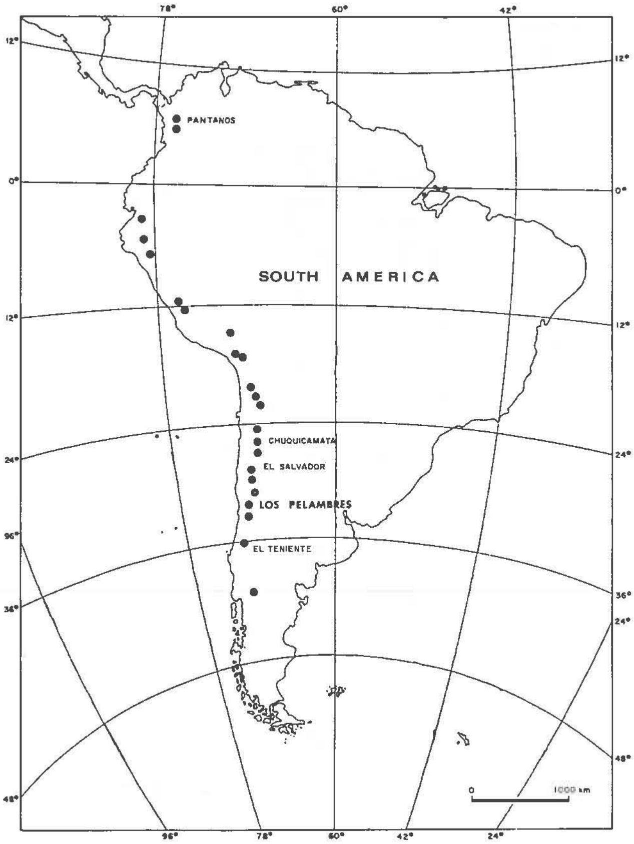

FIG. 1. Location of some of the major porphyry copper deposits of South America.

typical porphyry deposit in the sense that a central zone of potassic alteration is surrounded and partially overprinted by an outer zone of sericitic alteration (Sillitoe, 1973; Atkinson *et al.*, in press). On the other hand, the density of alteration halos in the central zone is lower than in some other deposits. Consequently, fresh rock can be observed between veins; halos surrounding veins can be easily recognized an followed, and superimposition of later veins on early veins is minimal. Furthermore, supergene effects are not developed to a great depth. The Los Pelambres porphyry deposit thus provides a unique opportunity to understand the relations between the formation of alteration and vein systems, particularly with respect to the early high-temperature stages of porphyry development which are often extensively overprinted in other deposits. Moreover, since the highest grades of mineralization at Los Pelambres occur in the center of the deposit in association with early potassic alteration (Sillitoe, 1973), study of vein systems in this part of the deposit should elucidate the genetic relations between veins, alteration, and mineralization.

Three main early-formed vein types, associated with copper and molybdenum mineralization, have been observed in drill cores from the central part of the Los Pelambres deposit (Fig. 3) (Atkinson *et al.*, in press; Skewes, 1984). One of these early vein types consist of a narrow central zone rich in green micas surrounded by a quartz and K-feldspar-rich halo. Previously these have been termed "Intermediate Potassic" type veins (Atkinson, 1981a; Skewes and Atkinson, 1981; Skewes, 1984). Here they will be referred more descriptevely as Green Mica Veins. A second type of vein is characterized by a central zone rich in quartz and K-feldspar, surrounded by a mica-rich halo several times wider than the central part. This vein type, termed Type 4, has been observed both crosscutting and being cut by Green Mica veins, indicating at least two generations of one or the other vein type. The third vein type, descriptively called the Quartz-Molybdenite type, is characterized by a wide central zone rich in quartz and molybdenite that is surrounded either by a K-feldspar or sericitic halo. The Quartz-Molybdenite veins, which are responsible for carrying most of the molybdenum mineralization at Los Pelambres, crosscut the other two vein types. Cutting these three vein types are late-formed sericite-rich veins. The mineral assemblages, textures, and fluid inclusions of the first three vein types, as described in this study, reflect the physico-chemical conditions prevailing during the early stage of development of the central high-grade zone of the Los Pelambres prophyry copper deposit. Early granular quartz veins and brown biotitic veins associated with breccias were identified among the earliest vein types but these veins are not described in this paper.

ALTERATION AND MINERALIZATION

The Los Pelambres porphyry deposit (Fig. 1) is centered on a Tertiary quartz diorite stock which intrudes into a sequence of andesitic lava flows, breccia and tuffs with intercalations of marine limestones of the Neocomian Los Pelambres Formation (Rivano and Sepúlveda, in prep.). The stock in which the Los Pelambres is centered consists principally of quartz diorite and porphyritic quartz

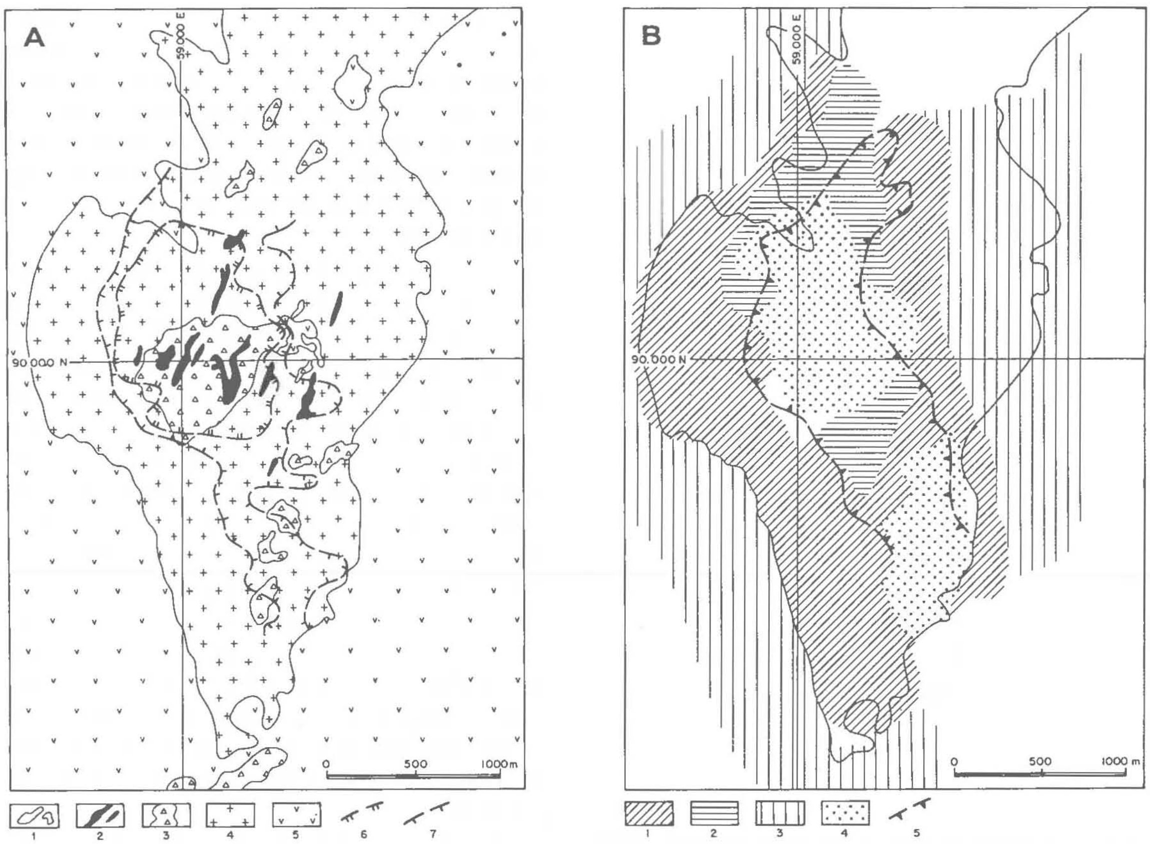

FIG. 2. Maps (Atkinson *et al.*, in press) of the Los Pelambres porphyry copper deposit, located in the Central Andes of Chile, show the igneous rock units (A) and the various alteration zones (B).

diorite with smaller dikes of quartz diorite porphyry (Porphyry A), quartz monzodiorite porphyry (Porphyry B), and quartz monzonite porphyry (Late Porphyry). The quartz diorite has a hypidiomorphic texture, and consists of plagioclase (An_{40-30}), biotite, quartz, K-feldspar, amphibole, and opaque minerals.

At Los Pelambres the central potassic alteration zone is surrounded by an irregular sericitic zone. Enclosing these two alteration zones is a broad propylitic zone (Fig. 2b; Sillitoe, 1973; Atkinson *et al.*, in press). The potassic zone is the zone of greatest economic significance in the deposit, in which the highest values of copper and molybdenum occur (Maranzana, 1972). Mineralogically the potassic zone is characterized by the presence of secondary K-feldspar, biotite, anhydrite, andalusite, chalcopyrite and bornite.

The earliest alteration feature recognized within the potassic zone of Los Pelambres is expressed by pervasive pseudomorphic biotitization of hornblende in the quartz diorite. These shreddy secondary biotite replacing amphibole has on the average slightly higher MgO and lower FeO and TiO_2 than igneous biotites (Fig.4; Skewes, 1985).

Later potassic alteration is mostly fracture and vein controlled at Los Pelambres. This later alteration is restricted to the halos of the veins. As vein density increases in the rock, the alteration effects become more pervasive and the original texture of the igneous rock is destroyed locally. Where vein density is low, the texture of the igneous rock between vein halos is preserved, and the only visible alteration effects not associated with the vein halos is the pseudomorphic replacement of magmatic amphibole by secondary biotite described above.

GREEN MICA VEINS

Green Mica Veins are characterized by a central selvage of micas surrounded by a K-feldspar and

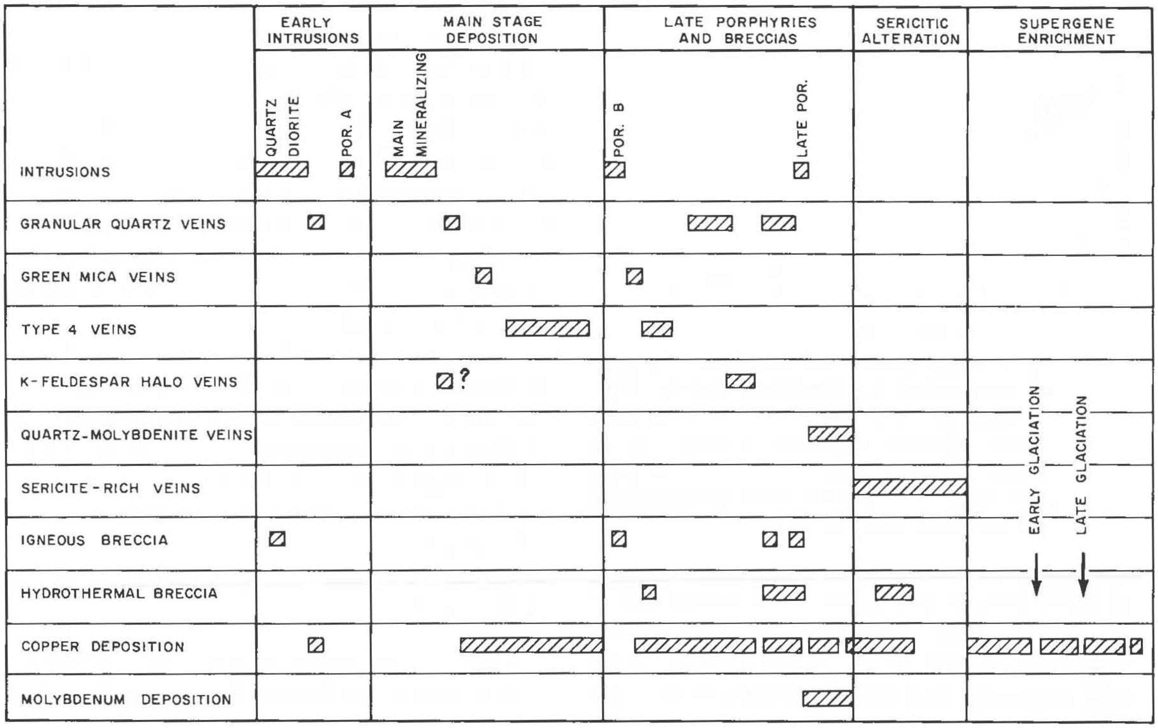

FIG. 3. **Paragenetic relationships between major igneous, mineralization, and alteration events at Los Pelambres (Atkinson *et al.*, in press).**

quartz-rich halo (Fig. 5). Veins of this type were observed not only in the inner central sections of the deposit, but also towards the edges of the potassic zone. Age relations of the Green Mica Veins are not completely clear (Fig. 3; Atkinson *et al.*, in press), but at least two generations of Green Mica Veins may be present. Green Mica Veins are cut by both quartz + pyrite + sericite and quartz-molybdenite veins.

The micaceous central veinlets of these veins are laterally zoned with respect to grain size and mica type (Fig. 6). The center of the vein typically consists of up to 50% of compact aggregates of fine-grained (0.01 mm) whitish or greenish sericitic mica bordered by a coarser (0.04-0.05 mm) green mica, which in turn is bordered by a coarser brown mica. Zoned veins exhibit compositional variations such that the most central olive-green biotite is relatively low in TiO_2 and high in Al_2O_3 while the surrounding brown biotite has somewhat higher TiO_2 and lower Al_2O_3 content, more similar to magmatic biotites (Fig. 4; Skewes, 1985).

The composition of sericite is quite variable in each individual vein, particularly with respect to Al_2O_3, MgO, FeO and even K_2O.

Anhydrite, quartz, K-feldspar, plagioclase, andalusite, corundum, bornite, and chalcopyrite are also present in the central veinlet of some Green Mica Veins. Chalcopyrite and bornite sometimes form a continuous veinlet in the central part of the Green Mica veins. Iron oxides, which are absent in these veins in the central and western parts of the deposit, are abundant in regions referred to as magnetite-rich zones by Sillitoe (1973).

The halos bordering the central veinlet of Green Mica Veins consist principally of quartz and K-feldspar, with smaller amounts of green and brown micas, plagioclase, chalcopyrite, bornite, pyrite, magnetite, titanomagnetite, ilmenite, rutile, and leucoxene. At the edge of central zone of the deposit, secondary K-feldspar in vein halos is commonly altered to sericite in veins in which biotite in the central veinlet is altered to chlorite. Primary magmatic minerals, particularly plagioclase, are replaced in the halo; it is generally altered to K-feldspar or secondary fine-grained biotite. Andalusite, which is locally present in the center of the vein, is only rarely observed in the halos. Although oxides are only rarely present in the central veinlet

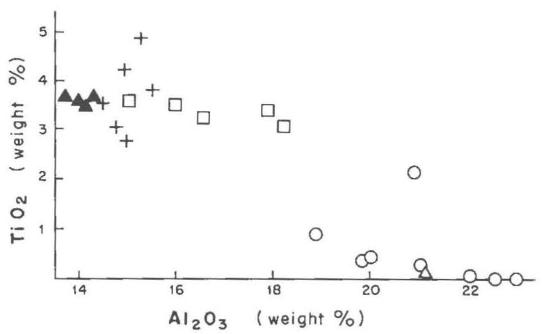

FIG. 4. Plot of weight percent TiO_2 versus Al_2O_3 in different biotites from Los Pelambres (Skewes, 1985), including primary magmatic biotites (crosses); biotite replacing amphibole (squares); brown biotites in Green Mica Veins (solid triangles); green biotites in Green Mica Veins (open triangles); and biotites in Type 4 veins (circles).

of Green Mica Veins located in the central part of the deposit, rutile, leucoxene, and ilmenite are commonly present in the alteration halo, along with magnetite and titanomagnetite. Rutile and leucoxene in the halo are often associated with biotite, usually along cleavage plains. Magnetite particularly is abundant in Sillitoe's (1973) magnetite-rich zones where it constitutes the most abundant opaque mineral.

Fluid inclusions in Green Mica Veins occur in the small quartz crystals in the vein halos but are not very abundant. The quartz crystals in the vein halos in which fluid inclusions do occur are very fine-grained (< 0.2 mm). The size of the inclusions is also small (less than 30μ and generally less than 15μ).

Two types of fluid inclusions are associated with intermediate type veins: halite-free and halite-bearing inclusions. The former are somewhat similar to the "B" fluid inclusions described by Roedder (1971), and Type II described by Nash (1976). Halite-bearing fluid inclusions are similar to Roedder's "A" type inclusions and Nash's halite-bearing inclusions. Both types contain a gas bubble and liquid, and coexist in the same crystal.

Two types of halite-free inclusions were noted. One contains a bubble ranging in size from 30 to 80 volume percent of the inclusion plus liquid, but no daughter of any type. The second type has a bubble ranging from 30 to 50 volume percent and a small opaque crystal (Fig. 7). Halite-bearing inclusions contain gas bubble (10-40 volume %) + halite ± opaque ± sylvite ± anhydrite + liquid.

Homogenization temperatures of fluid inclusions believed to be primary in the sense that they are related to the alteration event that created the halos of Green Mica Veins, range from 357°-378° C for halite-free inclusions and 364°-366°C for halite-bearing inclusions (Table 1). Salinities for halite-free fluid inclusions range from 3.0 to 6.0 weight percent NaCl. Halite-bearing fluid inclusions have higher salinities of around 43 weight percent NaCl (Table 1).

These data indicate that the halite-bearing fluid inclusions probably represent trapped highly saline fluids. Their coexistence with low salinity inclusions which homogenize at very similar temperatures suggests that the saline fluids boiled, with the halite-free fluid inclusions representing trapped vapor phase.

TYPE 4 VEINS

Type 4 veins consist of a quartz + K-feldspar central veinlet, surrounded by an alteration halo

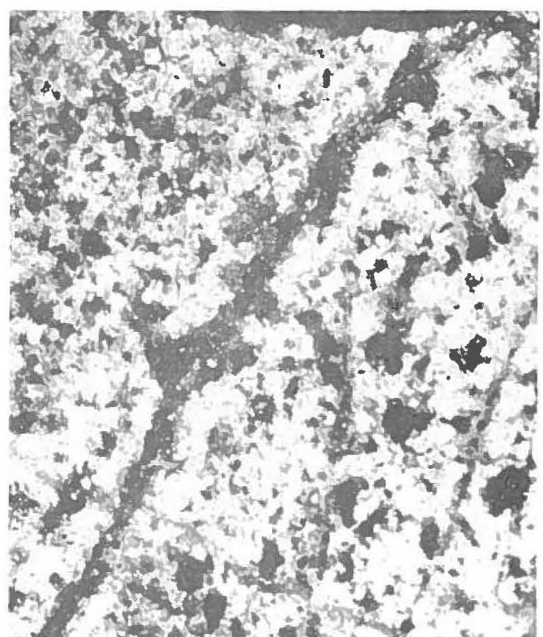

FIG. 5. Green Mica vein with mica-rich veinlet and quartz and K-feldspar halo. The central veinlet is approximately 0.3 cm wide and each side of the halo is almost 1 cm wide.

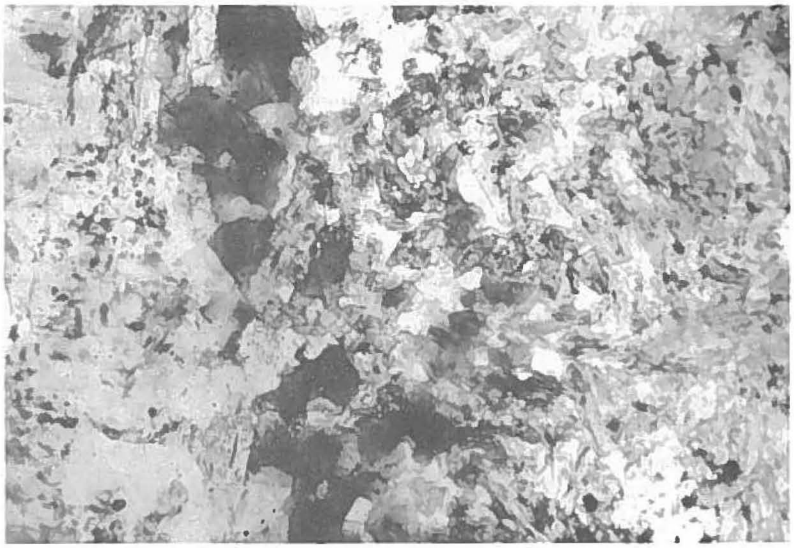

FIG. 6. Microphotograph (x 100) of a Green Mica Vein, with K-feldspar and quartz-rich halo at left, and central mica-rich veinlet at the right. Sericite is concentrated towards the center of the veinlet.

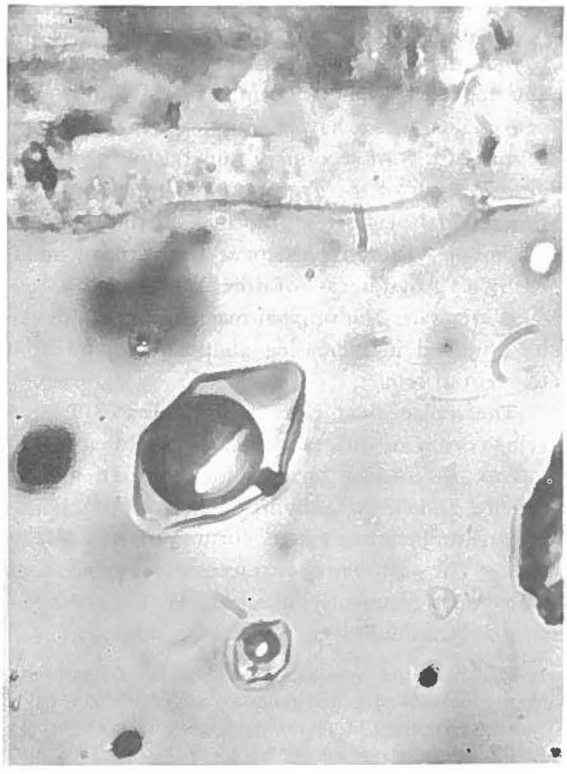

FIG. 7. Microphotograph of a halite-free fluid inclusion in a Green Mica Vein. The fluid inclusion has a gas bubble, liquid, and a cubic opaque mineral that is apparently pyrite.

FIG. 8. Type 4 vein with a quartz-rich central veinlet 1 cm in width and wide mica-rich halo cross-cut by a granular quartz vein. Outside the Type 4 vein halo it is possible to observe the igneous texture of the host rock.

TABLE 1. FLUID INCLUSION DATA FROM GREEN MICA VEINS IN SAMPLE 1–354.55

Phase present	Gas Bubble volume%	Homogenization temperature °C	Salinities Weight % NaCl
Halite-bearing			
Bubble + halite + opaque + liquid	30%	366	43
Bubble + halite + opaque + liquid	40%	364	42.5
Halite-free			
Bubble + opaque + liquid	40%	369	4.2
Bubble + opaque + liquid	30%	368	3.0
Bubble + opaque + liquid	30%	368	3.5
Bubble + opaque + liquid	50%	377	4.5
Bubble + opaque + liquid	50%	374	6

several times wider than the central veinlet (Fig. 8). The halo is dark, fine-grained, mica-rich with complex mineralogy. This vein type is generally straight, segmented only where it is cut by younger veins, and restricted to the intrusive rocks of the central area of the deposit. Spatial variations in the mineralogy of this vein types have been observed, particularly in the chalcopyrite/pyrite ratio, which decreases towards the outer edges of the stock (Atkinson, 1981a) where the abundance of Type 4 veins also decreases.

Both Type 4 and Green Mica Veins are cut by Porphyry B and later generations of each cut porphyry B. It appears that for both pre- and post-porphyry B veins, Green Mica Veins preceded Type 4 veins. Like Green Mica Veins, Type 4 Veins are cut by Quartz-molybdenite veins.

Type 4 veins are coincident with the high-grade copper distribution in Los Pelambres porphyry copper deposit and a plot of copper grade against the density of Type 4 veins halos shows a good correlation between the two (Atkinson, 1981a). Atkinson suggested that this vein type is the most important source of copper mineralization in Los Pelambres.

The central veinlet of Type 4 veins consists of granular subhedral quartz with smaller amounts of K-feldspar, anhydrite, bornite, chalcopyrite, and pyrite. K-feldspar can be up to 70% of the central veinlet in some cases, but usually is less abundant, with quartz being the predominant mineral. Crystals vary in size from 0.25 to 5.0 mm.

The halo bordering the central veinlet is 1.5 to 6.0 times wider than the central vein. Its color is grey with a greasy appearance due to the abundance of micas. The original texture and mineralogy of the host igneous rock has been destroyed and replaced by new assemblages in the Type 4 vein halos, which have a complex mineralogy and texture. Clots of secondary minerals occur together as a result of the alteration and replacement of the original plagioclase, biotite, and biotite after amphibole. These replacement clots are surrounded by a "groundmass" of other fine-grained secondary minerals. The original magmatic minerals can be observed in increasing abundance away from the central veinlet.

The replacement clots in the halos of Type 4 veins consist of different mineral combinations of quartz, K-feldspar, brown biotite, green biotite, sericite, andalusite, anhydrite, chalcopyrite, bornite, rutile, ilmenite, pyrite, corundum, and plagioclase. The different characteristic replacement clots most frequently observed in Type 4 veins consist of the following mineral assemblages:

1. **Brown biotite + andalusite:** This assemblage primarily consists of a fine-grained intergrowth of shreddy brown biotite (0.04 mm). Andalusite occurs as needle-like crystals ranging is size from 0.01 to 0.03 mm. Biotite and andalusite are commonly intimately associated (Fig. 9a). Because of the generally mafic composition of these clots they are interpreted to represent the replacement of altered amphibole.
2. **Green micas ± andalusite ± corundum ± K-feldspar ± anhydrite ± plagioclase ± quartz:** The relative propor-

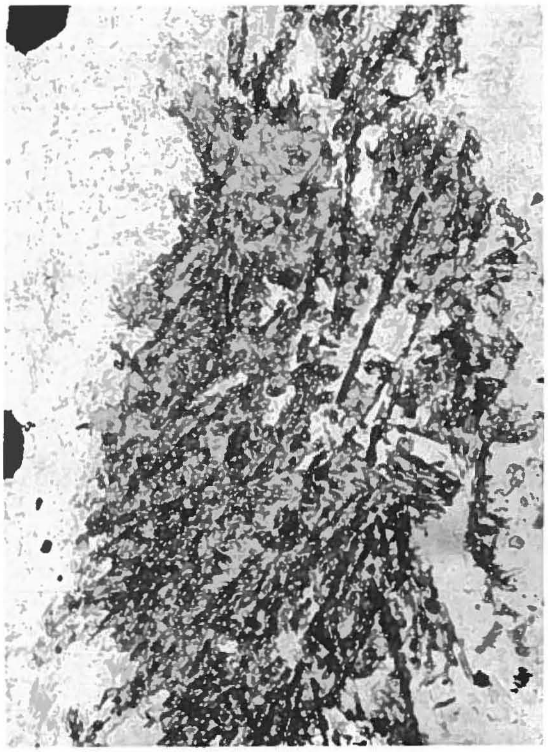

FIG. 9A **Microphotograph (x 100) of a replacement clot,** in the halo of a Type 4 vein, formed mainly by a fine-grained intergrowth of mostly brown biotite (low relief mineral), and andalusite (high relief mineral).

tions of these minerals is variable. Green mica, which is very fine-grained (0.02 to 0.03 mm), may constitute up to 95% of the assemblage locally (Fig. 9b). Albite, where present, borders this mineral assemblage. Andalusite and/or corundum, where present, are disseminated throughout the micaceous mineral assemblage. Anhydrite either border the assemblage or is associated with plagioclase. This type of clot probably represents the replacement of primary magmatic plagioclase.

3. **Brown biotite + andalusite ± plagioclase ± anhydrite ± corundum ± opaques ± K-feldspar ± quartz:** This aggregate generally has a smaller proportion of mica than does the two previously described mineral assemblages (Fig. 9c). Andalusite is present in large amounts, and constitutes as much as 45% of the total assemblage. It is fibrous, and is commonly intimately associated with biotite. Where corundum is present, it is almost invariably associated with anhydrite. This group of minerals also is interpreted to be a replacement of primary magmatic feldspar.

Surrounding the clotted mineral assemblages is the "groundmass" of the halo, consisting of quartz, K-feldspar, andalusite, corundum, disseminated chalcopyrite, and bornite, with minor amounts of pyrite. Biotite is not common in this "groundmass".

Changes in modal abundances of each mineral

FIG. 9B Microphotograph (x 100) of replacement clot, in the halo of a Type 4 vein, formed mainly by green micas with lesser proportions of andalusite and corundum (high relief mineral), and feldspar.

FIG. 9C Microphotograph (x 100) of a replacement clot, in the halo of a Type 4 vein. Andalusite, corundum and feldspar are present along with lesser amounts of brown micas.

were observed from the fresh rock through the halos to the central vein (Skewes, 1984). Plagioclase, which is present only in very small amounts in the halos, increses toward the outer halo edges, where the alteration effects on the rocks are not so strong. Mica which is absent from the central veinlet of Type 4 veins, is abundant in the halos. Both brown biotite and bright green phengitic sericite occur in the halos of Type 4 veins. The most common is a brown biotite. Brown biotite that is clearly the alteration product of amphiboles or biotite, such as in the first type of replacement clot described above, has a TiO_2 content of ~1% weight percent (Fig. 4; Skewes, 1985). When biotite is the alteration product of plagioclase, it has lower TiO_2 content.

Fluid inclusions in Type 4 veins were observed in quartz crystals from the central veinlet. Anhydrite crystals of the central veinlet also contain a small number of very small inclusions. As in the case of Green Mica Veins, two types of fluid inclusion coexist in the central veinlet of Type 4 veins: those that are halite-bearing and those that are not. Halite-bearing inclusions usually contain a gas-bubble (10-40%) + halite ± sylvite ± opaques + liquid (Fig. 10). Halite-free fluid inclusions include two different types, those with gas-bubbles (40-80%) + liquid and those with gas-bubble (40-70) + opaque mineral + liquid. Temperature of bubble dissapearance for halite-bearing fluid inclusions in the central veinlet of Type 4 veins ranged from 260°-352°C (Table 2). In some samples halite in the halite-bearing inclusions homogenize in two different ways: before and after the bubbles dissapears. In one case halite homogenized at 302°C, while the bubble disappeared at 352°C, giving a salinity of 37% NaCl (Table 2). In a different inclusion the bubble disappeared at 350°C while the halite daughter homogenized at 364°C giving a salinity of 42% NaCl. This difference in behavior suggests that solutions both satured and undersaturated with respect to NaCl, were present during the period in which Type 4 veins formed.

The lowest temperature of homogenization obtained for a halite-free inclusion was 365°C (Table 2). These gas-rich inclusions typically showed a wide range of homogenization temperatures and in some the bubble had not dissapeared even at temperatures at 595°C, the upper limit of the heating stage. Salinities for gas-rich inclusions from one sample are of 2 and 3 weight percent NaCl.

TABLE 2. FLUID INCLUSIONS IN TYPE 4 VEINS

	Homogenization Temp. (° C)	Salinities (Weight % NaCl)
Halite-free		
Sample 75-424.1		
B(70%) + liquid	397	
B(50%) + hematite + liquid	420	
B(45%) + liquid	502	
B(60%) + liquid	416	
B(70%) + 2 opaques + liquid	592	
B(60%) + opaque + liquid	595	
B(40%) + opaque + liquid	424	
B(30%) + opaque + liquid	540.5	
Sample 1-381.00		
B(40%) + liquid	365	2
B(45%) + liquid	365	3
B(45%) + opaque + liquid	366	
Sample 69-222.15		
B(70%) + 2 opaques + liquid	514	
Halite-bearing		
Sample 75-424.1		
B(25%) + halite + liquid	315	46
B(25%) + halite + sylvite + liquid	260	
B + halite + liquid	Th = 302	37
	Tb = 352	37
Sample 69-222.15		
B(30%) + halite + opaque + liquid	Th = 364	42
	Tb = 350	
B(25%) + halite + 2 opaques + liquid	282	36

B: bubble with volume % in parenthesis; Th: temperature at which halite disappears; Tb: temperature at which bubbles disappear.

As with Green Mica Veins, inclusions in Type 4 veins were probably formed by boiling of high salinity fluids, as shown by the coexistence of highly saline inclusions with halite daughters and low saline, halite-free inclusions. The wide range in homogenization temperatures in halite-free inclusions, from 365°C to more than 595°C, and the difference in homogenization temperatures of halite bearing and halite-free inclusions could be due to trapping of mixtures of various proportions of liquid and vapor (Roedder, 1967). The halite-free inclusions are very similar to B inclusions described by Roedder (1971), which also shows a wide range of homogenization temperatures.

QUARTZ-MOLYBDENITE VEINS

Quartz-molybdenite Veins are characterized by a wide quartz-rich central vein with comb structure and a narrow K-feldspar or sericitic halo. They are straight, with parallel borders. They cut both Green Mica and Type 4 veins, and are cut by later pyrite-sericite veins. Quartz-molybdenite Veins are the main carriers of molybdenum in Los Pelambres porphyry copper deposit.

The central veinlet of Quartz-molybdenite Veins is formed mostly of euhedral to subeuhedral quartz crystals growing inward from the walls of the veins, producing a comb texture. Subordinate amounts of chalcopyrite, molybdenite, pyrite and anhydrite may occur throughout the central veinlet. Occassionally molybdenite is concentrated along the center line of the quartz-rich central veinlet. In the center of the deposit, chalcopyrite is associated with bornite in the halos of Quartz-molybdenite Veins, whereas towards the edges of the potassic zone, pyrite is commonly associated with chalcopyrite and bornite is absent.

FIG. 10. Microphotograph (x 100) of a halite-bearing fluid inclusion in a Type 4 vein. The inclusion has a small gas-bubble, a halite daughter (cubic transparent mineral), a chalcopyrite daughter (pesudotetrahedral black mineral), and liquid.

TABLE 3. FLUID INCLUSIONS IN A QUARTZ-MOLYBDENITE VEIN, SAMPLE 41-124.30

	Homogenization Temp. (° C)	Salinities (Weight % NaCl)
Halite-free		
Bubble(45%) + opaque + liquid	413 (to vapor)	5.3
Bubble(50%) + opaque + liquid	401 (to vapor)	
Bubble(75%) + opaque + liquid	388 (to vapor)	
Bubble(30%) + opaque + liquid	445	
Bubble(45%) + liquid	452.8	12
Bubble(50%) + liquid	450	11
Bubble(45%) + liquid	453.8	11.8
Halite-bearing		
Bubble(20%) + halite + liquid	438.3	46
Bubble(25%) + halite + liquid	436	46
Bubble(20%) + halite + sylvite + liquid	439.1	46
Bubble(25%) + halite + sylvite + liquid	430	46

The alteration halos of Quartz-molybdenite Veins normally are narrow. They consist of either K-feldspar, or sericite after K-feldspar. Original biotite is completely sericitized within the halo, and a zone of chloritized biotite is common in the transition from the halo to the fresh rock. In the halo, chalcopyrite is often associated with sericite or bornite; molybdenite is absent.

As with the previously described veins, two types of fluid inclusions coexist in Quartz-molybdenite Veins, those that are halite-free (generally more abundant and larger), and those that are halite-bearing.

Halite-free fluid inclusions generally have both a vapor bubble, which can range up to 70% of the total volume, and liquid; some also have an opaque mineral. Homogenization temperatures for the halite-free inclusions range from 388°-454°C (Table 3). The halite-free fluid inclusions respond in two different ways upon heating. One type, which contains a small opaque mineral, homoge-

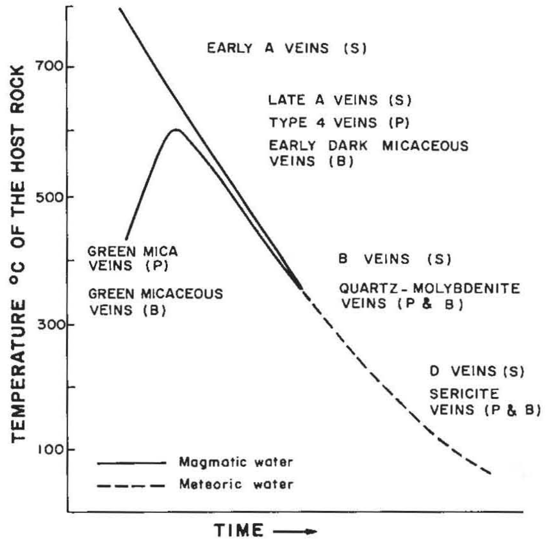

FIG. 11. **Summary of the temperatures evolution during the development of veins at Butte (B) and El Salvador (S), and the temperature evolution inferred by Skewes (1984) for Los Pelambres (P) on the basis of the similarity with Butte and other evidence discussed in the text.**

nizes to vapor at temperatures from 388°-413°C (Table 3). The second type, which contains only a bubble plus liquid, homogenizes to liquid at temperatures from 450°-454° (Table 3), that is, slightly higher than the temperatures obtained for the halite-free inclusions that contain an opaque mineral (Table 3).

Homogenization temperatures for halite-bearing inclusion types ranges from 430°-439° (Table 3) and these inclusions which have salinities of 46 weight percent (Table 3), formed from a saline fluid. On the other hand, the halite-free fluid inclusions with an opaque mineral, those which homogenize to vapor and have a low salinity probably represent the vapor phase resulting from boiling of the saline fluid.

The halite-free fluid inclusions with no opaque minerals homogenize to liquid rather than vapor. These inclusions have low salinities (~ 11 weight percent NaCl) relative to halite-bearing inclusions but not as low as the opaque-bearing halite-free inclusions which condensed from a vapor. These opaque-free, halite-free fluid inclusions might have formed from a low salinity liquid associated with and influx of less saline water into the system. These fluids may have circulated along the still open fractures resulting in the formation of the sericitic alteration of originally K-feldspar-rich halos of Quartz-molybdenite Veins.

DISCUSSION

Veins formed at different stages of development of a porphyry system can be quite distinct both mineralogically and texturally due to differences in the physico-chemical conditions at the time they form. Crosscutting relations of veins give information on the relative ages of different veins, and thus serve as the basis for intepreting the physico-chemical evolution of the porphyry system.

Fracturing of the wall rock is the first step in vein formation. New generations of fractures develop as a porphyry system evolves. These fractures serve as channels for escape of early hydrothermal fluids and later for influx of meteoric water. As they move through the fractures, fluids may penetrate into and react with the wall-rock. The degree to which a hydrothermal fluid can penetrate into and react with the host-rock is a function of the permeability of the host and the temperature of both the hydrothermal fluid and the host-rock. In a cool rock, hot hydrothermal fluids tend to quench within fractures, and deposition of vein material is rapid along the fracture. If the host is warm or hot, the degree of penetration, particularly by diffusion, of material from the fluid to the host-rock increases, and the hydrothermal fluids react with the host-rock surrounding a fracture, forming a vein halo in conjunction with precipitation of a veinlet within the fracture. Precipitation of material within a fracture proceeds inward from the edges in contact with the host-rock. If enough fluids continue to circulate, precipitation will eventually cause the fracture to seal.

Considerable changes in the physico-chemical nature of the porphyry system might possibly occur between the beginning of the formation of a single fracture, the formation of a vein halo around this fracture, and the final formation of the associated central veinlet, resulting in the sealing of the fracture. Many of the veins at Los Pelambres show evidence of internal zonation within both the halo and the central veinlet, indicating variations in fluid composition, or temperature, or both, during the formation of the vein.

Despite the range in physico-chemical conditions that each individual vein may reflect, the three different types of veins termed Green Mica, Type 4, an Quartz-molybdenite, which formed at an early stage of the hydrothermal activity producing the central potassic alteration zone of Los Pelambres porphyry copper deposit, are clearly distinct mineralogically, texturally, and geometrically. Thereby they reflect significant variations in the physico-chemical parameters of the porphyry at the time of development of the different generations of fracture systems within which vein types formed.

Although Green Mica and Type 4 veins at Los Pelambres are very similar to each other in their overall veinlet and halo mineralogy, they are very different in their internal distribution of mineral phases. Green Mica Veins consist of a mica-rich veinlet with a relatively narrow K-feldspar and quartz-rich halo, while Type 4 consist of a quartz-rich central veinlet surrounded by a mica-rich halo several times wider than the central veinlet.

The halite-bearing fluid inclusions in the halos of Green Mica Veins are highly saline. The saline nature of the fluids responsible for the formations of Green Mica Veins suggest that they probably equilibrated with a large reservoir of silicates at near magmatic temperatures as has also been suggested for early fluids in other porphyry systems (Gustafson and Hunt, 1975). The relatively narrow halos of Green Mica Veins suggest that the hot hydrothermal fluids responsible for the formation of these veins did not penetrate very efficiently into the wall rock. Instead, these fluids quenched and biotite precipitated in the fracture. The earliest biotite formed along the margins of the fracture has a low Al_2O_3/TiO_2 ratio, within the range between primary biotites and biotite replacing amphibole in quartz diorite (Fig. 4). The saline fluids from which they precipitated clearly were transporting significant amounts of Al_2O_3, TiO_2, FeO and MgO; consistent with a high temperature, magmatic-related origin. At a later stage in the development of Green Mica Veins, less TiO_2 -and FeO-rich fluids deposited sericite in the central part of the central veinlet, and caused early formed biotite to react to form chlorite plus rutile. Deposition of the assemblage andalusite-K-feldspar-sericite, found in the central part of some Green Mica Veins is indicative of high temperatures (> 550°C; Rose and Burt, 1979) at the time the central veinlet was formed.

The coexistence of both gas-rich and gas-poor inclusions in the halos of Green Mica Veins indicates boiling. Both types of inclusions have homogenization tmperatures of about 360°C. This low temperature is inconsistent with the high temperature implied by the andalusite-K-feldspar-sericite assemblage formed in the central veinliet of Intermediate Potassic Veins. Also, this low temperature implies a low pressure for boiling of a saline system although estimates of pressure of formation from other veins at Los Pelambres is higher and more in line with geological constraints. Thus, the homogenization temperatures determined for fluid inclusions in the halos of Green Mica Veins apparently do not represent the temperature of the hot fluids circulating through the vein, but suggest that these fluids cooled as they penetrated cooler host-rocks.

Hydrothermal fluids continued to move throuhg Los Pelambres system, and as new fractures developed, Type 4 veins were formed. The halos of Type 4 veins are very wide in relation to the central veinlet, indicating that at this stage the hydrothermal fluids were able to penetrate more efficiently into, and react with the host-rock, forming the wide alteration halos around fractures. This is likely to have been the result of an increase in the host-rock temperature. The andalusite-K-feldspar-sericite mineral assemblage of the halos of Type 4 veins indicate that the host-rock within the halo must have been heated up to temperatures above about 550°C (Rose and Burt, 1979).

Fluid inclusions in the central veinlets of Type 4 veins are two types: halite-bearing and halite-free. The gas-poor inclusions in the halo of these veins are very saline, indicating a probable magmatic origin for the hydrothermal fluids forming Type 4 as well as Green Mica Veins. The coexistence of these two types of fluid inclusions indicate that the fluids responsible for them might have been boiling. The temperature of homogenization for these fluids inclusions range from 300°C to more than 600°C. These temperatures and salinities for boiling fluids at Los Pelambres indicate formation at pressures of approximately 2 Kb, similar to estimates made for other porphyry deposits (Roedder, 1971).

After Type 4 veins formed, new fractures developed and the Quartz-molybdenite Veins formed. This vein type is very distinct mineralogically as well as texturally from both early types. The central veinlet consists of mainly subhedral to euhedral quartz crystals, with a comb texture, surrounded intermittently by a sericitic halo, possibly replacing an original K-feldspar halo. In this case, abundant amount of quartz deposited in the fractures, and a small zone of wall-rock was affected first by K-feldspar and later by sericite alteration. The fluids responsible for these veins were not able to diffuse through the wall rock as extensively as during the formation of Type 4 veins.

The hydrothermal fluids responsible for Quartz-molybdenite Veins were circulating at high temperatures, around 450° C, as indicated by the homogenization temperatures of the fluid inclusions present in the quartz within the veinlets. The fluid inclusions present in these veins are both halite-bearing and halite-free inclusions, consistent with continued boiling of the system. However, some of the halite-free inclusions correspond to liquid of low salinity, suggesting the influx of meteoric water at this stage of vein development.

COMPARISON WITH OTHER DEPOSITS

The veins recognized at Los Pelambres have both similarities and differences with veins described from ther porphyry deposits. Two of the best-studied deposits are Butte, Montana and El Salvador, in the Andes of Chile (Table 4).

Butte

Early hydrothermal veins in the Butte porphyry copper deposit were studied by Brimhall (1977). The veins belong to a period of alteration and mineralization called the "pre-Main Stage" which has been determined to have taken place 10 m.y. after the emplacement and crystallization of the Butte quartz-monzonite, which is their host-rock, and 5 m.y. before a later period of alteration and mineralization termed "Main Stage". From oldest to youngest, the hydrothermal veins that Brimhall recognized of the "pre-Main Stage" mineralization event are: 1) narrow brown biotitic veinlets and biotitic breccias; 2) green mica veins with alkali feldspar envelopes; 3) so-called Early Dark Micaceous veins with quartz-rich veinlets and mica-rich halos; and 4) quartz-molybdenite veins with or without alkali feldspar alteration halos.

Biotitic breccias and narrow biotitic veinlets are the earliest "pre Main Stage" structures recognized at Butte. Biotitic veinlets with alkali feldspar and anhydrite are very narrow and often are present as tiny veinlets streaming away from biotitic breccias associated with quartz porphyries intruding the Butte quartz-monzonite host. At Los Pelambres, narrow biotitic veinlets have been observed associated with biotite-rich breccias. Although breccias have not been studied in detail at Los Pelambres, there is some indication, according to Atkinson (1981b) that the breccias are genetically linked to porphyry B, which is an intrusion that is later than much of the veining related to mineralization (Atkinson, 1981a). Spatially, biotite-rich breccias and associated biotite veinlets are coincident with the bornite-rich zone in the potassic alteration zone of Los Pelambres.

Green mica veinlets at Butte, wich occur in the deep exposure of the Cu-Mo dome, are essentially all green biotite surrounded by a quartz and a brown biotite halo which are in turn surrounded by an alkali-feldspar-muscovite alteration halo (Brimhall, 1977). Green Mica Veins at Los Pelambres are very similar in their mineralogy, texture and geometry to the green micaceous veins of Butte (Table 4a). Zonation features observed in green micaceous veins at Butte by Brimhall in individual veins were also observed in veins at Los Pelambres.

The Early Dark Micaceous veins (EDM) of Butte in general contain varying amounts of quartz, anhydrite, alkali feldspar, andalusite, pyrite, chalcopyrite, molybdenite and minor amounts of muscovite and carbonates. They are one of the most complex types of veins, both mineralogically and texturally, described at Butte. Their centers are composed mainly of quartz plus minor alkali feldspar and anhydrite, and are surrounded by a mineralogically complex halo of minerals (Brimhall, 1977). Type 4 veins of Los Pelambres are similar to dark micaceous veins of Butte texturally, mineralogically, in their geometry, and in their relative age (Table 4a). Both vein types, Early Dark Micaceous and Type 4 veins, are characterized by having extensive alteration halos that destroy the texture and replace the mineralogy of the igneous host-rock. Common mineral assemblages in the halos include quartz, biotite, sericite, K-feldspar, anhydrite andalusite, chalcopyrite and pyrite.

At Butte, Brimhall (1977) developed a model of partitioning of alkalies between muscovite and alkali feldspar at quartz saturation, and determin-

TABLE 4A. CORRELATION OF VEIN TYPES AT EL SALVADOR, LOS PELAMBRES AND BUTTE

Veins in:	El Salvador*		Los Pelambres		Butte**
Early	Early A	≠	Green Mica	=	Green Micaceous
	Late A	=	Type 4	=	Early Dark Micaceous
	B	=	Quartz-molybdenite		
Late	D	=	Sericite-rich Veins		

* From Gustafson and Hunt (1975); ** From Brimhall (1977).

ed the temperature of formation of green micaceous veins and Early Dark Micaceous veins to range from 600°-700° C. Phase equilibrium calculations applied to mineral assemblages of the Early Dark Micaceous indicate temperatures of formation near the triple point andalusite-alkali feldspar-muscovite in the presence of quartz (Brimhall, 1977), consistent with the high temperatures obtained from the partitioning of alkalis.

Quartz or Quartz-molybdenite veins with or without alteration halos are the simplest vein type texturally and mineralogically at Butte. They consist mainly of quartz ± molybdenite ± chalcopyrite and small amounts of anhydrite and biotite (Brimhall, 1977). Quatz-molybdenite veins at Los Pelambres are very similar mineralogically, texturally, and in their age relations (Table 4A). At Los Pelambres and at Butte, quartz-molybdenite veins are characterized by their narrow and sometines intermittent sericite alteration halo.

El Salvador

The porphyry copper deposit at El Salvador, Chile, consists of several porphyritic bodies that intruded each other in a time-span less than 1 m.y., producing alteration almost simultaneously with intrusion (Gustafson and Hunt, 1975). Gustafson and Hunt (1975) identify two types of veins associated with the early stages of alteration in the deposit which they called "A" and "B" veins.

"A" type veins are granular assemblages of quartz, perthitic feldspar, anhydrite, chalcopyrite, and bornite. Alteration halos along these veins are practically indistinguishable from the strong background K-silicate alteration with which these veins are associated (Gustafson and Hunt, 1975). Only when these veins cut less pervasively altered rocks it is possible to see the halos, consisting of K-feldspar, anhydrite, chalcopyrite and bornite quartz, biotite, and accessory rulite. Andalusite is also locally present in the halos (Gustafson and Hunt, 1975). Older A veins are typically very irregular, discontinuous and segmented, while younger A veins tend to have more parallel walls and to occupy more continuous and systematically orientated breaks (Gustafson and Hunt, 1975).

The family of late A veins in El Salvador is similar to Type 4 veins at Los Pelambres, and commonly have andalusite, K-feldspar, biotite and sericite in the halos as do the Type 4 veins at Los Pelambres (Table 4a). No unambiguous equivalent of Early A veins has been observed at Los Pelambres. Early granular quartz veins with minor amounts of sulfides, sometimes having very narrow K-feldspar halos surrounding them, have been observed in some areas within the quartz diorite stock, but they are not a very abundant vein type (Fuenzalida, 1981). This granular quartz vein type differs from the Early A veins at El Salvador in many ways: they are usually straight, their borders are sharp, and when they do have small alteration halos these halos are easily distinguishable from the surrounding wall-rock. The granular Quartz veins at Los Pelambres may represent an early stage of vein formation after the intrusion of de quartz diorite stock, unrelated to the potassic alteration which was responsible for most of the copper mineralization at Los Pelambres.

"B" quartz veins in El Salvador are characteristically continuous planar structures with parallel walls and usually some form of internal banding. They are characterized by molybdenite and quartz and the lack of K-feldspar and hydrolitic alteration minerals either in the vein or in the halos. They cut A veins and almost all rock types. They are normally cut be late pyritic veins. B veins in the deep central zone of the deposit tend to contain sulfides different from the background mineralization molybdenite being the most important mineral (Gustafson and Hunt, 1975). Most of the molybdenum mineralization in El Salvador occurs in B type veins. B veins at El Salvador are similar to the Quartz-molybdenum veins at Butte and Los Pelambres (Table 4A).

At El Salvador, Gustafson and Hunt (1975) studied the fluid inclusion of the different vein types, Sheppard and Gustafson (1976) studied the oxygen and hydrogen isotopes of the minerals in the veins, and Field and Gustafson (1976) studied the sulfur isotopes in the different minerals of these veins. These studies determined the physico-chemical conditions prevailing at the time of formation of different vein types. Isotopic as well as fluid inclusion data (Gustafson and Hunt, 1975; Sheppard and Gustafson, 1976) indicate that the solutions responsible for A veins, formed during the early stage of hydrothermal alteration, apparently equilibrated isotopically at magmatic temperatures (450° to 650°C) with a large reservoir of igneous silicates. The isotopic composition of sulfur (1.6 per mil) assumed for the fluids of the early stage of alteration are close to 0. per mil, the value believed to be magmatic.

The $\delta^{18}O$ values of fluids from which B veins were precipitated, shifted toward lighter values in relation to A veins. The same type of fluid inclusions as in A veins are present in B veins, but in B veins, the distribution of these fluid inclusion appears to be zoned. Highly saline and high temperature inclusions ($T_h = 360^\circ$ to 600°C) are abundant near the margins of the veinlets and decrease in abundance toward the veinlet center, where only low temperature (175° to 310°C) and low salinity fluid inclusions are present. Gustafson and Hunt (1975) believed that these late inclusions in B veins represent the first influx of meteoric water into the system.

IMPLICATIONS FOR LOS PELAMBRES

At El Salvador multiple intrusions occurred almost simultaneously with alteration (Table 4b). The first mineralized hydrothermal solutions causing alteration were very hot and of magmatic origin (Fig. 11). These high tmperature hydrothermal fluids escaped the magmatic sources into the still hot host rocks. The irregular shape of the early A veins indicates that fluids may have been introduced before the complete crystallization of the main ingneous complex at temperatures around and possibly above the solidus (Fig. 11). The fluids apparently diffused rapidly into the host rock which shows pervasive alteration, and the halos of the early A veins are not distinguishable within this pervasively altered host. As the system continued to cool, later A veins show more continuity and halos around these veins become more visible. As the system cooled even further; meteoric water entered the fractures, was heated and formed B veins (Fig. 11). In summary, the evolution trend of the fluids in the El Salvador porphyry copper deposit was from near magmatic to meteoric in character (Fig. 11).

The alteration process at Butte involved the introduction of high temperature fluids into a cool quartz monzonite (Fig. 11). These fluids at first formed narrow biotitic veinlets with small halos and green micaceous veins (Table 4a). As more of these high temperature fluids circulated, the wall-rock began to warm up and veins with wide halos

TABLE 4B. COMPARISON OF HOST-ROCK, RELATIVE AGES OF INTRUSION AND ALTERATION, EARLY VEIN TYPES, AT EL SALVADOR, LOS PELAMBRES AND BUTTE

	El Salvador*	Los Pelambres	Butte**
Host Rock	Multiple Intrusives	Quartz-diorite	Quartz-monzonite
Time interval between intrusion and alteration	≈ 0 m.y.	?	≈ 10 m.y.
Early alteration	Early A veins	Breccias (?)	Biotitic breccias

* From Gustafson and Hunt (1975); ** From Brimhall (1977).

and complex mineralogy (Early Dark Micaceous Veins) formed (Table 4b; Fig. 11). As time went by, the fluids and wall-rock cooled, and veins of less complex mineralogy and narrower halos formed (Quartz-molybdenite Veins; Table 4A; Fig. 11).

Vein types and conditions at Los Pelambres appear to have been similar to Butte. Although the relation between the age of intrusion and alteration is not precisely determined for Los Pelambres main stock (Skewes, 1985), the similarity with Butte has been interpreted to suggest (Skewes, 1984) that the hot hydrothermal fluids which produced alteration and mineralization at Los Pelambres may have been intruded into a cool and fractured host-rock (Table 4B; Fig. 11) as also suggested by the narrow alteration halos of Green Mica veins. As the hot hydrothermal fluids continued to invade the host, heat was transferred and diffusion from the fractures into the wall-rock became more efficient and wide high temperature alteration halos formed aroung Type 4 veins (Fig 11). As the system cooled with the first influx of low saline meteoric waters, Quartz-Molybdenite veins formed (Fig. 11).

At Butte and at Los Pelambres, the introduction of hot hydrothermal fluids into a cool host rock produced fractures and vein-controlled mineralization and alteration. Cu-grade estimates at Los Pelambres can be made from the density of the ore-carrying veins. In deposits where alteration is more pervasive, such as at El Salvador, grade estimates have to be made considering the whole volume of rock where the mineralization concentrates.

ACKNOWLEDGMENTS

The authors are in debt to John Drexler, José Luis Fuenzalida, Jim Muñoz, Hernán Sosa and Alvaro Souvirón for their input, to Chuck Stern for critically reading both early and final versions of this manuscript, and to Carmen Holmgren and Fernando Henríquez for constructive reviews. We would also like to thank Cristina Maureira for typing the final version of this paper.

Much of this work represents the results of a Master thesis (by M.A.S.) supported by grants from the late Anaconda Copper Company (R.I.P.), Atlantic Richfield, and the Department of Geological Sciences of the University of Colorado in Boulder.

REFERENCES

ATKINSON, W. W. Jr., 1981a. The current status of knowledge of igneous rocks at Los Pelambres, Chile. Anaconda Copper Co. (Unpubl.).

ATKINSON, W. W. Jr. 1981b. A review of vein types at Los Pelambres, Chile. Anaconda Copper Co. (Unpublished).

ATKINSON, W. W. Jr.; SOUVIRON, A.; VEHRS, T. I. (in press). Geology and mineral zoning of Los Pelambres porphyry copper deposit, Chile. Econ. Geol.

BRIMHALL, G. H. Jr. 1977. Early fracture-controlled disseminated mineralization at Butte, Montana. Econ. Geol., Vol. 72, p. 37-59.

FIELD, C. W.; GUSTAFSON, L. B. 1976. Sulfur isotopes in the porphyry copper deposit at El Salvador, Chile. Econ. Geol., Vol. 71, No. 8, p. 1533-1548.

FUENZALIDA, J. L. 1981. Estudio de vetillas, Proyecto Los Pelambres. Anaconda Copper Co., Los Pelambres (Unpubl.).

GUSTAFSON, L. B.; HUNT, J. P. 1975. The porphyry copper deposit at El Salvador, Chile. Econ. Geol., Vol. 70, No. 5, p. 857-912.

LOWELL, J. D.; GUILBERT, J. M. 1970. Lateral and vertical alteration mineralization zoning in porphyry ore deposits. Econ. Geol., Vol. 65, p. 373-408.

MARANZANA, F. 1972. Application of the talus sampling to geochemical exploration in arid areas: Los Pelambres hydrothermal alteration area, Chile. Inst. Min. Metall., Trans., Sect. B., Vol. 81, No. 1, p. B26-B33.

NASH, J. T. 1976. Fluid-inclusion petrology-data from porphyry copper deposits and applications to exploration. U. S. Geol. Surv., Prof. Pap., No. 907-D, 16 p.

RIVANO, S.; SEPULVEDA, P. (en prep.). Hoja Illapel, Región de Coquimbo. Serv. Nac. Geol. Miner., Carta Geol. Chile, No. 69.

RIVANO, S.; SEPULVEDA, P.; HERVE, M.; PUIG, A., 1985. Geocronología K-Sr de las rocas intrusivas entre los 31°-32° S, latitud sur, Chile. Rev. Geol. Chile, No. 24, p. 63-74.

ROEDDER, E. 1967. Fluid inclusions as sample of ore fluids. *In* Geochemistry of hydrothermal ore deposits (Barnes, H. L.; ed.), 1st edition, Holt, Rinehart and Winston, p. 515-574. New York.

ROEDDER, E. 1971. Fluid inclusions studies on the porphyry-type ore deposits at Bingham, Utah; Butte, Montana; and Climax, Colorado. Econ. Geol., Vol. 66, p. 98-120.

ROSE, A. W.; BURT, D. M. 1979. Hydrothermal alteration. *In* Geochemisty of hydrothermal ore deposits (Barnes, H. L.; ed.), 2nd edition, John Wiley & Sons, p. 173-235, New York.

SHEPPARD, S. M. F.; GUSTAFSON, L. B. 1976. Oxygen and hydrogen isotopes in the porphyry copper deposit at El Salvador, Chile. Econ. Geol., Vol. 71, No. 8, p. 1549-1559.

SILLITOE, R. H. 1973. Geology of Los Pelambres porphyry copper deposits, Chile. Econ. Geol., Vol. 68, p. 1-10.

SKEWES, M. A. 1984. Petrology of the early formed hydrothermal veins within the central potassic alteration zone of Los Pelambres porphyry copper deposit, Chile. M.Sc. Thesis, Univ. Colorado, (Unpubl.) Boulder, Colorado.

SKEWES, M. A. 1985. Biotitas en la zona de alteración potásica del depósito de cobre porfídico Los Pelambres. *In* Congr. Geol. Chileno, No. 4, Actas, Vol. 2, p. 3-341-3-353. Concepción.

SKEWES, M. A.; ATKINSON, W. W. Jr. 1981. Petrographic report on Los Pelambres, Chile. Anaconda Copper Co. (Unpubl.).

Trabajo recibido: 08-01-86; aceptado: 15-04-86