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PORPHYRY COPPER GENESIS AT ELY, NEVADA

by

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ABSTRACT

Porphyry copper deposits near Ely, Nevada are parts of a single large sulfide system fragmented by normal faulting. Restoration of the system allows detailed study of a major porphyry copper deposit over a vertical range of 9000 feet. Five stages of formation are recognized.

1. Emplacement of a quartz monzonite magma to within 6000 feet of the surface. The magma was overheated (900-1000°C), water-undersaturated (1.4 wt%) and crystallized over a 300°C interval with a 10° to 25° C interval of final crystallization. Estimated copper content was 115 to 145 ppm. At the top of the magma column a 1200-foot thick water-saturated silicate melt layer formed, adjacent to which important iron metasomatism produced an anhydrous andradite-pyroxene-magnetite skarn in Ely Limestone. The deeper parts of the magma chamber were surrounded by an isochemical contact metamorphic aureole.

2. A sharp decrease in confining pressure resulted in rapid crystallization of the water-saturated melt layer as early quartz monzonite porphyry with concomitant formation of an extensive zone of potassic alteration. Catastrophic water release produced a zone of stockwork fracturing in early quartz monzonite porphyry and surrounding sediments which facilitated the inward flow of cool meteoric waters, thus cooling the area directly above the magma chamber. A new water saturation surface was established in the magma some 1000 feet below the base of the porphyry.

3. Magma convection caused by steep thermal gradients resulted in the movement of water-undersaturated magma volumes through the saturation surface with attendant release of volatiles, base metals and sulfur. The magmatic hydrothermal fluid was supercritical and contained 4 to 5 weight percent NaCl

equivalent and between 2000 and 4000 parts per million copper. Moving upward, the fluid entered a zone of throttling and was forced to boil. This zone of boiling coincides with a high silica-chalcopyrite zone located directly below the region dominated by meteoric water. Boiling produced a highly saline fluid phase and a low density acid vapor phase which, upon rising, reacted with porphyry and sediments to form quartz-sericite-pyrite and silica-pyrite zones. Moving outward, the now neutralized fluids reacted with porphyry to form argillic assemblages and with limestone to form pyritic marble.

4. Argillization and silica deposition in overlying rocks enabled the water-saturated magma layer to once again build up a fluid overpressure. Pressure release was followed by crystallization of late quartz monzonite porphyry with associated weak alteration, mineralization and stockwork fracturing. Magma convection stopped but upward diffusion of alkalies and volatiles in the crystal-silicate melt column resulted in a zone of potassium enrichment in quartz monzonite located directly below the porphyry phases. Subsequently, the meteoric convection system encroached upon the former zone of boiling, resulting in pervasive argillization of early quartz monzonite porphyry.

5. Following consolidation of the main magma body as quartz monzonite, the meteoric convection system entered the hot stock, resulting in the formation of quartz, zeolite and calcite veins.

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INTRODUCTION

Copper deposits in the Robinson Mining District near Ely, Nevada occur within an east-trending zone 5 miles long (Fig. 1). These deposits are fragments of a large porphyry copper system (James, 1976). Its reconstruction allows us to study a major porphyry copper system and associated stock over a vertical range of 9000 feet (Fig. 2), to determine the relation between magma crystallization, hydrothermal alteration and mineralization, and to establish the relative importance of magmatic and meteoric hydrothermal fluids in the ore-forming process.

Figure 1 near here

Porphyry copper formation at Ely is spatially and genetically related to the emplacement of a composite quartz monzonite stock in a structurally complex anticlinal structure consisting of Paleozoic dolomite, limestone, shale and sandstone. Mid-Tertiary extensional faulting resulted in fragmentation of the sulfide system.

Figure 2 near here

Alteration and mineralization patterns in the restored system are shown in Figures 3, 4 and 5. Zoning is well-developed and conforms to the generalized model proposed by Lowell and Guilbert (1970). A close spatial relation exists between the development of an aphanitic porphyritic texture (Fig. 6) and alteration and mineralization (Figs. 3, 4 and 5). The continuity of stratigraphic boundaries, pre-mineral structures, and alteration and metal zoning in the restored system strongly support the validity of the reconstruction.

Figures 3, 4 and 5 near here

Alteration paragenesis and distribution patterns, metal distribution patterns, fluid inclusion characteristics and oxygen and hydrogen isotope data are best explained in terms of a multiphase magmatic-hydrothermal mineralization model significantly different from models proposed previously (Burnham, 1967; Nielsen, 1968; Sheppard et al., 1971; White et al., 1971; Norton, 1972; Phillips, 1973; Whitney, 1975; Cathles, 1977, and Henley and McNabb, 1978). Two major phases are recognized, (1) a magmatic phase including emplacement, partial magma crystallization and the formation of a contact metamorphic aureole, and (2) a hydrothermal phase consisting of subsolidus hydrothermal alteration and mineralization.

THE MAGMATIC PHASE

The quartz monzonite magma intruded into a steeply dipping shale sequence and formed a near-vertical tabular body 3000 feet wide and in excess of 10,000 feet long. Some magma penetrated into the flat-dipping overlying calcareous sediments. Most likely, the melt was emplaced rapidly under isothermal conditions (Whitney, 1972). The roof over the stock was approximately 5000 feet thick, corresponding to 410 bar lithostatic or 150 bar hydrostatic pressure. The multiple intrusive event took place in Early Cretaceous time within a period of 5 to 7 million years (McDowell and Kulp, 1967). Hydrothermal events probably came to an end within the first one to two million years of this period.

The bulk of the magma crystallized as equigranular Weary Flat quartz monzonite. In the upper parts of the pluton and along its contacts with sediments, this quartz monzonite grades in a granitoid porphyritic quartz monzonite characterized by large late magmatic K-feldspar crystals. This porphyritic quartz monzonite has a gradational contact zone 35 feet wide with the overlying quartz monzonite porphyry with aphanitic groundmass (Kreis, 1973).

Figure 6 near here

Two porphyry phases have been recognized, an early quartz monzonite porphyry which represents the main mineralized porphyry phase and occupies the top of the pluton, and a late quartz monzonite porphyry which intrudes and grades into the early porphyry (Fig. 6). Both porphyries are characterized by an aphanitic groundmass and the presence of biotite phenocrysts. The early porphyry phase forms an irregular east-west elongated body some 12,000 feet long, and about 1,500 feet wide in the central and eastern part of the district. Early porphyry is always intensely altered and makes up approximately 80 percent of the hypogene ore in the district. Post-mineral hornblende granodiorite porphyry dikes and sills intruded the eastern part of the district.

Magma Crystallization

The medium to coarse crystalline hypidiomorphic Weary Flat quartz monzonite consists of andesine, hornblende, quartz, K-feldspar and minor augite. Biotite first appears as a late magmatic mineral 11,000 feet below the restored surface, i.e., at lithostatic pressures in excess of 900 bar. Magnetite, sphene and apatite are common accessory minerals. The distribution of various magmatic minerals is shown in Figure 7, and the crystallization sequence based on thin section studies is shown in Figure 8.

Figure 7 near here

Crystallization of the quartz monzonite magma at Ely was characterized by two crystal fractions separated by a significant temperature interval with little or no crystallization. The early crystal fraction consisting of andesine, hornblende, augite, magnetite and sphene forms 40 to 50% of the rock and crystallized above 900°C (Robertson and Wyllie, 1971). The silicate melt in equilibrium with these crystals had a granitic composition and contained most of the initial water content of the magma. This interstitial melt had a crystallization interval of only 10 to 25°C (Robertson and Wyllie, 1971) and solidified as quartz, K-feldspar and albitic plagioclase near 750°C.

Figure 8 and 9 near here

The presence of andesine as liquidus mineral indicates that the intruding magma contained less than 2% water (Eggler, 1972) a conclusion supported by the presence of small amounts of unaltered augite in deeper parts of the stock and the lack of biotite. Quartz was the last magmatic mineral to crystallize and it contains minute low salinity fluid inclusions, implying that by the time quartz crystallized the interstitial silicate melt had become water-saturated. The maximum initial water content of the magma can be estimated provided the residual melt approaches the minimum melt composition in the albite-orthoclase-quartz-H_2O system (Tuttle and Bowen, 1958). The modal quartz content was used to calculate the residual granitic melt volume and its water content at the appropriate lithostatic pressure. Maximum initial water content of the magma thus calculated averages 1.4 weight percent, of which 1.2% was expelled during final crystallization. The water content throughout the magma chamber is quite uniform with a slight increase in initial water content at the top of the magma column. Due to lower confining pressure, the interstitial silicate melt in the upper part of the stock must have been close to water saturation. Water distribution within the magma chamber closely resembled the pattern proposed by Whitney (1975) and the bulk of the magma chamber was water-undersaturated until final consolidation took place.

Contact Metamorphism

At deep levels in the system adjacent to Weary Flat quartz monzonite, a poorly developed narrow contact metamorphic aureole exists in shale, limestone and dolomite. The lack of calcsilicate formation in dolomite and the presence of andalusite, cordierite and graphitic material in hornfels point at a relatively dry condition of formation. This conclusion is supported by carbon and oxygen isotope data (Sheppard et al., 1971) of marble, which show that no significant isotope exchange took place with a magmatic hydrothermal fluid in this part of the system.

Metamorphic mineral assemblages indicate a contact temperature of 570°C decreasing to 300°C, 1500 feet from the contact. These flat temperature gradients suggest conduction as chief means of heat transport (Jaeger, 1959) with little involvement of meteoric or connate waters this deep in the system. The formation of hornfels and marble must have greatly reduced the permeability and porosity in the contact aureole, with a concomitant decrease in water content, thus effectively insulating the magma chamber.

Under the prevailing lithostatic pressure and water content in the magma, a 1200-foot thick zone at the top of the magma column consisted of a water-saturated melt-crystal mush at near solidus temperature. Within this saturated domain upward and outward diffusion of alkalies, silica and iron must have been important (Jahns and Burnham, 1969; Martin and Piwinskii, 1969) as shown by the presence of large masses of iron-rich contact metasomatic andradite-diopside-magnetite skarn in Ely Limestone adjacent to water-saturated quartz monzonite melt (Fig. 10).

Figure 10 near here

Magma Characteristics

Three characteristics common to quartz monzonite and granodiorite magmas are important in the subsequent development of the porphyry copper system (Figs. 8 and 9; Robertson and Wyllie, 1971):

1. A crystallization interval of 150 to 300°C with two distinct crystal fractions, (a) andesine, magnetite, clinopyroxene and hornblende, which are largely crystalline at 900°C, and (b) K-feldspar, albite and quartz which crystallize near 750°C.

2. The ability to remain 50 to 60% liquid while cooling as much as 200°C. The excess heat content of the melt will prove extremely important during later stages of the systems development.

3. A narrow interval of final crystallization (10-25°C) which forces a melt at near-solidus temperatures to crystallize instantaneously in response to pressure reduction, which in turn results in "catastrophic" water release and formation of a zone of stockwork fracturing.

THE HYDROTHERMAL PHASE

Stockwork Formation

At prevailing confining pressures and water content in the magma, melt in the upper 1200 feet of the magma column became water-saturated and magma temperature in this zone approached that of the quartz monzonite solidus (750°C). Continued cooling and crystallization caused the magmatic fluid pressure to exceed lithostatic pressure. Due to this pressure increase or in response to regional tectonic stresses, the roof of the magma chamber failed, and confining pressure changed from lithostatic to approximately hydrostatic. The water-saturated cap,and that part of the undersaturated melt that did not contain sufficient excess heat,crystallized instantly as a quartz monzonite porphyry with an aplitic aphanitic groundmass. Water contained in the melt was released in the process. The sharp lower boundary of quartz monzonite porphyry with an aphanitic groundmass occurs somewhat below the original water saturation surface in the magma chamber. Following crystallization of the early quartz monzonite porphyry, a new water saturation surface was established within the magma chamber less than 1000 feet below the base of the consolidated early porphyry, its position determined by the reduced confining pressure (Fig. 11). The deeper water-undersaturated part of the magma body was little affected by the pressure drop.

Figure 11 near here

An estimated one billion tons of early porphyry crystallized, expelling 15 million tons of water "vapor" in an area of 12,000 by 1,500 feet. Due to the relatively low permeability of the country rock, the resulting magmatic fluid overpressure was high enough to cause rock failure. A zone of stockwork fracturing developed in the upper part of the porphyry and in the contact aureole including the skarn envelope (Fig. 11).

Initially, the high magmatic fluid pressure kept the newly formed plumbing system open and the hot magmatic volatiles helped to disperse very significant amounts of latent heat of crystallization. A zone of biotite-orthoclase alteration formed that was far more extensive than its present size indicates. Remnant hydrothermal biotite crystals are present well within the quartz sericite zone.

With continued cooling and decreasing magmatic fluid overpressure, the intensely fractured rock volume overlying the magma chamber formed a zone of relatively low pressure and high permeability, and an inward and upward flowing meteoric hydrothermal convection system was set up above the top of the magma chamber (Fig. 12).

Figure 12 near here

Magma Convection

Deep within the magma chamber, the overheated water-undersaturated magma was insulated from cooler country rock by the hornfels contact aureole and conductive heat loss was low. Magma temperatures probably ranged from 900° to 950°C. The inflowing meteoric fluids at the fractured top of the chamber lowered the temperature in the roof to between 500° and 600°C. Thus, steep thermal gradients were likely to exist in the upper part of the magma chamber. At the prevailing temperature differential, magma viscosity, magma volume and chamber geometry, thermally driven magma convection was inevitable (Shaw, 1965; Bartlett, 1969).

Thermally-driven magma convection forced water undersaturated silicate melt through the newly established water saturation surface causing the melt to release part of its excess heat and volatiles. The cooler, heavier crystal-liquid mush sank back into the magma along the steeply dipping walls of the chamber.

The uniform nature of the Weary Flat quartz monzonite with respect to mineralogy, crystal size and crystallization history over a 5000 foot vertical range, is readily explained by magma convection which should result in complete redistribution of suspended crystals in the magma and in crystallization of an undifferentiated pluton (Bartlett, 1969). Magma convection is supported by the presence of flow lineations that dip 30° to 45° and parallel the chamber walls deep in the chamber. Near the top of the chamber, below the porphyry, the lineations steepen to 50-60°. According to Kreis (1973), the alignment of K-feldspar crystals within textural units of the

Weary Flat quartz monzonite suggests that the final stage of consolidation for all units coincided with the close of intrusive activity. Due to cooling and crystallization, convection came to a halt after a viscosity limit was reached,and additional magmatic hydrothermal fluids released during continued crystallization were trapped in the crystal mush.

The importance of the water-undersaturated nature of the magma, its large amount of available excess heat and its wide crystallization interval are readily apparent. Only water-undersaturated magma will be able to convect and maintain convection over a long period of time, as a result of which, a very large magma volume contributes volatiles, base metals and sulfur to the hydrothermal system above. Magma convection also adds significant amounts of heat to the upper part of the chamber allowing the magma to remain partly molten, thus prolonging mineralization and alteration processes and convective meteoric fluid flow over the top of the chamber.

Nature of the Magmatic Hydrothermal Fluid

Magma passing upward through the water saturation surface exsolves an aqueous vapor phase enriched in chlorine (Burnham, 1967; Kilinc and Burnham, 1971; Holland, 1972). Base metals will be fractionated into the vapor phase and fractionation is especially effective if the melt has a low initial water content (Holland, 1972). Metal-chlorine complexes probably are most important in transport and deposition of ore-forming metals (Helgeson, 1964). Copper concentrations in the magmatic hydrothermal fluid probably exceeded 2000 ppm (Rose, 1970) and sulfur concentrations may have been as high or higher.

Fluid inclusions in late magmatic quartz of the Weary Flat quartz monzonite do not contain daughter minerals, indicating that the expelled aqueous phase was supercritical at magmatic temperatures. Using known chlorine contents in the quartz monzonite (Bauer et al., 1966), the calculated initial water content of the magma and the fractionation coefficient of chlorine between silicate melt and vapor at 500 and 1000 bar confining pressure (Kilinc and Burnham, 1971), a salinity of the magmatic aqueous phase of 4 to 5 weight percent NaCl is arrived at. The magma did not release a highly saline brine!

Formation of the Copper Ore Shell

The porphyry system at Ely contains a well-defined copper ore shell, the upper part of which is rich in silica. Chalcopyrite is the hypogene copper sulfide. Quartz veins within the ore shell contain highly saline and low density vapor-rich fluid inclusions both in early porphyry and in quartz of the clay-sulfide stage of skarn formation (James, 1976; Chi I Huang, 1976). Evidence of boiling has been observed. The ore zone occurs at or near the interface of the domain with predominantly magmatic hydrothermal fluids and an overlying meteoric convection system.

Copper deposition may have taken place in response to a decrease in temperature, an increase in pH in the fluid during wall rock alteration, and due to boiling of the supercritical magmatic hydrothermal fluid under 150 to 200 bar hydrostatic pressure. Boiling resulted in formation of a highly saline fluid and a low density vapor phase enriched in H_2S. The zone of boiling probably was overlain by a vapor dominated reservoir (White et al., 1971; Cathles, 1977) which was cooled by inward flowing meteoric hydrothermal fluids.

The vertical extent of boiling will influence the thickness of the zone of copper mineralization. The duration of boiling (i.e. the amount of available excess heat in the magma chamber), and the initial copper content of the boiling fluid determine the grade. As a consequence, the highest hypogene copper grades should be associated with highly saline fluid inclusions. The size and shape of the copper ore shell depend on the size and shape of the heat source, its depth of emplacement, the isotherm and isobar configurations surrounding the magma chamber, and the permeabilities and reactivity of the wall rocks. The inverted cup-shape of many porphyry copper ore shells (James, 1971), reflects the shape of the water saturation surface in a cylindrical stock (Whitney, 1975).

Cooling of Magmatic Hydrothermal Fluids

Magmatic hydrothermal fluids were expelled from the magma at a lithostatic pressure of 550 bar and at a temperature of 750°C. Directly below the zone of stockwork fracturing, a zone of throttling probably existed in which the pressure was reduced to 150-200 bar over a vertical distance of 500 feet. Irreversible adiabatic expansion of the supercritical aqueous phase may have decreased the temperature to 400-450°C (Toulmin and Clark, 1967). Additional cooling probably took place by means of inflowing cooler meteoric hydrothermal fluids (Rose, 1970). Formation of a vapor-dominated system during early stages of the hydrothermal phase (Cathles, 1977) may have been the most effective means of transporting large quantities of heat with the land surface acting as ultimate heat sink (White et al., 1971).

The Importance of Meteoric Hydrothermal Fluids

Convecting meteoric hydrothermal fluids reacting with hot rock are theoretically able to form the alteration assemblages observed in porphyry copper deposits (Norton, 1972). However, Cathles (1977) pointed out the difficulty of forming a porphyry copper ore shell of limited vertical extent by copper deposition from convecting meteoric hydrothermal fluids in response to a decrease in temperature along the flow path. Besides, this porphyry copper formation model finds little support in the oxygen and hydrogen isotope compositions of hydrothermal biotite which indicate the preponderance of magmatic hydrothermal fluids during potassic alteration and copper deposition in most porphyry copper systems (Sheppard et al., 1971). Sulfur isotope compositions of sulfides found in porphyry copper deposits and peripheral base metal mineralization strongly suggest a deep crustal or mantle source of sulfur regardless of the nature and origin of the intruded rocks.

In the porphyry copper model proposed by Norton (1972), copper is derived from the wall rock and crystallized magma by leaching and re-deposited in the ore zone. Experimental data on hot water/rock interactions (Ellis and Mahon, 1964; 1967) and compositions of predominantly meteoric waters in geothermal systems (Ellis, 1967) indicate that base metal leaching is most effective at temperatures above 400°C, largely as a consequence of the increase in chlorine concentration. Copper concentrations in geothermal waters range from 0.08 ppm at Wairakei to 6 ppm in the Salton Sea system (Ellis, 1967), values well below the minimum concentration required to produce economically interesting metal concentrations (Barnes and Czamanske, 1967). Heated meteoric waters are capable of transporting significant concentrations of lead, zinc, silver, silica and H_2S.

Metamorphic mineral assemblages in the aureole around the Weary Flat stock at Ely indicate that the temperature did not exceed 400°C 600 feet from the contact (Chi I Huang, 1976). This severely limits the rock volume that could have been leached of copper and produced meteoric fluids with copper concentrations above one part per million. Background copper values of wall rock in the contact zone range from 6 to 11 ppm in limestone and from 15 to 50 ppm in shale (Nielsen, 1969). Regional geochemical surveys did not document a zone of copper depletion around the system; on the contrary, sediments within 1000 feet of the stock showed significant gains in copper content. It follows that copper must have been added by outward flowing magmatic hydrothermal fluids. However, remobilization of lead, zinc, silver and manganese by hot, moderately saline meteoric fluids could be locally important and may explain the formation of base metal halos well above the ore zone (Corn, 1975) and peripheral to copper-rich centers.

With the emplacement of the heat source at Ely, a meteoric convection system was set up above and adjacent to the top of the magma chamber (Cathles, 1977), even before significant volumes of magmatic hydrothermal fluids were released. Following formation of the zone of stockwork fracturing, meteoric fluid flow became important. These cooler fluids mixed with magmatic waters in the fracture zone and as a result, a quartz-sericite-pyrite zone was overprinted on part of the earlier potassic zone. Steep thermal gradients at the interface of meteoric fluid-dominated and magmatic fluid-dominated areas resulted in the formation of a zone high in silica and chalcopyrite at the top of the ore zone. Isotope data suggest that meteoric fluids predominated during copper deposition in this zone of mixing (Sheppard et al., 1971).

With continued cooling and crystallization in the magma chamber, the magmatic fluid flow rate diminished and the meteoric hot water system encroached upon the zone of potassic alteration. This resulted in superposition of a zone of pervasive argillization on the potassic zone. Isotope data confirm the dominantly meteoric nature of waters responsible for the formation of these clays (Sheppard et al., 1969).

Meteoric waters seemed of little significance in transporting and depositing chalcopyrite in the Ely system, but indirectly influenced the position and grade of the ore zone by cooling the top of the chamber, thus maintaining thermally-driven magma convection and indirectly the magmatic volatile and base metal supply.

Estimates of Magma Volume and Fluid Flow Rates

As demonstrated above, copper must have been largely of magmatic origin in the Ely porphyry copper system. Copper inventory in the restored system is estimated at 6 million tons present as chalcopyrite in early quartz monzonite porphyry and surrounding sediments. The early porphyry mass and the magmatic water volume released from this mass during crystallization are insufficient to have provided this amount of copper and the porphyry merely acted as receptacle for copper transported upward from the convecting magma body.

Assuming a copper concentration in the magmatic hydrothermal fluid of 2000 ppm (Rose, 1970) and an initial water content of the magma of 1.5 weight percent, three billion tons of water had to be expelled from 74 km^3 of magma depleting it by 30 ppm copper. Magmatic fluids released from the magma had to pass through a zone 1,500 by 600 meters at the top of the chamber. Assuming a copper concentration of 4000 ppm, the total magmatic fluid flow over the life of the system was 167 kg/cm^2 derived from 37 km^3 of magma that was depleted of 60 ppm of its copper content. The life span of ore-forming hydrothermal systems could range from a few thousand to a few tens of thousands of years (Skinner and Barton, 1973). The life of geothermal systems is estimated at several hundred thousand to several million years. If we assume 100,000 years to be a reasonable time to complete consolidation of the underlying magma chamber, the magmatic fluid flow rate must have been 1.7 $g/cm^2/yr$. Meteoric fluid flow during this period probably ranged from 250 to 300 kg/cm^2

over the top of the system (Cathles, 1977). Following the complete crystallization of the magma chamber, meteoric fluid flow continued for at least another 100,000 years during which, an additional 300 kg/cm^2 could have passed through much of the system, thus largely obliterating the magmatic oxygen and hydrogen isotope imprints on earlier alteration minerals.

The magmatic hydrothermal fluid volume can be generated by complete degassing of one million tons of magma a year, the equivalent of a magma layer 0.4 meter thick. Assuming that only part of the volatiles were released and that only a central zone within the chamber moved upward, the thickness of the magma layer that passed through the saturation surface probably ranged from five to ten meters per year. Shaw (1965) estimates magma convection rates to be in the order of 10 meters per year.

The importance of magma convection is demonstrated once again by considering cooling rates in plutons the size of the Weary Flat stock. Without convection and assuming heat loss by conduction only, the stock would be completely crystalline in 16,000 years (Jaeger, 1957). In order to derive the metal inventory of the system from this non-convecting magma, a magma column 41 kilometers deep would have to be tapped of its water and copper content implying an upward diffusion flow rate almost ten times as fast as in a convecting magma.

Late Magmatic and Hydrothermal Events

Before the main magma chamber completely crystallized, the hydrothermal system above the chamber was sealed off, presumably as a result of choking of the system by silica and clays (White et al., 1971). As a consequence, the water-saturated cap below the now altered and mineralized early quartz monzonite porphyry developed a hydrothermal fluid overpressure. Pressure release followed accompanied by crystallization of the late quartz monzonite porphyry phase and minor stockwork fracturing (Fig. 13). By this time, the underlying magma chamber had lost much of its excess heat and only a small volume of magmatic hydrothermal fluid was generated, resulting in weak alteration and mineralization in the late porphyry. This sequence of crystallization of a water-saturated cap with concomitant stockwork fracturing, retraction of the water saturation surface, alteration and mineralization and sealing of the system, followed by crystallization of a second porphyry phase with its stockwork zone and a repeat of the sequence could explain the formation of multiple ore shells, for example, at Climax (Wallace et al., 1968).

Figure 13 near here

In Ely, crystallization of the late quartz monzonite porphyry was followed by continued cooling and crystallization in the magma chamber. The increase in viscosity resulted in termination of magma convection. At this time, the magma still contained a substantial volume of interstitial granitic melt. With continued crystallization and cooling, the residual silicate melt became water-saturated throughout the magma column, and the presence of a vapor phase facilitated upward diffusion of water and alkalies through the crystal mush in response to temperature gradients and gravitational forces (Jahns and Burnham, 1969). This process is held responsible for the formation of a zone with large, late magmatic K-feldspar crystal aggregates in porphyritic quartz monzonite at the top of the Weary Flat quartz monzonite (Fig. 6). These alkali-rich rest fluids also crystallized as steeply dipping pegmatite and aplite veins. At the latest stage of crystallization, the aqueous magmatic fluids filled microscopic miarolitic cavities with quartz, calcite, minor epidote and apatite.

Following complete consolidation of the stock, the meteoric convection system encroached upon the consolidated stock (Cathles, 1977) and formed widely spaced quartz, calcite, zeolite and epidote veinlets.

FORMATION OF THE SULFIDE SYSTEM

The Ely sulfide system formed as a result of:

1. Emplacement of a quartz monzonite magma containing 115 to 145 ppm copper to within 6000 feet of the surface. Intrusion resulted in the formation of an isothermal contact aureole. Heat loss was largely due to thermal conduction. Once the country rock was heated, geothermal gradients became flat and heat loss was minimal. At the top of the chamber, a water-saturated cap formed, adjacent to which important iron metasomatism produced an anhydrous andradite-pyroxene-magnetite skarn envelope (Fig. 10).

2. Pressure failure possibly due to continued cooling and build-up of hydrothermal fluid overpressure resulted in rapid crystallization of the water-saturated top of the stock as early quartz monzonite porphyry. Catastrophic water release produced a zone of stockwork fracturing in the consolidated part of the stock and surrounding sediments, including the skarn envelope (Fig. 11). Rapid crystallization of the porphyry resulted in significant heating of the rocks above the stock and the formation of an extensive zone of early potassium-silicate alteration. Copper grades in rocks affected by this early mineralization stage range from 0.03 percent in the upper outer parts of the zone, to 0.1 percent in an area directly above the main copper ore zone. The formation of the zone of high permeability formed by the stockwork resulted in an inward flow of cooler meteoric fluids and a cooling of the top of the magma chamber (Fig. 12).

The main mineralization and alteration phase is related to stage 3:

3. As a result of thermal instability, magma convection started which resulted in tapping of a large volume of magma of its volatiles by moving water-undersaturated magma through the saturation surface at the top of the chamber. The rising magmatic fluids formed a zone of potassic alteration in early porphyry with hydrothermal biotite, secondary K-feldspar, magnetite, a low total sulfide content, and marginal copper grades at temperatures of 500-600°C. Upward-moving magmatic hydrothermal fluids entered a zone of throttling, boiling and cooling by inflowing meteoric waters over the top of the magma chamber, resulting in the formation of a silica-rich copper ore zone at the interface between a potassic zone below, and a quartz-sericite zone above (Figs. 3, 5 and 12).

4. Clogging of the system and formation of a fluid over-pressure in the water-saturated cap was followed by crystallization of late quartz monzonite porphyry with attendant weak stockwork development and minor alteration and mineralization (Fig. 13).

5. End of magma convection; late magmatic alteration in the deep quartz monzonite; encroachment of a meteoric convective system upon the former zone of boiling and the potassic zone, resulting in pervasive argillization of early porphyry and weaker argillization of late porphyry.

6. Consolidation of the Weary Flat quartz monzonite and superposition of the meteoric convection system on the hot consolidated rock resulting in formation of minor quartz-calcite, epidote, zeolite, and rare pyrite veins. High partial CO_2 pressures prevented the formation of anhydrite, but calcite veins are widespread.

7. Intrusion of granodiorite and granodiorite porphyry in the eastern part of the district.

HYDROTHERMAL SYSTEM MODEL

Alteration patterns and metal distribution as documented in the Ely sulfide system are best explained in terms of a vapor-dominated hot water system (White et al., 1971). A stationary heat source at the base of the system was provided by a convecting quartz monzonite magma which continuously expelled a supercritical vapor phase with 4 to 5 weight percent NaCl equivalent and 2000 to 4000 ppm copper. Copper mineralization was the result of hydrothermal introduction of copper in consolidated fractured early porphyry over a significant period of time and not the result of upward diffusion and concentration of copper during a late magmatic stage in the top of the magma chamber.

Magmatic hydrothermal fluids released at the saturation surface in the magma cooled to approximately 400°C as a result of adiabatic expansion in a zone of throttling where pressure changed from 500 bar lithostatic to 150-200 bar hydrostatic. Boiling of the supercritical magmatic fluid was the major cause of copper deposition. Boiling took place at a temperature below 425°C and a pressure below 220 bar and resulted in the formation of a NaCl saturated liquid that was subsequently trapped in fluid inclusions. The zones of throttling and boiling ultimately coincided with the zone of mixing with meteoric waters in the lower part of the zone of stockwork fracturing and the high silica-chalcopyrite zone was formed.

As a result of retraction of the initial boiling surface, a semi-steady state developed in which the heat contained in the expelled magmatic fluids that entered at the base of the system was transported upward and outward by boiling in a vapor dominated system and cooled by inflowing meteoric waters and condensates. Once this stationary configuration was established, copper was deposited in a relatively narrow zone of boiling at the interface of dominantly magmatic (below) and dominantly meteoric fluids (above) at the top of the magma column in early quartz monzonite porphyry. Copper deposition in the zone of boiling was enhanced by the dissociation of metal chloride complexes and HCl and the change in dominant sulfur species in solution from SO_4^{2-} or HSO_{4^-} to H_2S below 400°C (Helgeson, 1964). Copper was deposited in a narrow temperature interval but iron was in part transported beyond the copper shell to form pyrite in the quartz-sericite zone.

The vapor-dominated reservoir overlying the zone of boiling contained a low pH water vapor with H_2S, HCl and CO_2. Silica-pyrite and quartz sericite alteration formed in this environment at temperatures of 250° to 400°C (James, 1976; Chi I Huang, 1976). The rising acid vapor became neutralized by reaction with Ely Limestone and as a result, silica-pyrite rock without calcite higher in the system changes to a pyritic marble with numerous quartz veins. In areas overlain by less reactive Rib Hill Sandstone, the neutralizing effect was weak and during cooling and near-surface mixing with oxygenated groundwaters, an extremely acid hydrothermal solution formed that produced advanced argillic alteration assemblages.

The peripheral zone of pyritic marble and clay-calcite altered early porphyry low in pyrite formed in an environment of condensing steam or neutralized outward flowing meteoric fluids with only small volumes of magmatic fluids. In White's model, this zone is characterized by saturation with water rich in CO_2. Reaction of this condensate with rock silicates produced montmorillonite and kaolinite in the peripheral argillic zone at Ely. These clay minerals and condensed water clogged pore spaces and formed a lid over the system.

With continued cooling and crystallization in the magma chamber, a meteoric convective hot water system encroached upon the area of potassic alteration and copper mineralization. Still later, influx of meteoric water in the hot consolidated quartz monzonite below the hydrothermal system proper resulted in formation of quartz, quartz-calcite, calcite-zeolite and epidote veins which represented the final stage of the hydrothermal system. Meteoric recharge in the Robinson sulfide system was restricted to a zone above the magma chamber, and little or no meteoric water is thought to have entered the melt in deeper zones during the main phase of alteration and mineralization. The volume of meteoric fluid that passed through the system many times exceeded that generated from the magma, but essentially all copper, sulfur, and molybdenum have been derived from the magmatic fluid.

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LIST OF FIGURES AND CAPTIONS

Figure 1. Location map of porphyry copper deposits in the Robinson Mining District, White Pine County, Nevada showing cross section position, drill hole collars, and distribution of Lower Cretaceous quartz monzonites and granodiorites.

Figure 2. Restored cross section of the Robinson Mining District showing stock outline, location of drill hole intercepts and position of thin sections used in this study.

Figure 3. Hydrothermal alteration in igneous rock types in restored cross section A-A'.

Figure 4. Hydrothermal alteration in sediments in restored section A-A'.

Figure 5. Copper distribution in restored section A-A'. At depth copper distribution is only shown in igneous rocks.

Figure 6. Distribution of igneous phases in the Robinson sulfide system in restored section A-A'.

Figure 7. Distribution of magmatic biotite, hornblende, augite, and hydrothermal biotite in igneous rocks in restored section A-A'.

Figure 8. Crystallization Sequence in Quartz Monzonite (S= crystals, L= silicate melt, V= vapor phase)

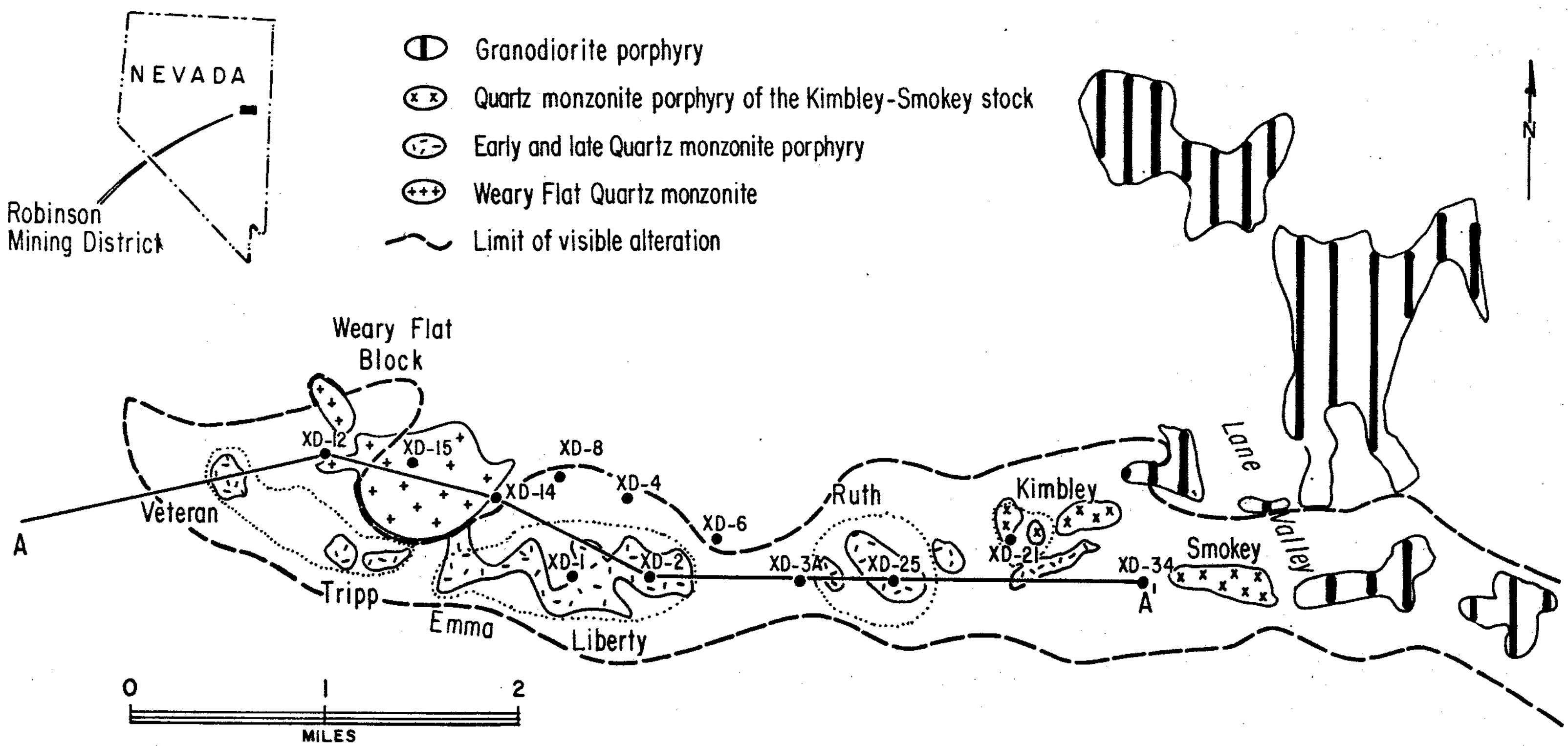
Figure 9. Relation between magma composition, crystallization interval, and melt volume as a function of temperature at 2 kbar water pressure. Re-drawn after Robertson and Wyllie (1971).

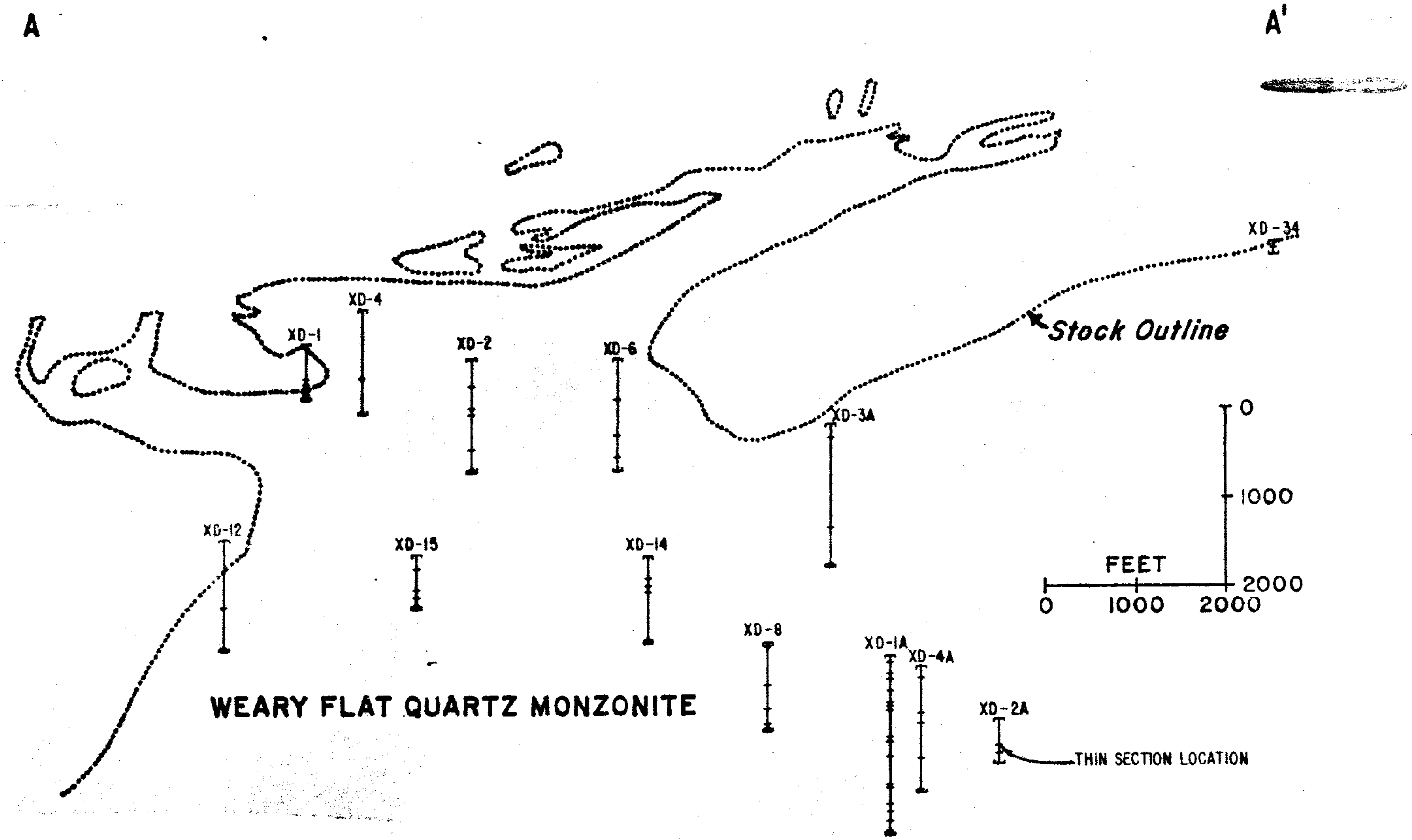
Figure 10. Cross-section A-A' showing effects of emplacement of overheated, water-undersaturated quartz monzonite magma and position of the water-saturated magma layer.

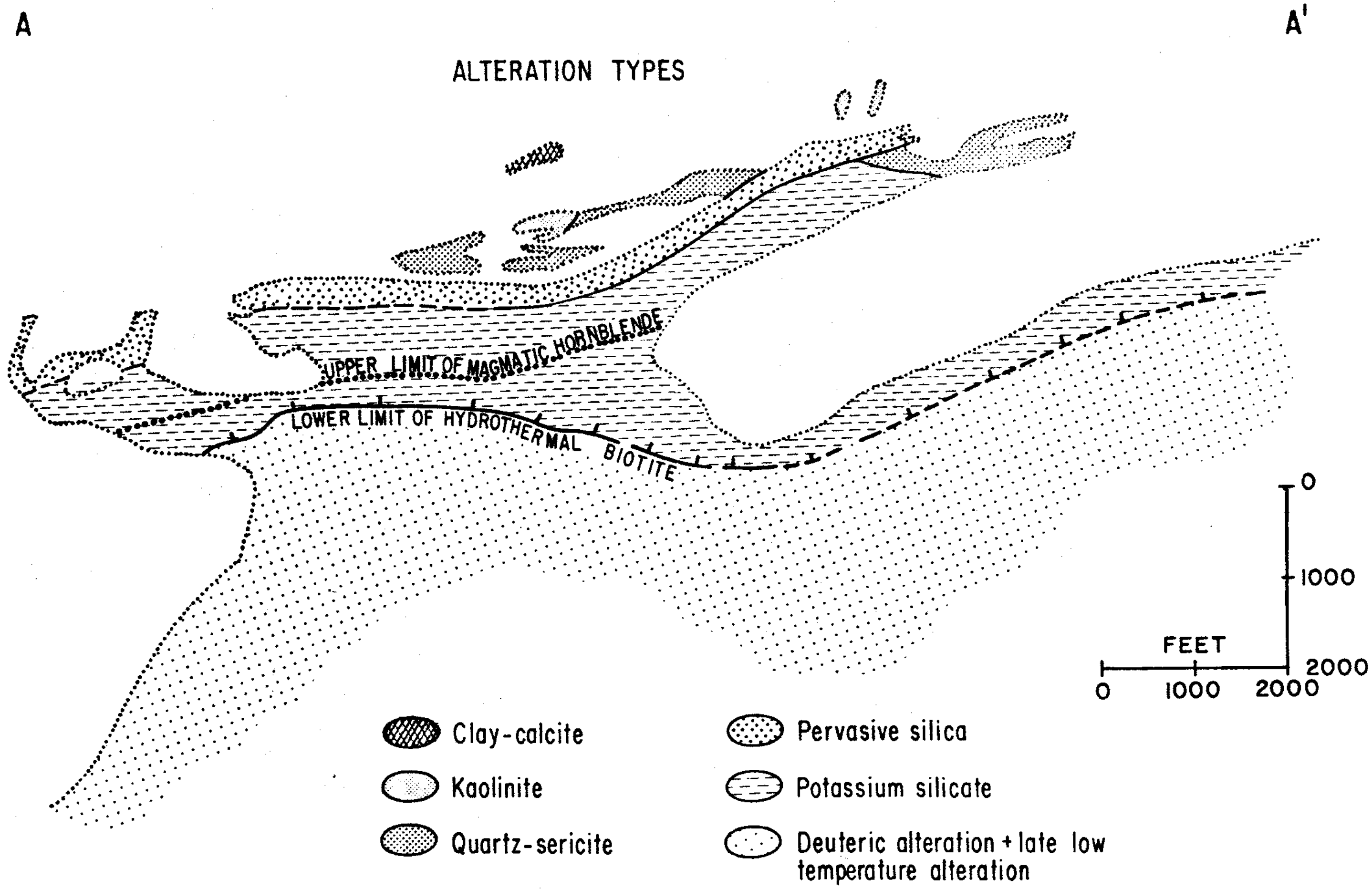
Figure 11. Schematic section A-A' showing the effects of rapid crystallization of water-saturated top of the magma chamber.

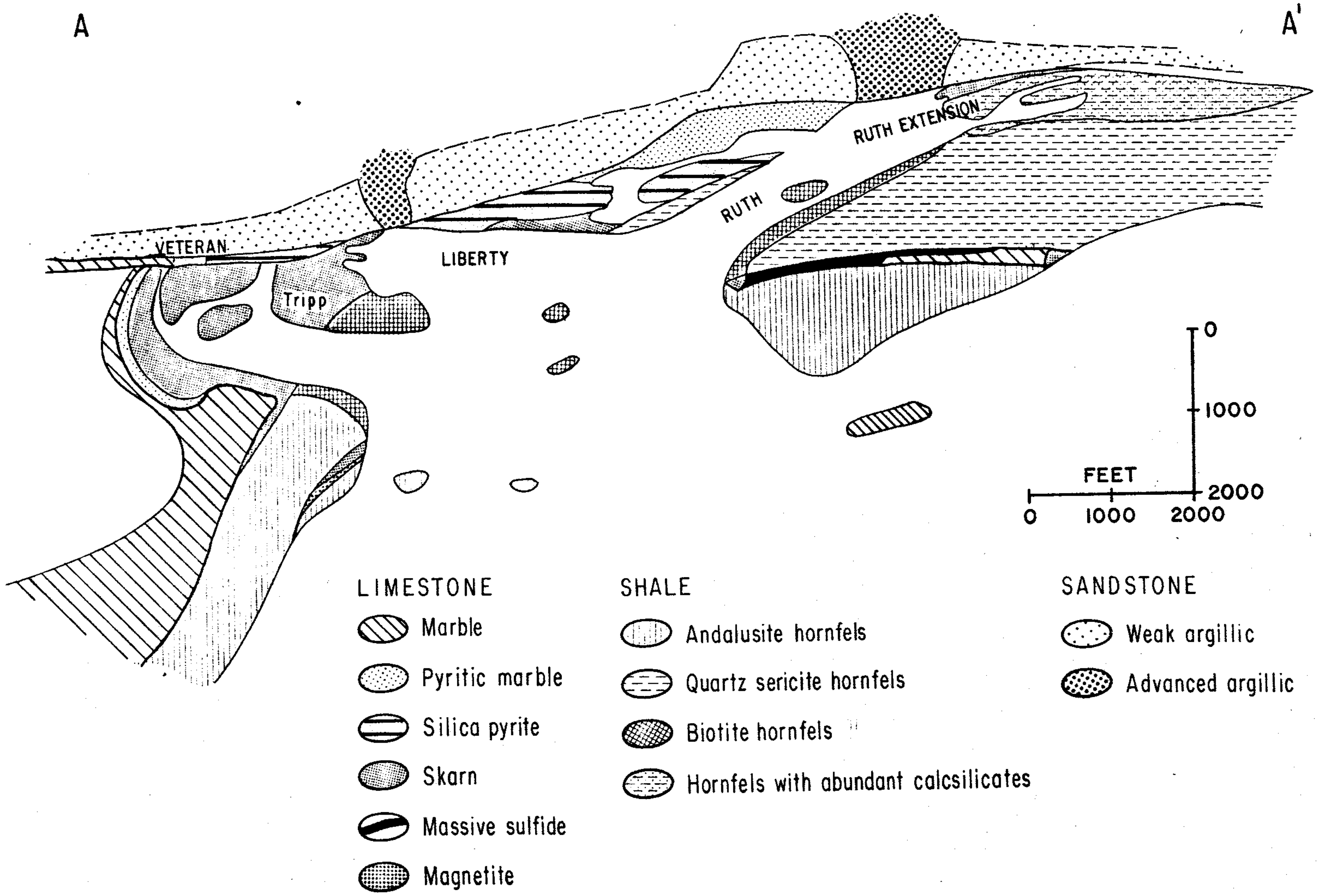
Figure 12. Schematic configuration of the hydrothermal system during the main mineralization phase.

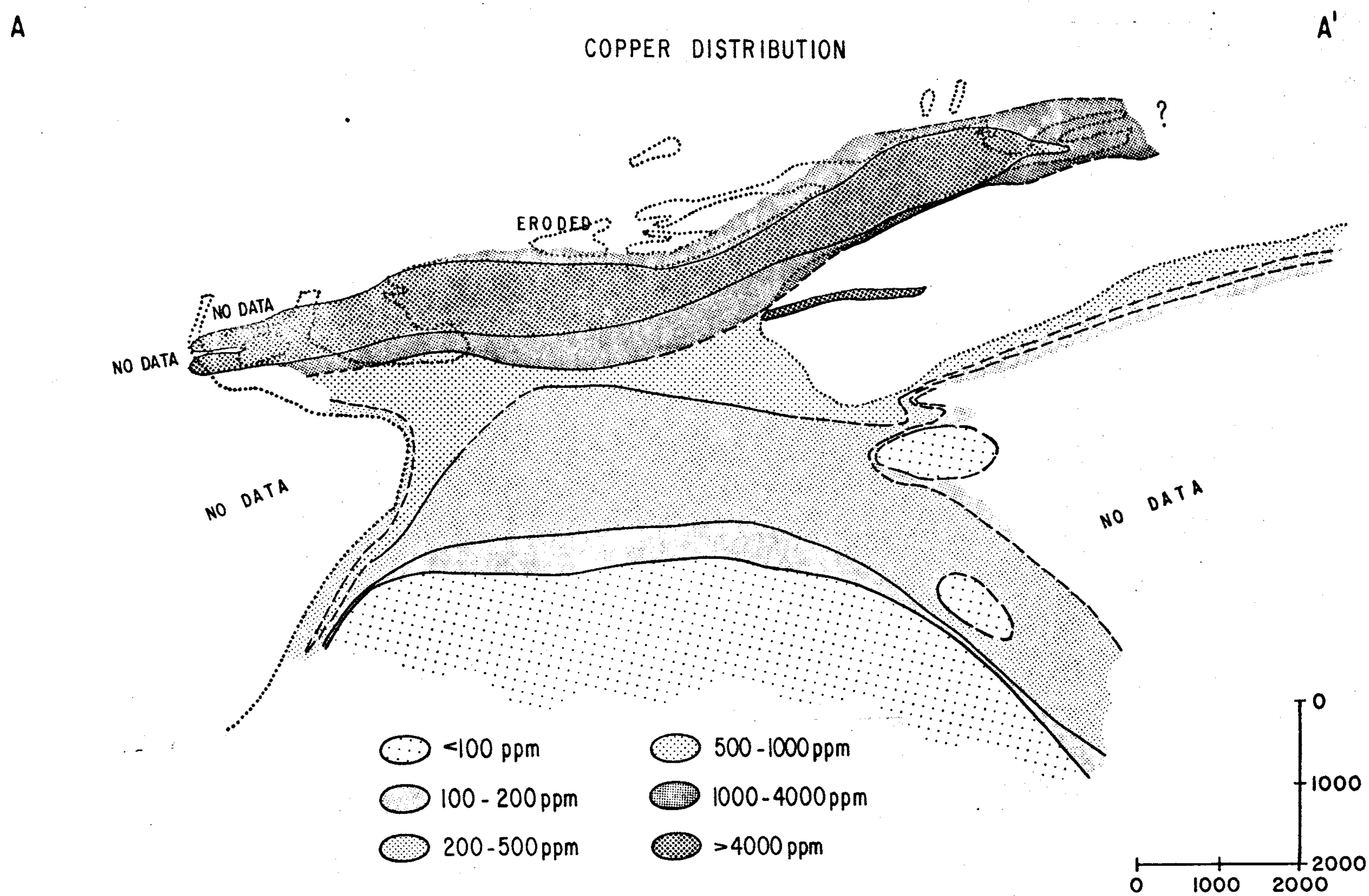
Figure 13. Section A-A' showing effects of crystallization of second water-saturated cap, stockwork formation, and crystallization of late quartz monzonite porphyry.

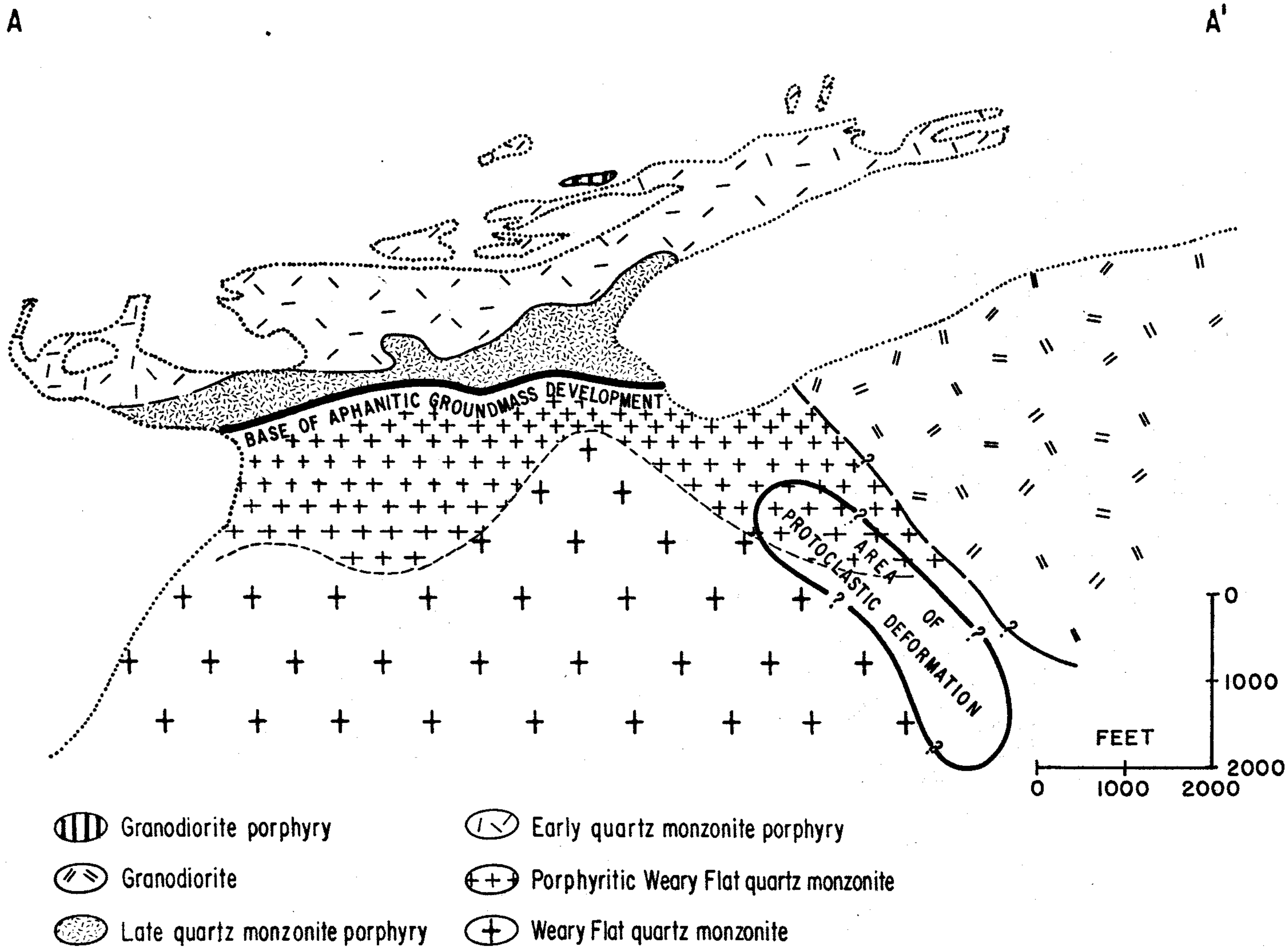

NEVADA
Robinson Mining District
Granodiorite porphyry
Quartz monzonite porphyry of the Kimbley-Smokey stock
Early and late Quartz monzonite porphyry
Weary Flat Quartz monzonite
Limit of visible alteration
N
Weary Flat Block
XD-12
XD-15
XD-8
XD-4
XD-14
XD-6
XD-1
XD-2
XD-3A
XD-25
XD-21
XD-34
Veteran
Tripp
Emma
Liberty
Ruth
Kimbley
Smokey
Lane Valley
A
A'
0
1
2
MILES

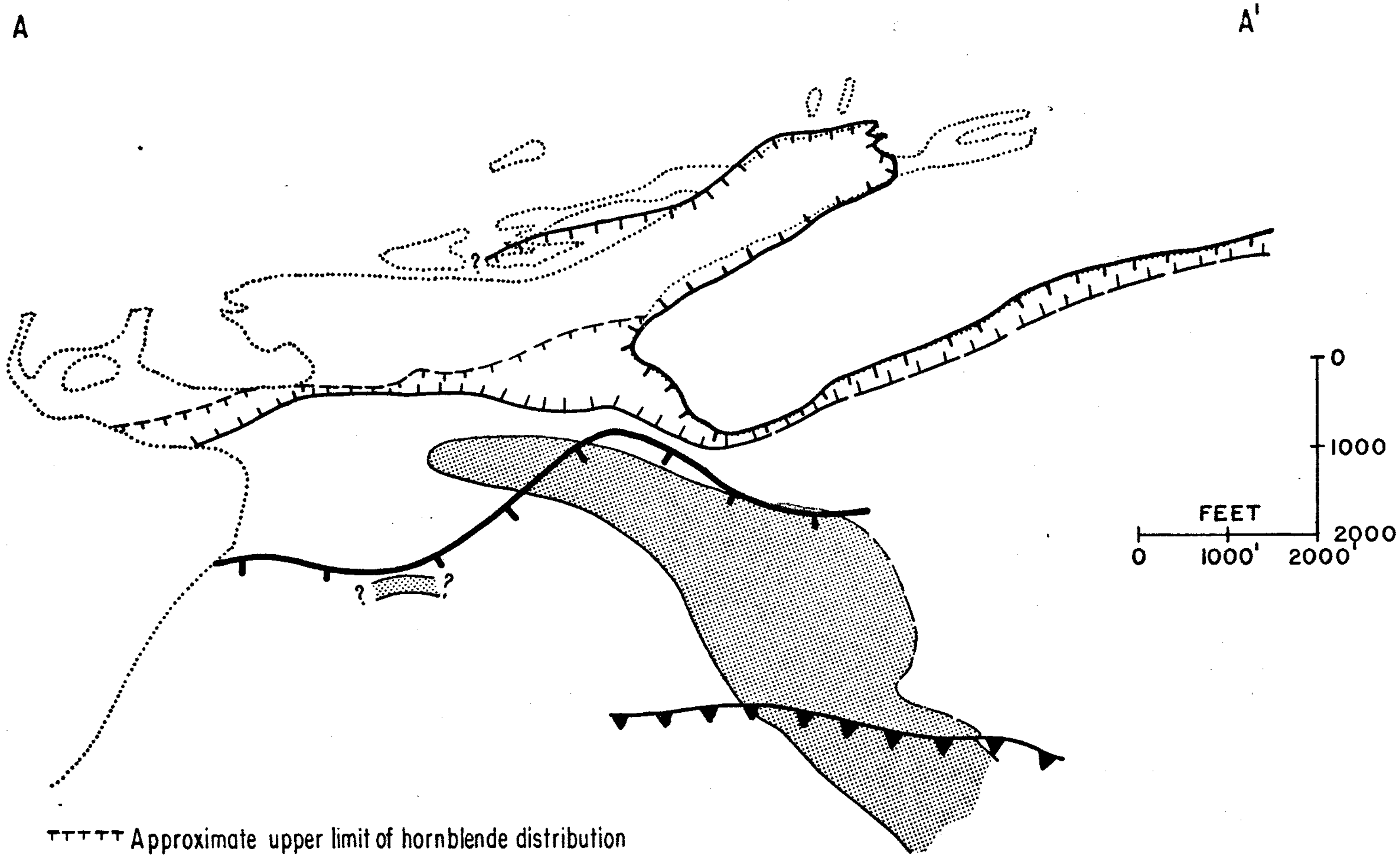

A
A'
XD-34
Stock Outline
XD-4
XD-1
XD-2
XD-6
XD-3A
0
1000
2000
FEET
0 1000 2000
XD-12
XD-15
XD-14
XD-8
XD-1A
XD-4A
XD-2A
THIN SECTION LOCATION
WEARY FLAT QUARTZ MONZONITE


A
A'
ALTERATION TYPES
UPPER LIMIT OF MAGMATIC HORNBLENDE
LOWER LIMIT OF HYDROTHERMAL BIOTITE
0
1000
2000
FEET
0 1000 2000
Clay-calcite
Kaolinite
Quartz-sericite
Pervasive silica
Potassium silicate
Deuteric alteration + late low temperature alteration


A
A'
VETERAN
Tripp
LIBERTY
RUTH
RUTH EXTENSION
0
1000
2000
FEET
0
1000
2000
LIMESTONE
Marble
Pyritic marble
Silica pyrite
Skarn
Massive sulfide
Magnetite
SHALE
Andalusite hornfels
Quartz sericite hornfels
Biotite hornfels
Hornfels with abundant calcsilicates
SANDSTONE
Weak argillic
Advanced argillic


A
A'
COPPER DISTRIBUTION
?
ERODED
NO DATA
NO DATA
NO DATA
NO DATA
<100 ppm
100 - 200 ppm
200-500 ppm
500-1000 ppm
1000-4000 ppm
>4000 ppm
0
1000
2000
0
1000
2000


A
A'
BASE OF APHANITIC GROUNDMASS DEVELOPMENT
AREA OF PROTOCLASTIC DEFORMATION
FEET
0
1000
2000
0
1000
2000
Granodiorite porphyry
Granodiorite
Late quartz monzonite porphyry
Early quartz monzonite porphyry
Porphyritic Weary Flat quartz monzonite
Weary Flat quartz monzonite



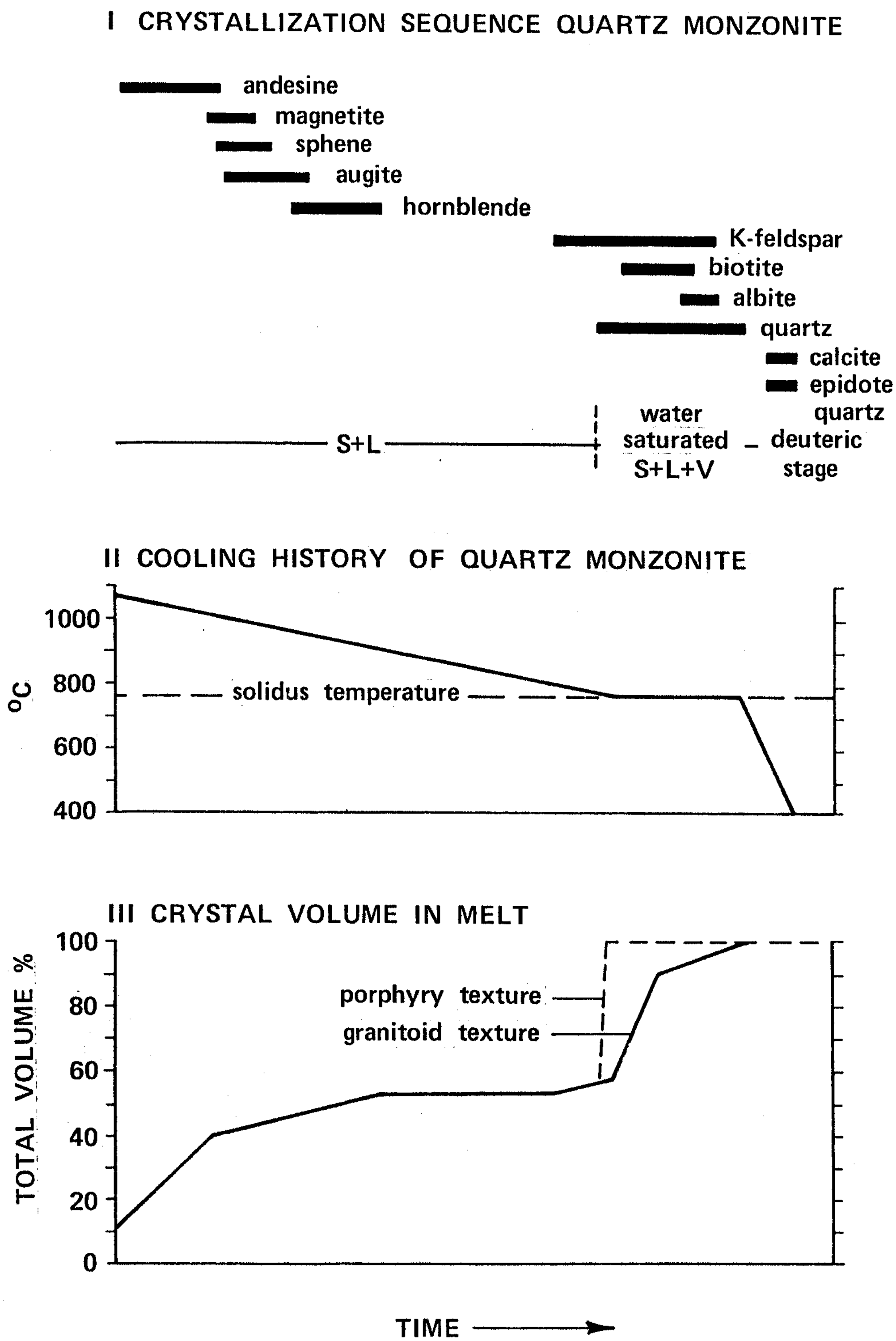
TTTTT Approximate upper limit of hornblende distribution

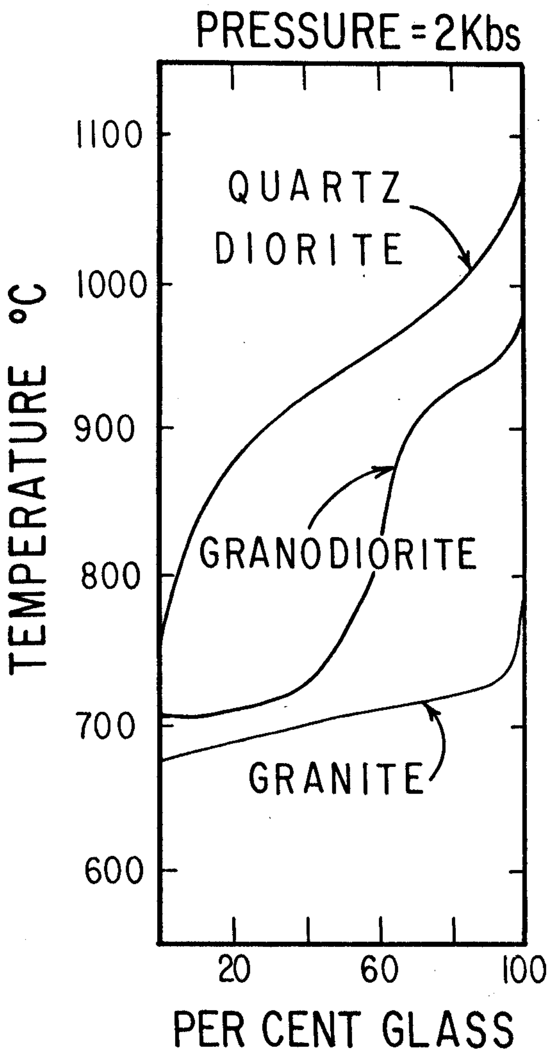
⊥⊥⊥⊥ Limit of hydrothermal biotite distribution

▼—▼ Upper limit of magmatic biotite distribution

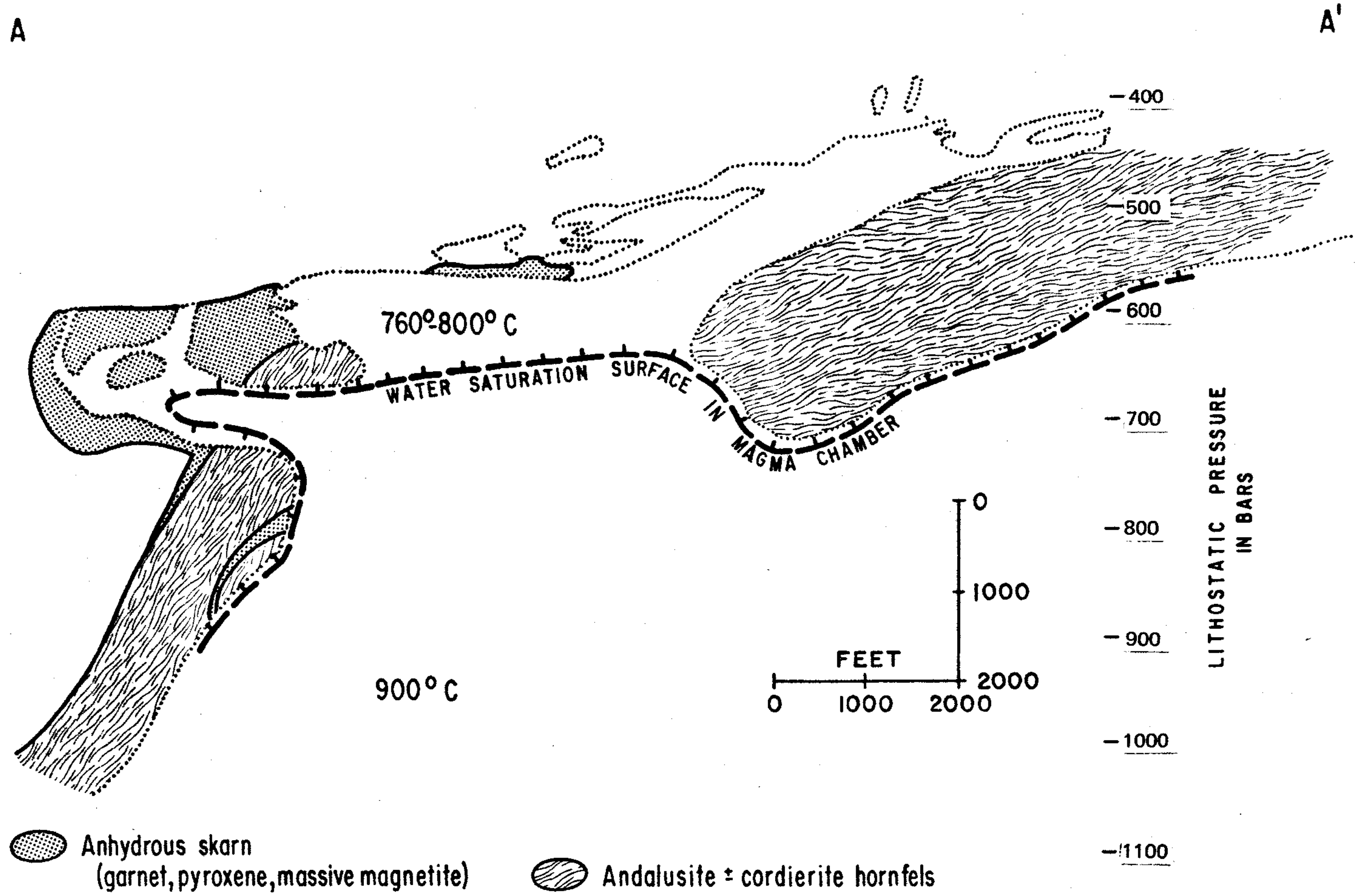
Upper limit of augite distribution

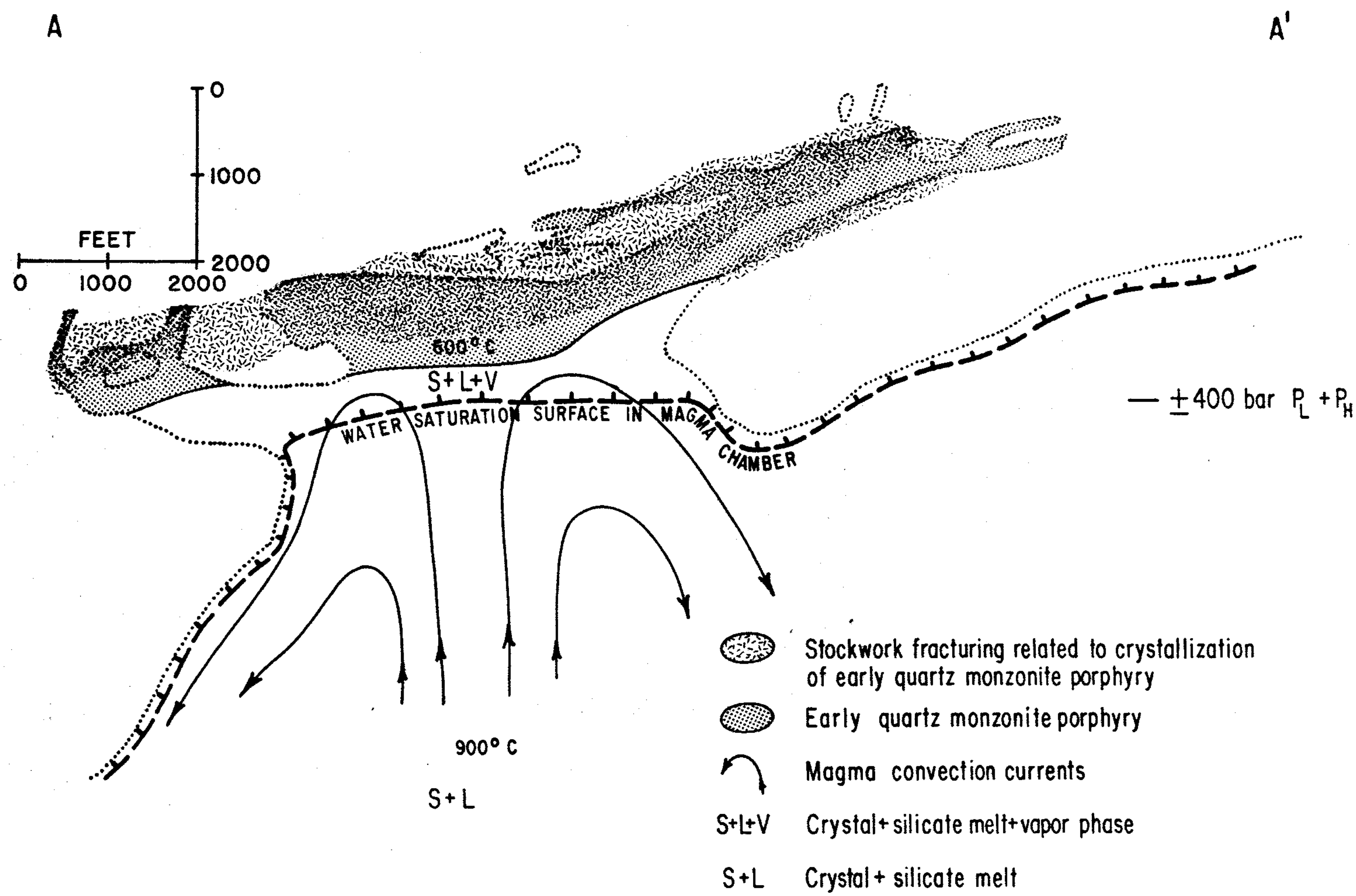
Zone of abundant myrmekite development

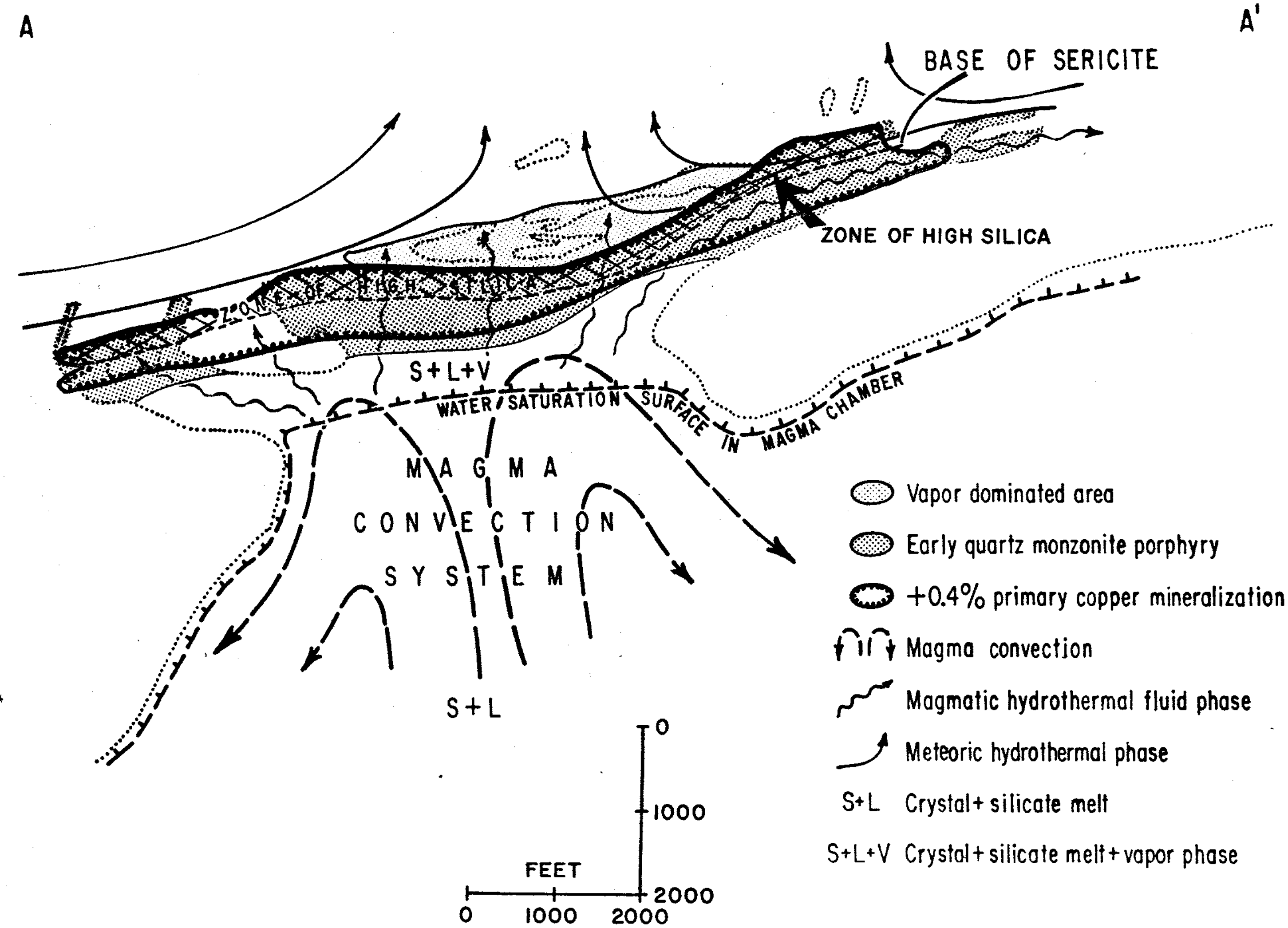

I CRYSTALLIZATION SEQUENCE QUARTZ MONZONITE
andesine
magnetite
sphene
augite
hornblende
K-feldspar
biotite
albite
quartz
calcite
epidote
S+L
water saturated S+L+V
quartz deuteric stage
II COOLING HISTORY OF QUARTZ MONZONITE
°C
1000
800
600
400
solidus temperature
III CRYSTAL VOLUME IN MELT
TOTAL VOLUME %
100
80
60
40
20
0
porphyry texture
granitoid texture
TIME



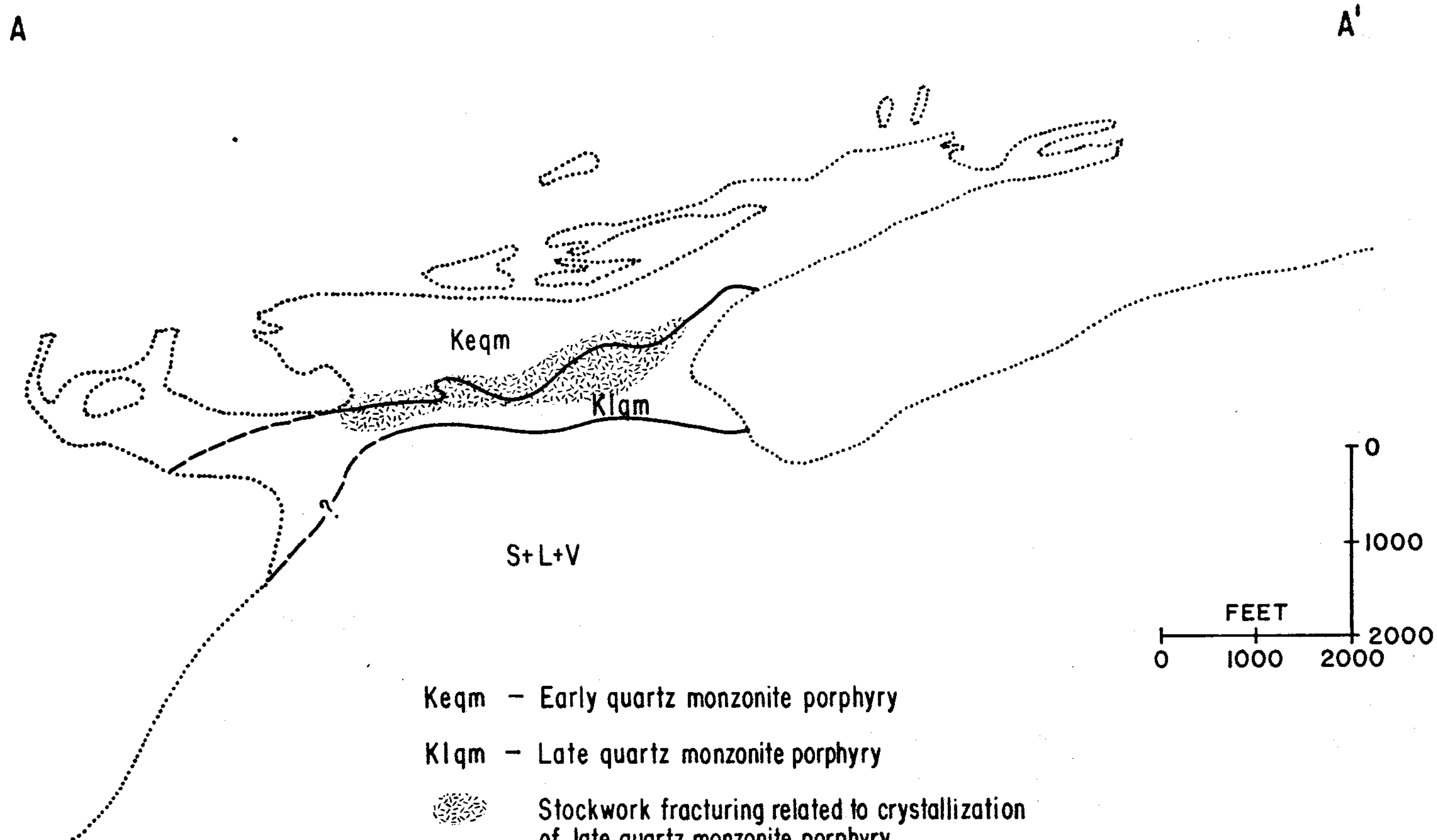
PRESSURE = 2Kbs
TEMPERATURE °C
1100
1000
900
800
700
600
QUARTZ DIORITE
GRANODIORITE
GRANITE
20
60
100
PER CENT GLASS


A
A'
760°-800° C
WATER SATURATION SURFACE IN MAGMA CHAMBER
900° C
FEET
0
1000
2000
0
1000
2000
-400
-500
-600
-700
-800
-900
-1000
-1100
LITHOSTATIC PRESSURE IN BARS
Anhydrous skarn (garnet, pyroxene, massive magnetite)
Andalusite ± cordierite hornfels


A
A'
FEET
0
1000
2000
0
1000
2000
600° C
S+L+V
WATER SATURATION SURFACE IN MAGMA CHAMBER
— ±400 bar $P_L + P_H$
900° C
S+L
Stockwork fracturing related to crystallization of early quartz monzonite porphyry
Early quartz monzonite porphyry
Magma convection currents
S+L+V Crystal+silicate melt+vapor phase
S+L Crystal+silicate melt



A
A'
BASE OF SERICITE
ZONE OF HIGH SILICA
ZONE OF HIGH SILICA
S+L+V
WATER SATURATION SURFACE IN MAGMA CHAMBER
MAGMA
CONVECTION
SYSTEM
S+L
0
1000
2000
FEET
0 1000 2000
Vapor dominated area
Early quartz monzonite porphyry
+0.4% primary copper mineralization
Magma convection
Magmatic hydrothermal fluid phase
Meteoric hydrothermal phase
S+L Crystal+ silicate melt
S+L+V Crystal+ silicate melt+ vapor phase



Keqm — Early quartz monzonite porphyry

Klqm — Late quartz monzonite porphyry

(stipple pattern) Stockwork fracturing related to crystallization of late quartz monzonite porphyry

S+L+V Crystals + minor silicate melt + aqueous vapor phase