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THE ARCHITECTURE OF THE PORPHYRY-METAL SYSTEM
AS A PROSPECTING STRATAGEM
IN THE SOUTHERN ROCKY MOUNTAINS

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ABSTRACT

A model of the porphyry-metal system characteristic of the consanguineous Cretaceous and Tertiary igneous rocks and associated ores of the southern Rocky Mountains is constructed from the bits and pieces exposed in the Colorado mineral belt and the San Juan volcanic field. Hydrothermally altered rocks in a part of the areas of mineralized rock associated with the Platoro caldera are matched against the model, to locate and to characterize latent mineral deposits for optimal prospecting and exploration. The latent deposits are two stockwork molybdenite deposits (porphyry-molybdenum) and one or two copper-gold-silver chimney deposits.

Introduction

Latent¹ mineral deposits can be identified and approximately located by matching the exposed mineralized rocks of a mining district with corresponding parts of a model (Briggs and Press, 1977; Krumbein and Graybill, 1965; Wallace, 1974; Whitten, 1964) of the applicable mineralizing system. Dimensional, compositional, and structural habits of the latent mineral deposits are inferred from the habits of exposed deposits of like character in the enclosing geochemical province. The argument is made for the porphyry-metal system and applied to mineralized rocks centered on the Platoro caldera (Lipman and Steven, 1971) of the southern San Juan Mountains of Colorado.

The Model

The porphyry-metal edifice² is an orderly assemblage of mineral deposits and hydrothermally altered rocks spatially and temporally related to the rocks and structures that make up and connect calc-alkalic batholiths and volcanoes (Brown, 1969; Hollister and others, 1974; Jacobsen, 1975; Jerome, 1966; Lowell and Guilbert, 1970; Sillitoe, 1973, 1975; Sillitoe and others, 1975). The model of the porphyry-metal system used here for guiding prospecting and exploration is composed in an hierarchy of three levels of progressively limiting sets of structural, petrographic, and chemical elements. The basic model (fig. 1) lists only those elements needed to define and to establish the porphyry-metal mineralizing system as a distinct and homogeneous class (Stanton, 1972; Titley, 1966). Variations (Guilbert and Lowell, 1974; Hollister, 1975; Kesler, 1973) of any of the definitive elements generally group geographically and(or) temporally; thus, a provincial model (fig. 2) can be constructed from the congruous properties of all the known fragments (James, 1971) of the porphyry-metal edifices in the province containing the study area. The provincial model more closely defines the probable structural and compositional habits of the latent mineral deposits.

¹ Present or potential, but not manifest (Morris, 1976).

² Edifice is the entire spatial assembly or structure of altered rocks, varied types of mineral deposits, and associated intrusive and extrusive rocks formed by the porphyry-metal mineralizing system.

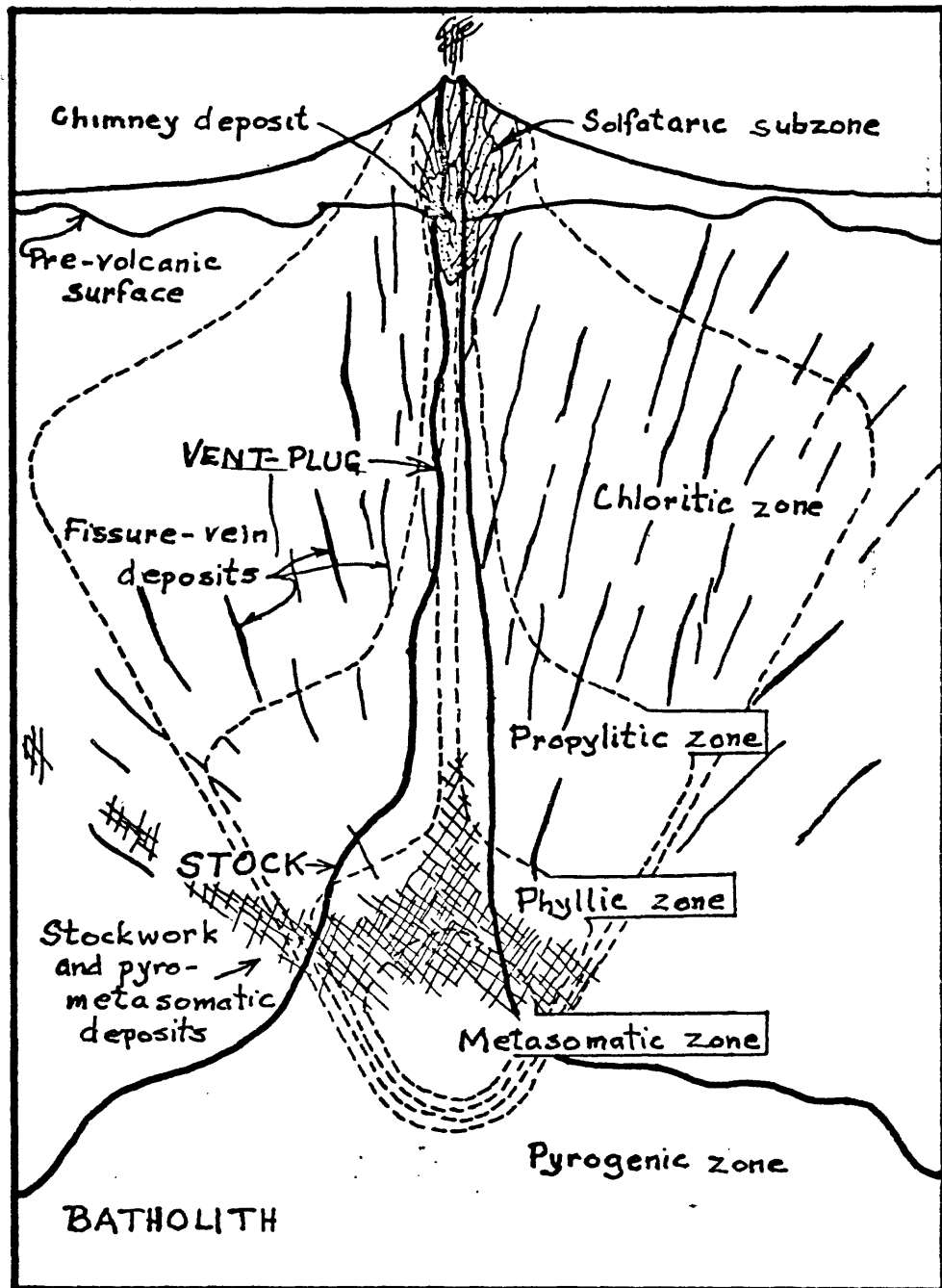


Figure 1.--The basic model of the porphyry-metal edifice, showing the arrangement of the intrinsic elements that define the porphyry-metal mineralizing system, drawn as if emplaced in an isotropically permeable host.

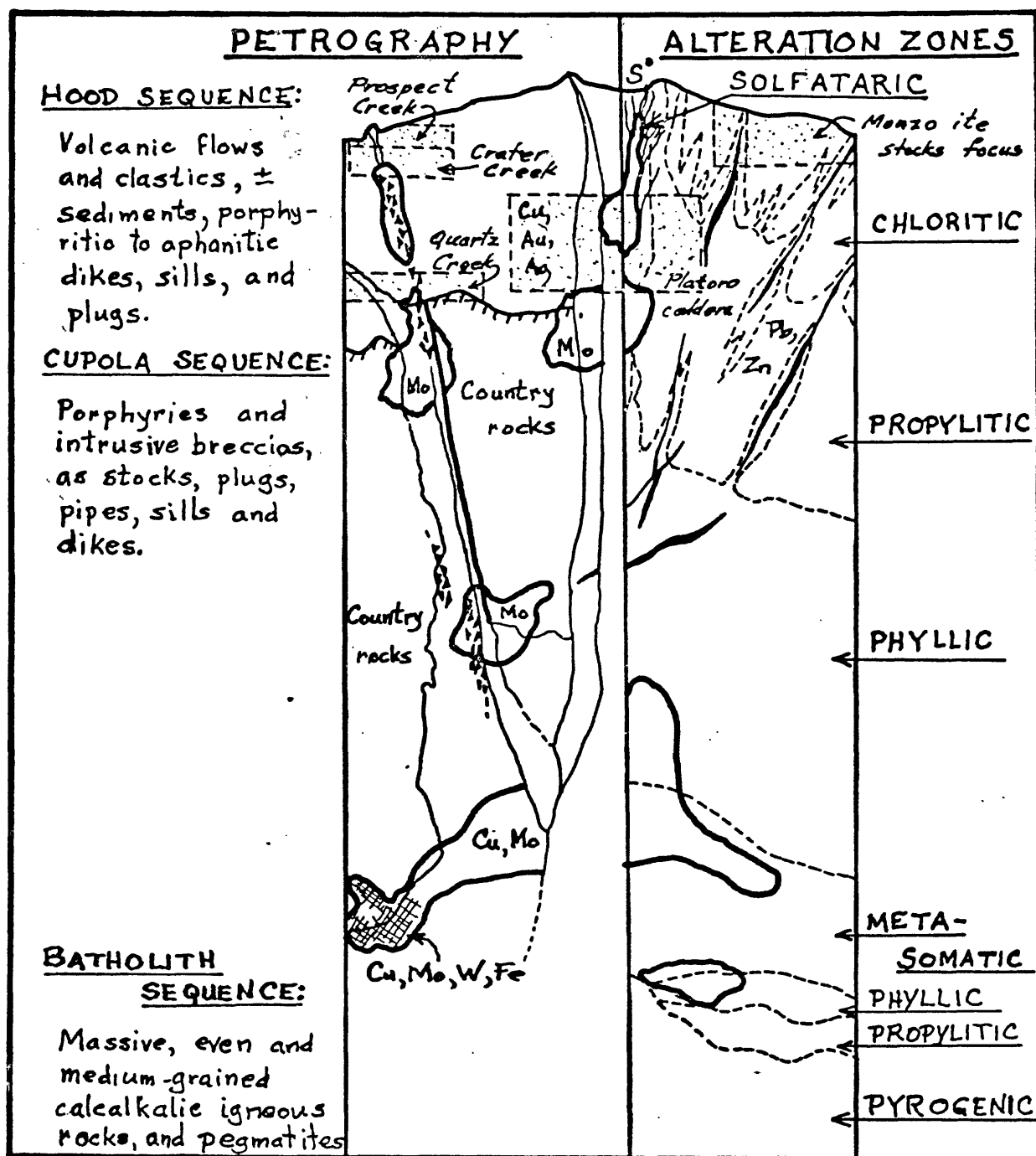


Figure 2.--Composite model of the porphyry-metal edifices of the southern Rocky Mountains, showing the parts of edifices exposed in the Crater Creek--Platoro caldera area of the San Juan volcanic field.

The final construction consists of the empirical patterns (Olade and Fletcher, 1976, p. 746-747) of mineralization in the geological framework of the study and adjacent areas. These parochial patterns are compared (Carson and Jambor, 1974; Jambor, 1974; Olade and Fletcher, 1976) with the provincial model to delimit optimal areas for prospecting and exploration.

The porphyry-metal mineralizing system is an inherent and integral part of the process of batholithic emplacement and venting (Emmons, 1940; Hulin, 1945; Kennedy, 1955; Morey, 1922; Sillitoe, 1972) along zones of crustal weakness (Rowan, 1975; Shawe and Stewart, 1976; Tweto and Sims, 1963). Mineralization results from the reaction of rock with a metalliferous hydrothermal fluid (Hemley and Jones, 1964) that separated from the magma in response to a decrease of confining pressure, the second boiling phenomenon (Burnham, 1967; Kennedy, 1955; Phillips, 1973; Whitney, 1975, 1977). Venting is episodic and the edifices of each episode are the sum of many cycles (Moore and Nash, 1974, p. 643) of generally alternating igneous and hydrothermal events (Bray, 1969). The separate edifices may be superimposed, as at Climax (Wallace and others, 1968) and Urad-Henderson (MacKenzie, 1970), but are more generally strung out along the structural feature that localized venting. Sites of the onset of alteration ("emanation centers" (Hosking, 1963)) and of mineralization ("centers of mineralization") and the positions and structural habits of mineral deposits and altered rocks change with successive venting episodes, being progressively physically and chemically restricted or displaced by the products of preceding episodes (Anderson, 1950; Burbank, 1950).

Most porphyry-metal systems are associated with salic varieties of calc-alkalic igneous rocks (De Geoffroy and Wignall, 1972; Ishihara, 1967), but the more relevant petrographic association is textural and structural (Carson and Jambor, 1974, p. 131; Stringham, 1966), a pertinence manifest in the name "porphyry-metal". The characteristic textures of the intrusive igneous rocks are porphyroclastic porphyritic with coarse-grained to aphanitic and even glassy groundmasses, to mylonitic, and aplitic to aphanitic. The characteristic forms are dikes, plugs, sills, and stocks of mostly massive igneous rocks and of breccias (Gilmour, 1977; Lowell and Guilbert, 1970) made of single or of mixed rock types, with and without an igneous matrix (Bryner, 1961). The distribution of intrusive forms along the vent column is essentially a property only of the local geology and not of the general system nor of the province. Crackle breccias, dilation breccias (Neuerburg and others, 1974) and vuggy-brecciated fissure veins characterize the mineral deposits of the system. Most of these textures and structures are the direct mechanical effects of tenuous fluids exsolving from magma and moving toward the surface along a negative pressure gradient (Bryant, 1968; Hulin, 1945; Moore and Nash, 1974; Phillips, 1972), guided by tectonically induced (Dandurand and others, 1972; Marler and White, 1975) permeable structures.

Chemical elements characteristic of the porphyry-metal mineral deposits are in two categories: (1) elements added to the edifice by the hydrothermal fluids, notably the chalcophile elements copper, lead, molybdenum, sulfur, zinc and less commonly arsenic, bismuth, tin, and tungsten, and (2) rock elements redistributed by the hydrothermal fluids, especially silicon (Knopf, 1929), but also barium, iron, manganese, and zinc. The ore-elements of the porphyry-metal system are not specific to the system, and are not therefore, definitive criteria for identifying the porphyry-metal edifice. However,

metals are distinctively distributed among mineral deposit types of the porphyry-metal system as listed below, and the relative abundances of the elements differ geographically (Kesler, 1973) and are a congruous property of groups of porphyry-metal edifices, useful in defining provinces. The porphyry-metal systems of the southern Rocky Mountains produced a molybdenum province (Clark, 1972); very few porphyry-copper systems are known or suspected (King, 1970, no. CO-42; Nelson, 1971; Bromfield and Williams, 1972, p. 55-58; Lovering and Goddard, 1950, p. 194-196).

Pervasive hydrothermal alteration (Creasey, 1959, 1966; Hemley and Jones, 1964; Meyer and Hemley, 1967; Rose, 1970) of distance-dependent intensity is the hallmark of the porphyry-metal system. This large-scale alteration is the most obvious and most widely expressed element of the porphyry-metal edifice and provides a universal framework to which all other characteristics can be conveniently related; alteration is conceptually the independent variable of the porphyry-metal system. The altering fluids were channeled by permeable rocks and structures, the conduits or plumbing of the system. The nature and intensity of alteration varies systematically with distance from (Sales and Meyer, 1948) and along (Pinckney, 1965) the conduit, which is commonly occupied by one or more mineral deposits. Alteration mineralogy varies little among quartzo-feldspathic rocks (Carson and Jambor, 1974), but does differ appreciably where carbonate rocks (James, 1976) or ferromagnesian rocks (Phillips and others, 1974) are involved. Provincial or epochal differences in alteration chemistry and mineralogy may also occur (Hollister, 1975).

The alteration sequence is usefully divided into zones (table 1), each defined by an assemblage of secondary minerals, by chemical composition, by physical properties, or by some combination of these parameters. Changes in alteration intensity (mineralogy) beyond the metasomatic zone are sequential (Meyer and Hemley, 1967, p. 188; Sales and Meyer, 1948, 1949, 1950) and thus primarily proportional to the quantity of hydrothermal fluid with which the rock has reacted. The principal compositional changes (Burnham, 1962) in quartzo-feldspathic rocks along the alteration sequence progress from (1) simple recrystallization to substitution, mainly of potassium (Seki and Kennedy, 1965) for calcium, in the metasomatic (or potassic) zone (Anderson, 1950; James, 1976; Nielsen, 1970) through (2) subtraction of calcium, iron, magnesium, and sodium (Anderson, 1950) and a major addition of sulfur and hydrogen in the phyllic (Hemley and Jones, 1964; U.S. Geological Survey, 1973, p. 18) and solfataric (Burbank and Luedke, 1969; Mukaiyama, 1959; Steiner, 1953; Steven and Ratte, 1960, p. 37-55) zones to (3) addition of mainly carbon dioxide, iron, sulfur, and water in the propylitic (Burbank 1960; Burbank and Luedke, 1969; Creasey, 1966; Whitebread, 1976) and succeeding zones. The amount of an element added or subtracted at any point in the alteration sequence differs among porphyry-metal systems even within provinces. Overall the magnitude of chemical change diminishes exponentially with distance from the center of mineralization, in keeping with the exponentially increasing volumes of altered rock in the outward succession of zones (fig. 1). The (mathematical) rate of change varies inversely with the width of the alteration halo.

Table 1.--Alteration zones in quartzo-feldspathic rocks, characteristic of the porphyry-metal systems of the southern Rocky Mountains (fig. 2).

PYROGENIC ZONE--The zone in which the hydrothermal fluid separated from the magma. Characterized by primary igneous minerals and by very small amounts of ore elements and minerals. The hydrothermal fluids removed most of the ore elements and some potassium from the magma. Pegmatites represent a final residue of hydrothermal fluids trapped in this zone by the sealing effects of crystallization.

METASOMATIC (potassic) ZONE--A principal site of stockwork deposits, and of pyrometamorphic deposits where the intruded rocks are carbonates. Commonly recrystallized to a granoblastic texture and characterized by the substitution of potassium for calcium and sodium in quartzo-feldspathic rocks and of silicon for carbon dioxide in carbonate rocks, thus a zone mainly of exchange. Biotite and K-feldspar are the principal secondary minerals, although muscovite and quartz commonly occur as greisen selvages along joints and veins. Permeability of this zone is usually a stockwork of fractures formed by thermal shrinkage and by dilation. The alternating opening of these fractures and their subsequent sealing by mineral fillings is the pressure-modulating mechanism for the cyclic deposition of ore and gangue minerals in the stockwork deposits. Fluids dammed by this zone during periods of sealing altered the underlying pyrogenic rocks to phyllic and propylitic stages (fig. 2).

PHYLIC (subtractive) ZONE--This is the zone of maximum exchange between rock and fluid, but also the zone where ore deposits are notably few. Cations are extensively leached from the rock in exchange for water and sulfur to produce a pyritic quartz-sericite or quartz-clay rock, corresponding to the destruction of all feldspars. Where both feldspars are present, plagioclase is replaced before K-feldspar begins to react (saussuritic subzone). An increase in permeability results from a net loss of rock substance, and differs greatly throughout the zone. The more permeable (visibly vuggy) and coarser grained (sericitic subzone) of the phyllic-altered rocks are along intrusive contacts and other structural breaks that have served as major conduits (U.S. Geological Survey, 1973) for hydrothermal fluids. The solute concentration of the fluid is greatly increased by fixation of water in sericite and clays and by dissolution of calcium and sodium in feldspar destruction. Ore metals are thus concentrated to the point of precipitation in the outer reaches of the phyllic zone and in the succeeding propylitic zone.

Solfataric subzone--

This zone which contains the associated chimney deposit as an integral part, is characteristic of the volcanic throat and is at or near the surface, where it is associated with deposits of native sulfur. Like vuggy-sericitic-altered rocks at depth, solfataric alteration is an extreme variety of phyllic alteration, wherein the rocks, mostly fragmented, are extensively leached, leaving a very porous residue of quartz and aluminous minerals. The secondary minerals are alunite, diaspore, kaolinite, and pyrophyllite, in addition to or in place of sericite, and chalcadony, opal, and recrystallized as well as relict quartz. Quartz forms a sheath on the chimney deposits within the solfataric zone; the cyclic forming and breaching of this sheath modulates the flow of hydrothermal fluids and the deposition of ore minerals. Intense weathering of phyllic-altered and even of propylitic-altered rocks produces changes like those resulting directly from solfataric alteration (Whitebread, 1976).

PROPYLITIC (additive) ZONE--A zone of net, if small, addition of substance to the rock and the principal site of argentiferous galena-sphalerite veins. Albite, calcite, chlorite, epidote, and montmorillonite are the prominent secondary minerals, derived from the breakdown of plagioclase and of mafic minerals. Iron sulfides and ore-metals, most conspicuously lead and zinc, are added to the rock. Fabric permeability is reduced, restricting subsequent fluids to structural openings and thereby forming fissure-vein mineral deposits. A thin sheath of additionally altered rock encloses these veins, and this rock is noticeably enriched in ore metals and minerals compared with equivalent rocks of the pervasive alteration zones that surround stockwork deposits.

CHLORITIC ZONE--The outermost zone of visibly recognizable hydrothermal-type alteration, which in volcanic rocks may equally result from reactions with surface waters during extrusion and deposition, and in metamorphic rocks by both progressive and retrograde metamorphism. Common secondary minerals are carbonates, celadonite (Wise and Eugster, 1964), chlorites, montmorillonitic clays, silica minerals, and zeolites, partly replacing rock minerals and partly lining fractures and other rock cavities. Traces of ore elements and minerals are sporadically added here, and in otherwise unaltered rocks beyond this zone. Vein deposits continue into and through this zone, but are uncommon and widely separated. Metal-enriched fracture coatings are the final expression of mineralization beyond the chloritic zone (Tweto and others, 1970, p. 37).

The mineral deposits of the porphyry-metal system are integral parts of the alteration sequence, being in one sense the latest and most intense zone of alteration (Sales and Meyer, 1949, p. 468, 1950, p. 265) wherein large amounts of ore-minerals are added to or wholly substituted for the country rock. Mineralization consists of added and redistributed elements whose precipitation resulted from changes in the hydrothermal fluid by rock alteration. Precipitated elements are spatially displaced into regions of post-alteration permeability: fabric openings--disseminated, cracks--stockworks, and fissures--veins. Like the other alteration zones, the arrangement of the various types of mineral deposits in the porphyry-metal edifice is systematic. Four major structural and compositional habits characterize mineral deposits of the porphyry-metal system:

- (1) Pyrometasomatic deposits: irregular, massive replacements of country rock by copper, iron, molybdenum, tungsten minerals, and quartz, mostly near the juncture of the batholith and its stocks and generally in the metasomatic zone of alteration (Kennedy, 1953; Kinnison, 1966; Knopf, 1942; Titley, 1973); a petrographic variant of
- (2) Stockworks of veinlets and disseminated copper and(or) molybdenum sulfides in metasomatic, phyllic, and silicic alteration zones. Quartz gangue, redistributed silicon, is prominent and extends outward as a halo over the sulfide ores. These deposits may occur anywhere along the vent column; they are the classical porphyry-copper (and porphyry-molybdenum) deposits.
- (3) Fissure-veins are in envelopes of additionally altered, already pervasively altered rock and are prominently associated with dikes. These veins are essentially an end member of propylitic alteration, superimposed on any or all of the other alteration zones, but mostly on the propylitic and chloritic zones. Lead, manganese, silver, and zinc are the principal metals of these veins, but bismuth and tungsten are locally ore-metals in the veins (Lovering and Tweto, 1953; Singewald, 1951) as well as in stockworks (Wallace and others, 1968, p. 623) in the southern Rocky Mountains.
- (4) Chimneys, or pipes, of vuggy, silicified and solfataric-altered brecciated rocks in the volcanic hood (Burbank and Luedke, 1969; Steven and Ratte, 1960). The principal ore-metals are arsenic, copper, gold, and silver.

Crater Creek study area

The study area, on the west edge of the Platoro caldera, is the Crater Creek drainage basin and environs at the head of the East Fork of the San Juan River in the southern San Juan Mountains, Colorado (fig. 3). The relationship of the Crater Creek study area to the San Juan volcanic field and the Colorado mineral belt is shown in figure 4. The area includes the Crater and Elwood mining districts, which have no recorded production. Mineralized rock, however, is abundantly evident in brightly iron-stained rocks, copper-lead-zinc veins in prospect pits and adits, an outcrop of molybdenite vein-stockworks, and deposits of ocher and ocher-cemented talus (fig. 5). The Crater Creek area was part of a wilderness study; sample data are presented in the wilderness reports (U.S. Geological Survey and U.S. Bureau of Mines, 1977; Whittington and others, 1976); and the geology of the area is described by Lipman (1974, 1975).

The mineralized rocks of the San Juan Mountains are in Clark's (1972) Colorado-New Mexico molybdenum province. This metallogenic province is essentially coextensive with the southern Rocky Mountains Cenozoic volcanic field (Steven, 1975), or petrographic province. Petrographic and chemical properties of the southernmost porphyry-metal edifices (Thompson, 1968) of Clark's province are not congruent with the rest of the province, and are herewith excluded. Three epochs of porphyry-metal mineralization are in the domain of the southern Rocky Mountains volcanic field and are each characterized by molybdenum. In addition to the Oligocene porphyry-molybdenum cluster, typified by Climax and Urad-Henderson, the other two epochs (fig. 4) are Cretaceous-Paleocene, represented by the Blowout at Ouray (King, 1970, no. CO-55) and the Apex stock (Tweto, 1968, p. 580; Cunningham and others, 1977), and Miocene, represented by Chicago Basin (Steven and others, 1969; Cunningham and others, 1977).

The mineralized rocks of Crater Creek are part of an arcuate cluster of porphyry-metal edifices, which are most extensively exposed in the Platoro caldera. Structural but not genetic association (Whitney, 1977) of mineralized rocks with calderas is a prominent congruous property of the San Juan Mountains segment of the southern Rocky Mountains province (Lipman and others, 1973; Steven and Lipman, 1976; Steven and others, 1974b). Identification of the Platoro caldera mineralized rocks with the other mineralized rocks of the San Juan Mountains is well established geologically (Lipman and Steven, 1971; Steven and Ratte, 1960) and further documented by chemical analyses (Fischer and others, 1968; Fisher and Leedy, 1973; Sharp and Gualtieri, 1976; Steven and others, 1969). Mineralization was localized (Lipman, 1975) by the intrusives and by faults in the caldera and by the Pass Creek-Elwood Creek-Platoro fault zone, a complicated graben structure that extends from southeast of Platoro northwestward to Wolf Creek Pass (fig. 3) for 33 km. Conspicuous features of the caldera and the graben are small stocks, a variety of dikes, iron-stained pervasively altered rocks, ocher deposits (Neuerburg and others, 1976), and scattered deposits of Cu, Au, Pb, Mo, Ag, and Zn minerals. Some of the mineral deposits had appreciable production (Patton, 1917; Steven and Ratte, 1960). Several episodes of intrusion and associated hydrothermal alteration and mineralization, collectively comprising periodic volcanic venting of the San Juan batholith are represented (Lipman and Steven, 1971; Lipman and others, 1976; Steven and Lipman, 1976). Most of the exposed mineralized rock in the graben and in the

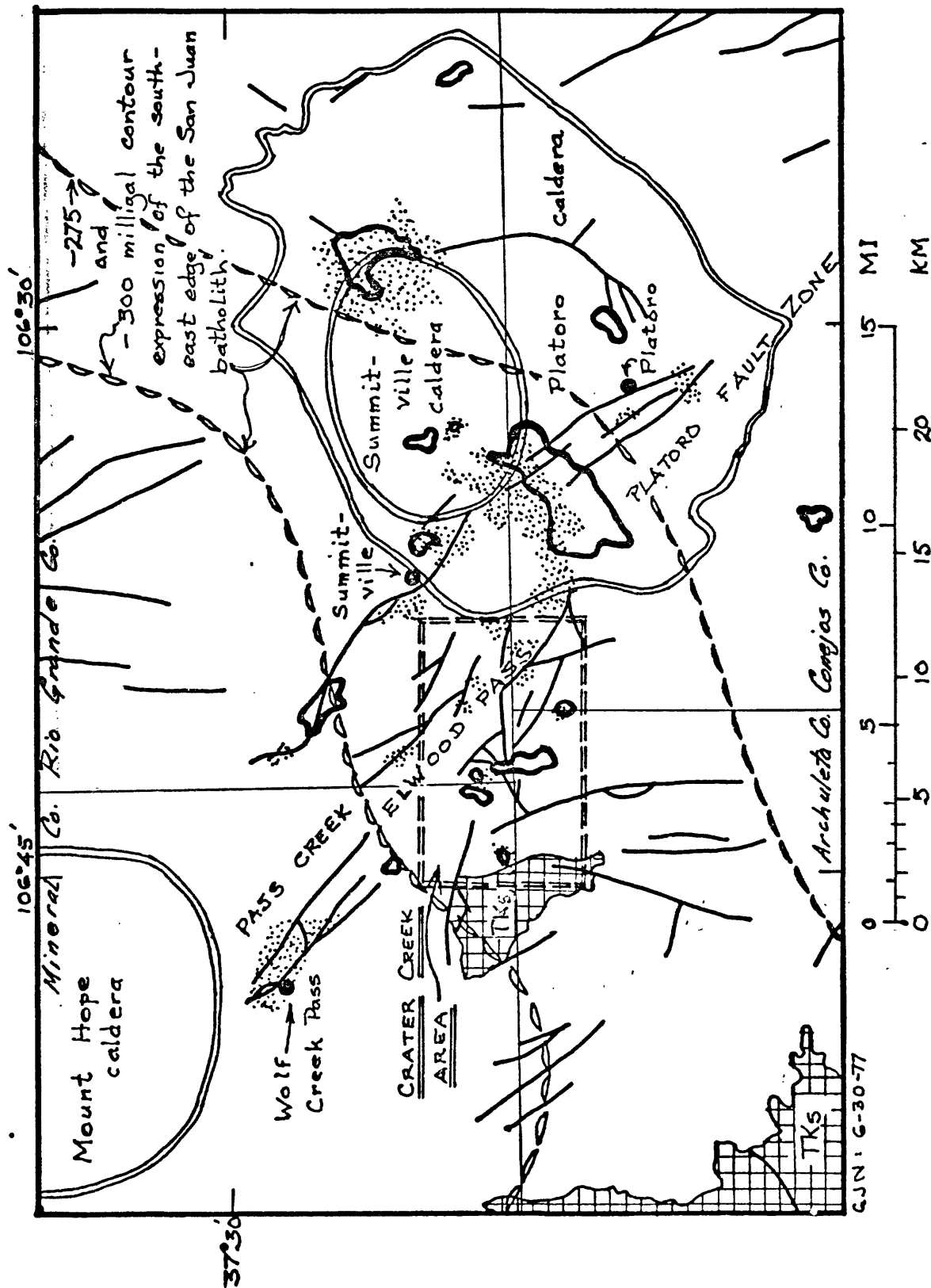


Figure 3.--Geologic setting of the Crater Creek area showing faults (solid lines), stocks (heavy outlines), altered rocks (stippled pattern), and Cretaceous and Tertiary sediments (grid pattern, TKS). Modified from Lipman (1975, fig. 51), Plouff and Pakiser (1972), Steven and others (1974a), and Steven and Lipman (1976).

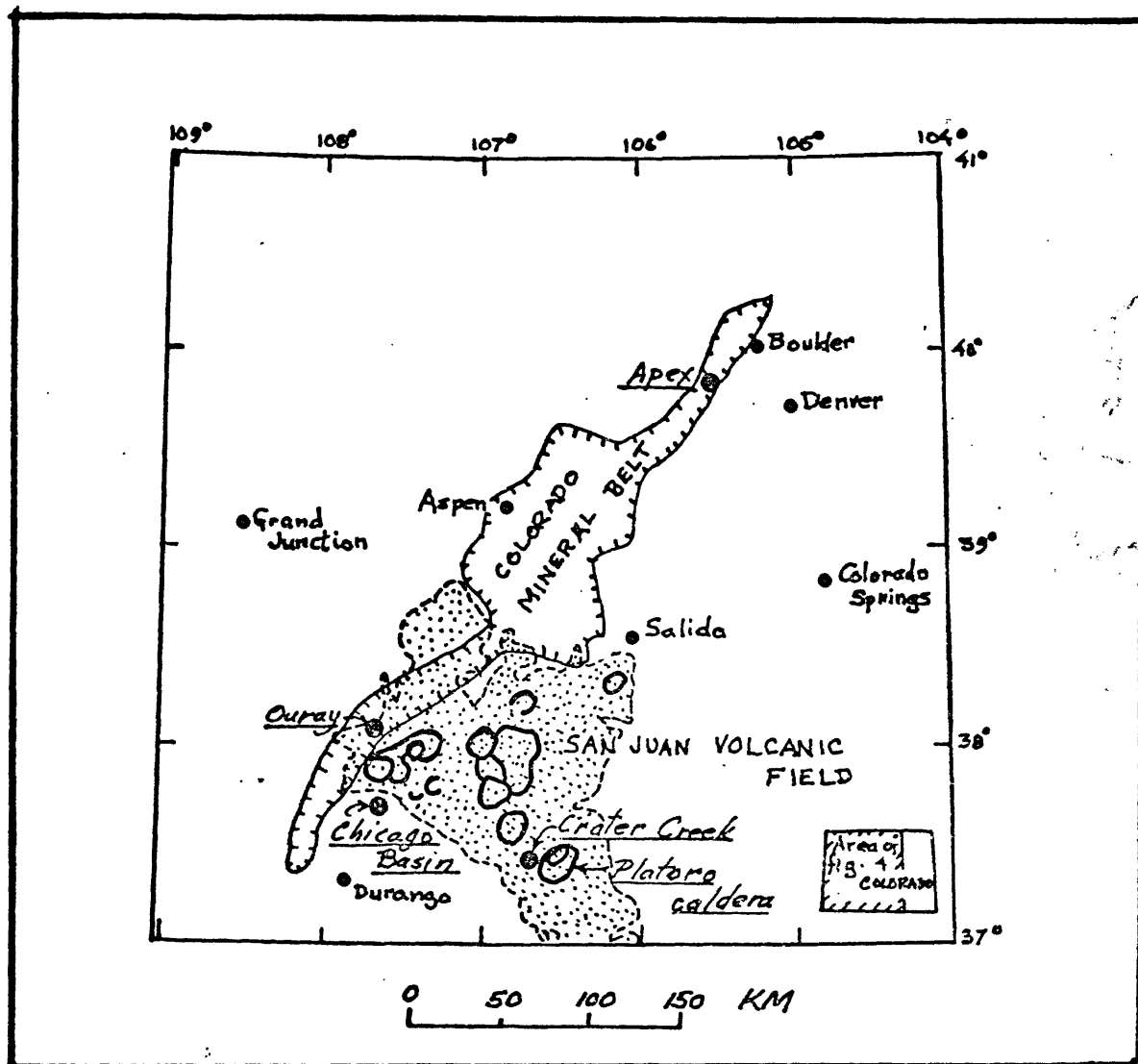


Figure 4.--Index map of central and western Colorado, showing the Crater Creek study area in relation to the San Juan volcanic field and the Colorado mineral belt. Calderas in the San Juan volcanic field (Lipman, 1974) are shown by heavy outline.

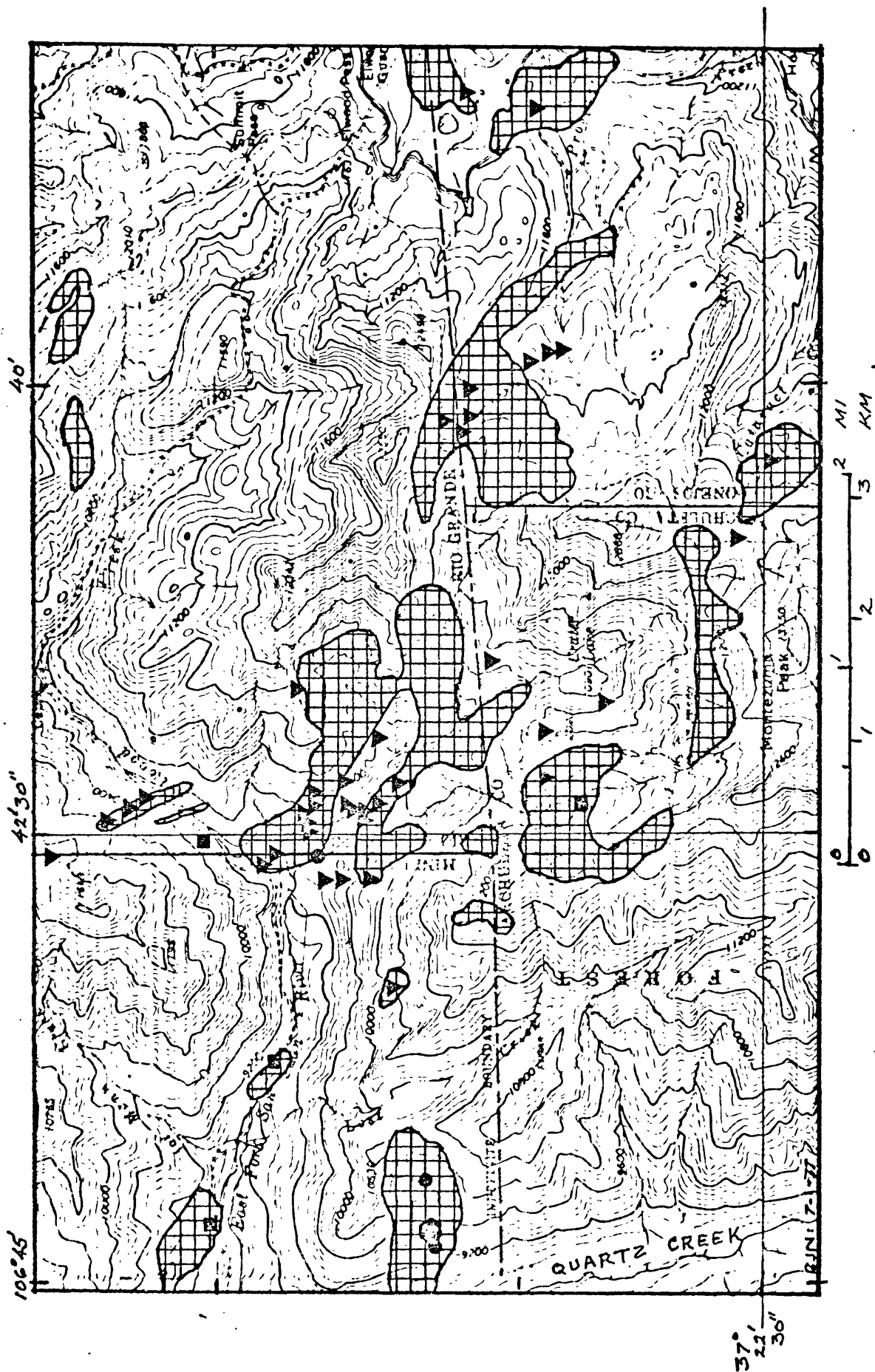


Figure 5.--Areas of iron-stained rock (grid pattern) and mineral deposits in the Crater Creek area: veins (triangles), stockwork molybdenum (hexagon), mineralized cobbles in a volcanic conglomerate (squares), and other-cemented gravels (circles).

Platoro caldera matches the upper part, or hood sequence, of the porphyry-metal edifice (fig. 2). The successive episodes of venting were all displaced laterally as far as can be determined from surface exposures.

Mineral deposits of the Platoro caldera are associated in particular with two of the several intrusive rock types of the region (fig. 6): (1) Oligocene stocks partly composed of a distinctive pyroxene monzonite or granodiorite, similar (fig. 7) to rocks of the Oligocene (Marvin and others, 1974) Ophir and Wilson Peak stocks of the San Miguel Mountains (Bromfield, 1967) on the west edge of the San Juan volcanic field, and to rocks of the Paleocene (Marvin and others, 1974) Caribou stock near the north end of the Colorado mineral belt (Bastin and Hill, 1917, p. 42-49), and (2) Miocene dikes of a texturally distinctive quartz latite porphyry. This texture (fig. 8) consists of large, 3-7 cm, K-feldspar porphyroblasts (Neuerburg and others, 1974) in a porphyry of appreciably smaller, 1 cm or less, phenocrysts and phenoclasts of plagioclase, quartz, and biotite in a fine-grained to aphanitic groundmass. Rock of this biporphyritic texture is conspicuous among the quartz phenocryst-bearing intrusive bodies with which most of the San Juan mineral deposits are associated (Lipman and others, 1976). Rocks of this texture, ranging in age from Paleocene to Oligocene, are commonly associated with ore throughout the Colorado mineral belt, where they are called "Lincoln porphyry." Parts of many biporphyritic intrusives are altered to the highly permeable vuggy quartz-sericite rocks that were major conduits for hydrothermal fluids (U.S. Geological Survey, 1973, p. 18), far more commonly than any other textural variety of intrusive rock associated with the porphyry-metal system. Biporphyritic texture is the outstanding congruous petrographic element of the southern Rocky Mountains porphyry-metal province. Biporphyritic texture of quartz-bearing igneous rocks and the pyroxene monzonite are unifying products of the long-lived batholith (Tweto and Case, 1972) that gave rise to the Cretaceous and Oligocene periods of mineralization of the Colorado mineral belt.

Areas of altered rock (table 2) in and near Crater Creek (fig. 4) enclose copper-lead-zinc veins of the chimney habit and of the pervasive propylitic zone (fig. 2), and also enclose a molybdenite stockwork. Five episodes of mineralization are recognized in the Crater Creek area.

- (1) The earliest episode is shown by cobbles of pyritized propylitic- and phyllic-altered rocks in a conglomerate bed of the Oligocene Conejos Formation. The cobbles are probably from the mineralized throat of a Conejos age volcano (Lipman and others, 1976). Locally they resemble an intrusive breccia, and are thus a potentially misleading feature in prospecting the area.
- (2) Widespread chloritic alteration in the lavas and volcaniclastic rocks of the area probably reflects reaction with meteoric waters during deposition, rather than a porphyry-metal alteration zone. No mineral deposits related to this chloritic alteration were identified, nor was any ore-element enrichment (Griffitts and Nakagawa, 1960) noted in samples of these rocks.
- (3) An episode of mineralization focused on the monzonite stocks along Crater Creek is represented by the outermost elements of a porphyry-metal edifice. Elongate patterns of hydrothermal alteration (fig. 9) are centered on planar zones of fluidized (Reynolds, 1954) microbreccias and mylonites within the stocks. The hydrothermal parameters are (a) propylitized and chloritized monzonite and adjacent volcaniclastic rocks,

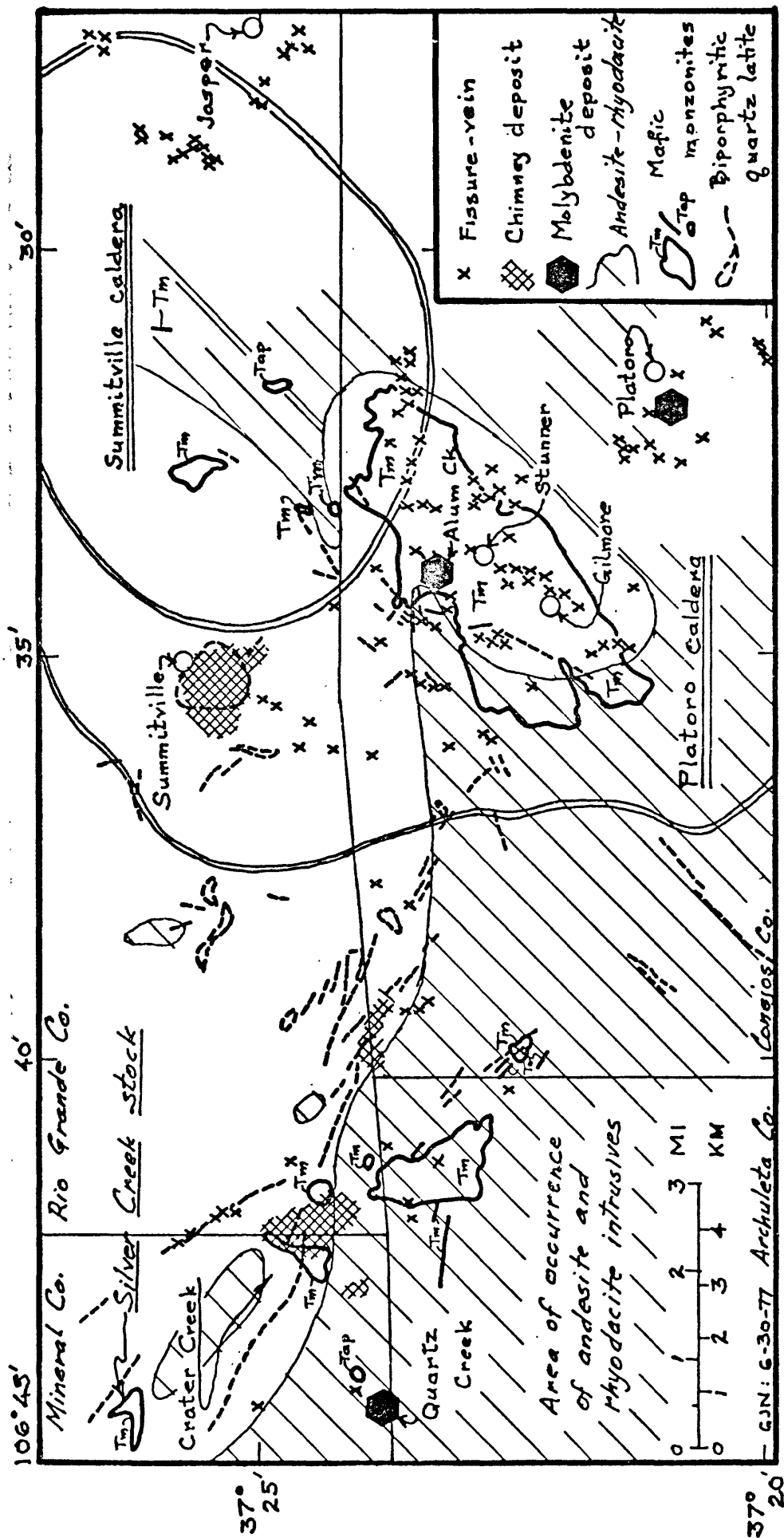


Figure 6.--Distribution of mineral deposits in relation to mafic monzonite and to bioporphyritic quartz latite in the Crater Creek--Platoro caldera area. Tm--monzonite and monzonite porphyry, Tap--andesite porphyry.

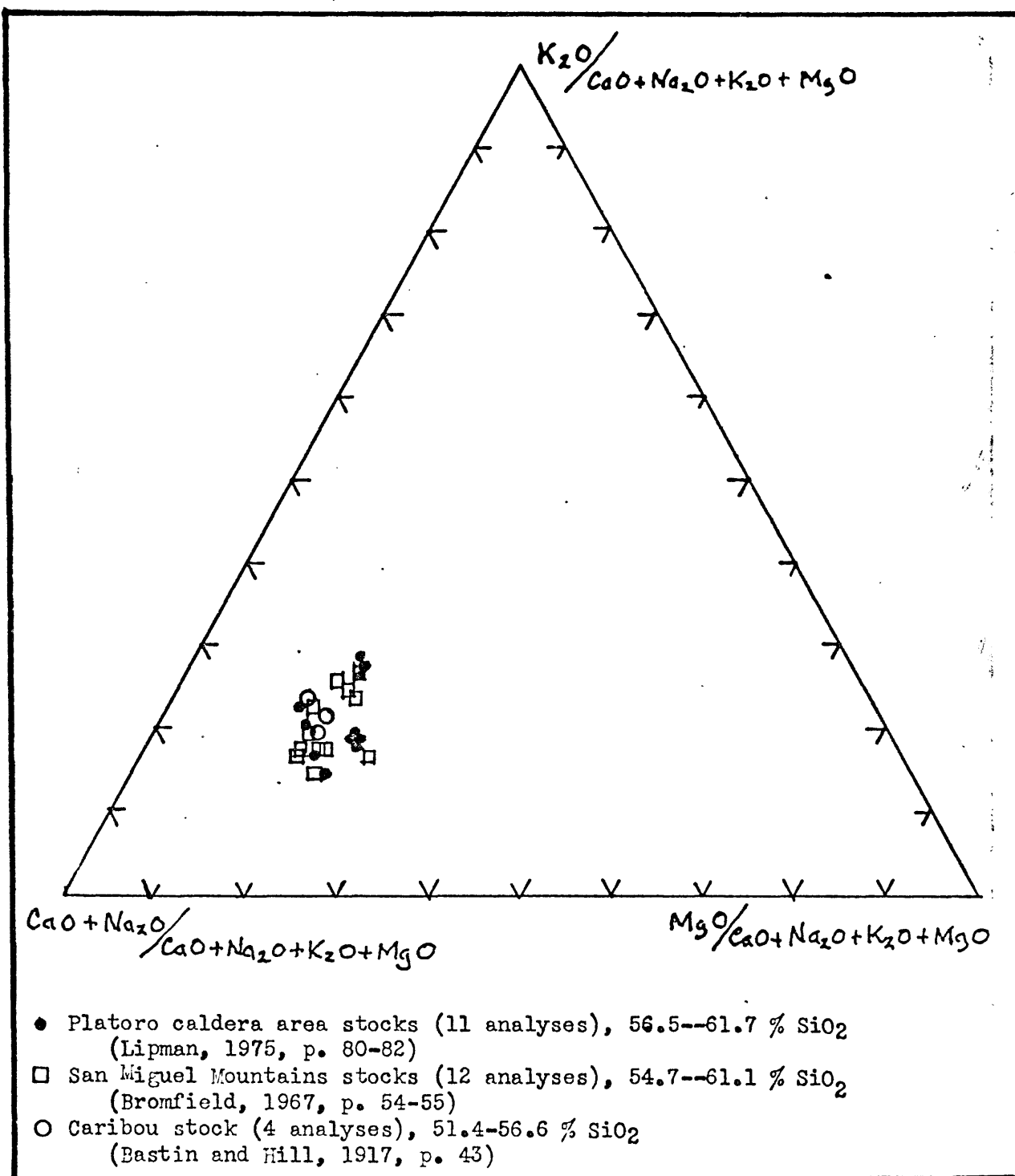


Figure 7.--Chemical congruence of mafic monzonites within the San Juan volcanic field and between the volcanic field and the Colorado mineral belt.

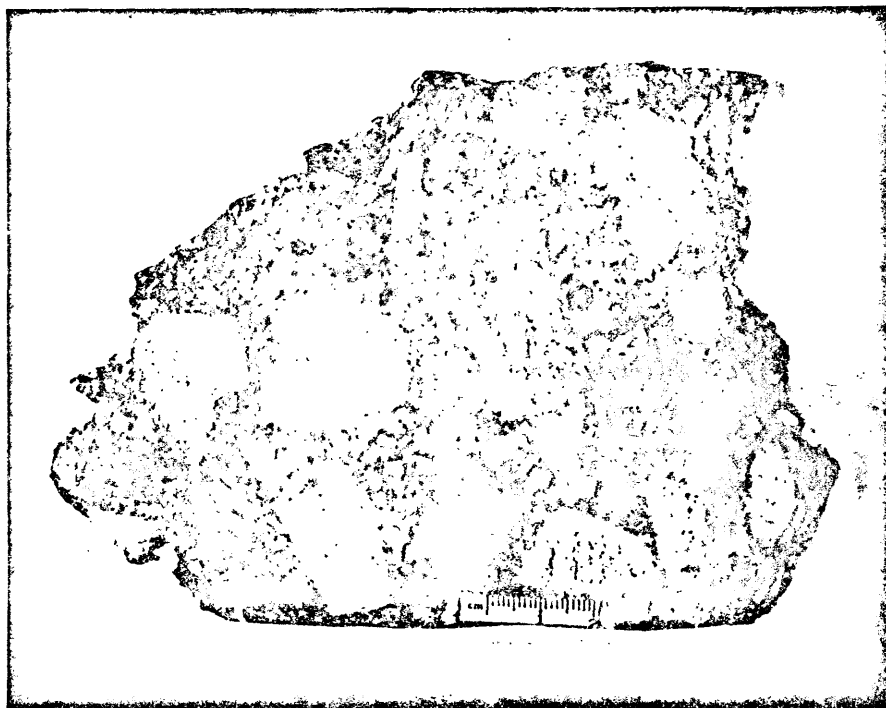


FIGURE 8. Biporphyrritic texture in alunitized and silicified quartz latite, Summitville.

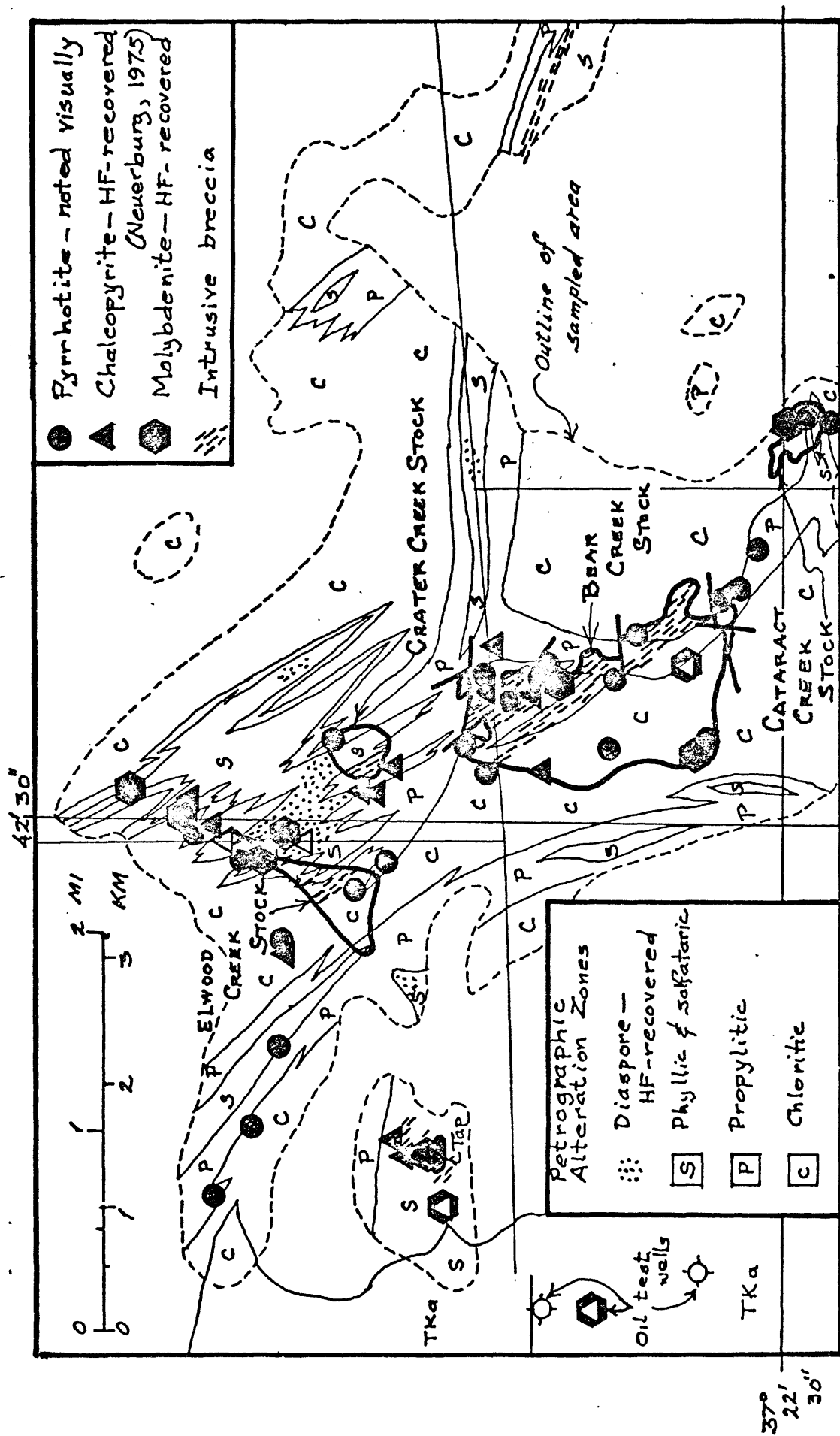


Figure 9.--Distribution of fabric-disseminated chalcopyrite, molybdenite, and pyrrhotite in relation to alteration zoning (table 2) and to mafic monzonite stocks in the Crater Creek area. (Tap - andesite porphyry; TKa - Animas' oration). See figure 11 for separation of phyllic and solfataric chemical alteration zones and figure 6 for location of the Silver Creek stock.

(b) trace amounts of disseminated chalcopyrite, molybdenite, and pyrrhotite, and (c) a few thin veins of quartz, pyrite, barite, and manganese carbonate along with small amounts of antimony, mercury, and tellurium.

- (4) Solfataric-altered rocks, superimposed on the propylitic-altered rocks at the mouth of Crater Creek, are the upper extremities of a chimney deposit. Solfataric alteration digitates upward and outward along faults and dikes from a center between the two stocks at the mouth of Crater Creek. Barite, chalcopyrite, galena, and sphalerite are vein fillings along these structures.
- (5) Sparse molybdenite coats fractures in phyllic-altered volcaniclastic rocks of the Conejos Formation and sandstones of the Upper Cretaceous and Paleocene Animas Formation on the east side of Quartz Creek (fig. 5). Alteration intensity centers to the east on a small plug of andesite porphyry bordered by intrusive breccia. Two exploratory drillings for oil along Quartz Creek (Sinclair, 1963), southwest of the molybdenite deposit, intersected propylitized porphyritic quartz diorite at about 300 m depth. A later drilling between these two drillings (fig. 9) penetrated 300 m of the quartz diorite, at which depth alteration is only slightly chloritic (core-sample courtesy of Benson-Montin-Greer Drilling, Farmington, N. Mex.). This sample yielded a zircon-fission track age of 24.2 ± 2.5 m.y. (Cunningham and others, 1977), in good agreement with the 22.4 ± 0.5 m.y. age for the intrusive rocks (Mehnert and others, 1973) that host the Summitville chimney deposit.

Table 2.--Petrographic and chemical (fig. 10) characteristics of altered rock zones in the Crater Creek area.

SOLFATARIO ZONE--A porous, granular assemblage of quartz, sericite, kaolinite, diaspore, corundum, zunyite, and(or) pyrophyllite, commonly veined by quartz and with abundant pyrite. Original texture may be unrecognizable. Rocks are white or gray on fresh fracture; white to tan yellow or bright brick red are characteristic outcrop colors. Contains 0.5 percent or less calcium and 0.5 percent or less magnesium.

PHYLLIC ZONE--Pyritic quartz-sericite rocks, some with K-feldspar. Pyrite is locally abundant; magnetite is lacking. Textures are blurred but recognizable in most outcrops. Rocks are white on fresh fracture; yellowish, tan, and light brown outcrops are usual. Contains 0.5 percent or less calcium, but 0.7 percent or more magnesium.

PROPYLITIC ZONE--Biotite, amphiboles, and pyroxenes are extensively chloritized. Plagioclase has a dull luster and is altered to albite, clouded by grains of calcite, clays, epidote, and illite. Magnetite is commonly augmented; pyrite and(or) pyrrhotite are common in easily noticeable amounts. Rocks are green on fresh fractures, and rust-brown outcrops are typical. Calcium and magnesium are both 0.7 percent or more; no zonally distinctive chemistry is evident.

CHLORITIC ZONE--Mafic minerals are slightly to moderately chloritized; cavities, fractures and pores may contain calcite, celadonite (Wise and Eugster, 1964), chalcidony, chlorites, and(or) zeolites. Pyrite and(or) pyrrhotite may be locally noticeable. Typically blotchy patterns of alteration. Gray to green, both on fresh fracture and in outcrops. No zonally distinctive chemistry is evident.

The Crater Creek porphyry-metal edifices are in a graben whereas those of the Summitville and adjacent mining districts are in a caldera. Otherwise the geology of the two areas is the same and is physically continuous; rock types, rock alterations, mineral deposits, and their structural interrelations match. Published descriptions of the Platoro caldera sample set (Sharp and Gualtieri, 1968, 1976; Lipman, 1975) do not include the mineralogical data needed to identify, sample by sample, with the petrographic alteration zones of Crater Creek (table 2). However, calcium and magnesium contents of Crater Creek samples group distinctively (fig. 10) with solfataric-, phyllic-, and propylitic- or less altered rocks, and thus serve to define alteration zoning on a common basis in the Crater Creek and Platoro caldera areas (fig. 11).

The porphyry-metal edifices of the Platoro caldera are more deeply eroded and more fully exposed than those of Crater Creek. A much larger proportion of solfataric-altered rocks is in the Platoro caldera sample set (fig. 11). Leaching of rock cations is both more intense and extensive and exposed metallization is more pronounced in the caldera. Weathering is also more intense in the caldera. Most spectrographic analyses of rocks from the caldera were (Sharp and Gualtieri, 1976) made about ten years earlier than those from Crater Creek (Whittington and others, 1976), and include a few from a different laboratory (Lipman, 1975). With these qualifications, distribution patterns of selected elements (fig. 12) from the Crater Creek and Platoro caldera sample sets in relation to phyllic- and solfataric-altered rocks, and thus to stockwork and to chimney deposits, are judged to be essentially congruent. The better known mineral deposits of the caldera thus can assuredly be used to predict the latent mineral deposits of the Crater Creek area.

Latent mineral deposits of Crater Creek

Optimal parts of the Crater Creek area to prospect, and to explore the latent mineral deposits, are shown in figure 13 and briefly described below.

- 1.-- An elongate porphyry-metal edifice is framed on a line of stocks extending from the Cataract Creek stock (fig. 9) northward 10 km to at least the Silver Creek stock (fig. 6). The hydrothermal patterns are conveniently narrow, presenting a well defined and limited area for prospecting. Exposure is of the uppermost extremity of the edifice (fig. 2). The outer edge of the fissure-vein zone is exposed and leakage haloes of latent veins may be detectable by detailed geochemical surveys. A location for the latent stockwork deposits, probably of molybdenite, is not inherent in the available data other than that it underlies the area outlined on figure 13 and is probably at considerable depth. The northern end of the Bear Creek stock might be a good place to start looking with geophysical techniques because it is at the intersection of two major structural trends that localized alteration (fig. 9).
- 2.-- A large area of solfataric-altered rocks at the mouth of Crater Creek and similar areas to the west, near Lost Creek, (2 W., fig. 13), and to the southeast, in Prospect Creek (2 E., fig. 13) delimit exploration of chimney deposits. Alteration in Crater Creek is most intense (fig. 9) and ore-grade veins of galena and sphalerite are found between the Elwood Creek and Crater Creek stocks. The satellitic areas are interpreted as

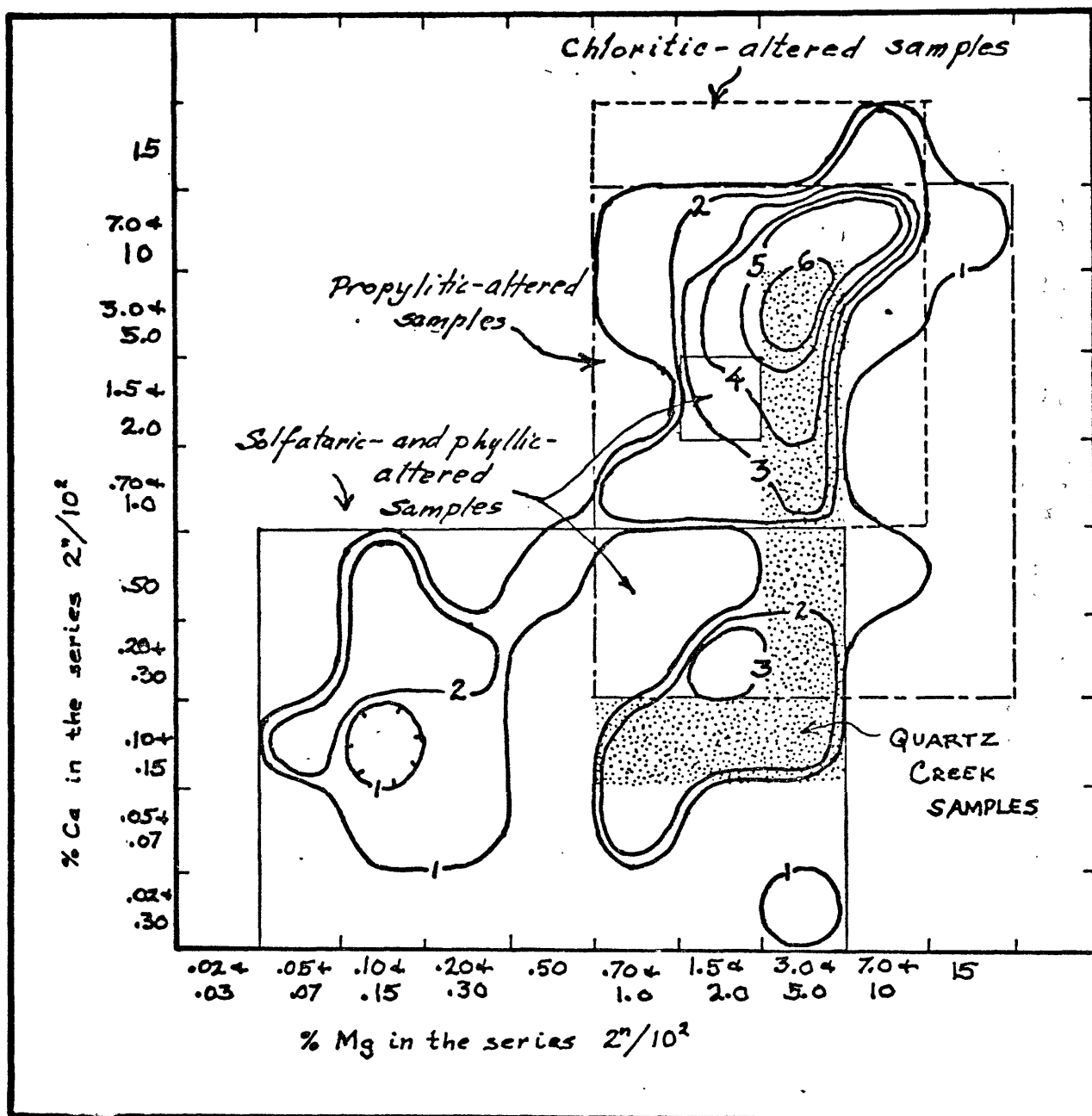


Figure 10.--Contoured scatter diagram (or 3-dimensional histogram) of calcium versus magnesium in relation to petrographic alteration stages (table 2) in samples from the Crater Creek area. Numbers of samples (frequency) contoured at intervals of n in the series 2^n .

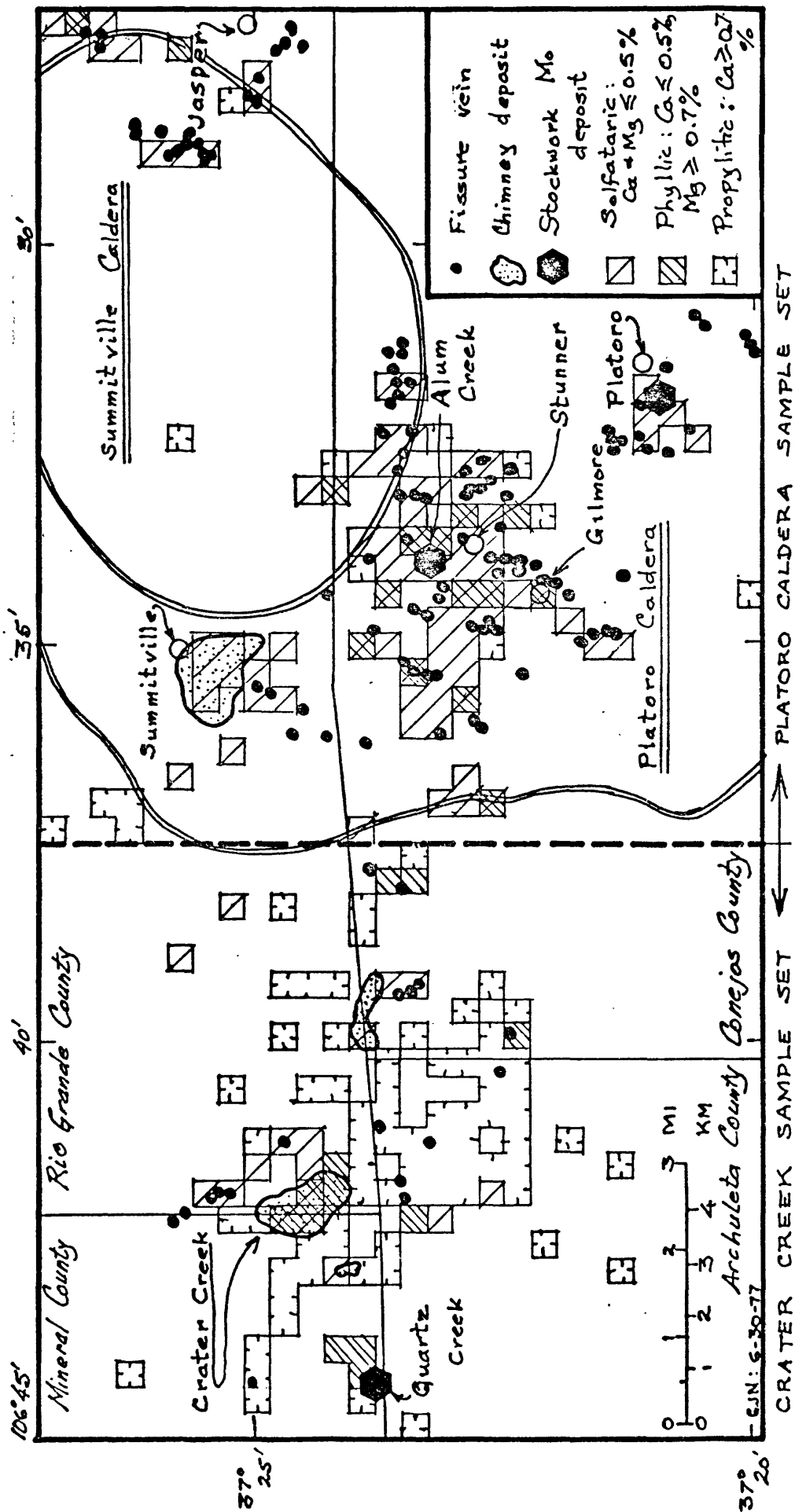


Figure 11.--Distribution of chemically defined self-tactic and phyllic-altered rocks, as products of separate episodes, and thereby superimposed in some cells, and of propylitic- or less altered rocks in the Crater Creek--Platoro caldera areas. Plotting base is a grid of 430 m on a side (2 cm at a scale of 1:24,000).

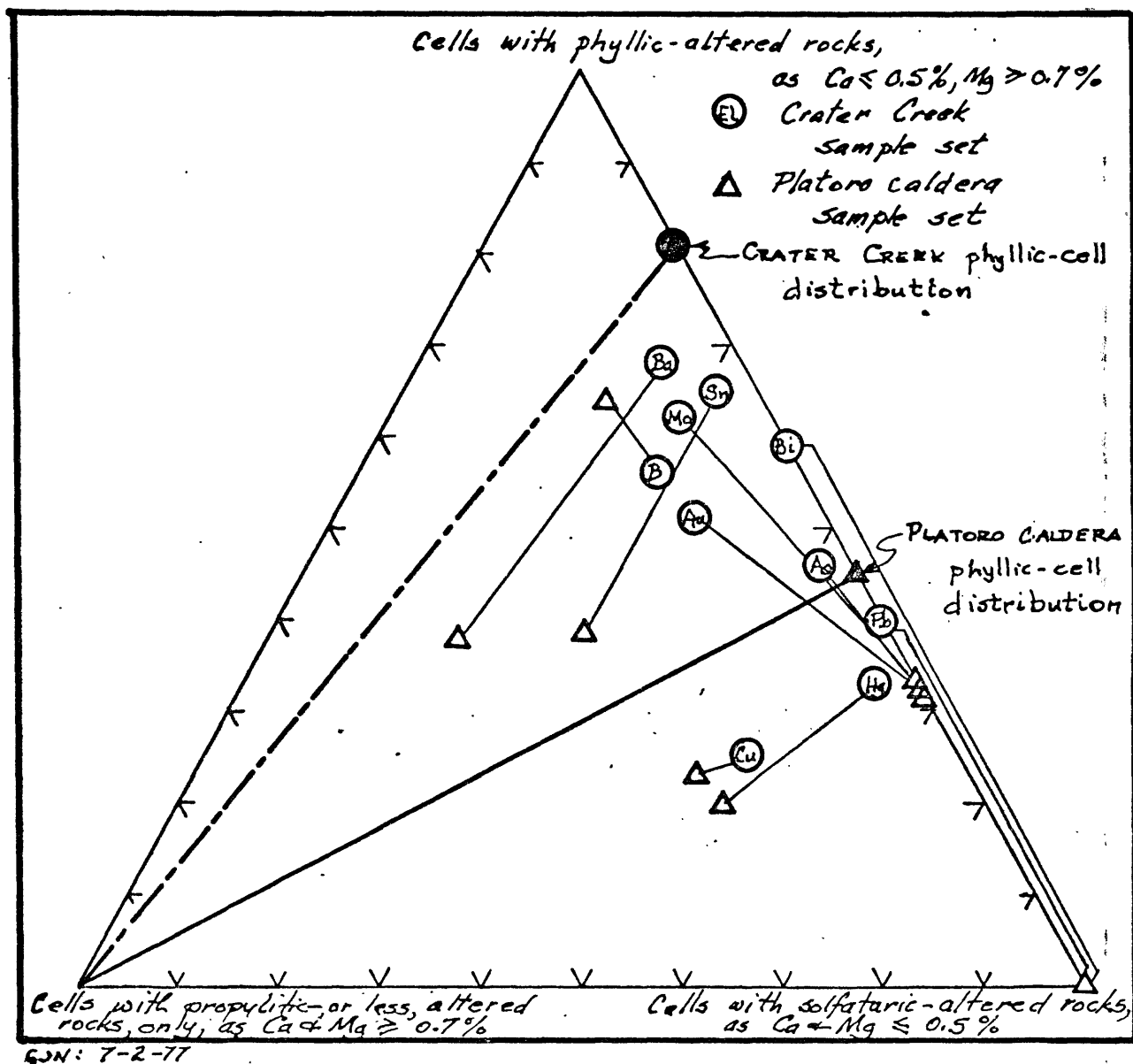


Figure 12.--Distribution of specified high values of selected elements of the Crater Creek sample set and of the Platoro caldera sample set among the alteration cells of figure 11. The highest value for each element from among all samples in each cell is assigned to that cell as its blip value (Neuerburg and others, 1974, p. 11). The distribution of the upper 12 blip values, corresponding to 12 phyllic cells in the Crater Creek set, among the three indicated alteration modes is determined, and recalculated to 100 % for plotting in the triangular diagram. The same is done for the Platoro caldera set, but using the upper 15 blip values to correspond to 15 phyllic cells.

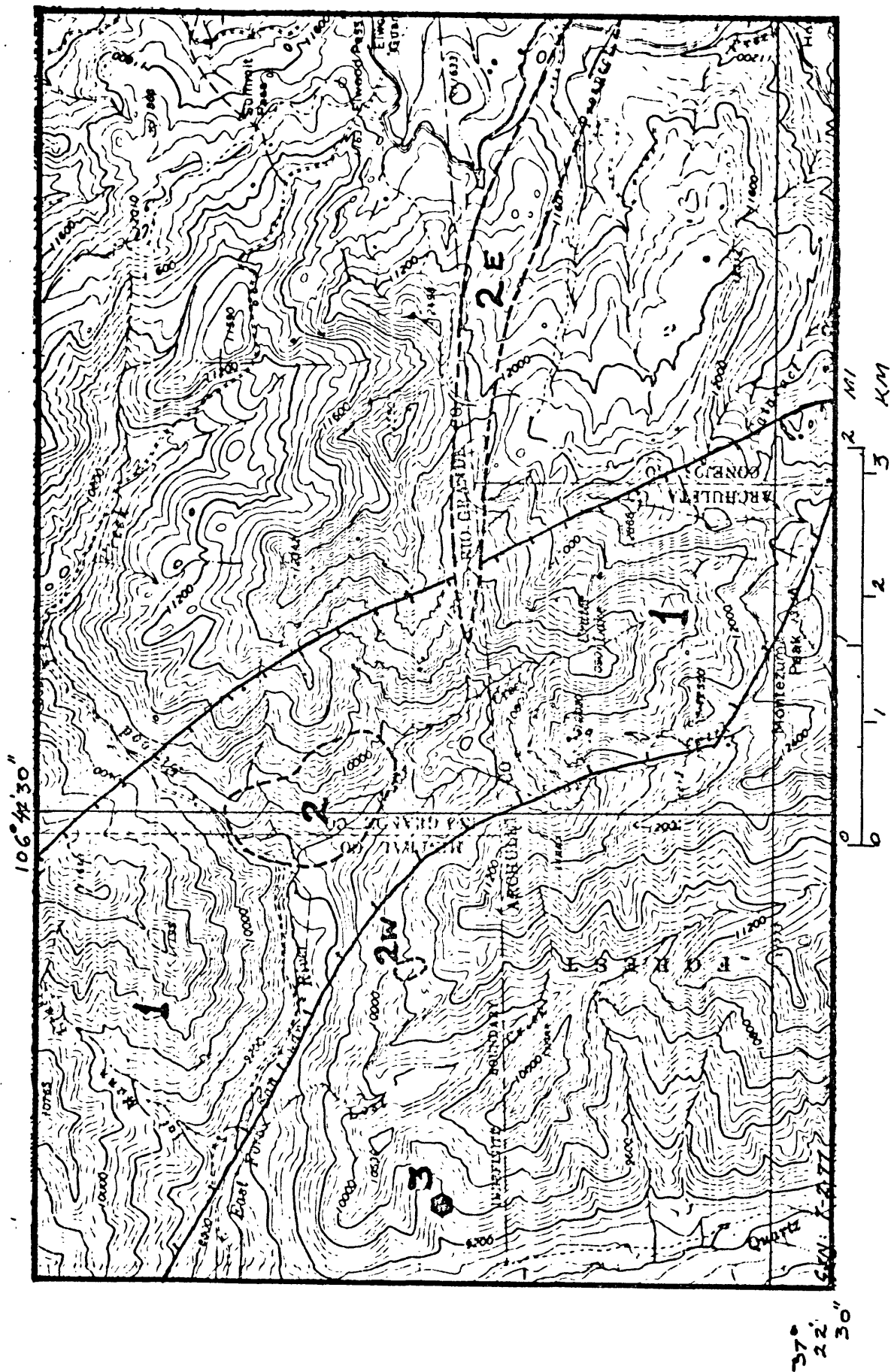


Figure 13.--Optimal areas for prospecting and exploring Grater Creek and vicinity, Archuleta, Conejos, Mineral, and Rio Grande counties, Colorado. See text for discussion of areas 1-3.

evidence of the mineralized structure widening with depth, although the one on the southeast, earlier noted by Steven and Ratte (1960, p. 39) is probably a separate structure, considering its size and distance, 2.5 km, from the area in Crater Creek. The Crater Creek mineralized structure is also indicated by aeromagnetic data (U.S. Geological Survey and U.S. Bureau of Mines, 1977, p. 70). Latent chimney deposits, of similar composition (copper) and size to Summitville (Steven and Ratte, 1960) are deduced to be a few hundred feet below the mouth of Crater Creek and somewhat deeper below Prospect Creek.

- 3.-- The outcrop of a molybdenite stockwork in Quartz Creek is an obvious place to explore. The structural, petrographic, and chemical traits of this deposit are predictable from the Climax (Wallace and others, 1968), Questa (Carpenter, 1968), and Urad-Henderson (MacKenzie, 1970) deposits. However, none of the several molybdenite deposits of the San Juan Mountains (Cook, 1960; King, 1970; Steven and others, 1969; Worcester, 1919) is sufficiently exposed to establish the more parochial habits of depth, size, and tenor of these deposits, much less, therefore, of the Quartz Creek deposit.

Suggestions for further exploration

Published characteristics of the mineralized rocks of the Platoro caldera (Bird, 1972; Calkin, 1967, 1971; Lipman, 1974, 1975; Lipman and Steven, 1971; Patton, 1917; Sharp and Gualtieri, 1968, 1976; Steven and Ratte, 1960) are consistent with the existence of more porphyry-metal edifices than just the chimney deposit of Summitville and the stockwork-molybdenite of Alum Creek (fig. 11). At least one latent chimney deposit is indicated by the extensive solfataric alteration (Sharp and Gualtieri, 1968) in the vicinity of Stunner. A small plug of andesite porphyry in altered Summitville andesite (Lipman, 1974), east of Elephant Mountain in the Platoro caldera, resembles the andesite porphyry plug in altered volcanoclastic rocks of the Conejos Formation near the Quartz Creek molybdenite deposit sufficiently to suggest looking for exposures of another molybdenite deposit. Indeed, the mere noting of an occurrence of molybdenite, as at Platoro (Dana, 1892, p. 1042--or Worcester, 1919, p. 52), is perhaps sufficient indication of a latent molybdenite stockwork deposit to initiate exploration (Rostad, 1969). In any event, more detailed geochemical and petrographic surveys of the Platoro caldera and application of the stratagem of this paper should identify additional latent mineral deposits.

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