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Alteration petrology in the Potosi Mining District Tobacco Root Mountains Montana

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ALTERATION PETROLOGY IN THE POTOSI MINING DISTRICT,

TOBACCO ROOT MOUNTAINS, MONTANA

by

Michael Burnside

B.A., University of Montana, 1970

Presented in partial fulfillment of the
requirements for the degree of

Master of Science

UNIVERSITY OF MONTANA

1975

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Alteration Petrology in the Potosi Mining District, Tobacco Root
Mountains, Montana

Director: Donald W. Hyndman   *(signature)*

   The purpose of this investigation was to study the geology and
alteration petrology of a 3600 by 5000 foot oval area of heavily
veined, fractured, and hydrothermally altered granodiorite in the
Tobacco Root batholith, Potosi Mining District, Montana. Mapping
revealed two steeply-dipping sets of fractures in the area, one
trending north and the other northeast. The Bismark fault, a high-
angle fault with considerable vertical and possible right-lateral
displacement, is the major structure in the area. Two main quartz
veining trends nearly parallel the trends of fractures. Vein
frequency was highest in a wide band north of and parallel to the
Bismark fault. Alteration mineral assemblages and zones consist of:
1. propylitic zone with chlorite, epidote, smectite, and sericite;
2. argillic zone with sericite, rutile, smectite, and quartz;
3. phyllic zone with quartz, sericite, and rutile; and 4. a weakly
pervasive potassic zone with secondary K-feldspar and biotite.
Whole-rock chemical analyses revealed that the phyllic zone was
depleted in Al_2O_3, CaO, and Na_2O, and enriched in SiO_2 and K_2O
relative to the propylitic zone. The argillic zone is intermediate
between the two. The map distribution of these alteration zones shows
a very crude concentric pattern, with an inner discontinuous ring of
phyllic alteration surrounded on all sides by argillic alteration,
which in turn is surrounded by propylitic alteration. Potassic
alteration appears sporadically in the other three zones, but their
mineralogy replaces the minerals of potassic alteration.

   The potassic alteration appears to have formed first, followed by
the propylitic, argillic, and phyllic zones. Of the latter, the
propylitic is least altered and the phyllic most altered. These three
zones probably formed nearly concurrently, as altering fluids migrating
outward from their source reacted with the wallrock, and formed the
phyllic zone nearest the source, the argillic zone intermediate, and
the propylitic zone farthest from the source.

ACKNOWLEDGMENTS

My deepest thanks go to Thomas Butler, of Noranda Exploration, for suggesting the initial project, for patient advice on mapping, sampling procedures, and on interpreting the geology of the area; and who, with Robert Neel, helped in obtaining funding for the project. Sam (Brian) Matthews was invaluable in helping to map and sample the area in that first long summer. Gordon Hughes, of Noranda, was of great help in critically reviewing the final manuscript. Dr. Donald Hyndman visited the area and provided advice on petrologic methods and analyses. Dr. Graham Thompson provided much needed assistance in clay mineral analyses. Dr. Thomas Margrave, with Drs. Hyndman and Thompson, reviewed the manuscript and offered many constructive criticisms.

Special thanks go to my wife, Sylvia, for her good-humored help in sampling, sample carrying, drafting, rock grinding, typing, and in the innumerable other things involved in building a thesis.

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CHAPTER I

INTRODUCTION

Purpose and Scope

The purpose and scope of this thesis is to examine the alteration petrology, extent and geologic setting of a small hydrothermally altered area in the Potosi mining district of the Tobacco Root Mountains. It is hoped that this study will help reveal the nature, shape, and orientation of this alteration pattern in order to aid in the exploration for ore in the area.

Location

The study area is located in the east-central portion of the Tobacco Root Mountains, about 7.5 miles south of Pony, Montana, on the south slopes of Potosi Peak (Fig. 1). The study area is primarily in sections 16 and 17, T. 3 S., R. 3 W. (unsurveyed) in the center of the Potosi mining district, Madison County, Montana. The area of primary interest is crudely oval in shape and in the field appears to be intensely altered hydrothermally. In map view, it has a north-south width of approximately 3600 feet and an east-west length of 5000 feet.

Previous Work

Previous reconnaissance work has been done in the district by Winchell (1914), and Tansley, Schafer, and Hart (1933). Loraine (1941)

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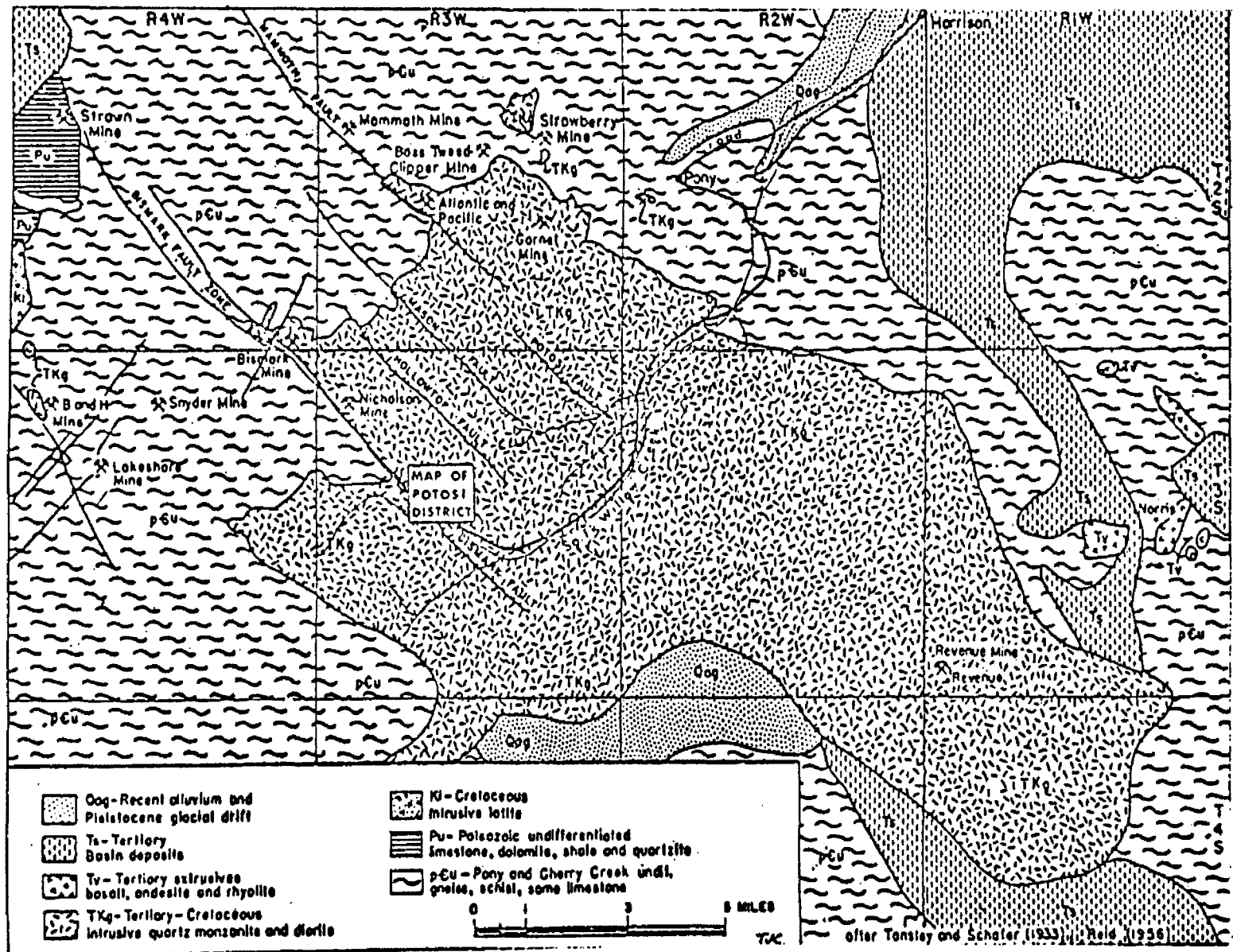
Fig. 1. Generalized geologic map of the Tobacco Root Batholith. Modified from Eyde (1958).

did field work and sampling for the U. S. Bureau of Mines in the district. R. Reid (1957) remapped the geology of the area, but dealt primarily with the Precambrian metamorphic rocks in the northern part of the Tobacco Root Mountains. Eyde (1958) studied the ores at Potosi. Smith's (1970) study of the petrology of the Tobacco Root batholith included mapping of rock types in the batholith based on chemistry and mineralogy.

Mining companies have also done extensive unpublished mapping and sampling in the area. The property is currently held by Noranda Exploration. While working for Noranda in the summer of 1973, the author mapped and sampled most of the study area. Additional mapping, sampling, and laboratory analyses were done in 1974, and were partly funded by a grant from Noranda.

CHAPTER II

GEOLOGIC SETTING

Topography and Surficial Geology

The area ranges from an elevation of 9600 feet at its northern edge to an elevation of 7400 feet at its southern edge (Fig. 2). This is a topographic difference of 2200 feet over a map distance of 3600 feet, an average slope of 31°. The area is on the north side of the U-shaped valley of the upper South Willow Creek drainage. The valley owes its steep-sided U-shape to Pleistocene alpine glaciation which carved the slopes of the valley periodically and left high lateral moraines. One of these lateral moraines blankets the southern part of the study area up to about 8200 feet, but scattered outcrops protrude through the blanket.

Actual outcrop exposure is about 5 percent of the total area. Outcrop exposure is mainly limited to the crests of three main ridges and various roadcuts. Small valleys between the ridges are partly filled with colluvium with some lateral morainal material in the lower ends of the small valleys. The southern ends of these small valleys curve to the east into the northwest-trending Bismark fault zone, which cuts through the southern third of the study area. The fault is discussed in the section on structure. The drainages of the small valleys appear to be subsequent upon this major fault.

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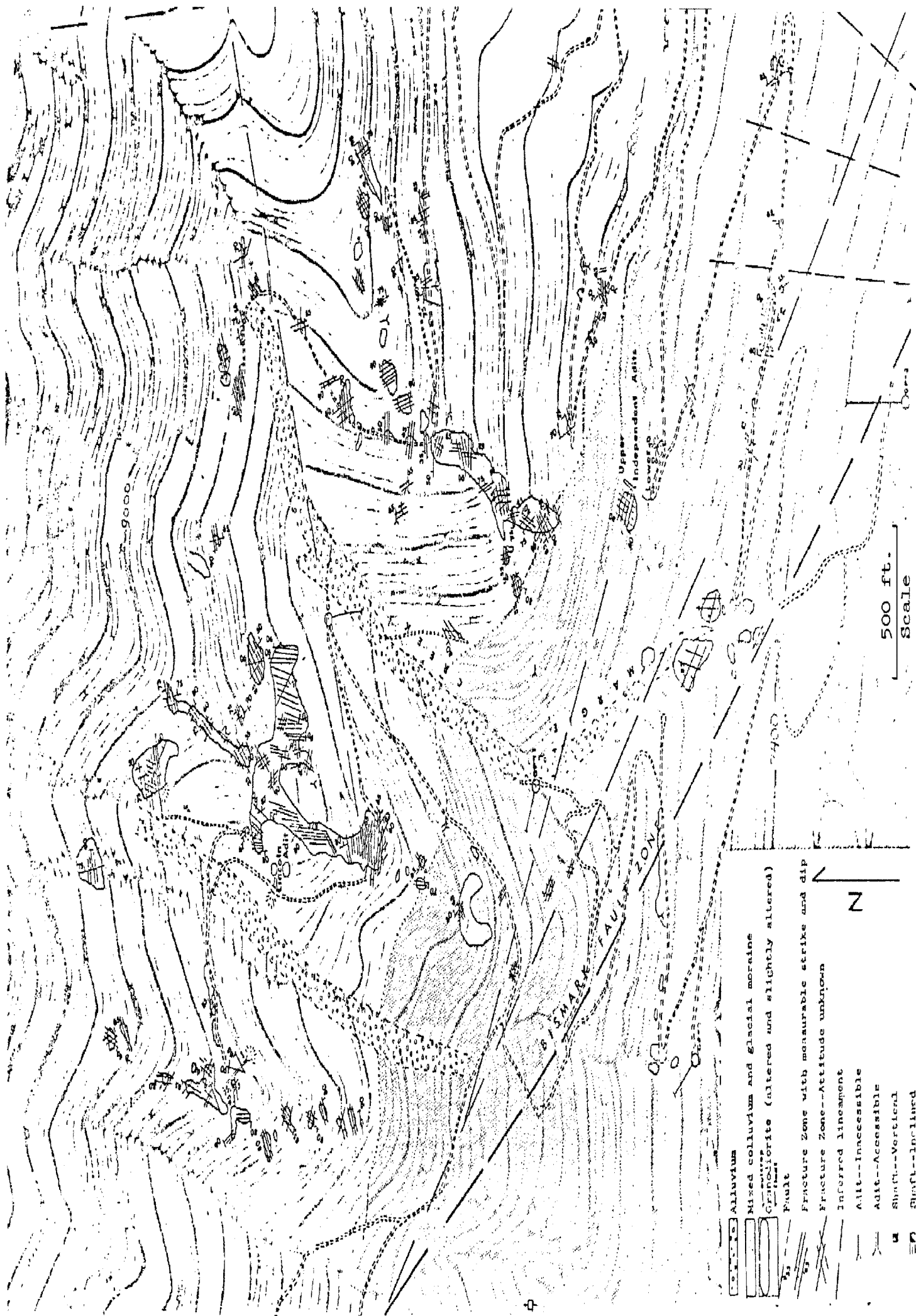
Fig. 2. Outcrop and structure map of the study area at Potosi.

Legend:
- Alluvium
- Mixed colluvium and glacial moraine
- Granodiorite (altered and slightly altered)
- Fault
- Fracture Zone with measurable strike and dip
- Fracture Zone--Attitude unknown
- Inferred lineament
- Adit--Inaccessible
- Adit--Accessible
- Shaft--Vertical
- Shaft--Inclined
- Diamond Drill Hole

500 ft.
Scale

N

Petrologic Setting

The study area lies entirely within the western portion of the Tobacco Root batholith, dated by K-Ar methods at 75 m.y. by Giletti (1966). The area is about one-half mile from the contact of the batholith with schists and gneisses of the Precambrian Pony and Cherry Creek Formations. The batholith, according to Smith (1970), is a single intrusive composed of gradational rock types varying from hornblende diorite and tonalite near the margins, to granodiorite, quartz mon-zonite, and granite near the center. Smith used a modification of Wahlstrom's (1955) rock classification. This system is vaguely similar to Streckeisen's 1973 system. Smith attributes the variation in rock composition primarily to a systematic cooling and crystallization of the batholith from the margins and roof toward the center. The more felsic rock types are concentrated in the center of the batholith. Pre-alteration rocks in the study area are called hornblende to biotite tonalite by Smith (1970). Hornblende tonalite extends through the southern part of the study area along the Bismark fault, ranging to mainly biotite tonalite away from the fault in the northern part of the area. Except for local variations, the present work confirms Smith's descriptions. The author found the unaltered rocks in the study area to be mainly granodiorite to granite in composition (Streckeisen's 1973 classification). These rocks are tonalite under Smith's classifi-cation.

A few small aplite dikes cut the batholith north of the altered area, but none were positively identified in the altered area itself.

Variation in the porphyritic nature of the granodiorite because of the presence or absence of large euhedral megacrysts of K-feldspar was noted in the unaltered rocks of the Potosi district. This distribution of K-feldspar megacrysts seemed to have no regular pattern. These K-feldspar rich areas form widely scattered patches about 10 to 30 feet in diameter. A drill hole south of the Bismark fault, and south of the most intensely altered area, penetrated a rock of unknown extent of near alkali granite composition. The origin of these alkali-rich areas is not known. Smith does not discuss them. It seems likely that they are differentiates of the original magma of the batholith. It is possible that a K-feldspar rich area could have existed in the study area prior to alteration, but no evidence of this has been seen.

Although local variation in rock composition may occur, it is concluded that the highly altered and veined rocks in the study area were, before alteration and veining, texturally and mineralogically essentially the same as the relatively unaltered igneous rocks surrounding the area. This appears reasonable because the study area is contained entirely within the batholith, which Smith (1970) finds is essentially a single intrusive phase. The author also found no evidence for separate intrusives other than the possible existence of a few small aplite dikes already mentioned. Other evidence in support of this is that relict textures suggestive of the original granitic rock texture can sometimes be found throughout the altered area. A gradational destruction and alteration of the texture of the surrounding granodiorite can be observed in a traverse through the area.

Structure

The tectonic fabric of the study area is dominated by the presence of the Bismark fault, which slices through the southern part of the area. It is a major regional high-angle fault. Reid (1957) has deduced that the north side of the Bismark fault moved upward in Precambrian time. He states that it offsets the Precambrian Pony Formation--Cherry Creek Formation contact from 20,000 to 30,000 feet vertically. He also finds that the north side moved upward in post-Paleozoic time (personal communication to Eyde, 1958). Reid (1957) is reluctant to ascribe any sort of strike-slip movement to the Bismark fault based on field evidence he has seen.

The implied displacement of the axis of the Noble Peak anticline suggests some right lateral movement along the fault at some time in the past. In Reid's (1957) map of the area, it appears that a west limb of the Noble Peak anticline may be preserved in the east part of the fault block between the Mammoth and Bismark fault zones. If it is the limb of that anticline, then some right lateral movement since early Precambrian time is indicated along the Bismark. Reid notes that the batholith fingers out along the major northwest faults, such as the Bismark, and suggests that they controlled the emplacement of the batholith.

Within the study area, the Bismark fault seems to widen out into a zone up to about 200 feet wide, of locally intense shearing (Fig. 2). One 10 to 20 foot-wide zone of gouge exposed in an adit on the fault in the study area was described by Eyde (1958). On the ground, the

fault is difficult to locate because of the widening out and the morainal cover. Aerial photo interpretation and Eyde's (1958) map were used to help locate the Bismark fault and other structural trends in the area. Because of lack of outcrop in crucial areas, it was difficult to completely substantiate the aerial photo interpretations. However, shear trends generally matched with implied major structures.

The fracture trends in the study area (Fig. 3) were found by plotting 155 poles to fractures on a Schmidt equal-area net and contouring point densities. Four point maxima emerged, forming a great circle distribution. The great circle distribution suggests the fracture sets are genetically related. If two point maxima occurred close together, they were considered to be one and averaged for interpretive purposes. The four point maxima reflect the two fracture trends generally found in outcrop in different parts of the area (Fig. 3).

The N 10° W, near-vertical shear set shows best development mostly in the northwest part of the area. These shears and faults show horizontal slickensides with a left-lateral sense of movement. Facing the shear and rubbing one's hand in the smoothest direction along the slickensides was the rule of thumb procedure to determine movement when no offsets of geologic features could be seen. Smoothest direction indicated the relative direction of movement of the near side. This set of shears typically cuts and offsets the veins that sub-parallel them. One outcrop in the extreme southern part of the map area, on the west bank of Margie Creek, showed some northwest shears with slickensides well

N 10 W
88 NE

N

N 56 E
75 NW

4%

4%

2%

4%

6%

8%

4% 6% 8%

2%

4%

6%

8%

D=155
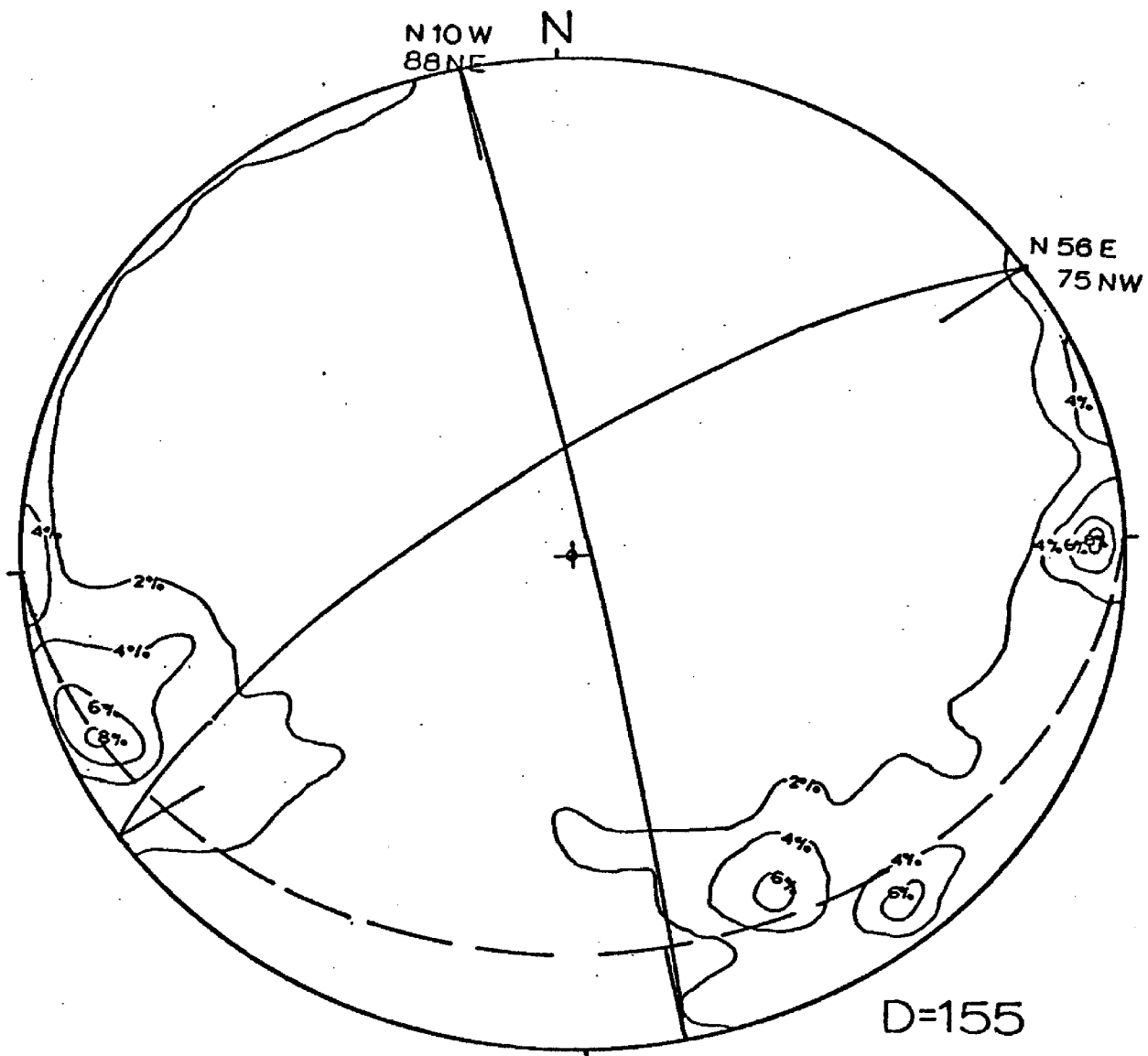
Fig. 3. Stereonet with contoured poles to fractures and generalized fracturing trends at Potosi.

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preserved. The shears are near vertical and have nearly horizontal slickensides that, using the rule of thumb described, suggest right-lateral strike-slip movement. Note on Figure 2 that this is very near the center of the inferred location of the Bismark fault zone. Eyde (1958) also described movement along some northwest fractures.

The northeast-trending set of fractures has an average attitude of N 56° E, 75° NW (Fig. 3). This set is best developed in the eastern part of the map area. It is characterized by fractures, shears, and small faults that vary in dip from 30° NW to 90°, averaging about 75° NW. A general sense of movement along this set of fractures could not always be determined in order to be able to label them all as shear fractures. Field evidence for shearing was scant. Some fractures showed slicken-sided surfaces whereas others did not. It is not known if this is due to the varying states of preservation of slickensided surfaces, or if some of the fractures are extensional or tensional features. However, in some cases these fractures offset veins, indicating movement on at least some of these fractures.

One northeast-trending fault dipping 80° NW displaced a major vein in the northeast part of the map area (Fig. 2). The surface separation of the vein is right-lateral. Whether this apparent displacement in outcrop was due to reverse movement on the fault and later erosion of the upthrown hanging wall, or right lateral strike-slip movement, or some combination of the two could not be determined.

Interpreting the trends of the two main fracture sets in order to infer principal stress axes is difficult, and beyond the scope of this

thesis. However, it seems certain that at least some of these shears must be related to the principal stress axes and movement of the Bismark fault. It also seems likely that the 2 sets are genetically related to each other, since their point maxima form an orderly great circle distribution. It is probable that the major stress axes which generated the fractures were nearly horizontal, since the fractures are relatively steep. There is a superficial geometrical similarity between the Bismark, and the fracture systems in the map area, and the right-lateral strike-slip San Andreas fault, and its wrench fracture systems, described by Moody and Hill (1956). Although this was not investigated further, using wrench fault tectonics to interpret the map area fracturing may be a viable way to explain them. Some circumstantial evidence supports the hypothesis that some post-batholith right-lateral movement took place along the Bismark, although the total movement since early Precambrian time may have been overwhelmingly normal, or dip slip. Some of this "evidence" is outlined in the next section.

Veining

The most striking visual characteristic of the study area, other than its bleached and limonite stained appearance, is the large silicified and heavily quartz-veined rock masses jutting out from the main ridge crests. Quartz veins in these outcrops and throughout the study area vary in width from hairline veinlets to a maximum of thirteen feet. Average width is probably less than a foot, although two to six foot veins are not uncommon. The veins have very little strike length and, according to Eyde (1958), probably do not extend very far down dip, either.

A prospect called the Lincoln Tunnel (Fig. 2) is driven in about 30 feet below the outcrop of a 2 foot quartz vein, yet only a 2 inch wide quartz vein was intercepted in the 100 foot long tunnel. These limitations in dip and strike extent imply that the quartz veins are flattened ellipsoidal bodies in shape (Eyde, 1958).

The veining trends in the area were determined by plotting on a Schmidt equal-area net 188 poles to veins and contouring point densities (Fig. 5). Three major point maxima emerged, although there was the faint hint of another. If two point maxima occurred extremely close together, they were considered to be one, and averaged. The major point maxima reflect the veining found in outcrops through the area. They form a great circle distribution, suggesting that the fractures that probably controlled the locations of the veins are genetically related.

The major northerly-trending set of veins is oriented $N 6^o E$, 79° NW (Fig. 5). The major northeast set can be represented by a plane at N 68° E, 72° NW (Fig. 5). This interpretation of quartz veining basically agrees with that found by Eyde (1958). The most obvious implication of the two major veining trends is that they roughly parallel and are thus possibly related to the north and northeast fracture trends described in the previous section. The primary difference is that there are three pronounced veining point maxima and four pronounced fracturing point maxima.

The northerly-trending vein set prevails in the western part of the map area (Fig. 4). The northeast-striking veins are most abundant in the eastern part of the map area. The quartz veins are of two types:
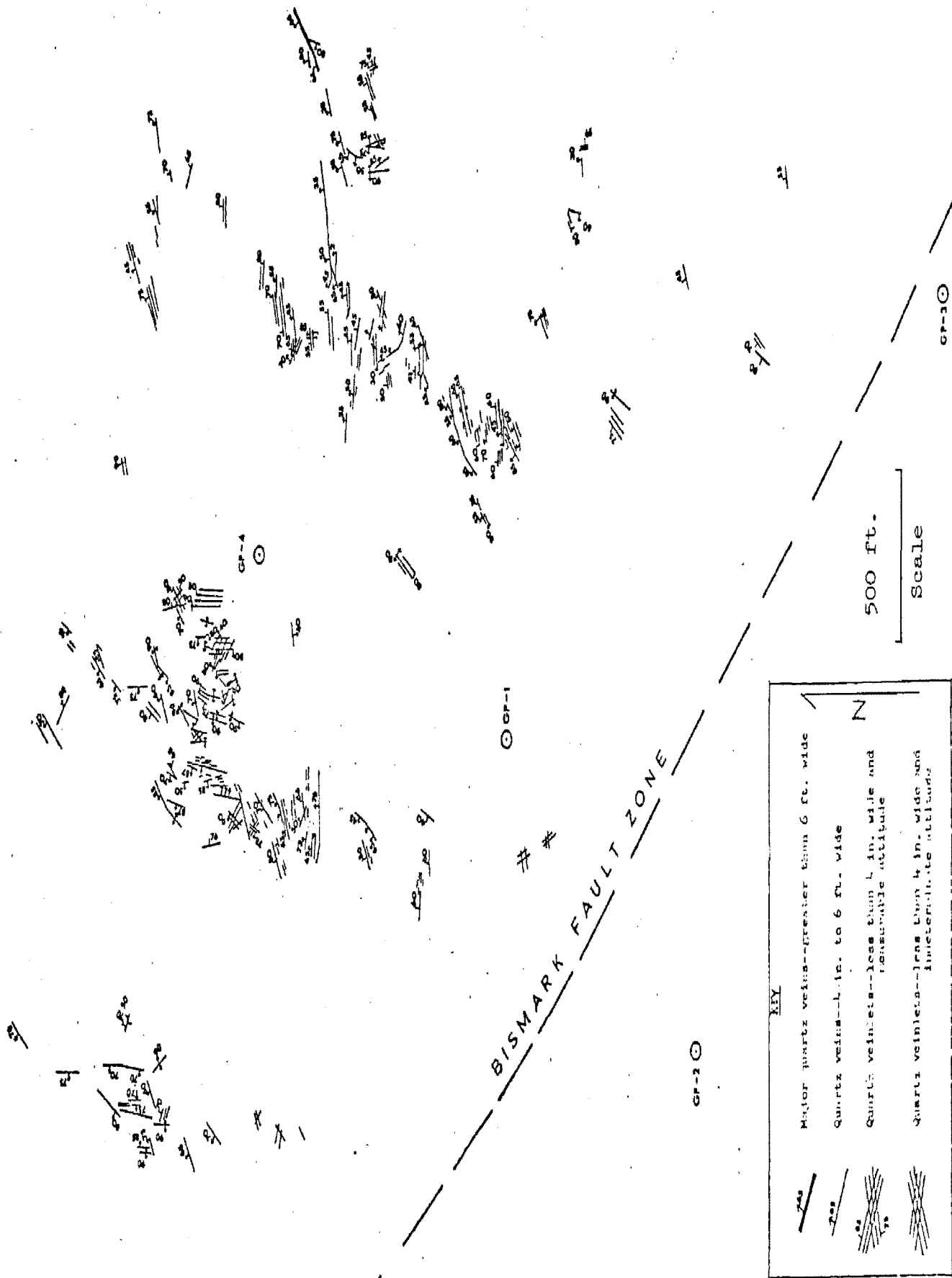
Fig. 4. Map of quartz veining at Potosi.
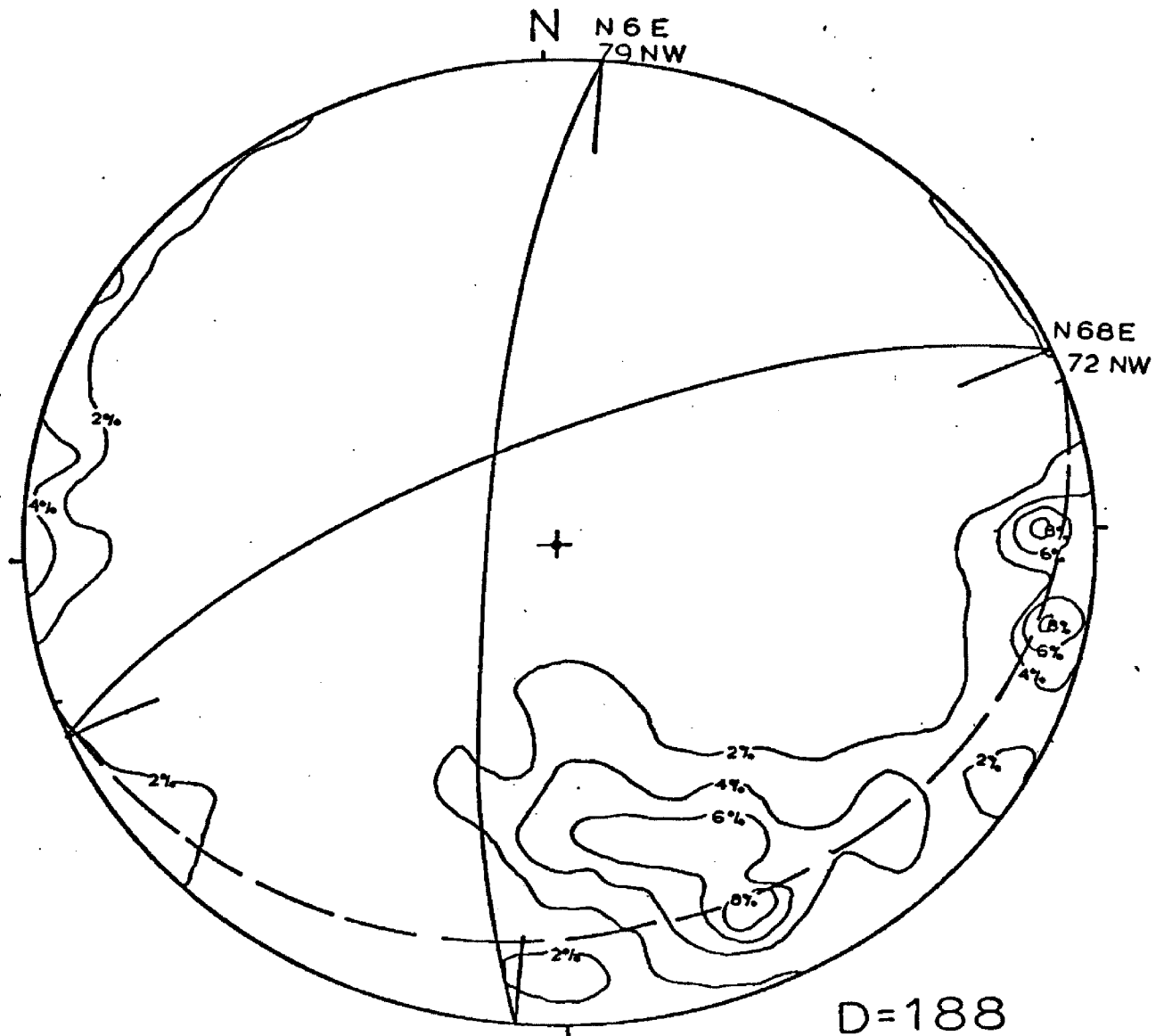
Fig. 5. Stereonet with contoured poles to veins and generalized veining trends at Potosi.

those with distinct boundaries and those with indistinct boundaries that in some cases grade into the country rock. The first type are probably fracture fillings and the second may be replacement veins localized along a fracture. Some veins are difficult to classify into either type. Fracture filling probably involves some replacement. The veins with the distinct boundaries are mostly, but not everywhere, peripheral to the most highly altered zones. Veins with the indistinct boundaries are commonly, but not exclusively, in the highly altered zones.

Many of the quartz veins seem to have formed over a narrow time span because where many major quartz veins intersect in the more highly altered areas, no clear cross-cutting relationships, or replacement textures of one vein through another can be seen in handspecimen. Thus, they seem to merge, suggesting near simultaneous emplacement. However, based on thin-section investigation, Eyde (1958) described four periods of quartz filling interspersed with brecciation. He does not suggest whether the different sets of veins were at different times. Most of the veining appears to have occurred over a narrow time span, though there may have been subsequent weaker episodes with less precipitation of quartz.

If the quartz veining stereonet is superimposed on the fracture stereonet (Fig. 5 on Fig. 3), the two major northerly and northeasterly veining trends correspond to the two similar northerly and north-easterly fracturing trends, but they do not coincide exactly. In order to make the two respective trends of veining and shearing coincide nearly exactly, the quartz veining stereonet must be rotated 12° counter-

clockwise. The fractures represented by the quartz veins on Fig. 5 are mostly earlier than the fracturing on Fig. 3 since large numbers of the fractures of Fig. 3 cut the veins of Fig. 5. If the stress axes were the same that produced both 1.) the fractures that were later filled by quartz, and 2.) the still later post-veining fractures, then rotation of the rocks has taken place before or concurrent with the formation of the post-veining fractures. The rotation would have been in a clockwise manner. This supposes that the quartz vein-filled fractures originally formed parallel to the post-veining fractures now seen, but have been rotated in some manner, perhaps by distortion of the block north of the Bismark. This distortion of the block would have had to have been in a right-lateral manner (clockwise) in relation to the Bismark and possibly involved movement along it. A rotation of the stress 12° could also produce this difference between veining and fracturing trends. This reasoning is purely speculative and based only on the aforementioned circumstantial evidence. However, since little is known about the past movements along the Bismark, this line of thought may bear investigating.

A quartz veining frequency distribution map (Fig. 6) was compiled for the study area. Data was obtained by counting, perpendicular to the average strike and dip of the veining, the number of veins and veinlets per linear foot. In order to provide more data in areas with little or no outcrop, counts were taken on large pieces of float that appeared to be very close to outcrop. Most of the data is from outcrops generally continuous along the three ridge crests and scattered road
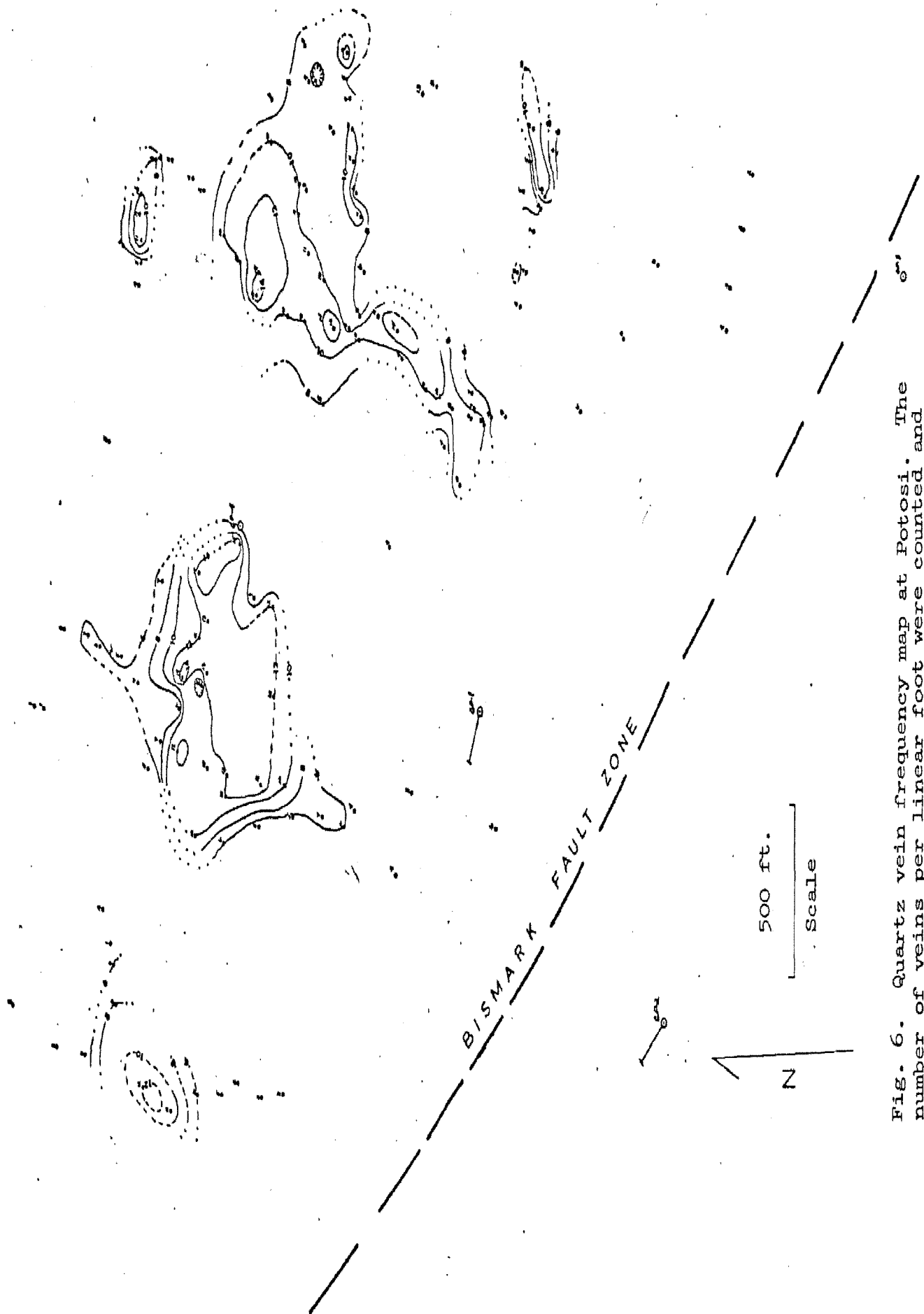
Fig. 6. Quartz vein frequency map at Potosi. The number of veins per linear foot were counted and contoured.

500 ft.

Scale

BISMARK FAULT ZONE

N

outcrops. Two possible ways to contour the data were considered: area wide contouring and contouring limited to the areas of data concentration, as the ridge crests. The latter method was used since the best data control exists there.

The map of veining frequency, although based on extremely limited data in terms of areal coverage, shows a definite pattern. The centers of highest vein frequency appear to lie in a wide band north of and crudely paralleling the Bismark fault. All the centers of highest vein frequency appear to coincide with centers of most intense alteration. However, the converse is not necessarily true.

CHAPTER III

ALTERATION

Alteration Mineralogy

Other than quartz, the predominant secondary, or post-magmatic, minerals in the study area are sheet silicates. X-ray diffraction analyses of 102 samples revealed that the most pervasive and probably most abundant of these was sericite. The term sericite, as used in this study, applies to the fine-grained, secondary, non-expandable, dioctahedral sheet silicate with a 10 $\overset{o}{A}$ lattice spacing. It is similar, if not identical to, muscovite. However, the term sericite is used widely in hydrothermal alteration work to denote a specific genetic origin, as well as a fine-grained secondary habit, so this precedent is followed here.

The second most pervasive sheet silicate was dioctahedral smectite. Smectite, as used here, refers to the fine-grained, secondary, diocta-hedral sheet silicate(s) which swells on glycolation from a lattice spacing of around 14.5$\overset{o}{A}$ to a spacing of 17 to 18$\overset{o}{A}$, and collapses on heating to about 10$\overset{o}{A}$ (see Appendix B). Montmorillonite is the term that has been used extensively in the past to refer to this sub-class of sheet silicates, but ambiguities arise from this usage since mont-morillonite is also used to refer to a specific type of smectite.

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In order to avoid this problem and to use terminology which is better and more widely accepted (by clay mineralogists), this study uses the terminology of Carroll (1970). According to Carroll, the sheet silicates which compose the sub-class dioctahedral smectite are biedellite, montmorillonite, and nontronite. These three are very similar, differing only slightly in chemistry and/or structural charge distribution. Interlayering of montmorillonite and biedellite structural units also can occur. All three show very similar properties and can be distinguished from each other only through complex and extensive chemical tests. Specifically which of these three varieties of smectite occur here was not determined in this study.

A third sheet silicate of relatively limited abundance was identified as chlorite (see Appendix B). A fourth sheet silicate, possibly kaolinite, occurs in such trace amounts that it could not be positively identified. It provides a weak indication of a 7$\overset{o}{A}$ spacing, negative test for chlorite, and possible positive test for kaolinite (see Appendix B).

Thin-section analyses confirm the identification of sericite and chlorite. They also reveal the occurrence of several other secondary minerals. These consist of biotite, K-feldspar, epidote, rutile, quartz, calcite, pyrite, and fluorite. Although other sulfides are present, pyrite is the only sulfide included in this study. However, other sulfide occurrences have been discussed by Eyde (1958).

Alteration Mineral Assemblages and Zones

The alteration minerals typically occur in definite assemblages that partially to wholly replace the original rock-forming minerals, and/or the alteration minerals of a different assemblage (see Table 1). For more detailed petrographic descriptions, refer to Appendix D. These alteration assemblages could generally be spatially separated into distinct zones (Fig. 7). These zones at least partially represent distinct mineralogical rock types. The mineralogical differences between zones can be due either to a change in metamorphic grade, a change in rock chemistry, or a combination of the two. Although the mineralogical assemblages existing in altered areas are not normally thought of as being due to differences in metamorphic grade, the possibility still exists (Burnham, 1962). Metamorphic grades are distinctive mineralogical assemblages in a rock which differ mainly due to the differences in temperature and/or pressure that were present when each assemblage formed, assuming no significant changes in the composition of the rock. The possible existence of a variation in metamorphic grade in the study area is considered in a following discussion. Other workers generally refer to these assemblages as alteration assemblages.

The obvious feature of the sequence and nature of the alteration mineral assemblages in the study area is that they are remarkably similar to the alteration assemblages described, for example, by Lowell and Guilbert (1970) (Table 2). This similarity suggests that the alteration assemblages in the study area represent hydrothermal alteration zones similar to those described by Lowell and Guilbert (1970), and by many other authors.
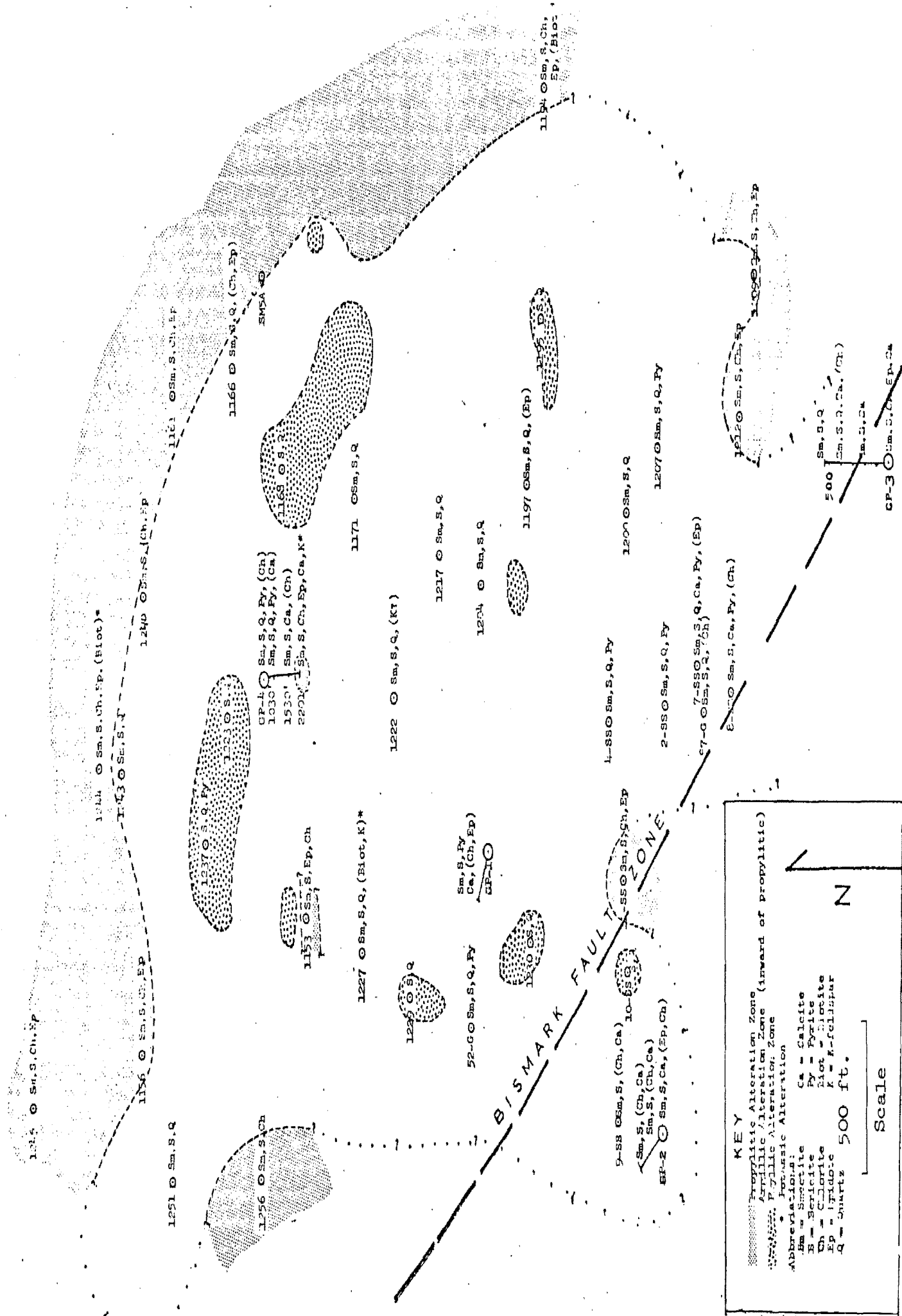
Fig. 7. Map of alteration zone distribution with sample locations and alteration mineralogy.

Table 1. Summary of Hydrothermal Alteration Assemblages at Potosi

FRESH ROCK	PROPYLITIC	ARGILLIC	PHYLLIC	POTASSIC
Quartz	No Change	Augmented	Greatly Augmented	Weakly Augmented to No Change
Orthoclase-Microcline	No Change	Weakly replaced by sericite & smectite	Partly to completely replaced by sericite (evident in thin sect)	Augmented or re-crystallized/ earlier than qtz
Plagioclase	Partly replaced by smectite, epidote, calcite, & sericite	Replaced by ser. & smect. Epid. rare & unstable. Calc rare	Heavily to totally replaced by seri-cite	Partly replaced by biot. along twin lamellae
Biotite	Partly to com-pletely replaced by chlorite and epidote	Replaced by seri-cite and rutile	Completely replaced by sericite w/lesser rutile, ± pyrite	Recrystallized or fresh
Hornblende	Partly to com-pletely replaced by chlorite and epidote	Replaced by chlorite, calc., seri., + oxides, pyrite(?), epid. rare	Replaced by Sericite	Biotized (± sericitized?)
Apparent Equilibrium	Qtz, K-spar, smect., seri., chlor., epid., rutile	Qtz, seri., smect., rutile, (calc.?, pyrite?)	Qtz, seri., rutile, pyrite	Qtz, K-spar, biot., (calc., seri., smect., chlor., epid.?)

Table 2. Summary of hydrothermal alteration assemblages at San Manuel--Kalamazoo.

(Lowell and Guilbert, 1970)

FRESH QM, PORPHYRIES	PROPYLITIC ZONE	ARGILLIC ZONE	PHYLLIC ZONE	POTASSIC ZONE
Quartz	No Change	Augmented	Augmented	Augmented
Orthoclase-Microcline	No Change	Flecked with Sericite	Sericitized	Recrystallized in part replaced by alteration K-feldspar-quartz
Plagioclase $(An_{35.45})$	Tr.Mont, flecks & granules ep, zois, car, chlorite, kaol.	Montmorillonite Kaolin	Sericitized	Fresh to completely replaced by brn-grn alt'n biotite, K-spar ser.
Biotite	Chlor, zois, car, leucoxene	Chloritized, + leucoxene, qtz	Sericite, pyrite, rutile	Fresh or recrystallized to sucrose brn-grn granules, + chlorite
Hornblende	Ep, car, mont, chlor (2 types)	Chloritized	Sericite, pyrite, (rutile?)	Biotite, + chlorite, rutile
Magnetite	trace pyrite	Pyritized	Pyritized	Pyritized

A-K-C-F

A = Al
K = K, Na
C = Ca salts
F = Fe, Mg

25
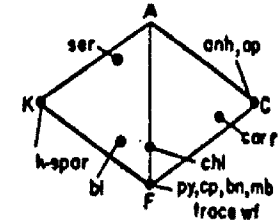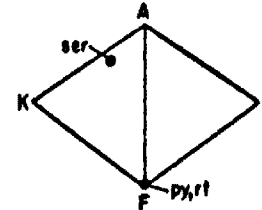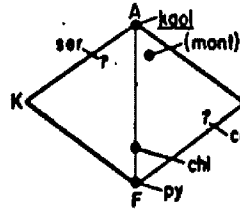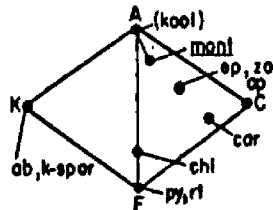
The alteration zones which exist in the study area are the propylitic, argillic, phyllic, and potassic zones. These zones are distinguished from each other by the apparent equilibrium mineral assemblages found in each (see Table 1). Difficulties arise in describing equilibrium assemblages in hydrothermally altered areas because of the characteristic briefness of the processes which caused them. This prevents pervasive and complete alteration from taking place. Other factors, such as an area's structure, rock types, and other episodes of alteration contribute to the difficulties of interpretation. Because the alteration reactions rarely reach completion, the presence of relict alteration minerals is likely. The fine-grained nature of the secondary minerals often makes replacement textures extremely difficult to decipher. Replacement textures reveal the sequence of secondary mineral replacement of the original rock, and the minerals that most recently approached equilibrium.

Microscopic replacement textures in the study area appear to be relatively straightforward. These textures were used where possible to group rocks with similar stable alteration minerals into alteration zones. In most instances, the relationships among rock-forming minerals, early alteration minerals (relict alteration minerals), and latest alteration minerals were easy to determine. Smectite, because of its near sub-microscopic grain size, was the major exception. Its stability in different zones could not be determined optically. However, X-ray diffraction analyses of clay separates in the less than 2 micron size fraction from ground whole rock revealed some distinctive, but very

semi-quantitative, variations in the amount of smectite in the rocks (see Appendix C). Smectite was most abundant in the argillic zone. It diminished in quantity outward through the propylitic zone, and was non-existent in the phyllic zone. It may be safe to assume that a mineral is stable where it is found in abundance, and unstable where it is not found. Smectite is, therefore, probably stable in the argillic zone, possibly stable in the propylitic zone, and probably unstable in the phyllic zone. Variations in intensity of alteration (that is, the amount and extent of the alteration) can explain the difference in quantity of smectite between propylitic and argillic zones, but not the difference between argillic and phyllic zones. The phyllic zone is the most intensely altered, based on the extent of destruction of the original rock texture and minerals. For all other minerals, the usual metamorphic textural criteria for sequence of replacement and stability of minerals were used, such as reaction rims and embayment of one mineral by another.

Although the identification of relict minerals could not positively be made, equilibrium tie lines were drawn between minerals on the ACFK diagrams of Fig. 8. These tie lines are based on a mixture of tentative but consistent textural relationships and the author's interpretations. The ACFK diagram for the propylitic zone appears to have crossing tie lines, implying that one or more of the minerals is out of equilibrium. The crossing tie lines are only apparent, however. The smectite presumably contains significant amounts of Na, since it is replacing plagioclase. Na is not plotted as a separate component on an ACFK diagram, but if it were the crossing tie lines would be eliminated. Thus, the

PROPYLITIC

A

Smectite
Sericite

Plagioclase
Epidote

+ 30% mean free
Quartz
+ Rutile

Chlorite K

·C   Hornblende — — —   K-feld-
spar
·Biotite

F

ARGILLIC

A

Smectite
Sericite

Plagioclase

+ 46% mean free
Quartz
+Rutile

K
K-feld-
C   spar
Calcite   ·Biotite

F

PHYLLIC

A

+ 49% mean free
Quartz
+Rutile & Pyrite

·Sericite

C   K
K-feld-
spar

F

POTASSIC

A

+ 28% mean free
Quartz
+ Rutile

Sericite

Plagioclase
Epidote

Chlorite

C   K-feld-
spar   spar
Calcite   Biotite

F

Fig. 8. ACFK diagrams of alteration zones at Potosi with whole rock plots of samples from those zones. Minerals not connected with tie lines are relict minerals.

minerals on this diagram could be in equilibrium.

The significance of these mineralogical differences between zones can be due either to a change in metamorphic grade, a change in rock chemistry, or a combination of the two. A comparison of the ACFK diagrams for the propylitic and argillic zones would suggest to the casual observer that the two zones differ in metamorphic grade. Specifically, if the smectite-calcite tie line of the argillic zone were plotted on the same ACF diagram as the epidote-chlorite tie line of the propylitic zone, it would appear that the two tie lines cross and that the two sets of minerals could not possibly be in equilibrium with each other. Further, it implies that the difference in mineralogy between propylitic and argillic zones is due to a difference in metamorphic grade so that the chemical constituents of one set of minerals were rearranged to form the other set of minerals. This assumes, however, that the composition of smectite plots on the surface of the ACF side of the ACFK tetrahedron. Actually, as discussed above, smectite probably contains Na since it is replacing plagioclase. Na is not represented on the diagram, but if it were the two tie lines mentioned would not cross. Therefore, the data neither supports nor denies the existence of different metamorphic grades in the study area. Based on this work, their existence is indeterminate in the study area.

The rock compositions of samples from the study area plotted on their corresponding alteration ACFK diagrams of Fig. 8 shows that each set is distinct from the others. This is shown below in a discussion of whole rock chemical analyses in the area. The ACFK diagrams clearly

imply that a change in rock composition (metasomatism) has occurred. Presumably this post-magmatic variation in rock chemistry is important in producing the variation in and distribution of the mineralogy in the study area.

Areal Distribution of Alteration Zones

The areal distribution of the alteration zones is shown on Fig. 7. Parts of the contacts are inferred because of lack of outcrop and the gradational nature of the contacts. Determination of the propylitic-- argillic zone contact was mainly based on the change in stability of certain minerals, observable in thin-section (Table 1). The argillic-- phyllic zone contact was partly based on the absence of smectite and presence of sericite, as shown by x-ray diffraction analyses. This is because smectite, as discussed above, is sub-microscopic. If the existence of relict smectite could be ascertained, the phyllic zone would presumably be much larger than that shown on Fig. 7.

The spatial distribution of three of the zones is fairly clearcut. The propylitic zone is typically peripheral to the other zones, except for the pottasic zone. The propylitic is in direct contact only with the argillic zone. The propylitic, argillic, and phyllic zones form a crude sequence, with the phyllic zone apparently innermost and the smallest of the three, and discontinuously developed.

The potassic zone is the most subtly expressed of all the zones in the study area. Its existence is inferred because of the presence of scattered outcrops with secondary biotite and/or secondary K-feldspar,

mostly in the northern part of the study area (Fig. 7). Other than quartz, these are the only two minerals that are characteristic of this zone. The potassic zone is not well defined. It appears to be over-lapped by the other zones, and as a result to be imprinted with their characteristic minerals. For example, where the secondary biotite of the potassic zone is overlapped by the propylitic zone, it is altered to chlorite. Where this biotite is overlapped by the argillic zone, it is altered to sericite. No secondary biotite, relict or otherwise, was positively identified in the phyllic zone. The preceding examples suggest that the potassic zone was earlier than at least the propylitic and argillic zones.

Distribution of Alteration Minerals Next to a Small Vein

Distribution of alteration minerals next to a small vein located in a weakly altered part of the propylitic zone proved to be a microcosm of the larger area-wide distribution pattern of alteration, except for the potassic zone (Fig. 9). Note that minerals characteristic of the propylitic zone are farthest from the vein and that those typical of the argillic and phyllic zones are inward from the propylitic, next to the vein. Semi-quantitative x-ray diffraction data indicate that the variation in quantity of smectite outward from the vein is very similar to that found outward from the phyllic zone.

Whole Rock Chemical Analyses of Altered Rock in the Study Area

Whole rock chemical analyses of 13 samples from the study area (see Appendix E) indicate that the 3 alteration zones are mostly chemically

-Chlorite replacing biotite
-Epidote replacing plagio-
  clase
-Smectite and sericite spor-
  adically replacing plag-
  ioclase

-Smectite greater than seri-
  cite. both replacing plag.
  and mafics
-Sericite greater than smec-
  tite. both replacing feld-
  spars and mafic minerals
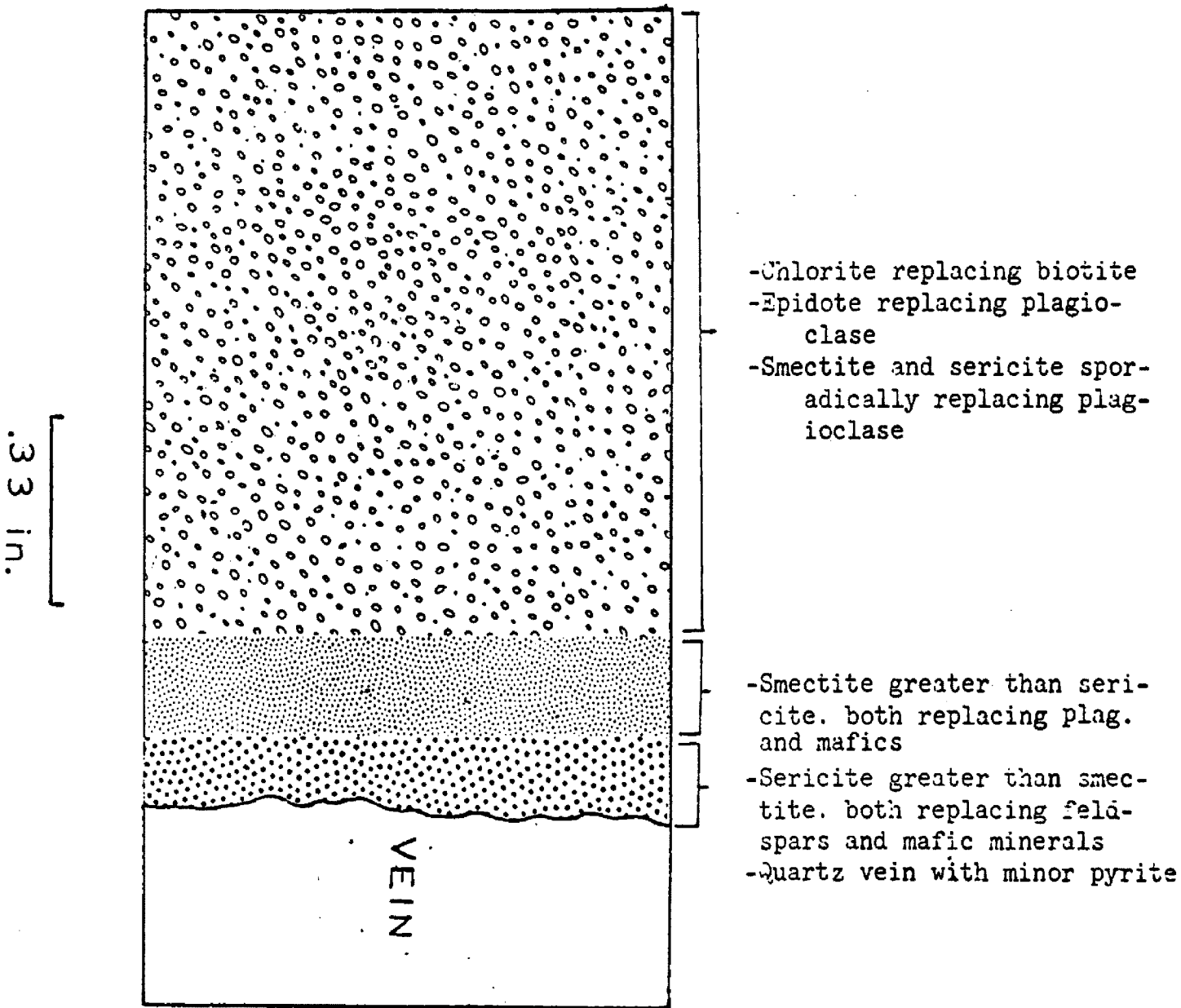-Quartz vein with minor pyrite

.33 in.

Fig. 9. Schematic diagram of development of alteration minerals
next to a small quartz vein located in weakly altered rock at Potosi.

distinct from each other. In Figures 10 to 14, whole rock percentages of oxide for each sample is plotted for that sample's respective zone of alteration. Definite trends are evident for most of the analyzed oxides. Na_2O and Al_2O_3 mean values in the phyllic zone are depleted with respect to the argillic zone, and mean values for both zones are depleted with respect to the propylitic zone. The CaO mean value in the phyllic zone is very close to that in the argillic, but appears to be depleted slightly with respect to the argillic. Both zones are depleted in CaO with respect to the propylitic. SiO_2 mean value in the phyllic zone is enriched with respect to the argillic zone, and mean values for both zones are enriched with respect to the propylitic zone. K_2O mean value in the phyllic zone appears to be nearly the same as in the argillic zone, but both zones are enriched in K_2O with respect to the propylitic zone. Fe_2O_3 (total iron) and TiO_2 mean values show indeterminate trends. However, Fe_2O_3 appears to be enriched in certain parts of the argillic zone, with respect to the other two zones. Mean values for the oxides of the different zones are connected with dashed lines on the diagrams to help schematically show the trends from one zone to another.

Analysis was performed for major oxides on one sample of the potassic zone, 4-2132. Secondary K-feldspar was apparent in handspecimen. The sample is outlined with a square on Figures 10 to 14. Its major oxide values were not used in determining mean values for the major oxides in the propylitic zone because of its potassic alteration characteristics. Sample 4-2132 showed high values for K_2O and Fe_2O_3 (total iron),
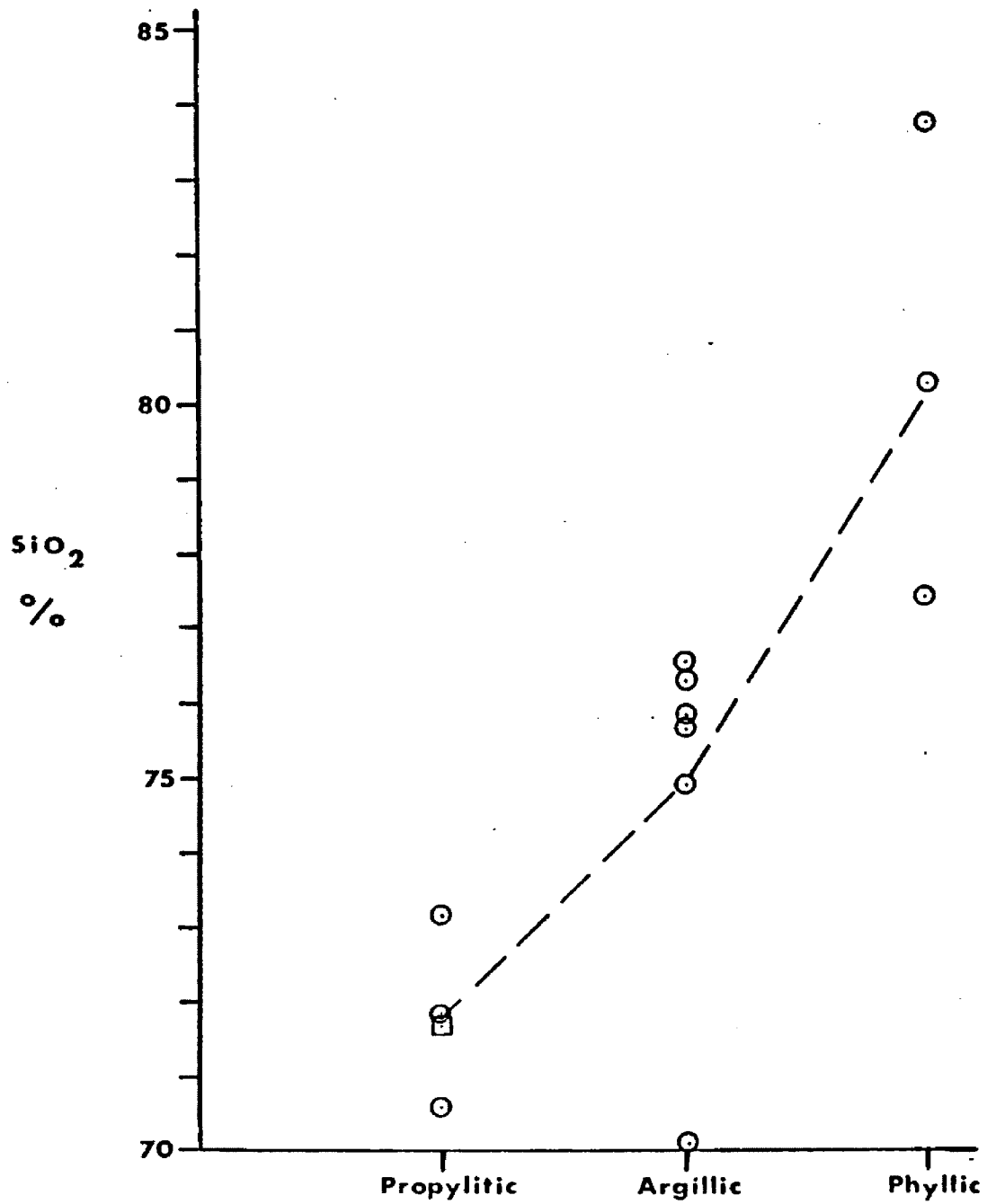
Fig. 10. Whole rock percentages of SiO_2 for 13 samples at Potosi vs. the samples' respective alteration zone.
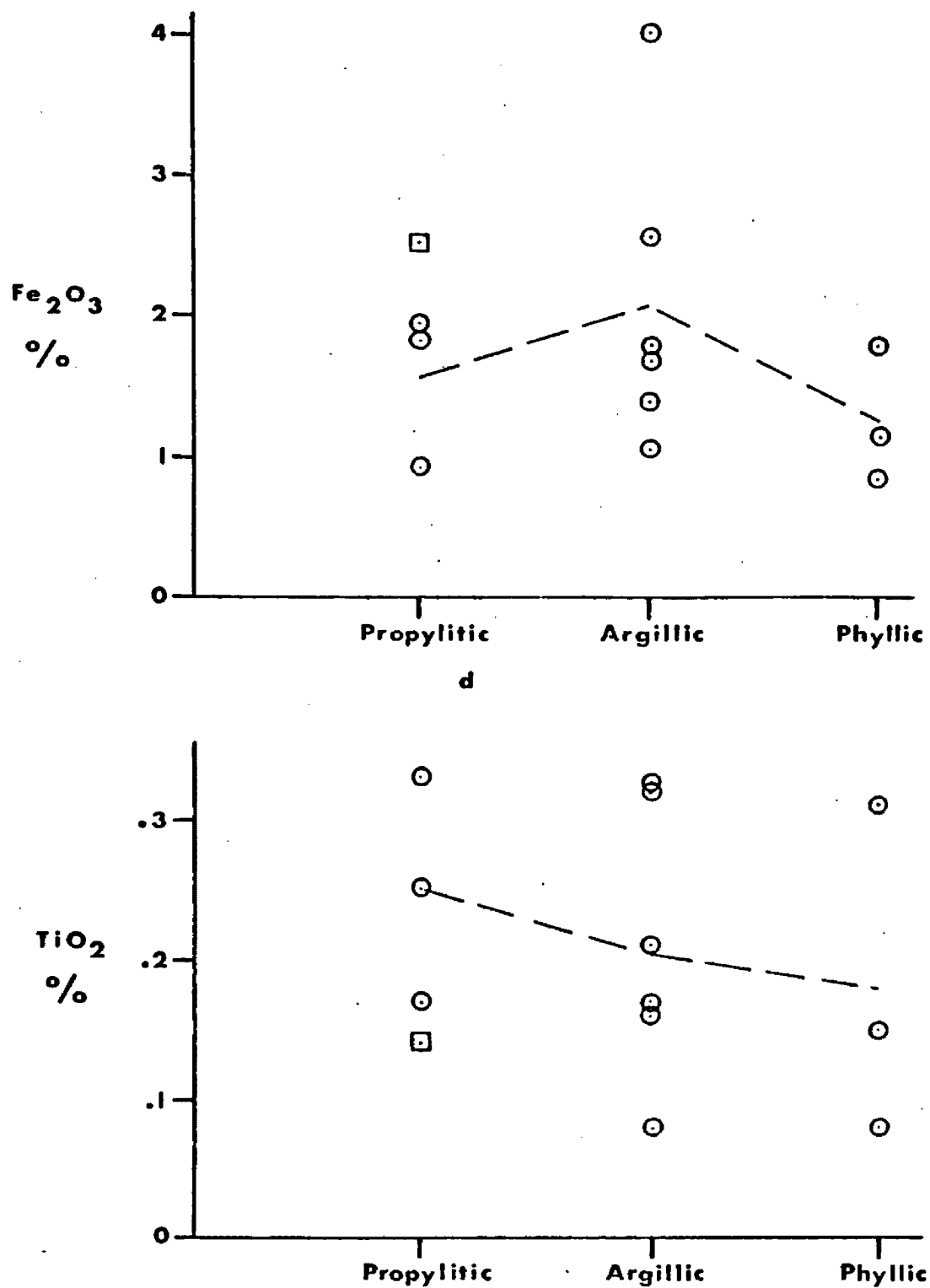
Fig 11. Whole rock percentages of Fe_2O_3 (top) and TiO_2 (bottom) for 13 samples at Potosi vs. the samples' respective alteration zone.
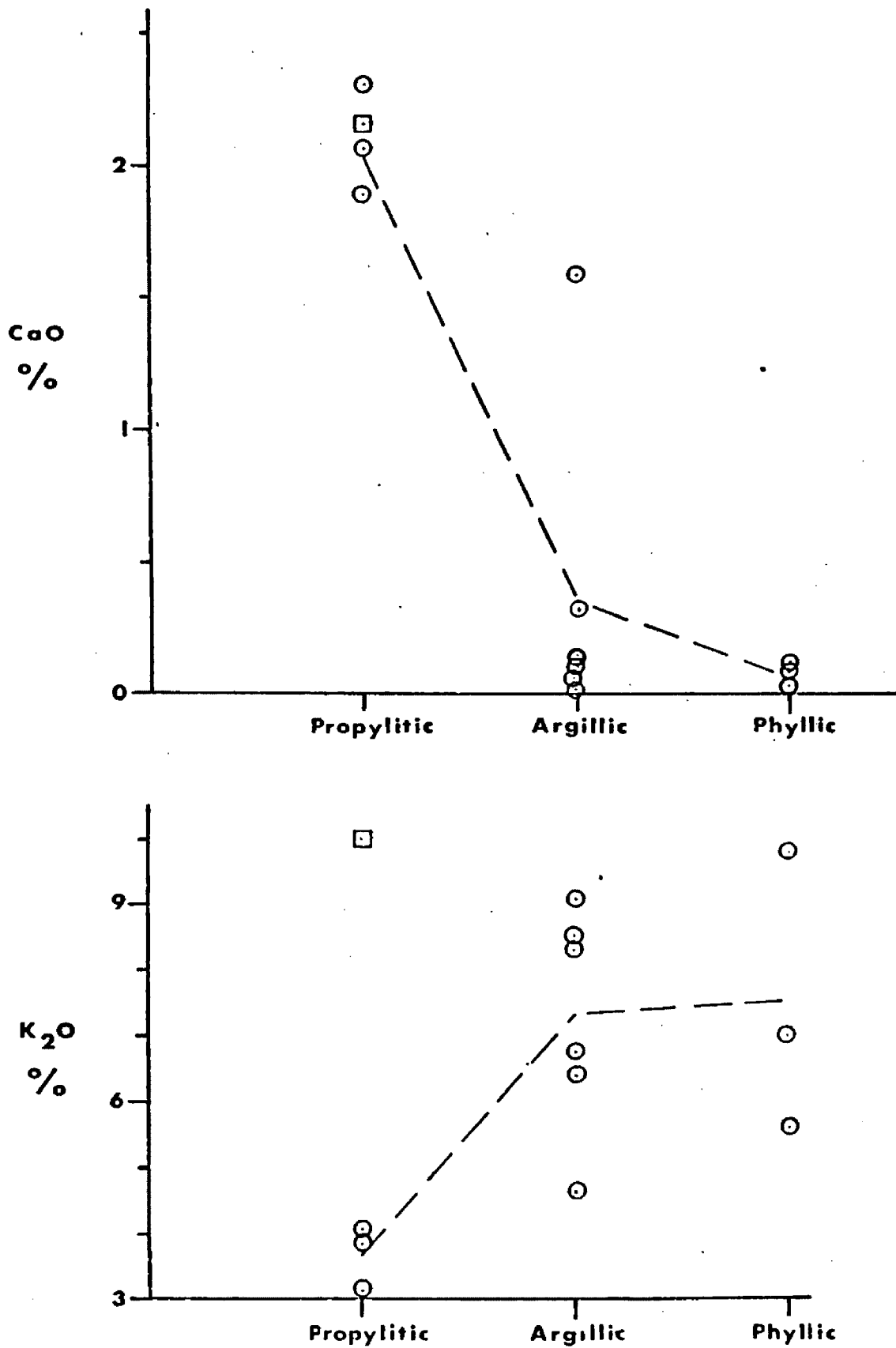
Fig. 12 Whole rock percentages of CaO (top) and K_2O (bottom) for

13 samples at Potosi vs. the samples' respective alteration zone.
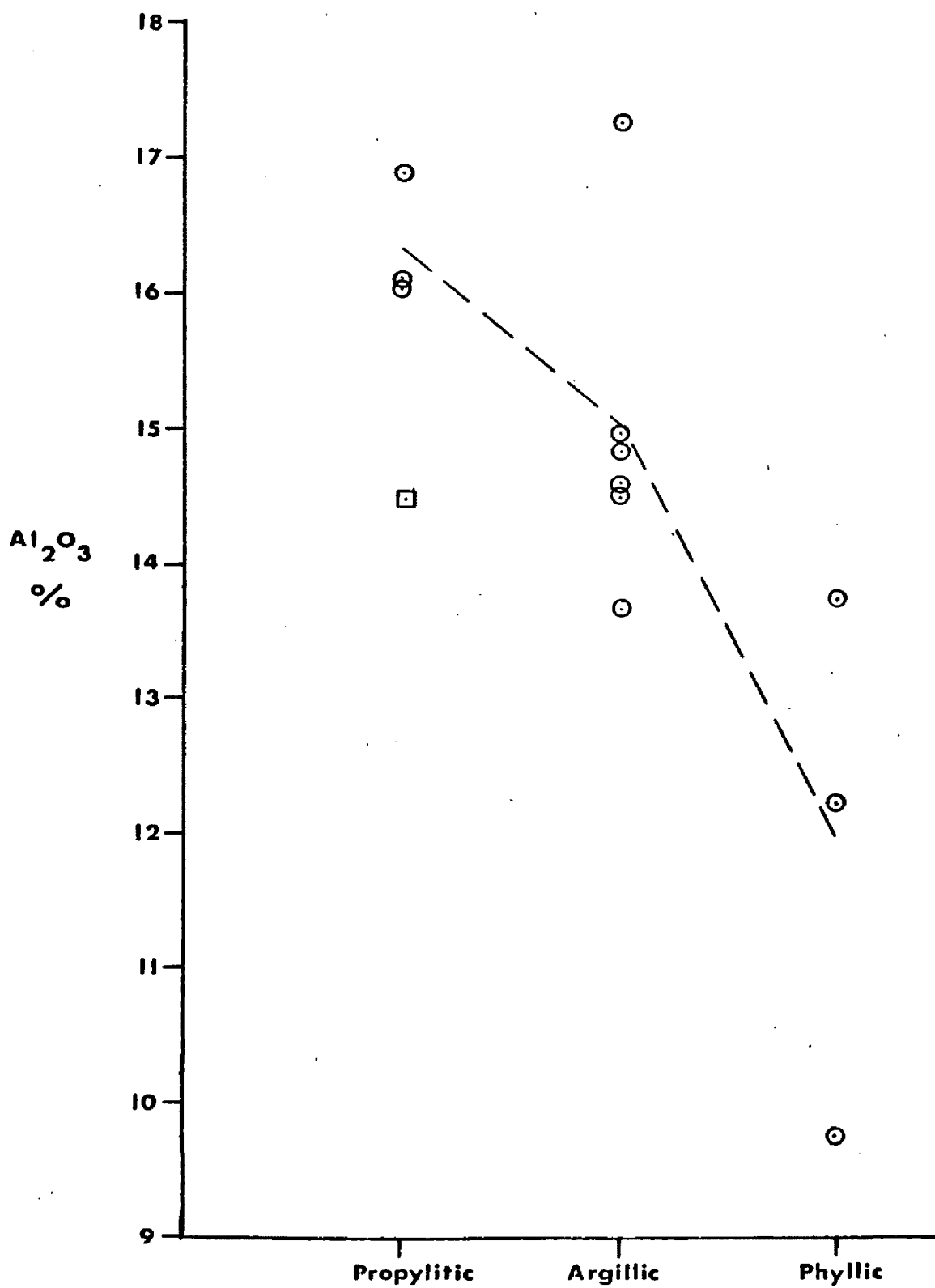
Fig.13. Whole rock percentages of Al_2O_3 for 13 samples at Potosi vs. the samples' respective alteration zone.
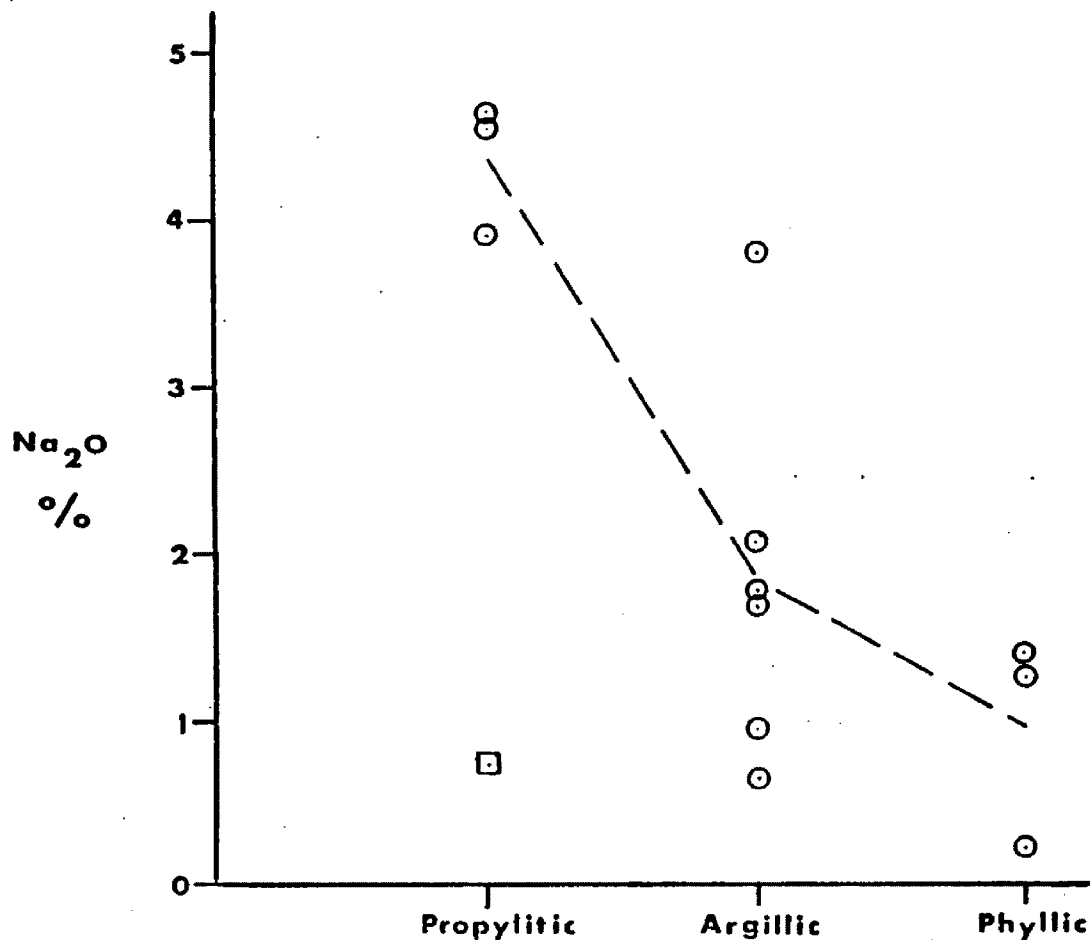
Fig.14. Whole rock percentages of Na_2O for 13 samples at Potosi vs. the samples' respective alteration zone.

and low values for Na_2O, Al_2O_3, and TiO_2 with respect to the propylitic zone. This sample has mineralogy partly characteristic of the propylitic zone (i.e., epidote), and probably has been exposed to two phases of alteration: first potassic, then later propylitic. MgO was present only in trace amounts in each sample, and could not be readily analyzed. Therefore, a standard amount of MgO, the same as standard USGS G-2, was assumed for each. This amount was assumed because x-ray fluorescence work indicated that each of the samples had at least the same or less

MgO than standard G-2 (0.76%). Assuming this trace amount should not greatly effect the percentages of the other oxides. Figure 15 of chemical trends of the altered rocks at Butte, Montana, is included for comparison with trends in Figures 10 to 14.
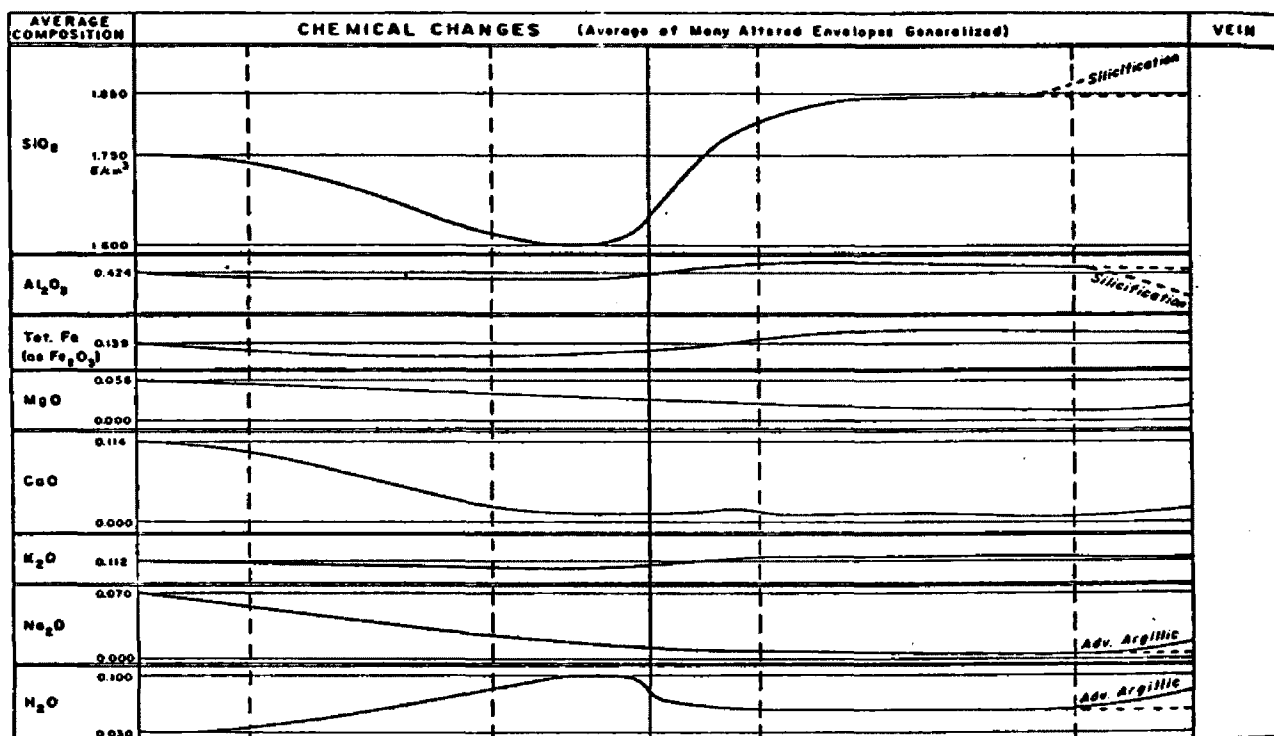
Fig. 15. Composite diagrammatic summary showing variations in chemical composition in wall-rock alteration accompanying ore introduction during the Main Stage hydrothermal activity at Butte, Montana, (Meyer, et al, 1968).

CHAPTER IV

INTERPRETATIONS AND CONCLUSIONS

The sequence, mineralogy, and chemistry of the alteration zones in the study area are very similar to hydrothermal alteration zones described in other areas, such as Butte. This suggests that the Potosi alteration may have formed in a similar way to the alteration patterns found around many mineralized and non-mineralized hydrothermally altered areas.

Sequence

Interpretation of the data to determine the sequence of events for the formation of the alteration zones strongly suggests that a weakly pervasive potassic zone formed first, then later the propylitic, argillic, and phyllic zones formed and were superimposed on the potassic zone. The sequence propylitic--argillic--phyllic is always found in that order, from least to most altered, with the argillic inward from the propylitic, and phyllic inward from the argillic zone. The propylitic zone was nowhere found in direct contact with the phyllic zone. Minerals characteristic of the propylitic assemblages are in some cases found in the argillic zone, but are being replaced there, along with the original rock forming minerals, by minerals characteristic of the argillic zone. This suggests that the propylitic zone formed before the argillic zone. Time

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relationships between the argillic and phyllic zones cannnot be determined on mineralogical and textural data alone. However, the phyllic alteration was probably the latest. If it were earlier, and independent of the argillic, it seems likely that the phyllic would at some point contact the propylitic zone without any intervening argillic zone. Therefore, some of the evidence suggests that the sequence of alteration development in the study area was 1.) potassic, 2.) propylitic, 3.) argillic, and 4.) phyllic, from oldest to youngest.

It appears that the intensity of alteration is proportional to the distance from the centers of phyllic alteration. These islands may represent the centers of hydrothermal activity. If this is so, then it may be that the propylitic, argillic, and phyllic zones formed nearly concurrently. That is, as a moving front of altering solutions migrated from these centers and modified the rocks, either through leaching or introduction of chemicals, the solutions themselves probably changed from reaction with the wall rock. Farthest from the source of the solutions, the reaction with the wall rock was least intense, or propylitic, and closest it was most intense, or phyllic, with the argillic intermediate. This implies that these three zones are interdependent and have a common origin. The crude concentricity of their areal distribution supports this. If they were independent of each other, it seems likely that the phyllic would at some point be in direct contact with the propylitic zone, instead of concentric with it. The potassic zone does not coincide concentrically with the other three zones, however. It appears to be sporadically developed, shows no definite gradient of intensity or other-

wise toward the centers of the other three alteration zones, and is spatially distributed seemingly independent of the other three zones. Evidence that the potassic zone was earliest has been cited previously in the section on distribution of alteration zones.

The very crude ring formed by the scattered islands of phyllic zone rock, and the argillic and propylitic concentric to the phyllic implies that the locus of the hydrothermal activity was a small area near the center of Figure 7. However, epidote appears to be stable in two samples in the interior of the phyllic "ring". Epidote is not generally present inward from the phyllic zone in other hydrothermally altered areas. This fact, plus the somewhat scattered, non-continuous development of the phyllic zone patterning suggests that the altering fluids may have migrated outward from several loci. Perhaps when these fluids didn't quite completely overlap and intensely alter the rock between loci, the propylitic islands shown on Fig. 7 were left.

Weathering

The possibility exists that the propylitic zone is not a true alteration zone, but a simple weathering phenomenon. Part of the mineralogy of the propylitic zone (chlorite and smectite) is certainly similar to that formed in the weathering environment. However, the intensity of the propylitization in the area increases from outside to inside the area. The propylitization appears to form a broad alteration halo concentric to the argillic and phyllic zones at Potosi. The propylitization also does not appear to diminish with moderate depth, as a weathering phenomenon might be expected to do. The propylitic zone does not seem

to be related entirely to fracturing, either. These characteristics do not seem to indicate weathering is the cause of the propylitic mineral assemblage.

The possibility that the argillic (smectite) zone is a supergene or weathering phenomenon is not likely, either. Drill hole evidence indicates no supergene blanket of sheet silicates or sulfides is now present in the area. Smectite quantity increases from outside to inside the area, and is most abundant in the argillic zone. Quantity of smectite in the area is not necessarily dependent on the intensity of the fracturing of the rock, which might indicate a weathering phenomenon. Fresh pyrite and other sulfides are often found in surface outcrop. Thin section and x-ray diffraction analyses of rocks surrounding the study area also suggest little weathering has occurred, except for slight chloritization of mafics and sometimes a slightly dusty appearance, caused by smectite, in the cores of plagioclase grains; or, this may be due to very extensive propylitization, and not to weathering at all.

Chemistry and Mineralogy

The chemical and mineralogical changes that apparently took place in the study area at the time of formation of the propylitic, argillic, and phyllic zones are, as noted above, fairly characteristic of most hydrothermally altered areas. On Figure 16 (from Hemley and Jones, 1964) possible pathways are drawn for alteration fluids that may have caused the mineralogical and chemical variations in the study area. Either changes in temperature, and/or changing NaCl/HCl and KCl/HCl activities could have been partly responsible for the observed changes.
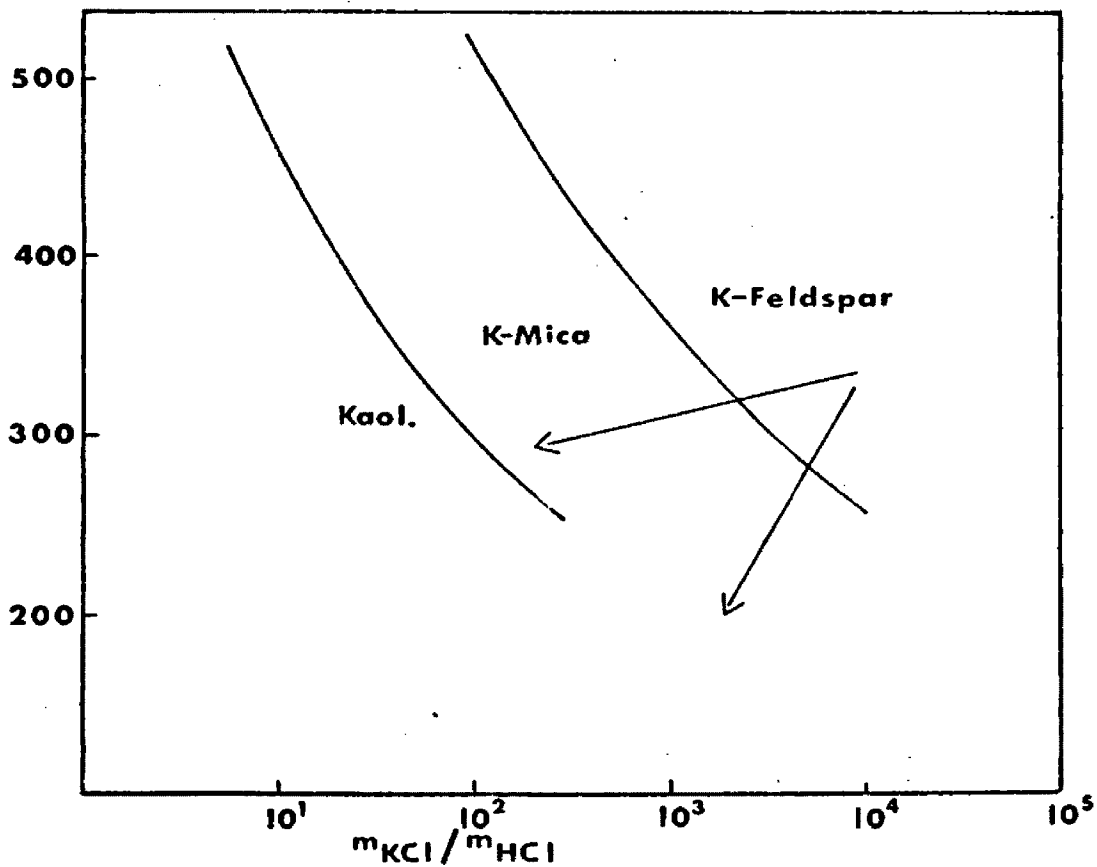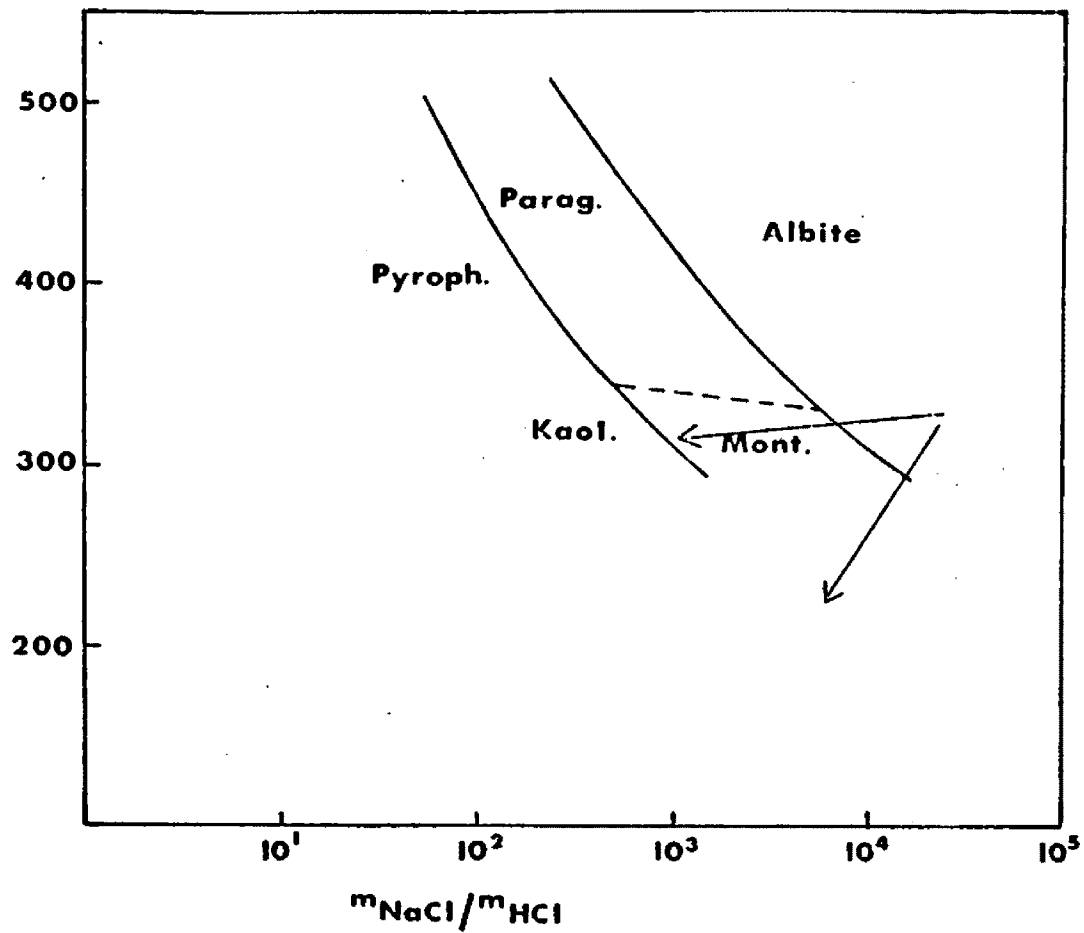
Fig. 16. Reaction curves for the systems $Na_2O-Al_2O_3-SiO_2-H_2O$ (top) &

$K_2O-Al_2O_3-SiO_2-H_2O$ (bottom). From Hemley & Jones (1964). Arrows show possible paths of alteration fluids at Potosi.

Research at Butte (Meyer and others, 1968) suggests that temperature variations were not extremely great across the altered area (less than $100^{\circ}C$) during their main stage alteration. This has been found in other hydrothermally altered areas as well, suggesting that most of the chemical and mineralogical changes may have been caused mainly by other factors, such as variations in $NaCl/HCl$, KCl/HCl and/or $CaCl_2/HCl$ activities. However, which of these factors was most important in the study area is not known.

The whole rock chemical analyses do suggest that extensive leaching of some cations took place in the phyllic zone, and to a lesser extent in the argillic zone. SiO_2 and K_2O were enriched in these same zones, perhaps partly because either they were left as the residual products of the destruction of the original silicates, or because they were transported into these phyllic zones with the alteration fluids. Most of the quartz and sericite is obviously secondary, but how much is re-mobilized residual material and how much has been introduced cannot be determined on the basis of this study. Al_2O_3 appears to have been leached from the phyllic and argillic zones. This differs with evidence found in some hydrothermally altered areas, such as Butte (Fig. 15) where Meyer and others (1968) found that little enrichment or depletion of Al_2O_3 had taken place in any of the alteration zones there. Patton and others (1973) found that leaching of Al_2O_3 did take place, however, in the sericite zone in an altered area in the central Cascades, Washington. Al_2O_3 is only soluble in very acid or very basic solutions, so perhaps the alteration solutions at Potosi had either a very low or very high pH.

However, current thought is that hydrothermal fluids are probably near neutral pH partly because of the buffering action of the wall rock. That is, the alkaline ions released from destroyed silicates would move an acidic pH toward basic, and released SiO_2 would move an alkaline pH toward acidic. Thus a simple explanation cannot be found for the variation in Al_2O_3 in the study area.

The one sample of potassic alteration, 4-2132, that was analyzed showed expected values for major oxides, relative to the propylitic zone. High values for K_2O and Fe_2O_3 (total iron) and a low value for Na_2O relative to other samples in the propylitic zone are similar to trends noted in other hydrothermal studies for potassically altered rocks (Meyer and others, 1968). An inexplicably low value for Al_2O_3 was noted for this sample. The values for K_2O, Fe_2O_3, and Na_2O support the contention that the sample was potassically altered, however.

Quartz Veining

The frequency of the quartz veining seems to be dependent on the intensity of alteration in that the areas of highest quartz vein frequency coincide with islands of phyllic alteration. However, some islands of phyllic alteration exhibit relatively little veining. That is, the islands of phyllic alteration nearest the Bismark fault usually have small veins and low veining frequency in comparison with the islands of phyllic alteration farthest north of the Bismark fault. The latter usually have large quartz veins and a high vein frequency. A possible explanation for this is that the fracturing near the Bismark fault was pervasive, and did not yield many large fractures to act as hydrothermal

conduits. The alteration was pervasive and intense enough to produce phyllic alteration, but there were no large cracks to act as loci for silica deposition. Thin sections reveal that the rocks in this area have a nearly cataclastic texture in some cases, illustrating the intensity of their deformation.

Farther from the Bismark fault, fracturing apparently was not as intense and many large fractures were created. These may have acted as the main conduits for the altering fluids. In the phyllic zone these large cracks may have provided the necessary loci and/or space for the easy deposition of mobilized silica to form quartz veins. The net result is that large veins and a high vein frequency is produced in these islands of phyllic alteration.

A second possible explanation for the areas of high quartz vein frequency being farthest away from the Bismark is that they are also topographically higher in the hydrothermal system than the islands of phyllic zone alteration next to the Bismark fault. Investigations of the alteration patterns in porphyry copper deposits (Lowell and Guilbert, 1970) reveals that the larger quartz veins are commonly structurally high in the hydrothermally altered body of rock. Perhaps this higher position represented a certain pressure, temperature, or some chemical state of the alteration solutions that was more conducive to vein formation than lower in the same system.

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APPENDICES

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A. Collection of rock samples

Rock samples were collected from outcrops throughout the study area. Samples were selected as systematically as possible in order to attempt to make a fair representation of all the diverse rock types in the area, based on handspecimen examination. Selection of individual samples involved careful examination of each outcrop in order to select a sample or samples that represented at least most of the outcrop. Samples that appeared to be weathered were avoided. Fresh rock in from the face of the outcrop was collected for all samples used in this study. Obviously biased samples, such as next to large veins, were avoided where possible, except where sample traverses were made near a vein to investigate the effects of the vein on the alteration pattern. The low percentage of outcrop exposure limited mainly to the ridge crests introduced a natural bias into the collection of samples that can not be discounted. Some drill hole data and a few road cuts in the valleys helped supply more complete sample coverage in areas lacking outcrops, but the data is biased in that most of the data comes from the ridge crests. Locations of samples primarily used in this study are on Fig. 7.

B. X-ray diffraction identification of the secondary sheet silicates

Identification of the nearly sub-microscopic secondary sheet silicates in the study area was based primarily upon x-ray diffraction data. Samples were prepared by hand grinding rock samples in a large steel mortar and pestle to a fine size in order to release the secondary sheet silicates. Each sample was then mixed with distilled water and subjected to an ultrasonic disaggregator for 5 minutes to help release additional clay-sized minerals. After this, the supernatant slurry was poured off and centrifuged for 120 seconds at 1000 rpm in order to settle the greater than 2 micron size fraction (Jackson, 1956). The supernatant liquid containing the less than 2 micron size fraction was centrifuged for 20 minutes at 1500 rpm to remove all the suspended particles. In order to prepare oriented samples for the x-ray diffraction unit, part of the less than 2 micron size fraction was mixed with a small amount of water to make a thick slurry and placed on microscope slides with an eyedropper. These samples were allowed to dry overnight, then placed in a glycol atmosphere. This procedure causes the sheet silicates to orient themselves parallel to the glass slide as the water evaporates. Oriented samples give stronger basal peak reflections for easier identification. When randomly oriented samples were needed, an amount of separate was dried, powdered, and evenly sprinkled on a Vaseline coated slide.

The less than 2 micron size fraction was the primary separate examined because other workers have determined that most clay minerals

are generally in this size fraction, the clay-size fraction. The term clay refers to a size fraction as well as a general group of minerals, the clay minerals, which are mostly hydrous sheet silicates. Fortunately, clay minerals make up most of the material found in the clay-size fraction. Selected samples of the greater than 2 micron size fraction were analyzed. These samples indicated that most of the secondary sheet silicates, except for sericite and, to a much less extent, smectite was indeed in the less than 2 micron size. Sericite seemed to be present in all size fractions. For this reason, any semi-quantitative inter-pretations of relative sheet silicate abundances based on comparing x-ray diffraction peak heights from oriented samples of the less than 2 micron size fraction will probably substantially underestimate the abundance of sericite.

The prepared slides were analyzed in a Norelco x-ray diffractometer with a scanning goniometer. Nickel filtered Cuk alpha radiation was used with a 1° diverging slit and .006" receiving slits. Scanning speed was 1° 2θ per minute and chart speed was 2° per inch. The results on which the mineral identifications are based as discussed below.

Smectite

This mineral has a layer spacing of $14.5\overset{\circ}{A}$ that expands to around $17\overset{\circ}{A}$ upon glycolation (Fig. 17). Heating to 650° C generally caused an irreversible collapse to $10.5\overset{\circ}{A}$. Treating with 2N HCl had no effect. Comparison of the position of the 002--003 peak between 5.3 and $5.7\overset{\circ}{A}$ with Reynolds and Hower's (1970) calculated diffraction patterns in-dicated that the smectite was 100 percent expandable. That is, there seemed to be no mixed layering in the smectite. The spacing of the

060 reflection peak of selected randomly oriented samples was approximately 1.50Å indicating that the smectite is dioctahedral.

Sericite

This mineral gave a very sharp basal reflection peak of about 9.8 to 10Å, with lesser peaks at 5 and 3.3Å (Fig. 18). Heat and acid treatment had no effect on the peaks. The 060 peak of a randomly oriented sample was about 1.50Å, indicating that the sericite is dioctahedral.

Kaolinite

This mineral was suspected to be present because of the presence of a weak 7.15Å peak in the diffraction patterns of a few oriented samples from the propylitic zone (Fig. 19). The peak persisted after treatment with 2N HCl, but disappeared when the sample was heated to 575°C for one hour. The difficulties in positively identifying kaolinite because of its presence in such trace amounts and its extremely local distribution made its usefulness very uncertain as a characteristic mineral for a certain alteration zone. The presence of chlorite, a mineral with a similar x-ray diffraction pattern, further complicated the positive identification of kaolinite. Therefore, kaolinite was not included in Table 1.

Chlorite

This mineral was identified in thin section and x-ray diffraction patterns. On all diffraction patterns in which chlorite appeared, its
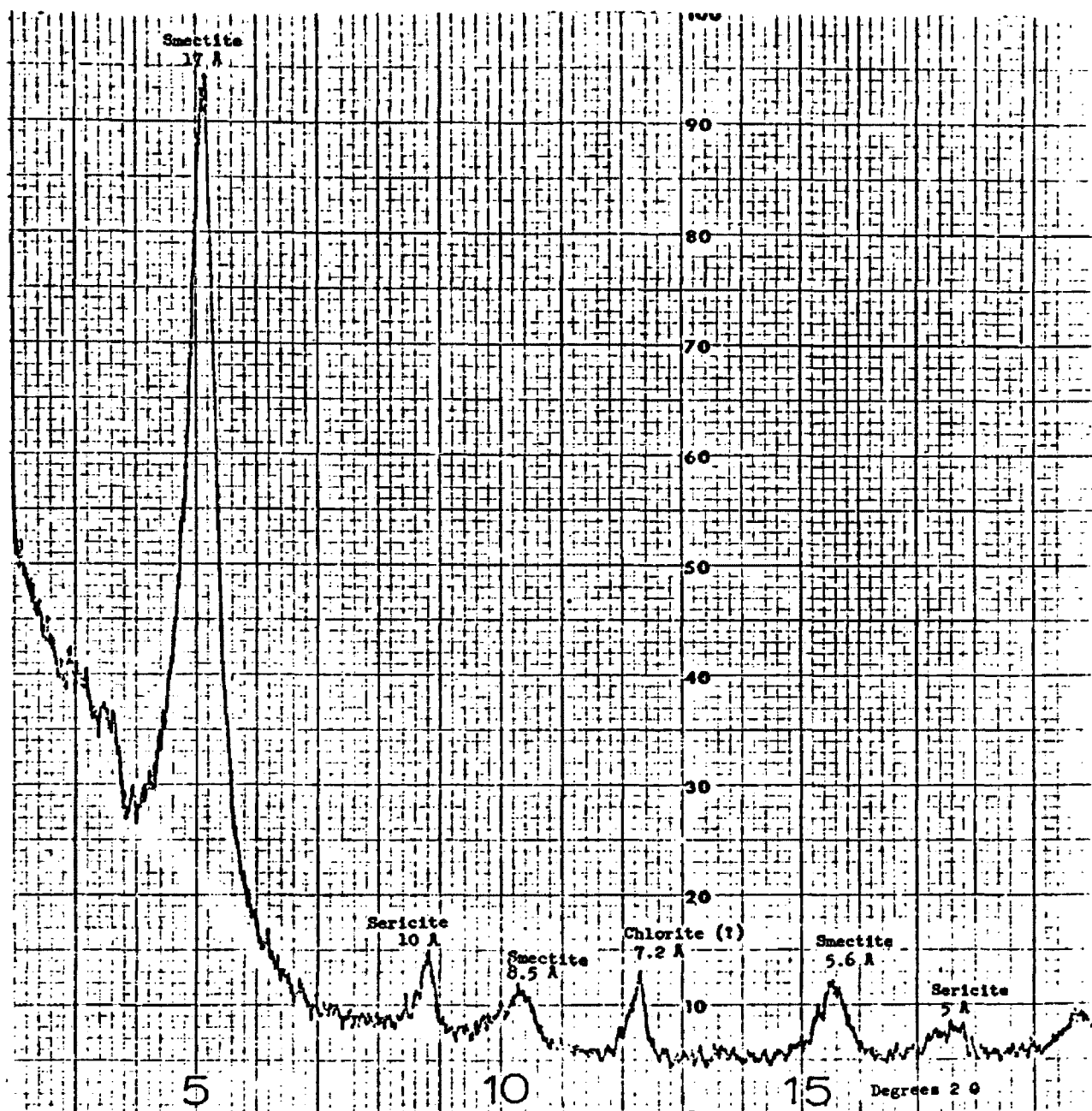
Fig. 17. X-ray diffraction pattern for smectite (001=17Å) and chlorite (?) (002=7.2Å) at Potosi, with some sericite (001=10Å).

Sericite
10 A

100
90
80
70
60
50
40
30
20
10

Sericite
5 A

5   10   15   Degrees 2θ

Fig. 18.   X-ray diffraction pattern for sericite (001=17Å) at Potosi.
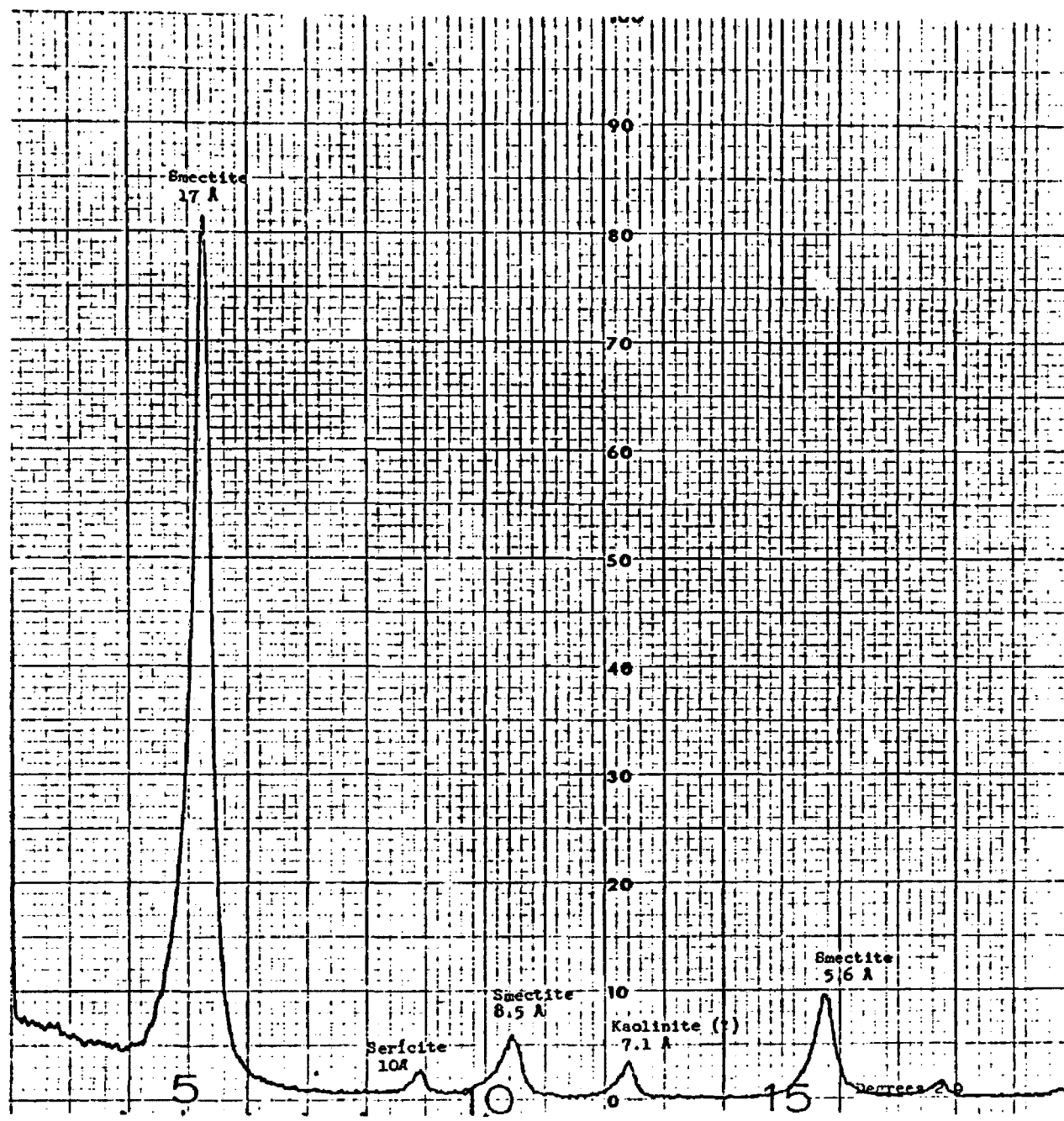
Fig. 19. X-ray diffraction pattern for smectite (001=17Å) and kaolinite (?) (001=7.1Å) at Potosi.

001 peak at 14.5$\overset{o}{A}$ was obscured by the very strong 16.5 to 17$\overset{o}{A}$ peak of the smectite. Thus chlorite was identified on the basis of a 7$\overset{o}{A}$ peak (002) that diminished, but persisted after heat treatment at 575°C for 1 hour, and disappeared completely with 2N HCl treatment at 95°C for 1½ hours (Fig. 17).

C. Estimation of some secondary sheet silicate abundances

Variations in relative abundances of the secondary sheet silicates in the less than 2 micron size fraction can be crudely estimated by comparing certain diffraction pattern peak heights to each other (Perry, 1970). For example, comparing all the 001 smectite peaks to each other gives a general idea of the relative quantity and distribution of smectite in the study area. Comparisons could also be made between sericite and smectite, ideally. However, this procedure is very limited because, as stated in Appendix B, much sericite is removed in the greater than 2 micron size fraction. Peak height variations are shown in Fig. 20, and appear to show an increase in the smectite $17\mathring{A}$ peak heights from propylitic to argillic alteration zones. The $17\mathring{A}$ peak does not appear in the phyllic zone sample. Peak heights for smectite in the less than 2 micron size fraction show a similar increase toward a vein, from less to more altered rock (Fig. 21).

Factors other than variation in quantity can influence peak heights. Variations in crystallite size, orientation, and the number and kinds of different minerals present are among these. The procedure partly controls some of these variables, but the quantitative determination of abundances of clay minerals is far from foolproof.
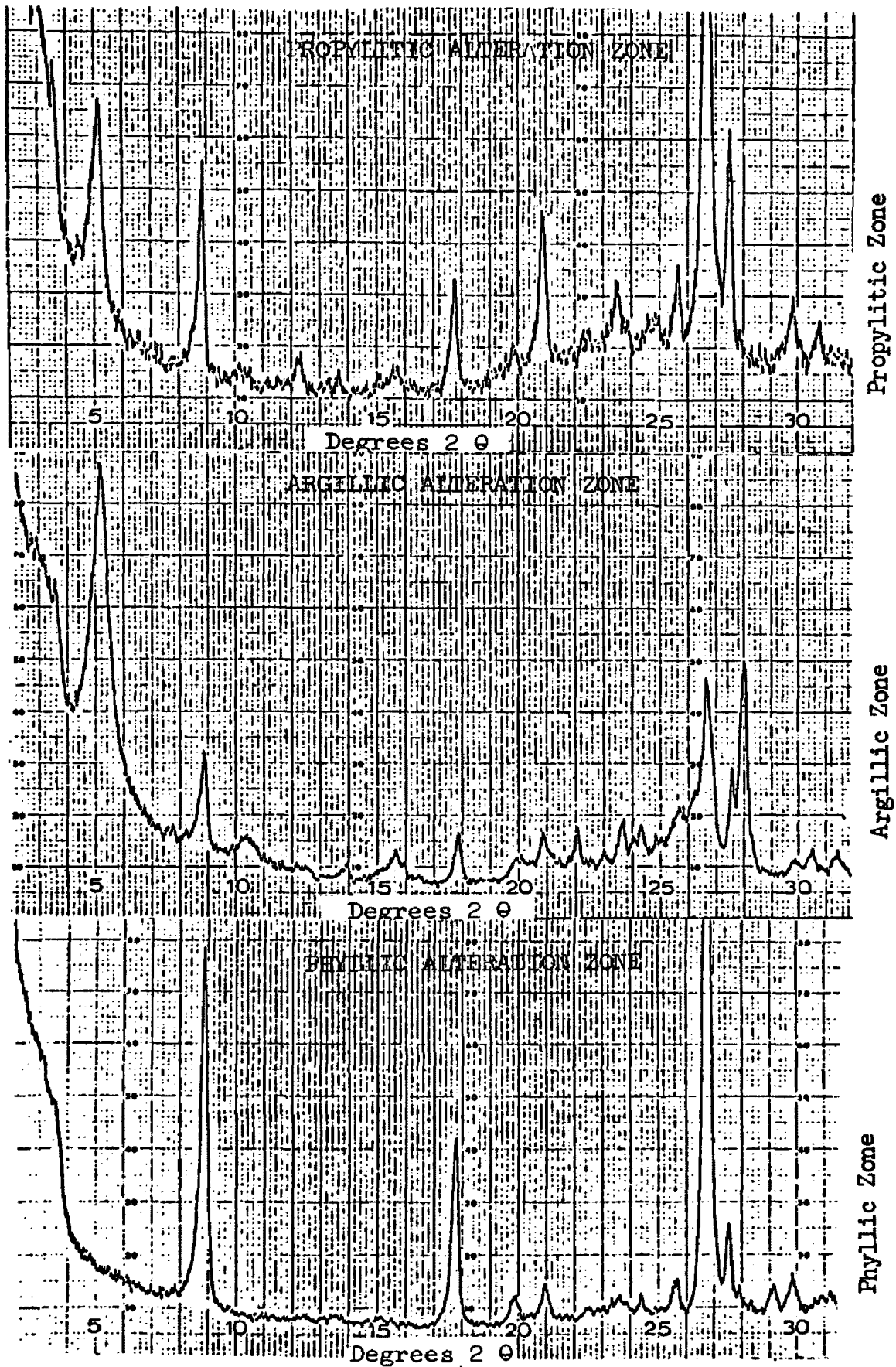
Fig. 20. X-ray diffraction patterns of the less than 2 micron size fraction from 3 alteration zones at Potosi.
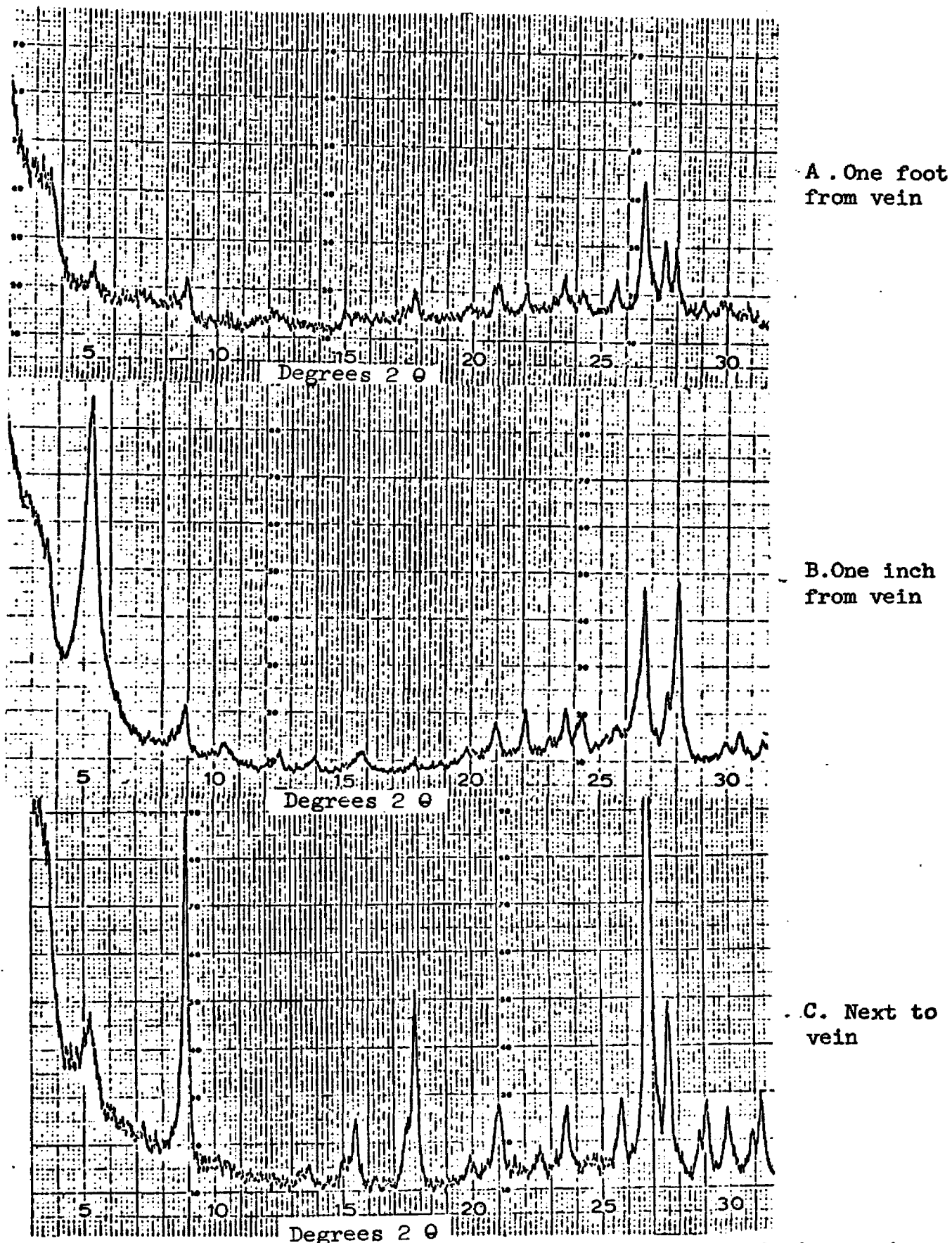
A.One foot
from vein

Degrees 2 θ

B.One inch
from vein

Degrees 2 θ

C. Next to
vein

Degrees 2 θ

Fig. 21. X-ray diffraction patterns of the less than 2 micron size
fraction from 3 samples taken along a traverse perpendicular to a
small vein.

D. Petrographic descriptions of alteration rock types

Petrographic descriptions of representative rock samples from the different alteration zones are discussed below. Visual estimates of mineral percentages were made. Sericite and smectite could not be distinguished reliably in thin section and are estimated together.

Propylitic zone--sample 1245

The sample contained the following minerals:

plagioclase	40%
quartz	33
K-feldspar	22
biotite	1
epidote	1
sericite and smectite	1
chlorite	1
sphene	trace
hornblende	trace
magnetite	trace
total	100%

This slightly porphyritic, hypidiomorphic, medium-grained granodiorite has an overall weakly altered appearance. The plagioclase is zoned and subhedral. Some of the plagioclase appears to have been fragmented before the rock solidified because some zoned grains are only half present, yet the rock does not appear to have been greatly deformed. The plagioclase is slightly altered to sericite and smectite in the cores of some grains. Some epidote may be replacing the plagioclase, as well.

Quartz is anhedral and fresh looking. It is slightly undulose and it appears that the C-axes of some of the grains are aligned. The K-feldspar is present as anhedral grains in the groundmass, and as a

few ½- to 1-inch megacrysts. The megacrysts are anhedral to subhedral, and are slightly poikilitic with inclusions of tiny anhedral plagioclase. These tiny grains sometimes form crude rings paralleling the margins of the megacrysts. The K-feldspar is slightly perthitic. Except for the patches of included plagioclase, the K-feldspar appears to be unaltered.

The biotite is dark brown and anhedral. It appears to be undergoing a sequential alteration from brown biotite, to green biotite, to chlorite and possibly epidote. Hornblende also appears to be altered to chlorite and epidote. Sphene appears as mostly fresh subhedral to euhedral grains. Magnetite may be slightly altered to limonite. The alteration minerals sericite and smectite are very fine grained. Smectite grains are nearly sub-microscopic, but some sericite grains clearly show the muscovite "birds-eye" texture. Chlorite is medium grained and forms pseudomorphs after the biotite grains. Epidote is anhedral and fine grained.

Argillic zone--sample 87-G

This sample contained the following minerals:

quartz		48%
plagioclase		20
K-feldspar		15
sericite and smectite		16
biotite		trace
chlorite		trace
pyrite		trace
sphene		trace
apatite		trace
rutile		trace
	total	100%

This rock is a moderately altered, slightly porphyritic, hypidiomorphic, medium grained rock. The quartz is anhedral, and fresh

looking. Some of the quartz grains may be secondary since they appear
to fill embayments in the plagioclase. The original plagioclase is less
than half altered to sericite and smectite. The sericite and smectite
give the plagioclase a dusty to freckled appearance. The cores of
plagioclase grains are mostly replaced by the sericite and smectite.
K-feldspar is again present in the groundmass and in megacrysts. It
may be very slightly altered, but appears mostly to be unaltered.
Biotite is probably a relict mineral and unstable in the argillic al-
teration zone. It is rarely found in any samples in the argillic zone.
The biotite is in anhedral grains that are being replaced by chlorite
and/or sericite, and tiny needles of rutile. The chlorite replacing
the biotite is itself being replaced by sericite. Sericite and smectite
have the same appearance here as in sample 1245, although the sericite
may be slightly coarser. Sphene is being replaced by unidentified opaque
oxides. Pyrite is in euhedral cubes, sometimes associated with relict
biotite. Most of the pyrite has been altered to some extent to limonite.
Plagioclase albite twins and sericite grains are bent, indicating the
rock has been deformed.

Phyllic zone--sample 1229

This sample contained the following minerals:

quartz		55%
K-feldspar		20
sericite		20
plagioclase		5
	Total	100%

This rock has an extremely altered and fractured appearance in handspecimen and in thin section. Quartz is the main mineral present and is at least in part secondary. It forms anhedral grains varying from fine to medium in size. Some small quartz veinlets cut the rock. The quartz is highly undulose and the C-axes are somewhat aligned. The grains often show rehealed fractures.

The K-feldspar forms anhedral grains in the ground mass and ½ to 1 inch pink megacrysts. It is slightly altered to sericite. The plagioclase is nearly completely altered to sericite. Both K-feldspar and plagioclase are slightly undulose. The sericite forms fine grains that optically appears to be like ordinary muscovite. Other samples in the phyllic zone are typically more vuggy than this sample. K-feldspar varies in the extent to which it is being altered from sample to sample also.

Potassic zone, with argillic zone superimposed upon it--sample 1227

This sample contained the following minerals:

quartz	38%
plagioclase	25
K-feldspar	20
sericite and smectite	15
biotite	trace
oxides	trace
Total	100%

The rock is similar in overall texture to that described for sample 87-G. The quartz is fresh and in anhedral grains in the groundmass. A veinlet that cuts the rock is composed of secondary K-feldspar next to the country rock, with quartz in the core of the veinlet. The quartz and K-feldspar grains in the veinlet are much more angular than those

in the groundmass. Some of the K-feldspar is slightly dusty in appearance and may be weakly altered. The plagioclase is moderately altered to sericite and smectite in the manner described in previous samples. However, some of the plagioclase is being replaced along albite twin lamellae by a fine grained, somewhat feathery brown biotite. This biotite is itself being replaced by sericite. The oxides form from radiating, fibrous to granular, amorphous looking masses of yellow-- brown grunge between some of the grains. These oxides were not positively identified, but may be goethite and/or limonite.

E. Whole rock chemical analyses

Representative rock samples were selected from each of the 4 alteration zones, as determined first by thin section and x-ray diffraction analyses. The rock samples analyzed were slightly larger than fist-size. These samples were crushed in a Chipmunk steel crusher and ground in a disk grinder. A magnetized needle and a binocular microscope were used to separate as much of any introduced iron as possible. The sample was then split down to about 0.5 grams in a sample splitter, ground in a tungsten carbide ball mill for 5 to 10 minues, and heated to $950^{\circ}C$ for $1\frac{1}{2}$ hours in a porcelain crucible to dehydrate, dehydroxylize, and oxidize it. The sample was then ground by hand in an agate mortar and pestle, weighed, diluted with $Li_2B_4O_7$ (sample $/Li_2B_4O_7 = 1/2$), mixed in a ball mill, and fused in a graphite crucible at $1050^{\circ}C$ for 3 hours. The fused bead was then cracked, ball milled, hand ground to a fine powder, and pressed with boric acid into a flat pellet with the sample forming one surface of the pellet.

The prepared pellet was exposed to radiation from a Cr target x-ray tube in a Norelco X-ray Vacuum Spectrograph. The standard used for the x-ray analyses was a silicate rock standard USGS G-2—a standard granite. Whole-rock chemical analyses for 13 samples from the study area are listed in Table 3.

The computer program used to correct for matrix effects in the samples and standard was a version written by John Hower, et. al. (1965),

Table 3. Whole rock chemical analyses of 13 samples from Potosi

	Propylitic Zone			Argillic Zone						Phyllic Zone			Potassic Zone
	1161	11-SS	SM5A	52-G	1204	1251	1-100	2-SS	1166	1229	1168	1195	4-2132
Fe_2O_3	.92	1.94	1.86	2.59	1.67	1.06	1.40	1.78	4.03	.84	1.16	1.79	2.55
TiO_2	.17	.33	.25	.32	.21	.08	.14	.16	.32	.15	.08	.31	.17
CaO	1.89	2.33	2.06	.10	.11	.04	1.59	.06	.33	.08	.02	.09	2.16
K_2O	3.86	3.91	3.15	8.32	8.56	9.05	4.60	6.40	6.70	9.82	5.61	6.96	9.97
SiO_2	70.61	73.15	71.68	76.31	75.84	74.91	75.65	76.55	70.13	77.44	83.87	80.26	71.68
Al_2O_3	16.93	16.03	16.07	14.62	15.03	13.72	14.88	14.60	17.32	13.79	9.81	12.27	14.50
MgO	.76	.76	.76	.76	.76	.76	.76	.76	.76	.76	.76	.76	.76
Na_2O	4.63	4.59	3.90	.94	1.78	.67	3.81	1.76	2.09	1.29	1.42	.22	.70
Total	99.78	103.06	99.73	103.96	103.96	100.29	102.84	102.08	101.69	104.17	102.74	102.66	102.50

as modified by Kathleen Beall and Jerry Sayers at the University of

Montana. The input data consisted of the calculated intensity ratio

of the standard to the unknown for K_2O, CaO, MgO, SiO_2, Al_2O_3, Fe_2O_3

(total iron), and TiO_2. Na_2O was calculated using thin section estimates

of mineral abundances, and an inferred sodium content for those minerals

as listed in Deer, Howie, and Zussman (1969) for similar rocks. Na_2O

content is thus just an estimate and may not be completely accurate.