GEOLOGY AND ALTERATION OF THE COMMONWEALTH MINE, COCHISE COUNTY, ARIZONA

by

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ABSTRACT

The Commonwealth Mine at Pearce, Cochise County, Arizona, is an epithermal precious-metal quartz-vein deposit in post-Bisbee Formation volcanics. The district produced 10 million dollars in silver and gold before 1940 and is currently being re-evaluated in light of high silver and gold prices.

This study included surface and underground mapping, and petrographic and X-ray studies of the hydrothermally altered rocks. The Pearce Volcanics include andesite flows, quartz latite (?) and rhyolite ash-flow tuffs, and epiclastic volcanic sediments. On Pearce Hill near the veins these have been altered by potassium metasomatism; they must now be chemically and petrographically classified as trachytes and rhyolites. The veins occur along N 85° W, steeply south-dipping normal faults and associated sub-vertical sheeted zones. Dip separation within the fault system is approximately 2,000 feet. Pearce area hills are separated by N 40° W post-ore Basin and Range faults along which the volcanics are tilted 10° to 40° east-northeast. Structure, wall-rock alteration zoning, and gangue mineralogy suggest that the Commonwealth veins formed in a hot spring-like environment.

Fracturing characteristics of the rocks and their initial depth of burial were primary ore deposition controls and should be considered in further exploration in the Pearce Volcanics.

CHAPTER 1

INTRODUCTION

The Commonwealth Mine is an epithermal silver-gold quartz vein deposit in Tertiary (?) volcanic rocks. It was operated from the late 1800s to around 1930, and has had sporadic small scale production since that time. It has produced slightly more than $10 million worth of ore, and is currently being reexamined for production in light of the rising prices of silver and gold.

The deposit is of the classical bonanza type, consisting of high grade ore shoots which have been enriched by secondary processes. The dominant ore minerals are silver halides and native gold. Most of the high grade material was mined out long ago, but a few pockets and shoots remain. The Commonwealth offers an excellent opportunity to re-evaluate one of the bonanza type deposits, most of which are now inaccessible, since portions of six levels of underground exposures have remained open and available. This thesis includes both a general geologic study of rock types and general geology of the area around the Commonwealth (Figures 1, 2, and 3, in pocket) and a detailed look at the structure (Figure 4, in pocket) and alteration associated with the

vein system in light of what is now known about this type of epithermal deposit.

Location and Accessibility

The Commonwealth Mine is located on Pearce Hill, near the town of Pearce, in central Cochise County, Arizona. Figure 5 is a location map showing the approximate location of Pearce. The Commonwealth occupies the S½NE¼ Sec. 5, T. 18 S., R. 25 E. The area mapped for this study includes Pearce, Huddy, Metat, and Sixmile Hills, and several small un-named hills, and covers parts of Secs. 4, 5, 6, 7, and 8, T. 18 S., R. 25 E. It is shown on the Pearce, Arizona, 15' Quadrangle.

The town of Pearce (Figure 6) is about 50 highway miles south of Willcox, and 50 highway miles north of Douglas. It is approximately one-half mile from U.S. Highway 666, and is connected with that highway by both a paved and a gravel road. The roads to various parts of the study area are unpaved, and vary in their passability. Some of the roads require a high-clearance vehicle, but none require 4-wheel drive. Railroad service to Pearce was discontinued in 1932; parts of the old Arizona and Eastern railroad bed may be seen from Pearce north to Cochise and south to Courtland and Douglas.

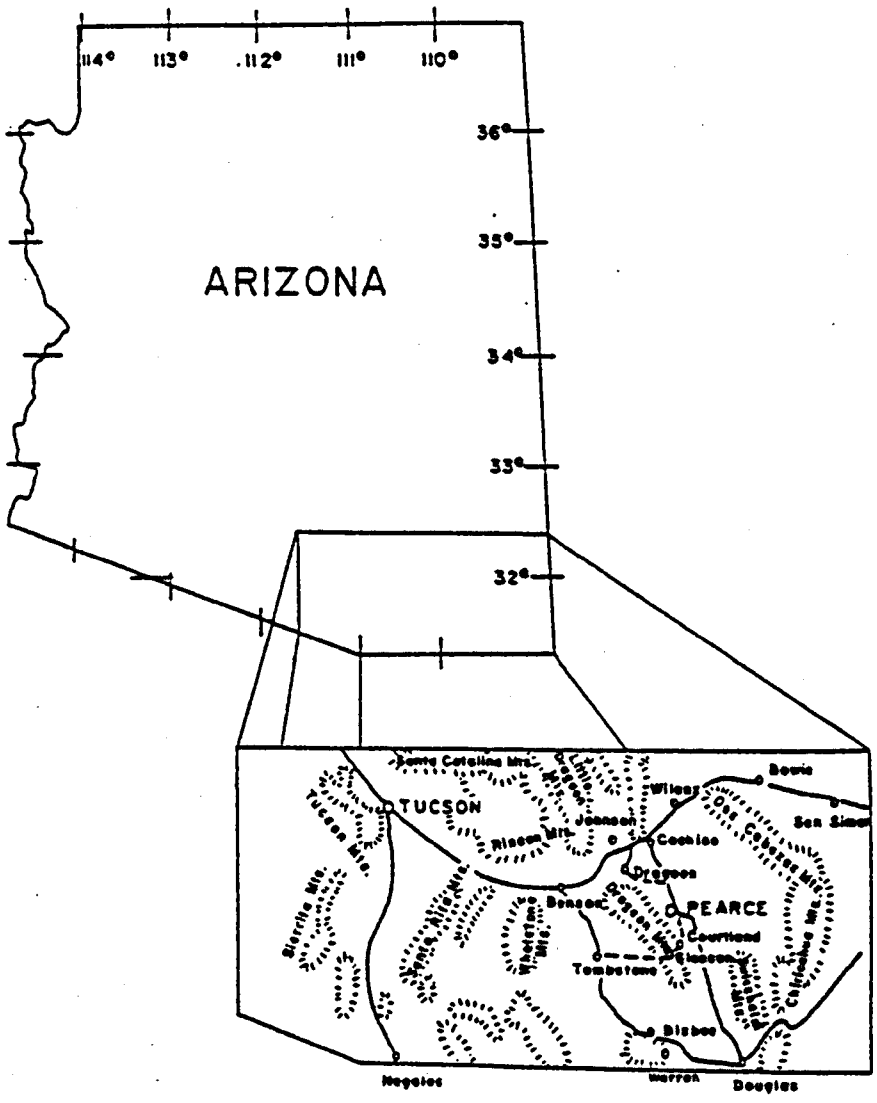


Figure 5. Location Map.

Figure 6. The Town of Pearce As Seen from the Top of Pearce Hill.

The Old Store is at the crossroads, and the Thetford Mill is in the foreground. The rock outcrop is Tf_2.

Physiography

Pearce Hill (Figure 7) is one of a number of isolated hills and buttes which rise sharply from the alluvium of the central Sulphur Springs Valley. The elevation of the valley floor is around 4400 feet, and the hills rise 100 to 500 feet above it. They occupy a divide between drainage northward to the Willcox Playa and southward through Whitewater Draw to the San Bernardino River (Gilluly, 1956). The central and southern Sulphur Springs Valley is flanked by the Dragoon and Mule Mountains on the west and the Dos Cabezas, Chiricahua, Pedrogosa, and Swisshelm Mountains on the east (see Figure 5). The northern Sulphur Springs Valley trends northwestward, and the southern part trends essentially north-south. The general trend of the group of hills is northwest, and they align with a northwestward extension of the Swisshelm Mountains. Many of the individual hills have a northwest elongation.

The volcanic rocks which underlie most of the hills weather to a coarse, blocky rubble which is characteristic of mechanical weathering in an arid environment. The hills in the vicinity of Pearce generally have smooth northeast slopes and steep southwest slopes characterized by cliffs and large boulders. Blocks and boulders of the more resistant rock types generally cover contacts between resistant and less resistant units, making precise mapping difficult. Such contacts must be inferred from occasional small outcrops and

Figure 7. Panoramic View of Pearce and Sixmile Hills.

Looking south along the Ghost Town Trail from U.S. Highway 666.

from float. Vegetation on the hills is sparse and exposures are good. The alluvium thickens rapidly off the flanks of the hills. Some shafts sunk several tens of feet from an outcrop go through 30 to 40 feet of gravel and alluvium before encountering bedrock. Locally the gravel is strongly cemented by caliche, especially in the vicinity of veins.

Activity and Underground Accessibility

The Commonwealth Mine is the largest of a number of small gold and silver mines scattered among the hills. The workings on Pearce Hill are rather extensive; there are numerous shafts and adits, some of which have caved in. A number of stopes were worked to the surface, and a large one on the east side of Pearce Hill has formed an impressive glory hole several hundred feet across. The hanging wall of the Main Vein was allowed to cave in after about 15 years of mining, and two large areas of subsidence now exist across the top of Pearce Hill along the trend of the vein. Subsequent mining activity has produced adits into the caved material.

The underground workings consist of eight levels spaced at irregular intervals. The main shafts were sunk on a 60° to 70° incline into the footwall of the vein system, and crosscuts were driven from them across the structural trend to allow access to the veins. Much of the mining was by the shrinkage stope method which left large openings along the veins. Ground support consisted of stulls and

occasional square sets. Approximately two miles of workings on four levels are still accessible (Figures 8 and 9) and two of the main shafts are open. No headframes or hoists remain. The top of C Shaft is covered by a small shed, and the top of D Shaft is boarded up. C Shaft, in the middle of Pearce Hill, has two small compartments. The hoisting compartment has rails extending down the incline to the 7th level, and has been used by the current lessees to hoist equipment up the shaft. There are relatively good ladders in the manway extending from the surface to the 7th level. The 8th level may be reached by climbing down from the 7th level on a rope, but the writer was told by the lessees that only the station on that level is accessible. D Shaft, on the east side of Pearce Hill, is the largest of all the shafts, having three large compartments. The east end of the 5th level may be reached by D Shaft from the 6th level, but the manway ladders are incomplete above the 5th level. The ladder in D Shaft extending from the 6th level to the east end of the 7th level came loose and fell down the shaft during the early part of this study, leaving most of the 7th level inaccessible. One or two other shafts, especially the Brockman Shaft on the west side of the hill, have partial ladders, but for safety reasons no attempt was made to go down them. Repair or replacement of those ladders might make another fairly large part of the mine accessible. The 3rd level is accessible

Figure 8. Stope on Renaud Vein, 3rd Level.

Figure 9. Drift Along North Vein, 3rd Level.

Fault Plane forms hanging wall.

through an adit into the north side of the hill between the two tailings piles; this is where the writer generally entered the mine.

The history and production of the Commonwealth up to 1926 are discussed by Smith (1927), and in material in the files of the Arizona Bureau of Mines. Little information is available on subsequent activity, until the current lessees obtained a five-year lease on the property in November, 1972. In April, 1975, Platoro Mines, Inc., of Tucson, obtained an option on the patented claims from these lessees and staked claims on the south side of Pearce Hill and north of Sixmile Hill. Previous lessees did some underground mining, and dumped their waste rock down D Shaft, destroying the lower part of it. Patented claims covering the north side of Pearce Hill are owned by the Strong and Harris estate, Silver City, New Mexico. They have been leased by Mr. Carl Thetford and Dr. Don A. Cargill since November, 1972. Mr. Thetford currently resides on the claims. He has erected a small flotation mill at the base of the hill with the intention of milling the tailings along the north side of the hill. These tailings have been reprocessed several times using cyanidation with mediocre precious metal recovery. The lessees have conducted metallurgical tests and made a few test runs in the mill, but they have not shipped any concentrate. According to Mr. Thetford, there are 1 to 4 million tons of tailings, and the average assay value of 100 samples is 0.185 oz/ton gold and 2.7 oz/ton silver. Platoro is doing

bulk sampling underground and in the caved area, and conducting metallurgical tests. They are considering the possibility of mining the remaining Commonwealth vein material by open-pit methods if their results are satisfactory.

Previous Work in the Area

G.K. Gilbert described this part of Arizona in 1875. Ransome (1904), in his U.S.G.S. Professional Paper on the Bisbee Quadrangle, established the essential elements of the stratigraphy in southeastern Arizona. Meinzer and Kelton (1913) described the physiography, geology, and hydrology of the Sulphur Springs Valley. Gilluly (1956) described the Pearce volcanics in his U.S.G.S. Professional Paper on the geology of central Cochise County. The Cretaceous paleogeography of the area is discussed by Hayes (1970).

Smith (1927) gave a detailed account of the geology and mining at the Commonwealth. A brief description of the district was given by Endlich (1897) and Scott (1916), and capsulized discussions may be found in the Arizona Bureau of Mines (1961) Bulletin on gold placers, the 1969 Bulletin on Arizona water and mineral resources, and Keith's (1973) bulletin on mining properties in Cochise County.

The general geology of the area is shown on the state geologic map (Wilson, Moore, and Cooper, 1969), and on the geologic map of Cochise County (Arizona Bureau of Mines, 1959). A number of studies

have been made on areas immediately surrounding the Sulphur Springs Valley. They include: Cederstrom (1946a, 1946b), Cooper (1959), Bock (1962), and Perry (1964) on the Dragoon Mountains; Shields (1940), Enlows (1951, 1955), Raydon (1952), Papke (1952), Brittain (1954), Sabins (1955, 1957a and 1957b), Cooper (1960), Erickson (1969), and Drewes and Williams (1973) on the Dos Cabezas and Chiricahua Mountains; Loring (1947), Galbraith and Loring (1951), Dunne (1957), Rogers (1957), and Diery (1964) on the Swisshelm Mountains; and Epis (1956) on the Pedregosa Mountains. Masters' theses have been done on the Willcox Playa, to the north of the study area, including Pine (1963), Pipkin (1964), and Robinson (1965). Ettinger (1962) described the volcanic rocks and economic geology of the Pat Hills to the northeast of the study area.

Field Work and Scope of Investigation

Field work for the present study was done over the summer and fall of 1973, with some work continuing through the spring of 1975. A total of 25 to 30 days were spent mapping the surface and mapping and sampling the underground workings. The laboratory part of the study included preparation and examination of approximately 100 thin sections and 15 polished surfaces. Twenty slabs were prepared for complete staining with sodium cobaltinitrite, and most of the thin sections were partially stained with sodium cobaltinitrite.

Petrographic work was supplemented by X-ray diffraction analysis using both a Debye-Scherrer camera and a diffractometer. Approximately 20 film patterns and 35 to 40 diffractometer traces were made. The locations of these samples and their assay values are given in Appendix A.

The current investigation includes a re-evaluation of the general geology of the Pearce area, with emphasis on the volcanic rocks, and a detailed look at the alteration of those rocks in the vicinity of the Commonwealth veins. Many new ideas concerning the nature of ash flow tuffs and the genesis of epithermal precious metal deposits have evolved since Smith's thesis was written in 1927. This thesis will attempt to evaluate data given by previous workers, and information obtained during the course of field and laboratory work, on the basis of what is now known about epithermal deposits in volcanic rocks in general and the Commonwealth deposit in particular.

CHAPTER 2

GEOLOGY

Pearce Hill and the hills surrounding it are "islands" of bedrock in the alluvium of the Sulphur Springs Valley. The hills are isolated from one another, and rock units cannot be followed from one hill to another. A combination of poor exposure, structural complexity, and the laterally variable nature of volcanic rocks makes it difficult to correlate rock units from one hill to another, but Lithologic similarities and stratigraphic sequence can be used in making tentative correlations. The degree of hydrothermal alteration in the vicinity of the Commonwealth veins and the uncertainty of correlations with less altered rocks makes it impossible to assign compositional names to the rock units. Therefore, the names used in this study are as descriptive as possible and do not imply mineralogy or chemical composition of either the altered rocks or their presumed unaltered equivalents.

Most of the rocks in the area are volcanic or volcanic ash sediments. They were named the Pearce Volcanics by Gilluly (1956). These rocks overlie the Cretaceous Bisbee Formation, and are overlain by Tertiary-Quaternary sediments and flows within the Sulphur

Springs Valley. This study deals mainly with the volcanic and related rocks; the older Bisbee Formation is mapped and described briefly, and all post-volcanic material is mapped as Quaternary alluvium. The volcanic sequence consists of several flows of a dark, porphyritic rock which was given a field name of andesite porphyry, several rhyolitic ash flow tuffs exhibiting varying degrees of welding, and lenses and beds of volcaniclastic arkoses and conglomerates which appear in great part to be water-lain. Due to extensive faulting in the area, and the weathering characteristics of the rock, it was not possible to construct an accurate, measured stratigraphic column for the study area. For the diagrammatic stratigraphic column given in Figure 10, thicknesses were determined from projections in cross-section using both surface and underground information. The possibility of undetected faulting and thickness variations, and inaccuracies in mapping and construction of the cross sections, makes these thicknesses tentative at best. Two of the units are overlain by an erosion surface everywhere in the map area, so that thicknesses given for them represent only minima.

Most of the prominent hills in the area are capped by one of the rhyolitic ash flows. These units are extremely resistant to weathering, and form coarse rubble and blocks up to tens of feet across. Such material generally covers the base of the unit, so that its location must be inferred from occasional small outcrops and

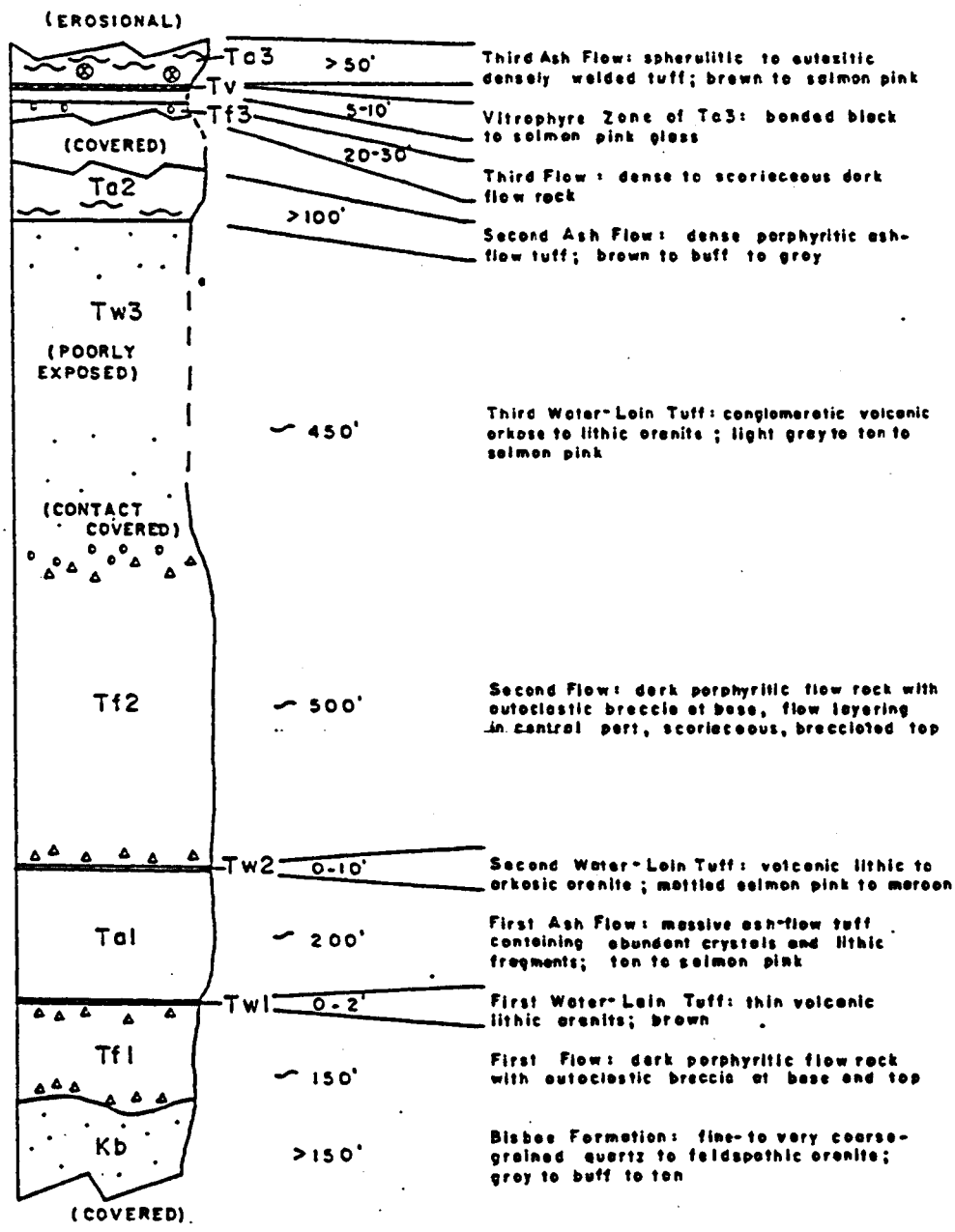


Figure 10. Diagrammatic Stratigraphic Column of the Pearce Volcanics Near Pearce, Arizona.

Scale approximately 1" = 300'.

float of the underlying lithology. For this reason, very little projection of contacts was done on the geologic maps. The rock units are discussed in detail in the following section. Alteration of the rocks will be discussed in a later chapter.

Rock Units

Bisbee Formation (Kb)

In the absence of fossils, this unit cannot be conclusively identified as Bisbee Formation although lithologic information is convincing. Smith (1927) and Gilluly (1956) correlate it primarily on the basis of lithologic similarities. It is conceivable that the unit is as young as early- or mid-Tertiary, but it will be referred to as "Bisbee" in this study. Smith and Gilluly both describe the Bisbee Formation in the more eastern hills of the Sulphur Springs Valley, and Smith maps it underground at the Commonwealth. This writer has mapped as Bisbee Formation a small outcrop of highly altered sandstone in the vicinity of No. 9 shaft in the footwall of the North Vein (Figure 11). The primary basis for this designation is stratigraphic. Other small, questionable outcrops of Bisbee Formation occur around the old mill foundations along the north side of Pearce Hill. Bisbee units are exposed in several adits driven into the north base of the hill. The adit which provides access to the 3rd level goes through over 500 feet of Bisbee Formation before it is faulted

Figure 11. View of Pearce Hill from Huddy Hill.

The Main vein is caved in. The North vein extends from left center of photo and Bisbee Formation crops out to the north (right) of the vein. Ta_1 occupies the foreground; the vehicle on the road is for scale.

against one of the lower volcanic units. Throughout this distance, the rock remains a fine- to medium-grained, well sorted sandstone to quartzite. Some of the exposures on the 5th and 6th levels contain fine-grained pebble conglomerate lenses and mudstone beds. The Bisbee Formation on the surface of Pearce Hill weathers gray to buff, and is light tan on a fresh surface. In most exposures underground it is strongly stained by iron oxides and has an earth red color. Except where it is near veins, it is soft and friable. It is generally permeable; the only dampness or standing water observed underground is within this unit.

In thin section, the unit is quite variable. Samples examined range from fine- to very coarse-grained quartz arenite to feldspathic arenite, using Williams, Turner, and Gilbert's (1954) classification. Some are calcareous arenites and sandy limestones containing up to 70 percent calcite. There are also quartzites, consisting almost entirely of over-grown, interlocking quartz grains. These samples were taken in the vicinity of veins, and some or all of the recrystallization may be due to hydrothermal activity. One sample contains approximately 50 percent argillaceous matrix, and others contain minor clay between grains. This clay appears to be poorly crystallized illite on the basis of optical and X-ray examination. The grains in these rocks include quartz, minor potassium feldspar (including microcline), plagioclase, chert, and traces of muscovite, biotite,

zircon, tourmaline, apatite, chlorite, carbonate, glauconite (?), opaque minerals (now hematite), and argillized lithic fragments which have poorly-preserved volcanic textures. The grains are sub-rounded, equigranular, and well-sorted. This widespread equigranular character distinguishes the Bisbee Formation from the inter-volcanic sediments, which are equigranular only within relatively thin beds. In small outcrops, these sediments could be mistakenly identified as Bisbee Formation, but the differences in stratigraphic intervals thicker than 10 or 20 feet are apparent..

First Flow (Tf_1)

The lowest volcanic unit in the study area is a dark, aphanitic, locally porphyritic, locally brecciated flow which is estimated as 150 feet thick on Pearce Hill. It crops out along the west side of Pearce Hill and north of the North Vein near Huddy Hill. The base of this unit is not exposed on the surface, and underground the contact is complicated by possible faulting and intense alteration. Surface outcrops near the base consist of a breccia in which fragments make up approximately 40 percent of the rock. The fragments are dark gray and porphyritic, containing 10 to 15 percent altered amphibole phenocrysts up to 0.5 cm long. The matrix is lighter gray and porphyritic, containing white feldspar laths which are generally less than 0.3 cm long. Upward in the flow, the number of

fragments decreases and the abundance and size of feldspar phenocrysts in the matrix increases. Near the base of the flow, the matrix shows strong flow layering. The upper 15 to 20 feet of the flow also consist of breccia. The fragments are lithologically similar to the central part of the flow, and the matrix is black, aphanitic, and heavily stained by iron oxides. The fragment content decreases toward the top of the breccia, and the flow top is entirely aphanitic (Figure 12). Both the upper and lower breccias fit Parsons' (1969) definition of auto-brecciation. This flow is poorly exposed and its stratigraphy must be pieced together from outcrops at several different locations. It does appear to be a single flow. No partings or zones of scoria or breccia have been observed in the interior of the flow. A conglomeratic lense several inches thick overlies this flow, all of the clasts of which are of the underlying lithology.

All the samples of this unit examined in thin section are highly altered. The breccia fragments consist of 60 to 90 percent altered feldspar and 10 to 40 percent quartz stringer, calcite, and iron oxide. The breccia fragments are glomeroporphyritic, containing clumps of zoned, subhedral to euhedral potassium feldspar phenocrysts up to 0.3 cm long. These phenocrysts consist of simple twins, with the twin planes seldom sharply defined (Figure 13). Few of the phenocrysts give a satisfactory interference figure, but those that do have a low 2V similar to that of sanidine. They take a

Figure 12. Contact of Tf_1-Tw_1-Ta_1, West Side of Pearce Hill.

Autoclastic breccia in Tf_1, lower right, is overlain by the dense aphanitic flow top; there is thin Tw_1 at the contact and a light colored possible air-fall tuff above contact. Normal Ta_1 appears at the upper left. Sixmile Hill is in the background.

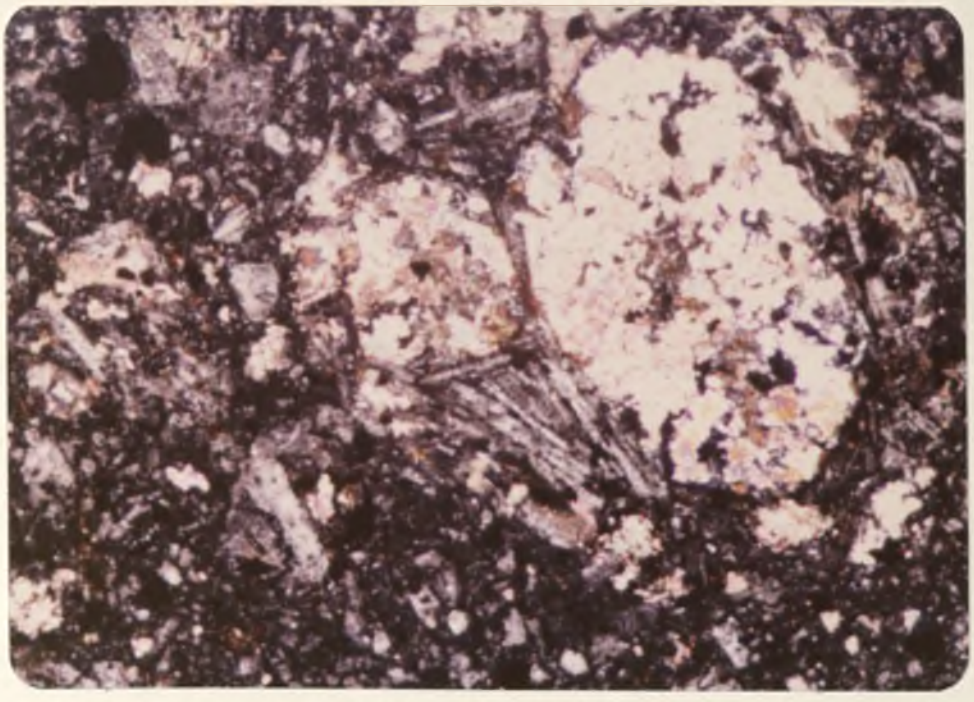


Figure 13. Photomicrograph of Tf_1 Showing Altered Feldspars.

The breccia fragment in right center contains phenocrysts altered to calcite and minor iron oxide and montmorillonite. The microlites now consist of potassium feldspar which is thought to be secondary. Zones of low birefringence and "shadowy" extinction vaguely resemble albite twinning; crossed Nicols, X40.

light stain with sodium cobaltinitrite and yield a sanidine-like X-ray pattern. Appendix C gives a more detailed discussion of the X-ray data. Five to 10 percent of the fragments consists of euhedral amphibole phenocrysts which are completely altered. The remainder of the fragments consists of a trachytic mat of feldspar laths which are generally less than 0.02 cm long. These crystals take a light stain with sodium cobaltinitrite, and none of them exhibit polysynthetic twinning. One or 2 percent of the fragments consists of very fine-grained opaque minerals which are altered to iron oxides.

The matrix of the lower breccia, and the rock in the central part of the flow, are also porphyritic. The feldspar phenocrysts are subhedral to euhedral and generally less than 0.1 cm long. The groundmass consists of up to 10 to 15 percent granular opaque iron oxide and very finely crystalline material which stains lightly with sodium cobaltinitrite. The breccia matrix at the top of the flow is heavily stained by iron oxide and appears to be a devitrified glass. It contains a few small feldspar phenocrysts, and the groundmass is almost isotropic.

Due to the extensive alteration and variability of this unit, it is difficult to give it a petrographic name. Thin section examination and staining indicate that it contains considerable potassium feldspar. It is uncertain whether this potassium feldspar is primary or secondary; this problem will be discussed in a later chapter. No

chemical analyses are available, and their usefulness would be questionable due to the extent of alteration of the rocks. On the basis of thin section examination and visual estimation of percent potassium feldspar in stained slabs, the unit is tentatively named a trachyte porphyry.

First Water-Lain Tuff (Tw_1)

This unit is a volcanic-derived lithic arenite which appears to be water deposited. It ranges from 0 to 2 feet thick, and is broken out as a separate unit because it is a marker bed where it is present. It falls within the size range of a tuff, according to Williams, Turner, and Gilbert (1954) The unit is not entirely locally derived, as it contains up to 45 percent quartz, a mineral not found in the underlying flow. In addition to quartz, it contains up to 20 percent potassium feldspar which has a low 2V and no polysynthetic twinning and minor opaque minerals, chert, plagioclase, biotite, tourmaline, and apatite. Lithic fragments comprise up to 50 percent of the rock, and include sub-angular clasts which are of the underlying flow rock, up to 0.8 cm diameter, with smaller broken fragments of sanidine spherulites and occasional flattened, altered pieces of pumice. There is up to 20 percent potassium feldspar cement which stains evenly with sodium cobaltinitrite. This cement is too finely dispersed to be separated for X-ray analysis.

First Ash-Flow (Ta_1)

This ash-flow tuff is exposed along the west side of Pearce Hill, in a fault block along the north side of Pearce Hill, and on the west side of Huddy Hill (Figure 2, in pocket). It has an estimated thickness of 200 feet. The best exposure is on the west side of Pearce Hill in the caved area (Figure 9). The lower 5 to 10 feet of this unit are white to light tan, and contain very few lithic fragments. This part contains fewer than 10 percent crystals, locally exhibits poorly defined bedding, and may be an air fall tuff (Figure 12). It is in gradational contact with the overlying ash-flow tuff, which is massive and unbedded (Figure 14). This unit consists of from 10 to 40 percent accessory lithic fragments and from 10 to 30 percent crystals. The phenocrysts include clear gray glassy quartz blebs, somewhat chatoyant euhedral feldspar crystals, and very minor biotite. The fragments include the underlying flow rock and altered green to gray pumice. They appear to increase in size and abundance toward the center of the flow, where they reach a maximum diameter of 8 to 10 cm. This part of the unit might be classified as a tuff-breccia. The only suggestion of layering in the unit is the elongation of collapsed pumice lapilli. On a weathered surface, this structure is emphasized by the weathering out of pumice which leaves elongate holes. This rock is extremely hard wherever it is exposed.

Figure 14. Ta_1 Exposed in Caved Area.

Note the dark lithic fragments and light pink color; the hammer is for scale.

Thin section examination confirms its identification as an ash-flow tuff. It is completely devitrified, but the shard texture is preserved in the less altered samples (Figures 15 and 16). The shards are most readily visible under plane polarized light where their outlines are accentuated by iron-oxide staining. They are randomly oriented, and occasional unbroken vesicle walls are present. The shards now consist of clear anhedral potassium feldspar which stains evenly with sodium cobaltinitrite. The matrix surrounding the shards is cloudy, finely crystalline, and stains unevenly. It probably consists of a fine intergrowth of quartz and potassium feldspar. Some of this shard and matrix material was ground into a powder and run on the X-ray diffractometer. The results indicate that the dominant constituents are quartz and sanidine (?). No cristobalite or tridymite has been detected in any of the X-ray or optical work done.

The phenocrysts in this unit consist of 5 to 10 percent quartz which is generally rounded and embayed, 10 to 15 percent potassium feldspar which occurs as cracked and broken euhedral crystals, very minor biotite, what Coats (1940) refers to as "pseudo-dichroic" apatite, and possible un-twinned plagioclase. There are two varieties of potassium feldspar phenocrysts. One stains strongly with sodium cobaltinitrite and exhibits a "patchy" extinction (Figure 17). The other stains only lightly and exhibits sharp, uniform extinction. Both give

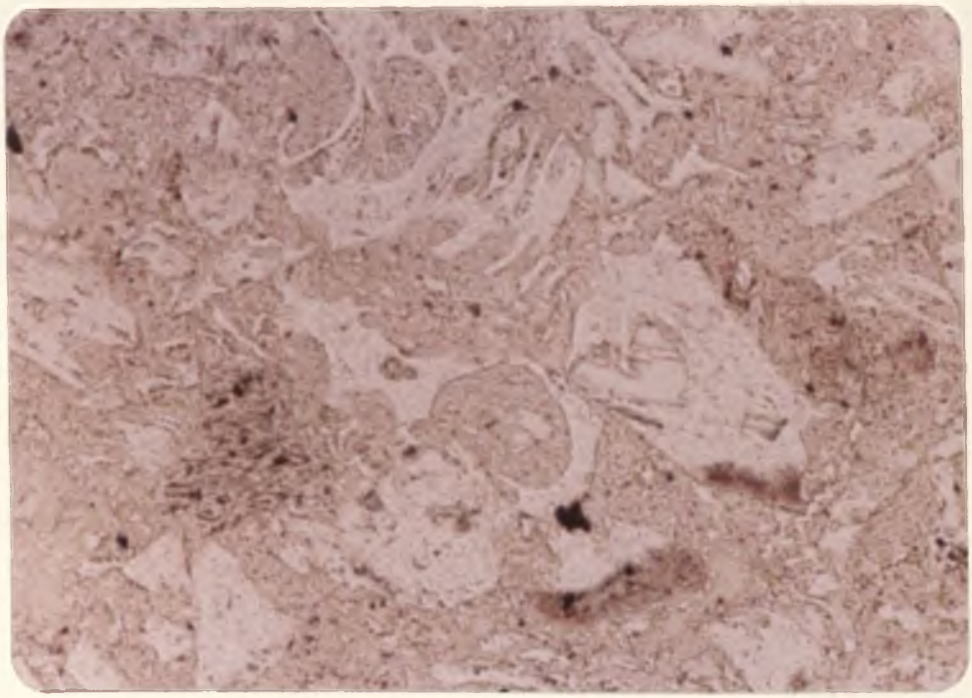


Figure 15. Photomicrograph of Shards in Ta_1, Plane Polarized Light.

The shards are more visible with plane light. Note the nearly round bubble walls and the lack of compaction; this tuff is not densely welded; X40.

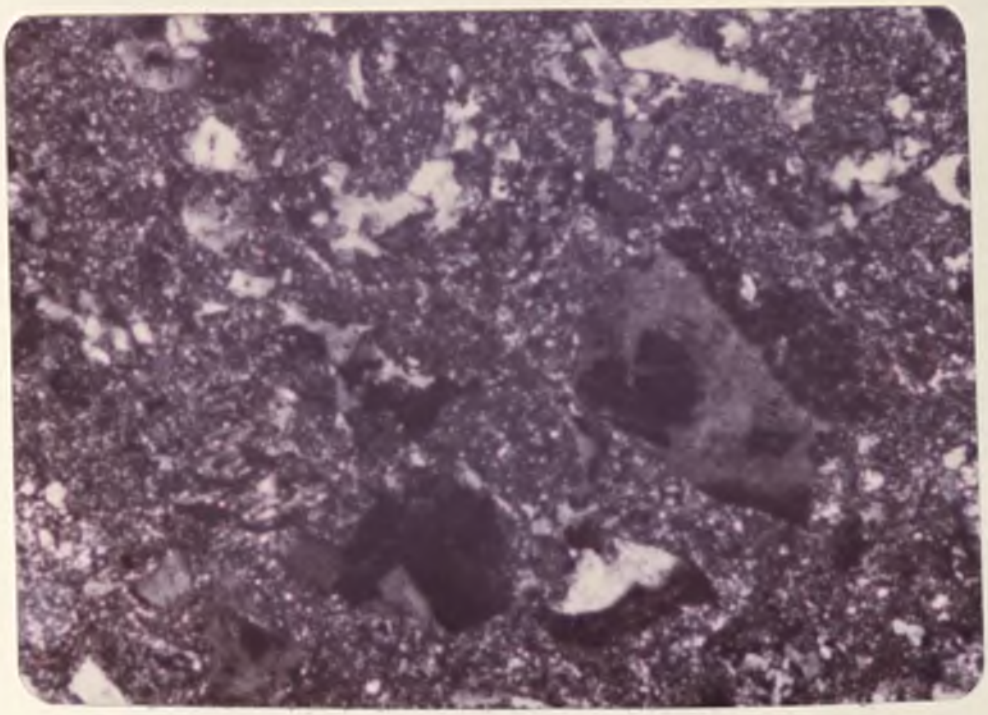


Figure 16. Photomicrograph of Shards in Ta_1, Crossed Nicols.

The shards are difficult to distinguish; they exhibit a mosaic texture rather than the axiolitic texture more typical of devitrified ash-flow tuffs; X40.

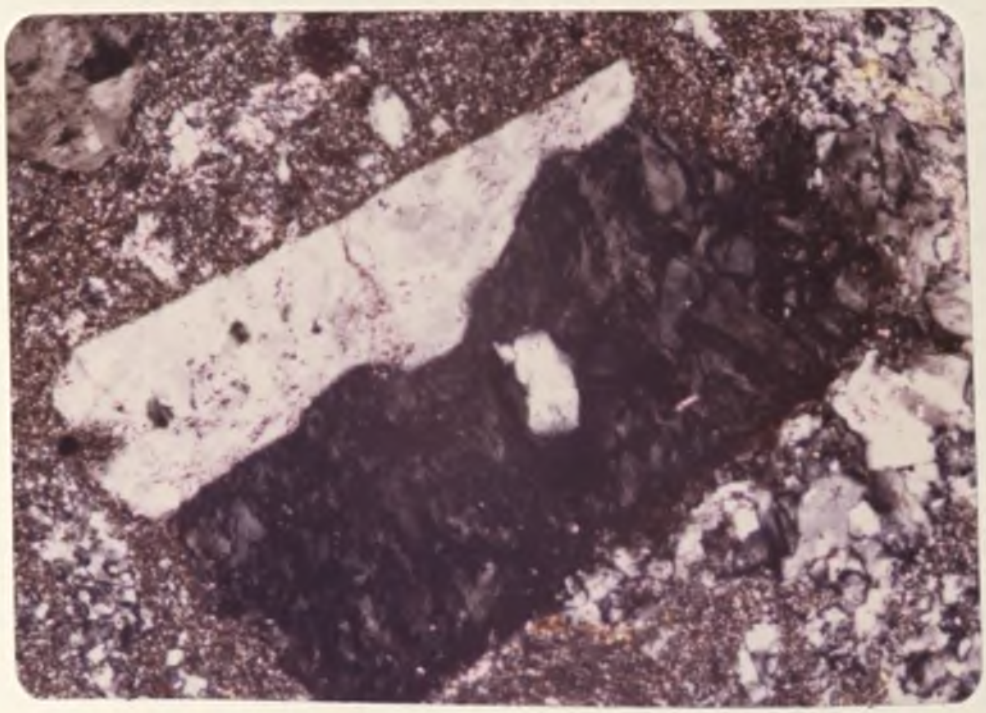


Figure 17. Photomicrograph of Potassium Feldspar Phenocryst Showing "Patchy" Extinction, Crossed Nicols; X40.

interference figures with a 2V of 0^{o} to 30^{o}, and are assumed to be sanidine. The two types of phenocryst yield different alteration products, as will be discussed later in the chapter on alteration. The lithic fragments are often altered beyond identification. Many appear to be of the underlying trachyte porphyry, and some are of a Bisbee-like lithology. There are also angular fragments of sanidine spherulites (Figure 18) of varying sizes, some of which contain branching rutile fibers. These spherulites were X-rayed, and were found to consist entirely of sanidine. They are not intergrown fibers of sanidine and cristobalite, as is typical of spherulites according to Ross and Smith (1960). The pumice lapilli are generally altered to montmorillonite. They are radially flattened and the ends are wispy and frayed. Ribbon texture is occasionally preserved in the devitrification and alteration products. Some of the less flattened pumice has been converted to potassium feldspar similar to that in the shards. This unit appears to be a slightly welded rhyolite ash-flow tuff or possibly a sillar.

Second Water-Lain Tuff (Tw_2)

This unit is a volcanic lithic to arkosic arenite and ranges from 0 to 10 feet thick. It is a useful marker bed for mapping. It is exposed sporadically for several hundred feet across the saddle high on the west side of Pearce Hill. It occurs at the contact between the

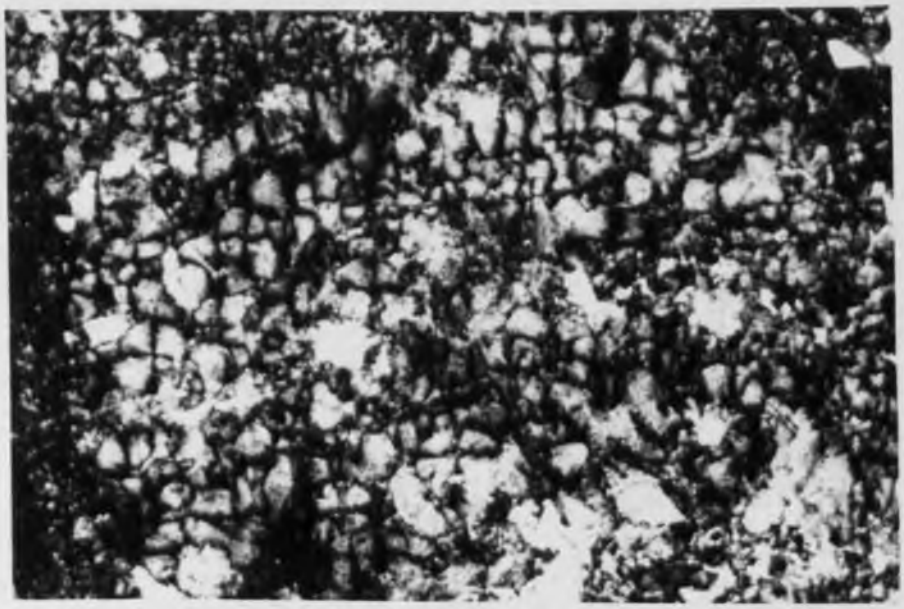


Figure 18. Photomicrograph of Spherulitic Potassium Feldspar in Ta_1.

Probably sanidine formed from the devitrification of pumice. Note the pseudo-isogyres in individual spherulites; crossed Nicols, X40.

first ash-flow tuff and the second flow. It is well-bedded and relatively well-sorted, and appears to be water-lain. The rock is well indurated and is extremely hard to occasionally friable. It has a mottled salmon pink and maroon color on both fresh and weathered surfaces.

Two samples of this rock were examined in thin section. They contain about 30 percent sub-rounded quartz grains, 30 percent potassium feldspar crystals, 30 percent lithic fragments, and minor opaque minerals, biotite, and clay minerals. The average grain size varies from about 0.05 cm to 0.15 cm, and in finely conglomeratic beds there are pebbles up to 1 cm. The lithic clasts include pieces of the lower flow, broken sanidine spherulites, and occasional altered pumice. No shards were observed in either thin section, but their presence may have been obscured by subsequent crystallization. Most of the grains are coated by iron oxide, and the rock contains about 10 percent potassium feldspar cement (Figures 19 and 20). This cement stains evenly with sodium cobaltinitrite both in thin section and stained slab. As was the case with the first water-lain tuff, the cement is unsuitable for X-ray analysis.

Second Flow (Tf_2)

This flow caps Pearce Hill. It has been mapped in a fault block in the vicinity of D Shaft and on the east side of Huddy Hill. In

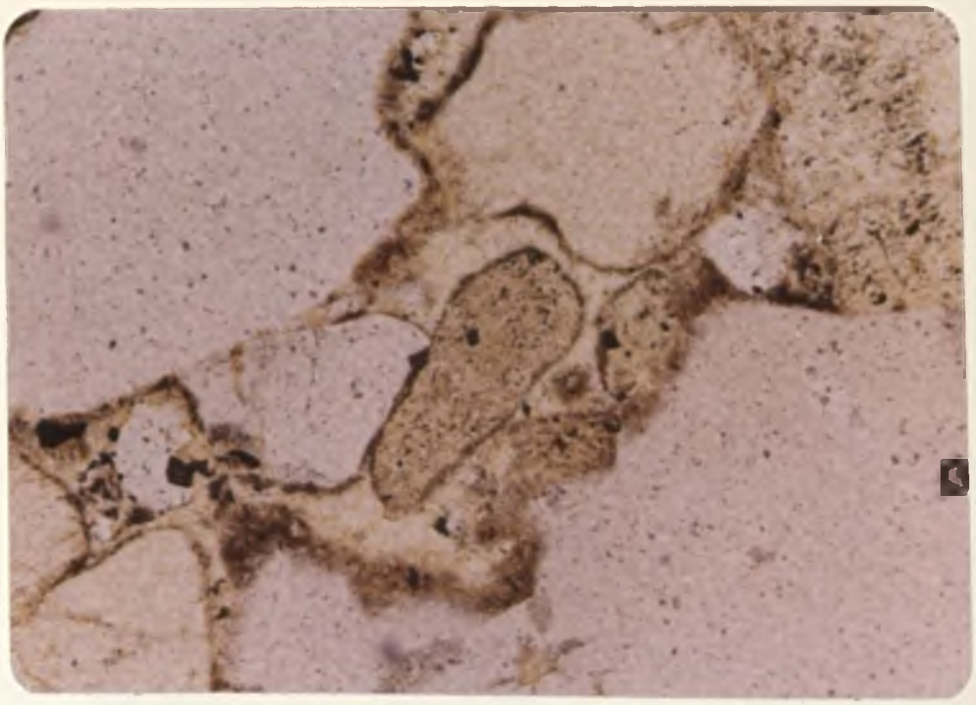


Figure 19. Photomicrograph of Potassium Feldspar Cement in Tw_2, Plane Polarized Light.

The yellow color is due to sodium cobaltinitrite stains. The clear grains are quartz; X40.

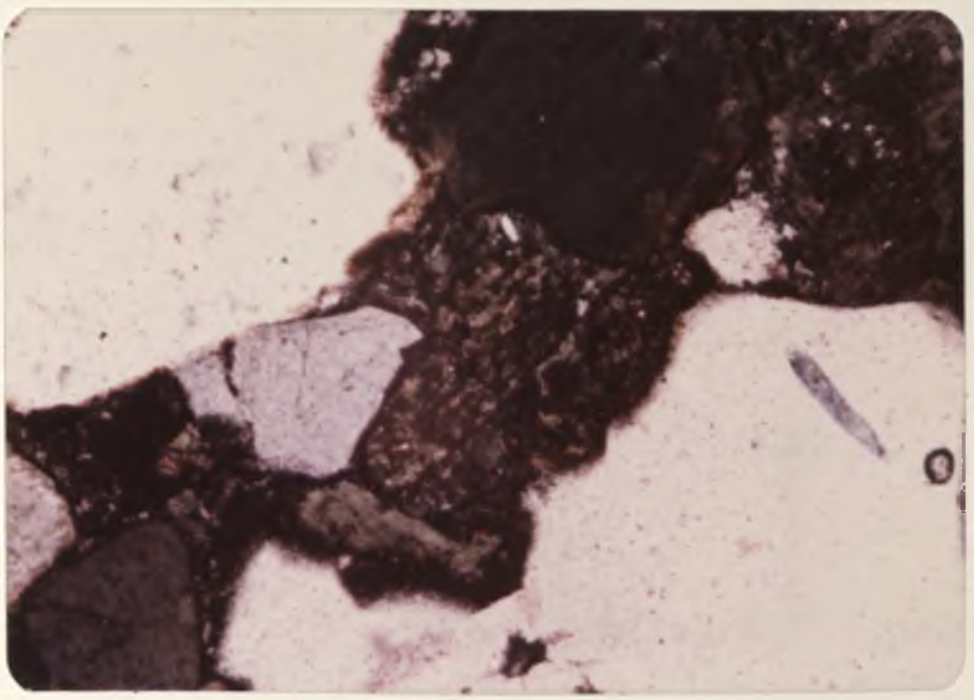


Figure 20. Photomicrograph of Potassium Feldspar Cement in Tw_2, Crossed Nicols.

Note the extremely low birefringence of the potassium feldspar, as compared with quartz; X40.

addition, it crops out on several low hills about half a mile south of Pearce Hill, and on the northernmost of the three knobs south of Sixmile Hill. Its thickness is estimated at 500 feet. This flow is much better exposed than the lower flow, but the top is generally covered and its nature must be inferred from float and dump material. The exposure south of Sixmile Hill is near the top of the section. This flow weathers light gray to maroon, and is light to dark gray on a fresh surface. It overlies the second water-lain tuff unit, but the contact itself is covered. There is a poorly-defined breccia at the base (Figure 21). The lower third of this flow exhibits a rather pronounced flow lamination in the form of different-colored bands and subparallel alignment of feldspar laths (Figure 22). This part of the flow consists of about 5 percent euhedral amphibole phenocrysts, up to 0.3 cm long, and 20 to 30 percent chalky white to glassy feldspar phenocrysts, up to 0.3 cm long. Some of the groundmass feldspar laths are large enough to be seen with a hand lens, but the groundmass is dominantly aphanitic. It is gray with wispy, irregular, salmon pink patches. Near the top of the flow, amphibole makes up as much as 10 to 15 percent of the rock, and feldspar phenocrysts become subordinate. The flow top is scoriaceous for a thickness of several tens of feet. It consists of minor large amphibole and smaller feldspar phenocrysts in an aphanitic groundmass. Vesicles in this scoria are occasionally filled with calcite, olive green to almost white

Figure 21. Autoclastic Breccia at Base of Tf_2.

Near the top of Pearce Hill; hammer is for scale.

Figure 22. Flow Layering in Tf_2.

Near the top of Pearce Hill. The pole is at the highest point on the hill; the hammer is for scale.

montmorillonite, and chalcedonic to coarsely crystalline quartz. No zeolites have been observed.

As was true of the first flow, this unit is altered in all thin sections examined. Samples toward the base of the flow are glomeroporphyritic, containing clumps of subhedral feldspar phenocrysts from 0.01 to 0.3 cm long, and smaller, single, subhedral to euhedral phenocrysts 0.005 to 0.20 cm long. The total phenocryst content ranges from 20 to 50 percent. The feldspar phenocrysts generally exhibit zoning and simple twinning. In the central portion of the flow, the plagioclase content increases. Some thin sections have 10 to 15 percent altered albite-twinned plagioclase, commonly mantled by potassium feldspar. Approximately a third of the way up the thickness of the flow, the larger phenocrysts consist almost entirely of plagioclase which exhibits albite twinning and no apparent mantling. Its composition is around An_{50}. Higher in the flow, potassium feldspar again becomes the dominant feldspar. Throughout this unit, euhedral amphibole is present. It is entirely altered wherever it has been observed, but the euhedral crystal outlines are preserved. A few of the altered crystal outlines could be pyroxene and some are probably biotite, but the amphibole form is dominant. There is quartz in all the samples examined, but it appears to be secondary in origin.

The groundmass of this unit is either trachytic or is a mosaic intergrowth of extremely fine grained material. The groundmass takes

a relatively strong stain with sodium cobaltinitrite, and it is assumed to consist mainly of potassium feldspar with minor and varying amounts of opaque minerals and clays. The flow layering which is so pronounced in hand specimen is not nearly as obvious in thin section. It is reflected by alignment of the phenocrysts and locally trachytic texture in the groundmass. On the basis of estimations of potassium feldspar content of thin sections and stained slabs, this rock must be classified as a trachyte porphyry. It is difficult to estimate the plagioclase content due to its uneven distribution within the flow and to its stronger susceptibility to alteration. Furthermore, some or all of the potassium feldspar may be of secondary origin, as will be discussed in the following chapters. This unit appears to be laterally equivalent to an andesite flow.

Third Water-Lain Tuff (Tw_3)

This unit is a locally conglomeratic volcanic arkose or lithic arenite. It is approximately 450 feet thick, although it is seldom well exposed for much of its thickness. It crops out along the west side of Sixmile Hill and along the west side of the valley in the center of the hill. It is overlain by a resistant ash-flow so that exposures are not always good. Part of what is mapped as Tw_3 in Figure 1 may in fact overlie the ash-flow tuff. This unit crops out along the west side of two of the hills south of Sixmile Hill. It underlies the

valley between Pearce and Metat Hill, and makes up a major component of the dump material around shafts sunk in the valley.

This unit is dominantly an arkosic arenite although in places it contains boulders up to 1 or 2 feet across. It is bedded and locally cross-bedded. It contains minor graded beds. The character of the unit varies greatly from place to place (Figure 23). It ranges from friable and poorly cemented to extremely well indurated. The color ranges from light gray to tan to salmon pink, the latter color being the most common. The coarse lithic clasts consist of the underlying lithologies and rhyolitic rock which does not resemble the underlying units. The lower part of the unit consists dominantly of an earthy red lithic arenite to conglomerate containing pebble- to cobble-size clasts of the underlying flow top.

The thin sections examined are of dump material from the valley between Pearce and Metat Hills. They all contain 35 to 40 percent sub-angular to sub-rounded quartz, 10 to 40 percent potassium feldspar, 0 to 20 percent plagioclase, mostly oligoclase, up to 20 percent rounded opaque grains, and traces of biotite, muscovite, apatite, epidote, and clays. The lithic clasts include volcanics, fragments of spherulites, and altered pumice. No shards were observed in any of the samples. Two of the thin sections contain 5 to 15 percent calcite cement, and a third has 10 percent finely crystalline material as a matrix, probable quartz, potassium feldspar, and clays. The sample

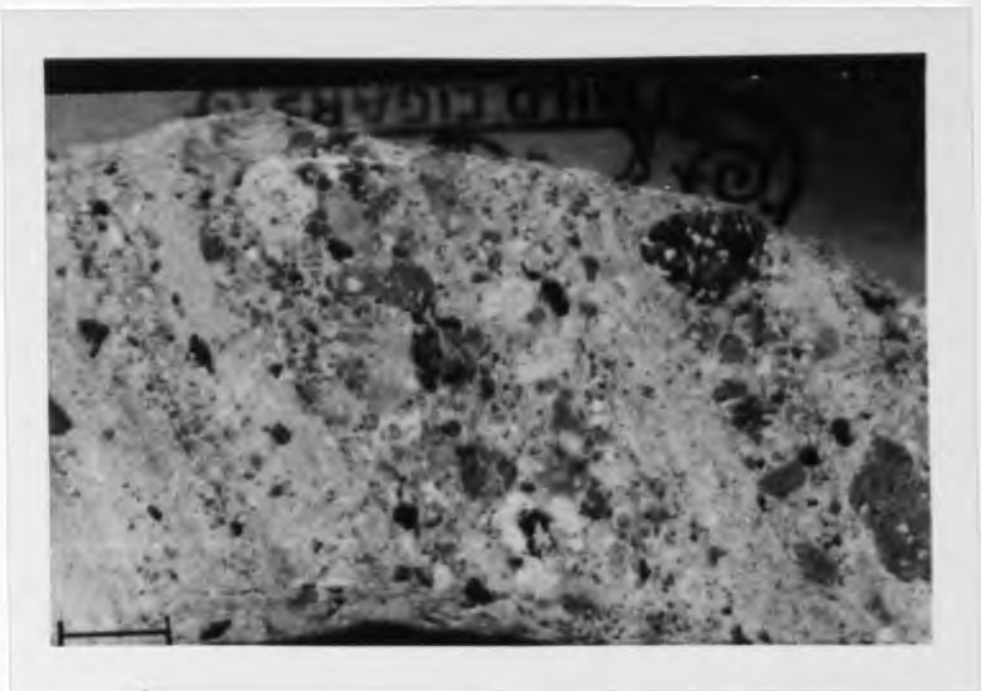


Figure 23. Conglomeratic Portion of Tw_3.

From a dump between Pearce and Metat Hills; scale bar 1 cm.

nearest the top of the unit, from a dump at the base of Metat Hill, contains more plagioclase at 20 volume percent than any other rock examined during this study (Figure 24).

Second Ash-Flow (Ta_2)

This unit caps the western half of Sixmile Hill (Figure 25) and two of the hills south of Sixmile Hill. It also crops out in a few scattered locations along the fault on the west side of Metat Hill. This correlation is somewhat questionable, and was made on the basis of general lithologic similarities and stratigraphic position. The rock is dense and porphyritic, with phenocrysts from 10 to 25 percent. It is light buff to rusty brown on weathered surfaces, and dark gray to chocolate brown on fresh surfaces. On Metat Hill it is bleached and stained by iron oxides. The base of the unit contains collapsed pumice lapilli which range up to 5 or 6 inches long (Figure 26). The ratio of length to thickness is generally less than 6:1 and is never more than 10:1. Higher in the flow, only small scattered pumice fragments and a few dark lithic fragments are present. Most of the unit is massive and un-bedded. Only occasional collapsed pumice fragments define the attitude of the flow.

Two thin sections of this unit were examined, both from the west side of Metat Hill. They contain 10 to 15 percent quartz and sanidine phenocrysts, a trace of biotite, 5 to 15 percent pumice, and

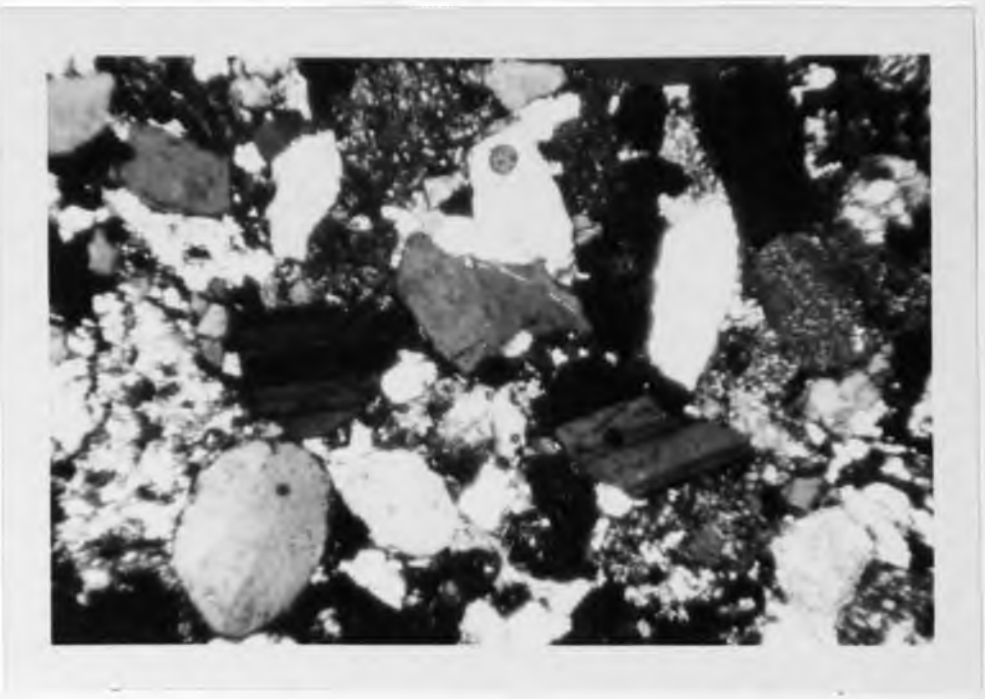


Figure 24. Photomicrograph of Fresh Plagioclase, Top of Tw_3, Crossed Nicols; X20.

Figure 25. Lower Part of Ta_2, West Side of Sixmile Hill.

Tw_3 crops out along the base of the massive cliff, and is very poorly exposed; looking north.

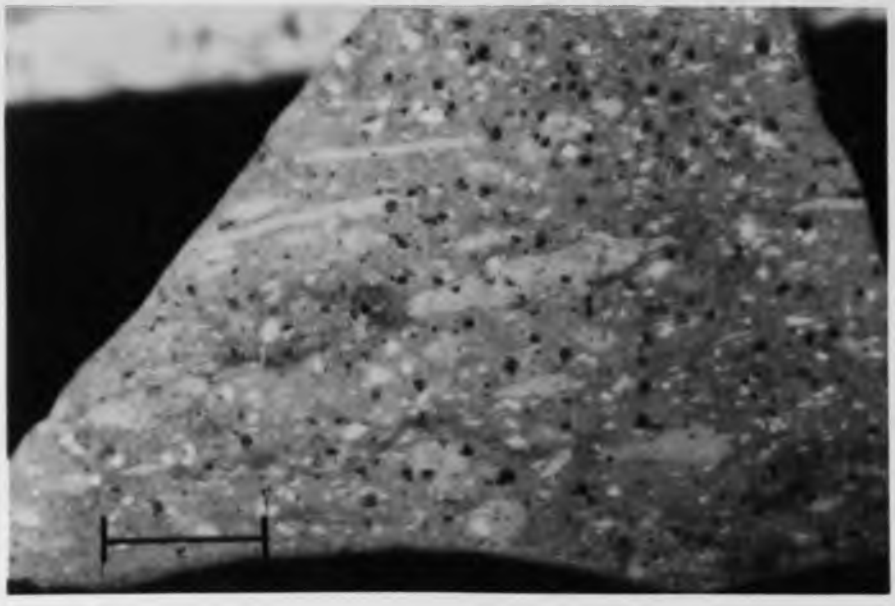


Figure 26. Hand Specimen of Basal Ta_2.

Note the flattened pumice, quartz (dark) and feldspar (white) phenocrysts; scale bar 1 cm.

devitrified tuffaceous groundmass. The quartz phenocrysts are rounded and embayed, and range from 0.05 to 0.15 cm across. Sanidine equals quartz in abundance, and resembles one of the types of sanidine in the lower ash-flow. It occurs as occasionally broken, euhedral crystals up to 0.2 cm long, exhibiting sharp uniform extinction and simple twinning, and it takes a light even stain with sodium cobaltinitrite. The collapsed pumice consists of acicular to axiolitic potassium feldspar interlayered with anhedral, mosaic-textured quartz up to 0.05 cm across. This quartz has probably recrystallized from axiolitic quartz or cristobalite. The shards consist of axiolitic potassium feldspar and montmorillonite, an alteration product (Figure 27). The shards stain evenly and exhibit no variations in relief which would suggest an intergrown silica phase. The matrix material surrounding the shards consists of finely intergrown quartz and potassium feldspar. The shards are mildly compacted, but a few vesicle walls are preserved with round or oval shapes. This unit appears to be a partially-welded tuff which has been further indurated by devitrification and crystallization.

Third Flow (Tf_3)

This unit is very poorly exposed, and most of the evidence concerning its distribution is in dump material. It crops out in a few scattered locations along the central valley of Sixmile Hill, mostly in

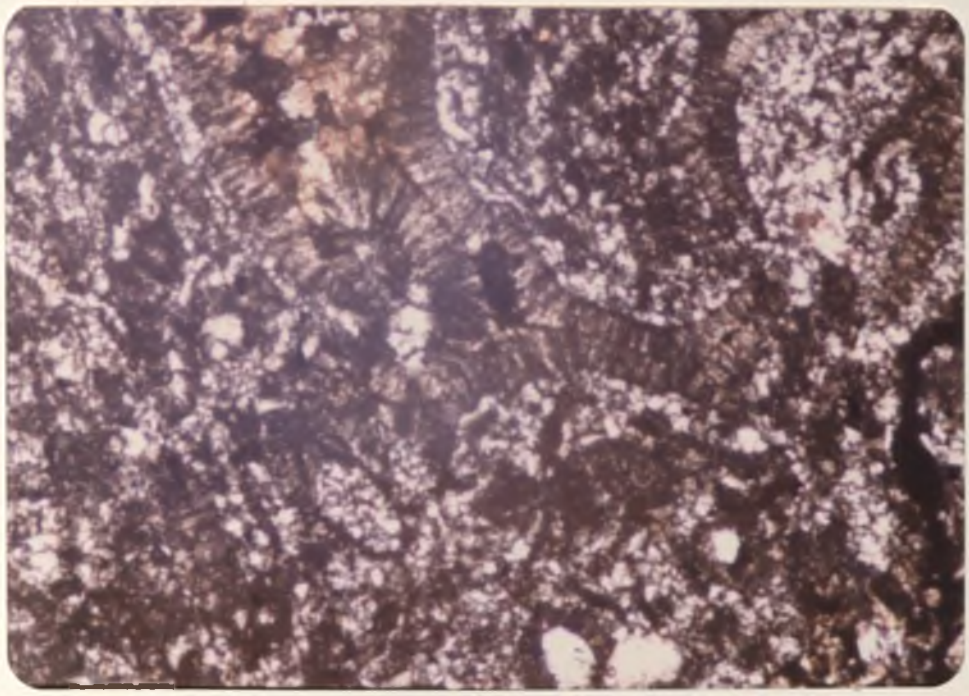


Figure 27. Photomicrograph of Ta_2 Showing Axiolitic Texture of Shards.

The material surrounding the shards is a mosaic of quartz and potassium feldspar. The bronze to pink coloration of the potassium feldspar is due to montmorillonite alteration; crossed Nicols, X40.

prospect pits. There are a few questionable outcrops on Metat Hill. This dark flow rock occurs in prospect pits and dumps along the fault on the west side and in a dump at the north end near the old railroad grade. Aphanitic and scoriaceous near the top, the lower part is nowhere exposed, and the thickness of the unit is unknown. It is dark gray to brown on fresh surfaces and weathers rusty orange. Much of it is altered, having a dark olive-green color. The scoria vesicles are filled with chalcedonic to coarsely crystalline euhedral quartz or tan to green montmorillonite. Some of the coarse quartz is faintly amethystine. No zeolites have been observed.

No thin sections of this unit were examined, but several slabs were stained with sodium cobaltinitrite. The extent of staining is highly variable. The feldspar microlites in one specimen are emphasized by the staining. It is not known how much staining is due to potassium feldspar, and how much is due to alteration products such as montmorillonite. This rock would be classified as an andesite or a basalt in the field, although based on potassium feldspar staining it might be called a trachyte.

Third Ash Flow (Ta_3, Tv)

This unit includes a vitrophyre zone (Tv) which will de discussed together with the rest of the flow. The vitrophyre zone was mapped as a separate unit because it is a useful marker in the field.

The Third Ash-Flow caps the eastern half of Sixmile Hill and Metat Hill, where it is in fault contact with the Second Ash-Flow. It has a minimum thickness of 50 feet and was probably originally several hundred feet thick. The vitrophyre has not been found on Metat Hill, perhaps because it weathers readily and is generally covered. Its absence may be due to poor exposure, or it may pinch out in the mile between Sixmile and Metat Hill.

The vitrophyre is a black and dark salmon pink, finely perlitic glass (Figure 28). It contains 20 to 30 percent subhedral bipyramidal quartz crystals and minor altered mafic minerals. It ranges from dense and homogeneous to strongly eutaxitic, with alternating streaks of black glass and pink material which appears to be partially devitrified. The base of the vitrophyre has not been observed in the field, but it is at least 5 or 10 feet thick. The upper part is in gradational contact with the overlying devitrified zone. The upper part of the vitrophyre is cut by dikes up to several inches wide of pink feldspathic rock which resembles the overlying devitrified material in hand specimen. These dikes are nowhere seen cutting the overlying rock, and are thought to be devitrification dikes similar to those described by Simons (1962).

The devitrified rock is salmon pink on weathered surfaces and dark chocolate brown on fresh ones. The lower 20 feet of the devitrified zone is strongly spherulitic, and appears to be densely welded.

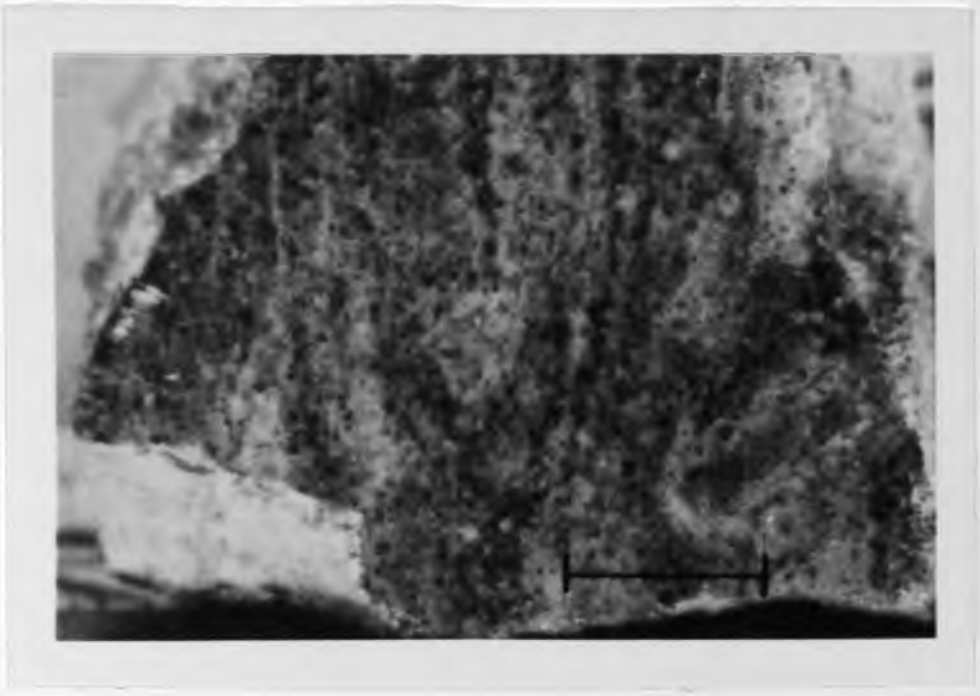


Figure 28. Hand Specimen of Tv.

Scale bar 1 cm.

Spherulites comprise up to 60 percent of the rock, and diminish in abundance upward in the unit. The rock contains 15 to 25 percent subhedral quartz crystals similar in form to those in the vitrophyre. The spherulites are roughly round and many of them coalesce. They consist of concentric bands of white milky quartz and radiating fibrous potassium feldspar, probably sanidine. This texture is emphasized by potassium feldspar staining in a sawed hand specimen (Figure 29). No eutaxitic texture has been observed in the lower part of the flow, but the spherulites exhibit a roughly planar distribution which is emphasized by weathering (Figure 30).

Above the strongly spherulitic zone is a eutaxitic zone 10 to 15 feet thick which contains strongly flattened and distorted pumice fragments. Minor spherulites are present with only 10 to 15 percent quartz phenocrysts. This part of the unit contains ovoid cavities of uncertain origin which are filled with milky-white botryoidal quartz. This material weathers out leaving 1 to 3-inch long holes in the rock. Above this zone, the rock is strongly eutaxitic and generally contains only 5 to 10 percent phenocrysts. The shard texture in this zone is sometimes visible in hand specimen (Figure 31). The shards are of milky-white quartz, and the surrounding material is dominantly pink to gray potassium feldspar.

Only two thin sections of this unit were examined, both from near the top of the west side of Metat Hill. At the time these samples

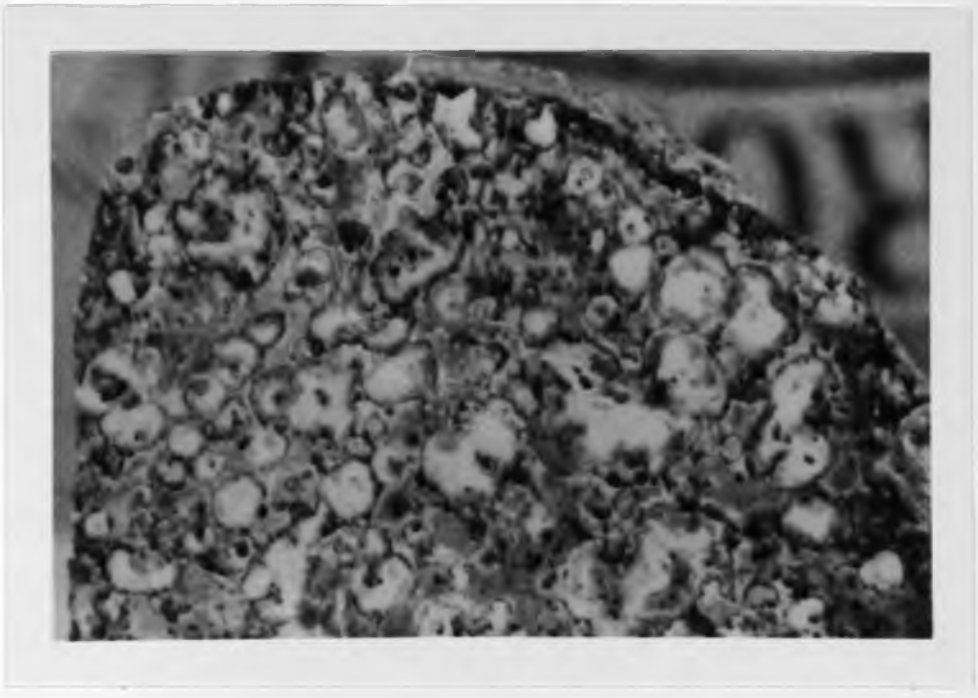


Figure 29. Hand Specimen of Ta_3, Spherulitic Zone.

The white is quartz and the gray is potassium feldspar; the small dark spots are quartz phenocrysts; scale bar 1 cm.

Figure 30. Compaction Foliation in Spherulitic Zone, Lower Part of Ta_3.

From east-central Sixmile Hill; the hammer is for scale.

Figure 31. Hand Specimen of Ta_3, Eutaxitic Zone.

The white is quartz and the gray is potassium feldspar; note the shard forms; scale bar 1 cm.

were collected, all the ash-flow outcrops on Metat Hill were thought to be one unit. However, distinct petrographic differences exist between the two. The samples examined contain 5 to 10 percent sanidine and quartz phenocrysts. The sanidine resembles that in the second ash flow. The quartz is subhedral to euhedral and less embayed than the quartz in the lower ash flows. No shard structures were observed in these samples. The thin sections show undulating parallel bands of alternating anhedral mosaic quartz and fibrous, axiolitic potassium feldspar (Figure 32). Up to 15 percent of the samples consist of spherulites in which the bands are arranged concentrically. Occasional collapsed, frayed pumice lapilli can be recognized, now crystallized to mosaic quartz. All of the feldspar is strongly altered to montmorillonite and takes a light stain with sodium cobaltinitrite. Both of these samples appear to come from the densely welded part of the unit. No thin sections of the vitrophyre were examined.

Correlations

One of the reasons for the detailed rock unit descriptions given here is that there are considerable discrepancies between what is found in the immediate Commonwealth area and what has been described elsewhere in the Pearce Volcanics. Possible reasons for these discrepancies will be discussed in subsequent chapters.

Figure 32. Photomicrograph of Ta_3, Spherulitic Zone.

The white is quartz; the low-birefringent bands consist of potassium feldspar (sanidine?). Note the embayed quartz phenocryst at upper right; crossed Nicols, X20.

Due to the laterally variable nature of volcanic rocks in general and these units in particular, care must be exercised in correlation of these units with those on other hills in the Sulphur Springs Valley. Smith (1927) and Gilluly (1956) described the Pearce Volcanics in some detail and Ettinger (1962) described the Pat Hills Volcanics, which may be contemporaneous. Smith described the rocks in the Pearce area itself, and Gilluly gave a measured section from the Sulphur Hills, 6 miles away. Smith's descriptions agree fairly well with those given here. He cited two units within the lower part of the sequence which appear to be only a faulted repetition of the First Flow. He refers to the flow units as andesites on the basis of field and petrographic examination. Gilluly, in his description of the section in the Sulphur Hills, also identifies the flow rocks as andesites. There is little doubt that these andesites are correlative with the flows described here, and the discrepancies in mineralogy are puzzling. The presence of abundant potassium feldspar in the rocks on Pearce Hill has been confirmed in this study by both staining and by X-ray analysis. Only on top of Pearce Hill and on the 7th level has any significant amount of plagioclase been observed as crystals which exhibit albite twinning and do not stain. They are commonly mantled by potassium feldspar which does stain. Possibly the earlier petrographic descriptions were done on samples collected from the parts of the flows which contain plagioclase, but that seems unlikely. In

the absence of staining or X-ray work, the occasionally minor potassium feldspar may not have been detected. Smith notes that the twinning of the plagioclase is often destroyed by alteration; these crystals may have been misidentified potassium feldspar. The discrepancy with Gilluly's description may be due to alteration of the rocks near the Commonwealth veins, an idea discussed in later chapters. A third possibility is that these flows do not correlate with the andesitic flows described elsewhere.

The First Ash Flow described here appears to correlate with a rhyolite described by Gilluly in the Sulphur Hills. He mentions sanidine and quartz phenocrysts but no lithic fragments. The Third Water-Lain Tuff appears to correlate with three units of Gilluly's: a thick water-lain tuff, a tuff-breccia, and a thick rhyolite agglomerate. Lack of better exposures in the Pearce area precludes any correlation with his specific units. He adds that in the Sulphur Hills the water-lain tuff is partially impregnated with native sulfur. The Second and Third Ash Flows resemble the later rhyolite flows of Gilluly, except that minor oligoclase is present in the Sulphur Hills flows which has been looked for but not recognized in the Pearce area. The Third Flow reported here occupies the same stratigraphic position as a unit of interbedded rhyolite tuff and thin flows in Gilluly's section.

Smith described the Second Ash Flow of this study in the Central Butte and Little Jessie Hills as being vitrophyric at the top and having a range in thickness of several hundred feet. He described the top of the Third Ash Flow as containing presumed air fall tuff and glass, but he did not state where the exposure is located.

Ettinger (1962) described the volcanic sequence of the Pat Hills which lie 15 miles northeast of Pearce, near the eastern edge of the Sulphur Springs Valley. He describes porphyritic andesite, lahar breccia, porphyritic dacite, altered acid volcanics, and various intrusive rocks. There is no clear similarity in the volcanic sequences of the two areas, but they could be laterally equivalent.

Enlows (1955), Marjaniemi (1968, 1970), and Drewes and Williams (1973), among others, have described the volcanic rocks of the northern Chiricahua Mountains approximately 30 miles northeast of the Pearce area. These rocks include andesite, basalt, and rhyodacite flows and thick rhyolite welded tuffs. Marjaniemi gives a date of 25.7 $\pm$ 0.8 m.y. for one of the lower units of the thick mid-Tertiary volcanic sequence. The Chiricahua sequence is part of a large volcanic field which includes the central and southern Pelloncillo Mountains and the Animas Mountains of New Mexico. Drewes and Williams also describe andesite in the Chiricahua Wilderness Area which they place within the Bisbee Formation. They describe dacite

lava and breccia which overlies the Bisbee and may be Cretaceous or Tertiary.

Loring (1947), Rogers (1957), and Diery (1964) described the geology of the Swisshelm Mountains, and all make brief mention of rhyolitic volcanics which appear to have once overlain all the older units and which might correlate with units in the study area. Rogers gives a relatively detailed description of these units, and Marjaniemi (1970) states that some of the Swisshelm Volcanics correlate with members of the Chiricahua rhyolitic sequence.

Gilluly (1956) states that the Pearce Volcanics are probably correlative with the S.O. Volcanics, a thick sequence of quartz latite tuff and hornblende andesite flows on the southwest flank of the Dragoon Mountains. A quartz latite tuff from this unit gives a K-Ar age of 47 ± 2 m.y. (Marvin et al., 1973).

No direct correlation is possible between the Pearce Volcanics and those of the surrounding mountain ranges, but they may well be contemporaneous or laterally equivalent. Much more detailed study would be necessary to make any such long-range correlations. Such a study should include age dating, detailed geochemistry, and petrography.

Interpretation of Rock Units

Many ideas concerning the nature and origin of ash-flow tuffs have evolved since Smith first systematically described the Pearce rocks in 1927. It seems appropriate here to evaluate some of the features of the Pearce Volcanics in light of the currently accepted models of ash-flow tuffs and related fragmental materials. A number of papers define and describe ash-flow tuffs, including Ross and Smith (1960) and Smith (1960a,-b). Their terminology is followed throughout this thesis.

Ross and Smith define an ash-flow tuff as consolidated volcanic ash fragments mostly under 0.4 cm in diameter, deposited from an explosively ejected, turbulent mixture of high temperature gas and pyroclastic materials which travels downslope along the ground surface. This term therefore implies composition, grain size, and mode of emplacement. The Second and Third Ash Flows fit this definition nicely. Part or all of the First Ash Flow might better be called a lapilli tuff or even a tuff-breccia, using Parsons' (1969) definition. However, the amounts of lapilli and block size fragments are subordinate when the unit is considered as a whole; shards, dust, and ash-size crystals almost always make up more than half of the rock. The high percentage of lithic fragments may be due to incorporation of earlier deposited material on the ground as the ash flow moved over it or of material scaled off by partial disruption of the vent. The

latter explanation seems more reasonable, since the coarser lithic fragments occur in the central part of the unit rather than near the base. However, this evidence is not conclusive.

The three ash-flow tuff units exhibit varying degrees of welding. In the lower two, the primary evidence of compaction and welding is the presence of collapsed pumice. The shards do not appear to be greatly deformed, and bubble walls are preserved in almost circular shapes. Smith (1960b) states that due to temperature considerations, ash flows showing crystallization to sanidine-tridymite or sanidine-cristobalite must also be mildly welded if they are thick enough to show deformation of pumice or shards. Therefore these units must be partially welded ash-flow tuffs rather than true sillars.

The First and Second Ash Flows exhibit only vague zoning near their bases. The First Ash Flow contains a possible air fall at the base, which may have been "fused" by crystallization in a manner similar to that described by Christiansen and Lipman (1966), where an air-fall tuff was covered by a hot rhyolite flow which heated it to crystallization temperature and compressed it. The lower 5 to 10 feet of the Second Ash Flow appears to be a more densely welded zone. The Third Ash Flow exhibits poorly defined welding zoning and crystallization zoning. It is the most densely welded of the ash flows. The vitrophyre is a dense, black glass which represents the ultimate product of the welding process (Smith, 1960a). Together with the

devitrified spherulitic zone above it, it makes up the zone of densest welding. The eutaxitic rock above this zone would represent the zone of partial welding. The base of the vitrophyre is covered in the study area, and it is not known whether or not there is a partially welded zone beneath it to correspond to the upper one. This would be expected, according to Smith.

The bedded, arkosic units in the study area have been assumed to be water-lain, but they may at least in part have originated in a manner described by Walker (1971). He states that all the welded tuffs he has observed have a very heterogeneous basal layer consisting of lithic fragments and crystals, in part well sorted and cross-bedded, irregularly stratified, and coarser-grained than the ash flow itself. He attributes the absence of shards and pumice in this layer to the sorting and winnowing action of a strong gas stream at the base of the ash flow. This layer is generally thin at the base of a thick ash flow unit, but may be equal in thickness to a thin ash-flow tuff.

The flow units all appear to be true lava flows with scoria or breccia zones at the tops and bases. The breccias are monolithologic and appear to be autoclastic flow breccias as defined by Parsons (1969).

The nature of the volcanic units and the absence of any intrusive rocks in the study area suggests that they were deposited at some distance, probably several miles, from their source. The thickness of the units is relatively uniform, and there are no coarse

breccias or rapid lateral changes which would suggest proximity to a vent. Evidence as to the location of the source area is inconclusive. If the vitrophyre of the Third Ash Flow does indeed pinch out at Metat Hill, this would be in keeping with a southwesterly source. However, assuming that the correlations suggested here are valid, most of the units tend to thicken toward the Sulphur Hills, suggesting a source to the northeast. The presence of plutonic rocks, dikes, breccia pipes and lahars in the Pat Hills suggests that this area could possibly have been the source for at least some of the Pearce Volcanics. An even more speculative suggestion would advance a genetic relationship with Marjaniemi's (1970) Turkey Creek caldera. Such long-range correlations cannot be made on the basis of what is currently known about the volcanics, and there is no real evidence of a local source.

Structure

Although a detailed discussion of the structural history of southeastern Arizona is beyond the scope of this study, a few general comments on the post-Cretaceous structural evolution of the ranges surrounding the Sulphur Springs Valley will be made before the local structure is discussed.

Regional Structure

Drewes (1968, 1972) presents a general picture of deformation in southeastern Arizona developed from 90 m.y. to 52 m.y. ago,

extending from before to after the Laramide interval. This deformation consisted of two distinct phases which were separated by a period of relative quiescence and a reorientation of regional stresses. Structures of the earlier Piman phase reflect northeast-directed tectonic stresses, and include thrust faults, tear faults, and folds accompanied by intrusive and volcanic activity. Structures of the Helvetian phase are best developed in the northwestern part of the region and consist of northwestward-directed thrusts and left-lateral tear faults accompanied by igneous intrusion and mineralization (Drewes, 1968).

Laramide tectonism in the Dos Cabezas Mountains produced faults that trend west-northwest and show both right lateral and reverse movement, followed by vertical faults trending north-northeast and having relatively small net slip (Erickson, 1968, 1969). Laramide deformation of the Chiricahuas resulted from horizontal compression from the south and southwest which produced northwest-striking thrusts, northeast-striking left-lateral tear faults, folding, and reverse faults (Sabins, 1957b). According to Loring (1947), the Swisshelm Mountains were deformed during Laramide time by north to northwest-striking, east to northeast-dipping thrusts, northeast-striking tear faults, and anticlinal folding having a north-south-trending, eastward-dipping axial plane. The Dragoon Mountains are

deformed by Laramide thrusts and folds having east and north-northwest trends (Gilluly, 1956).

The next apparent period of deformation in the vicinity of the Sulphur Springs Valley is the Basin and Range Orogeny, which began sometime between Oligocene and mid-Miocene (Gilluly, 1963, and Christiansen and Lipman, 1970). There are three basic models for Basin and Range structures (Stewart, 1971): landslide-type deformation caused by blocks sliding off of regional highs or by removal of lateral support; structures related to strike-slip deformation; and deformation caused by fragmentation of the crust above zones of deep-seated extension.

The ranges bounding the Sulphur Springs Valley trend north to northwest, as is typical of the Basin and Range topography of southeastern Arizona (Anderson, 1966). Steeply-dipping boundary faults are described or inferred along the west side of the Chiricahuas (Sabins, 1957b) and the east side of the Dragoons (Gilluly, 1956). Loring (1947) maps a high angle fault along the east side of the Swisshelms, where Tertiary rhyolite is down-dropped against Paleozoic and Cretaceous rocks. The nature of the western boundary of the Swisshelms is not clear. Gilluly (1956) considered the isolated hills of the Pearce Volcanics to be the northwestern extension of the Swisshelm Mountain trend and states that the hills are probably the nearly-buried remains of a fault block mountain range. Data included in

Aiken and Sumner (1974) support such a suggestion. The Bouger gravity anomaly map of southeastern Arizona included in that report shows a bedrock ridge extending northwest from the Swisshelms beneath the Pearce Volcanics. It dies out about 10 miles north of Pearce. Deep basins lie to the north, south, and southeast of the Pearce area. Gravity and drilling information indicate that there is another bedrock high extending southwest from the Pearce area toward the Dragoons. Deep holes drilled through the alluvium of the valley bottom in Cretaceous or Tertiary rocks. In the deepest part of the southern basin, east of the southern tip of the Swisshelms, a drill-hole bottomed at 5450 feet in Tertiary volcanics and sediments. The timing of this deformation and of the volcanism is not known, due to the lack of fossils or isotopic dates.

Local Structure

The post-Bisbee rocks in the study area strike an average of N 40° W and dip 10° to 40° NE. No precise attitudes could be determined on the Bisbee rocks, but they appear to dip generally northeast. The flow contacts and bedding planes in the bedded units range in strike from about N 25° W to N 55° W, and in dip from 5° to 55° NE. Flow-layering in the volcanic units shows a wider range in dip, varying from 10° SW to 50° NE. The best indication of overall strike and dip of the flows is their outcrop pattern. There appears to

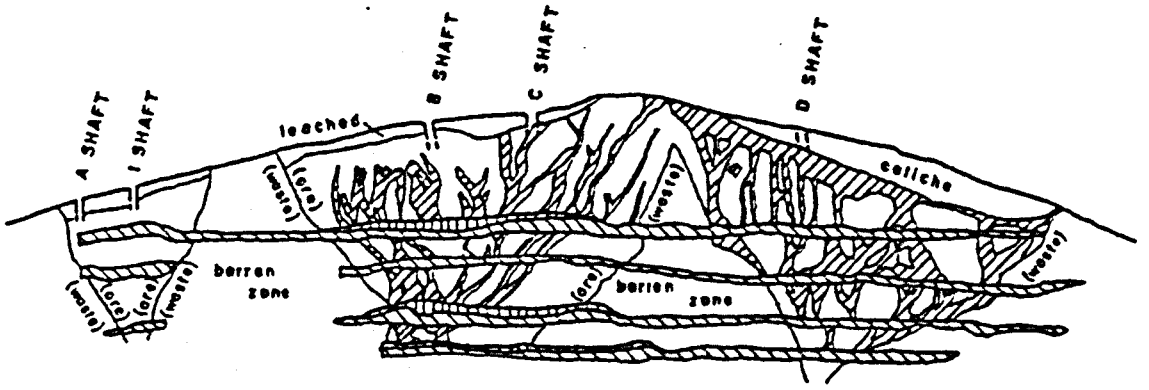
be some variation in overall dip from hill to hill, but as far as can be determined the units on any given hill are conformable. No angular unconformities have been observed in the study area, although they have been described elsewhere in the Pearce Volcanics. It must be remembered that discordant contacts within a volcanic sequence may represent variations in the underlying topography or edges of flows, but they do not necessarily imply structural deformation.

The jointing characteristics of the different rock types are relatively uniform in areas away from the veins. The Bisbee Formation displays widely-spaced orthogonal joint sets. The ash flows have very wide-spaced blocky jointing on the order of 2 to 4 feet and the flows have more closely spaced joints, frequently 1 or 2 feet apart. In zones of sheeting, the flow rocks are finely broken and platy, sometimes having an almost fissile appearance with fractures only inches apart. The Bisbee rocks tend to form fracture sets parallel to zones of sub-vertical sheeting and impermeable gouge zones. The ash flows are extremely competent and brittle and generally contain vugs and open spaces where sheeted. There is more of a tendency for stockworks to form in the ash flows than in the other rock types.

The most important veins in the study area occur on Pearce Hill, where the Commonwealth Mine is located. Low grade veins similar to the Commonwealth veins occur on other hills, and will be

discussed only briefly. Due to the extent of mining and limited accessibility of the veins, the writer must rely heavily on previous descriptions. Smith (1927) includes sketches and detailed descriptions of the important veins, and an assay longitudinal section from which Figure 33 is adapted.

The Commonwealth veins lie along a branching group of faults along which there has been considerable offset. These faults vary in strike from east-west to N 70° W, and dip from 40° S to vertical (Figures 2, 34, 35, and 36). The average dip is around 60° S. No direct evidence of direction of movement, such as slickensides, has been observed. The dominant component is normal dip slip, but a component of right-lateral strike slip may also be present. Dip separation along the vein faults, as determined by graphical methods (Dennison, 1968) ranges from 35 to over 1000 feet and amounts to approximately 2000 feet for the entire system of faults. Strike separation for the system amounts to almost 2900 feet. The vein faults converge on the west side of Pearce Hill and diverge on the east side, making determinations of separation somewhat difficult. All of the displacement on a few closely-spaced fault planes on the west side is spread among several separate faults on the east side. Not enough information is available to determine if the displacement is greater at one end than at the other. Veined faults of similar trend at the north end of Sixmile Hill (Figure 22) show strike separation of up



Horizontal Silver Zones (50-250 oz/t silver, 0.5-2.5 oz/t gold)

Horizontal Gold Zones (60-100 oz/t silver, 1.5-2.5 oz/t gold)

Vertical High-Grade Zones (14-200 oz/t silver, 0.15-1.6 oz/t gold)

(ore)/(waste) Shoot outline; grade in barren zone less than 8 oz/t silver, 0.1 oz/t gold

Figure 33. Generalized Longitudinal Section of the Main Vein.

After Smith, 1927.

Figure 34. Stope on North Vein, North Side of Pearce Hill.

View is looking east toward Huddy Hill. Note the sharp hanging wall; both hanging wall and footwall are Ta_1.

Figure 35. Massive Quartz Vein Remnant of Main Vein, Pearce Hill.

Sub-vertical sheeting occurs in both the hanging wall and footwall of the vein. The Main Vein Fault is not well shown. The North Vein Fault is at the far left of the picture. The view is looking east in the western caved area; the faults and sheeting dip south.

Figure 36. View of Metat Hill Looking East from North Vein.

Note the massive quartz vein in the foreground. The N 40° W fault on the side of Metat Hill can be projected between the upper line of the dumps. The lower dump at left-center yielded sample #6 containing fresh plagioclase.

to several hundred feet. These faults generally dip south and show dominantly normal dip slip.

The Commonwealth veins lie in the footwalls of the faults. Along the hanging walls, the veins tend to be massive and tabular (Figure 34), but they generally grade into zones of sheeting or stockworks with no clearly-defined footwall. The sheeted and stockwork zones consist of mineralized stringers and late gouge zones. The vein paragenesis will be discussed in detail in the section on mineralization and alteration. Offset within the sheeted zones generally appears to be minor, although there are occasional slices of several different rock units within them. Most of the displacement appears to have been along a few discrete fault planes. The character of the veins depends on the footwall lithology. The Bisbee Formation is the most incompetent of the rock units. Fractures in this unit are generally gouge zones, and there is little open space. Veinlets and stringers in the Bisbee Formation are much less abundant than in the other rock units, and the overall wallrock grade is lower (see the chapter on Economic Potential and Appendix A). Where Bisbee Formation lies in the footwall of a vein, the zone of quartz stringers dies out rather abruptly against a narrow gouge zone. The flows are of moderate competence and form wide, strongly sheeted zones in vein footwalls. These zones contain quartz and calcite stringers and late gouge. Vugs and comb texture are present, but they are not as

abundant as in the ash flows. The ash flows exhibit sheeting and stockwork veining. Stringers and veined fractures frequently show a roughly hexagonal pattern with drusy vugs at intersections. Typical epithermal comb and cockade textures, as described by Lindgren (1933), are well developed in veins where this unit is in the footwall.

Movement along the fault veins continued during and after vein formation. At some localities, especially in the North Vein, where it crops out between Pearce and Huddy Hills (Figure 6), massive vein quartz is brecciated and re-cemented by more quartz. Several different ages of veining are apparent, and all veins are cut by barren gouge-coated fractures along the same trend as the veins.

The sheeting exhibited by the Commonwealth veins appears to fit Wisser's (1960) suggestion that sheeted zones are frequently the result of tensional stress rather than shearing. Abundant evidence of tension and relatively little of shearing is present at the Commonwealth. Brittle failure is by far the predominant mode of failure.

There are east to east-northeast trending faults of small to moderate displacement across the central and southern parts of Sixmile and Metat Hills. These generally contain narrow breccia zones which are cemented by minor amounts of quartz. The direction of movement on these faults cannot be determined with confidence and their age relative to the other groups of faults is unknown.

The fault veins appear to be offset by a group of faults which strike about N 40° W. There is some minor quartz veining along smaller faults of this trend, but most of the faults are characterized by gouge zones. These faults generally underlie alluvium and their location must be inferred from stratigraphic evidence. Smith (1927) described the fault which offsets the Commonwealth veins on the west, and called it the Brockman Fault. This part of the mine is no longer accessible, but stratigraphic offset requires a fault which is down to the west. One of this group of faults is exposed on the east side of Huddy Hill and in scattered outcrops on the west side of Metat Hill (Figures 1 and 2). Its trace is marked by a line of prospect pits on both hills. Where it is exposed, it dips 50° to 70° NE and shows normal dip slip. Any strike-slip component which might be present would be right lateral. The deflection of the fault traces by topography indicates that they are everywhere steeply inclined and show normal dip slip. The block containing Pearce Hill is a horst and is structurally higher than the other fault blocks in the study area. The northeastward tilting of the units probably occurred during this episode of faulting, although there is no conclusive evidence in the study area. The variations in overall dip from hill to hill can be explained by differential tilting along these faults.

The uniformity of the faults within the two groups suggests that they are genetically related, although the exact nature of this

relationship is not clear. The fault veins appear to have formed in response to roughly north-south directed tension or east-west compression. The source of this tension can only be speculated. The possibilities include subsidence to the south due to settling over a magma chamber, or subsidence of the basin in the southern Sulphur Springs Valley and uplift or doming to the north, which could also reflect either adjustments of the parent magma of the volcanics or Basin and Range movement. The younger group of faults is parallel on the general trend of the Swisshelms and to the gravity high shown on the map in Aiken and Sumner (1974). They appear to reflect northeast-southwest tension, and are most likely related to Basin and Range structural activity in the area.

CHAPTER 3

MINERALIZATION AND ALTERATION

This chapter describes major features of mineralization and alteration at the Commonwealth Mine and in similar veins on the other hills studied. Interpretation of these features will be deferred to Chapter 5 on genetic models. Smith (1927) presents detailed descriptions and illustrations of the Commonwealth veins, and his work will not be repeated here. Much of what he described is no longer accessible. The present descriptions are based on material accessible in workings left by the early miners, which have not caved in. The picture given by this study of the physical aspects of the veins themselves is sketchy at best. The emphasis here is on wall-rock alteration and gangue mineralogy of the remaining portions of the veins. Comparison of this alteration with that described around active hot springs in similar lithologies provides insight into the genesis of the Commonwealth mineralization and of epithermal mineral deposits in general.

Introduction

Alteration described in this chapter may include devitrification products of the ash-flow tuffs and deuteric alteration of the flows,

although it concentrates on hydrothermal wall-rock alteration and vein filling, and on the overprint on these assemblages of oxidation and supergene activity. It is difficult, and sometimes impossible, to distinguish these types of alteration on the basis of mineralogy and texture. Furthermore, it is likely that deuteric, hypogene, and supergene alteration are gradational in the epithermal environment. This idea, and the genetic implications of the alteration assemblage, will be discussed in the chapter on genetic models. The present chapter will describe with a minimum of genetic interpretation the alteration mineralogy and textures in the Commonwealth area.

The most pervasive alteration minerals in the Commonwealth area are potassium feldspar and montmorillonite; quartz, calcite, and sericite are more restricted in distribution. Chlorite and epidote are rare in most of the mine area. Potassium feldspar is found throughout the study area as a rock-forming mineral and a devitrification and alteration product. How much of it is hydrothermal in origin, one of the major questions raised by this study, is discussed in subsequent chapters. Veinlet adularia is somewhat more restricted in distribution, being of roughly the same extent as the quartz and calcite. Montmorillonite is found throughout the study area as an alteration product of pumice and rock-forming minerals, as fracture coatings, and as vesicle fillings in scoria. It is found replacing pumice everywhere on Pearce Hill, and appears to be an alteration product of

potassium feldspar in all the samples examined from Metat Hill. Quartz and calcite occur abundantly as stringers, amygdules, and replacements within several hundred feet of veins. Caliche is also spatially related to veins and fractures. Epidote has been identified in hand specimen, and the flow rocks have an overall green color at the fringes of the study area. However, none of the "epidote" has given a satisfactory copper radiation X-ray pattern, possibly due to the high fluorescence background from associated iron oxides. The only epidote unquestionably identified in thin section occurs as trace grains in the Bisbee Formation. Chlorite occurs in minor amounts as an alteration of mafic minerals in samples from the east end of the 7th level.

Vein Mineralogy

The Commonwealth veins consist of sheeted or stockwork zones with or without massive quartz veins along hanging walls. The foot-wall zones generally show a gradual decrease in fracture intensity and ore grade away from the vein. There are several different types of veinlets which make up the stockworks and sheeted zones. These include various combinations of quartz, adularia, and "black calcite"; clear or "white calcite"; and fracture coatings of montmorillonite. The textures exhibited in the Commonwealth veins are typical of the epithermal environment. Drusy vugs, comb texture, and

crustification are common; cockade, hackly, and lamellar textures are present, but are less abundant. All of these textures are defined by Lindgren (1933). The zonation and paragenetic sequence of the vein minerals is quite vague, although general trends have been observed. The adularia and "black calcite" veinlets appear to be more common between the massive quartz veins in the sheeted and stockwork zones. The massive parts of the veins consist of quartz cut by "white calcite" veinlets and montmorillonite-coated fractures. All of the veinlets of the quartz-adularia-"black calcite" group appear to be roughly contemporaneous. In detail, there appears to have been a minor, very early quartz stage, followed by an adularia-"black calcite" stage, followed by a quartz-adularia-"black calcite" stage. Wherever adularia occurs with another mineral in veinlets, it appears to precede them, and lines the walls as subhedral to euhedral crystals (Figure 37). This sequence is speculative at best, and may vary from place to place in the vein system. Any of the minerals of this group may occur alone in veinlets, or any two or all three may occur together.

The adularia occurs as anhedral to euhedral crystals with a rhombic cross section. Euhedral crystals up to 0.5 cm long commonly project inward from the edges of veinlets, and the centers are filled with quartz or "black calcite." Many of the crystals exhibit poorly-defined polysynthetic twinning around the edges similar to that described by Chaisson (1952). Interference figures of the adularia

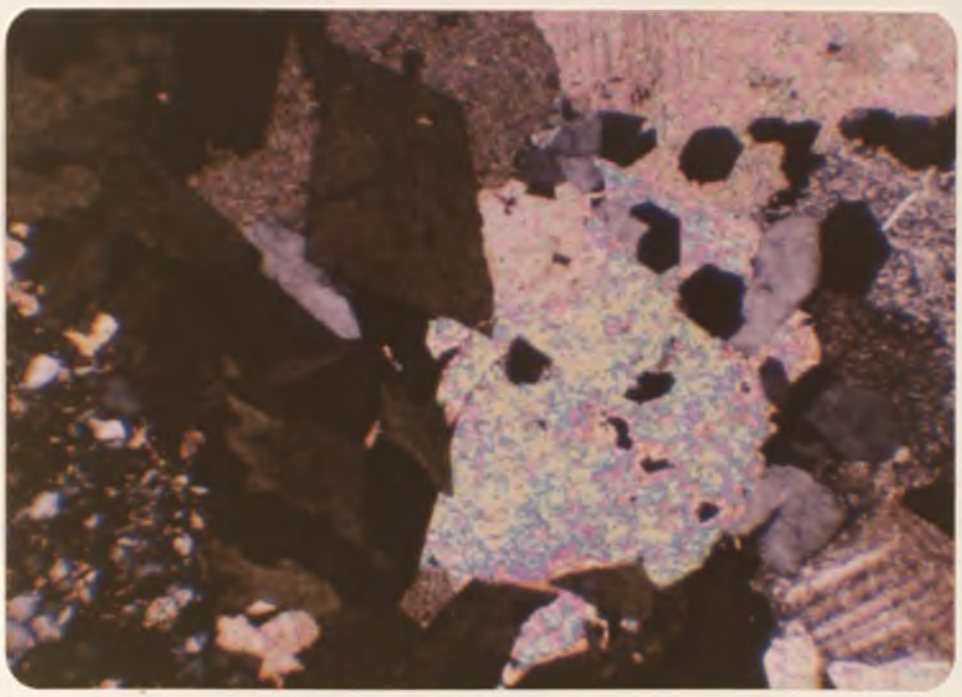


Figure 37. Photomicrograph of Quartz-"Black Calcite"-Adularia Veinlet.

The yellow cast of the adularia is due to sodium cobaltinitrite staining. Note the rhomb-shaped crystals of adularia and euhedral quartz crystals (not stained); crossed Nicols, X20.

show a 2V of less than 30°. An X-ray diffractogram of this mineral is indistinguishable from several other patterns made of potassium feldspars in the study area. It most closely resembles the patterns of the devitrified ash-flow material, and all of them fit the standard A.S.T.M. sanidine pattern better than that of the other potassium feldspar phases. The X-ray patterns of various minerals from the study area are given in Appendix A.

The calcite associated with this group of veinlets, referred to here as "black calcite" to distinguish it from the white to clear calcite which fills late fractures, is black to brown to clear and of uneven coloration. It appears to be clouded by very fine-grained inclusions which are thought to consist in part of manganese oxides. Black manganese-oxide coatings and dendrites are abundant in the mine area, and manganese-bearing black calcite is fairly common in the epithermal environment. Some of it contains significant amounts of silver (Hewett and Radke, 1967, Radke, Taylor, and Hewett, 1967). This calcite resembles siderite in hand specimen, but it effervesces freely in hydrochloric acid and several X-ray patterns indicate that it is calcite. In thin section, it frequently contains opaque grains and iron-oxide staining along cleavage planes. Although siderite may be present in the mine area, it has not been conclusively identified in the samples studied.

There are numerous textural and color varieties of quartz which appear to constitute one sequential mineralizing event. There are cross-cutting relationships, and brecciated quartz cemented by more quartz, but for the system as a whole the main stage of quartz deposition appears to have been continuous.

The earliest quartz occurs as euhedral crystals within quartz-adularia-"black calcite" veinlets. Individual quartz crystals are aligned in polygonal patterns, and are surrounded by "black calcite" (Figure 37). Anhedral quartz which occurs with adularia in veinlets also appears to be early. This early quartz is gray to white and glassy in hand specimen.

The massive main-stage vein quartz and stockwork stringers appear to be somewhat later than most adularia-"black calcite" veinlets, as quartz stringers cross-cut adularia stringers more often than the reverse. This quartz ranges from less than 0.005 cm to 0.5 cm across and from anhedral chalcedonic or mosaic to euhedral. The coarsest euhedral crystals project into vugs. Little adularia or "black calcite" occurs with main-stage quartz. In hand specimen the quartz ranges in color from white to gray, yellow, and waxy green, and in texture from massive to crustified, vuggy, and hackly. The hackly textures within the main-stage quartz indicate that calcite leaching occurred prior to the end of quartz deposition. Blades along former calcite cleavage planes are coated with drusy quartz.

The highest assay values obtained during this study, ranging up to 15 or 20 oz./ton silver, are from the waxy green, finely-crystalline quartz, which Smith referred to as "talc quartz." Smith reported values as high as 2,000 oz./ton silver from "talc quartz" veins. He attributed its green color to finely dispersed cerargyrite and embolite. In thin section this quartz contains extremely fine-grained inclusions which may be fluid inclusions or mineral matter. These inclusions commonly form bands and layers in both finely-crystalline, crustified quartz and single euhedral crystals (Figure 38). This material may contain some of the precious-metal values. The visible ore minerals all appear to be secondary. Cerargyrite and embolite occur in vugs and may be replacing primary silver minerals which were deposited there. Native gold occurs as minute flecks in the massive quartz. Subhedral to euhedral pyrite occurs in minor amounts, generally less than 1 or 2 percent, within this quartz and the wall-rock fragments included in it.

The last quartz to be deposited forms large euhedral crystals up to several centimeters long which are glassy and clear to amethystine. This quartz fills comb-textured veins which have finely-crystalline, cloudy, banded quartz along the walls, and fills vugs in massive vein quartz. Amethyst commonly fills stockwork veinlets in the First Ash Flow. According to Smith, this quartz does not

Figure 38. Photomicrograph of Massive Vein Quartz Showing Inclusions, Crossed Nicols; X40.

generally contain economic mineralization; in this study, assay values up to 5 oz./ton were obtained from samples containing minor amethystine quartz.

Fragments of the wall rock are common within the massive veins. They are silicified to varying degrees and often surrounded by quartz in cockade textures. Pyrite and other opaque minerals appear to be preferentially concentrated within and around these fragments.

There appears to have been a distinctly later stage of calcite deposition in the Commonwealth area. This calcite is clear or white, and can usually be distinguished from the "black calcite" in hand specimen. It is generally the only calcite present in massive veins themselves, and it always fills cross-cutting fractures. Some of these fractures are lined with drusy quartz, but many of them contain only calcite. No adularia has been observed in association with this calcite.

The latest fractures in the vicinity of the veins are coated with montmorillonite-rich gouge. This material ranges in color from green to rusty tan to white. All of the samples X-rayed indicate that it is an expanding clay with a montmorillonite structure. Appendix A presents the X-ray characteristics of this clay in more detail. A spectroscopic analysis of one sample indicated the presence of Na, K, Mg, Fe, and SiO_2. It is probable that much of the montmorillonite was thought by Smith to be kaolinite or alunite which was looked for

but not found during this study. Smith states that the gouge zones are rich in silver, which he attributes to the presence of embolite or cerargyrite. Some of the values could also be adsorbed onto montmorillonite clays or limonite.

Few of the ore minerals are visible in veins that are now exposed. A trace of native gold has been observed in the massive quartz, and embolite-cerargyrite occurs in vugs and fractures. A black, sectile fracture coating thought to be acanthite occurs in some of the vein material. The veins and adjacent wall rocks contain up to 5 percent pyrite which has been almost entirely altered to iron oxides. The writer examined a polished surface of mill concentrate from the lease operation, and found native gold and intergrown native silver and argentite (acanthite?). The relationship of the latter two minerals is not clear; the silver occurs as blebs and blades in the argentite (acanthite?) in what resembles an emulsion texture.

A number of minerals have been observed in the caved area above the main vein. Embolite and cerargyrite are present, along with conichalcite, fluorite, and possible aurichalcite. Smith describes minor amounts of chalcopyrite, galena, tetrahedrite, molybdenite, proustite, and wulfenite from the lower levels. He states that argentite occurs below the 4th level as veinlets and films around pyrite and quartz.

The distribution of assay values from channel samples on the 3rd level is given in Appendix A, as are assays of chip samples on the 3rd, 5th, 6th, and 7th levels. The channel values are significantly higher than the chip samples, the discrepancy thought to result from the sampling method. Figure 33 is a sketch adapted from Smith's longitudinal assay section on the Main Vein. It shows upward-flaring, high-grade ore shoots separated by relatively barren zones. Unfortunately, none of the ore shoots is now accessible. Smith also shows a number of horizontal gold and silver ore zones which he related to supergene processes.

Wall-Rock Alteration

The various processes which have acted upon the wall rocks in the Commonwealth area have produced a rather simple suite of minerals including potassium feldspar, quartz, calcite, montmorillonite, sericite, and iron oxides after pyrite. At distances of 500 feet or more from the veins, epidote has been observed replacing amphibole phenocrysts in the flow rocks. Epidote and chlorite have been sought in thin section, but the only definite occurrences of either are detrital grains in the Bisbee Formation.

Potassium feldspar is ubiquitous in the study area. It is the dominant devitrification product of the ash-flow tuffs and forms much of the cement in the water-lain tuffs. Unfortunately, the types of

potassium feldspar identified in the study area generally cannot be distinguished on the basis of X-ray patterns or optical properties. Therefore, it cannot be definitely determined how much of the potassium feldspar is of igneous origin formed as a devitrification product at relatively high temperatures, and how much is a hydrothermal product formed at low temperatures.

There appears to have been considerable recrystallization of quartz and potassium feldspar in the rocks of the Pearce area. Any cristobalite or tridymite which was originally present in the ash-flow tuffs has recrystallized to mosaic-textured quartz. The coarse mosaic quartz inter-layered with fibrous sanidine in some spherulites was probably originally fibrous quartz or cristobalite. In addition, many of the shards in the First Ash Flow on Pearce Hill now consist of mosaic-textured potassium feldspar. They may have originally been axiolitic, as are the shards in the ash-flow tuffs on Metat Hill.

Wall-rock alteration in the mine area exhibits only rough, broadly-defined zonation (Figure 39). Laterally, the most intense argillic alteration occurs over 10 to 20-foot intervals between the veins and appears to be fracture-controlled. Within 10 to 15 feet of the veins, especially in the footwall zone, the feldspar phenocrysts of all rock units consist of fresh potassium feldspar. There is minor alteration of biotite to iron oxides. Vertically, the extensiveness of argillic

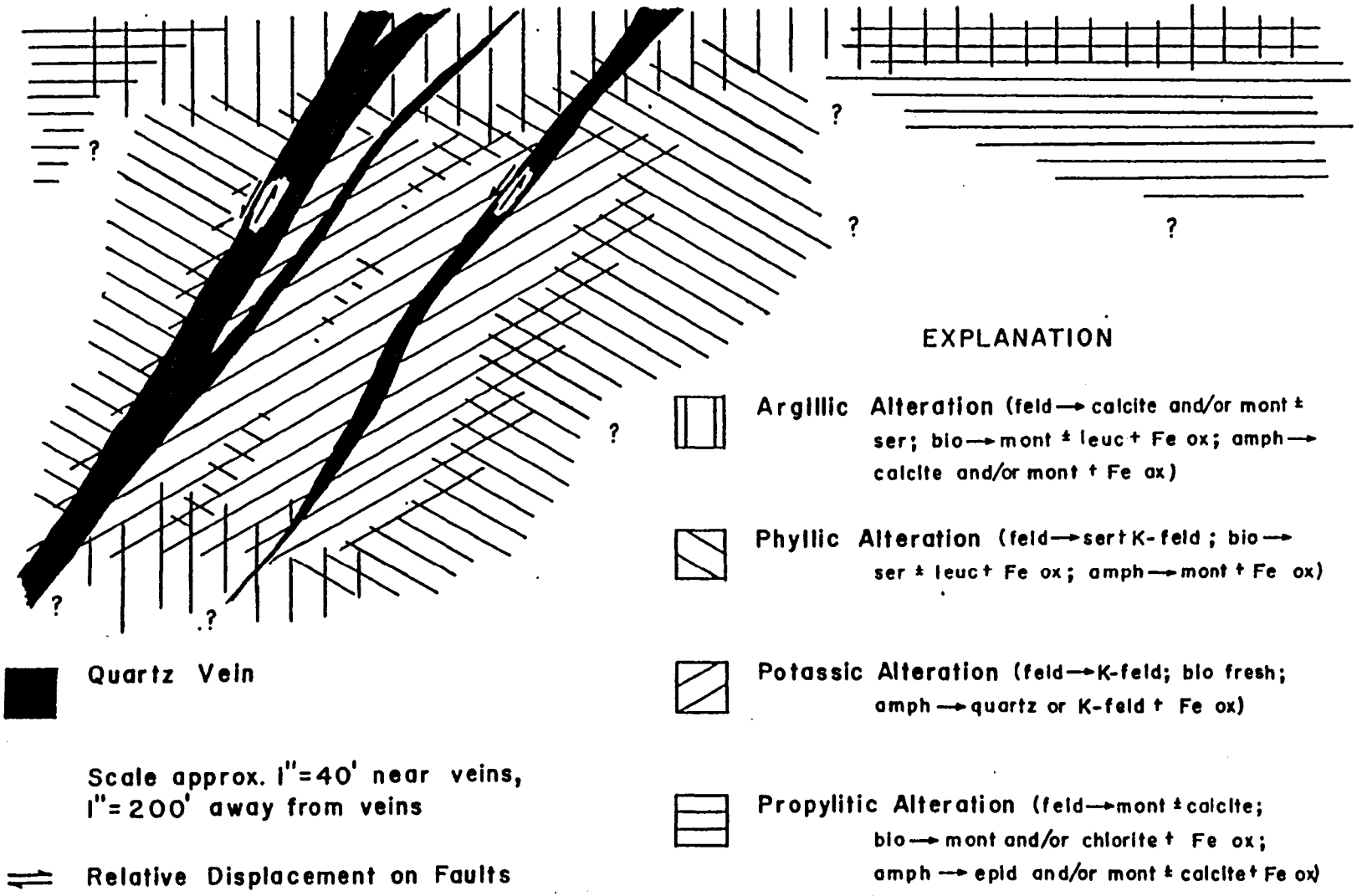


Figure 39. Schematic Diagram of Alteration Zones at the Commonwealth.

alteration appears to increase both upward and downward away from the main levels of the mine.

The mineral most susceptible to alteration in the Commonwealth area is the amphibole of the two flow units. No fresh amphibole has been observed either in thin section or in hand specimen. The alteration products vary with distance from the veins. On the south end of Pearce Hill, and in dump material from the valley between Pearce and Metat Hills, the amphiboles are either entirely replaced by iron oxides, or they have an iron-oxide rim with epidote in the center. None of this epidote has been observed in thin section. In most thin sections examined from areas between the veins, the amphiboles are altered to an iron-oxide rim which is predominantly hematite, and to a bronze to light tan, pleochroic, highly birefringent, micaceous clay mineral. This mineral resembles what is sometimes referred to as "hydrobiotite", but it generally exhibits swelling properties. A rather poor powder-camera X-ray pattern exhibited expansion upon glycolation, and some of this mineral has plucked out of the thin sections during grinding; it is therefore tentatively identified as montmorillonite. In the immediate vicinity of veins within 5 or 10 feet, the amphiboles are replaced by anhedral quartz or potassium feldspar, with or without montmorillonite, and iron-oxide rims. On the 7th level, the amphiboles are replaced either by

montmorillonite or calcite, or both, with iron oxides around the edges and along the amphibole cleavage directions.

Biotite is relatively unaltered in most of the mine area. It is fresh or slightly stained by limonite within 20 to 30 feet of the veins, in the zone where potassium feldspar is stable. Some biotite crystals have been observed with anhedral quartz or potassium feldspar along cleavage directions, and the crystal bulges and appears to be deformed around these inclusions. In the sericite zones between veins, biotite is "bleached" in color and is sometimes completely replaced by sericite, leucoxene, and iron oxides. The only chlorite which has been observed replacing biotite is in samples from the east end of the 7th level, and it is minor in abundance. No secondary biotite has been recognized in thin section.

The alteration of the rock feldspars in the Pearce area has been the most puzzling problem encountered during this study. On most of the mine levels, the feldspar phenocrysts consist of fresh potassium feldspar within 20 to 30 feet of the veins, and consist of potassium feldspar and clays between the veins. The fresh potassium feldspar exhibits "patchy" extinction, as described in the section on rock units and shown in Figure 17, and a vague "progressive" extinction of lath-shaped crystals. Farther than 20 to 30 feet from veins, potassium feldspars are generally altered to sericite. This sericite

has a high birefringence, and is therefore presumably a well-crystallized illite. X-ray diffraction data on the suspended clay fraction of these rocks indicates that the sericite is not well-ordered enough to be a true muscovite. An exception to this alteration pattern is the ash-flow sanidine which exhibits uniform extinction. This sanidine is dusted with very fine-grained montmorillonite where it is not strongly altered. Where the rocks exhibit extensive argillic alteration, the feldspars are almost completely replaced by mixtures of clear sericite and light tan to bronze montmorillonite. These alteration products commonly occupy the centers of crystals where replacement is incomplete.

Montmorillonite is the most obvious alteration product at the Commonwealth. On the 7th level, and to a lesser extent near the surface, the feldspars alter to a mixture of montmorillonite and finely-crystalline calcite. Pumice and mafic minerals alter to montmorillonite throughout the mine (Figure 40). No kaolinite has been conclusively identified in thin section, although a few questionable patches have been observed. The presence of kaolinite has not been indicated by any of the X-ray work.

A few samples of the flow units examined in thin section contain albite-twinned plagioclase. These rocks are from the crest of Pearce Hill and from the east end of the 7th level 60 to 80 feet in the foot wall of the main vein. The plagioclase is more or less altered in all thin

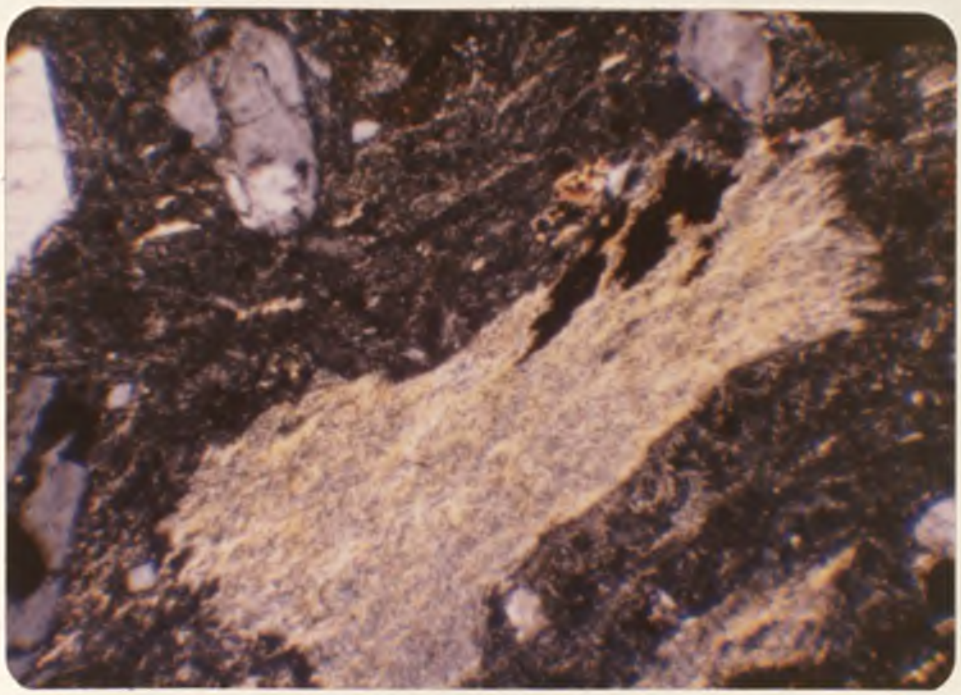


Figure 40. Photomicrograph of Pumice Altered to Montmorillonite.

The bronze cast is the color of the mineral; crossed Nicols, X20.

sections (Figure 41). It contains montmorillonite and less abundant sericite along fractures and cleavage directions, or montmorillonite-calcite at the centers. Some of the larger crystals contain patches which stain with sodium cobaltinitrite, and many of them stain along fractures. The un-stained feldspar only occasionally does not exhibit albite twinning, and it is distinctive in its relatively uniform extinction and its birefringence. The birefringence of the plagioclase is slightly but importantly higher than that of all the various forms of potassium feldspar in these rocks. Therefore, even in the absence of cobaltinitrite staining, un-twinned plagioclase can generally be distinguished from potassium feldspar. The portions of the plagioclase phenocrysts which stain with sodium cobaltinitrite have a lower birefringence, and are therefore considered to be some form of potassium feldspar. Several interference figures obtained on potassium feldspar rims around plagioclase phenocrysts have the 0° to 30° 2V which is characteristic of all the potassium feldspar observed in the study area.

Most of the collapsed pumice in the First Ash Flow is altered to montmorillonite which varies from almost colorless to dark bronze and pleochroic. It is finer-grained and has somewhat lower birefringence than the montmorillonite which replaces the amphiboles. The elongation of the montmorillonite flakes tends to lie roughly parallel to the flattened direction of the pumice (Figure 40). In the less argillically-altered areas, some of the less-flattened pumice

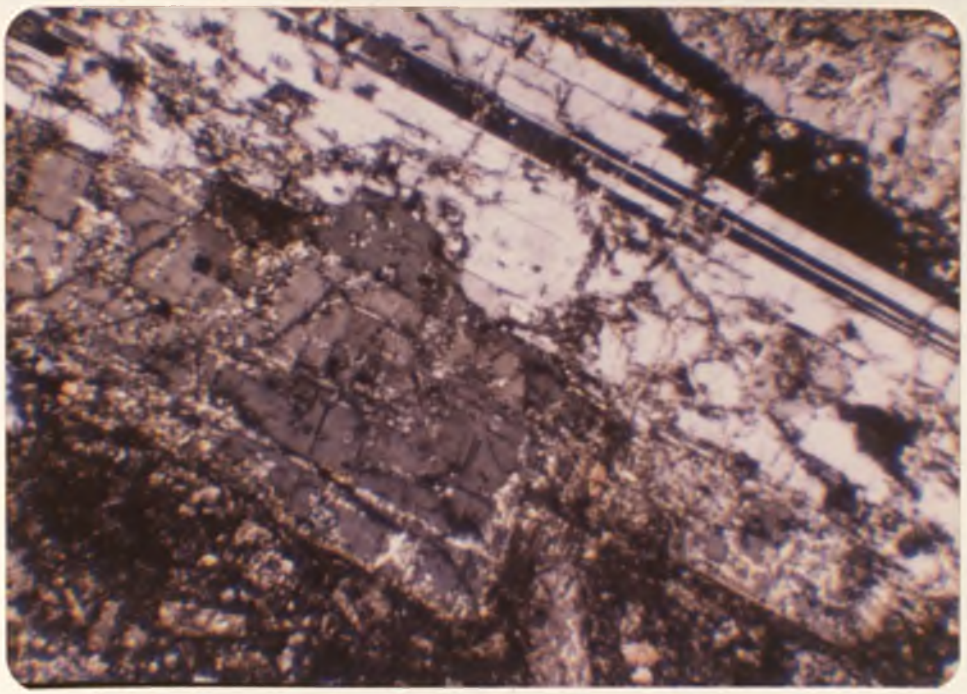


Figure 41. Photomicrograph of Partially Altered Plagioclase from Ta_1, 7th Level.

The dark patch at lower left is potassium feldspar; note the lower birefringence of the potassium feldspar particles. The clay is probably montmorillonite; crossed Nicols, X20.

consists of fibrous sanidine and mosaic quartz. The pumice of the ash-flow tuffs on Metat Hill consists of axiolitic and acicular sanidine and mosaic quartz (Figure 32); the sanidine is more or less altered to extremely fine-grained, highly-birefringent montmorillonite. However, none of it is entirely altered to montmorillonite like that on Pearce Hill. An X-ray diffractogram of the pumice in the First Ash Flow on Pearce Hill indicates that it is pure montmorillonite, with no detectable sericite.

The lithic fragments of the First Ash Flow and the water-lain units are generally more highly altered than the enclosing rock. The feldspars alter to montmorillonite and sericite, and the mafic minerals are replaced by iron oxides. The sanidine spherulite fragments are fresh in all of the Pearce Hill rocks examined. Sanidine in the spherulites from Metat Hill is clouded by fine-grained montmorillonite similar to that developed in the phenocrysts.

The groundmass of the First Ash Flow responds to alteration in a manner similar to the phenocrysts. Where the phenocryst potassium feldspar is fresh, the shards consist of anhedral, mosaic potassium feldspar and the surrounding material consists of finely-crystalline, mosaic-textured quartz and potassium feldspar. In areas of extreme argillic alteration, both the shards and the surrounding material consist predominantly of montmorillonite. The groundmass of the flows varies in texture. Within several tens of feet of the veins,

it generally consists of a mosaic of quartz and potassium feldspar, with varying amounts of iron oxide. Away from the veins the rocks have more of a trachytic texture, and microlites of potassium feldspar are present in the groundmass. A few of the samples from the surface and from the lower levels exhibit good microlitic textures. In addition, lithic fragments in the First Ash Flow and the water-lain tuffs occasionally exhibit trachytic, microlitic textures. The breccia fragments of the First Flow contain up to 20 percent calcite as patches and stringers, which may in part replace the groundmass.

CHAPTER 4

HYDROTHERMAL ALTERATION IN SIMILAR ENVIRONMENTS

Schmitt (1950b) and White (1955), among others, note similarities between hydrothermal alteration of epithermal ore deposits and that produced by active hot springs. For the sake of comparison with, and a better understanding of, the Commonwealth alteration mineralogy, brief descriptions will be given here of some well-studied hot springs, namely Steamboat Springs, Nevada; Yellowstone Park, Wyoming; Wairakei and Waiotapu, New Zealand; and Sulphur Bank, California. Few epithermal mineral deposits have been studied in detail with respect to alteration mineralogy. As Schmitt (1950a) has observed, many of the alteration minerals of epithermal deposits, especially the clays, have been misidentified. A few of the better-studied epithermal precious metal deposits of similar alteration type to the Commonwealth will also be reviewed here, including the Comstock Lode and Tonopah, Nevada, and Bodie, California. Finally, stable isotope data on both hot springs and epithermal deposits will be discussed briefly. The following chapter will outline a general genetic model for this type of mineral deposit, and attempt to fit the Commonwealth into that model with respect to alteration mineralogy,

especially feldspathic alteration, and structural relationships. Figure 42 summarizes the alteration zoning of the systems discribed on the following pages.

Hot Springs

The following descriptions are abstracted from the published literature. These hot springs were selected on the basis of both alteration mineral assemblages and zoning and the availability of good, detailed descriptions.

Steamboat Springs, Nevada

One of the most extensively studied active hot-spring areas is at Steamboat Springs, Washoe County, Nevada. These hot springs issue from recent faults, and many of them are actively depositing a variety of minerals. Brannock et al. (1948) and White, Thompson and Sandberg (1964) describe the general geology of the area. Most of the springs occur in granodiorite intrusive rock which is thought to be related to the Sierra Nevada Batholith. Although the area is surrounded by abundant mid- and late-Tertiary volcanic rocks, only limited occurrences are found within several miles of the springs. The most widespread volcanic rock is what White, Thompson, and Sandberg call a soda trachyte, considered to be a member of the Alta Formation, which is much more extensive in surrounding areas.

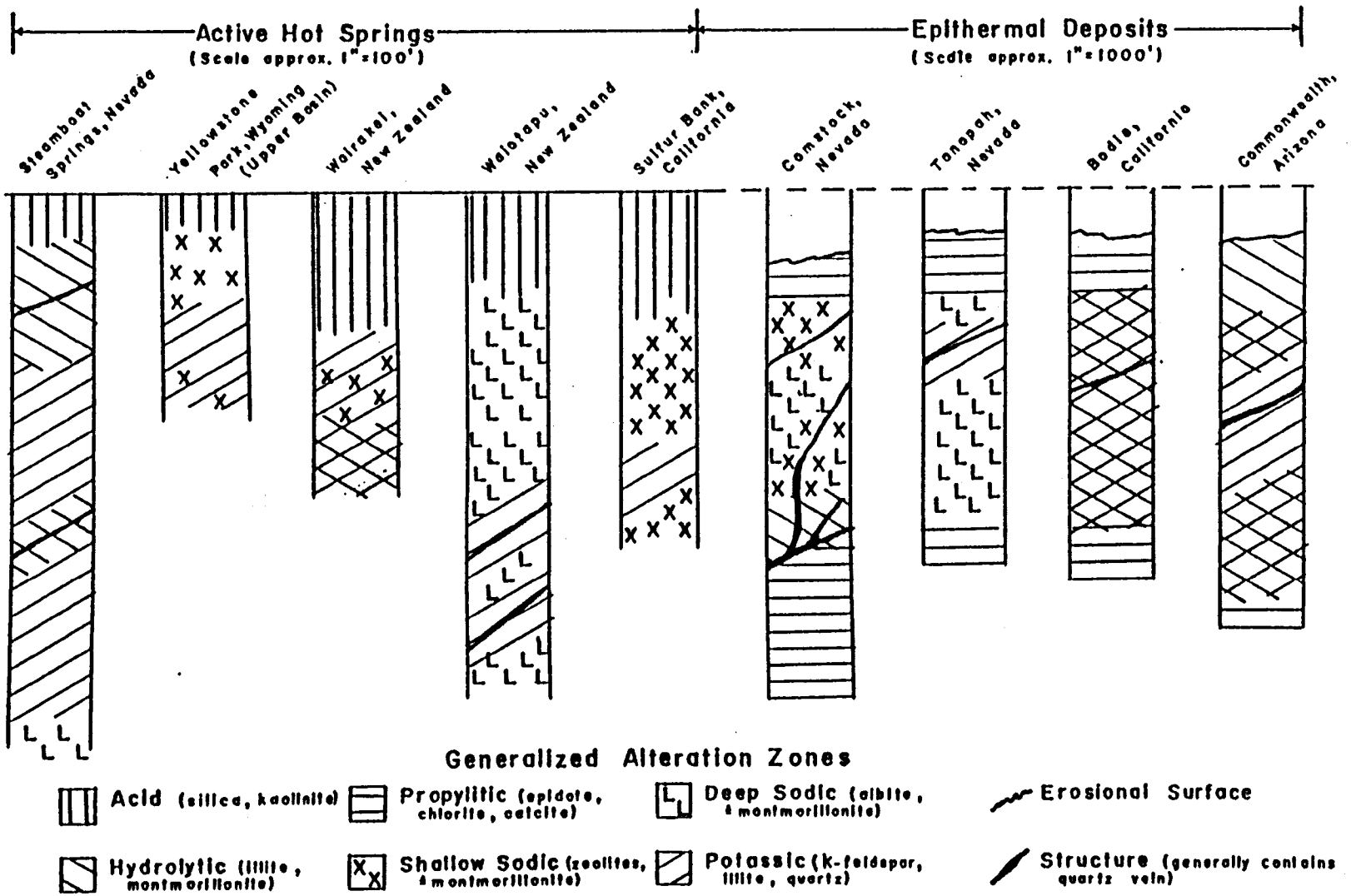


Figure 42. Generalized Alteration Zoning of Some Hot Springs and Epithermal Deposits.

Significantly, Thompson (1956) describes the thick Alta Formation of the Virginia City Quadrangle as an andesite. Above this unit in the Steamboat Springs area is a Tertiary or Quaternary basalt, Quaternary pumiceous rhyolite domes, and alluvium.

A number of holes have been drilled both in active hot-spring areas and in deposits around formerly active springs. Sigvaldson and White (1961, 1962), and Schoen and White (1965) describe the wall-rock alteration produced by these hot springs in considerable detail. Gianella (1939) and Brannock et al. (1948) describe the spring waters and the various minerals they are currently depositing. According to Brannock et al., the pH of the issuing springs depends upon temperature. The waters which are actively boiling have the highest pH, and the cooler springs are progressively more acidic. The measured range in pH is 5.3 to 9.1, the higher values being in springs with a high chloride content. The hot springs are depositing a number of metallic minerals along with siliceous sinter or calcium carbonate. Cinnabar, pyrite, stibnite, metastibnite (?), and gold and silver in unknown forms have been described. Some of these minerals, especially cinnabar and gold, are of economic concentration. They generally occur in muds around the springs. According to Gianella (1939), siliceous sinter is more commonly deposited on the surface around springs, but calcium carbonate is deposited in well casings in the area.

Hydrothermal alteration associated with these springs has been studied in detail from drill core. Although most of the holes studied are in the granodiorite, Sigvaldson and White state that the hydrothermal mineral assemblage is virtually independent of rock type. The extent of alteration depends upon the abundance of susceptible minerals in the rock, and upon structural controls. Acidic alteration is generally prevalent near the surface, with alkaline at and below the ambient water level. Several of the drill holes studied have a potassium feldspar zone near the surface and beneath the acid zone. In one hole, potassium feldspar and quartz are dominant from depths of 90 to 280 feet below the surface, and in another from 100 to 300 feet. Potassium feldspar replaces plagioclase irregularly. Generally, the more calcic central zones of the plagioclase phenocrysts are replaced by clays, and the outer more sodic zones by potassium feldspar. At greater depths, plagioclase normally alters to albite plus calcite or calcium montmorillonite.

The mineral most susceptible to alteration is hornblende, which alters to a random mixed-layer illite-montmorillonite and the iron-rich chlorite chamosite. Below the zone of potassium feldspar alteration, biotite alters to chlorite. The most intense alteration is along fractures, where all feldspars, chlorite, and mixed-layer illite-montmorillonite are altered to illite, quartz, and pyrite.

Elsewhere below the potassium feldspar zone, clays consist of various types of montmorillonite and mixed-layer illite-montmorillonite.

In a hole drilled where there is no active spring, the water is acid and alteration reflects acid leaching. Opal and kaolinite predominate at the surface; montmorillonite is dominant at depth.

Yellowstone Park, Wyoming

Boyd (1961) describes the geology of the volcanic rocks at Yellowstone Park. The Rhyolite Plateau, where active hot-springs occur, is made up of flows and welded tuffs with minor rhyolite domes, basalt, and rhyolite-basalt mixed-lava. These flows occupy a tectonic basin rimmed by the older Yellowstone Tuff and pre-volcanic rocks. Fenner (1936) and Rayamakashay (1968) describe the hydrothermal alteration produced by Yellowstone hot springs. There are two different types of hot spring. The acid type, represented by the Norris Basin springs, produces kaolinite, alunite, opal-cristobalite, and native sulfur, and leaches potassium feldspar. The alkaline type, represented by the Upper Basin springs, produces thick deposits of silica along controlling fractures which generally obscures the wall-rock alteration. The pH range measured by Rayamakashay of springs within tens of feet of each other is as high as 2.5 to 8.5.

According to Fenner, the most notable effect of the alkaline hot springs is the addition of silica and the molar replacement of

sodium and calcium feldspars by potassium. This replacement is more complete in the groundmass feldspars. He states that this groundmass replacement would probably not have been noticed without evidence of hot-spring activity, and that many potassium-rich rocks have been formed in a similar manner. Fenner describes the secondary potassium feldspar as orthoclase, but states that it has a 2V of 35° to 42°. This value is too low for true orthoclase or microcline. Similar potassium feldspar occurs in veinlets in the rock. The replacement of plagioclase by potassium feldspar was observed in drill core from depths of about 60 feet to at least 120 feet; in the lower part of the zone, below 90 feet, the dominant secondary potassium feldspar occurs with heulandite and sporadically distributed calcite. Above the potassium feldspar zone is a zone of so-called "reverse" metasomatism characterized by analcite and heulandite. At the surface, these hot springs are characterized by siliceous sinter which grades downward into crystalline quartz. Rayamakashay states that older descriptions of alkaline spring alteration note the presence of pervasive "beidellite" clay. The alkaline spring waters analyzed by him plot in the stability field of an idealized sodium montmorillonite phase between 25 and 95°C.

Wairakei, New Zealand

The hot springs at Wairakei, on the North Island of New Zealand, are somewhat different from those at Steamboat Springs and Yellowstone in that extensive fractures which might allow for the movement of fluids have not been observed. No veins are found, and veinlets are rare. Steiner (1953) describes the general geology and hydrothermal alteration at Wairakei. The hot-spring area occurs in the central part of a tectonic basin, and contains abundant boiling springs and geysers issuing from recent sedimentary and volcanic rocks. These rocks include diatomaceous claystones, mudstones, siltstones, vitric tuffs, pumiceous sandstones, lapilli tuffs, and recent alluvium. The lapilli tuffs are called "plagioclase rhyolites", and contain andesine, quartz, hypersthene, and hornblende phenocrysts. Presumably the hot fluids move through permeable zones in the rocks rather than along major fractures.

The tuffaceous and arenaceous rocks are hydrothermally altered in the vicinity of these hot springs but the argillaceous rocks are not, a fact attributed to the lower permeability of the argillaceous units. Steiner (1953) recognizes four zones of progressive alteration associated with the hot springs. A zone of acid leaching occurs at the surface, and a zone of argillization beneath it. Superimposed on the argillic zone are zeolite and feldspar zones. Near the ground surface is a zone of sulfuric acid leaching, the sulfuric acid attributed to

near-surface oxidation of hydrogen sulfide. This zone is characterized by kaolinite, alunite, and opal at depths above about 80 feet. At a depth of 90 feet, siderite is present. Below 80 feet is a zone of argillization characterized by montmorillonite-like clay and pyrite upon which the other two zones are superimposed. In this zone glass and shards are altered to montmorillonite. Pumice in this zone is a deep olive-green color in hand specimen, and the montmorillonite in thin section is faintly pleochroic and oriented radially or spheruliti-cally. It has a relatively high birefringence.

Zeolite and feldspar zones are superimposed upon the argillic zone. Nearer the surface is a zone characterized by the zeolite ptilolite which contains sodium, calcium, and minor potassium, and by minor heulandite and analcite. These zeolites fill pores and vesicles in the rock. The feldspar zone is characterized by quartz and secondary potassium feldspar which commonly contains wisps of sericite and is generally limited to the replacement of plagioclase rather than vein filling. Steiner (1953) states that this replacement is accomplished by the substitution of potassium for sodium and calcium in the presence of excess silica. The replacement process also pro-duces fine-grained sphene, which is distributed throughout the rock. No zeolites have been found in association with secondary potassium feldspar. Steiner postulates a deep zone of potash leaching as a

source of the potassium. However, no evidence of such a zone has been found in drill core.

Waiotapu, New Zealand

This hot-spring area is located about 30 miles north-northeast of Wairakei and differs from it in several ways. The general geology of the area is described by Grindley (1963) and the hydrothermal alteration by Steiner (1963). The area is located at the north end of a tectonic depression at the intersection of two fault trends. The rocks in the area include tuffaceous and pumiceous siltstones, sandstones, and breccias, vitric tuffs, dacite, and andesite flows, ignimbrites, and pumiceous tuffs. Hot water rises along faults, and recent hydrothermal eruptions have occurred due to fault movements. At the present time, active calcite deposition clogs drill holes and cements aquifers in the area.

The hot-spring deposits at Waiotapu contrast sharply with those at Wairakei. Veins and veinlets are abundant, and albitization is a significant form of alteration. Steiner recognizes a surfical zone of sulfuric acid leaching which is characterized by alunite, pyrite, and opal. Beneath this zone are zones of potassium silicate alteration and albitization. The mineral most susceptible to alteration is magnetite. Hornblende and pyroxene are always completely altered, even where plagioclase remains fresh. Volcanic glass is also highly susceptible

to alteration; biotite is less so. The potassium silicate alteration is characterized by hydromica and potassium feldspar replacing plagioclase together or by hydromica alone after plagioclase. Calcite is generally associated with the hydromica in replacement relationship with plagioclase in andesites. There is no evidence of mutual replacement of potassium feldspar and hydromica. Steiner (1963) notes this type of alteration commonly results in complete replacement. A zone of albitization occurs beneath the zone of potassium silicate alteration. The replacement of sodium-calcium plagioclase by albite is commonly incomplete. Calcite and wairakite are associated with this alteration.

The potassium-silicate alteration is spatially related to steeply-dipping, pyritized fissure veins, and the alteration zones are repeated with depth in drill core where multiple intersection of fissures are logged. Steiner (1963) explains this repetition with the idea that solutions moved outward from the fractures which eventually became choked and sealed by potassium silicate alteration. Later albite alteration is thought to be independent of potassium silicate alteration. Steiner suggests that it is caused by a gaseous phase ascending through more restricted pores and channels.

Weissberg (1969) has studied the metal content of hot-spring precipitates in New Zealand. Gold and silver are being precipitated from hot springs and drillhole discharges in the thermal area along the edge of the Taupo volcanic zone. The values generally occur as

red-orange amorphous sulfides associated with opaline silica. At Waiotapu, the sinter around the Champagne Pool contains 50 ppm Au (2.7 oz/ton), 175 ppm Ag (5.8 oz/ton), 170 ppm Hg, 320 ppm Tl, 15 ppm Pb, 50 ppm Zn, 2,000 ppm Cl^-, 2 percent As, and 2 percent Sb. The surface temperature of this hot pool is 70° to 75° C. The metal content of the sinter decreases over distances measured in meters away from the pool. In a drill hole in the vicinity of the Champagne Pool, the alteration zones include unaltered rock down to a depth of 76 feet, potassium feldspar from 76 to 213 feet, potassium mica from 213 to 365 feet, and albite below 365 feet. At depth in this hole are minor amounts of pyrite, pyrrhotite, sphalerite, galena, and chalcopyrite.

Sulphur Bank, California

Sulphur Bank, northwest of Sacramento, California, is a unique hot-spring area. Considerable commercial mineral production has come from the area, and it differs in a number of ways from other hot springs described here. Native sulfur was mined in the late 1800's, and an estimated 200,000 flasks of mercury have been produced. White and Roberson (1962) describe the geology and alteration at Sulphur Bank. The rocks consist of the upper Mesozoic Franciscan Formation

and Quaternary alluvial and lacustrine sediments and andesite lava. The andesite overlies lake deposits, and was probably extruded onto wet ground.

The hot water at Sulphur Bank is presently cooler than that of most other active hot springs. Furthermore, it is chemically and isotopically different from most thermal waters associated with recent volcanics. The waters are very high in total CO_2, B, NH_3, Na, and I, and low in SiO_2 and K. They are acid near the surface and nearly neutral at depths between 45 and 80 feet. Native sulfur is being deposited near the surface; at and below the water table cinnabar, marcasite, pyrite, dolomite, calcite, quartz, zeolites, and sporadic metacinnabar and stibnite are being deposited.

Hydrothermal alteration is zoned both horizontally and vertically. White and Roberson recognize three depth zones in the andesite with all three zones grading horizontally into nearly fresh andesite over short distances. Zone 1, from the surface downward 15 to 50 feet, is a bleached zone produced by acid leaching. It consists of white opalized andesite containing native sulfur, kaolinite and halloysite. The end products of acid leaching are opal and anatase. The base of this zone is presumed by White and Roberson to represent the position of the water table before mining began. Zone 2 is the intermediate or "boulder" zone and is characterized by chemical attack along orthogonal joints, with fresh andesite at the

centers of the "boulders". The upper part of the "boulder" zone contains cinnabar, opal, cristobalite, kaolinite, alunite, iron oxides, hydrocarbons, native sulfur, and sulfates in veins and open spaces between joint blocks. The sulfates include traces of barite, alunite, jarosite, gypsum, and coquimbite, a hydrous iron sulfate. The lower surface of this zone is irregular, and the average thickness is about 30 feet. The basal zone, Zone 3, is characterized by hydrothermal alteration localized along columnar joints. The alteration minerals, which consist of montmorillonite and an un-named zeolite, commonly replace plagioclase. The zeolite is the most widely-distributed of the hydrothermal minerals. It contains essential NH_4^+ in its lattice structure; some of the montmorillonite contains NH_4^+ as an exchangeable cation. The richest orebodies occur at the base of the basal zone and in the underlying lake sediments.

There are differences between Sulphur Bank and the other hot-spring systems presented here with respect to alteration mineralogy. Very little secondary potassium feldspar is present at Sulphur Bank. It is restricted to a zone in a lakebed just beneath the andesite, where it occurs with the only calcite found in the system. In general, carbonates are rare or absent; where carbonate is present, it is generally dolomite.

Other Epithermal Precious-Metal Deposits

A number of epithermal precious-metal deposits exhibit features of hydrothermal alteration similar to those of the Commonwealth. Others are completely unlike the Commonwealth, and their alteration assemblages more closely resemble those produced by acid hot springs, which have been only briefly mentioned here. A summary of the geology and hydrothermal alteration of a few representative deposits will be presented here for comparison with the Commonwealth and with the active hot springs described in the preceding section.

Comstock Lode, Nevada

The Comstock Lode is one of the most famous epithermal precious-metal deposits in western North America. It lies near Virginia City in Storey County, Nevada, and has produced almost $400,000,000 worth of ore. Most of this value was from gold and silver, although minor amounts of copper and lead were produced.

The geology of the Comstock Lode vicinity is described by Gianella (1936, 1959) and Bonham (1969), among others. The rock units in the district include Mesozoic metamorphic rocks and Cenozoic andesites, rhyolites, tuffs, intrusive granodiorite, and lacustrine sedimentary rocks. The Comstock veins cut the older Tertiary volcanic units, the Hartford Hill Rhyolite, the Alta Formation, the

American Ravine Andesite Porphyry, and the Davidson Granodiorite which intrudes them. They are overlain by at least part of the lower Pliocene Kate Peak Formation. An age of mineralization of 17.2± 0.6 m.y. has been determined using the K-Ar method on Comstock veinlet adularia (Bonham, 1969). The veins of the district occur along major faults, including the Comstock, Silver City, and Occidental Faults. Thompson (1956) estimates the pre-mineral dip slip along the Comstock Fault as 2,500 feet. The Silver City Fault appears to be a branch of the Comstock Fault, and much of the bonanza ore of the Comstock was found in nearly vertical hanging-wall branches of the fault. Branching of the veins is common, and high grade shoots occur at intersections. Albers and Kleinhampl (1970) suggest that the Comstock District is coincident with a large Tertiary volcanic center. The distribution and thickness of the Alta Formation suggest that one of its eruptive centers lies within the Comstock District.

The Comstock veins consist of brecciated quartz with variable amounts of calcite, abundant sphalerite, galena, chalcopyrite, and pyrite, and less abundant argentite, native gold, and polybasite. The gold to silver ratio is about 1:40. In the Silver City area, the veins consist of quartz with or without calcite, pyrite, native gold, native silver, electrum, occasional argentite, and rare chalcopyrite. Only 1 to 2 percent of the Silver City veins consist of sulfides. The Occidental Lode, which lies about 2 miles east of the Comstock,

contains quartz, calcite, abundant adularia, and low grade ore similar in mineralogy to the Comstock. The richest ore at the Comstock is above a depth of 1,900 feet, and although some production has come from as deep as 3,300 feet, the orebodies appear to have a definite bottom below which the veins consist of barren quartz. According to Bastin (1922), the Comstock ores are fine-grained at generally less than 1 mm grain sizes and banding and crustification are rare. Quartz, sphalerite, galena, chalcopyrite, pyrite, and calcite are contemporaneous and argentite, native gold, and polybasite are late and interstitial to quartz and sphalerite. He states that supergene enrichment of the ores has been minor, and active only above a depth of 500 feet.

Coats (1940) discusses the pervasive propylitic alteration of the rocks in the Comstock area, with emphasis on the Alta Formation andesite. This alteration is widespread, and does not appear to be spatially related to the mineralization. It is better developed in the foot wall of the Comstock Fault than in the hanging wall. Where the intensity of propylitization is mild, labradorite is replaced by veinlets of albite and by flakes of sericite, calcite, and epidote; hornblende is replaced by chlorite, albite, calcite, and sparse quartz. Where propylitization is more complete, the feldspar is entirely replaced by epidote, clinozoisite, and albite, the mafic minerals by epidote, and

the groundmass by albite, epidote, and secondary quartz. The mafic minerals are more extensively altered than the feldspars in the same rock.

The hanging wall of the Comstock Fault is affected more than the footwall by other types of alteration. Coats attributes this fact to the greater degree of fracturing in the hanging wall. Zeolitic alteration is spatially associated with mineralized fractures. Plagioclase alters to albite with or without zeolites (natrolite?), calcite, and pyrite. This alteration of the feldspar may occur without appreciable alteration of the mafic minerals. In the immediate vicinity of the veins, silicification and sericitization are the dominant alteration types. Wall-rock alteration in the Silver City area, 5 miles south of Virginia City, generally consists of silicification near the veins which gives the rock a fresh appearance. Propylitic alteration consists of radiating fibrous chlorite, epidote, calcite, and pyrite.

Tonopah, Nevada

The Tonopah District, in Nye and Esmeralda Counties, Nevada, is another classic epithermal precious-metal deposit. It has produced more than $150,000,000 in gold and silver; the gold to silver ratio for the district as a whole is nearly 1:100. This district has been studied by Bastin and Laney (1918), Campbell (1933), and Nolan (1935). Short descriptions are found in Lindgren (1933) and

Finch (1933). According to Albers and Kleinhampl (1970), the Tonopah District is located on the northwest side of a volcanic center which consists of domes, plugs, and flows of rhyolite, quartz latite, and andesite. The rock units consist of the Tonopah Formation volcanic breccias, tuffs, and flows, the Sandgrass Andesite, the Mizpah Trachyte, an albitized andesite, the Extension Breccia, the West End Rhyolite, and the post-ore Fraction Breccia and Oddie Rhyolite.

The mineralization is associated with a curved branching fault, the Tonopah Fault. The throw on each of the three major branches is 500 to 1,500 feet. It and other unmineralized faults are thought to be related to an intrusion at depth which caused uplift after volcanic collapse (Nolan, 1935). According to Nolan, the veins are primarily replacements which lack well-defined walls, such that most of the veins have assay walls. The veins follow faults and associated minor fractures. Ore-cemented breccia, crustification, comb-structure, and other open-space filling textures are rare. The ore minerals include seleniferous electrum, argentite, polybasite, arsenical pyrargyrite, native silver, and base metal sulfides. In a surfical zone there are minor amounts of cerargyrite, iodyrite, and embolite. Gangue includes quartz, finely-crystalline mixed carbonate, barite, and adularia. The ore is vertically limited within a zone 600 to 1,000 feet thick, which is convex upward and shallowest in the central part

of the district, where hydrothermal alteration is most intense (Nolan, 1935). There is a decrease in the gold to silver ratio away from this apical area.

According to Nolan, and also Campbell (1933), hydrothermal alteration at Tonopah consists of three types: propylitic, albitic, and potassic. The apparently early propylitic alteration is pervasive, and is especially well-developed in andesites. It is characterized by chlorite, calcite, pyrite, and siderite. The feldspars alter to calcite and minor quartz; epidote is not abundant. A second type of alteration is the virtually complete albitization of the Mizpah Trachyte (andesite). This replacement of plagioclase by secondary albite occurs nearly everywhere in the district, resulting in a massive keratophyric flow. The third type of alteration is less extensive and occurs primarily within the central part of the district in association with ore of low gold to silver ratio. This type of alteration is characterized by quartz, adularia, and sericite. According to Lindgren, the plagioclase is replaced by quartz and sericite or quartz and adularia. Locally, the wall rocks are almost entirely replaced by these minerals. Lindgren notes that the most prominent effect of alteration in the vicinity of the veins is the almost complete removal of ferrous iron, calcium, magnesium, and sodium, and the partial removal of ferric oxide. There is even a slight removal of apatite and rutile. Silica has increased significantly, and potassium and water less so.

Bodie, California

The Bodie Mining District is located in Mono County, California, about 8 miles from the Aurora Mining District in Nevada. It has produced approximately $30,000,000 in gold and silver, and the gold to silver ratio is about 1:2. It lies in a re-entrant in the outcrop pattern of the Sierra Nevada Batholith at the western edge of the Basin and Range Province. The district lies near the eastern margin of a complex field of Miocene volcanics that make up the southern part of the Bodie Hills. The volcanic geology of the area is described by Chesterman (1968). Wisser (1960) and Albers and Kleinhampl (1970) describe the structural geology of the district. O'Neil et al. (1973) give a good summary of the geology and hydrothermal alteration, and Clark (1970) presents a brief history of mining activity.

The rock units in the Bodie District include the Plato Peak Formation andesite and tuff breccia, the Silver Hill Volcanic Series dacite and tuff breccia, the Murphy Spring tuff breccia, and various intrusive rocks. Rock compositions range from rhyolite to subalkaline-olivine basalt. The orebodies occur mostly in porphyritic biotite-hornblende dacite flows and tuff breccia which have been intruded by small hornblende dacite plugs. Albers and Kleinhampl have recognized several volcanic centers in the area, and Chesterman describes a small caldera to the west of the district: Most of the volcanic rocks are between 8 and 9.5 m.y. old, but the range in ages for the district

is 5 to 14 m.y. The major structure in the district is an irregular anticline upon which several domes have been superimposed. The mineralized faults lie parallel and normal to the anticlinal axis, and many are associated with an apical graben. The veins cut both extrusive and intrusive rocks. They consist of finely-crystalline, banded, white, porcelaneous quartz; some of the veins are sheeted and have limonite along seams and partings. Open spaces and vugs are common, and in the southern part of the district the vein material is brecciated. The ore minerals include native gold and silver, acanthite, pyrite, and sphalerite, and cerargyrite in the upper oxidized portion. The southern part of the district contains more complex ores which are higher in silver and include galena, chalcopyrite, tetrahedrite, and pyrite. Gangue mineralogy consists of ubiquitous adularia, and quartz and calcite. Some adularia crystals are up to 2 cm. across.

Hydrothermal alteration in the Bodie District includes propylitization around the margins and potassium-silicate alteration near the major veins. The potassium-silicate assemblage includes adularia, quartz, and K-mica in pervasively veined rocks; relict chlorite and epidote occur in minor amounts. The first effect of potassium-silicate alteration is addition of potassium feldspar to the groundmass of the rock. With increasing alteration intensity, there is a recrystallization of the groundmass and replacement of chlorite.

The plagioclase phenocrysts are replaced by adularia, quartz, and K-mica, the mafic minerals by K-mica and pyrite by hematite. Some rocks are almost completely converted to potassium feldspar. O'Neil et al. studied the chemistry of alteration in the Silver Hill Volcanic Series and concluded that Ca and Mg were removed first, followed by Na and Fe removed. Total SiO_2 increased slightly. They studied the K:Rb ratios of fresh and altered rocks, and concluded that although the ratio is considerably lower in altered rocks there is no direct correlation between K or Rb content and distance from major veins. They attribute this fact to the pervasive development of small veins and stringers between major veins.

Stable Isotope Data

Recent studies of the stable isotope ratios of minerals and water associated with hydrothermal systems have provided considerable information on the origin and nature of hydrothermal fluids. A brief summary will be presented here of some published stable isotope work on both epithermal mineral deposits and active hot springs. Taylor (1967) gives a general discussion of oxygen isotope theory and techniques and describes their applications to hydrothermal mineral deposits.

Craig (1963) discusses isotopic geochemistry of water and carbon in geothermal areas; White, Craig, and Begemann (1963) discuss

Steamboat Springs; and Banwell (1969) discusses New Zealand thermal waters. It is important to determine the isotopic compositions of both the hydrogen and oxygen in water to fully understand its geologic history. Since almost all rock forming minerals contain oxygen, isotopic exchange can occur between the oxygen of rocks and the oxygen of hot water in contact with them. Hydrogen is less abundant in the rock-forming minerals and more closely retains its initial isotopic ratio in water. Craig measured the oxygen and hydrogen isotope compositions, expressed as δO^{18} and δD, of the water from active hot springs at Yellowstone Park, The Geysers, Steamboat Springs, Lassen Park, the Salton Sea, Wairakei, and Larderello, Italy. He measured δO^{18} and δD of waters which occur as steam or as neutral or slightly alkaline hot springs. When these values are compared with δO^{18} and δD of the local meteoric water, it is found that only δO^{18} values differ; δD is the same for both the hot springs and the local ground water. If the hot-spring water were a mixture of meteoric and juvenile water, δD would be expected to vary with the amount of inter-mixed juvenile water for at least some of the areas studied. Craig concludes that the water is at least 95 percent of meteoric origin, and that the variation of δO^{18} values is due to isotopic exchange between oxygen in the water and oxygen in the rocks through which it travels. The variation in isotopic composition of acid hot springs is more complicated than that of near-neutral chloride-type springs. There is

a systematic shift of δD value in acid thermal waters which Craig attributes to evaporation near the ground surface at temperatures below the boiling point of water.

The carbon isotope geochemistry of several hot-spring areas has also been studied. Craig concludes that about 80 percent of the carbon in springs at Steamboat Springs is of magmatic origin, that is to say, that the carbon could have come directly from magmatic emanations or have been leached from igneous rocks containing carbon with magmatic isotopic characteristics. At Yellowstone and other areas containing limestone, the carbon isotope ratios in thermal waters resemble that of the limestone.

The isotopic nature of epithermal ore fluids may be studied either directly or indirectly. The oxygen and hydrogen isotope ratios may be determined from fluid extracted from primary fluid inclusions in vein minerals, and the oxygen isotope ratios may be determined for minerals which were precipitated in equilibrium with the hydrothermal fluids. Relatively recently, the hydrogen isotope ratios have been studied in hydroxyl-bearing alteration minerals. The nature of the hydrothermal fluid and its interaction with rocks can also be reflected by the oxygen isotope ratio of the entire rock. Taylor (1973) examined oxygen isotope ratios at Tonopah, Comstock, and Goldfield, Nevada, and O'Neil et al. (1973) report results from Bodie, California. O'Neil and Silberman (1974) studied both oxygen and hydrogen isotope

ratios of fluid inclusions in gangue minerals from 15 precious-metal deposits. Isotopically "normal" igneous rocks of the earth and moon have a δO^{18} value of approximately +5.5 per mil. Meteoric water at the latitude of Nevada has a δO^{18} value of around -13 per mil. It has been found that rocks in the vicinity of many epithermal precious-metal deposits have abnormally low values of δO^{18}.

Within the Mizpah Trachyte at Tonopah, the lowest values of δO^{18} are in the center of the district at depths of 750 to 1,250 feet, corresponding to the apex of Nolan's ore shell. At a distance of 1 km away from the center, Mizpah rocks still have an abnormally low δO^{18} of +3.3 per mil. The post-ore volcanic units have mostly "normal" δO^{18} values. Taylor's explanation of the anomalous oxygen isotope ratios in the pre-ore rocks is that the rocks equilibrated isotopically with a hydrothermal fluid having a δO^{18} of around -13 per mil. The variation of δO^{18} of rocks within the district can be attributed to varying temperatures of equilibration, or varying rock to water ratios. He concludes that the hydrothermal fluid which deposited the vein minerals at Tonopah remained at a relatively uniform temperature of probably 200° to 300° C during the main stage mineralization, that the ratio of water to rock was very high, and that the water was almost entirely of meteoric origin.

The Comstock Lode is also characterized by low δO^{18} rocks, but they are not as low as those at Tonopah. This difference may be atrributed to the apparent greater depth of formation of the Comstock orebodies or to the 20 percent magmatic water component of the hydrothermal fluid. A greater depth would probably result in a lower water to rock ratio at Comstock. The lowest values of δO^{18} are in the vicinity of the Davidson stock, and "normal" ratios in the Alta Formation are not found closer than 2 miles from the stock.

O'Neil et al. determined that the δO^{18} of phenocrysts in the rocks at Bodie is always greater than that of the whole rock. They attributed this reversal to the fact that the temperature of mineralization was too low for large phenocrysts to exchange completely with the hydrothermal fluid. They also concluded that the hydrothermal fluid which produced the mineralization and alteration at Bodie was almost entirely of meteoric origin.

O'Neil and Silberman (1974) measured both δO^{18} and δD values in specimens from a number of epithermal precious-metal districts in the Great Basin of California, Idaho, and Nevada. Although the values of δO^{18} in these rocks and in fluid inclusions in vein minerals vary due to variable conditions of isotopic exchange, the δD values of fluid inclusions are uniform because of a lack of exchange with the enclosing minerals. All but one sample examined by them have δD values within a -90 to -139 per mil range which

corresponds to the range of δD for modern spring waters in the Great Basin. This evidence deomonstrates the dominance, even the exclusivity, of meteoric water in the ore-depositing fluids of all but one deposit. The one anomalous δD value is from a fluid inclusion in quartz in bonanza silver ore from the Comstock Lode. This sample suggests that a minor magmatic component may be present in the hydrothermal fluid.

Sheppard, Nielsen, and Taylor (1969, 1971) examined oxygen and hydrogen isotope ratios of alteration minerals from porphyry copper deposits and other types of ore bodies. From their data they have concluded, at least for the porphyry copper deposits studied, that all of the montmorillonite is of hypogene origin. Furthermore, the waters which produced the argillic and sericitic alteration at these deposits has a significant meteoric component. Oxygen isotope data for the quartz-potassium feldspar-biotite-chalcopyrite assemblage, and hydrogen isotope data for biotite, indicate that magmatic water was the dominant component of the fluid which produced this assemblage. It thus appears, in keeping with models prepared by White, Muffler, and Truesdell (1971) and by Taylor (1973) and others, that meteoric water becomes an increasingly important component of hydrothermal fluids, both as the surface is approached and toward the end of a given mineralization event.

CHAPTER 5

GENETIC MODELS

There are many features of epithermal mineral deposits that distinguish them from other types of deposits. Lindgren (1933) and Schmitt (1950a,-b) include descriptions of the general characteristics of this type of deposit. Epithermal mineralization is almost always spatially associated with Tertiary or younger volcanic terrains. It most commonly occurs as fissure veins which cut through older rocks and volcanic rocks ranging in composition from andesite to rhyolite. The veins increase in structural complexity upward and the fissures may flare in two or three directions toward the surface. Sheeted veins, stockworks, and brecciation are abundant. The mineralized faults are frequently of major displacement. The vein textures are characterized by open-space filling and include crustification, comb texture, and drusy cavities and vugs. Quartz is the most abundant gangue mineral, and it ranges from finely-crystalline and chalcedonic to coarsely euhedral. The most distinctive gangue mineral is adularia, which occurs in at least trace amounts in most well-known epithermal precious-metal veins. Other gangue minerals include calcite, dolomite, barite, fluorite, alunite, kaolinite, and occasional

siderite, rhodochrosite, rhodonite, and zeolites. Epithermal precious-metal deposits are universally low in pyrite, and copper-bearing minerals are rare. Galena and sphalerite are abundant in some deposits. The dominant ore minerals reported include native gold, electrum, argentite, silver sulfosalts, and native silver, acanthite, and silver halides in the oxidized zone. The reported argentite is generally actually acanthite. Some deposits also contain stibnite, cinnabar, marcasite, tetrahedrite, and alabandite; arsenopyrite is rare and pyrrhotite and magnetite are generally absent. The paragenetic sequence is nearly constant from deposit to deposit, and follows the order of decreasing solubility and generally of hardness of the ore minerals. Quartz, pyrite, arsenopyrite, and oxides are followed by simple sulfides, sulfosalts, precious metals, and mercury. These minerals are "telescoped" rather than distinctively zoned. Although the mineralized structures persist at depth, the economic mineralization is generally restricted to depths of less than 3,000 feet below the surface. Beneath the ore zone, veins of barren quartz may continue downward. There is no apparent structural shift at the lower limit of economic mineralization.

Any genetic model proposed for the classic epithermal precious-metal deposits, which Schmitt (1950a,-b) calls "epithermal", must account for these and other characteristic features already cited. This chapter will briefly review some of the proposed modes

of origin for these deposits, and attempt to show the evolution of thought concerning them. Then, experimental information on the types of hydrothermal alteration found around these deposits will be applied to the genetic models, and a revised picture of the environment of mineraliation will be presented. Finally, the environment in which the Commonwealth veins formed will be discussed and a hypothetical model for their origin will be presented.

Evolution of Ideas

Schmitt (1950a) lists the various hypotheses for the origin of epithermal mineral deposits which have at some time been seriously considered by students of mineral deposits. These include deposition by lateral secretion, a fluid "differentiate" from a magma, volcanic emanations absorbed by ground water, telluric fluids, injection in the molten state, and deposition from the gaseous phase. Any hypothesis must consider the shallow depth of formation of these deposits, the apparently low temperature and pressure of formation, and the close spatial association with areas of Cenozoic volcanism. The great similarities of physical environment and mineralogy between epithermal mineral deposits and active hot springs, including occasional economic concentrations of ore metals as at Waiotapu, have naturally caused speculation as to their relationship. Indeed, in some cases

active hot springs are now depositing minerals characteristic of epithermal deposits. However, the volume and grade of the Tertiary epithermal precious-metal deposits are not known to have been duplicated by any modern hot spring.

One of the strongest early proponents of the hot-spring association of epithermal mineralization was Lindgren. Throughout much of his professional career, he emphasized the close spatial relationship of these deposits to volcanism and pointed out the many similarities between epithermal deposits and active hot springs (Finch, 1933, and Lindgren, 1933). In his 1933 textbook, he describes examples of modern hot-spring deposition of quartz, calcite, fluorite, barite, galena, and traces of other metals. He cites mineral deposits which are spatially associated with active hot springs, and points out similarities in composition between hot-spring waters and the hot water currently found in some epithermal mineral deposits such as the Comstock Lode. Lindgren considered the evidence to be convincing that deposits of mercury, antimony, arsenic, gold, and silver form near the earth's surface from hot ascending water related to volcanic phenomena. At least part of the water, and most of its dissolved gases and salts, are of magmatic origin and may be mixed to varying degrees with meteoric water. In contrast to Lindgren's ideas, Daubree and many European geologists believed that all of the

material of hot springs is derived from the circulation of meteoric water.

White (1955) presents summaries of the characteristics of various hot springs and epithermal mineral deposits. The epithermal deposits most closely associated with hot springs are those of mercury. The springs at Sulphur Bank, California, and Steamboat Springs, Nevada, deposited commercial concentrations of mercury. He suggests that the water responsible for the mineralization contains a relatively minor volcanic component in the case of Steamboat Springs and is entirely of meteoric or connate origin at Sulphur Bank. Gold and silver deposits are less clearly related to active hot springs than those of mercury, but White cites the similarities of gangue mineralogy and wall-rock alteration as evidence that these deposits are probably closely related to high-temperature volcanic hot springs. Hot-spring sinters may contain significant although sub-economic concentrations of gold and silver. White observes that adularia is characteristic of both high-temperature alkaline hot springs and epithermal gold-silver deposits, but is rare or absent in other types of hot springs and ore deposits. He proposed that epithermal mineral deposits and hot-spring deposits have similar origins, and that some form from dominantly magmatic water and others from circulating meteoric or connate water.

Schmitt (1950a,-b) discussed hot spring models of epithermal mineralization, especially with respect to hydrothermal alteration. He outlines a proposed sequence of alteration for hot springs and epithermal deposits using the alkaline springs at Yellowstone Park as an example. The first encounter of H_2CO_3-rich hot-spring water with wall-rock silicates produces a beidellite-type clay. The water removes alkalies, alkaline earths, and some silica, and leaves a stable clay. Schmitt calls this preliminary stage of alteration the "carbon dioxide-leaching" phase. As a result of this interaction, the hot water eventually becomes saturated with potassium. A second alteration phase, the "potassic" phase, then occurs in which potassium replaces sodium and calcium in the rock feldspars. This process causes the sodium and calcium content of the water to increase until the third "sodic" alteration phase occurs, and sodium replaces potassium in feldspars, and sodium and calcium zeolites and calcite are deposited. Quartz is stable at all stages of alteration except the initial beidellite stage.

The spatial distribution of the various phases of alteration is variable due to the upward and outward migration of zones and the subsequent superposition of one zone upon another. At depth, the hot-spring water is neutral or slightly alkaline. Schmitt attributes the near-surface production of sulfuric acid, which produces kaolinite-group clays, sulfates, and massive silicification, to near-surface

oxidation of H_2S contained in the ore fluid. However, Nordlie (1971) indicates that the sulfur species of magmatic gases at Kilauea is SO_2 rather than H_2S. Near-surface oxidation of SO_2 could still produce the sulfuric acid postulated.

Schmitt suggests that the ore metals are transferred to the meteoric-water shell by volcanic emanations. The dominantly meteoric hot-spring water absorbs CO_2, H_2S, NH_3, CH_4, HCl, HF, NaCl, and the ore metals. He states that the hot-spring model of epithermal mineralization, involving meteoric water which absorbs its volatile constituents from a volcanic source, explains many of the characteristic features of the deposits, including the shallow bottoming of ore and the distribution of the ore zones along a horizontal surface which frequently parallels topography; the delicate layering of vein minerals which may result from periodic climatic changes affecting the amount of water in the system; the difficulty in distinguishing hypogene from supergene deposition due to the fact that the two environments merge into each other in hot-spring systems; and the fact that epithermal orebodies commonly do not crop out but appear to be effected by steep gradients near the surface. Furthermore, the abundant free silica found in these deposits can be derived solely from wall-rock alteration, and an exotic source for it need not be postulated. He states that "volcanic emanations" can be produced

by merely heating a wide variety of rock types, so that the only role of a hypothetical magma at depth may be that of a heat source.

Stable isotope studies, such as those reviewed in the preceeding chapter, have provided valuable evidence as to the source of the water associated with hot springs and epithermal mineralization. In all of the hot springs cited, and most of the epithermal precious-metal deposits, the water which produced both the alteration and mineralization has been shown to be predominantly of meteoric origin. According to O'Neil and Silberman (1974), rocks anomalously deficient in O^{18} are found only around epizonal intrusions emplaced in highly fractured, relatively flat-lying volcanic rocks, which is the environment in which epithermal mineral deposits are found. Carbon isotope data of CO_2 and calcite from hot springs and epithermal precious-metal deposits permit a volcanic source of CO_2. Sulfur isotope data at Goldfield, Nevada (Jensen, Ashley, and Albers, 1971) suggest a magmatic source for the sulfur there. All of this evidence supports Schmitt's hypothesis of a meteoric ore fluid which is heated by and absorbs volatiles from a magma at depth.

Experiments by Ellis and Mahon (1964, 1967), however, indicate that a direct magmatic source is not essential even for the volatile components of a hydrothermal fluid. They derived solutions having similar compositions to northern New Zealand thermal waters by the interaction of distilled water with volcanic rocks and greywackes

from the North Island at temperatures of 150° to 600°C. At temperatures from 150° to 350°C, components such as Cl, F, B, As, NH_3 and the alkalies enter the solution readily, and few alteration products are formed. These solutes are extracted more easily and in greater abundance from crystalline rocks than from glasses. Ellis and Mahon conclude that at temperatures below 350°C, most of these solutes are removed from the surfaces of pores and cracks in the rocks rather than from the silicate minerals. On the other hand, at temperatures from 350° to 600°C, the concentration of most solutes is controlled by mineral solubilities or ion exchange equilibria. These solutes include K, Rb, Ca, Mg, F, $SO_4^{=}$, NH_3, and SiO_2. Upon cooling, the higher temperature solutions have an acid pH, and the lower temperature solutions are slightly alkaline. Before cooling, the low temperature solutions have a neutral pH, like the New Zealand alkaline chloride waters at depth. Therefore, it appears to be possible that in some cases of hot-spring and epithermal alteration, the only role of a hypothetical magma is a source of heat. Furthermore, Boyle (1968) considers the metals of epithermal deposits to be derived from leaching of the volcanic pile in which the deposits occur.

Genetic Implications of Hydrothermal Alteration

If it may be assumed that the hydrothermal alteration associated with mineral deposits is caused by the same fluids which deposited

the ore minerals, then an understanding of the processes of hydrothermal alteration can provide valuable insight into the environment of ore deposition. Most epithermal silver deposits are thought to have formed under conditions similar to those present in and around hot springs of the alkaline chloride-bicarbonate type, such as those of the Upper Basin at Yellowstone, rather than the acid-sulfate type, such as those of the Norris Basin. A gross vertical zoning of alteration types is evident in most of the hot springs and epithermal deposits described in the preceeding chapter (see Figure 42). The hot springs have a surficial zone characterized by minerals such as opal, kaolinite, and alunite with or without pyrite. This alteration is attributed to leaching by sulfuric acid formed by the near-surface oxidation of hydrogen sulfide or sulfur dioxide. Beneath this zone, in all the hot-springs described here, is one characterized by montmorillonite, zeolites, chlorite, and epidote. These alteration minerals occur as replacements of rock minerals, especially the feldspars, and as open-space filling, mostly in the case of the zeolites.

There also appears to be a more localized type of alteration zoning with respect to fractures in both hot springs and epithermal mineral deposits. Fracture-controlled alteration includes potassium feldspar, quartz, montmorillonite, sericite, and pyrite. At Steamboat Springs and Comstock this assemblage consists mostly of sericite,

quartz, and pyrite; at Waiotapu and Bodie, it consists of secondary potassium feldspar and quartz, with less abundant sericite.

Pertinent Experimental Work

In order more fully to understand the formation of these alteration patterns, it is helpful to review some of the experimental work which has been done on the various alteration assemblages characteristic of the epithermal and hot-spring environment. Most of the alteration effects observed in this environment can be attributed to sodium, potassium, or hydrogen metasomatism.

Orville (1963) investigated the system $KAlSi_3O_8$-$NaAlSi_3O_8$-NaCl-KCl-H_2O from 350° to 700°C at a pressure of 2,000 bars and total alkali-chloride concentration of 2M. The ratio of K:(K + Na) in the vapor phase co-existing with two alkali feldspars and an alkali-chloride solution decreases with decreasing temperature, which agrees with the low K:Na ratio characteristic of hot-spring water. According to Orville, the fractionation of alkalies between a fluid phase and crystallizing feldspars is strongly dependent upon temperature, but only slightly dependent upon the physical state of the fluid. The diffusion behavior of alkali ions through a vapor will therefore resemble their solution behavior in a liquid during alkali metasomatism.

In response to a magmatic or metamorphic thermal gradient, the feldspars of the warmer rocks tend to become enriched in sodium and depleted in potassium, and those of the cooler rocks become enriched in potassium and depleted in sodium. Stated another way, a fluid in equilibrium with two alkali feldspars at high temperatures will upon cooling be capable of replacing a certain amount of sodium feldspar with potassium feldspar if equilibrium is maintained. Orville notes that this replacement is occurring at the present time around active hot springs such as Yellowstone and Wairakei. Under natural conditions, such an equilibrium can probably be attained between alkalies in solution in a fluid phase and alkalies in feldspars at temperatures below 400°C. Orville emphasized the reciprocal nature of alkali metasomatism under ideal conditions, where a thermal gradient exists in rocks containing two alkali feldspars and a pervasive vapor phase of the alkali-chloride type. Under conditions of regional metamorphism this vapor phase probably acts as a passive medium for diffusion, whereas during hydrothermal alteration it is probably an active transporting agent.

Althaus and Johannes (1969) examined similar ionic fractionations between alkali-chloride solutions and silicate minerals such as illite, glauconite, montmorillonite, and muscovite at temperatures of 350° to 550°C and a pressure of 1,000 bars. They found that the K:Na ratio of an alkali-chloride solution in equilibrium with these minerals

increases with increasing temperature. With increasing temperature, Na^{+} enters the mineral phases and K^{+}, Ca^{+2}, Mg^{+2}, and Fe^{+2} enter the fluid phase, and the pH approaches 1 or 2.

Experimental results such as Orville's and Althaus' and Johannes' may be applied to alkali metasomatism in a variety of geologic environments. In general, it appears that zoning of alkali metasomatism may result from the establishment of a thermal gradient in feldspathic rocks which contain an alkali-chloride bearing vapor or aqueous fluid phase. Experimental work indicates that potassium metasomatism would be expected to occur at a greater distance from the heat source than sodium metasomatism. Hemley and Jones' (1964) temperature vs. alkali to hydrogen chloride diagrams show that for the same alkali to hydrogen ratio, albite is stable at temperatures at least 40°C higher than potassium feldspar. Within any given increment of rock undergoing such metasomatism, the first effect of a temperature increase will be an enrichment of the rock feldspar in sodium and an enrichment of the associated fluid in potassium. Increasing temperature will promote further sodium metasomatism. When the temperature of the rock begins to decrease, as due to cooling of a hypothetical heat source, reverse metasomatism will commence in which potassium replaces sodium in the rock feldspars. This mechanism agrees well with the observed sequence of alkali metasomatism in rocks such as keratophyres and trachytes. Battey (1955)

gives a detailed description of alkali metasomatism in keratophyres on the North Island of New Zealand. On the basis of chemical and petrographic work, he concludes that the keratophyres were probably formed from andesites as the result of sodium metasomatism. Secondary potassium feldspar partially or completely replaces the albite of the keratophyres, but the reverse of this replacement is not observed. The extent of potassium metasomatism varies within the flows and exhibits no discernible pattern. However, the total alkali content of the rocks is essentially constant. Battey notes that in many other well-studied keratophyres secondary potassium feldspar is found replacing albite, but albite does not replace secondary potassium feldspar.

Hess (1966) presents a complete phase diagram for the system K_2O-Na_2O-Al_2O_3-SiO_2-H_2O at 25°C and 1 bar. Presumably, these are the conditions approached by a cooling hydrothermal fluid. As shown in Hess' diagram, potassium feldspar and albite are both stable under surface conditions at a sufficiently high alkali ion concentration in solution. The stability field of potassium feldspar is large, and it is stable at relatively low concentrations of potassium ion (K:H less than 10^4) in the presence of a high silica concentration (SiO_2 concentration greater than 10^{-2} M). Authigenic potassium feldspar is common in sedimentary rocks ranging in age from lower Paleozoic to Quaternary; some of these feldspars are described by Glover and

Hosemann (1970) and Sheppard and Gude (1973). Albite and analcite are more restricted in stability, and their presence indicates a high Na:H ratio in solution (greater than 10^8). Authigenic analcite is relatively common in sediments.

Hemley (1959), Hemley et al. (1961), Hemley and Jones (1964), and Meyer and Hemley (1967) present various phase relationships in the system K_2O-Na_2O-Al_2O_3-SiO_2-H_2O at temperatures ranging from about 200° to 500°C and pressures from about 350 to 2,000 bars. It is evident from their work that as the temperature of the system decreases, higher and higher alkali ion concentrations are required for the feldspars to be stable. At some temperature, feldspathic alteration may cease and sericite, paragonite, or sodium montmorillonite become stable. This alteration is commonly referred to as hydrogen metasomatism. Although such alteration generally results from an increase in the hydrogen to alkali ion ratio, it may result from a decrease in temperature only. The phase relationships within this system depend upon temperature, pressure, and the concentrations of all of the components involved (Meyer and Hemley, 1967). As sodium metasomatism progresses, both the H:Na and the K:Na ratios of the fluid increase; therefore, depending upon the H:K ratio, either potassium feldspar or potassium mica may become stable. Likewise, during potassium metasomatism, the H:K and Na:K ratios increase; albite, paragonite, or sodium montmorillonite may become stable at a

sufficiently low potassium ion concentration. The concentration of silica in solution also effects these equilibria. As can be seen in the phase diagrams in Hess, and in Rayamakashay (1968), a high silica concentration promotes the stability of potassium feldspar even at high H:K ratios.

General Model of Epithermal-Hot Spring Alteration

The complexity of hot-spring phase equilibria is enhanced by the presence of other components in the system which are present in hot-spring water and alteration minerals. However, since calcite is the only major alteration phase at the locations discussed here which is not included in the system K_2O-Na_2O-Al_2O_3-SiO_2-H_2O, this system will be emphasized in the interpretation of alteration processes.

Work such as that of Orville, and Althaus and Johannes, suggests that the initial stage in the development of a hot-spring or epithermal system may result in sodium metasomatism. In a sequence of rocks containing both potassium and plagioclase feldspars and a pervasive chloride-bearing fluid phase, a rising thermal gradient will cause diffusion of sodium to the areas of higher temperature and potassium to areas of lower temperature. This early high temperature process may explain the presence of "soda trachytes" in the vicinity of hot springs and epithermal districts such as Tonopah, Steamboat Springs, and Waiotapu. It may also explain the occasional abundance

of albite in propylitic alteration assemblages associated with epithermal deposits.

At Tonopah and Steamboat Springs, potassium feldspar and mica replace albite in the trachytes along fractures and within the potassic depth zone. At Waiotapu, no mention is made of potassium feldspar replacing secondary albite, but potassic alteration occurs along fractures whereas sodic alteration is pervasive. Steiner considers the albite alteration to be later than the potassic alteration, but does not cite any clear-cut evidence as to the temporal relationship of these two alteration types. The repetition of potassic and sodic alteration zones in drill core at Waiotapu suggests the possibility of early, pervasive sodium metasomatism followed by structurally controlled potassium metasomatism. As has been mentioned previously, the cooling of such a system can have the effect of superimposing potassium metasomatism upon sodium metasomatism. Where the process of potassium metasomatism is incomplete due to a lack of sufficient potassium in the system or to a rapid decrease in temperature, alteration relationships such as those observed at Tonopah, Steamboat Springs, and Waiotapu will result. Where potassium metasomatism is nearly complete within or above the zone of sodium metasomatism, alteration such as that observed at Yellowstone, Bodie, and Wairakei will result.

Orville's work does not explain the presence of the sodium-rich alteration zone which occurs above the potassic zone in most alkaline hot springs, and which corresponds to Schmitt's "sodic" phase of alteration. The mineral phases present in this zone include montmorillonite and analcite which do not require as high a Na:H ratio as albite. Albite appears to be uncommon above the potassic zone. This sodic zone can be attributed to an increase in the Na:K ratio of the hydrothermal fluid as a result of potassium metasomatism.

Sericite and montmorillonite near the surface and along structures result from a late stage of metasomatism in which the circulating fluid is depleted in alkalies and lower in temperature or pH. The uppermost alteration zone of the alkaline hot springs is characterized by kaolinite, alunite, and silica. These phases indicate a high H:K ratio and the presence of sulfate. Most of the authors cited in the preceding chapter on hot-spring alteration attribute this alteration zone to hydrolysis in an environment of near-surface oxidation of hydrogen sulfide in the hydrothermal fluid, which produces sulfuric acid.

The vertical zoning patterns of hydrothermal alteration are complicated by zoning with respect to fractures in most of the systems described. The younger alteration assemblages are more closely related to fractures than the older ones. Where sodium metasomatism is observed, it appears to be pervasive rather than fracture-controlled.

Potassium metasomatism appears to be entirely related to fractures in some systems, such as Comstock and Waiotapu, and more pervasive at Bodie and Wairakei. Potassium mica and montmorillonite are spatially associated with fractures in many of the systems described here.

Hypothetical Evolution of the System

The structural evolution of these systems was apparently contemporaneous with the evolution of at least some of the alteration. A model is proposed here for the combined sequence of events in a hot-spring or epithermal system. It appears that the early stages of metasomatism occur in relatively undisturbed rocks, probably by a diffusion mechanism such as that described by Orville, through a fluid phase derived from a meteoric or volcanic source. As the thermal gradient of the system increases, presumably due to a magma at depth, convection of this fluid begins, which aids in ionic transport. Sodium metasomatism occurs in the warmer rocks, potassium metasomatism farther from the heat source. This heat source may in most cases be the parent magma of the volcanic rocks being altered.

At some time the system is fractured, by withdrawal of magma at depth and caldera collapse, as suggested by the work of Albers and Kleinhampl, or by some tectonic disturbance. This fracturing is accompanied by a decrease in temperature and increase

in the amount of fluid in the system. Convection is probably enhanced by the increased permeability produced by fracturing. Boiling and dilution of the hydrothermal fluid change its alteration properties, and a combination of hydrogen metasomatism and silicification is the usual result. The silica released by phyllic and argillic alteration is deposited within the fractures as quartz veins. In many systems, fracturing continues during vein deposition.

Quartz is the major constituent of the veins, but adularia and calcite are common. The calcite forms from calcium removed from rock plagioclase during alteration and from carbon dioxide in solution in the hydrothermal fluid. The adularia may form from potassium released by sericitization of potassium feldspar and from potassium entering the hydrothermal fluid due to alteration at depth. As Hemley and Jones point out, over-saturation with silica causes potassium feldspar to be stable at H:K ratios which would otherwise produce sericite. This fact may explain the presence of adularia within many epithermal veins and in the immediately adjacent wall rocks.

These processes are continuing at the present time around active hot springs. Continued fault movements at Waiotapu cause hydrothermal eruptions. In addition, there are occasional "pulses" of metal-rich sludges which last for periods of 5 to 10 years. During these anomalous periods of hot-spring deposition, economic concentrations of precious metals may be deposited. If Schmitt's analogy

of hot springs and epithermal mineral deposits is valid, then these "pulses" may represent ore deposition at depth. Some of what is commonly called "invisible" gold and silver ore may have formed in a manner similar to the precious metal deposition at Waiotapu. Metal-rich sludges are covered by layers of siliceous sinter, producing delicately banded chalcedonic quartz rich in precious metals.

Genetic Model for the Commonwealth System

The preceding discussions of other systems and of experimental work on various phase equilibria were presented in the hope that this information may lead to a better understanding of the environment in which the Commonwealth vein system was formed. From stratigraphic reconstructions, the level of the Commonwealth veins now exposed was probably overlain by 1,500 to 2,000 feet of volcanic rocks at the time of vein formation. The deposit exhibits structural and textural features typical of epithermal deposits. The hydrothermal alteration observed at the Commonwealth is strikingly similar to that associated with the alkaline-type hot springs and the epithermal mineral deposits described in the preceding chapter. The alteration described in this study probably resembles that of the hot springs more closely than that of the epithermal deposits. However, this may be due to the fact that the hot springs have been more thoroughly studied with respect to wall-rock alteration. Feldspathic

alteration, especially when it only affects the groundmass of the rock, is easily overlooked. When pervasive feldspathic alteration was observed in older studies, it was frequently considered to be a primary magmatic feature of the rock, as is probable in the case of the Mizpah Trachyte at Tonopah.

Wall-Rock Alteration at the Commonwealth

As was discussed in the chapter on General Geology, the flows of the Commonwealth area appear to be laterally equivalent to andesites described by Gilluly (1956). The Commonwealth rocks must be classified as trachytes on the basis of their mineralogy. However, considering the occurrence of pervasive feldspathic alteration around many other epithermal and hot-spring systems, it seems reasonable to assume that much of the potassium feldspar observed in the Commonwealth rocks is secondary. Further evidence to support this view is the appearance of plagioclase in rocks at the uppermost and lowermost exposures of the system. This plagioclase contains potassium feldspar along fractures and cleavages and as rims around crystals. The microscopic textures exhibited by the potassium feldspar resemble those of secondary feldspar described by Battey (1955) in the New Zealand keratophyres, and by Lindgren (1933) at Tonopah. The microlitic texture of the groundmass of the flows has been destroyed in most of the thin sections examined, a phenomenon which has been

described at Yellowstone and Bodie. In the upper and lower parts of the system, where some plagioclase remains unaltered, montmorillonite and calcite are important alteration products.

The occurrence of abundant fresh potassium feldspar in the flows is restricted laterally to zones tens of feet wide adjacent to the major veins. Vertically, fresh potassium feldspar occurs over a range of 600 feet, which corresponds roughly to the zone of economic-grade mineralization. Between the major veins, the wall-rock feldspars are altered to varying amounts of montmorillonite, sericite, and potassium feldspar. In some samples, the feldspars now consist entirely of montmorillonite. This pattern resembles the potassium feldspar zones of most of the hot-spring systems described in the preceding chapter. At Wairakei, Yellowstone, and Steamboat Springs, montmorillonite is pervasive. It is not as commonly described in epithermal systems, possibly because many of these systems were described before X-ray techniques of clay identification were developed.

The abundance of potassium feldspar near the veins may in part be due to supersaturation in silica near the veins, while farther into the wall rock, silica was not over-saturated and sericite was the stable alteration phase. The potassium was probably derived both from the sericite and montmorillonite alteration of the volcanic rocks, and from the fluid moving along fractures.

Potassium metasomatism may also explain the two different types of potassium feldspar phenocrysts in the First Ash Flow. The phenocrysts which exhibit "patchy" extinction alter to minor sericite while the phenocrysts having uniform extinction alter to montmorillonite within the same thin section. If the "patchy" phenocrysts are the result of replacement by secondary potassium feldspar, then this feldspar would be expected to contain less sodium than igneous sanidine. The alteration of the normal sanidine phenocrysts to montmorillonite may indicate that they have a relatively high sodium content, as is common for volcanic sanidine. A replacement origin would explain the unusual textures exhibited by the "patchy" phenocrysts.

A major problem encountered during this study was the distinction of the various types of potassium feldspar. The volcanic sanidine and the veinlet adularia have very similar optical properties and X-ray patterns. Studies on authigenic potassium feldspars have shown that they exhibit optical and X-ray properties similar to sanidine. The authigenic feldspar described by Sheppard and Gude (1973) from the Big Sandy Tuff in western Arizona is structurally similar to high sanidine, and that described by Glover and Hosemann (1970) from New Zealand ranges in structural configuration from orthoclase to low and high sanidine and has a range in 2V from 0^{o} to 65^{o}. Thus, it appears that potassium feldspar crystallized at low temperatures

structurally resembles volcanic sanidine. In the absence of chemical data on the Commonwealth feldspars, the best clue to their composition may be the alteration products derived from them. All of the phenocrysts with uniform extinction, and the spherulites and axiolites of fibrous potassium feldspar, alter to finely-crystalline montmorillonite, whereas the phenocrysts in the lower units which exhibit patchy and shadowy extinction alter to sericite. If the patchy feldspar is considered to be secondary, replacing plagioclase, and the uniform feldspar is considered to be igneous sanidine, then the volcanic units on Pearce Hill would have been andesite flows and quartz latite welded tuff before alteration. This explanation would make correlation with Gilluly's measured section in the Sulphur Hills more reasonable, and would enhance the possibility that these rocks may correlate with S.O. Volcanics as Gilluly suggested. The upper ash-flow tuffs contain only "normal" phenocrysts and therefore would be true rhyolites.

Due to access limitations and the problems of distinguishing between hydrothermal and volcanic potassium feldspar, it is difficult precisely to determine the extent of potassic alteration. Fibrous potassium feldspar is probably a devitrification product formed immediately after the ash-flow tuffs were deposited. It appears that much of the mosaic-textured potassium feldspar replacing shards in the First Ash Flow is merely recrystallized axiolitic sanidine. The potassium feldspar which cements the water-lain tuffs on Pearce Hill

may be either authigenic or hydrothermal in origin. It is interesting that the stratigraphically highest samples examined from the Third Water-Lain Tuff between Pearce and Metat Hills are cemented by calcite or clays rather than potassium feldspar. The uppermost of these samples contains abundant fresh plagioclase grains. Potassium metasomatism is most intense within the stratigraphic interval of the First Flow and First Ash Flow, and within the footwall blocks of the Main Vein on Pearce Hill and the North Vein between Pearce and Huddy Hills. Sufficient information is not available to determine whether this difference in degree of alteration is due to greater permeability in the footwall blocks or to the originally higher position of the handing wall blocks, which would place them above the potassic alteration zone.

Environment of Alteration-Mineralization

If the analogy between epithermal mineral deposits and hot springs is valid, as Lindgren, White, Schmitt, and many other workers suggest, then some generalizations can be made about the Commonwealth system. The alteration mineralogy and distribution closely resemble that produced by the alkaline chloride type of hot spring. If the Commonwealth alteration was produced under the same conditions, then the hydrothermal fluid was probably near-neutral in pH at the level now exposed and the chloride content may have been

anywhere from 1 ppm, as measured in an alkaline spring at Yellowstone, to 2 percent, as measured by Nash in fluid inclusions in some Nevada epithermal gold deposits. This fluid contained H_2S and CO_2 and other volatiles in unknown amounts. There was probably a zone of sodium-calcium metasomatism above the level currently exposed characterized by calcite, montmorillonite, zeolites, and possibly chlorite. Above this zone, within several tens of feet of the surface, a zone of acid-sulfate leaching would be expected. This zone probably consisted of opaline silica, kaolinite, and alunite. The total thickness of these zones is not known. A rough estimate of the minimum thickness of the potassic zone, assuming post-ore tilting of the vein system, would be 600 feet. Assuming a 50-foot thickness for the zone of acid leaching, then the upper sodic zone may have been as thick as 2,000 feet.

Not much can be said about the primary mineralization at the Commonwealth. As compared with the other precious-metals deposits described here, it appears to have been poor in base-metal sulfides. Pyrite seldom makes up more than 1 or 2 percent of the vein material. The ore minerals were argentite/acanthite and silver sulfosalts. The primary ore shoots at the Commonwealth, as shown in Figure 33, flare upward toward the surface along the Main Vein. Subsequent supergene effects have converted almost all the pyrite to hematite and goethite, and the silver minerals to native silver, acanthite, cerargyrite, and

embolite. Although ferric sulfate and sulfuric acid must have resulted from the oxidation of the pyrite, their effects on the wall rocks do not appear to have been great. Very little kaolinite has been observed, and no alunite. Fresh secondary potassium feldspar occurs in the same thin section as totally oxidized pyrite.

It cannot be determined with certainty whether the pervasive montmorillonite is hypogene or supergene in origin. The finely-crystalline dusty montmorillonite which forms as an alteration product of the sanidine in the Second and Third Ash Flows may be supergene. However, the well-crystallized, coarsely-crystalline montmorillonite which occurs in the units on Pearce Hill appears to be hypogene. The abundance of hypogene montmorillonite in active hot-spring alteration supports this idea. If most of the montmorillonite is hypogene, then supergene effects at the Commonwealth are restricted to oxidation of pyrite and formation of silver halides and minor acanthite and native silver.

Smith delineates several horizontal high-grade ore zones on his assay longitudinal section of the Main Vein, from which Figure 38 is taken. He attributes these to different levels of the water table as controlled by the level of Pleistocene Lake Cochise. If the tilting of the rock units on Pearce Hill occurred after the formation of the mineralized faults, as has been assumed on the basis of structural evidence in the study area, then these horizontal concentrations must

be secondary in nature, because they have not been tilted. Gold as well as silver has been concentrated in horizontal zones. Immediately above three of Smith's horizontal silver zones are zones of significantly higher gold to silver ratios. The average, according to his data, is 1:40, as compared with about 1:135 for the entire system. As discussed by Krauskopf (1951) and Cloke and Kelly (1964), gold is soluble only under very restricted conditions. In acid solutions, it is transported as $AuCl_4^-$ in the presence of a great excess of Cl^- and a strong oxidizing agent such as MnO_2, O_2, Fe^{+3}, or Cu^{+2}; H^+ and SO_4^{-2} are not sufficiently strong under surface conditions. Cloke and Kelly describe the Eh and Cl^- concentrations at which gold is soluble, and on an Eh-chloride concentration diagram the solubility of Au as $AuCl_4^-$ above the line $Eh = 0.90 - 0.08 \log (Cl^-)$ is greater than 10^{-5} moles/liter, or 2 ppm. Only part of this region is below the upper stability limit of water. According to Krauskopf, the solubility of gold as $AuCl_4^-$ increases with increasing temperature.

Silver is more soluble under surface conditions than gold, but is less mobile in the supergene environment than copper, lead, or zinc. Hypogene silver minerals may be dissolved by sulfuric acid by the reaction

$$Ag_2S + H_2SO_4 = Ag_2SO_4 + H_2S$$

In order for Ag S to continue to dissolve, H_2S must be oxidized by ferric iron or some other suitable oxidizing agent. Furthermore, for

AgCl to be precipitated from such a solution, very little H_2S can be present or Ag_2S will be precipitated instead. Cooke (1913), Emmons (1917), Boyle (1968), and others discuss the chemical details of the supergene behavior of silfer. By the hot-spring analogy, primary alteration and mineralization at the level now exposed at the Commonwealth were probably accomplished by near-neutral fluids containing H_2S. Any significant re-distribution of gold and silver must have been accomplished by acid, strongly oxidizing fluids containing Cl^-, Fe^{+3} or $Fe_2(SO_4)_3$, and H_2SO_4. Such conditions might be expected in the vadose zone in an arid or semi-arid climate. Evaporation of chloride-bearing water in the vadose zone, in the presence of ferric sulfate from the oxidation of pyrite, might on a small scale produce chloride concentrations sufficiently high to dissolve gold and move it short distances, and to transport silver as chloride complexes. According to Cooke (1913), a solution of approximately one molar chloride ion is necessary for silver to be transported as chloride complexes. At lower concentrations, the complexes dissociate, and the relatively insoluble Ag^+ ion is the dominant species in solution. Thus, as soon as such a concentrated chloride solution is diluted by an influx of fresh water, native gold and cerargyrite will be precipitated.

The process of concentration can be envisioned as occurring in small increments depending upon seasonal climatic variations which control evaporation and dilution. A further aid to this type of secondary

concentration might be the waning stages of the same thermal gradient which previously drove the hot-spring system. The solubility of gold as a chloride complex increases with increasing temperature and the proposed evaporation process would be enhanced by a high geothermal gradient. The horizontal high-grade zones at the Commonwealth probably represent former levels of the water table which were maintained for long periods of time. The position of the gold zones above the silver zones would be due to the lower solubility of gold than silver. The absence of a gold zone above Smith's second silver zone may be due to a larger volume of water involved in this particular cycle of concentration.

Hypothetical Sequence of Events

To summarize a hypothetical sequence of events at the Commonwealth, the processes which produced the hydrothermal alteration probably began soon after the extrusion of the volcanic units. Some of the pervasive potassium feldspar may have been derived from the devitrifying ash-flow tuffs. Thermally driven potassium metasomatism may have begun while the flows were still warm after deposition. The presence of a magmatic heat source at some unknown depth established a thermal gradient which promoted the processes of diffusion and convection in the volcanic pile. The zone of potassic alteration on Pearce Hill was at a depth of 1,500 to 2,000 feet at this time. Above

this level, sodic or propylitic alteration may have been occurring and sodic alteration may have occurred beneath it. Montmorillonite alteration of mafic minerals and glass may also have begun at this time.

After the devitrification of the ash-flow tuffs, either before or after the beginning of metasomatism, fracturing of the system began. The cause of this fracturing cannot be determined, but it may have been related to magmatic adjustments causing either doming to the north of the Commonwealth area, or subsidence to the south. A branching, sub-vertically sheeted fault zone was produced which trends roughly east-west. The dominant component of stress on the system was north-south tension. The increased permeability along this fault zone allowed greater circulation of heated meteoric water, which produced the primary alteration and mineralization. At this stage, the system probably began to resemble modern hot springs, with hot water issuing at the surface and depositing siliceous sinter. Fracturing probably changed conditions in the system. Meteoric fluids which had previously circulated slowly through relatively impermeable volcanic rocks, producing widespread potassium metasomatism, were diluted and began to flow along fractures. Quartz was deposited in the veins and and the wall rocks were hydrothermally altered. Due to the high activity of silica near the veins, potassium feldspar was stable. At distances of around 20 or 30 feet from major fractures, hydrogen

metasomatism was the dominant alteration process. The silica released by this metasomatism was deposited as veins and stringers along fractures.

Early in the vein-forming process, calcite and adularia were deposited. Later, possibly at the time ore deposition began, the hydrothermal fluid changed so that previously deposited calcite was dissolved, leaving blades of silica along former calcite cleavages. This change was due to a change in pH, $(HCO_3)^-$ concentration, or some other factor. The main stage of mineralization was accompanied by quartz deposition. Some of the mineralization may have occurred as alternating layers of silica and metalliferous "muds" like those at the Champagne Pool at Waiotapu. Toward the end of the vein-forming episode, minor fault movement was still occurring, and calcite again became stable. Late calcite veinlets formed cutting the quartz veins, and clay-coated fractures cross-cut all earlier vein material.

After the vein-forming convection cycle ceased, Basin and Range faulting occurred in a N40°W direction, which tilted the blocks between faults in a northeast direction. The Pearce Hill block was uplifted as a horst and tilted about 40° to the northeast. After uplift, erosion stripped approximately 1,500 feet of volcanics from the block. Supergene enrichment of gold and silver occurred after tilting, and mineral transport in the vadose zone may have been enhanced by a high geothermal gradient remaining after the ore-depositing episode ceased.

Erosion has probably continued through the present time, and enrichment may still be occurring on a small scale. Placers rich in both gold and silver derived from the eroded portions of the veins, occur along the flanks of Pearce Hill.

Broader Generalizations Based on Wall-Rock Alteration

Unlike Waiotapu and Steamboat Springs, most of the well-studied modern hot springs have not deposited significant concentrations of the ore metals. This fact is the primary argument that epithermal mineral deposits are not "fossil" hot springs. It is beyond the scope of this study to discuss these arguments in detail. The similarities of environment of formation and hydrothermal alteration suggest that the processes which have produced epithermal precious-metal deposits and hot springs are similar, although possibly not identical.

The alteration zones at the Commonwealth have reconstructed thicknesses of 50 feet for the surficial zone of acid leaching, up to 2,000 feet for the upper sodic zone, and at least 600 feet for the potassic zone. All of these thicknesses greatly exceed the observed thicknesses of alteration zones at the active hot springs described. At Steamboat Springs, the potassic zone averages around 200 feet thick and the overlying sodic zone 100 feet. At Waiotapu, the potassic zone is as much as 300 feet thick. The base of the mineralized zone at the

Commonwealth may have been as much as 2,800 feet beneath the surface at the time of vein formation. At Comstock ore is found as deep as 3,000 feet below the present surface, and at Tonopah, 2,000 feet. It appears from such comparisons that the greatest difference between active hot springs and the Tertiary epithermal precious-metal deposits is scale. The most obvious explanation for this difference is a difference in the magnitude of the heat source. Temperatures measured at the bottoms of drill holes at Steamboat Springs average around 170°C; fluid includion filling temperatures measured by Nash (1972) for quartz-adularia gold veins range from 200° to 330°C. If the volume of volcanic rocks extruded during the Tertiary greatly exceeded that extruded in Recent times, then so also might the volume of the underlying parent magmas be expected to vary. The greater concentration of precious metals in the mid-Tertiary systems may be the result of a larger or higher heat capacity system of convection and metal leaching than in the modern hot springs.

CHAPTER 6

ECOMOMIC POTENTIAL

Significant increases in silver and gold prices within the past several years have resulted in renewed interest in many epithermal precious-metal deposits such as the Commonwealth. The Commonwealth is unusual in that several miles of the old underground workings are still accessible. Because of extensive irrigated farming in the Sulphur Springs Valley, the water table has dropped below the mineralized zone leaving the mine dry down to the 8th level. At the present time the economic potential of the remaining vein and wall-rock material at the Commonwealth, as well as the old mill tailings, is being evaluated.

Current Activity

During the course of this study, Platoro Mines, Inc., of Tucson, Arizona, acquired control by option or claim staking of the old Commonwealth workings and tailings, part of the town of Pearce, and the prospects on the north side of Sixmile Hill. The company is currently conducting a program of bulk sampling and metallurgical testing to determine whether or not an orebody exists which is amenable

to open-pit mining. Past operators of the Commonwealth have encountered considerable metallurgical problems with the Commonwealth ore. The estimated one million tons of tailings north of Pearce Hill have been re-processed at least once by cyanide leaching, but they still contain an average of 2.5 to 3.0 oz./ton silver. The Thetford operation (1972-75) attempted to recover these values from the tailings by a flotation process. Although they achieved over 94 percent gold recovery, they generally ran less than 40 percent silver recovery. In addition to containing significant amounts of silver halides, the ore contains manganese in part as "black calcite" which may also contain silver but which was not recovered. Achieving good metallurgical recovery is a major factor in determining whether or not the Commonwealth orebody can be mined at a profit by any company. In addition to examination of Commonwealth reserves proper, there may be exploration for extensions of the Commonwealth vein system and for similar un-exploited vein systems of economic grade. The geologic information presented in this study can be valuable in these endeavors.

Extensive sampling by Platoro Mines (1975) confirmed the of grade distribution that would be expected on the basis of geologic examination. During March and April, 1975, 648 10-to 20-pound samples were taken on the surface and underground over 5- to 12-foot widths. The grade of the wall rock decreases gradually into the footwall of each major structure from the highest gold and silver values

which occur on the footwall sides of the old stopes. There is a decrease in value with distance into the footwall until another stope is encountered. A zone of strongly anomalous silver and gold values can be delineated which corresponds roughly to the sheeted zone between the Main Vein and the North Vein. Few samples of the hanging wall of the Main Vein are available, but these are of much lower grade than the average of the sheeted zone between the veins. Likewise, the Bisbee Formation in the footwall of the North Vein proves to contain significantly lower values. Platoro distinguishes four categories of grade, based on their sampling of all accessible workings. The higher grade zones contain 4 to 5 oz./ton silver and 0.04 oz./ton gold; the moderate grade zones contain 2 to 3 oz./ton silver and 0.03 oz./ton gold; the low background zones contain 1 to 2 oz./ton silver and 0.02 oz./ton gold; the very low background zones contain 0 to 1 oz./ton silver and 0.01 oz./ton gold. Most samples in the latter range of values are of the Bisbee Formation. Within the mine area, the Bisbee Formation generally assays less than 0.5oz./ton silver.

Platoro Mines (1975) determined that between 5 and 25 million tons of open-pitable ore with an average grade of 2 to 4 oz./ton silver and 0.02 to 0.03 oz./ton gold exist at the Commonwealth. The stripping ratio of this orebody would be 3:1. A major draw-back to open-pit mining of the Commonwealth system is the large, low grade

hanging wall block at the top of Pearce Hill which would have to be removed in order to recover the deeper ore.

Potential Outside the Mine Area

The fact that the Bisbee Formation is a poor host is probably in great part due to its structural incompetence. Widely spaced joints and gouge zones predominate rather than the sheeting and stockworks that characterize deformation of the more brittle volcanics. Furthermore, the highest-grade mineralization in the Bisbee rocks occurs in the quartzitic layers. If an analogy can be made between the Bisbee Formation and the less indurated beds of water-lain tuff, then these beds would likewise be poor hosts for economic-grade mineralization. The Commonwealth faults cut the Bisbee Formation on the west side of Pearce Hill, and the Main Vein Fault cuts the Third Water-Lain Tuff on the east side of Pearce Hill. According to old mine records and Smith's work, the grade of mineralization drops off on both the east and west ends of the vein system. Therefore, the value of locating the Main Vein beneath the valley between Pearce and Metat Hills is uncertain. If economic mineralization does occur there, it is probably at depth in the First Flow and First Ash Flow which would constitute the best target away from Pearce Hill itself.

Along with fracturing characteristics, stratigraphic position appears to control the occurrence of ore at the Commonwealth. Pearce

Hill is structurally higher and stratigraphically lower than any of the surrounding fault blocks. Veins of similar attitude and gangue mineralogy occur on Sixmile Hill, but they have not proven to be of economic importance. If depth of burial at the time of mineralization was indeed one of the factors controlling precious-metal deposition, then higher grade material might be expected at depth along these structures. If the coincidence of high grade ore at the Commonwealth with the potassic depth zone of alteration is a genetic relationship, then this is further evidence that depth of burial was a control on mineralization. Potassic alteration of the lower units of the Pearce Volcanics might prove to be a favorable exploration target.

CHAPTER 7

SUMMARY AND CONCLUSIONS

The Commonwealth Mine is one of the many epithermal precious-metal deposits which were highly productive for a short period during the early 1900's. Approximately 10 million dollars' worth of silver and gold were produced from the Commonwealth veins before 1930. At 1975 prices, this figure would exceed 100 million dollars. Like many other old districts of this type, the Commonwealth is being re-evaluated at the present time in light of current high gold and silver prices. Unlike most of the classical epithermal precious-metal deposits which are flooded and inaccessible, at least about one-tenth of the original underground workings at the Commonwealth are still accessible, including laterals, drifts, and crosscuts. This provides an excellent opportunity not only for a thorough economic evaluation but also for a detailed study of the alteration mineralogy associated with an epithermal precious-metal deposit and the application of techniques and information which were not available when most of these deposits were originally described.

The Commonwealth veins occur along major normal faults and in sub-vertical sheeted zones between them. Gangue mineralogy of the

veins includes quartz, calcite, and adularia, which exhibit typical epithermal textures such as comb texture and crustification. The primary ore minerals have been almost totally altered by secondary processes. Redistribution of both gold and silver have resulted in ore shoots whose economic minerals are native gold, cerargyrite, embolite, and minor acanthite and native silver. Two types of high-grade zones exist at the Commonwealth: upward-flaring vertical shoots and horizontally-disposed zones enriched in gold or silver. The former may be primary, but the latter must have formed after the mineralized volcanic units were tilted along post-ore Basin and Range faults. The mineralized faults trend about N80°W and dip about 60° south. Although the cause of this faulting is unknown, it must have been such that generally north-south directed tension with relative subsidence to the south resulted. Major post-ore faults along the same N40°W trend as the Swisshelm Mountains have broken the Pearce Volcanics into a series of tilted fault blocks. The Commonwealth Mine occupies a horst which is tilted about 40° to the northeast.

The Pearce Volcanics, as described by Gilluly, consist of andesites, rhyolites, and associated epiclastic sediments. On Pearce Hill, the equivalent volcanic units must be classified as trachytes and rhyolites on the basis of petrographic examination. The explanation offered here for the discrepancy in rock compositions is pervasive potassium metasomatism of the lower members of the Pearce

Volcanics in the vicinity of the Commonwealth Mine. Such feldspathic alteration has analogies in both active hot-spring areas and other epithermal precious-metal districts, and appears to fit into a relatively uniform vertical zoning pattern. The earliest and deepest zone of alteration is sodic, resulting in several instances in complete replacement of rock feldspars by albite. The Mizpah Trachyte at Tonopah and the soda trachyte member of the Alta Formation at Steamboat Springs appear to have formed in this manner. Superimposed upon and above this zone of sodium metasomatism is one of potassium metasomatism. In this zone, rock feldspars are replaced by potassium feldspar which has a lower 2V than is typical of orthoclase or microcline, and which may be structurally similar to sanidine. Sericite and secondary quartz may also occur in this zone, especially along fractures. In both hot springs and epithermal districts, argillic alteration may be coincident with this zone, indicating rampant locally variable chemical conditions and overall disequilibrium. Pervasive montmorillonite or mixed-layer illite-montmorillonite are common. Above the potassic zone around hot springs is another sodic zone which is characterized by lower temperature and lower Na:H ratio mineral phases such as sodium montmorillonite and analcite, other zeolites, calcite, and minor albite. In epithermal districts, this zone has generally been removed by erosion.

At the Commonwealth, the zone of potassium metasomatism is exposed at the surface. The predominant alteration phases are potassium feldspar, montmorillonite, sericite, quartz, and calcite. The depth of burial of the top of this zone at the time it formed was probably 1,500 to 2,000 feet, which is significantly deeper than the depth at which potassium metasomatism is observed around active hot springs. A possible explanation for the much wider alteration zones associated with epithermal mineral deposits is that the regional thermal gradients were more widespread and longer-lasting than those of modern hot springs. If this were true, then the resulting potential convection system of meteoric water would be larger and persist longer, enhancing the effectiveness with which it could introduce or re-distribute alkalies and precious metals.

It appears, then, that depth of burial as well as structural controls may have influenced ore deposition at the Commonwealth. Such a possibility would imply that similar veins may have formed elsewhere in the lower part of the volcanic pile in areas of major fracturing. Further exploration in the Pearce Volcanics should consider these possibilities. Pervasive potassic alteration of the lower flows in the vicinity of major tensional structures would be a favorable exploration target. Within the Commonwealth system itself, the precious-metal mineralization within sub-vertically sheeted zones in the vein footwalls is currently being evaluated with respect to open-pit

mining potential. The mineralization appears to have a true bottom below the 8th level and old records of drilling below this level do not encourage deeper exploration. Lateral extensions of the Commonwealth veins may contain ore-grade mineralization. On the west side of Pearce Hill, the veins are faulted off near the pre-tilting bottom of the system. Therefore, the benefit of locating this extension of the veins is questionable. On the east side of the hill, beneath the valley between Pearce and Metat Hills, the Main Vein structure appears to persist. The incompetent Third Water-Lain Tuff does not appear to have been a good host for ore. However, assuming post-ore tilting, economic mineralization might be found beneath this unit in the First Flow and First Ash-Flow Tuff, at a depth 400 feet or more below the base of the Third Water-Lain Tuff. If the Main Vein persists to the major N40°W fault on the west side of Metat Hill, then it would be offset to the north and may occur at depth somewhere near Highway 666.

APPENDIX A

SAMPLING AND ASSAY DATA

The locations of samples collected for this study are shown on the Sample Location maps, Figures A-1 through A-4. One- to five-pound rock samples were taken at 10-foot intervals in the areas shwon in these figures. The location of the sample on the side of the drift or the back is indicated by an "x", and the sample number indicated. Samples which were used for thin sections or fire-assay are indicated. Forty-nine of the samples collected were assayed for gold and silver content. These values are shown on the sample location maps. Samples were also taken for assay by Mr. Bob Helming for Essex International, Inc., in April, 1974. Three- to four-foot channel cuts were taken on the 3rd level, and the locations and assay values of these samples are shown on Figure A-1.

Additional "grab" samples were collected on the surface, for thin sections and staining. Those on Pearce Hill are located on Figure 2. The location and rock types of the other samples are described below.

EXPLANATION

Tf2 — SECOND FLOW

Tw2 — SECOND WATER-LAIN TUFF

Tal — FIRST ASH FLOW

Tw1 — FIRST WATER-LAIN TUFF

Tf1 — FIRST FLOW

Kb — BISBEE FORMATION

STRIKE AND DIP OF FAULT

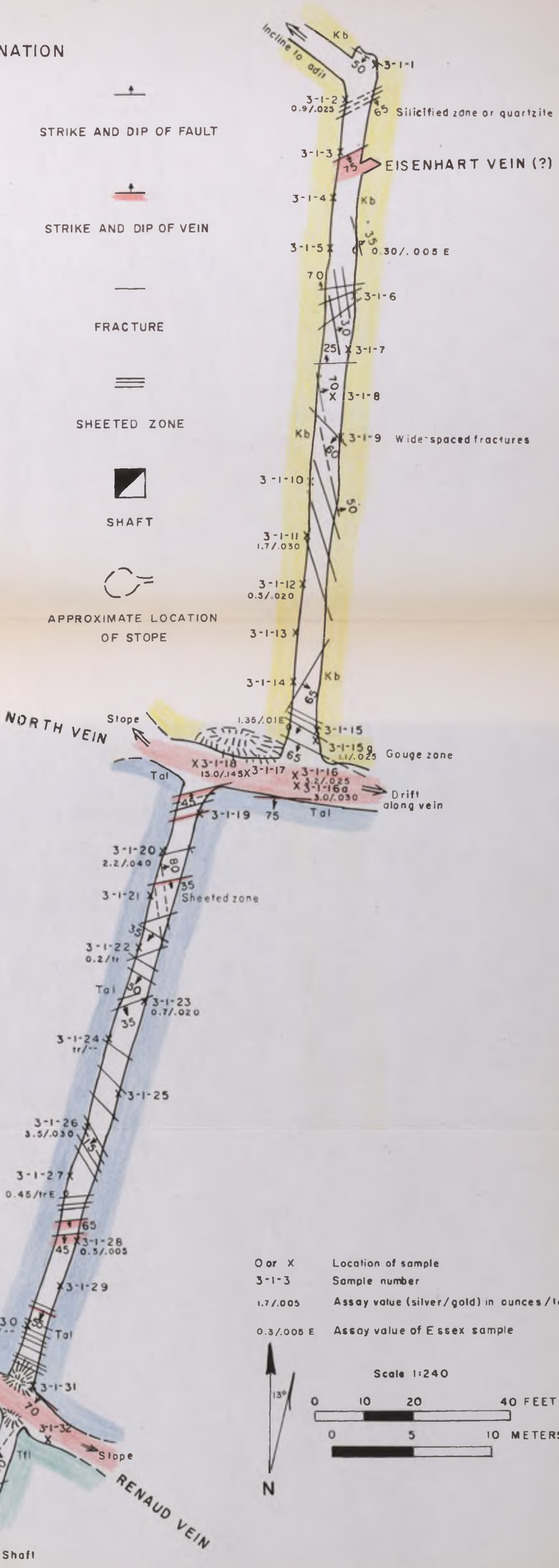
STRIKE AND DIP OF VEIN

FRACTURE

SHEETED ZONE

SHAFT

APPROXIMATE LOCATION OF STOPE



O or X — Location of sample

3-1-3 — Sample number

1.7/.005 — Assay value (silver/gold) in ounces/ton

0.3/.005 E — Assay value of Essex sample

Scale 1:240

0 10 20 40 FEET

0 5 10 METERS

N

Figure A-1. Sample Location Map of 3rd Level.

Figure A-2. Sample Location Map of 5th Level.

See Figure A-1 for explanation.

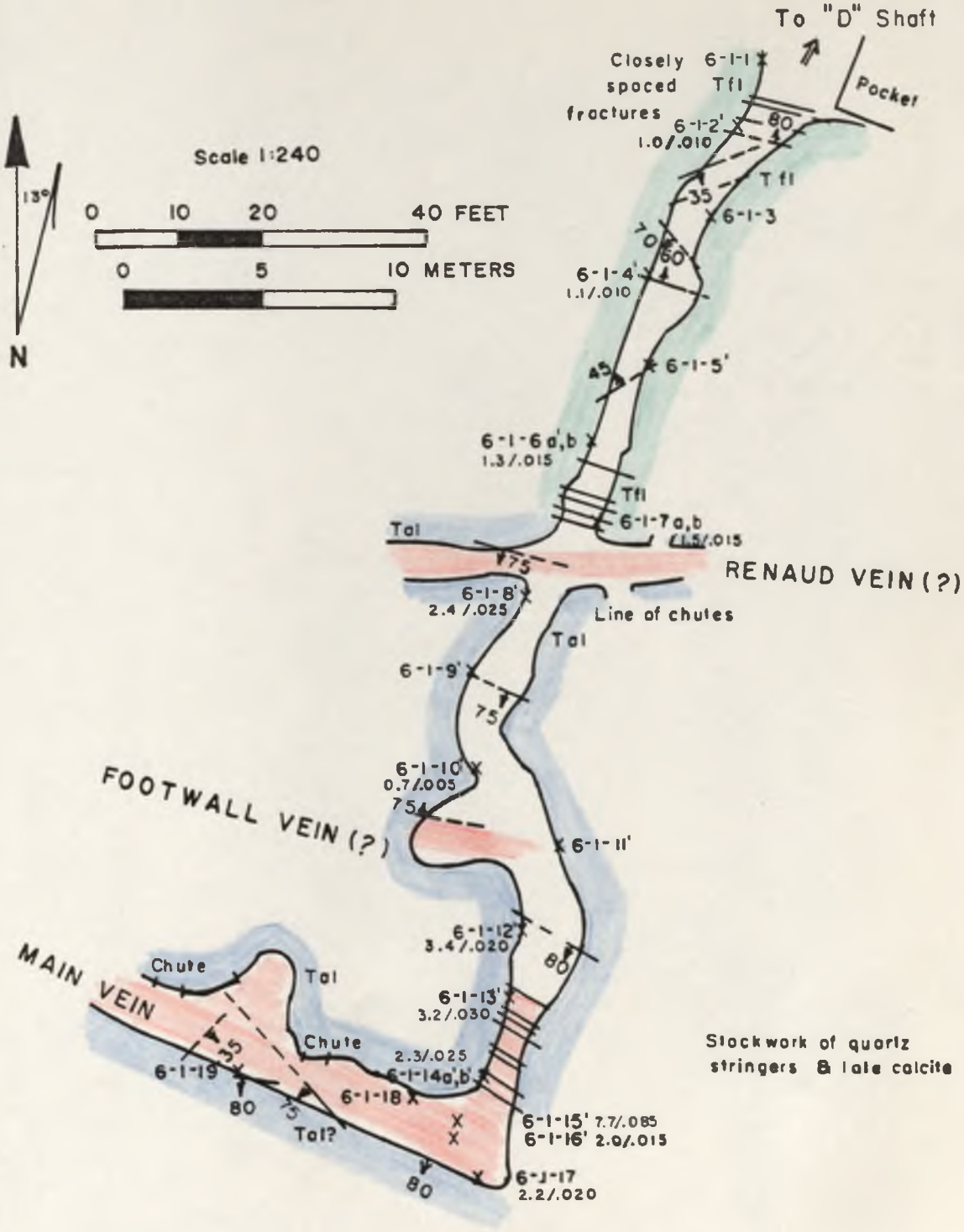


Figure A-3. Sample Location Map of 6th Level.

See Figure A-1 for explanation.

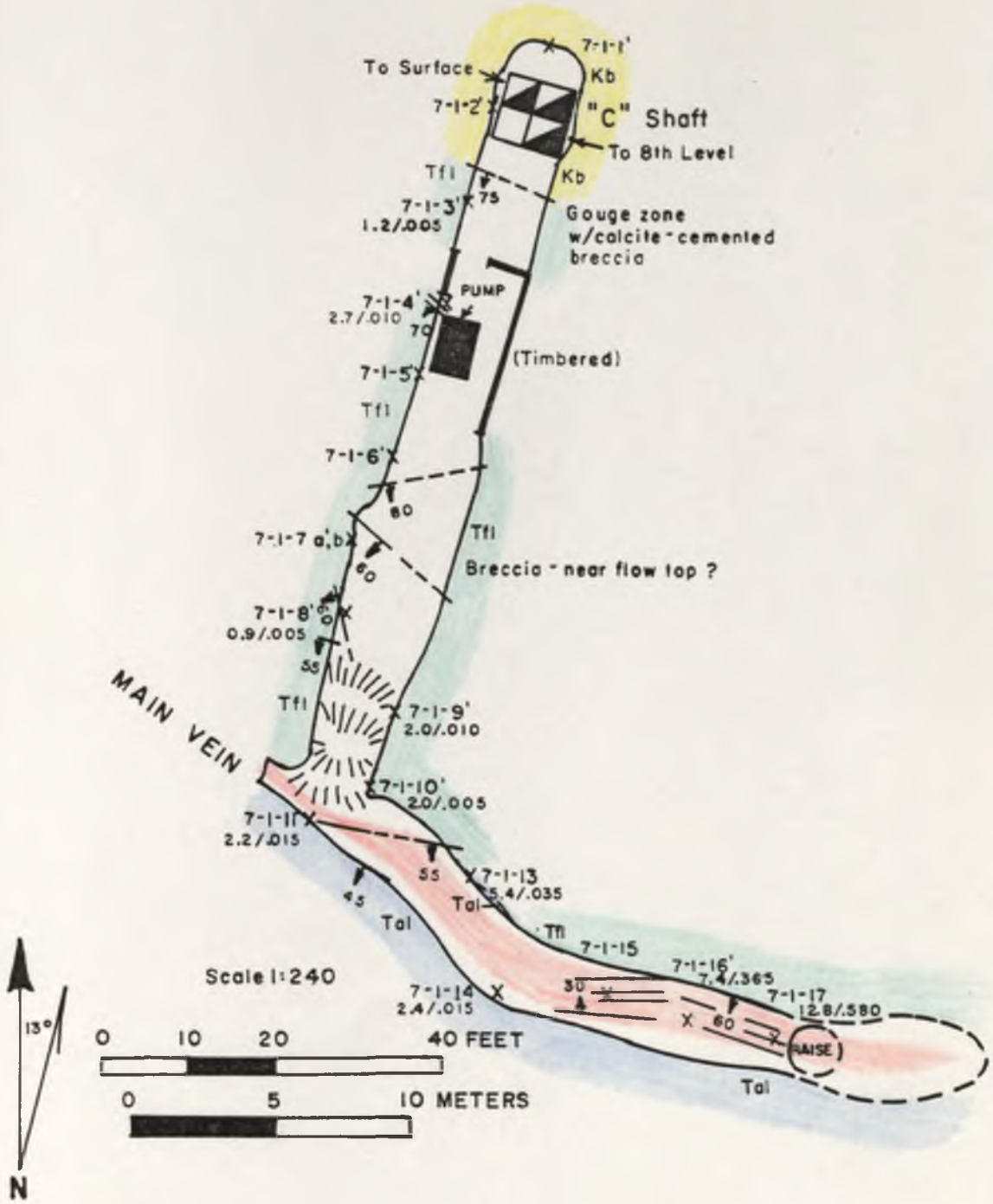


Figure A-4. Sample Location Map of 7th Level.

See Figure A-1 for explanation.

Locations of "Grab" Samples

Sample No.	Rock Unit	Location
23	Ta_2	south end of Metat Hill, isolated outcrop
23	Ta_2	dump on NW side of Metat Hill by deep shaft
25	Ta_3	west side of Metat Hill, above shaft
26	Ta_3	west side of Metat Hill, near top
M-0, M-2, M-3	Tf_2(?)	dump at NE base of Metat Hill
M-1	Ta_3	top of Metat Hill, center
M-4	Tf_2(?)	dump across RR grade, NE of Metat Hill
GS-1 - GS-4	Ta_3	east side of Sixmile Hill, sequence up section
6M-1	Ta_3	base of unit, N end of Sixmile Hill
6M-2	Tf_3	dump, far NE side of Sixmile Hill, scoreaceous flow rock
6M-3	Tf_3	Scoria, dump at adit, N center of Sixmile Hill
6M-4	Tv	vitrophyre, dump at adit, N center of Sixmile Hill
6M-4a	Tv	vitrophyre outcrop, N central Sixmile Hill
6M-5 - 6M-7	Ta_3	east central Sixmile Hill, above spherulitic zone, sequence up section

Locations of "Grab" Samples

Sample No.	Rock Unit	Location
6M-8 - 6M-10	Ta_2	above base of unit, SW side of Sixmile Hill
PF1, PF2	Tf_2	near dump at Pearce Shaft, SE of Pearce Hill

APPENDIX B

STAINING

Much of the pervasive potassium feldspar at the Commonwealth might have been overlooked if thin sections and slabs had not been stained for potassium feldspar. The staining method used on the Commonwealth rocks was modified from those described by Chayes (1952) and Bailey and Stevens (1960). Thin sections were etched in the vapors of HF for 5 to 10 seconds, and soaked in the sodium cobaltinitrite solution for approximately 30 seconds. Only half of the thin sections were stained; the other half was covered with cellophane tape to prevent etching. Hydrofluoric acid was placed in the bottom of a paraffin mold and the thin sections were placed face down over the mold. The welded tuffs required 5 to 7 seconds of etching for a light stain, and the flow rocks required 10 to 12 seconds. The thin sections were not rinsed between the etching and staining stages, but were thoroughly rinsed after staining. The cellophane tape was carefully removed after the stain dried and the un-stained portion of the thin section was cleaned with acetone before the cover glass was mounted.

Slabs of many rock types were also stained for potassium feldspar. The technique used was derived from Williams (1960) and

from discussions with students. The rock slab to be stained was cut and ground on a lap down to 600-mesh grit. The surface was then thoroughly cleaned. Some of the samples were etched in HF vapors for 1 minute, and soaked in the sodium cobaltinitrite solution for 1 to 2 minutes. Other samples were placed in direct contact with the HF for 45 to 60 seconds, rinsed, and soaked in sodium cobaltinitrite solution for 4 minutes. The extent of staining was comparable for both methods, but the stain was more intense on the slabs that were soaked in acid. Clays stained more readily with this method, but they can be distinguished from potassium feldspar by hardness.

In thin section, montmorillonite stained lightly, but sericite stained only in sections which were etched too long. The veinlet adularia, shards, and phenocrysts with "patchy" extinction took a strong, evenly distributed stain. The normal phenocrysts, groundmass material, and phenocrysts with shadowy extinction took a light, sometimes irregular stain.

APPENDIX C

X-RAY DATA

The following X-ray data were gathered during the course of this thesis work. Most of the X-ray patterns were obtained with a Norelco diffractometer. Those which were obtained using a Debye-Scherrer camera are designated as powder camera samples. Lines on the powder camera film were indexed using a standard template, and several were checked with a film-measuring device. All intensities were visually estimated and are given as very strong (vs), strong (s), moderately strong (ms), moderate (m), moderately weak (mw), weak (w), very weak (vw), and broad (b), in a manner similar to that used by Grim (1953). The phyllosilicate mineral samples for which a specific mode of occurrence is designated were removed from the specimen under a binocular microscope and ground with a small mortar and pestle. The powder was then mixed with distilled water, deposited on a glass slide, and allowed to dry. This technique produced oriented mounts which gave very satisfactory patterns. The samples designated as "suspended clay fraction" were derived from the whole rock. Rock chips about 4 cm in diameter were ground and pulverized and the powder was mixed with approximately 100 ml of distilled water in a

beaker. The mixutre was allowed to settle for one to two hours, and the upper three or four centimeters of the fluid was removed and allowed to evaporate to near-dryness. The resulting slurry was then deposited on a glass slide and allowed to dry. Non-clay mineral samples were removed from the specimen with a Vibrograver and ground to a powder with a mortar and pestle. The diffractometer samples were mounted on glass slides with acetone; powder camera samples were mounted on glass fibers with silicone gel.

Glycolation and heating of the phyllosilicate samples were done according to the method of Carroll (1970). Samples to be glycolated were placed in a dessicator containing liquid ethylene glycol in the bottom, and were exposed to the vapors for one hour at 60°C. Longer glycolation times or direct contact of the sample with ethylene glycol did not change the degree of expansion. Heating to 150°C and above was done in a ventilated muffle furnace for a period of one hour.

Attempts to determine the sodium content and structure of the potassium feldspar samples using X-ray diffraction data were mostly unsuccessful. Using Wright's (1968) method based on the $(\bar{2}01)$ reflection, the sodium content of sanidine phenocrysts from the First and Second Ash Flows appears to be around 15 percent, whereas the sodium content of the veinlet material appears to be less than 5 percent. The phenocrysts plot within Wright's orthoclase series on the

basis of the ($\bar{2}04$) and (060) reflections. However, the X-ray patterns of all of the feldspars resemble the A.S.T.M. standard sanidine pattern more closely than any of the other standard feldspar patterns, and the optical properties are those of sanidine.

Conditions under which the phyllosilicate specimens were run were kept as uniform as possible; the samples were X-rayed, glycolated, and heated in groups of 4 to 6. Most of the 10 angstrom lines are broad and there are few basal reflections. Therefore, this mineral is assumed to be poorly-ordered illite. The peaks became sharper and more well-defined upon heating, suggesting that the structure was becoming more ordered at higher temperatures. Glycolation and heating caused some of these peaks to split, change position, or disappear entirely. There appears to be a very minor exchangeable component in the 10 angstrom phyllosilicates. Using Hower and Mowatt's (1966) work as a basis for comparison, there is probably less than a 15 percent expandable component in these illites. The 14 angstrom phyllosilicates are montmorillonites on the basis of combined X-ray and optical evidence. The variable nature of expansion and the incomplete degree of collapse upon heating to 600°C are attributed to the presence of strongly bonded inter-layer ions or water. However, this clay could possibly be similar to the 1:1 mixed-layer chlorite-vermiculite described by Bradley and Weaver (1956) which expands only one angstrom upon glycolation. No descriptions of the optical

properties of this clay have been found in the literature. It has been found in X-ray patterns around active hot springs.

The following X-ray data are from samples whose locations are shown on Figures A-1 through A-4 or described in Appendix A as "grab samples".

Sample #M - O

Altered Amphibole - Tf_2 (Powder Camera)

Minerals Present: Hematite (?)

d(A^o)	I	Comments
2.72	vs	Hematite (?)
2.48	m	Hematite (?)
2.09	m	
1.92	mw	
1.82	w	
1.68	w	Hematite (?)
1.58	w	
1.44	vw	

Sample #6M - 3a

Fine-grained Silica Amygdule

Minerals Present: Quartz

d(A°)	I	Comments
4.25	vs	
3.34	vvs	
2.46	s	
2.28	m	
2.23	m	
2.13	m	
1.98	m	
1.82	s	
1.67	m	
1.66	mw	
1.61	w	
1.54	ms	

Sample #GS - 3

Spherulite - Ta_3 (Powder Camera)

Minerals Present: Quartz

d(A^o)	I	Comments
4.25	s	Quartz
3.35	vs	Quartz
2.45	w	
2.28	w	
2.23	vw	
2.13	w	
1.99	vw	
1.82	mw	Quartz
1.67	vw	
1.54	w	
1.30	mw	
1.36	mw	
1.29	vw	
1.16	vw	
1.20	vw	
1.17	vw	

Sample #9

Feldspar Pheno-Bx Frag in Tf_1 (Powder Camera)

Minerals Present: Sanidine, Calcite, Hematite

d(A^o)	I	Comments
4.2	w	Sanidine
3.77	mw	Sanidine
3.45	vw	Sanidine
3.32	s	Sanidine
3.22	s	Sanidine
3.02	mw	Sanidine, Calcite
2.70	w	Sanidine, Hematite
2.58	w	Calcite
2.51	w	Calcite, Hematite?
1.99	s	Calcite?
1.80	w	Sanidine
1.74	w	
1.72	w	Hematite
1.69	w	

Sample #9a

Spherulite (Powder Camera)

Minerals present: Sanidine

d(A^o)	I	Comments
4.4	m	Sanidine?
3.75	m	Sanidine
3.45	w	Sandine
3.32	s (6)	Sanidine
3.20	s (6)	Sanidine
3.0	w	Sanidine
2.9	w	Sanidine
2.75	vw	Sanidine
2.58	w	Sanidine
2.53	vw	
2.16	vw	Sanidine
1.99	w	
1.84	vw	
1.80	vw	Sanidine

Sample #10

Trachytic Bx Frag, Tf_1 (Powder Camera)

Minerals Present: Sanidine (?)

d(A^o)	I	Comments
3.70	s	Sanidine (?)
3.32	m	Sanidine
3.22	m	Sanidine
3.08	m	Sanidine
2.37	vw	

Sample #14

Feldspar Phenocryst (Powder Camera)

Minerals present: Sanidine, Quartz (?)

d(A^{o})	I	Comments
7.5	ms	
4.28	w	Quartz (?)
4.10	w	Sanidine (?)
3.85	s	
3.80	m	Sanidine (?)
3.48	ms	Sanidine (?)
3.32	ms	Sanidine, Quartz
3.24	ms	Sanidine
3.01	mw	Sanidine
2.92	mw	Sanidine
2.77	mw	Sanidine
2.58	mw	Sanidine
2.54	w	Sanidine
2.38	mw	
2.32	mw	
2.18	mw	
2.14	mw	
2.07	w	
2.02	w	Sanidine
1.81	mw	
1.51	mw	

Sample #22

Glassy Feldspar Phenocrysts--First Ash-Flow Tuff

Minerals Present: Sanidine, Quartz

d(A^{o})	I	Caoments
4.19	m	Quartz
3.74	m	Sanidine
3.59	mw	Sanidine
3.43	mw	Sanidine
3.30	vs	Quartz & Sanidine
3.20	s	Sanidine
2.97	mw	Sanidine
2.88	mw	Sanidine
2.75	w	Sanidine
2.56	mw	Sanidine
1.81	w	Quartz
1.79	w	Sanidine

Sample #24

Feldspar Phenocrysts--Second Ash-Flow Tuff

Minerals Present: Sanidine, Quartz

d(A°)	I	Comments
6.46	w	Sanidine (?)
5.82	vw	Sanidine (?)
4.21	m	Quartz (?)
3.95	w	
3.77	m	Sanidine
3.60	w	Sanidine
3.45	mw	Sanidine
3.34	vs	Quartz, Sanidine (?)
3.23	s	Sanidine
2.98	m	Sanidine
2.77	w	Sanidine
2.57	mw	Sanidine
2.17	w	Sanidine
1.82	vw	Quartz
1.80	mw	Sanidine

Sample #24

Welded Tuff Matrix

Minerals Present: Quartz, Sanidine (?)

d(A^{o})	I	Comments
7.25	w	
6.56	w	
4.27	s	Quartz
3.95	vw	
3.79	m	Sanidine (?)
3.62	w	Sanidine (?)
3.47	mw	Sanidine (?)
3.34	vvs	Sanidine (?) Quartz
3.24	m	Sanidine (?)
3.09	w	
3.04	m	
3.01	m	
2.92	mw	
2.75	mw	Sanidine (?)
2.59	w	Sanidine (?)
2.45	mw	
2.28	mw	
2.20	mw	
2.17	w	
2.13	mw	

Sample #3-1-7

Veinlet Potassium Feldspar

Minerals Present: Adularia (Sanidine?)

d(A°)	I	Comments
4.23	s	Quartz (?)
3.93	w	
3.75	ms	Sanidine (?)
3.45	m	
3.33	vvs (6)	Quartz & Sanidine?
3.22	s	Sanidine (?)
2.99	m	
2.90	mw	
2.76	w	
2.57	w	
2.46	mw	
2.28	mw	
2.23	w	
2.17	w	
2.11	mw	
1.97	w	
1.81	s	Quartz
1.79	mw	
1.67	w	
1.66	w	
1.54	m	

Sample #3-1-7

Carbonate from Veinlet

Minerals Present: Calcite, Minor Quartz

d(A°)	I	Comments
4.25	w	Quartz
3.87	w	Calcite
3.34	m	Quartz
3.02	vvs	Calcite
2.84	w	Calcite
2.49	m	Calcite
2.28	m	Calcite
2.09	m	Calcite
1.91	s	Calcite
1.87	m	Calcite
1.62	w	Calcite

Sample #3-1-7

Veinlet Material

Minerals Present: Quartz, Calcite

d(A°)	I	Comments
4.27	m	Quartz, Calcite
3.80	mw	
3.65	w	
3.47	w	
3.35	s	Quartz
3.23	vw	
3.16	vw	
3.12	vw	
3.03	vs	Calcite
2.26	m	
2.07	w	
1.88	w	
1.85	w	
1.78	w	

Sample #3-1-20

Spherulite (Powder Camera)

Minerals Present: Sanidine (?)

d(A^{o})	I	Comments
4.9	vw	
4.6	mw	
3.8	vw	Sanidine (?)
3.6	mw	
3.32	mw	Sanidine
3.22	mw	Sanidine
2.92	vw	
2.65	mw	
2.56	mw	
2.40	mw	
2.0	w	
1.8	vw	
1.74	vw	
1.52	mw	
1.50	mw	

Sample #5-2-3

Feldspar Phenocryst (Powder Camera)

Minerals Present: Sanidine

d(A^{o})	I	Comments
4.20	ms	
3.75	ms	
3.43	m	
3.28	s	
3.22	s	
3.00	ms	
2.96	m	
2.87	mw	
2.75	w	
2.59	w	
2.56	w	
1.79	mw	

Sample #P-F2

Olive Green-White Banded Amygdule

Clays Present: Montmorillonite

X-ray pattern		After 1 hr. at 60°C glycolation		After heating 1 hr. at 150°C		After heating 1 hr. at 300°C		After heating 1 hr. at 600°C	
d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I
--		30.5	w	--		--		--	
14.5	s	15.5	s	--		--		--	
11.3	vw	--		--		--		--	
7.20	vw	--		--		--		--	
4.98	w	--		--		--		--	
4.51	mw	--		--		--		--	

Sample #6M-3

Green-White Banded Amygdule

Clays Present: Montmorillonite

X-ray pattern		After 1 hr. at 60°C glycolation		After heating 1 hr. at 150°C		After heating 1 hr. at 300°C		After heating 1 hr. at 600°C	
d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I
--		32.7	w(b)	--		--		--	
14.7	vs	16.7	vs	--		--		--	
--		8.19	w	--		--		--	
4.48	vw	--		--		--		--	

Sample #8

Suspended Clay Fraction

Clays Present: Montmorillonite, Illite

X-ray pattern		After 1 hr. at 60°C glycolation		After heating 1 hr. at 150°C		After heating 1 hr. at 300°C		After heating 1 hr. at 600°C	
d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I
14.5	m	17.0	ms(b)	--		--		--	
10.5	ms	9.82	m	--		--		--	
5.01	w	--		--		--		--	
4.29	w	4.29	mw	--		--		--	

Sample #22

Bronze Alteration Prod. of Pumice, Ta_1

Clays Present: Montmorillonite

X-ray pattern		After 1 hr. at 60°C glycolation		After heating 1 hr. at 150°C		After heating 1 hr. at 300°C		After heating 1 hr. at 600°C	
d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I
28.5	m	30.5	m	--		--		--	
14.0	s	15.5	s	--		--		--	
5.75	w	7.69	m	--		--		--	
4.80	w	--		--		--		--	
4.55	mw	--		--		--		--	
4.25	vs	--		--		--		--	

Sample #3-1-7

Suspended Clays

Clays Present: Montmorillonite, Illite

X-ray pattern		After 1 hr. at 60°C glycolation		After heating 1 hr. at 150°C		After heating 1 hr. at 300°C		After heating 1 hr. at 600°C	
d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I
14.5	m	15.0	ms	14.3	mw	13.6	mw	13.8	m(b)
10.6	mw	9.94	mw	10.5	mw	10.0	mw	10.2	m
8.42	w	--		--		--		--	
7.14	mw(b)	7.20	m	7.20	mw	7.20	vw	--	
4.27	s	4.27	s	--		--		--	

Sample #3-1-15

Suspended Clays

Clays Present: Montmorillonite, Illite

X-ray pattern		After 1 hr. at 60°C glycolation		After heating 1 hr. at 150°C		After heating 1 hr. at 300°C		After heating 1 hr. at 600°C	
d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I
14.0	mw	15.8	m	13.8	w	12.3	w	--	
10.0	m	10.2	m(b)	10.0	ms	10.0	ms	--	

Sample #3-1-17

Fracture Coating

Clays Present: Montmorillonite, Illite (?), Kaolinite (?)

X-ray pattern		After 1 hr. at 60°C glycolation		After heating 1 hr. at 150°C		After heating 1 hr. at 300°C		After heating 1 hr. at 600°C	
d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I
--		30.5	s	--		--		--	
14.5	vs	15.5	vs	--		--		--	
9.51	w(b)	9.31	w	--		--		--	
7.90	mw	7.69	m	--		--		--	
4.85	w	--		--		--		--	
4.48	w	--		--		--		--	
4.27	m	--		--		--		--	

Sample #3-1-23

White Clay Fract. Coating and Alt. Product

Clays Present: Montmorillonite and (Illite?)

X-ray pattern		After 1 hr. at 60°C glycolation		After heating 1 hr. at 150°C		After heating 1 hr. at 300°C		After heating 1 hr. at 600°C	
d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I
		30.5	vw	--		--		--	
14.7	m	17.7	m	--		--		--	
10.7	w(b)	--		--		--		--	
9.82	w(b)	9.83	m	--		--		--	
5.01	m	--		--		--		--	
4.48	ms	--		--		--		--	
4.25	ms	--		--		--		--	

Sample #3-1-32a

Lt. Green Fracture Coating-Edge of Renaud Vein

Clays Present: Montmorillonite

X-ray pattern		After 1 hr. at 60°C glycolation		After heating 1 hr. at 150°C		After heating 1 hr. at 300°C		After heating 1 hr. at 600°C	
d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I
13.4	vs	16.1	vs	--		--		--	
4.46	w(b)	4.46	m	--		--		--	

Sample #5-2-22

Suspended Clay Fraction

Clays Present: Montmorillonite

X-ray pattern		After 1 hr. at 60°C glycolation		After heating 1 hr. at 150°C		After heating 1 hr. at 300°C		After heating 1 hr. at 600°C	
d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I	d(A°)	I
13.8	mw	15.0	m	14.3	m	--		13.6	w(b)
				8.00	w	--		--	
7.38	w	7.50	w	7.20	mw	--		--	
6.56	w	6.56	w	6.56	w	--		6.61	w
5.10	w								
4.25	m	4.25	m	4.25	m	--		--	

REFERENCES CITED

Aiken, C.L.V. and Sumner, J.S., 1974, A Geophysical and Geological Investigation of Potentially Favorable Areas for Petroleum Exploration in Southeastern Arizona: Arizona Oil and Gas Conservation Commission Report of Investigation 3, 40 pp.

Albers, J.P. and Kleinhampl, F.J., 1970, Spatial Relation of Mineral Deposits to Tertiary Volcanic Centers in Nevada: U.S. Geol. Survey Prof. Paper 700-C, pp. 1-10.

Althaus, E. and Johannes, W., 1969, Experimental metamorphism of NaCl-bearing aqueous solutions by reaction with silicates: Am. Jour. Sci., vol. 267, pp. 87-98.

Anderson, C.A., 1966, Areal geology of the southwest, in Titley, S.R. and Hicks, C.L., Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, The University of Arizona Press, 287 pp.

Arizona Bureau of Mines, 1959, Geologic Map of Arizona.

Arizona Bureau of Mines, 1961, Gold Placers and Placering in Arizona: Ariz. Bureau of Mines Bull. 168.

Arizona Bureau of Mines, 1969, Mineral and Water Resources of Arizona: Ariz. Bureau of Mines Bull. 180, 638 pp.

Bailey, E.H. and Stevens, R.E., 1960, Selective staining of K-feldspar and plagioclase on rock slabs and thin sections: Am. Mineralogist, vol. 45, pp. 1020-1025.

Banwell, C.J., 1969, Oxygen and hydrogen isotopes in New Zealand thermal areas, in Tongiorgi, E., ed., Nuclear Geology of Geothermal Areas: Spoleto, Consiglio Nazionale Delle Richerche, 254 pp.

Bastin, E.S., 1922, Bonanza Ores of the Comstock Lode, Virginia City, Nevada: U.S. Geol. Survey Bull. 735-C, pp. 41-63.

Bastin, E.S. and Laney, F.B., 1918, The Genesis of the Ores at Tonopah, Nevada: U.S. Geol. Survey Prof. Paper 104, 50 pp.

Battey, M.H., 1955, Alkali metasomatism and the petrology of some keratophyres: Geol. Mag., vol. 92, pp. 104-126.

Bock, C.M., 1962, The Distribution of Some Selected Alkali Metals and Alkaline Earths in the Stronghold Granite, Cochise County, Arizona: The University of Arizona unpublished Ph.D. thesis, 95 pp.

Bonham, H.F., 1969, Geology and Mineral Deposits of Washoe and Storey Counties, Nevada: Nevada Bureau of Mines Bull. 70, 140 pp.

Boyd, F.R., 1961, Welded tuffs and flows in the rhyolite plateau of Yellowstone Park, Wyoming: Geol. Soc. America Bull., vol. 72, pp. 387-426.

Boyle, R.W., 1968, The Geochemistry of Silver and Its Deposits: Geological Survey of Canada Bull. 160, 264 pp.

Bradley, W.F. and Weaver, C.E., 1956, A regular interstratified chlorite-vermiculite clay mineral: Am. Mineralogist, vol. 41, pp. 497-504.

Brannock, W.W., Rix, P.R., Gianella, V.P., and White, D.E., 1948, Preliminary geochemical results at Steamboat Springs, Nevada: Am. Geophys. Union Trans., vol. 29, pp. 211-226.

Brittain, R.L., 1954, Geology and Ore Deposits of the Western Portion of the Hilltop Mine Area, Cochise County, Arizona: The University of Arizona unpublished M.S. thesis, 97 pp.

Campbell, I., 1933, Some interrelations between phases of alteration and types of rocks in the Tonopah Mining District, Nevada (abs.): Geol. Soc. America Bull., vol. 44, p. 164.

Carroll, D., 1970, Clay Minerals: A Guide to Their X-ray Identification: Geol. Soc. America Special Paper 126, 80 pp.

Cederstrom, D.J., 1946a, Geology of the Central Dragoon Mountains, Arizona: The University of Arizona unpublished Ph.D. thesis, 93 pp.

Cederstrom, D.J., 1946b, The structural geology of the Dragoon Mountains, Arizona: Am. Jour. Sci., vol. 244, pp. 601-621.

Chaisson, U., 1952, The optics of triclinic adularia: Jour. Geology, vol. 58, pp. 537-547.

Chayes, F., 1952, Notes on the staining of potash feldspar and sodium cobaltinitrite on thin sections: Am. Mineralogist, vol. 37, pp. 337-340.

Chesterman, C.W., 1968, Volcanic geology of the Bodie Hills, Mono County, California, in Coats, R.R., Hay, R.L. and Anderson, C.A., Studies in Volcanology--A Memoir in Honor of Howel Williams: Geol. Soc. America Memoir 116, pp. 45-68.

Christiansen, R.L. and Lipman, P.W., 1966, Emplacement and thermal history of a rhyolite flow: Geol. Soc. America Bull., vol. 77, pp. 671-684.

_____, 1970, Cenozoic volcanism and tectonism in the western United States and adjacent parts of the spreading ocean floor Part 2: late Cenozoic: Geol. Soc. America Abstracts, 1970, 66th Annual Meeting, Cordilleran Section, pp. 81-82.

Clark, W.B., 1970, Gold Districts of California: California Division of Mines and Geology Bull. 193, 186 pp.

Cloke, P.L. and Kelly, W.C., 1964, Solubility of gold under inorganic supergene conditions: Econ. Geology, vol. 59, pp. 259-270.

Coats, R.R., 1940, Propylitization and related types of alteration on the Comstock Lode: Econ. Geology, vol. 35, pp. 1-16.

Cooke, H.C., 1913, The secondary enrichment of silver ores: Jour. Geology, vol. 21, pp. 1-28.

Cooper, J.R., 1959, Some geologic features of the Dragoon Quadrangle, Arizona: Arizona Geological Society Guidebook II, Southern Arizona, pp. 139-145.

_____, 1960, Reconnaissance Map of the Willcox, Fisher Hills, Cochise, and Dos Cabezas Quadrangles, Cochise and Graham Counties, Arizona: U.S. Geol. Survey Misc. Field Studies Map MF-321.

Craig, H., 1963, The isotopic geochemistry of water and carbon in geothermal areas, in Tongiorgi, E., Nuclear Geology on Geothermal Areas: Spoleto, Consiglio Nazionale Delle Richerche, 254 pp.

Dennison, J.M., 1968, Analysis of Geologic Structures: New York, W.W. Norton and Company, Inc., 209 pp.

Diery, H.D., 1964, Petrography and Petrogenetic History of a Quartz Monzonite Intrusive, Swisshelm Mountains, Cochise County, Arizona: The University of Arizona, unpublished M.S. thesis, 100 pp.

Drewes, H., 1968, The Laramide orogeny of Arizona southeast of Tucson, in Abstracts for 1968, Geol. Soc. America Special Paper 121, pp. 501-502.

_____, 1972, Structural Geology of the Santa Rita Mountains, Southeast of Tucson, Arizona: U.S. Geol. Survey Prof. Paper 748, 35 pp.

Drewes, H. and Williams, F.E., 1973, Mineral Resources of the Chiricahua Wilderness Area, Cochise County, Arizona: U.S. Geol. Survey Bull. 1 385-A, 53 pp.

Dunne, J.A., 1957, Tungsten Mineralization at the Swisshelm Mountains, Cochise County, Arizona: Columbia University, unpublished M.A. thesis.

Ellis, A.J. and Mahon, A.W.J., 1964, Natural hydrothermal systems and experimental hot water/rock interactions (Part I) Geochim. et Cosmochim. Acta, vol. 28, pp. 1325-1357.

_____, 1967, Natural hydrothermal systems and experimental hot water/rock interactions (Part II) Geochim. et Cosmochim. Acta, vol. 31, pp. 519-538.

Emmons, W.H., 1917, The Enrichment of Ore Deposits: U.S. Geol. Survey Bull. 625, 530 pp.

Endlich, F.M., 1897, The Pearce Mining District, Arizona: Eng. Mining Jour., vol. 63, p. 571.

Enlows, H.E., 1951, The igneous geology of Chiricahua National Monument, Arizona: Tulsa Geological Society Digest, vol. 18, pp. 105-107.

Enlows, H.E., 1955, Welded tuffs of the Chiricahua National Monument, Arizona: Geol. Soc. America Bull., vol. 66, pp. 1215-1246.

Epis, R.C., 1956, Geology of the Pedregosa Mountains, Cochise County, Arizona: University of California at Berkeley, unpublished Ph.D. thesis.

Erickson, R.C., 1968, Geology and geochronology of the Dos Cabezas Mountains, Cochise County, Arizona, in Arizona Geological Society, Southern Arizona Guidebook III, pp. 195-198.

_____, 1969, Petrology and Geochemistry of the Dos Cabezas Mountains, Cochise County, Arizona: The University of Arizona, unpublished Ph.D. thesis, 441 pp.

Ettinger, L.F., 1962, Geology of the Pat Hills, Cochise County, Arizona: The University of Arizona, unpublished M.S. thesis, 47 pp.

Fenner, C.N., 1936, Bore hole investigations in Yellowstone Park: Jour. Geology, vol. 44, pp. 225-315.

Finch, J.W., Chairman, 1933, Ore Deposits of the Western States (Lindgren volume): New York, Am. Inst. Mining Metall. Engineers, 797 pp.

Galbraith, F.W. and Loring, W.B., 1951, Arizona Zinc and Lead Deposits; Swisshelm District: Arizona Bureau of Mines Bull. 158, pp. 30-36.

Gianella, V.P., 1936, Geology of the Silver City District and the Southern Portion of the Comstock Lode, Nevada: Nevada University Bull. 30, No. 9, 105 pp.

_____, 1939, Mineral deposition at Steamboat Springs, Nevada: Econ. Geology, vol. 34, pp. 471-472.

_____, 1959, Period of mineralization of the Comstock Lode, Nevada (abs.): Geol. Soc. America Bull., vol. 70, p. 1721.

Gilbert, G.K., 1875, Report on the Geology of Portions of New Mexico and Arizona: U.S. Geol. and Geol. Survey W. 100th Meridan Report, vol. 3.

Gilluly, J., 1956, General Geology of Central Cochise County, Arizona: U.S. Geol. Survey Prof. Paper 281, 169 pp.

_____, 1963, The tectonic evolution of the western United States: Geol. Soc. of London Quarterly Jour. vol. 119, pp. 133-174.

Glover, J.E. and Hosemann, P., 1970, Optical data on some authigenic feldspars from Western Australia: Mineralog. Mag., vol. 37, pp. 588-592.

Grim, R.E., 1953, Clay Mineralogy: New York, McGraw-Hill Book Co., Inc., 384 pp.

Grindley, G.W., 1963, Geology and structure of the Waiotapu geothermal field, in Waiotapu Geothermal Field: New Zealand Dept. of Scientific and Industrial Research Bull. 155, pp. 10-15.

Hayes, P.T., 1970, Cretaceous Paleogeography of Southeastern Arizona and Adjacent Areas: U.S. Geol. Survey Prof. Paper 658-B, 42 pp.

Hemley, J.J., 1959, Some mineralogical equilibria in the system K_2O-Al_2O_3-SiO_2-H_2O: Am. Jour. Sci., vol. 257, pp. 241-270.

Hemley, J.J. and Jones, W.R., 1964, Chemical aspects of hydrothermal alteration, with emphasis on hydrogen metasomatism: Econ. Geology, vol. 59, pp. 538-569.

Hemley, J.J., Meyer, C., and Richter, D.H., 1961, Some Alteration Relations in the System Na_2O-Al_2O_3-SiO_2-H_2O: U.S. Geol. Survey Prof. Paper 424-D, pp. 338-340.

Hess, P.C., 1966, Phase equilibria of some minerals in the K_2O-Na_2O-Al_2O_3-SiO_2-H_2O system at 25°C and 1 atmosphere: Am. Jour. Sci., vol. 264, pp. 289-309.

Hewett, D.F. and Radke, A.S., 1967, Silver-bearing black calcite in the southwestern U.S.: Econ. Geology, vol. 62, pp. 1-21.

Hower, J. and Mowatt, T.C., 1966, The mineralogy of illites and mixed-layer illite montmorillonites: Am. Mineralogist, vol. 51, pp. 825-854.

Jensen, M.K., Ashley, R.P., and Albers, J.P., 1971, Primary and secondary sulfates at Goldfield, Nevada: Econ. Geology, vol. 66, pp. 618-626.

Keith, S.B., 1973, Index of Mining Properties in Cochise County: Arizona Bureau of Mines Bull. 190, 98 pp.

Krauskopf, K.B., 1951, The solubility of gold: Econ. Geology, vol. 46, pp. 858-870.

Lindgren, W., 1933, Mineral Deposits, 4th ed.: New York, McGraw-Hill Book Co., Inc., 930 pp.

Loring, W.B., 1947, Geology and Ore Deposits of the Mountain Queen Area, Northern Swisshelm Mountains, Arizona: The University of Arizona, unpublished M.S. thesis, 65 pp.

Marjaniemi, D.K., 1968, Tertiary volcanism in the northern Chiricahua Mountains, Cochise County, Arizona: Arizona Geological Society, Southern Arizona Guidebook III, pp. 209-214.

_____, 1970, Geologic History of an Ash-Flow Sequence and its Source Area in the Basin and Range Province of Southeastern Arizona: The University of Arizona, unpublished Ph.D. thesis 176 pp.

Marvin, R.F., Stern, T.W., Creasy, S.C., and Menhert, H.H., 1973, Radiometric Ages of Igneous Rocks from Pima, Santa Cruz, and Cochise Counties, Southeastern Arizona: U.S. Geol. Survey Bull. 1379, 27 pp.

Meinzer, O.E. and Kelton, F.C., 1913, Geology and Water Resources of Sulphur Spring Valley, Arizona: U.S. Geol. Survey Water-Supply Paper 320, pp. 9-213.

Meyer, C. and Hemley, J.J., 1967, Wall rock alteration, in Barnes, H.L., Geochemistry and Hydrothermal Ore Deposits: New York, Holt, Rinehart, and Winston, Inc., pp. 167-235.

Nash, J.T., 1972, Fluid inclusion studies of some gold deposits in Nevada: U.S. Geol. Survey Prof. Paper 800-C, pp. 15-19.

Nolan, T.B., 1935, Underground Geology of the Tonopah Mining District, Nevada: Univeristy of Nevada Bull., Vol. XXIX, No. 5, 49 pp.

Nordlie, B.E., 1971, The composition of the magmatic gas at Kilauea and its behavior in the near surface environment: Am. Jour. Sci., vol. 271, pp. 417-463.

O'Neil, J.R. and Silberman, M.L., 1974, Stable isotope relations in epithermal Au-Ag deposits: Econ. Geology, vol. 69, pp. 902-909.

O'Neil, J.R., Silberman, M.L., Fabbi, B.P., and Chesterman, C.W., 1973, Isotope and chemical relations during mineralization in the Bodie Mining District, Mono County, California: Econ. Geology, vol. 68, pp. 765-784.

Orville, P.M., 1963, Alkali ion exchange between vapor and feldspar phases: Am. Jour. Sci., vol. 261, pp. 201-237.

Papke, K.G., 1952, Geology and Ore Deposits of the Eastern Portion of the Hilltop Mine Area, Cochise County, Arizona: The University of Arizona, unpublished M.S. thesis, 99 pp.

Parsons, W.H., 1969, Criteria for the Recongnition of Volcanic Breccias: Review: Geol. Soc. American Memoir 115, pp. 263-304.

Perry, D.V., 1964, Genesis of the Contact Rocks at the Abril Mine, Cochise County, Arizona: The University of Arizona, unpublished M.S. thesis, 97 pp.

Pine, G.S., 1963, Sedimentation Studies in the Vicinity of the Willcox Playa, Cochise County, Arizona: The University of Arizona, unpublished M.S. thesis, 38 pp.

Pipkin, B.W., 1964, Clay Mineralogy of the Willcox Playa and Its Drainage Basin, Cochise County, Arizona: The University of Arizona, unpublished Ph.D. thesis, 160 pp.

Platoro Mines, Inc., 1975, Company Report: Tucson, Arizona.

Radke, A.S., Taylor, C.M., and Hewett, D.F., 1967, Aurorite, argentian todorokite, hydrous silver-bearing lead manganese oxide: Econ. Geology, vol. 62, pp. 186-206.

Ransome, F.L., 1904, Geology and Ore Deposits of the Bisbee Quadrangle, Arizona: U.S. Geol. Survey Prof. Paper 21, 167 pp.

Rayamakashay, B.C., 1968, A geochemical study of rock alteration by hot springs in the Paint Pot Hill area, Yellowstone Park: Geochim. et. Cosmochim. Acta, vol. 32 pp. 499-522.

Raydon, G.T., 1952, Geology of the Northeastern Chiricahua Mountains, Arizona: University of California, unpublished M.A. thesis.

Robinson, R.C., 1965, Sedimentology of Beach Ridge and Near Shore Deposits, Pluvial Lake Cochise, Southeastern Arizona: The University of Arizona, unpublished M.S. thesis, 111 pp.

Rogers, T.H., 1957, Stratigraphy and Structure of the Southern Swisshelm Mountains, Cochise County, Arizona: Univeristy of California at Berkeley, unpublished M.A. thesis.

Ross, C.S. and Smith, R.L., 1960, Ash-Flow Tuffs: Their Origin, Geologic Relations, and Identification: U.S. Geol. Survey Prof. Paper 366, 81 pp.

Sabins, F.F., Jr., 1955, Tectonic history of part of the Dos Cabezas and Chiricahua Mountains, Arizona (abs): Geol. Soc. America Bull., vol. 66, p. 1610.

_____, 1957a, Stratigraphic relations in the Chiricahua and Dos Cabezas Mountains, Arizona: Am. Assoc. Petroleum Geologists Bull., vol. 41, pp. 466-510.

_____, 1957b, Geology of the Cochise Head and western part of the Vanar Quadrangles, Arizona: Geol. Soc. America Bull., vol. 68, pp. 1315-1342.

Schmitt, H.A., 1950a, The fumarolic-hot spring and "epithermal" mineral deposit environment: Colorado School of Mines Quarterly, vol. 45, pp. 209-229.

_____, 1950b, Origin of the "epithermal" mineral deposits: Econ. Geology, vol. 45, pp. 191-229.

Schoen, R. and White, D.E., 1965, Hydrothermal alteration in GS-3 and GS-4 drill holes, main terrace, Steamboat Springs, Nevada: Econ. Geology, vol. 60, pp. 1411-1421.

Scott, W.A., 1916, Commonwealth mine and mill at Pearce, Arizona: Mining Eng. World, vol. 45, pp. 187-188.

Sheppard, R.A. and Gude, A.J. 3d, 1973, Zeolites and Associated Authigenic Silicate Minerals in Tuffaceous Rocks of the Big Sandy Formation, Mohave County, Arizona: U.S. Geol. Survey Prof. Paper 830, 36 pp.

Sheppard, S.M.F., Nielsen, R.S., and Taylor, H.P., Jr., 1969, Oxygen and hydrogen isotope ratios of clay minerals from porphyry copper deposits: Econ. Geology, vol. 64, pp. 755-775.

_____, 1971, Hydrogen and oxygen isotope ratios in minerals from porphyry copper deposits: Econ. Geology, vol. 66, pp. 515-542.

Shields, J.C., Jr., 1940, Geology and Ore Deposits of the Dives and Gold Ridge Groups, Dos Cabezas, Arizona: The University of Arizona, unpublished M.S. thesis, 67 pp.

Sigvaldson, G.E. and White, D.E., 1961, Hydrothermal Alteration of Rocks in Two Drill Holes at Steamboat Springs, Washoe County, Nevada: U.S. Geol. Survey Prof. Paper 424-D, pp. 116-122.

_____, 1962, Hydrothermal Alteration in Drill Holes GS-5 and GS-7, Steamboat Springs, Nevada: U.S. Geol. Survey Prof. Paper 450-D, pp. 113-117.

Simons, F.S., 1962, Devitrification dikes and giant spherulites from Klondyke, Arizona: Am. Mineralogist, vol. 47, pp. 871-885.

Smith, L.A., 1927, The Geology of the Commonwealth Mine: The University of Arizona, unpublished M.S. thesis, 73 pp.

Smith, R.L., 1960a, Zones and Zonal Variations in Welded Ash Flows: U.S. Geol. Survey Prof. Paper 354-F, pp. 149-159.

_____, 1960b, Ash flows: Geol. Soc. America Bull., vol. 71, pp. 795-842.

Steiner, A., 1953, Hydrothermal rock alteration at Wairakei, New Zealand: Econ. Geology, vol. 48, pp. 1-13.

_____, 1963, The rocks penetrated by drill holes in the Waiotapu thermal area, and their hydrothermal alteration, in Waiotapu Geothermal Field: New Zealand Dept. of Science and Industrial Research Bull. 155, pp. 26-34.

Stewart, J.H., 1971, Basin and Range Structure: A system of horsts and grabens produced by deep-seated extension: Geol. Soc. America Bull., vol. 82, pp. 1019-1044.

Taylor, H.P., Jr., 1967, Oxygen isotope studies of hydrothermal mineral deposits, in Barnes, H.L., Geochemistry of Hydrothermal Ore Deposits: New York, Holt, Rinehart, and Winston, Inc., pp. 112-142.

_____, 1973, O^{18}/O^{16} Evidence for meteoric-hydrothermal alteration and ore deposition in the Tonopah, Comstock Lode, and Goldfield Districts, Nevada: Econ. Geology, vol. 68, pp. 747-764.

Thompson, G.A., 1956, Geology of the Virginia City Quadrangle, Nevada: U.S. Geol. Survey Bull. 1042-C, pp. 45-77.

Walker, G.P., 1971, Grain size characteristics of pyroclastic deposits: Jour. Geology, vol. 79, pp. 696-714.

Weissberg, B.G., 1969, Gold-silver ore-grade precipitates from New Zealand thermal waters: Econ. Geology, vol. 64, pp. 95-108.

White, D.E., 1955, Thermal springs and epithermal ore deposits, in Bateman, A.M., ed.: Econ. Geology 50th Anniversary Volume, pp. 99-154.

White, D.E., Craig, H., and Begemann, F., 1963, Summary of the geology and isotope geochemistry of Steamboat Springs, Nevada, in Tongiori, E., Nuclear Geology of Geothermal Areas: Spoleto, Consiglio Nazionale Delle Richerche, 254 pp.

White, D.E., Muffler, L.J.P., and Truesdell, A.H., 1971, Vapor dominated hydrothermal systems compared with hot water systems: Econ. Geology, vol. 66, pp. 75-97.

White, D.E., and Roberson, C.E., 1962, Sulfur Bank, California, a major hot-spring quicksilver deposit, in Engle, A.J.E., James, H.L., and Leonard, B.F., Petrological Studies: A Volume in Honor of A.F. Buddington: Geol. Soc. America, pp. 397-428.

White, D.E., Thompson, G.A., and Sandberg, C.H., 1964, Rocks, Structure, and Geologic History of Steamboat Springs Thermal Area, Washoe County, Nevada: U.S. Geol. Survey Prof. Paper 458-B, 63 pp.

Williams, H., Turner, F.J., and Gilbert, C.M., 1954, Petrography, An Introduction to the Study of Rocks in Thin Section: San Francisco, S.H. Freeman and Company, 406 pp.

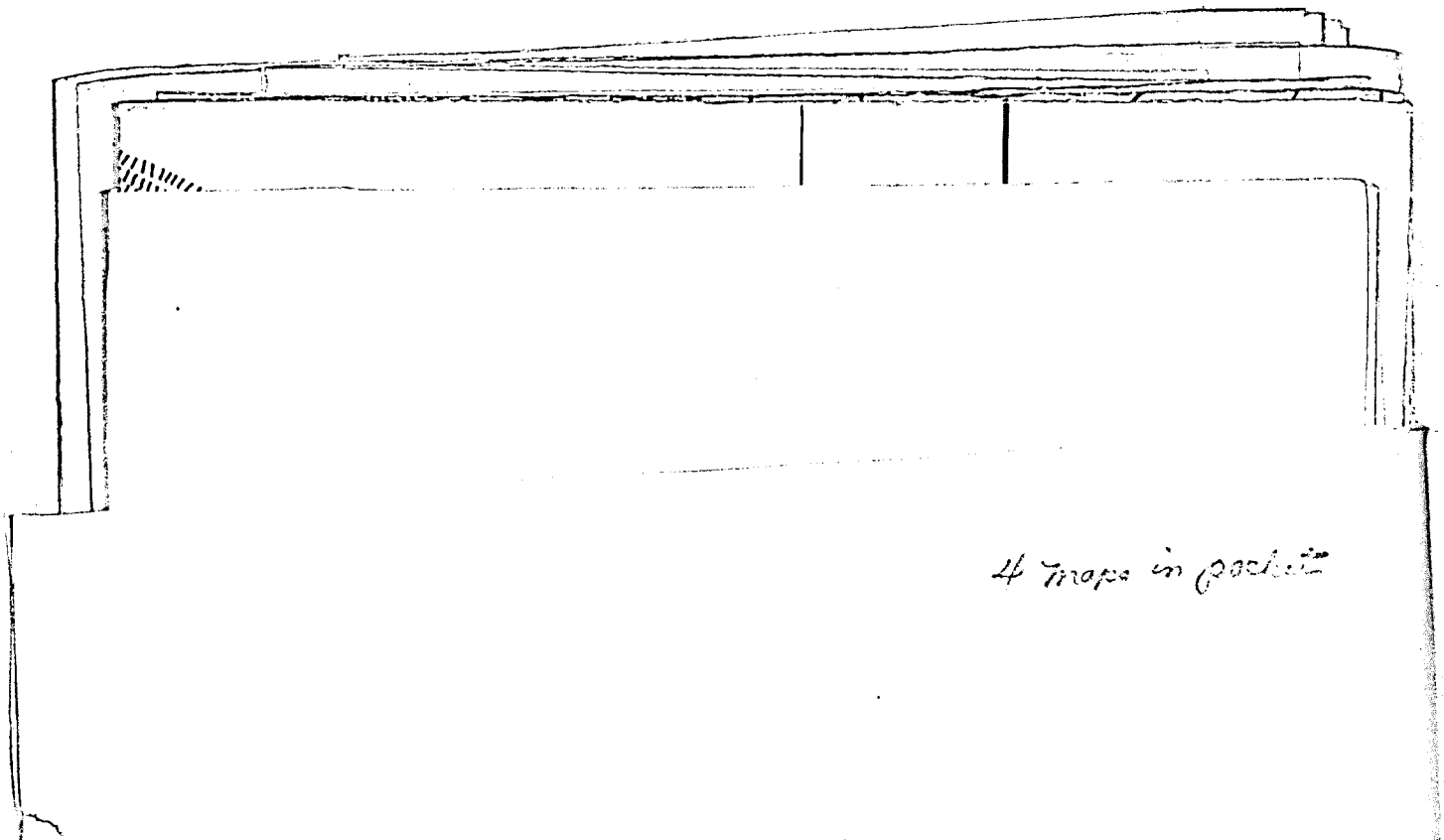
Williams, P.L., 1960, A stained slice method for rapid determination of phenocryst composition of volcanic rocks: Am. Jour. Sci., vol. 258, pp. 148-152.

Wilson, E.D., Director, 1969, Gold Placers and Placering in Arizona: Arizona Bureau of Mines Bull. 168, 176 pp.

Wilson, E.D., Moore, R.T., and Cooper, J.R., 1969, Geologic Map of Arizona: Arizona Bureau of Mines and U.S. Geol. Survey.

Wisser, E., 1960, Relation of Ore Deposition to Doming in the North American Cordillera: Geol. Soc. America Memoir 77, 117 pp.

Wright, T.L., 1968, X-ray and optical study of alkali feldspar: II an X-ray method for determining the composition and structural state from measurement of 20 values for three reflections: Am. Mineralogist, vol. 51, pp. 825-854.



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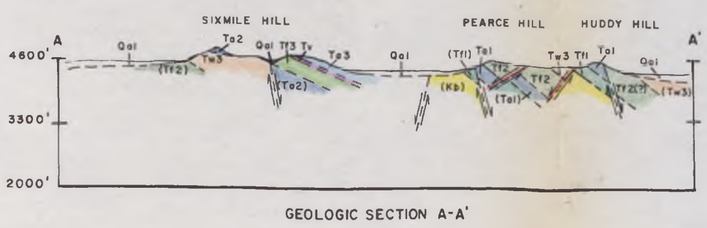


GEOLOGIC SECTION A-A'

EXPLANATION

QUATERNARY

POST-LOWER CRETACEOUS

LOWER CRETACEOUS

Qal	Alluvium
Ta3	Third ash flow
Tv	Vitrophyre zone
Tf3	Third flow
Ta2	Second ash flow
Tw3	Third water-lain tuff
Tf2	Second flow
Tal	First ash flow
Tf1	First flow
Kb	Bisbee formation

Strike and dip of contact

Strike and dip of bedding

Strike and dip of fault
dashed where approximate
dotted where inferred

Strike and dip of vein
dashed where approximate
dotted where inferred

Strike and dip of flow structure
or compaction foliation

Scale = 1: 31,250

0 .5 1 1.5 MILES

0 1 2 KILOMETERS

CONTOUR INTERVAL 40'

13°
TRUE NORTH
MAGNETIC NORTH

APPROXIMATE MEAN DECLINATION, 1958

GEOLOGY BY KIM K. HOWELL, 1974

TOPOGRAPHY ENLARGED FROM U.S.G.S. PEARCE, AZ., 30' QUADRANGLE

FIGURE 1: GEOLOGIC MAP AND SECTION OF THE PEARCE AREA, COCHISE COUNTY, ARIZONA

Howell, 1977 Geosciences Thesis

TOPOGRAPHIC BASE AFTER SMITH, 1927

GEOLOGY BY K.K. HOWELL, 1973-4

CONTOUR INTERVAL 50 FEET

SCALE 1:1920

0 80 160 240 320 400 480 FEET

0 50 100 200 300 METERS

TRUE NORTH

13°

MAGNETIC NORTH

APPROXIMATE MEAN DECLINATION, 1958

EXPLANATION

ROCK UNITS

QUATERNARY

- Qal — ALLUVIUM

POST-LOWER CRETACEOUS

- Tw3 — THIRD WATER-LAIN TUFF
- Tf2 — SECOND FLOW
- Tw2 — SECOND WATER-LAIN TUFF
- Tal — FIRST ASH FLOW
- Tw1 — FIRST WATER-LAIN TUFF
- Tf1 — FIRST FLOW

LOWER CRETACEOUS

- Kb — BISBEE FORMATION

SYMBOLS

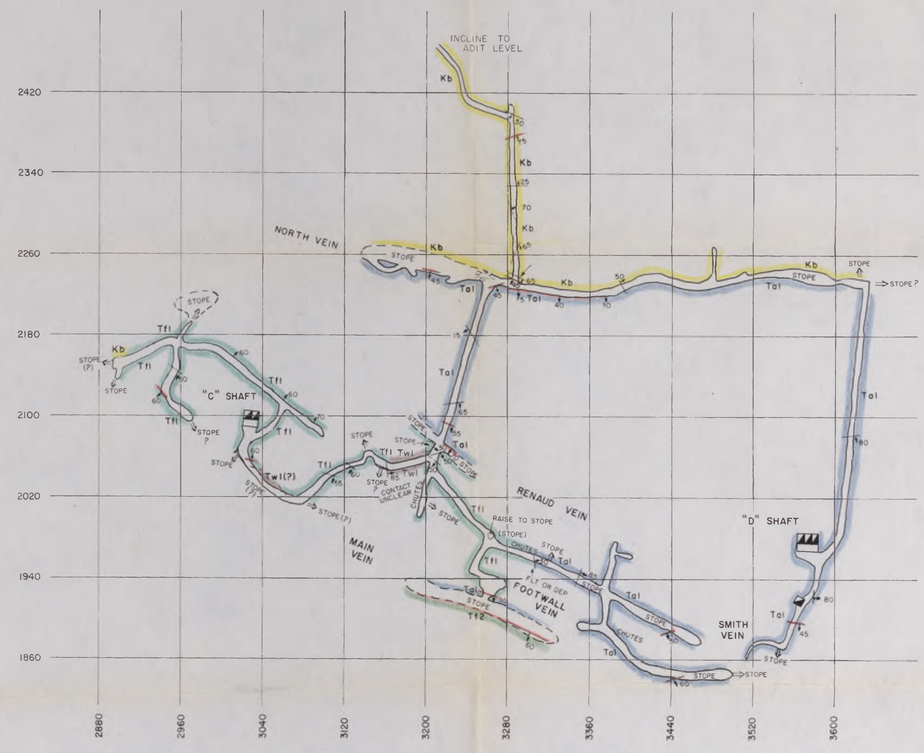
- STRIKE AND DIP OF CONTACT DASHED WHERE APPROXIMATE
- STRIKE AND DIP OF BEDDING
- STRIKE AND DIP OF FAULT DASHED WHERE APPROXIMATE DOTTED WHERE INFERRED
- STRIKE AND DIP OF VEIN DASHED WHERE APPROXIMATE
- SHEETED ZONE
- STRIKE AND DIP OF FLOW STRUCTURE OR COMPACTION FOLIATION
- ZONE OF FLOW BRECCIA
- SHAFT
- ADIT
- EDGE OF CAVED AREA
- PROSPECT PIT
- DUMP
- TAILINGS
- APPROXIMATE LOCATION OF STOPE
- 2400 3300 — POINT ON MINE COORDINATE SYSTEM
- (16) — SAMPLE LOCATION, NUMBER

FIGURE 2

GEOLOGIC MAP OF THE SURFACE NEAR THE

COMMONWEALTH MINE

COCHISE COUNTY, ARIZONA

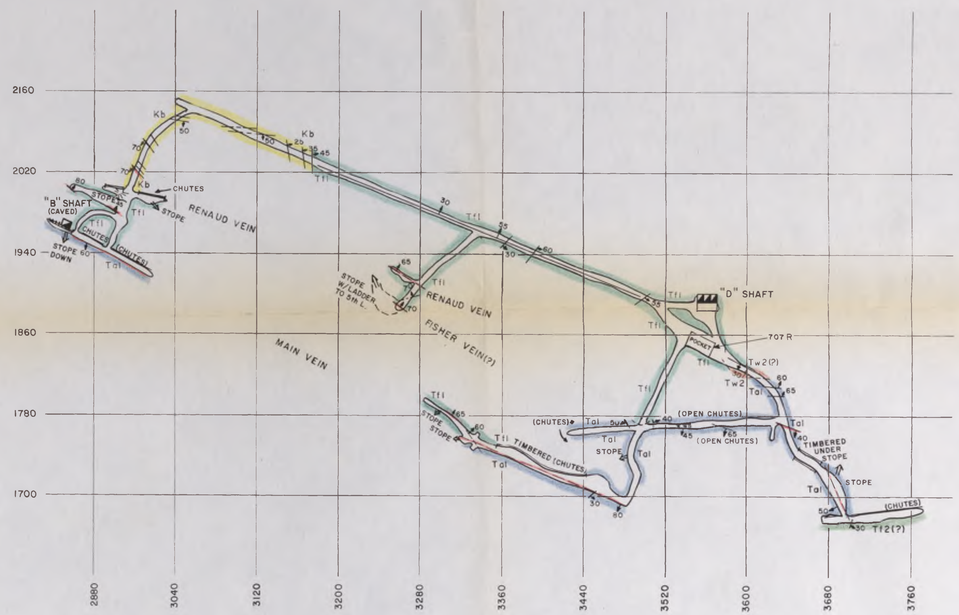


GEOLOGIC MAP OF THE 3rd LEVEL

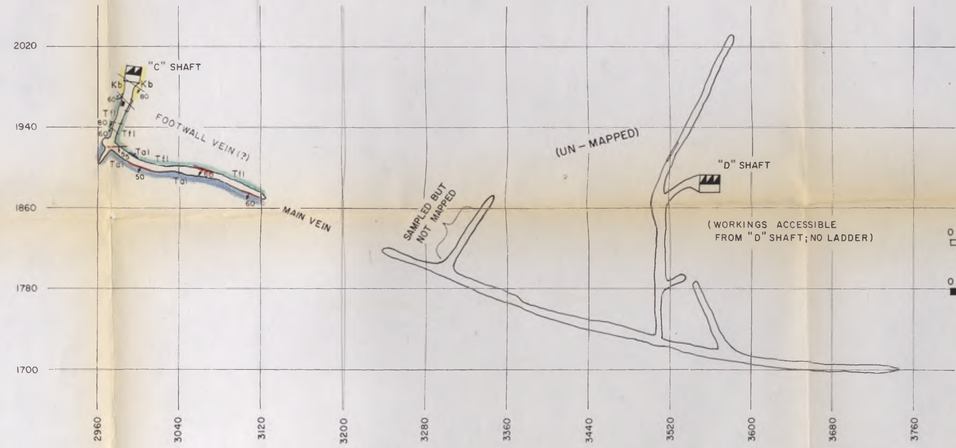
GEOLOGIC MAP OF THE 5th LEVEL

EXPLANATION

- Tf2 — SECOND FLOW
- Tw2 — SECOND WATER-LAIN TUFF
- Tal — FIRST ASH FLOW
- Tw1 — FIRST WATER-LAIN TUFF
- Tfl — FIRST FLOW
- Kb — BISBEE FORMATION
- STRIKE AND DIP OF FAULT
- STRIKE AND DIP OF VEIN
- FRACTURE
- SHEETED ZONE
- SHAFT
- APPROXIMATE LOCATION OF STOPE



GEOLOGIC MAP OF THE 6th LEVEL



GEOLOGIC MAP OF THE 7th LEVEL

APPROXIMATE MEAN DECLINATION, 1958

GRID APPROXIMATE AFTER SMITH (1927)

SCALE 1: 960

0 80 160 240 320 FEET

0 50 100 METERS

WORKINGS ON 3rd, 5th, & 7th LEVELS AFTER SMITH (1927); 6th LEVEL MAPPED WITH TAPE & COMPASS

GEOLOGY BY K.K. HOWELL 1973-74

FIGURE 3
GEOLOGIC MAPS OF THE UNDERGROUND WORKINGS COMMONWEALTH MINE

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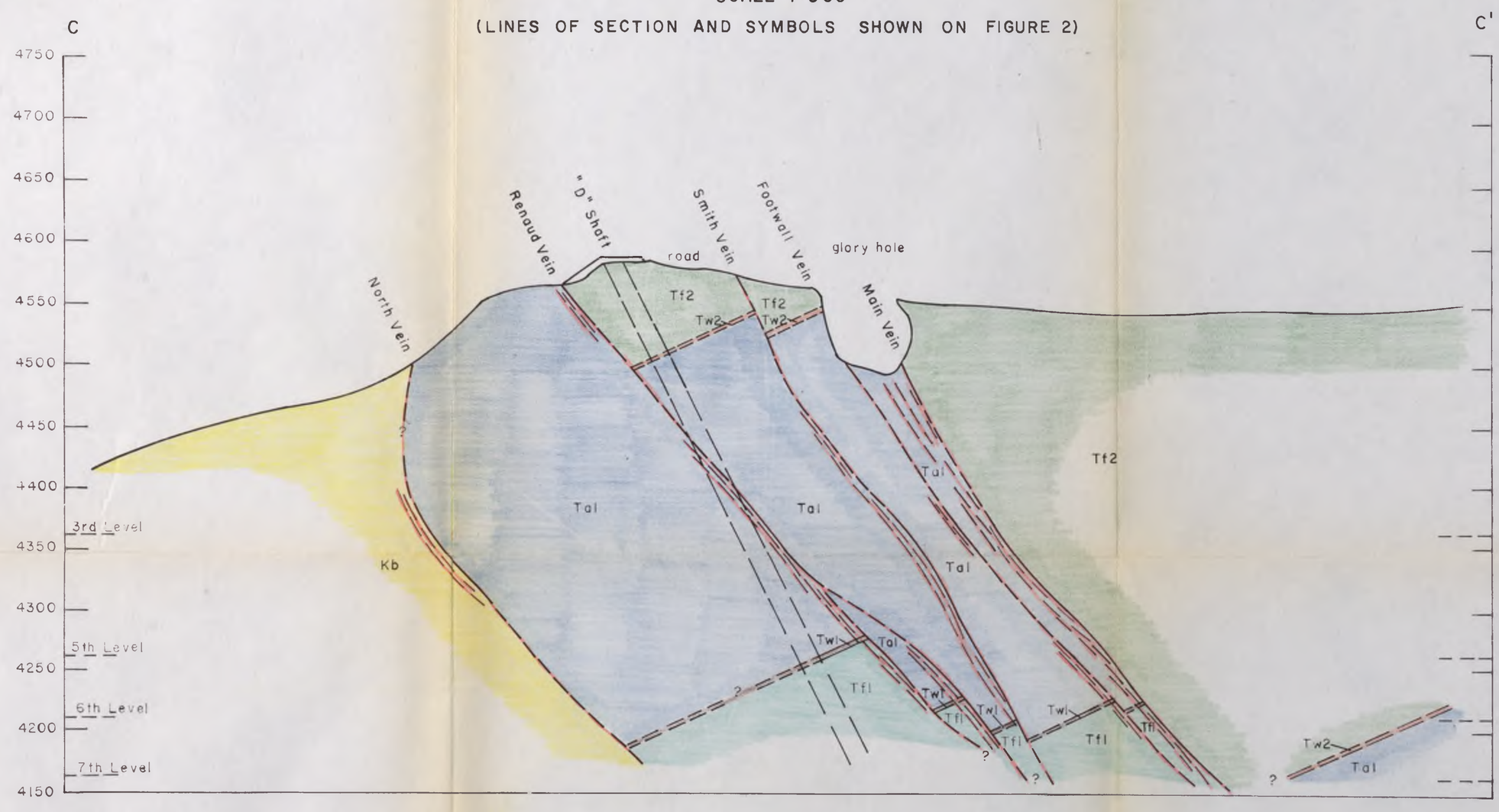
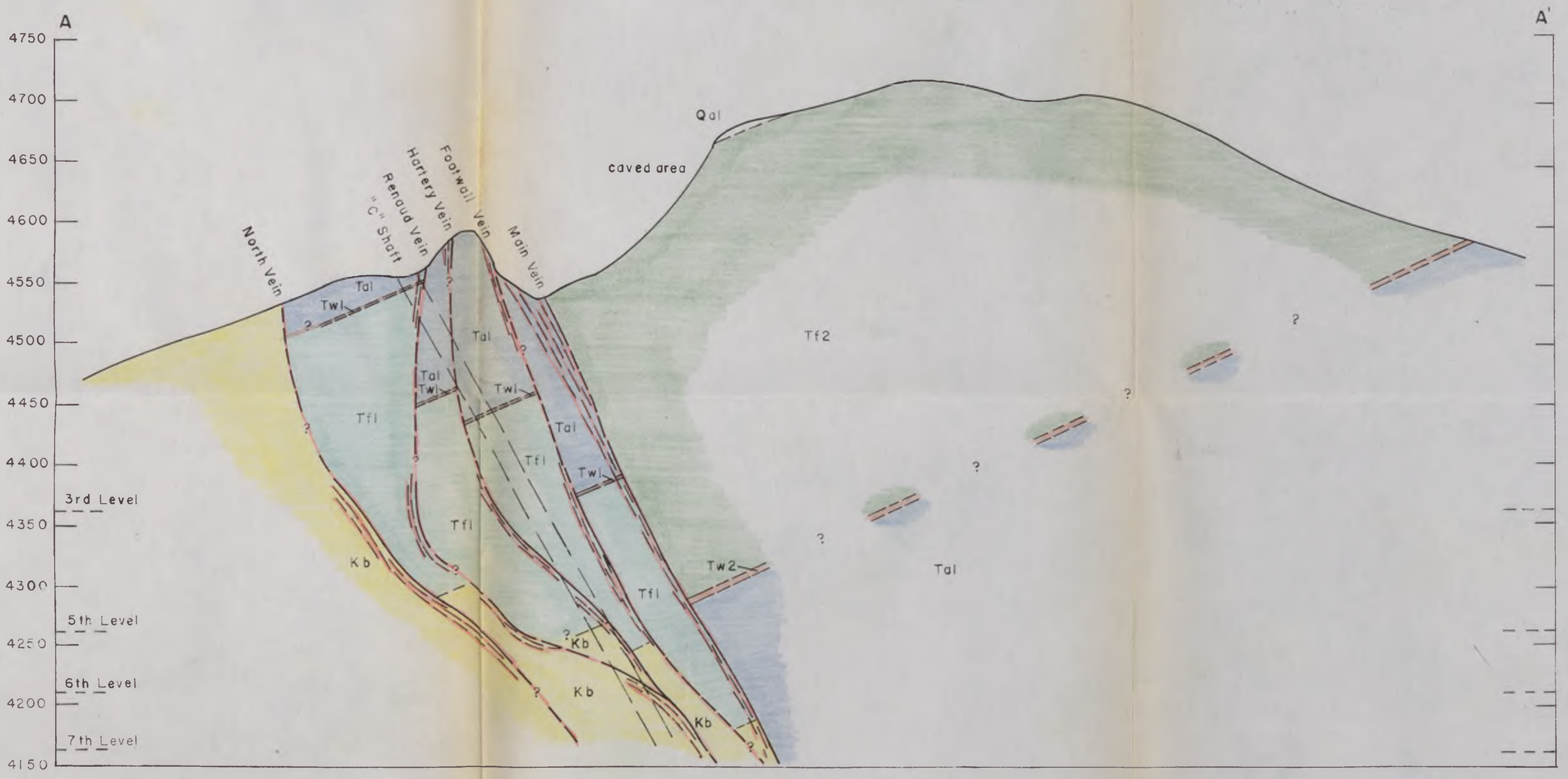
FIGURE 4

GEOLOGIC CROSS SECTIONS OF THE COMMONWEALTH MINE

SCALE 1·960

(LINES OF SECTION AND SYMBOLS SHOWN ON FIGURE 2)





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