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HYDROTHERMAL ALTERATION OF ASH-FLOW TUFFS IN THE INDIAN PEAK DISTRICT OF SOUTHWESTERN UTAH

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BY

MICHAEL ALLAN TOLLEY, 1947-

A THESIS

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Approved by

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ABSTRACT

Careful petrographic study of the ash-flow tuffs in the Indian Peak District of southwestern Utah reveals hydrothermal alteration around the fluorite veins. The alteration minerals themselves and the intensity of alteration vary with distance from the veins.

Primary plagioclase has altered to secondary feldspar, calcite, sericite, and traces of epidote and zoisite. Hornblende and biotite have altered to chlorite, calcite, and secondary iron oxide, and traces of epidote and zoisite. Diopside has changed to calcite and secondary iron oxide.

An overall picture of the mining district shows that certain minerals increase and others decrease as one nears the veins. Hydrothermal quartz veins and veinlets increase in concentration toward the veins. Epidote and zoisite appear only in trace and small amounts and have no particular trend of concentration. Sericite generally increases toward the vein, but decreases immediately adjacent to it. Secondary feldspar varies very little until immediately near the veins, it decreases, as sericite does. Chlorite generally increases away from the vein. Secondary iron oxide occurs only in small amounts and seems to have no particular general trend. Calcite appears to increase away from the vein. Hydromuscovite appears only near the veins. The primary mineral content decreases toward the veins.

ACKNOWLEDGEMENT

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NOMENCLATURE

Since some of the terms used in this thesis may have varied definitions, the writer felt that it was wise to define several terms referred to in the text.

An ash-flow is defined as both the flow itself and the deposit resulting from the passage of a nuée ardente. Ignimbrite is a synonymous term. Translated literally an ignimbrite is a "fire cloud rock".

A lava flow is a stream or viscous or solidified fragmented lava which issues from a volcanic cone or from a fissure with little or no explosive action. A lava flow is also considered to be the solidified rock formed when the lava stream congeals. Mackin (1960) suggests that there are ash-flows, lava flows, and flows with certain characteristics of each.

A nuée ardente is a hot, rapidly expanding, turbulent, highly mobile gas flow, which erupting from a volcano or a fissure carries with it intratelluric crystals and liquid droplets from the exploding magma as well as rock fragments torn from the vent or swept up from the ground surface. Also, in discussion of the factors that give nuée ardentes the properties of flowing, Anderson and Flett (1903) say:

> As this turbulent mixture of expanding gases and fine dust pours down the surface of the mountain, the small solid grains are unable at first to rest on the ground, even when they may have sunk to the base of the cloud, and they are swept up again and borne along till they reach some sheltered hollow or the violence or the expansive force lessens and the turmoil diminishes.

A tuff is an indurated pyroclastic rock made up of particles less than four millimeters in diameter. Thus, it is indurated volcanic dust or ash. If the majority of the pyroclastic particles in the rock are less than four millimeters in diameter, the rock is considered to be a tuff.

An ash-flow is now an inclusive term for consolidated ash-flow beds and rocks that may or may not be completely or partly welded (Ross and Smith, 1961).

Welding is a process which promotes the union and cohesion of glassy fragments and in the process promotes the deformation of pumiceous fragments and shards (Smith, 1961).

A welded tuff is a rock type which has been indurated by the combined action of the heat retained by the particles and the enveloping hot gases. Oftentimes, the result is welded shards of glass and pumice.

Sillar is the unwelded part of a rock of nuée ardente origin.

Devitrification is the process by which glassy rocks crystallize into definite minerals; the minerals are usually minute crystals of quartz and feldspar. This process occurs after solidification and is the most common crystallization process in welded ash-flows (Smith, 1961).

I. INTRODUCTION

A. Purpose and Scope

The purpose of the research leading to this thesis was to examine the petrography of samples collected and to search for evidence of possible hydrothermal alteration. There have been articles written on hydrothermal alteration of surrounding areas, but to the writer's knowledge, nothing has appeared in print concerning hydrothermal alteration in this chosen area of study. The study of the hydrothermal alteration of this area was chosen with this lack of previous work in mind.

One hundred sixty-seven samples were collected for the purpose of studying their possible hydrothermal alteration. One hundred twenty selected thin sections were prepared with the same purpose in mind. X-ray diffraction was used to help identify the clay minerals found. Variations of concentrations of hydrothermal alteration minerals with distance from the fluorite veins was of particular interest.

B. Location

The area of study in this thesis is southwestern Utah. More specifically, the area includes parts of southwestern Beaver County and northwestern Iron County. From Cedar City, Utah, the area is west on Highway 19 to Lund, Utah. A dirt road leads northwest from Lund to the area shown in Figure 1. Samples were collected from the following fluorite mines which appear on the map in Figure 1: Cougar Spar Mine, Holt-Bluebell Mine, New Arrowhead Mine, Utah #1 Mine, and J.B. #1 Mine.

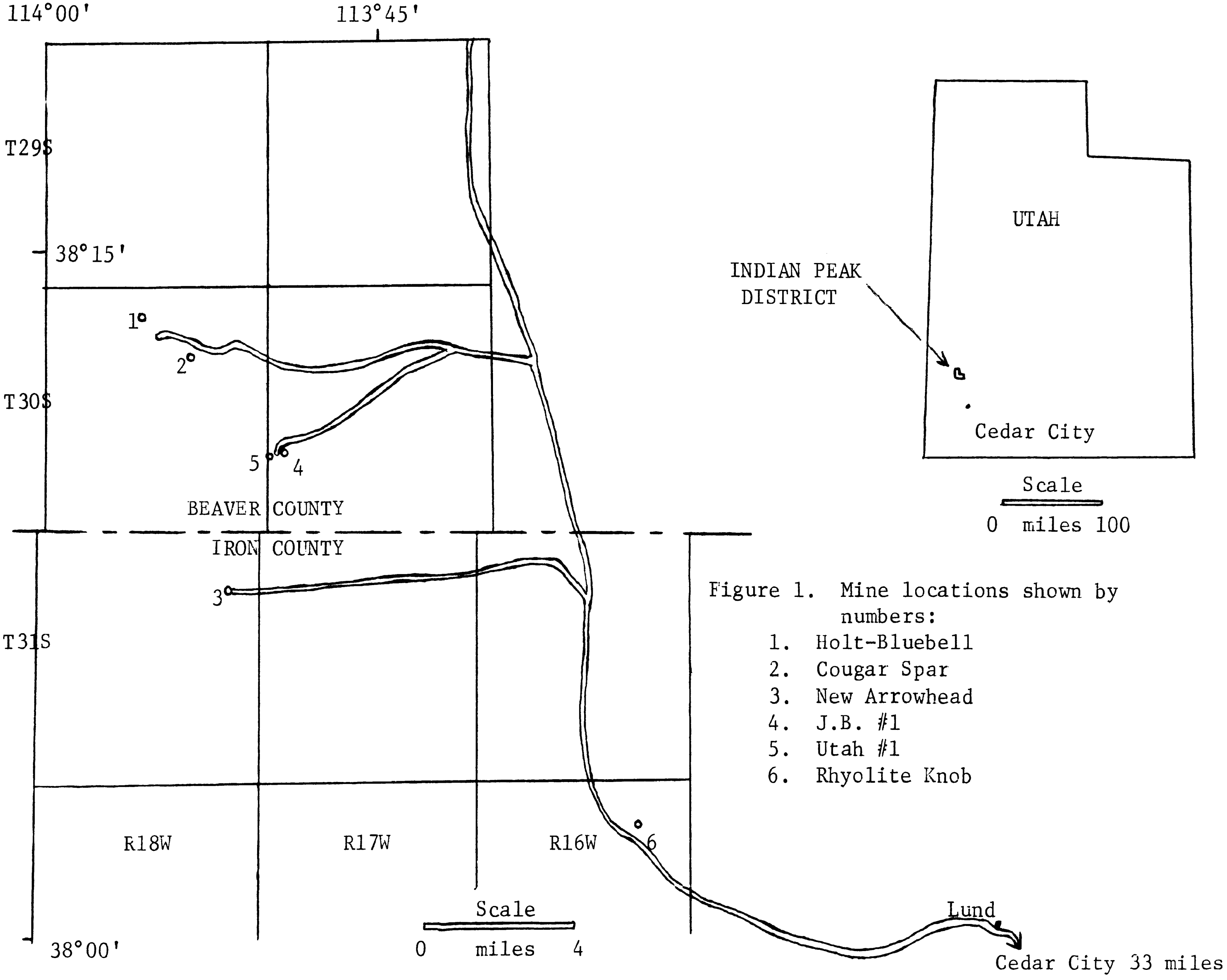

Figure 1. Mine locations shown by numbers:

1. Holt-Bluebell
2. Cougar Spar
3. New Arrowhead
4. J.B. #1
5. Utah #1
6. Rhyolite Knob

II. PREVIOUS WORK

A. Introduction

Even though hydrothermal alteration is a relatively new field of study, there has been a great deal of previous work done in this general field. Many specific localities have been discussed in the literature. Many generalities have also been expressed. The writer will first consider the generalities of hydrothermal alteration and then go into the specific area of interest to this thesis. There has been very little specific information obtained on hydrothermal alteration of the thesis area, but what has been previously discussed will be reviewed here.

B. General

The changes due to hydrothermal solutions are discussed by Park and MacDiarmid (1964) and Scott (1966). Hydrothermal activity can change the composition of the wall rock by introduction, rearrangement, recrystallization, and removal of ions. McKinstry (1955) states that the hot ascending waters are of uncertain origin, but are charged with igneous emanations. Grim (1968) suggests that hydrothermal solutions usually are acidic and oftentimes carry chlorine, sulphur, carbon dioxide, and/or silica.

The alteration products are considered, by Park and MacDiarmid (1964), to be as much due to the mineralizing processes as is the ore itself. They go on to say that the nature of the alteration products usually depends upon the character of the original wall rock, the character of the invading fluid, and the temperature and pressure at which the reaction takes place. It should be noted, however, that there are cases cited where the nature of the original wall rock was not a criteria for determining the alteration products. Sometimes with the same fluids and the same original wall rock, different alteration products are formed. Conversely, sometimes with different hydrothermal fluids and different original rocks, the same alteration products are produced. It can, thus, be seen that the criteria upon which the nature of the alteration products depend, are oftentimes complex. Therefore, each mining district should be treated as a separate case.

Park and MacDiarmid (1964) state that the physical products of wall rock alteration include changes in permeability, color, porosity, and recrystallization. Bleaching, darkening, and aureoles of different colors are examples of changes in color. The porosity usually increases because of recrystallization to a coarser grain size. Also the hardness of the wall rock is, oftentimes, lessened by hydrothermal alteration.

They continue on to state that different kinds of ore deposits are typified by certain alteration minerals and different degrees of alteration. Because of their depth of burial, wall rock around deep-seated ores is relatively impermeable and usually about as hot as are the ore-bearing fluids. Therefore, the alteration zone is likely to be thin and inconspicuous. Conversely, hot solutions that invade cool, shallow, permeable rocks typically produce prominent, widespread, alteration halos because the country rock is far out of equilibrium with the hydrothermal fluids.

In many hydrothermal clay bodies, a zonal arrangement of clay minerals is observed. Schwartz (1955) and Meyer and Hemley (1967) discuss this aspect. Oftentimes, there is an inner (veinward) zone termed the advanced argillic zone, then a sericitic zone, then an intermediate argillic zone, then a propylitic zone. Some also place a potassium silicate zone at different places within this zonation.

Grim (1968) expresses that there are two differing concepts that have been suggested to explain the zonation. One is that the alteration is essentially contemporaneous with the deposition of the ore and that different mineralogical zones in the surrounding rocks may be regarded as reaction rims, representing diminishing activity of the solutions depositing the ore minerals. The second concept states that the rock alterations are zones of different ages. They seem to have developed in stages by differing solutions appearing at different periods separated by intervals of relative inactivity. Oftentimes, according to this second concept, there is early development of chlorite furthest from the ore, later development of kaolinite, halloysite, and smectite, and still later development of sericite nearest the ore.

Grim (1968) feels that both concepts are applicable to particular deposits.

The reactive capacities of hydrothermal solutions can be defined in terms of the activity of the hydrogen ion; the more acidic the solution, the higher its reactive capacity. Helgeson (1970) discusses reaction rates in hydrothermal solutions. He suggests that acidic hydrothermal solutions may travel long distances at high temperatures through granitic rocks without losing their reactive capacities if the fractures through which they flow have widths greater than one millimeter. He also concludes that if an acidic hydrothermal solution were flowing through an open fracture in reactive rock and encountered a zone in which the surface area was much higher than that in the open fracture, the solution should react rapidly with its environment, which may cause intense alteration of wall rock and the deposition of ore minerals.

Helgeson's calculations suggest that the minimum required time for isothermal deposition of major ore deposits is of the order of a thousand to ten thousand years, depending upon the temperature and geometry of the veins. Therefore, as Helgeson suggests, one can see that hydrothermal reactions with the environment are "instantaneous" in the context of geologic time.

C. Classification

There are different forms of the classification of hydrothermal alteration minerals, but the following is considered by the writer to be one of the best. Meyer and Hemley (1967) also prefer this classification and parts of it have survived the years. It is based upon mineral assemblages in the major types of wall rock alteration. The minerals named on each diagram are the common phases of each type of alteration. All five different assemblages and their subgroups will be discussed. Reference to Figure 2 will be helpful.

1. Advanced Argillic Alteration Assemblages

Advanced argillic assemblages are characterized by dickite, kaolinite, pyrophyllite, usually with sericite, quartz, and frequently with alunite, pyrite, tourmaline, topaz, beidellite, zunyite and amorphous clays (See Figure 2). This type of alteration is found as an inner or veinward zone adjoining the vein, pipe, or ore-bearing zone.

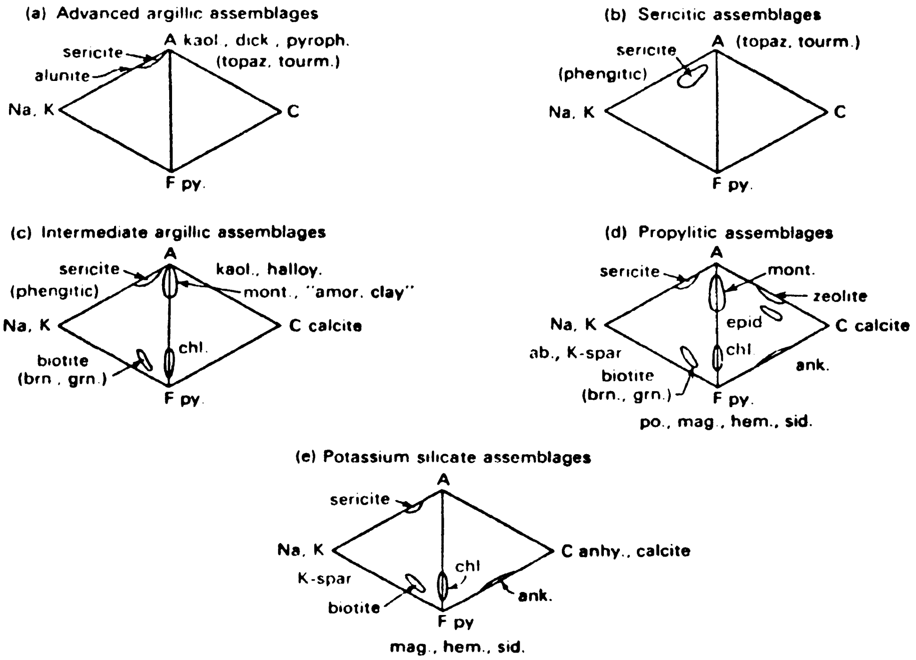

Figure 2. Mineral assemblages in major types of wall rock alteration (silica activity not necessarily controlled by quartz). The minerals named on each diagram are the common phases of each type of alteration. Except for the zeolites, and to a lesser extent kaolinite, these have wide pressure-temperature ranges of formation. High temperature equivalents of the aluminous argillic assemblages would be andalusite-bearing assemblages. kaol.=kaolinite; dick.=dickite; halloy.=halloysite; pyroph.=pyrophyllite; tourm.=tourmaline; chl.=chlorite; mont.=montmorillonite; K-spar.=K-feldspar; ab.=albite; epid.=epidote; ank.=ankerite; py.=pyrite; po.=pyrrhotite; mag.=magnetite; hem.=hematite; sid.=siderite.
(Meyer and Hemley, 1967)

2. Sericitic Alteration Assemblages

Sericite, quartz, and pyrite are the prominent phases in sericitic alteration (See Figure 2). Topaz and tourmaline may also be present. With inclusions of potassium feldspar and/or biotite, sericitic alteration grades into the potassium silicate assemblage. It also shows gradations to advanced and intermediate types of argillization.

Sericitic alteration is probably the most abundant, significant, and widespread of all alteration assemblages. Spatially, sericitization is probably the alteration type most closely associated with sulphide ore.

The name "sericite" began as a field term to designate a fine-grained white mica associated with ore deposits. As such, it has survived many attempts to redefine it and abandon it. It is believed that it still has merit as a general designation, as the word did when it was coined.

Two explanations for the prevalence of sericite as an abundant hydrothermal product are that the potassium silicates are relatively stable under hydrothermal conditions and there is quite a high tendency for hydrothermal solutions to carry potassium ions.

3. Intermediate Argillic Alteration Assemblages

In intermediate argillic alteration kaolin and smectite minerals predominate principally as alteration products of intermediate and calcic plagioclases in intermediate igneous rocks. Amorphous clays are locally important. Potassium feldspar may be present and biotite may be partly recrystallized from chlorite. Sericite, calcite, and pyrite are usually important also (See Figure 2). Sulphides are generally not important.

Intermediate argillic alteration is developed chiefly in plagioclase-bearing rocks commonly grading zonally to propylitic alteration toward fresh rock and to sericitic alteration toward a vein. The intermediate argillic zone itself may be internally zoned, with smectite clays predominating near the outer fringe of alteration and kaolin minerals nearer the sericitic zone. Four kaolin minerals are common in intermediate argillic alteration: dickite, kaolinite, halloysite, and metahalloysite.

The loose bonding of cations, such as sodium and calcium, in the montmorillonites facilitates their possible removal during alteration. As leaching progresses, kaolin-type layers probably become interleaved between montmorillonite layers, but because of the poor ordering of both structures, this does not usually produce regular mixed-layer X-ray diffraction effects.

4. Propylitic Alteration Assemblages

Propylitic alteration assemblages include epidote (zoisite, clinozoisite), albite, K-feldspar, biotite, chlorite, septechlorite, and carbonates; commonly with sericite, pyrite, pyrrhotite, or iron oxides; and less commonly with zeolites or montmorillonites (See Figure 2). Such processes as hydrogen-, magnesium-, and sodium-metasomatism are oftentimes important in propylitic alteration.

In deposits where hydrothermal alteration is zoned, the propylitic alteration is usually a fringe effect grading into fresh rock.

Propylitization is a term that is best reserved for the weak metasomatic alteration that generally has little or no addition of base cations because there is little hydrolysis. The predominant changes in propylitic alteration are the addition of water, chlorine, carbon dioxide in the form of carbonates, and base exchange reactions. Since propylitic alteration is concerned with only weak alteration, strong alteration, such as chloritization, albitization, carbonatization, and zeolitization are, therefore, described separately. They are considered to be subtypes of propylitic alteration, even though the mineral assemblages of all of them may be essentially intergradational with the propylitic assemblage.

a. Albitization

Albitization has been mentioned as an important phase in propylitic alteration resulting from the concentration of sodium liberated by the breakdown of more calcic plagioclases. As a separate type of alteration, albitization is reserved for those processes where sodium is introduced metasomatically. Soda mestasomatism locally becomes intense, with conversion of nearly all aluminous material to white, soda-rich plagioclase, locally associated with soda-rich amphiboles. The composition of the new plagioclase ranges from almost pure albite to sodic plagioclase. Associated minerals are generally those of the propylitic assemblages, especially epidote. Sulphides are generally not abundant in intensely albitized rock, but iron oxides commonly exist.

b. Chloritization

Chlorite has a wide range of composition, therefore, it does not seem unusual that it has a wide distribution of hydrothermal alteration of many types. Where chloritization is active, there have been large additions of magnesium and/or iron. Chlorite may be present alone, or be associated with quartz or sericite or tourmaline in a very simple assemblage. Also, usually it is associated with at least minor amounts of the other minerals of the propylitic assemblages, particularly albite, epidote, and the carbonates. Paragonite, chloritoid, talc, septechlorite, amphiboles, and anhydrite may also be present. Pyrite and pyrrhotite are both common sulphides associated with chloritization.

Actually, there are two somewhat distinctive occurrences of chlorite that are formed hydrothermally. One is a result of addition of large amounts of magnesium and iron. The other is a result of alteration of ferromagnesian minerals. The latter is concerned with propylitization. In a sense, chlorite is the counterpart of sericite as an alteration product of the ferromagnesian minerals rather than, as in sericite, an alteration product of feldspar. Thus, chlorite probably develops to more of an extent when ferromagnesian minerals are present in the original unaltered rock - such as in gabbros and basalts.

c. Zeolitization

Zeolites are quantitatively significant as alteration minerals in only a few ore deposits of the base metals, but they are relatively abundant in hot spring environments. Native copper, chalcocite, and bornite are associates, commonly with iron oxides insteady of pyrite. Other minerals of the propylitic assemblages are generally also present as well as prehnite and pumpellyite. The zeolites are chiefly those of intermediate and low silica content: laumontite, and natrolite, for example, associated with analcite, stilbite, and heulandite.

d. Carbonatization

Along with sericite and chlorite, the carbonates are among the most widespread of the alteration minerals. Magnesium, iron, calcium, and manganese are the chief metals fixed as carbonates in alteration assemblages. Dolomitization of limestone wall rock commonly involves magnesium metasomatism as a base-exchange process. It is commonly associated with weak propylitic alteration of nearby aluminous rocks. Conversely, carbonatization of silicate rocks may involve chiefly anionic metasomatism with the introduction of carbon dioxide rather than the introduction of bases.

5. Potassium Silicate Alteration Assemblages

Potassium feldspars and micas are the essential minerals of the potassium silicate type of alteration. Clay minerals are mostly absent, though a small amount of chlorite may be occasionally interleaved with the essential minerals. Biotite, magnetite or hematite; pyrite, chalcopyrite, molybdenite, siderite, ankerite, anhydrite, and calcite may also be present (See Figure 2).

6. Other Alteration Assemblages

According to some classifications, there are more types of hydrothermal alteration. For instance, when there is a great deal of silica added hydrothermally, some prefer to term it silicification rather than place it in one of the other previously discussed categories. Similarly if there is a great deal of alunite formed hydrothermally, some prefer to add another category called alunitization. The same argument may be given for feldspathization, tourmalinization, pyritization, and biotitization.

Silicification involves an increase in the proportion of quartz, jasperoid, chalcedony, and/or opaline silica in an altered rock. If the silica were added hydrothermally, it may result in the extreme case of being replacement vein material. Silicification is a type of alteration which is commonly most closely associated with sulphide deposition in sulphide ore deposits, and quartz is commonly the most abundant vein mineral. Silicification can result from activity of solutions over a wide range of chemical environments, for it may be associated with and grade into advanced argillic alteration, sericitization, chloritization, potassium silicate alteration, albitization, and carbonatization.

Feldspathization is the formation of secondary feldspar during hydrothermal alteration. The secondary feldspar is usually orthoclase, adularia, or albite. Secondary albite has already been discussed in detail under the heading albitization.

D. Experiments in Hydrothermal Alteration

Armstrong (1940) discussed decomposition and alteration of feldspars and spodumene by water. It was found that all of the constituents of the minerals diffused through the membrane of a dialyzer. This was interpreted as evidence that silica and alumina, as well as the alkalis were present in solution as ions, indicating that clay minerals may probably form at least in part by ionic reactions rather than by colloidal reactions.

Norton (1939 and 1941) discussed hydrothermal formation of clay minerals in the laboratory. He took a number of feldspars and other aluminum silicate minerals and exposed them to carbon dioxide-charged percolating water under high pressures and temperatures in a reaction chamber. A study of the end products indicated that the least stable of these materials readily broke down to form clay minerals. The greatest reaction rate occurred at 300°C and at a maximum carbon dioxide pressure. Norton also found it interesting to note that the parent materials were stable at temperatures outside the range of 250°C to 350°C. The production of clay minerals similar to, if not identical with, kaolinite, beidellite, sericite, pyrophyllite, and gibbsite was accomplished. Here, the resulting end product seemed to be determined by the nature of the parent rock as well as by the temperature and acidity during the reaction.

Leonard (1927) discussed hydrothermal alteration of certain silicate minerals. He discussed each of them separately, but the writer will discuss only generalities.

At 100°C alkali carbonates, chloride, and sulphate solutions did not alter the feldspars or spodumene, excepting a slight corrosion of some grains of albite and bytownite in treatment with sulphate solutions. Hydrochloric acid partly decomposed labradorite, producing a small percentage of residual silica. Sulphuric acid apparently did not attack microcline or albite but almost completely decomposed labradorite and bytownite, with only silica as a decomposition product.

Alunite was produced from feldspars at 22°C, 65°C, and 100°C at atmospheric pressure and at 200°C at 15 atmospheres of pressure. The alunite was produced by the addition of aluminum sulphate to sulphuric acid, potassium sulphate and sodium sulphate solutions, and by aluminum sulphate solution alone. Alunite was also formed purely synthetically from mixtures of aluminum sulphate and alkali sulphate solutions.

Alunite was not found at 350°C in water vapor experiments at atmospheric pressure.

Hydrochloric and sulphuric acid reactions at 200°C and somewhat below 15 atmospheres of pressure resulted in partial or complete solution of the feldspar or decomposition with a residual silica product. Kaolinite was not produced, at least not in noticeable amounts, in any of the experiments.

Folk (1947) discussed the alteration of feldspar and its products found in the laboratory. He found that kaolinite formed in acidic solutions up to about 350°C if the aluminum content were rather high and the potassium content were rather low. Muscovite formed from 200°C through 525°C in slightly basic and rather acidic solutions if the potassium and aluminum content were high. Pyrophyllite formed from about 300°C to about 550°C if the aluminum and potassium content were both low.

In most conditions of hydrothermal alteration around ore deposits, sericite is formed because most metallizing solutions are alkaline. Kaolinite, however, is formed near the surface by acidic waters, and may replace sericite through leaching with carbonate and sulphate waters. The formation of pyrophyllite in nature may be rare because there is probably much aluminum available in solution.

By reference to Figure 3, one may review the conclusions discussed by Folk.

Kennedy (1944) discussed the solubility of silica. He ran tests at 300 atmospheres of pressure and found that the solubility is essentially zero at temperatures below 200°C and increases to a maximum of 0.20 parts silica per 100 parts of water at 360°C. Solubility fell off

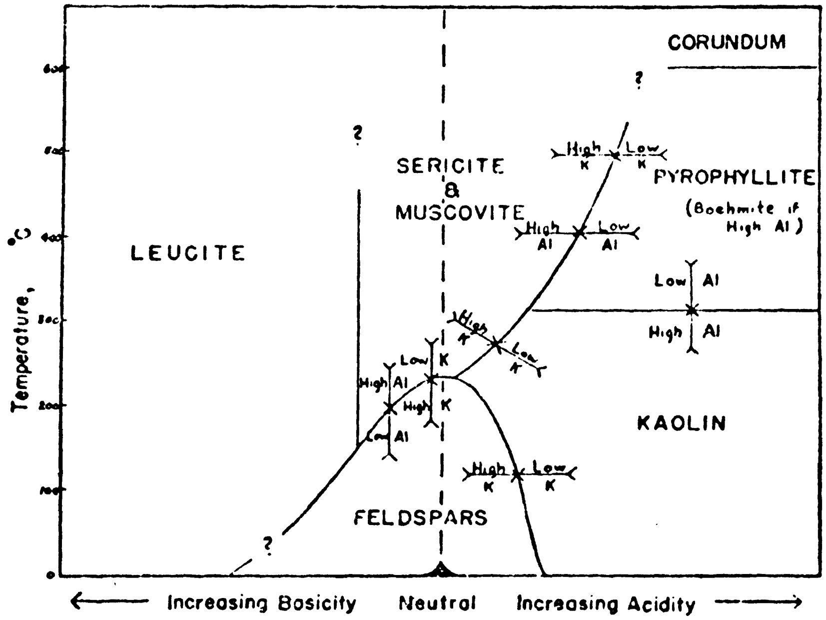

Figure 3. Effect of temperature and pH on the alteration of feldspars. Minerals form in the fields indicated. Within these major fields, changes in K and Al concentration tend to drive the boundaries in the directions shown by the arrows. (Folk, 1947)

beyond the 360°C point.

E. Hydrogen Metasomatism

Hemley and Jones (1964) discuss hydrogen metasomatism (the hydrolytic process) and its varying extent from intense to incipient. Intense hydrolytic alteration is represented by the alunite-quartz-kaolinite-bearing assemblages in areas of some hot springs and epithermal base-metal deposits. Weak or incipient hydrolytic alteration is represented by propylitic mineral suites. Intermediate between these extreme types and indicating conditions of moderate hydrolysis are assemblages that include quartz, sericite, biotite, kaolinite, illite, and montmorillonite. Such assemblages are characteristic of Butte-type alteration and are common in the porphyry copper deposits and many other base-metal deposits.

Kaolinite is an example of a mineral that cannot be used by itself to judge the extent of hydrolytic attack, for kaolinite is found in both the intense and intermediate associations described above.

The formation of kaolinite is favored by low temperature and low alkali-ion/hydrogen ion ratios, which is in accord to its abundant development in supergene alteration. Supergene processes take place in a leaching environment and in some cases there would be rapid removal of dissolved material compared to the rate of crystallization of intermediate products such as illite. Under such conditions most silicate minerals would tend to alter directly and completely to kaolinite.

Considering the common sericitic-argillic banded alteration in the intermediate igneous rocks, if sericitization and argillization both accompanied ore deposition, the solutions must have lost hydrogen ions (plus sulphur, carbon dioxide, and sometimes potassium) and gained sodium, calcium, magnesium, and perhaps other base ions and silica. However, if only sericitization accompanied deposition of sulphides and this was superimposed on previously argillized rock from an earlier alteration epoch, then the solution gained hydrogen ions and lost potassium ions, sulphur ions, and silica.

F. Physical Chemistry and Hydrothermal Alteration

The following paragraphs include a discussion of the different controlling factors of mineral stabilities. The factors are such variables as temperature, pH, mNaCl/mHCl, and mKCl/mHCl ratios. Hemley, Meyer, Richter, and Stringham give excellent discussions of the subject.

Hemley (1959) discussed some mineralogical equilibria in the system K_2O-Al_2O_3-SiO_2-H_2O. An experimental investigation was made at elevated temperatures and pressures of the hydrolysis of potassium feldspar to mica and silica, and of mica to kaolinite. The solution pressure for most of the experimental runs was 15000 psi. Above about 350°C the assemblage mica-kaolinite changed to mica-pyrophyllite-boehmite, and at still higher temperatures, mica-pyrophyllite-andalusite formed (See Figure 4).

Hemley's experimentation shows that the most important controls on the fields of stability of these previously mentioned minerals are the K^+/H^+ activity ratio and the temperature. At a given temperature and with increasing K^+/H^+ ratio, the fields of kaolinite, mica, and potassium feldspar are successively traversed. Similarly, at a constant K^+/H^+ ratio with increasing temperature, this same sequence is observed. Figure 4 shows the variations of the equilibrium quotient

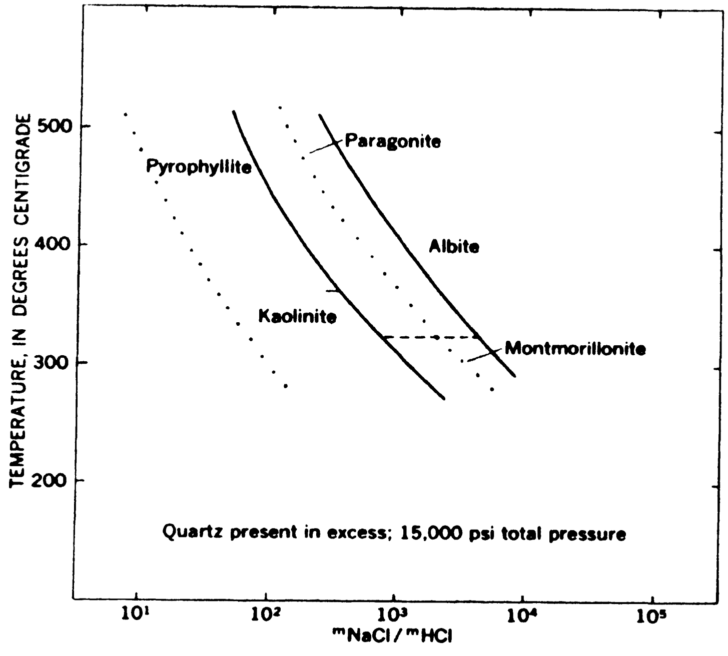

Figure 4. Some stability relations in the system $Na_2O-Al_2O_3-SiO_2-H_2O$ as a function of temperature and the m NaCl/m HCl ratios. Corresponding relations in the terms of m KCl/ m HCl are indicated by dotted lines for the system $K_2O-Al_2O_3-SiO_2-H_2O$. The field of potassium mica is between the dotted curves, with potassium feldspar at higher values of KCl/HCl and pyrophyllite and kaolinite at lower values. (Hemley, Meyer, and Richter, 1961)

with temperature for the two mineral assemblages potassium feldspar-mica-silica and mica-kaolinite. The curves are essentailly parallel and separated by an interval of acid concentration corresponding to about 1.5 pH units.

Hemley goes on to state that by reference to Figure 4, one may see that the equilibrium K^+/H^+ ratios trend toward higher acidities at higher temperatures. This slope means that the potential of hydrothermal solutions to alter the wall rock as it ascends from environments of higher temperatures would increase as the temperature falls if the rate of migration were sufficiently rapid in comparison with the rate of reaction with the wall rock.

Hemley, Meyer, and Richter, (1961) discussed some alteration reactions in the system Na_2O-Al_2O_3-SiO_2-H_2O. The experiments involved albite and its decomposition products in an aqueous chloride environment at elevated temperatures and pressures. Stability relationships are shown in Figure 4 in terms of the molal NaCl/HCl ratio or equilibrium quotient of the reaction and the temperature.

Experimental decomposition temperatures rather than true stability limits, which are probably somewhat lower, are shown by broken lines for the sodium montmorillonite and the kaolinite (See Figure 4). The values indicated are for 4m NaCl solutions.

The experimental results are valuable in the interpretation of field relations in hydrothermally altered rocks. The decomposition of plagioclase results in the formation of kaolinite rather than montmorillonite at low Na^+/H^+ ratios. This agrees with field alteration patterns in which argillized wall rock characteristically shows dominant kaolinite and lower sodium content closer to the vein, and montmorillonite and higher sodium content farther from the vein.

Stringham (1952) discussed the fields of formation of common hydrothermal alteration minerals. The information discussed is not original to Stringham but is a compilation of the available findings to that publication date. Figure 5 is a chart representing the fields of formation of the common hydrothermal minerals. The abscissa represents the pH of the depositing solutions and the ordinate represents temperature. A line at 350°C has been drawn which divides the chart into two parts and serves as a convenient reference for two reasons. It is near the critical temperature of water, and 300-400°C has been found to be the range in which some important changes take place in laboratory experiments. If a mineral is known to form over a range in temperature, a solid arrow is drawn between the temperature extremes, and a dashed arrow is drawn where data is not conclusive. The fields on both sides of pH 7 are more or less qualitative in nature in that the distance a mineral is placed from the neutral line is suggestive rather than real. The very important sericite field is outlined by dashed lines. The chlorite field is outlined by dotted lines. Many important hydrothermal minerals such as quartz and pyrite are missing from the chart. These are believed to have such a wide range in their fields of formation that they are not diagnostic and are therefore intentionally deleted. Pressure and the chemical composition of the depositing media were ignored in the chart because it was believed that it would complicate matters and the general utility of the chart would be lessened.

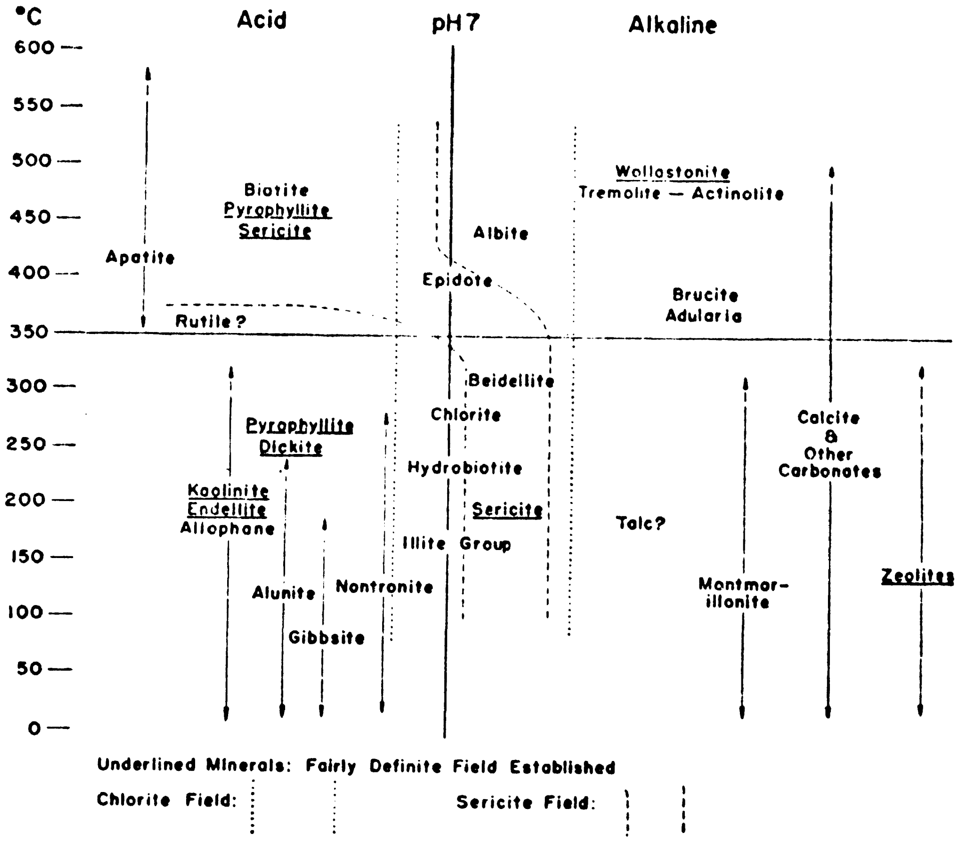

Figure 5. Fields of formation of some common hydrothermal minerals. Temperature versus pH. If a mineral is known to form over a range in temperature, a solid arrow is drawn between the temperature extremes, and a dashed arrow is drawn where data is not conclusive. (Stringham, 1952)

G. Deuteric Alteration in Ash-Flows and Plutonic Rocks

Scott (1966) states that deuteric fluids alter the original composition of the aqueous-rich volcanic units by transfer, exchange, and removal of ions by an aqueous phase during cooling. On the other hand, hydrothermal alteration can significantly change the bulk composition by introduction, redistribution, recrystallization, and removal of ions. It is necessary to distinguish between the two differing processes.

Scott discussed the origin of chemical variations within east-central Nevada ignimbrite cooling units. He found that the vertical chemical variations of deuteric alteration were mainly potassium-sodium exchanges and magnesium and iron redistributions. He found that the presence of an aqueous phase during cooling of the ignimbrite created ideal conditions for deuteric alteration.

Scott found that the degree of welding of ignimbrites is an independent and sensitive record of the temperature and pressure conditions under which deuteric alteration operated. He found compatible results in five different areas of study. His findings concerned relationships between the different oxides and the degree of welding of the ignimbrites. Sodium oxide content increased as the degree of welding increased. Potassium and magnesium oxides increased as the degree of welding decreased. Calcium oxide content increased as the degree of welding decreased, but was slightly irregular in its pattern. Ferric oxide content was irregular in its pattern. Aluminum oxide content was nearly constant.

Scott feels that chemical variations in compound cooling units can be explained by several means: One, is that there was original magmatic differences in composition between the different layers of a magma erupted at different times. This is characterized by inhomogeneities in phenocryst composition, phenocryst abundance, and characteristics in welding. Two, is that hydrothermal alteration existed. This is characterized by lack of chemical continuity laterally, Three, weathering may have been active. This is characterized by leaching of mobile ions and abundant growth of secondary weathering products. Four, is that deuteric alteration may have been active. Scott found that, in his area, he could rule out the first three and justify deuteric alteration because he found that the more significant chemical trends of the variations parallel those of laboratory ion exchange experiments and predicted deuteric results. It is postulated that those chemical trends that can most readily be explained by ionic exchanges should be attributed to deuteric alteration, whereas those that show evidence of leaching or show association with weathering products should be attributed to weathering.

Magnesium oxide variations were attributed to deuteric alteration. Magnesium is among the more mobile ions and therefore oftentimes is concerned with weathering. However, if the magnesium were mobile during weathering, it would be leached from the more porous zones. However, the magesium content is higher in the more porous zones. This is the reason Scott feels that the magnesium oxide is of deuteric origin.

Deuteric alteration probably controlled most of the sodium and potassium variations in the more welded zones of the cooling unit, but leaching of sodium by weathering greatly affected the less welded zones.

The moderately to slightly welded (and presumably cooler) parts of the ignimbrite sheet are richer in potassium oxide than are the more highly welded zones, which are richer in sodium oxide. This would be the expected result from an ion-to-ion exchange between sodium and potassium. Thus, deuteric alteration was the postulated phenomenon.

The plagioclase phenocrysts and devitrified glass shards are partially replaced by calcite and calcium-montmorillonite in the more porous samples. This evidence suggests that most of the calcium variations are the result of weathering which mobilized and redeposited the calcium in patches of calcite and calcium-montmorillonite.

The ferric oxide may be partly controlled by movement of iron in a fluid phase during deuteric alteration.

Smith (1961) discusses products of deuteric alteration. He includes zones of devitrification, vapor-phase crystallization, and granophyric crystallization. In the zones of devitrification, the glass is devitrified and forms spherulitic and axiolitic intergrowths and aggregates of cristobalite and feldspar. Vapor-phase crystallization is the growth of crystals from a vapor phase in pore spaces. This product of deuteric alteration is usually coarser-grained than devitrification. Granophyric crystallization is characterized by groundmass quartz intergrown with or blebs associated with alkali feldspar. This has the typical granophyric or micrographic texture.

Vitaliano (1957) discussed wall rock alteration in the Broken Hills Range, Nevada, where he suggested that both deuteric and hydrothermal alteration occurred. He stated that deuteric alteration of the host rock resulted in kaolinitization, sericitization, and albitization of feldspar, biotitization of hornblende, and chloritization of primary biotite and hornblende. The hydrothermal alteration minerals were talc, tourmaline, pyrophyllite (?), sericite, brucite, and chlorite. Vitaliano found it necessary to carefully distinguish between what he called deuteric alteration products and the hydrothermal alteration products. He found that the hydrothermal chlorite differs from the deuteric chlorite in being fine-grained and colorless and in that it replaces talc.

Huang (1962) lists several of the common plutonic deuteric alteration minerals. They include chlorite, biotite, sericite, serpentine, the zeolites, the kaolin group, and other clay minerals.

Huang continues on to state that the following processes are oftentimes deuteric in nature in plutonic rocks: albitization, chloritization, zeolitization, uralitization, scapolitization, and the development of such quartzofeldspathic intergrowths as micropegmatite.

H. Specific Previous Work Done in Thesis Area

Thurston, et al. (1954) discussed the fluorspar deposits of Utah. Of importance to this thesis, he discussed Cougar Spar, Utah, J.B., and Holt-Bluebell Mines in the Indian Peak District. He stated that the fluorite occurs as fissure veins in fault and breccia zones in volcanic and intrusive rocks. Thurston stated that the Cougar Spar Mine is in a fault zone near the contact between the intrusion and the volcanic rock exposed there. Thurston stated that through geologic mapping, the Utah Mine was located by tracing the vein zone from the J.B. Mine.

Since the summer of 1962, Sheldon Kerry Grant has spent his summers working in the Indian Peak District and the surrounding vicinity. He has written an article on the "Geology and Ore Deposits of the Indian Peak Fluorspar District, Beaver County, Utah" (in press). In it, he concentrated on the history, general geology, structure, and the fluorite deposits of the Indian Peak District. Grant stated that the Needles Range Formation is a complexly faulted, somewhat discontinuous representative of otherwise typical Basin and Range geology. He stated also that the fluorspar deposits at the Indian Peak District are epithermal quartz-fluorite veins. The individual mine locations such as Cougar Spar, Holt-Bluebell, Utah, and J.B. were discussed. All of these mines were historically and structurally analyzed.

To the writer's knowledge, Dinkel (1969) is the only reference on hydrothermal alteration of the thesis area. He states that the principal products of alteration are magnetite rimming hornblende, and biotite and calcite replacing plagioclase. He states that not only from the point of view of a single thin section, but from the point of view of the whole field that was studied, the alteration is quite selective. Only certain minerals are affected and each alteration mineral selects a specific host. From the whole field point of view, some localities are much more altered than others. Some locations are unaltered. This type of selectivity should indicate a post-depositional type of alteration, such as hydrothermal, controlled by fractures and fluid conduits. In many thin sections the groundmass is unaltered (other than devitrification) around the altered mineral. This would point toward deuteric alteration resulting from hot gases emanating from within the ash-flow. These emanations should, therefore, affect all locations equally, however, as has already been stated, the alteration has not affected the area equally. Dinkel suggests that the alteration is either deuteric, hydrothermal, or a combination of the two. He eliminates weathering from the possibilities because he states that it should be pervasive, especailly in the porous tuffs. The total lack of alteration in several places and the lack of typical weathering minerals lead one to believe that weathering is not an important process in the alteration of these ash-flow tuffs.

III. GEOLOGIC SETTING

A. General

As Grant (in press) states, the Needles Range is a complexly faulted, somewhat discontinuous representative of otherwise typical Basin and Range geology. Paleozoic sedimentary rocks, folded and thrust-faulted during the Laramide Orogeny, serve as the basement on which tremendous sheets of Mid-Tertiary ash-flow tuffs have been deposited. There are few exposed sedimentary rocks in the immediate vicinity of the thesis area. There are several intrusives in the thesis area; one is a granodiorite body at the Cougar Spar Mine. Extrusive igneous rocks are predominantly of ash-flow origin and are of Oligocene age. The Needles Range Formation is the most important geologic unit in the Indian Peak District.

B. Needles Range Formation

The Needles Range Formation was defined by Mackin (1960) as consisting of two prominent members. These members were the Wah Wah Springs Tuff and the Minersville Tuff. Cook (1965) recognized five members. Later, Grant (personal communication) established the following members: Frisco, Escalante, Shingle Springs, Wah Wah Springs, Mackleprang, Indian Peak, and Lund members.

Except for the previously discussed intrusive at the Cougar Spar Mine, all of the mine locations are stratigraphically in the Wah Wah Springs Tuff Member. This member is a pale reddish brown crystal-vitric phenodacite. Its average crystal composition is: 5 per cent quartz, trace alkali feldspar, 64 per cent plagioclase, 9 per cent biotite, 18 per cent hornblende, and 34 per cent crystals, with traces of pyroxene. A moderate amount of lithics is present. Its type section is just south of Wah Wah Springs where Utah Highway 21 crosses the Wah Wah Range. Its thickness ranges to 750 feet in the surrounding area, but in the thesis area, it ranges to 2000 feet.

C. Structure

The thesis area occurs within the Basin and Range province. However, ash-flows do not necessarily require a basin for deposition. Deposits should build up around the source, even if the pre-eruptive surface was a horizontal plane. Cook (1965) and Conrad (1969) suggest that subsidence may have been associated with deposition of the ash-flow field. However, this subsidence is not required to explain the post-depositional expression of many of the ash-flows.

D. Mineralogy

The hydrothermal minerals that appear in the thesis area are secondary quartz, fluorite, calcite, sericite, secondary feldspar, epidote and zoisite, secondary iron oxide, chlorite, and hydromuscovite. Limonite and nontronite (?) are believed to be weathering products.

Secondary quartz at the Indian Peak District appears as veins and veinlets. It is typical hydrothermal quartz in that it is fine-grained. This is an excellent means of distinguishing it from primary quartz.

The fluorite almost always occurs in massive form. Most of the fluorite is colorless, green, purple, and/or yellow.

Oftentimes, secondary white lamellar calcite and brown and white massive calcite are associated with the fluorite. Calcite is found also as an alteration of plagioclase, hornblende, biotite, and diopside. There are many patches of calcite replacing plagioclase. Sometimes calcite (and secondary iron oxide) pseudomorphs occur after hornblende and diopside. Calcite appears in trace amounts in the cleavage planes of biotite. In order to assure that the rhombohedral carbonate mineral was calcite, the index of refraction was taken on several random samples.

Sericite appears as fine-grained blades, plates, and veinlets replacing plagioclase. Sometimes, there are both calcite and sericite replacing plagioclase. The difference in birefringence was the main criteria used to distinguish between the two fine-grained alteration minerals.

The secondary feldspar is an alkali variety. It appears as hairlike veinlets, patches, or complete replacements of primary plagioclase laths. The secondary alkali feldspar has an index of refraction less than balsam. Primary plagioclase has an index greater than balsam. The secondary feldspar also has a slightly higher birefringence.

Epidote and zoisite appear as alteration products of biotite, hornblende, and plagioclase. Epidote and zoisite stand out well since they have high relief and distinctive birefringence. Epidote may be distinguished from zoisite in that epidote has a stronger birefringence, however, since the two are so very similar, the writer would prefer to always group the two. Epidote and zoisite sometimes occur in columnar aggregates, but more often occur as fine-grained aggregates that are difficult to distinguish.

The secondary iron oxide is believed to be "hematite". It appears as rims around and inclusions in chlorite pseudomorphs after hornblende and biotite. Secondary iron oxide also appears as an alteration product of diopside. The secondary iron oxide sometimes appears as cubes. This leads one to believe that "hematite" may have altered from pyrite. This idea is probable because the writer observed pyrite cubes at the dump piles at J.B. and Utah mines. Also, Grant (in press) has reported pyrite at Holt-Bluebell. Oftentimes, the gray "hematite" has a red oxidizing rim around it.

Chlorite is found in many samples collected at the Indian Peak District. The variety of chlorite that seems to be most prevalent is penninite. The index of refraction of randomly selected chlorite grains is near 1.58. Many grains give the anomalous "Berlin blue" interference color. With these optical characteristics in mind, a diagram of birefringence versus index of refraction by Hey (1954) was utilized. It was found that the chlorite in question was a ferromagnesian variety. This correlates with the optical observances that point to the mineral penninite.

Bonorino (1959) described hydrothermal alteration in the Front Range Mineral Belt, Colorado. The most abundant alteration mineral at this mineral belt was hydromica. Bonorino described it as occuring as the innermost zone. Sericite oftentimes occurred with it, but hydromica was much less crystalline. Sericite occurred as better defined plates when compared with the grayish to creamy white hydromica. The refractive indices were $\alpha = 1.545$ and $\gamma = 1.580$.

The X-ray diffraction pattern of Bonorino's hydromica gives a 9.8 Å peak for the (001) reflection. He states that its spacing is low probably because of the interlayered montmorillonite.

All of the preceding information can be applied to a clay mineral found at the Indian Peak District. It is a grayish clay mineral associated with sericite and appearing only immediately adjacent to the vein. It is not perfectly crystallized. The refractive index is 1.56. The X-ray diffraction pattern gives a peak at 11.2 Å. This is higher than Bonorino's, however, the sample does not show any evidence of containing any montmorillonite. The sample at the Indian Peak District was ethylene glycolated and the peak was shifted to 10.2 Å. The dry sample was intensely heated and the peak shifted to 10.7 Å. All of the preceding evidence points to the conclusion that the clay mineral at the Indian Peak District is hydromica.

Limonite appears as a stain on some specimens found at the Indian Peak District. The limonite is brown in reflected light and opaque to translucent in refracted light. It is believed to be a weathering product.

A mineral that appeared as rims around iron oxide is believed to be nontronite (?)(an iron-rich montmorillonite). It has the optical properties of nontronite, such as color, index of refraction, and birefringence. Nontronite is a typical weathering product of iron oxides.

IV. METHODS OF INVESTIGATION

A. Sample Collection and Preparation

In July of 1970 the writer collected rock samples near selected fluorite mines in southwestern Utah. The mine locations are shown in Figure 1. It was desirable to take rock samples in a traverse perpendicular to the fluorite veins. However, sometimes due to lack of good exposures perpendicular to the vein, other traverses had to be made. Where feasible, two traverses were taken at each mine location.

Out of the 167 rock samples collected, 120 selected thin sections were made by the writer. The concentrations of the different hydrothermal minerals were plotted versus the distance from the vein for all the traverses for all the mines studied. The variations in the concentrations were of most significance. The mines were then considered as a whole and the overall conclusions were drawn concerning the variations in the concentrations of the hydrothermal minerals.

B. Petrography

A detailed petrographic study of the 120 thin sections was undertaken. Each thin section was carefully studied with respect to minerals present, their abundance, and the amount of hydrothermal alteration of each.

The mineral percentages were calculated by use of a grid ocular. Random fields were viewed and the minerals falling within the grid lines were counted. Five fields (1500 points) were counted for each section.

The relative error in grain counts was taken to be $1/\sqrt{n}$, $\underline{n}$ being the number of points counted for a particular mineral. For example, if 100 points out of five fields were counted for secondary feldspar, then the per cent of secondary feldspar would be six and seven tenths and the relative error would be one tenth of the six and seven tenths per cent, or plus or minus sixty-seven hundredths per cent.

X-ray diffraction techniques were employed to distinguish the clay minerals found. When a clay mineral appeared in a thin section, the powdered rock sample was X-rayed in order to aid in its identification. The optical properties together with the peaks shown on the diffraction pattern usually, at least, narrowed the identification of the clay mineral.

The X-ray technique used involved powdering the rock sample, placing it in a beaker of water, and allowing it to settle. After 24 hours the top of the slurry was placed by use of an eye dropper on a microscopic slide, was allowed to dry, and then the concentrated fine clay portion of the rock was X-rayed.

V. HYDROTHERMAL ALTERATION OF SPECIFIC MINE AREAS

A. Cougar Spar Traverse

The Cougar Spar Fluorite Mine may be located by reference to Figure 1. At this mine a N 34° W strike of the fluorite vein was noted. Due to the lack of good exposures perpendicular to the vein, a 1300-foot north-south traverse curving to an east-west direction was sampled. At Cougar Spar, the north-south part of the traverse crosses the vein at 2100 feet north and 1500 feet west of the southeast corner of section 10, T 30 S, R 18 W. The north-south part of the traverse is west of the open cut. The east-west part of the traverse crosses the vein at 1400 feet north and 1100 feet west of the southeast corner of section 10, T 30 S, R 18 W. The east-west part of the traverse is south of the open cut. The sampling went from the north to the east.

Dinkel (1969) pointed out that the hydrothermal alteration of the thesis area is selective. Dinkel states that only certain minerals are affected and each alteration mineral selects a specific host. The writer agrees that only certain minerals are affected; however, each alteration mineral does not necessarily select a specific host. The minerals that were partially or wholly affected are primary plagioclase, biotite, and diopside. The only completely unaffected mineral is primary quartz. Primary plagioclase alters mostly to sericite and secondary feldspar and a trace of epidote, zoisite, and calcite. Mostly chlorite and a secondary iron oxide appear at the expense of biotite. Epidote, zoisite, and calcite are also accessory products of biotite. Primary diopside alters partially to calcite and secondary iron oxide.

The hydrothermal alteration products in the Cougar Spar traverse are several. Nearest the major fluorite vein, the original host rock is almost completely hydrothermally altered. The samples taken immediately adjacent to the fluorite vein contain mainly hydrothermal quartz veinlets, a secondary red iron oxide (presumably "hematite"), secondary feldspar, and sericite.

A hydrothermal origin was concluded for the quartz veinlets because of the finer grain size of the quartz and the simple fact that they formed veins. This is typical of hydrothermal quartz. Primary quartz would have been coarser grained and not in vein-type structures. The primary quartz that was present was not affected by hydrothermal alteration. Silicification, the hydrothermal introduction of SiO_2, is the process responsible for the quartz veins and veinlets. The red "hematite" occurred in the quartz vein and veinlets. This led the writer to believe a hydrothermal origin for the red "hematite" also. The red "hematite" was also found in "bleached" biotite. The hydrothermal fluids did not actually replace the biotite with an alteration mineral, but did "bleach" it.

Another alteration product that was found in great abundance in the samples near the major fluorite vein was sericite. Sericite and secondary feldspar almost completely replaced the primary plagioclase.

As to the hydrothermal alteration products of the rocks at some distance from the fluorite vein, the products are chlorite, a gray secondary iron oxide, secondary feldspar, calcite, epidote and zoisite, sericite, and hydrothermal quartz. Red "hematite" appears to be the only hydrothermal alteration product that is found immediately adjacent to the fluorite vein and not found further away from it.

Chlorite seems to be present in every sample taken except in the immediate vicinity of the fluorite vein. Primary biotite is the original mineral that was altered to chlorite and a gray secondary iron oxide. Oftentimes, the biotite is altered but not completely replaced. The chlorite is found along the cleavages of the biotite and some biotite grains are completely replaced by chlorite. Many are actually chlorite pseudomorphs after biotite. There are also traces of epidote and zoisite in chlorite after biotite.

Primary plagioclase alters mostly to sericite and secondary alkali feldspar and somewhat to calcite and traces of epidote and zoisite. The primary plagioclase invariably contains blades, plates, and veinlets of sericite. Sometimes the sericite occurs scattered uniformly throughout the primary plagioclase crystals and sometimes the sericite occurs in patches here and there. The uniformly scattered sericite appears to be the more common.

A few hydrothermal quartz veins and veinlets also appear in the original host rock a little further away from the vein. However, most of the hydrothermal quartz is found immediately adjacent to the fluorite vein.

By use of a grid ocular in a polarizing microscope, the writer gathered per cents of concentration of chlorite, secondary iron oxide, hydrothermal quartz, sericite, secondary feldspar, and the primary mineral content. The percentages and their variations were of particular significance.

The amount of chlorite present increases away from the vein. There is no chlorite found in the sample immediately adjacent to the vein. The percentage of chlorite increases to 20 per cent 500 feet from the vein. It may increase further away from the vein even more, however, samples were not taken greater than 500 feet from the vein.

The secondary iron oxide content was also noted. Difficulty was encountered when it was necessary to distinguish between primary and secondary iron oxides. It was thus presumed that if an iron oxide was within a known secondary mineral, it was counted as a secondary mineral. For example, most of the secondary iron oxide appeared to rim and form inclusions in the chlorite after biotite. If the iron oxide mineral was not found within a known secondary mineral, it was not counted as a secondary iron oxide. On this basis, there was little variance in the content of secondary iron oxides, except for the sample immediately adjacent to the fluorite vein. It had 12 per cent secondary iron oxide, while the other samples contained an essentially constant three per cent.

The trend of hydrothermal quartz throughout the traverse is rather striking. As in the secondary iron oxide trend, there is little variance in the percentage of hydrothermal quartz, except for the sample immediately adjacent to the fluorite vein. It had 51 per cent hydrothermal quartz, whereas the other samples contain about 10 per cent. The hydrothermal fluids responsible for the introduction of SiO_2 evidently had a wide area of influence. There are small amounts of hydrothermal quartz veinlets found as far away from the fluorite vein as 500 feet. However, most of the hydrothermal quartz was found near the fluorite vein.

The trend of sericite is very distinctive. The percentage of sericite increases toward the fluorite vein, except about 15 feet before the vein, it decreases. The apparent reason for the decrease near the vein is the presence of such a large percentage of hydrothermal quartz. On the other side of the vein, the sericite again increases and then decreases.

The percentage of secondary feldspar is relatively constant except near the fluorite vein. The per cent drops sharply near the fluorite vein. This, as in sericite, is apparently brought about by the simple presence of such a large percentage of hydrothermal quartz. On the other side of the vein, the secondary feldspar again becomes nearly constant at about 33 per cent.

As one might expect, the concentration of primary minerals decreases toward the fluorite vein. Conversely, secondary minerals increase in abundance toward the vein. The primary minerals were biotite, plagioclase, primary quartz, and accessory diopside and apatite. At 500 feet from the vein, there is still about 85 per cent hydrothermal minerals. This suggests that the hydrothermal zones are very wide. The intensity of alteration is still great at 500 feet from the vein. The hydrothermal fluids have obviously had a great range of influence on the original country rocks.

The variations in concentration of the different alteration minerals at Cougar Spar may be noted in Figure 6.

B. J.B. Traverse

The J.B. #1 Fluorite Mine may be located by reference to Figure 1. The 35-foot, N 65°E traverse at J.B. is right along the vein. Sample

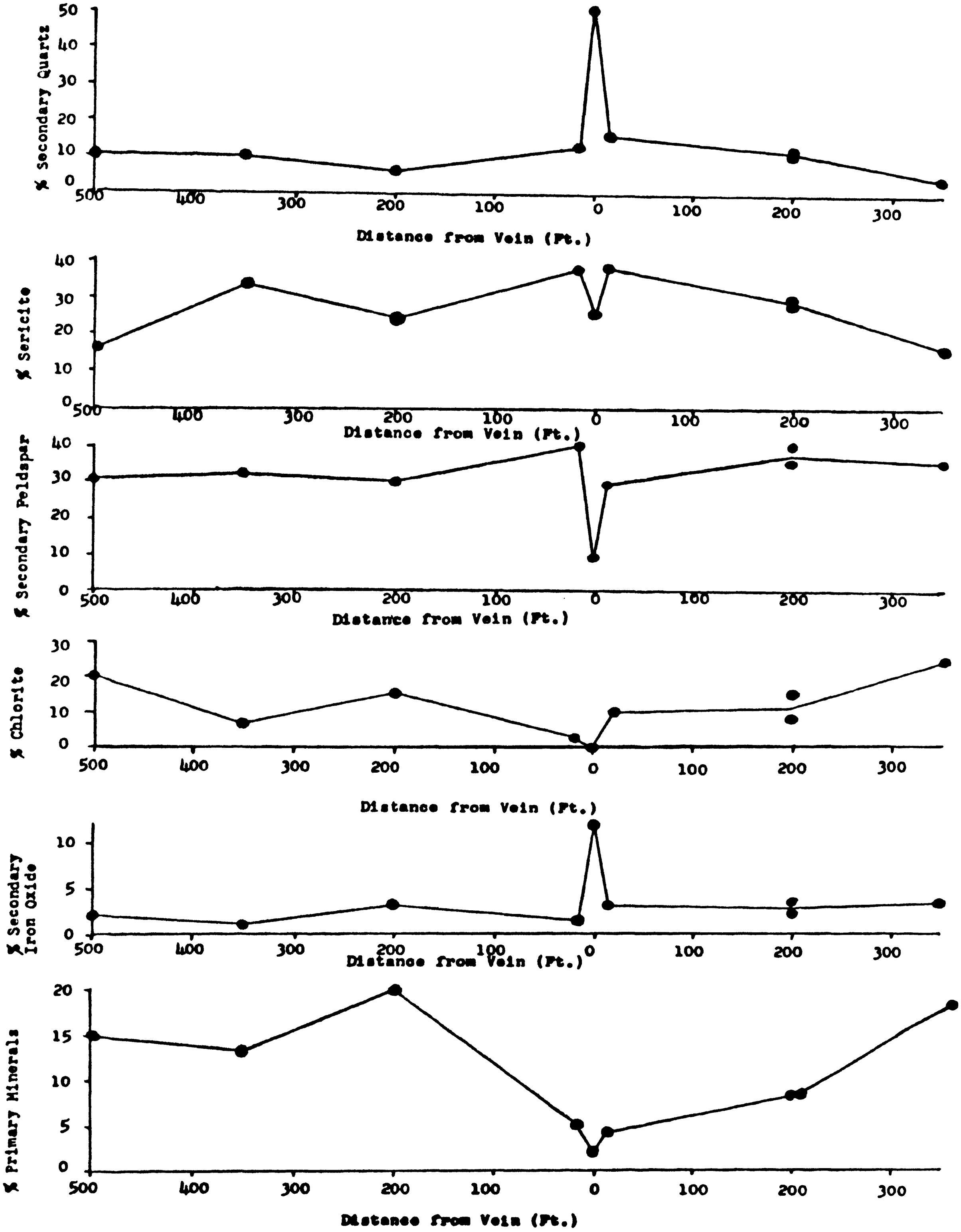

Figure 6. Variations in Concentrations of Alteration Minerals at Cougar Spar

number 164 is nearest the shaft. The traverse was started toward the west and ended toward the east. The S 15°E far traverse at J.B. ended at the shaft and began 450 feet from it.

The primary minerals that were wholly or partly affected by hydrothermal solutions are primary plagioclase, biotite, and hornblende. The only completely unaffected mineral is primary quartz. Primary plagioclase alters mostly to sericite and secondary feldspar. There are also traces of epidote, zoisite, and calcite replacing the primary plagioclase. Biotite alters partly to chlorite and a secondary iron oxide. Epidote, zoisite, and calcite are also accessory products of chlorite after biotite and chlorite after hornblende. However, the hornblende alters mostly to chlorite and a secondary iron oxide, just as the biotite has done.

The hydrothermal alteration products nearest the major fluorite vein include hydrothermal quartz, sericite, secondary feldspar, secondary red "hematite", a gray secondary iron oxide, and some hydromuscovite, chlorite and "bleached" biotite. The hydrothermal quartz occurs in veins and veinlets of a fine grain size. The sericite and secondary feldspar almost completely replace the primary plagioclase, showing high intensity of alteration near the vein. The red "hematite" only appears relatively near the vein. The gray secondary iron oxide rims and makes inclusions in the chlorite after biotite and in the chlorite after hornblende. Some of the biotite instead of being actually replaced by chlorite has been "bleached" instead. A small amount of hydromuscovite also appears near the fluorite vein.

As to the hydrothermal alteration products of the rocks at some distance from the vein, the products are sericite, secondary feldspar, a gray secondary iron oxide, and chlorite. There are also traces of epidote, zoisite, and calcite. The minerals that appear near the vein and not further away from it are hydrothermal quartz, secondary red "hematite", hydromuscovite, and "bleached" biotite.

Sericite and secondary feldspar replace the primary plagioclase, but with a lower intensity of alteration than there was near the vein. The primary plagioclase contains blades, plates, and veinlets of sericite. The secondary feldspar usually makes up most of the remainder of the original calcite plagioclase laths. Traces of epidote, zoisite, and calcite also appear in the primary plagioclase.

Chlorite appears as a partial or total replacement of biotite and hornblende. Inclusions and rims of secondary iron oxide appear in the chlorite after biotite and in the chlorite after hornblende. Traces of epidote, zoisite, and calcite appear in chlorite after biotite and in chlorite after hornblende.

The concentration of hydrothermal quartz, sericite, secondary feldspar, chlorite, secondary iron oxide, and the primary mineral content were plotted versus the distance from the vein. The amounts of the preceding minerals were plotted for the far traverse only of the J.B. #1 Mine. The variation in these amounts are of particular interest.

The chlorite decreases generally in both traverses from about 19 per cent at 450 feet from the vein, to about seven per cent near the vein. Thus, the amount generally decreases toward the fluorite vein.

The secondary iron oxide does not vary a great deal in either traverse. There is about seven per cent secondary iron oxide 450 feet from the vein. The amount decreases to about two per cent at 200 feet from the vein, and again increases to about seven per cent very near the vein. The variance seems to be so small that it is probably not too distinctive, however, it is very regular.

Hydrothermal quartz increases toward the vein. The amount varies from zero at a distance from the vein to about 40 per cent near the fluorite vein.

The general trend of sericite is to increase from 12 per cent at 450 feet from the vein to 23 per cent 50 feet from the vein. The concentration again decreases to about 12 per cent as one nears the vein.

The secondary feldspar stays between 51 and 27 per cent, showing no particular trend, other than a slight decrease near the vein.

No hydromuscovite is noted until about 15 feet from the vein. It is then about five per cent. The only place where hydromuscovite seems to exist is immediately near the fluorite vein.

The primary minerals generally decrease toward the fluorite vein. At 450 feet from the vein, the concentration is about 14 per cent, and near the vein, it decreases to about seven per cent. This trend is not too distinctive because there are a few irregularities in the trend of concentrations. However, it should be noted that within 450 feet of the vein, the concentration of the primary minerals does not exceed 17 per cent.

The variations in concentration of the different alteration minerals at J.B. #1 Mine may be noted in Figure 7.

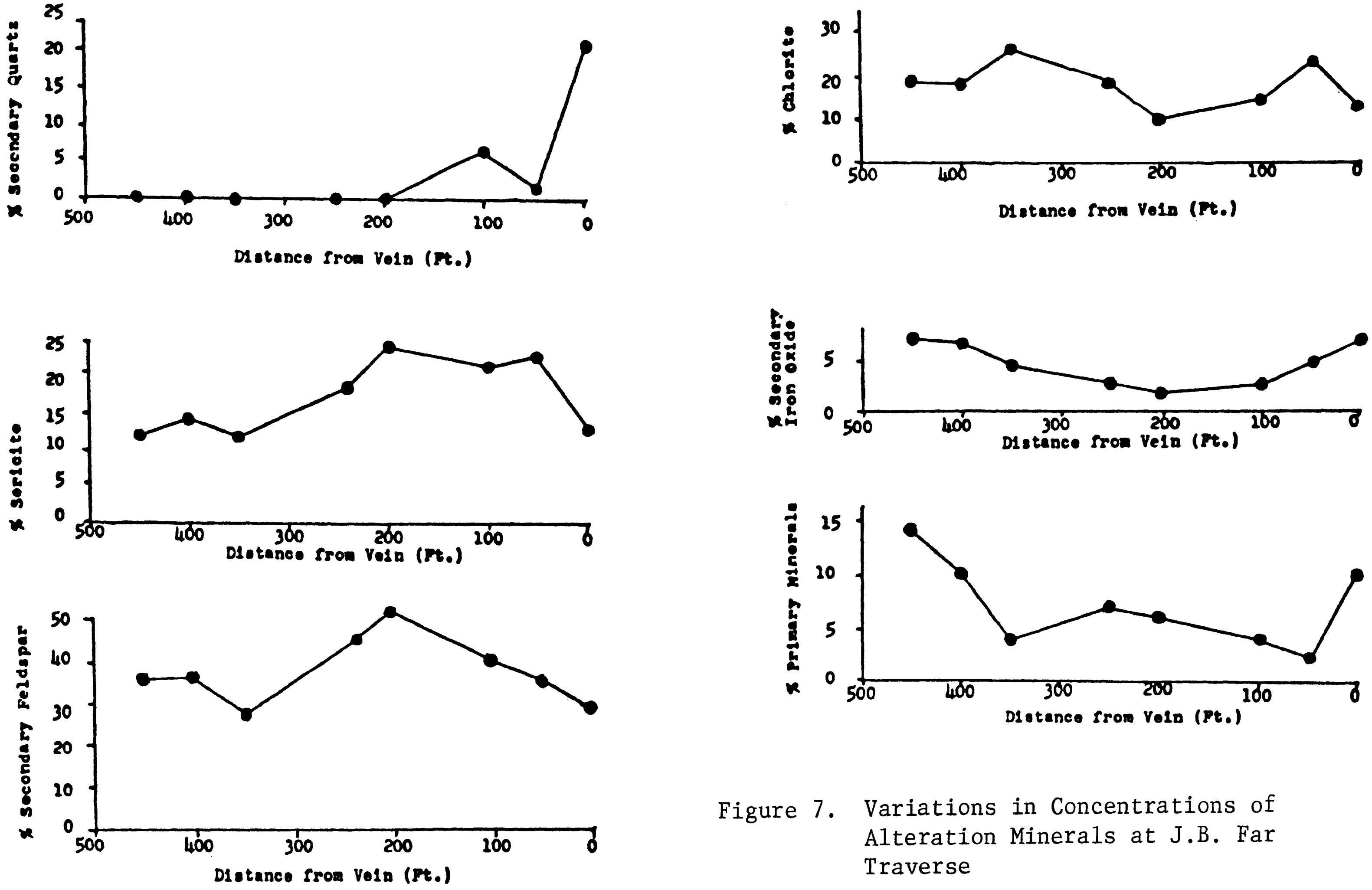

Figure 7. Variations in Concentrations of Alteration Minerals at J.B. Far Traverse

C. New Arrowhead Traverse

The New Arrowhead Pb-Zn Mine may be located by reference to Figure 1. A 225-foot traverse was begun on the side of the small hill 1000 feet north of the mine shaft. The traverse goes southwesterly toward the volcanic-sedimentary contact. The traverse crosses the extrapolated vein.

The primary minerals that were wholly or partly affected by the hydrothermal solutions are primary plagioclase, biotite, and hornblende. The only completely unaffected primary mineral is primary quartz. Primary plagioclase alters mostly to sericite, secondary feldspar, and calcite. There are also traces of epidote and zoisite in primary plagioclase. Biotite alters partly or wholly to chlorite and a secondary iron oxide. Epidote, zoisite, and calcite are accessory products of chlorite after biotite. Hornblende alters mostly to chlorite and a secondary iron oxide, with some epidote, zoisite, and calcite.

The hydrothermal alteration products nearest the major vein are mostly hydrothermal quartz veins and veinlets and patches of hydromuscovite. Some sericite and secondary feldspar replace primary plagioclase. Secondary iron oxide and calcite partly and sometimes totally replace biotite and hornblende.

The hydrothermal alteration products found at a distance from the major vein include sericite, secondary feldspar, chlorite, secondary iron oxide, and calcite. The minerals that appear near the vein that do not appear at some distance from it are hydromuscovite and hydrothermal quartz.

The concentrations of chlorite, secondary iron oxide, hydrothermal quartz, sericite, secondary feldspar, calcite, and the primary mineral content were plotted versus the distance from the vein.

The chlorite concentration decreases from about 25 per cent at 150 feet from the fluorite vein to zero immediately adjacent to the vein.

The secondary iron oxide decreases toward the vein. The apparent reason for this is that the secondary iron oxide occurs at the New Arrowhead Mine only in the chlorite after biotite and in the chlorite after hornblende. Therefore, since the chlorite decreases toward the vein, the secondary iron oxide decreases toward the vein. At the New Arrowhead Mine no secondary red "hematite" was noted as a hydrothermal product near the vein as it was in some of the other mines.

The hydrothermal quartz increases abruptly in the immediate vicinity of the vein. At 50 feet from the vein the concentration is about seven per cent, whereas immediately adjacent to the vein, the hydrothermal quartz has a content of 77 per cent. This is a tremendous change in a short distance that shows a narrow margin of migration of the fluids depositing the hydrothermal quartz.

Sericite decreases from only about six per cent at 150 feet from the vein to zero immediately adjacent to the vein. The percentage of sericite again increases immediately on the other side of the vein for several feet.

Secondary feldspar has a similar trend compared to sericite. The per cent of secondary feldspar at 150 feet from the vein is 28, whereas immediately adjacent to the vein, it is zero. The concentration increases on the other side of the vein where it essentially levels off at 35.

The trend of hydromuscovite seems to be very distinctive. There is hydromuscovite only relatively near the vein. At 50 feet from the vein, the concentration is 25 per cent. Immediately adjacent to the vein, the concentration is 37 per cent.

The primary mineral content decreases toward the vein. The per cent of primary minerals at 100 feet from the vein is 17, whereas near the vein almost all of the original rock has been hydrothermally altered.

The variations in concentration of the different minerals at the New Arrowhead Mine may be noted by reference to Figure 8.

D. Holt-Bluebell Traverse

The Holt-Bluebell Fluorite Mine may be located by reference to Figure 1. A strike of N 35° W was noted for the fluorite vein at this location. The width of the major vein at this point is about eight feet. The near traverse was within the open cut, the traverse beginning 80 feet south of the shaft. Samples seven through 13 were collected on a N 20° E line; samples 14 through 21 were collected on a N 30° W line. The N 20° E part was sampled from west to east. The N 30° W part was sampled from east to west. The Holt-Bluebell far traverse was begun 1000 feet south of the open cut where the road crosses the ridge. It ended at the open cut where the road crosses the ridge.

In the traverse near the fluorite vein, the hydrothermal alteration products are hydrothermal quartz, "bleached" biotite, sericite,

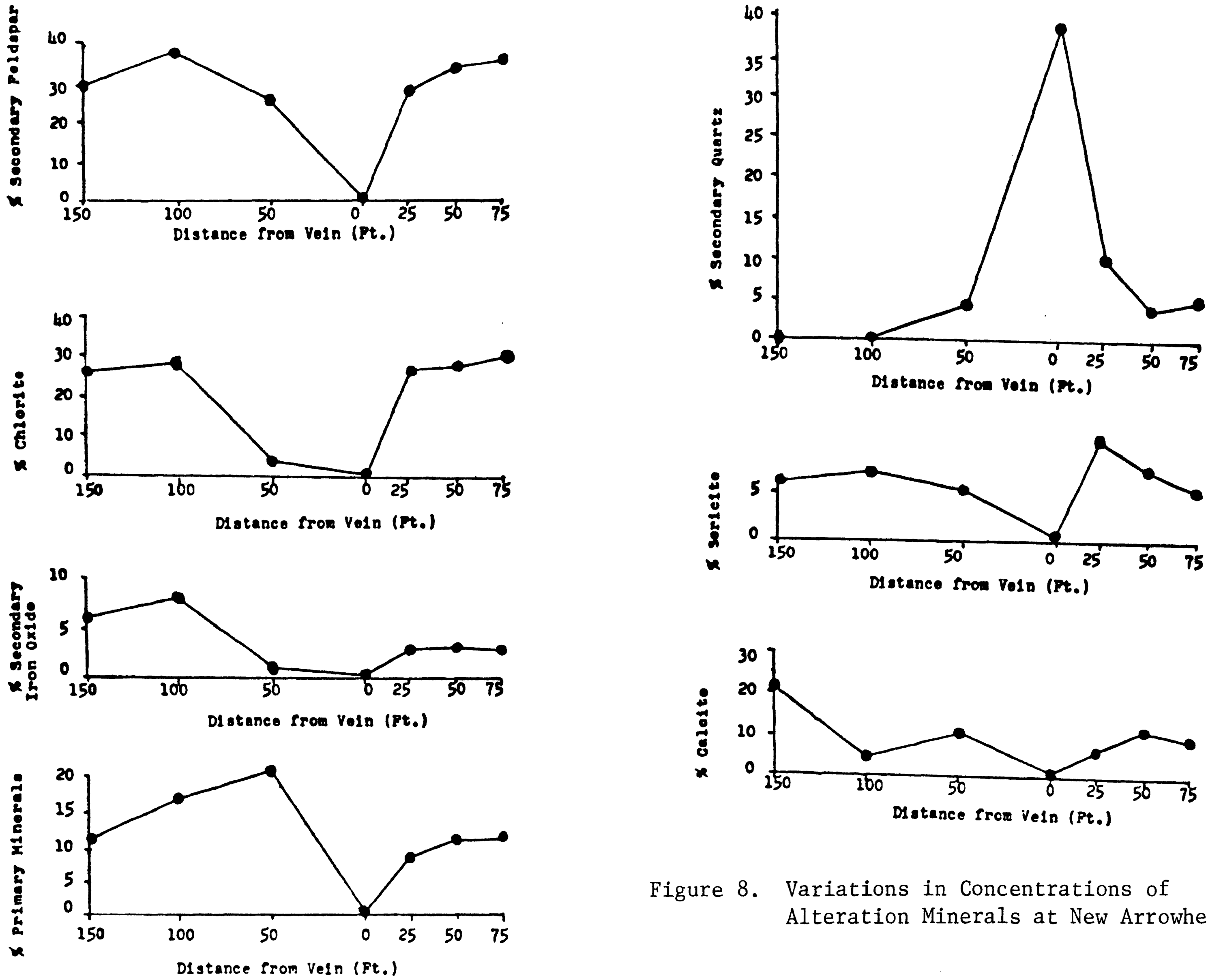

Figure 8. Variations in Concentrations of Alteration Minerals at New Arrowhead

secondary feldspar, hydromuscovite, and secondary iron oxide. In the traverse at some distance from the vein, the hydrothermal products are sericite, secondary feldspar, hydromuscovite, secondary iron oxide, and calcite. Therefore, hydrothermal quartz and "bleached" biotite occur near the vein and not at some distance from it. Limonite also appears near the vein and not at some distance from it; however, it is believed that limonite is a weathering product. Calcite appears at some distance from the vein, but does not occur near the vein.

Where plagioclase is altered, it alters to secondary feldspar, sericite, and/or calcite, with traces of epidote and zoisite. Biotite at the Holt-Bluebell traverse is usually "bleached" near the vein, with some traces of epidote, zoisite, and secondary iron oxide. At some distance from the vein, biotite is not altered. Hornblende alters to calcite and secondary iron oxide, but since hornblende is just an accessory product of the host rock, not a great amount of calcite and secondary iron oxide appear at the expense of hornblende. Primary accessory diopside is hydrothermally altered completely to calcite and traces of secondary iron oxide.

At the traverse near the fluorite vein, the per cent of hydrothermal quartz ranges from zero to 73, with an average of about 42 per cent. The concentration of sericite ranges from zero to five per cent. Secondary feldspar varies from zero to 10 per cent. It is noted that in this traverse, where the secondary feldspar increases, the sericite also increases. The converse is also true. Hydromuscovite varies from zero to 28 per cent, with the average being about 14 per cent. Limonite "dusting" of the thin sections studied was from six per cent to 24 per cent. The average is about 15 per cent. The primary mineral content ranges from four per cent to 37 per cent, the average being 12 per cent.

The concentration of the hydrothermal minerals in the traverse at some distance from the fluorite vein was also plotted versus the distance along the traverse. Sericite varies from zero to eight per cent, the average being three per cent. Secondary feldspar varied from five to 36 per cent, the average being 24 per cent. Calcite varies from zero to 12 per cent, the average being four per cent. Hydromuscovite varies from zero to 10 per cent, the average being two per cent. The primary mineral content varies from 37 to 95 per cent, the average being 64 per cent.

The long traverse shows a weaker alteration intensity and a less distinct zoning. Since this traverse is associated with only a weak development of the main vein, these observations are not surprising. They indicate that intensity of alteration is controlled by the same factors that control development of the vein.

The variations in the concentrations of the alteration minerals at the Holt-Bluebell Mine may be referred to in Figure 9.

E. Rhyolite Knob Traverse

The location of the rhyolite knob may be noted be reference to Figure 1. The knob is located one and two tenths miles north of Zane and nine and two tenths miles north or Lund immediately adjacent to the dirt road. A 2100-foot, N 55° W traverse was sampled. The sampling began 2100 feet south-westerly from the knob on a series of three prominent hills and ended

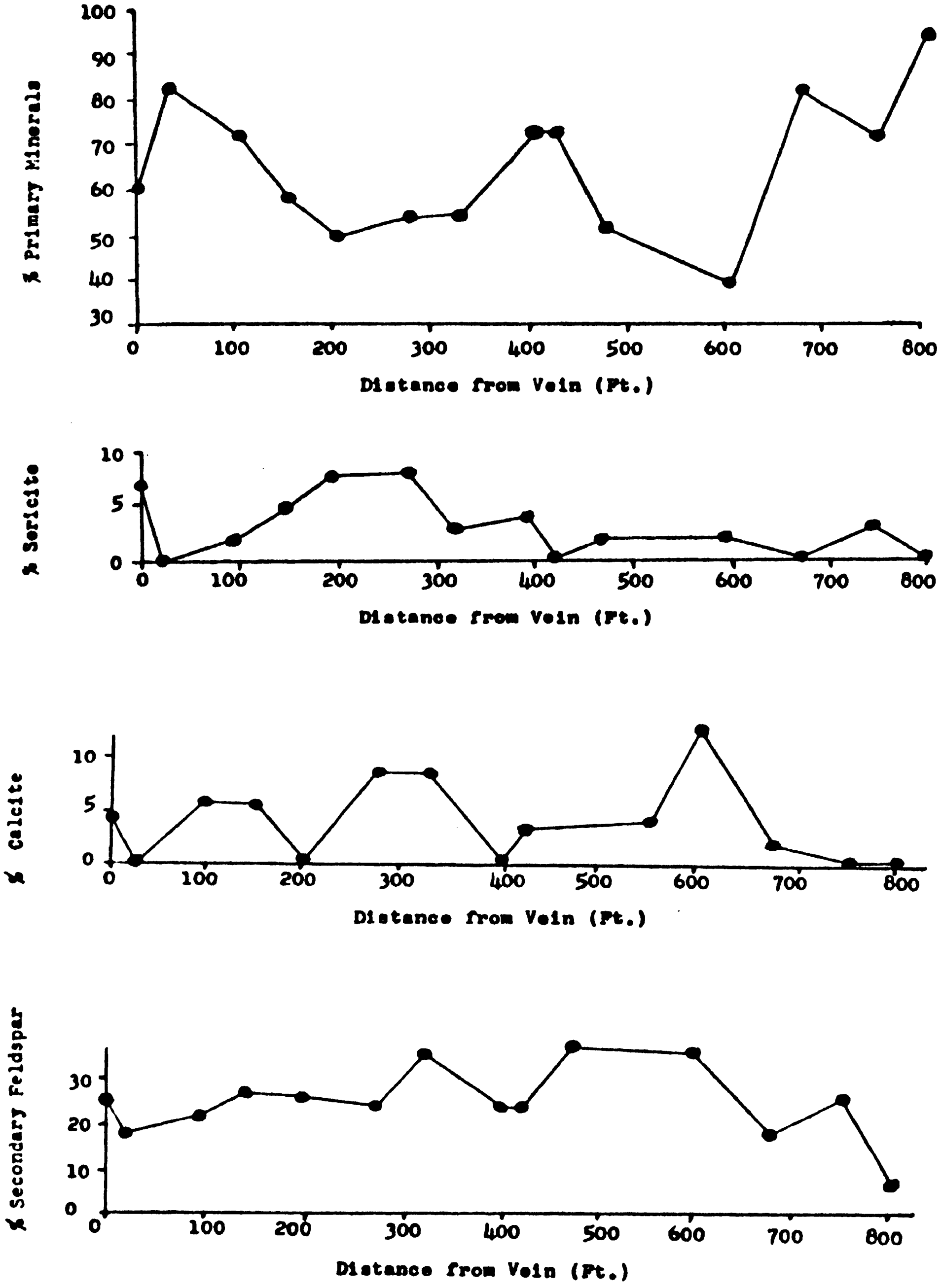

Figure 9. Variations in Concentrations of Alteration Minerals at Holt-Bluebell Far Traverse

immediately adjacent to the knob. The Isom Formation exists around this rhyolite knob. It is a post-Needles Range vitric tuff. The Isom is a deep reddish brown and contains only a small amount of plagioclase and biotite crystals. Large tubular vesicles are always present. The Isom lies directly on the uppermost member of the Needles Range Formation. The reason for choosing to include a traverse near this rhyolite knob is mainly for comparison of mineralogy and petrography. There are distinct differences between the mineralogy and petrography found at the rhyolite knob compared to the previously discussed mine locations.

The secondary alteration products at the rhyolite knob differ somewhat when compared to the products at the previously discussed mine locations. No secondary feldspar, epidote, zoisite, chlorite, or hydromuscovite were noted at this location. The secondary products that were noted at both the mine areas and the rhyolite knob location are secondary quartz, sericite, secondary iron oxide ("hematite"), and calcite. The only minerals found near the knob and not found at the mine locations are nontronite (?)(an iron-rich montmorillonite) and limonite. The limonite and nontronite (?) are probably weathering products. The limonite seems to dust the thin sections studied. The nontronite (?) appears mostly around the "hematite". The "hematite" has, thus, partially been weathered to an iron-rich montmorillonite (?). Sometimes, gray "hematite" is rimmed by red "hematite" is rimmed by nontronite (?). Elsewhere, there is simply nontronite (?) rimming red "hematite" or nontronite (?) rimming gray "hematite".

The secondary quartz forms very minute veinlets through the glassy matrix. They are much smaller veinlets when compared with the veinlets noted at the mine locations.

Sericite is absent except very near the knob. There, it totally replaces the primary plagioclase. Calcite also partly replaces the primary plagioclase, but farther away from the knob than the sericite. Calcite and "hematite" have completely replaced diopside. There are several relic octagonal pseudomorphs of calcite after pyroxene.

The primary minerals were plagioclase, quartz, clinopyroxene, and volcanic glass. The glass has partially been devitrified.

The secondary quartz content is small partially due to the minute size of the veinlets. The content of secondary quartz never exceeds 10 per cent and is rather irregular with distance from the knob.

As previously mentioned, sericite is found only immediately adjacent to the knob. Its content is 41 per cent there, whereas there is only a trace any more distant than immediately adjacent to the rhyolite knob. This is an abrupt change, especially when one compares it to the gradual change found at the mine sites.

The secondary red and gray "hematite" content never exceeds nine per cent in the 2100-foot traverse. It generally is less toward and more away from the knob, but only varies between zero and nine per cent. The variation is small and irregular.

The content of calcite is around four per cent about 200 to 500 feet from the source and zero nearer to and farther from the knob.

The trend of nontronite (?) is increasing away from the source from zero to 23 per cent 1800 feet from the source.

The concentration of limonite dust is about nine per cent near the knob, about one per cent 400 feet from the source, and about eight per cent 1800 feet from the knob.

The concentration of primary minerals is very high when one compares it with the content of primary minerals at the mine locations. The per cent is around 80 far from the source and goes to a low of 48 per cent immediately adjacent to the source. Devitrified glass has been considered as a primary mineral because it is not of hydrothermal origin. This is one reason that the concentration of the primary minerals seems high in comparison with the mine locations.

F. Summary

There are many similarities when one compares all of the mine locations. The writer believes that generalities that may be obtained from the mining district as a whole are of great significance (See Figure 10). For instance, in all the mine locations the intensity of alteration increases toward the vein. This is shown by the fact that the primary mineral content decreases toward the vein. Another phenomenon common to all of the mines is that only certain minerals are affected by the hydrothermal fluids.

The primary minerals that were affected by hydrothermal solutions are plagioclase, biotite, hornblende, and diopside. Plagioclase, biotite, and hornblende appear in the New Arrowhead and J.B. locations. Plagioclase, biotite, hornblende, and diopside appear at the Holt-Bluebell location, whereas only plagioclase, biotite, and diopside appear at Cougar Spar. The only unaffected primary mineral found at all of the mine locations is primary quartz.

At Cougar Spar and J.B., plagioclase has altered to sericite, secondary feldspar, and traces of epidote, zoisite, and calcite. At New Arrowhead and Holt-Bluebell, plagioclase has altered to sericite, secondary feldspar, calcite, and traces of epidote and zoisite.

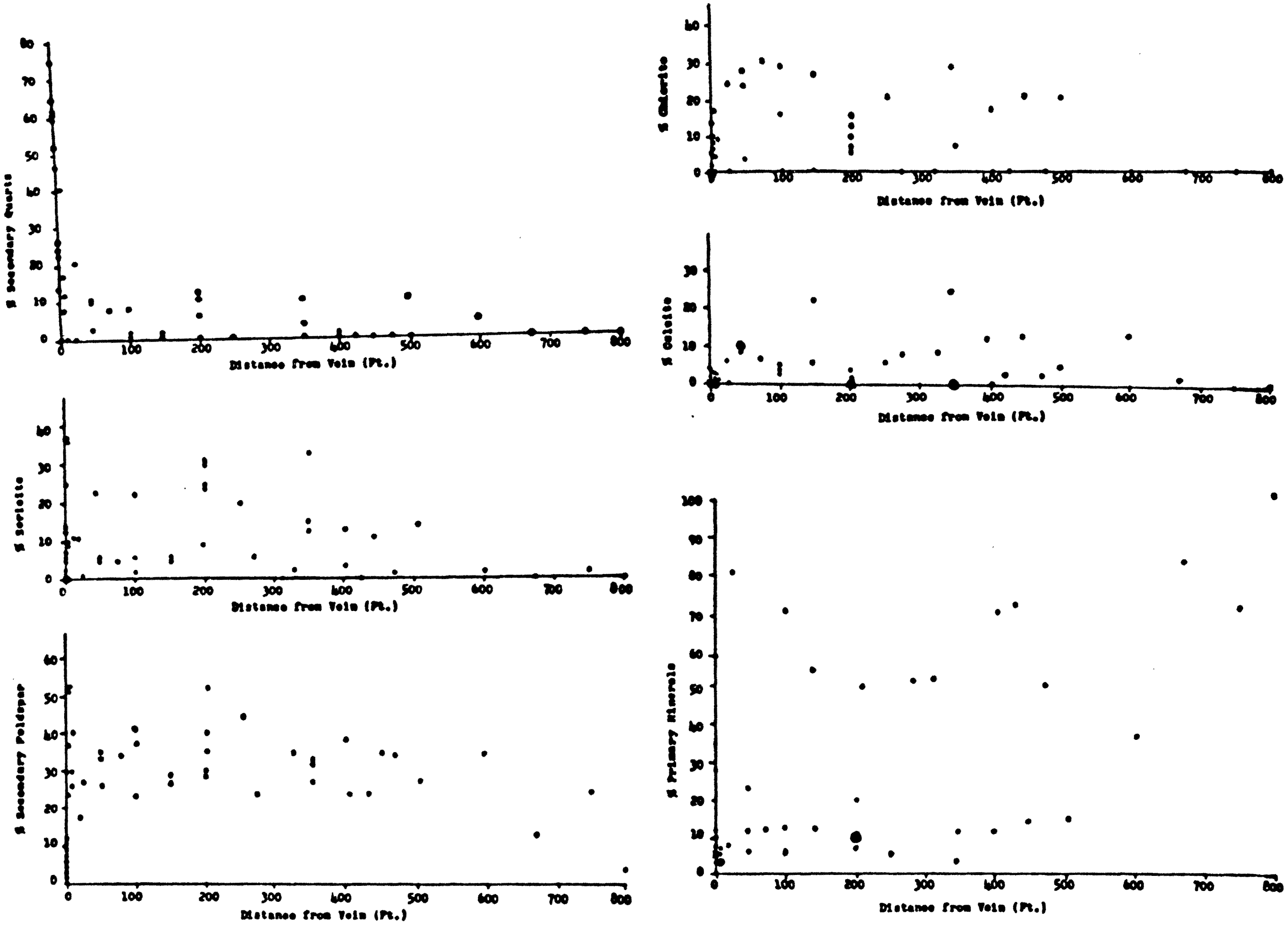

Figure 10. Composite Variations in Concentrations of Alteration Minerals at All Mine Locations; • = 1 point, ⊙ = 2 points, △ = 3 points, X = 4 points, ⊡ = 8 points.

At Cougar Spar, New Arrowhead and J.B., primary biotite has altered to chlorite and secondary iron oxide with traces of epidote, zoisite, and calcite. Holt-Bluebell has only a small amount of biotite altered to chlorite.

At Cougar Spar and Holt-Bluebell, diopside has altered to calcite and secondary iron oxide. At New Arrowhead and J.B., no accessory diopside was in the original host rock. Therefore, no secondary calcite or secondary iron oxide after diopside appeared.

At New Arrowhead and J.B., hornblende has altered to chlorite and secondary iron oxide. At Holt-Bluebell some of the trace hornblende has altered to chlorite and secondary iron oxide.

The hydrothermal alteration products near the vein are quite similar from mine to mine. In all of the mine locations, hydrothermal quartz, secondary iron oxide, sericite, and secondary feldspar appear near the vein. "Bleached" biotite also appears at Cougar Spar, J.B., and Holt-Bluebell near the vein. Hydromuscovite appears at New Arrowhead, J.B., and Holt-Bluebell near the vein.

The hydrothermal alteration products found at some distance from the vein are several. Chlorite appears at all of the mines in quite large concentrations except at Holt-Bluebell. Secondary feldspar, sericite, secondary iron oxide, and calcite appear at all the mine locations at some distance from the vein. Some hydromuscovite appears at some distance from the vein at Holt-Bluebell only.

The trend of concentrations of chlorite increases away from the vein at Cougar Spar, New Arrowhead, and J.B. There is not much chlorite found at Holt-Bluebell, so therefore, a trend is not prominent.

At Cougar Spar the secondary iron oxide increases toward the vein. At New Arrowhead the secondary iron oxide decreases toward the vein. At J.B. and Holt-Bluebell, the variation is very small and rather insignificant.

At Cougar Spar, New Arrowhead, J.B., and Holt-Bluebell, the hydrotermal quartz increases toward the vein.

At Cougar Spar, New Arrowhead, J.B., and Holt-Bluebell, the sericite increases toward the vein, but immediately near the vein, the sericite decreases. Secondary feldspar at the Cougar Spar, New Arrowhead, and Holt-Bluebell traverses has a similar trend. At the J.B. Mine secondary feldspar has no particular trend.

Calcite, at the New Arrowhead and Holt-Bluebell locations increases away from the vein. At Cougar Spar and J.B., calcite is found only in traces.

At the J.B. Mine hydromuscovite appears only near the vein. At Holt-Bluebell hydromuscovite appears near the vein and at some distance from it.

When one compares the mineralogy of the rhyolite knob with the mineralogy of the mine locations, he finds that there is no secondary feldspar, epidote, zoisite, chlorite, or hydromuscovite found at the rhyolite knob traverse. Plagioclase and pyroxene are the primary minerals affected by the hydrothermal solutions. Biotite is partially affected since some grains contain traces of secondary iron oxide. As compared to the mine locations, primary quartz is the only mineral unaffected by the hydrothermal solutions at the rhyolite knob. Plagioclase has altered to sericite and calcite. Pyroxene has altered to calcite and secondary iron oxide.

The concentration of secondary quartz at the rhyolite knob appears to be rather irregular. The secondary iron oxide has a small variance as at the J.B. and Holt-Bluebell mines. Sericite appears only immediately adjacent to the knob, whereas at the mine locations, it appears at some distance from the vein also. Calcite also appears only immediately adjacent to the knob, whereas at the New Arrowhead and the Holt-Bluebell mines, calcite increases away from the vein. At the mine locations, the primary minerals decrease toward the vein. At the rhyolite knob, the primary minerals also decrease toward the knob. Limonite concentration seems to be irregular. Nontronite (?) increases away from the knob. However, limonite and nontronite (?) are believed to be weathering products.

VI. RESULTS

The analysis of the data accumulated at the mine locations and the rhyolite knob consists of statistical tests. The means and the standard deviations have been computed for all of the separate traverses and then the overall mean and standard deviation for all of the mine locations as a whole were computed. Also the means and standard deviations have been computed for the rhyolite knob traverse. The means and standard deviations were also utilized in a statistical test termed the Student's *t*-test. The mean is the average of the data. The standard deviation is the square root of the average of the square of the individual deviations from the mean.

The means and standard deviations were analyzed for the following minerals: hydrothermal quartz, epidote and zoisite, sericite, secondary feldspar, chlorite, secondary iron oxide, calcite, hydromuscovite, limonite, and the primary minerals.

The results of the statistical tests are found on pages 62-66.

Generally, the standard deviations of secondary quartz are quite high. This means that there is quite a great deviation from the mean. This phenomenon seems to be quite reasonable since there is quite a difference between the concentration of secondary quartz at the vein versus the concentration at some distance from the vein.

Chlorites's standard deviations are relatively high also. This, again is to be expected since there is not much chlorite near the veins, but it does appear more readily at some distance from the vein.

The standard deviations that seem to be moderate in amount are the standard deviations for sericite, secondary feldspar, hydromuscovite, limonite, and the primary minerals.

The standard deviations that seem to be relatively low are those for secondary iron oxide and calcite. The deviations of these minerals do not seem to be too far from the mean. The concentrations of these minerals do not vary a great deal with distance from the vein.

The previous discussion of the relative standard deviations always took the mean into consideration. Therefore, this is the relative standard deviation, or the coefficient of variation, which is defined as the ratio of the standard deviation to the mean.

Another statictical test is the Student's _t_-test. The purpose of the test is to attempt to prove that significant differences exist between the parameter means obtained at each locality sampled. Mean values are analyzed for the following: secondary quartz, epidote and zoisite, sericite, secondary feldspar, chlorite, secondary iron oxide, calcite, hydromuscovite, and the primary minerals.

The equation for _t_ is:

$$t = \frac{\overline{Y} - u}{s \ / \sqrt{n}}$$

in which $\overline{Y}$ is the mean of the group being tested, _u_ is the mean of the total population, _s_ is the standard deviation of the total population, and _n_ is the number of samples in the group being tested.

The applicable _t_ values for the .20 significance level are:

$t_{.2}(4) = 1.476$ $\quad$ $t_{.2}(8) = 1.383$

$t_{.2}(6) = 1.415$ $\quad$ $t_{.2}(13) = 1.345$

The numbers in parentheses are the degrees of freedom which are equal to the number of samples minus one. If the *t*-test gives a value greater than the above values, then one rejects the hypothesis that there is no difference between the means from the localities sampled, i.e., variations are present.

The following results are obtained by use of the Student's *t*-test:

Quartz $u = 13.7$ $s = 24.4$

t_{CS} (9 samples) = 0.0984 (1.383) accepted

t_{NA} (7 samples) = 0.2278 (1.415) accepted

t_{JB-N} (5 samples) = 0.4032 (1.476) accepted

t_{JB-F} (7 samples) = -1.3557 (1.415) accepted

t_{HB-N} (7 samples) = 3.6009 (1.415) rejected

t_{HB-F} (14 samples) = -2.0859 (1.345) rejected

The results indicate that the Holt-Bluebell near traverse has a concentration of secondary quartz slightly higher than the average. At the Holt-Bluebell far traverse, exactly the opposite occurs. The concentration of secondary quartz is significantly lower than the mean. The other traverses have secondary quartz concentrations that approximate the mean

Epidote and Zoisite $u = 0.2$ $s = 0.2$

t_{CS} (9 samples) = 2.9985 (1.383) rejected

t_{NA} (7 samples) = -2.6459 (1.415) rejected

t_{JB-N} (5 samples) = -2.2359 (1.476) rejected

t_{JB-F}(7 samples) = 6.6146 (1.415) rejected

t_{HB-N}(7 samples) = -1.3229 (1.415) accepted

t_{HB-F}(14 samples) = -3.7418 (1.345) rejected

All of the traverses except the Holt-Bluebell near traverse have a concentration of epidote and zoisite that vary slightly from the mean.

Sericite $u = 11.0$ $s = 15.0$

t_{CS} (9 samples) = 3.3800 (1.383) rejected

t_{NA} (7 samples) = -0.9173 (1.415) accepted

t_{JB-N}(5 samples) = 0.0596 (1.476) accepted

t_{JB-F}(7 samples) = 1.2701 (1.415) accepted

t_{HB-N}(7 samples) = -1.5347 (1.415) rejected

t_{HB-F}(14 samples) = -1.9209 (1.345) rejected

At Cougar Spar and Holt-Bluebell, the concentration of sericite varies slightly when compared to the mean. At New Arrowhead and J.B., the concentrations are near that of the mean.

Secondary Feldspar $u = 26.4$ $s = 29.5$

t_{CS} (9 samples) = 0.4780 (1.383) accepted

t_{NA} (7 samples) = 0.0000 (1.415) accepted

t_{JB-N}(5 samples) = 0.8868 (1.476) accepted

t_{JB-F}(7 samples) = 1.1212 (1.415) accepted

t_{HB-N}(7 samples) = -1.9912 (1.415) rejected

t_{HB-F}(14 samples) = -0.2917 (1.345) accepted

The only traverse that slightly varies from the mean of the concentration of secondary feldspar is the Holt-Bluebell near traverse.

Chlorite u = 8.8 s = 13.1

t_{CS} (9 samples) = 0.5954 (1.383) accepted

t_{NA} (7 samples) = 2.2420 (1.415) rejected

t_{JB-N}(5 samples) = 0.1707 (1.476) accepted

t_{JB-F}(7 samples) = 2.0198 (1.415) rejected

t_{HB-N}(7 samples) = -1.7774 (1.415) rejected

t_{HB-F}(14 samples) = -2.3423 (1.345) rejected

New Arrowhead, J.B. far traverse, and the Holt-Bluebell traverses vary significantly from the mean of chlorite concentration. Cougar Spar and J.B. near traverse do not vary significantly.

Secondary Iron Oxide u = 2.9 s = 3.5

t_{CS} (9 samples) = 0.4286 (1.383) accepted

t_{NA} (7 samples) = 0.3024 (1.415) accepted

t_{JB-N}(5 samples) = 1.4694 (1.476) accepted

t_{JB-F}(7 samples) = 1.3607 (1.415) accepted

t_{HB-N}(7 samples) = -1.2096 (1.415) accepted

t_{HB-F}(14 samples) = -1.7107 (1.345) rejected

The only traverse that varies somewhat from the mean concentration of secondary iron oxide is the Holt-Bluebell far traverse.

Calcite u = 4.3 s = 6.7

t_{CS} (9 samples) = -1.7015 (1.383) rejected

t_{NA} (7 samples) = 1.6587 (1.415) rejected

t_{JB-N}(5 samples) = -0.5006 (1.476) accepted

t_{JB-F}(7 samples) = 2.8040 (1.415) rejected

t_{HB-N}(7 samples) = -1.6982 (1.415) rejected

t_{HB-F}(14 samples) = -0.3351 (1.345) accepted

At Cougar Spar, New Arrowhead, J.B. far traverse, and Holt-Bluebell near traverse, the calcite concentration is slightly to moderately different from the mean. At the J.B. near traverse and the Holt-Bluebell far traverse, the calcite concentration approximates the mean.

Hydromuscovite $u = 4.3$ $s = 9.2$

t_{CS} (9 samples) = -1.4022 (1.383) rejected

t_{NA} (7 samples) = 1.2367 (1.415) accepted

t_{JB-N}(5 samples) = 0.1215 (1.476) accepted

t_{JB-F}(7 samples) = -1.2367 (1.415) accepted

t_{HB-N}(7 samples) = 2.8186 (1.415) rejected

t_{HB-F}(14 samples) = -0.8948 (1.345) accepted

At Cougar Spar and the Holt-Bluebell near traverse, the concentration of hydromuscovite varies slightly from the mean.

Primary Minerals $u = 25.9$ $s = 37.0$

t_{CS} (9 samples) = -1.2324 (1.383) accepted

t_{NA} (7 samples) = -1.0369 (1.415) accepted

t_{JB-N}(5 samples) = -0.9669 (1.476) accepted

t_{JB-F}(7 samples) = -1.4017 (1.415) accepted

t_{HB-N}(7 samples) = -0.8582 (1.415) accepted

t_{HB-F}(14 samples) = 3.9038 (1.345) rejected

At Holt-Bluebell far traverse, the concentration of the primary minerals is significantly larger than the average concentration. This phenomenon may also be noted by comparison of the concentrations of primary minerals at the different mine locations.

VII. INTERPRETATIONS

A. Zonation

There seem to be roughly concentric zones about the fluorite veins. There is a veinward zone of hydrothermal quartz near the fluorite veins. This process of introduction of SiO_2 hydrothermally is termed silicification. There is a narrow zone of hydromuscovite generally immediately adjacent to the vein. There is a sericite zone outward from this. The propylitic zone fringes the district. The mineralogy here is chlorite, sericite, secondary alkali feldspar, calcite, and epidote and zoisite traces.

These zones, particularly the propylitic zone, are quite wide. It is believed that hot solutions that invade shallow, cool, permeable rocks typically produce prominent, widespread, alteration halos because the country rock is far out of equilibrium with the hydrothermal fluids. This district is an excellent example of this principle.

The width of the zones has been calculated. The width is considered here to be where the mean meets the curves found in Figures 6-10.

The width of the hydromuscovite zone at New Arrowhead is from immediately adjacent to the vein, to 50 feet from it. At the J.B. near traverse, the width of this zone is from immediately adjacent to the vein, to 20 feet from the vein. At the Holt-Bluebell near traverse, it occurs only immediately adjacent to the vein. At the Holt-Bluebell far traverse, it occurs between 125 and 300 feet and between 450 and 625 feet from the vein. When one takes all of the mine locations into consideration, the hydromuscovite zone occurs from immediately adjacent to the vein to 60 feet from it.

At the Cougar Spar Mine, the secondary quartz has a zone width from the vein, to 10 feet from the vein. At New Arrowhead it is from the vein, to 35 feet from the vein. At the J.B. far traverse, the width of secondary quartz is from the vein to 150 feet from the vein. When one takes all of the mine locations into consideration, the width of the secondary quartz zone is from the vein, to 10 feet from the vein.

The width of the sericite zone was next calculated. At Cougar Spar the width of the sericite zone is from the vein, to 300 feet from the vein. At New Arrowhead it is from 20 feet to 150 feet from the vein. At J.B. far traverse, the zone is from 10 feet from the vein, to 250 feet from the vein. At Holt-Bluebell far traverse, the width is from 10 feet to 400 feet from the vein. When one takes all of the mine locations into consideration, the width of the sericite zone is from 10 feet from the vein to 450 feet from the vein.

The width of the chlorite zone was calculated also. At Cougar Spar the width of the chlorite zone is from 100 feet from the vein, to 500 feet (plus) from the vein. At New Arrowhead the width of the chlorite zone is from 50 feet to 150 feet from the vein. At J.B. far traverse, the width is from 250 to 450 feet from the vein. When one takes all of the mine locations into consideration, the width of the chlorite zone is from 50 to 500 feet from the vein.

There is not a great deal of overlap at any of the mine locations, however, there is a small amount. At Cougar Spar, secondary quartz and sericite appear together from the vein to 10 feet from the vein, although sericite continues on to 300 feet from the vein. The sericite zone overlaps a bit into the chlorite zone; however, the chlorite zone does not go nearer the vein than 100 feet distant from it. At New Arrowhead there is only a very small amount of overlap between the secondary quartz, hydromica, and sericite zones. A little more overlap occurs between the sericite and chlorite zones. At J.B. there is no overlap between the zones, excepting a 10-foot overlap between hydromica and sericite. At Holt-Bluebell there is more overlap than at any other mine location. This is between the secondary quartz, hydromica, and sericite zones.

B. Monoascendent Versus Polyascendent

Lovering (1949) discussed rock alteration at the East Tintic District, Utah. He came to the conclusion that the macroscopic structure and the microscopic details both reflect age relations of a series of successive semi-independent stages of alteration, of which the last and least extensive was metallizing. The term polyascendent is now applied to such alteration that occurs in successive stages. Wide-spread dolomitization of limestone and a chloritic alteration of the lavas occurred before the main period of intrusion of quartz monzonite porphyry and monzonite porphyry. Argillic alteration occurred when these porphyries were being intruded. Jasperoidization occurred even later. Sericite-hydromica alteration occurred later and was restricted to ore channels only. This separation of alteration stages by time at East Tintic, Utah, is a classic example of polyascendent alteration.

Sales and Meyer (1948) discussed wall rock alteration at Butte, Montana. They concluded that alteration at Butte (sericitization and argillization) was district-wide and contemporaneous. The term monoascendent is now applied to such alteration that occurs in contemporaneous stages. Sales and Meyer's main argument for monoascendent alteration was that sericite was always adjacent to the ore-bearing vein, and that clay minerals were always found between the sericitized rock and fresh quartz monzonite, except where overlap of alteration effects between adjacent fissures has eliminated the lower grade mineralogical products. Sales and Meyer went on to state that as long as active circulation continued in the channel, each zone migrated away from the fissures, that is, it grew at its outer edge and simultaneously receded at its veinward edge because of encroachment by the next innermost zone.

Sales and Meyer continued on to state that if an early period of alteration was succeeded by a later period, the later one would be superimposed on the earlier one around the early formed fractures. This did not occur at Butte. Furthermore, the two types of alteration occupied the same relative positions.

By reviewing the reasons why Lovering chose polyascendent and Sales and Meyer chose monoascendent, the writer has concluded that the thesis area seems to parallel the monoascendent theory more closely. That is, the alteration in the thesis area was formed contemporaneously. As at Butte, sericite at the Indian Peak District always appeared next to the vein and chlorite always appeared between the sericite and the fresh rock. There also did not appear to be any superposition of one type of alteration over another. Moreover, the two types of alteration always occupied the same relative positions, sericite closer to the vein and chlorite farther away from it. Due to the previously mentioned arguments, monoascendent alteration is the probable process occurring at the Indian Peak District.

C. District-wide Alteration

District-wide alteration is of conclusive importance also. To describe the zonation of the entire district, a central point was necessary to consider. That point is the highest peak in the Needles Range (9785 feet of elevation). Geologically, it is located in the lower most cooling unit of the Wah Wah Springs Tuff. It is two miles south-southwest of the Cougar Spar Mine, three miles west of J.B., four miles north-northwest of New Arrowhead, and three miles south of Holt-Bluebell. One may note by the distances that this point is centrally located. For this reason, this topographic point has been chosen as a reference point for the distances from the center of the district.

From the standpoint of district-wide alteration, essentially three areas of high concentration of alteration minerals exist. From the center point of the districts there is a high concentration southeast of it, east of it, and northwest of it. The one southeast of the center of alteration is the largest area of high concentrations. The alteration is approximately three and two tenths miles in all directions from the center of the district. Most of the exposed alteration was found to be concentrated in the lower part of the stratigraphic section.

VIII. CONCLUSIONS

Since the hydrothermal products of the thesis area in southwestern Utah are secondary quartz, sericite, hydromica, secondary alkali feldspar, epidote, zoisite, chlorite, calcite, and secondary iron oxide, the oxides formed by hydrothermal introduction, rearrangement, replacement, removal, and/or recrystallization are SiO_2, K_2O, Al_2O_3, H_2O, Na_2O, CaO, Fe_2O_3, FeO, MgO, and CO_2.

The SiO_2 was probably introduced by the hydrothermal fluids in mass quantity due to the great quantity of hydrothermal quartz veins and veinlets near the fluorite veins.

Hydrothermal fluids are known to have contained much K_2O in other districts. This is a factor in favor of formation of sericite replacing the primary plagioclase laths.

The secondary alkali feldspar is either orthoclase or albite or a solid-solution of both. Therefore, K_2O and/or Na_2O were probably introduced to form it.

The epidote and zoisite occur as products replacing biotite, hornblende, and plagioclase. The oxides forming epidote and zoisite may have been simply rearrangements and recrystallizations of oxides already present in the biotite and hornblende, or may have been introduced by the hydrothermal fluids. The epidote and zoisite in plagioclase could have been rearrangements and recrystallizations of the oxides forming plagioclase but with the introduction of Fe_2O_3 to form the epidote, or all or some of the oxides needed to form epidote and zoisite may have been introduced by the hydrothermal fluids.

Chlorite is formed after biotite and hornblende. All of the necessary constituents are in hornblende and biotite to form chlorite. Therefore, maybe only rearrangement and recrystallization of the oxides gave rise to chlorite. On the other hand, it is possible that all or some of the oxides were introduced to form chlorite.

In order to form secondary calcite, one needs CO_2. Therefore, CO_2 had to be introduced to form the secondary calcite found in plagioclase, hornblende, biotite and diopside. The CaO could have come from the original plagioclase, hornblende, biotite, and diopside, or it may have been introduced.

Secondary iron oxide is found in biotite, hornblende, and diopside. Iron oxide is already in the chemical composition for these minerals, therefore, there may have been simply rearrangement and recrystallization to form the iron oxide in hydrothermal quartz veinlets, which leads one to believe a secondary remobilization of iron oxide.

APPENDIX A

Mineralogic Data

Table 1. Cougar Spar Traverse

Smpl No	Dist/ Vein (FT)	% Sec Qtz	% Ep& Zoi	% Ser	% Sec Feld	% Chl	% Sec Fe Ox	% Cal	% Hymu	% Prim Mins
107	500	10.0	0.9	17.1	30.8	19.7	2.0	4.5	0.0	15.1
108	350	10.0	1.1	34.3	32.5	7.1	1.3	0.0	0.0	13.5
109	200	6.0	0.9	25.0	30.3	15.1	2.9	0.0	0.0	19.9
110	10	11.7	0.7	36.9	40.0	2.8	1.0	0.0	0.0	7.0
35	0	51.3	0.0	25.5	8.7	0.0	12.1	0.0	0.0	2.3
114	10	16.2	0.0	38.1	29.0	10.0	3.0	0.0	0.0	3.7
113	200	11.3	0.0	29.1	39.5	8.7	2.7	0.3	0.0	8.3
111	200	10.0	0.2	29.7	35.0	14.7	2.3	0.0	0.0	8.3
112	350	3.7	0.0	15.6	34.5	24.4	3.3	0.0	0.0	18.5
Mean		14.5	0.4	27.9	31.1	11.4	3.4	0.5	0.0	10.7
Std. Dev.		14.3	0.5	8.0	9.3	7.9	3.4	1.5	0.0	6.3

Table 2. New Arrowhead Traverse

Smpl No	Dist/ Vein (Ft)	% Sec Qtz	% Ep& Zoi	% Ser	% Sec Feld	% Chl	% Sec Fe Ox	% Cal	% Hymu	% Prim Mins
78	150	0.0	0.2	6.1	28.8	25.7	6.0	21.6	0.0	11.5
79	100	0.0	0.0	6.7	36.7	28.4	8.1	3.1	0.0	16.9
80	50	9.7	0.0	5.3	24.9	3.2	0.9	10.1	24.9	21.3
85	0	64.5	0.0	0.0	0.0	0.0	0.0	0.0	35.5	0.0
92	25	19.7	0.0	10.3	27.1	25.8	3.1	5.7	0.0	8.2
91	50	8.8	0.0	6.9	32.2	27.2	2.7	10.7	0.0	11.2
90	75	8.0	0.0	5.5	35.4	29.2	2.6	8.3	0.0	11.0
Mean		15.8	0.0	5.8	26.4	19.9	3.3	8.5	8.6	11.4
Std. Dev.		22.5	0.0	3.1	12.4	12.6	2.8	6.9	15.1	6.7

Table 3. J.B. (Far Traverse)

Smpl No	Dist/ Vein (Ft)	% Sec Qtz	% Ep& Zoi	% Ser	% Sec Feld	% Chl	% Sec Fe Ox	% Cal	% Hymu	% Prim Mins
152	450	0.0	1.3	12.2	35.6	19.8	6.9	12.1	0.0	12.1
153	400	0.0	0.2	13.9	37.1	18.2	6.8	13.5	0.0	10.1
154	350	0.0	0.7	12.1	26.9	26.5	5.2	24.6	0.0	4.5
156	250	0.0	0.3	19.5	44.9	19.1	3.1	6.6	0.0	6.5
157	200	0.0	0.2	25.4	52.2	10.1	2.5	5.0	0.0	5.6
159	100	7.0	0.9	21.8	40.5	14.5	3.1	8.6	0.0	3.9
160	50	1.8	1.1	22.7	34.9	23.3	5.4	9.6	0.0	1.6
Mean		1.2	0.7	18.2	38.9	18.8	4.7	11.4	0.0	6.3
Std. Dev.		2.6	0.4	5.5	8.1	5.4	1.8	6.5	0.0	3.6

Table 4. J.B. (Near Traverse)

Smpl No	Dist/ Vein (Ft)	% Sec Qtz	% Ep& Zoi	% Ser	% Sec Feld	% Chl	% Sec Fe Ox	% Cal	% Hymu	% Prim Mins
162	10	39.9	0.0	8.7	26.4	15.0	1.3	3.3	3.5	1.6
164	0	20.8	0.0	13.2	29.3	13.5	6.7	3.7	3.2	10.3
165	5	23.8	0.0	12.5	37.5	4.7	8.0	3.1	7.3	3.5
166	10	6.1	0.0	10.7	48.5	7.6	6.7	2.0	1.7	17.0
167	15	0.0	0.0	11.8	48.9	8.4	3.5	1.9	8.5	16.9
Mean		18.1	0.0	11.4	38.1	9.8	5.2	2.8	4.8	9.9
Std. Dev.		15.7	0.0	1.8	10.5	4.3	2.8	0.8	2.9	7.2

Table 5. Holt-Bluebell (Far Traverse)

Smpl No	Dist/ Vein (Ft)	% Sec Qtz	% Ep& Zoi	% Ser	% Sec Feld	% Chl	% Sec Fe Ox	% Cal	% Hymu	% Prim Mins
116	800	0.0	0.0	0.0	5.1	0.0	0.9	0.0	0.0	94.1
118	750	0.0	0.0	3.1	25.0	0.0	1.0	0.0	0.0	70.1
121	675	0.0	0.0	0.0	15.5	0.0	1.0	2.2	0.0	81.3
124	600	4.2	0.0	2.3	34.9	0.0	4.1	11.6	4.7	38.3
129	475	0.0	0.0	2.3	35.7	0.0	2.0	4.0	4.8	51.3
131	425	0.0	0.0	0.0	23.5	0.0	1.0	3.1	0.0	72.5
132	400	0.0	0.0	4.3	23.7	0.0	1.0	0.0	0.0	71.1
135	325	0.0	0.0	3.3	34.9	0.0	1.1	8.3	0.0	52.5
137	275	0.0	0.0	8.3	24.1	0.0	1.1	8.3	5.3	52.9
140	200	0.0	0.0	8.4	25.8	5.1	1.1	0.0	10.4	49.2
142	150	0.0	0.0	5.1	26.6	0.0	1.2	5.1	4.5	57.4
144	100	0.0	0.0	2.0	21.1	0.0	1.2	4.7	0.0	71.1
147	25	0.0	0.0	0.7	17.0	0.0	0.9	0.0	0.0	81.4
148	0	0.0	0.0	6.9	24.6	4.0	1.1	4.1	0.0	59.4
Mean		0.1	0.0	3.3	24.1	0.6	1.3	3.7	2.1	64.5
Std. Dev.		1.1	0.0	2.9	8.2	1.7	0.8	3.7	3.3	15.4

Table 6. Holt-Bluebell (Near Traverse)

Smpl No	Dist/ Vein (Ft)	% Sec Qtz	% Ep& Zoi	% Ser	% Sec Feld	% Chl	% Sec Fe Ox	% Lim	% Hymu	% Prim Mins
7	0	72.3	0.9	0.0	0.0	0.0	0.0	20.3	0.0	6.5
14	0	43.0	0.0	4.3	5.1	0.0	2.0	17.5	16.7	11.9
16	0	24.1	0.0	0.0	0.0	0.0	3.0	24.2	20.7	28.0
18	0	10.8	0.0	1.0	4.1	0.0	2.0	18.9	28.3	35.1
24	0	58.7	0.0	0.0	0.0	0.0	0.9	12.1	22.7	5.3
26	0	60.1	0.0	5.3	10.0	0.0	1.0	12.9	5.3	5.2
30	0	59.1	0.0	5.5	10.3	0.0	0.0	14.7	5.1	5.2
Mean		46.9	0.1	2.3	4.2	0.0	1.3	17.2	14.1	13.9
Std. Dev.		22.2	0.3	2.6	4.6	0.0	1.1	4.3	10.1	12.5

Table 7. All Mine Traverses

	% Sec Qtz	% Sp& Zoi	% Ser	% Sec Feld	% Chl	% Sec Fe Ox	% Cal	% Lim	% Hymu	% Prim Mins
Mean	13.7	0.2	11.0	26.4	8.8	2.9	4.3	2.5	4.3	25.9
Std. Dev.	24.4	0.2	15.0	29.5	13.1	3.5	6.7	6.6	9.2	37.0

Table 8. Rhyolite Knob Traverse

Smpl No	Dist/ Knob (Ft)	% Sec Qtz	% Ser	% Sec Fe Ox	% Cal	% Nont (?)	% Lim	% Prim Mins
47	2100	0.7	0.0	5.2	0.0	9.0	6.6	78.4
50	1800	9.8	0.0	0.0	0.0	22.6	7.8	59.7
58	1000	0.7	0.0	8.8	0.0	6.7	8.4	75.3
61	700	0.0	0.0	7.2	0.0	0.8	3.3	88.3
63	500	6.4	0.2	5.3	4.8	0.0	0.5	83.0
65	300	0.0	0.0	5.3	0.0	2.7	1.1	90.7
66	200	0.0	0.0	6.7	5.2	0.1	5.9	81.9
68	100	6.4	0.0	0.2	0.4	0.0	8.3	84.5
69	0	0.0	40.9	0.9	0.0	1.1	9.3	47.7
Mean		2.7	4.6	4.4	1.2	4.8	5.7	76.6
Std. Dev.		3.8	4.8	3.2	2.9	7.4	3.3	14.1

BIBLIOGRAPHY

ASH-FLOW REFERENCES

Cook, Earl F., 1965, Stratigraphy of Tertiary Volcanic Rocks in Eastern Nevada, Nevada Bureau of Mines Reports, Report 11.

Dinkel, Ted, 1969, Vertical and Lateral Variations in a Welded Tuff: Master's Thesis, University of Missouri at Rolla.

Kreider, John, 1970, The Lund Ash-Flow Tuff: Master's Thesis, University of Missouri at Rolla.

Lipman, P.W., and Christiansen, R.L., 1964, Zonal Features of an Ash-Flow Sheet in the Piapi Canyon Formation, Southern Nevada, U.S.G.S. Prof. Paper 501B, pp. B74-B78.

Lipman, P.W., 1964, A Welded Tuff Dike in Southern Nevada, U.S.G.S. Prof. Paper 501B, pp. B79-B81.

Lipman, P.W., Christiansen, R.L., and O'Connor, J.T., 1966, A Compositionally Zoned Ash-Flow Sheet in Southern Nevada, U.S.G.S. Prof. Paper 524F.

Mackin, J. Hoover, 1960, Structural Significance of Tertiary Volcanic Rocks in Southwestern Utah, Am. Jour. of Sci., Vol. 258, No. 2, pp. 81-131.

_______, 1963, Reconnaissance Stratigraphy of the Needles Range Formation in Southwestern Utah, Guidebook to the Geology of Southwestern Utah, pp. 71-78.

Miller, Gerald M., 1963, Outline of Structural-Stratigraphic Units of the Wah Wah Mountains, Southwestern Utah, Guidebook to the Geology of Southwestern Utah, pp. 96-102.

Ross, Clarence S., and Smith, Robert L., 1960, Ash-Flow Tuffs: Their Origin, Geologic Relations, and Identification, U.S.G.S. Prof. Paper 366.

Scott, Robert, 1966, Origin of Chemical Variations Within Ignimbrite Cooling Units, Am. Jour. of Sci., Vol. 264, No. 4, pp. 273-288.

Smith, Robert L., 1960, Ash-Flows, Geol. Soc. of Am., Bull. 71, No. 6, pp. 795-842.

______, 1961, Zones and Zonal Variations in Welded Ash-Flows, U.S.G.S. Prof. Paper 354, pp. 148-159.

HYDROTHERMAL ALTERATION REFERENCES

Armstrong, Lee C., 1940, Decomposition and Alteration of Feldspars and Spodumene by Water, Am. Min., Vol. 25, No. 12, pp. 810-820.

Bonorino, Felix Gonzalez, 1959, Hydrothermal Alteration in the Front Range Mineral Belt, Colorado, G.S.A., Bull. 70, pp. 53-90.

Bray, R. Eldon, 1969, Igneous Rocks and Hydrothermal Alteration at Bingham, Utah, Econ. Geol., Vol. 64, No. 1, pp. 34-49.

Folk, Robert L., 1947, The Alteration of Feldspar and Its Products As Studied in the Laboratory, Am. Jour. of Sci., Vol. 245, No. 6, pp. 388-394.

Grant, S.K., Geology and Ore Deposits of the Indian Peak Fluorspar District, Beaver County, Utah (in press).

Grim, Ralph E., 1968, Clay Mineralogy, McGraw-Hill, Inc., New York, New York, pp. 490-503.

Harvey, Richard P., and Vitaliano, Charles J., 1964, Wall Rock Alteration in the Goldfield District, Nevada, Jour. of Geol., Vol. 72, No. 5, pp. 564-579.

Helgeson, Harold C., 1970, Reaction Rates in Hydrothermal Flow Systems, Econ. Geol., Vol. 65, No. 3, pp. 299-303.

Hemley, J. Julian, 1959, Some Mineralogical Equilibria in the System K_2O-Al_2O_3-SiO_2-H_2O, Am. Jour. of Sci., Vol. 257, No. 4, pp. 241-270.

_______, Meyer, Charles, and Richter, D.H., 1961, Some Alteration Reactions in the System Na_2O-Al_2O_3-SiO_2-H_2O, U.S.G.S. Prof. Paper 424D, Article 408, pp. D338-D340.

_______, and Jones, W.R., 1964, Chemical Aspects of Hydrothermal Alteration with Emphasis on Hydrogen Metasomatism, Econ. Geol., Vol. 59, No. 4, pp. 538-569.

Henderson, F.B., III, 1969, Hydrothermal Alteration and Ore Deposition in Serpentinite-Type Mercury Deposits, Econ. Geol., Vol. 64, No. 5, pp. 489-499.

Hey, M.H., 1954, A New Review of the Chlorites, Mineralogical Magazine, Vol. 30, p. 284.

Huang, Walter T., 1962, Petrology, McGraw-Hill, New York, N.Y., p. 192.

Kelley, Dana R., and Kerr, Paul F., 1957, Clay Alteration and Ore, Temple Mountain, Utah, Geol. Soc. of Am., Bull. 68, No. 9, pp. 1101-1116.

Kennedy, George C., 1944, The Hydrothermal Solubility of Silica, Econ. Geol., Vol. 39, No. 1, pp. 25-36.

Kerr, Paul F., 1968, The Marysvale, Utah, Uranium Deposits, Ore Deposits of the U.S., Graton/Sales Volume II, A.I.M.E., pp. 1020-1042.

Landwehr, W.R., 1968, The Genesis and Distribution of Major Mineralization of Major Mining in Western U.S., Econ. Geol., Vol. 63, No. 8, pp. 967-970.

Leonard, R.J., 1927, The Hydrothermal Alteration of Certain Silicate Minerals, Econ. Geol., Vol. 22, No. 1, pp. 18-43.

Lovering, T.S., and Shepard, Anna O., 1960, Hydrothermal Alteration Zones Caused by Halogen Acid Solutions, East Tintic District, Utah, Am. Jour. of Sci., Bradley Volume, Vol. 258A, pp. 215-229.

Lowell, J. David, and Guilbert, John M., 1970, Lateral and Vertical Alteration - Mineralization Zoning in Porphyry Ore Deposits, Econ. Geol., Vol. 65, No. 4, pp. 373-408.

Lovering, T.S., 1949, Rock Alteration As a Guide to Ore-East Tintic District, Utah, Economic Geology, Monograph 1.

Mackin, J. Hoover, 1968, Iron Ore Deposits of the Iron Springs District, Southwestern Utah, Ore Deposits of the U.S., Graton/Sales Volume II, A.I.M.E., pp. 992-1019.

McKinstry, H.E., 1955, Structure of Hydrothermal Ore Deposits, Econ. Geol., Fiftieth Ann. Vol., Part I, pp. 170-225.

Meyer, Charles, and Hemley, J.J., 1967, in Geochemistry of Hydrothermal Ore Deposits, Barnes editor, Holt, Rinehart, and Winston, Inc., New York, New York, pp. 166-235.

Meyer, Charles, _et al._, 1968, Ore Deposits at Butte, Montana, Ore Deposits of the U.S., Graton/Sales Volume II, A.I.M.E., pp. 1373-1416.

Morey, George W., and Ingerson, Earl, 1937, The Pneumatolytic and Hydrothermal Alteration and Synthesis of Silicates, Econ. Geol., Vol. 32, No. 5, pp. 607-761.

Norton, F.H., 1939, Hydrothermal Formation of Clay Minerals in the Laboratory, Part I, Am. Min., Vol. 24, No. 1, pp. 1-17.

_______, 1941, Hydrothermal Formation of Clay Minerals in the Laboratory, Part II, Am. Min., Vol. 26, No. 1, pp. 1-17.

Park, Charles F., Jr., and MacDiarmid, Ray A., 1964, Ore Deposits, W.H. Freeman and Co., San Francisco, pp. 138-160, 259-266.

Peterson, N.P., Gilbert, C.M., and Quick, G.L., 1946, Hydrothermal Alteration in the Castle Dome Copper District, Arizona, Econ. Geol., Vol. 41, No. 8, pp. 820-840.

Raymahashay, Bikash C., and Holland, Heinrich, D., 1969, Redox Reactions Accompanying Hydrothermal Wall Rock Alteration, Econ. Geol., Vol. 64, No. 3, pp. 291-305.

Sales, Reno H., and Meyer, Charles, 1948, Wall Rock Alteration at Butte, Montana, A.I.M.E., Trans., Vol. 178, pp. 9-35.

Schwartz, George M., 1955, Hydrothermal Alteration as a Guide to Ore, Econ. Geol., Fiftieth Ann. Vol., Part 1, pp. 300-323.

Shepard, W.M., Morris, H.T., and Cook, D.R., 1968, Geology and Ore Deposits of the East Tintic Mining District, Utah, Ore Deposits of the U.S., Graton/Sales Volume I, A.I.M.E., pp. 941-965.

Sigvaldason, Gudmundur E., and White, Donald E., 1961, Hydrothermal Alteration of Rocks in Two Drill Holes at Steamboat Springs, Washoe County, Nevada, U.S.G.S. Prof. Paper 424D, Article 331, pp. D116-D122.

Silberman, M.L., and Ashly, R.P., 1970, Age of Ore Deposition at Goldfield, Nevada, from K-A Dating of Alunite, Econ. Geol., Vol. 65, No. 3, pp. 352-354.

Stringham, Bronson, 1952, Fields of Formation of Some Common Hydrothermal Alteration Minerals, Econ. Geol., Vol. 47, No. 6, pp. 661-664.

_________, 1953, Granitization and Hydrothermal Alteration at Bingham, Utah, Geol. Soc. of Am., Bull. 64, No. 8, pp. 945-991.

Thompson, Tommy B., 1968, Hydrothermal Alteration and Mineralization of the Rialto Stock, Lincoln County, New Mexico, Econ. Geol., Vol. 63, No. 8, pp. 943-949.

Thurston, W.R., Staatz, M.H., Cox, D.C., et al., 1954, Fluorspar Deposits of Utah, U.S.G.S. Bull. 1005.

Vance, Joseph, 1965, Zoning in Igneous Plagioclase: Patchy Zoning, Jour. of Geol., Vol. 73, No. 4, pp. 636-651.

Vitaliano, Charles J., 1957, Wall Rock Alteration in the Broken Hills Range, Nevada, Jour. of Geol., Vol. 65, No. 2, pp. 167-177.

VITA

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