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GEOCHRONOLOGY OF HYDROTHERMAL ALTERATION AND MINERALIZATION: TERTIARY EPITHERMAL PRECIOUS METAL DEPOSITS IN THE GREAT BASIN

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ABSTRACT

Hydrothermal mineral deposits can be dated directly by the K-Ar method because a variety of potassium-bearing gangue and wall rock alteration minerals are formed by the hydrothermal fluids that deposit the ore metals. The minerals muscovite (sericite), adularia, alunite, natroalunite, biotite, amphibole, and chlorite seem to quantitatively retain argon produced by the radioactive decay of potassium. K-Ar ages of the hydrothermal alteration minerals have been used successfully to determine the ages of formation of precious metal vein and disseminated deposits, poly-metallic base metal vein deposits, porphyry copper, molybdenum and tin deposits, tungsten and base metal scarn deposits, mercury deposits, and thermal spring systems. The hydrothermal mineralization ages have provided useful information about the temporal relationships between ore deposition and spatially associated igneous rocks, and on the patterns of mineralization within tectonic evolution and magmatic and metamorphic timing on a regional scale.

Only a few geochronologic studies on ore deposits have been done in enough detail to yield conclusive evidence on the duration of an entire hydrothermal event or on the timing of individual ore deposition and alteration episodes within that event. The most conclusive data from volcanic-hosted precious metal vein and disseminated deposits, thermal spring systems, and porphyry copper deposits suggest that on average, the total time span of hydrothermal activity is about 1 m.y., although the range of activity is between 0.6 and 2.5 m.y. From textural and theoretical studies of volcanic hosted precious metal deposits a consensus is developing that ore deposition episodes within the overall framework of hydrothermal activity are short lived, transitory, and repetitive.

INTRODUCTION

The timing of hydrothermal alteration and mineralization is important to investigate for a number of academic and practical reasons in the context of comments to the following questions:

(1) How is the time of hydrothermal activity related to volcanism and plutonism? Geochronological studies of epithermal precious metal deposits and porphyry copper deposits have shown that alteration and mineralization can be related to specific stages of igneous activity of a very local nature (e.g. Silberman and others, 1972; Ashley and Silberman, 1976; Chivas and McDougal, 1978; Whalen and others, 1982). In epithermal precious metal deposits a consistent relationship between hydrothermal alteration and later stages of volcanic activity in a cycle can be demonstrated (Silberman and others, 1972; Ashley and Silberman, 1976).

(2) What is the duration of hydrothermal activity, including both alteration and mineralization? Estimates of the duration of hydrothermal activity in ore deposits or thermal spring systems vary from nearly 3 million years (Silberman and others, 1979) to considerably less than one million years (Whalen and others, 1982; Noble and Silberman, 1983, in press). It is still uncertain as to how long it takes for ore deposition to occur within overall hydrothermal phases of activity. Studies of the physical characteristics of hot spring type and vein type of Au, Ag deposits (Buchanan, 1981; Berger and Eimon, 1983, in press; Silberman, 1982b) and attempts at detailed geochronology in complex alteration-mineralization systems (Noble and Silberman, 1983, in press) suggest that the ore depositing episode or episodes are short lived. On the other hand, there are indications from geochronology that major precious metal deposits form in conjunction with hydrothermal systems where the overall period of activity is relatively lengthy, on the order of at least 1 and perhaps greater than 3 m.y. (Silberman and others, 1972; Silberman, unpubl. data; Ashley and Silberman, 1976), and are characterized by repetitive and episodic, short lived hydrothermal processes (Silberman, 1982a; Berger and Eiman, 1983, in press).

(3) What are the regional age relationships of ore deposits within the context of the tectonic framework, including structural evolution, igneous activity and metamorphism? Age determinations of hydrothermal alteration and mineralization have been successful in relating mineral deposits to

the tectonic framework; as examples, Silberman and others (1976), and Rowen and others (1983, in press), in the Great Basin, Mitchell and others (1981), Silberman and others (1980), and Wilson (1980), in southern Alaska, and Clark and others (1982), and Damon and others (in press) in Mexico, related the timing of mineralization to tectonic processes impacting the areas in question.

Perhaps the most significant hydrothermal deposit type that has not been studied conclusively as to its age of mineralization and timing of hydrothermal activity are the carbonate sedimentary rock-hosted (Carlin type) disseminated gold deposits. Silberman and others (1973) determined the age of mineralization at the Getchell deposit, Nevada, and reported ages from a similar deposit at Gold Acres, Nevada. Data exist for similar deposits at Northumberland and Pinson, Nevada (Silberman and others, unpub. data, 1973 to 1982), but in general attempts to interpret the age relations in these deposits unequivocally have been unsuccessful. Geochronological technology, particularly the widespread application of spectrum Ar-Ar dating, is adequate to determine the hydrothermal alteration and mineralization timing in these important deposits and an attempt to carry out the studies should be made.

ACKNOWLEDGEMENTS

Many of the data presented in this paper were produced or gathered during USGS sponsored research between 1967 and 1982. The ideas were crystallized during my work with Anaconda Minerals Co. in 1982 and 1983. I am appreciative of the assistance of many colleagues and co-authors of previous reports at the USGS, the Nevada Bureau of Mines, the California Division of Mines and Geology, the Mackay School of Mines, University of Nevada, and many mining companies whose properties I worked on, upon which this summary is based. I am particularly indebted to Paul Damon and Donald White for their pioneering work on geochronology of ore deposits and on the relationship of thermal spring systems and epithermal ore deposits, respectively.

METHODS AND MATERIALS--EPITHERMAL PRECIOUS METAL DEPOSITS

Several methods of isotopic age determination can be applied to dating hydrothermal alteration, but the most widely applied one has been conventional K-Ar analyses. Hydrothermal fluids that deposit ore metals also deposit K-bearing gangue and wall rock alteration minerals that can be dated by the method. The alteration mineralogy in any hydrothermal system depends on a variety of factors including original host rock mineralogy, hydrothermal fluid temperature, composition, pH, and eH (Meyer and Hemley, 1967; Rose and Burt, 1979).

The K-bearing minerals used to determine the age of hydrothermal alteration include hydrothermal K-feldspars (adularia) (Silberman and others, 1972; Koski and others, 1978), sericite (Silberman and others, 1973), (muscovite), alunite and natroalunite (Ashley and Silberman, 1976; Mehnert and others, 1973), and jarosite (Erickson and others, 1978). All of these are common gangue and wall rock alteration minerals in epithermal vein and disseminated Au, Ag deposits. Adularia, sericite, and alunite are the most commonly dated alteration phases in epithermal deposits. Other minerals that have been used to date alteration directly are hydrothermal biotite and phlogopite (Moore and Lanphere, 1971), hydrothermal amphibole (Silberman and others, 1977), chlorite (Silberman and others, 1977), mariposite (Silberman and Dodge, unpublished data, 1979), and whole rock samples containing combinations of the K-bearing phases (Silberman and others, 1972; Morton and others, 1977; Silberman and others, 1979a; 1979b).

The second most widely applied method of geochronology of alteration has been fission track dating. Apatite, zircon, and sphene have been used successfully to study age relations in alteration systems (Ashley and Silberman, 1976; Lipman and others, 1976). The combination of K-Ar and fission track techniques has been particularly useful as the temperature of annealing of fission tracks in minerals is better known than that for diffusional loss of argon (Nasser and Faul, 1969). Combined fission track and K-Ar data allows a more complete thermal history of an alteration system to be constructed.

EXAMPLES OF ORE DEPOSIT GEOCHRONOLOGY

There are numerous examples of detailed geochronological studies of hydrothermal alteration and mineralization in the literature. I have chosen to summarize two here because of the large numbers of isotopic ages reported in them and because they were specifically designed to answer parts of the questions posed in (1) and (2) of the introduction. Silberman and others (1972) reported on the age of mineralization at Bodie, California in a paper that summarized results of 40 K-Ar analyses from rocks and veins within and nearby the district. Silberman and Ashley (1970) and Ashley and Silberman (1976) summarized the results of 55 K-Ar and fission track ages from the Goldfield district, Nevada.

Bodie mining district

Geology of the mining district

The Bodie mining district, which produced more than 34 million dollars worth of Au and Ag from fissure veins in volcanic rocks of intermediate composition, is near the eastern margin or the Bodie Hills, a volcanic massif of approximately 35 km^3 volume and thickness of up to 1300 feet (400 m). The area surrounding the Bodie Hills contitutes a major volcanic province (fig. 1) which has been subdivided on the basis of dominant overall lithology and age of activity (Kleinhampl and others, 1975; Chesterman, 1968; Gilbert and others, 1968).

Chesterman (1968) and Chesterman and Gray (1975) defined five volcanic formations of Tertiary age rocks in the Bodie Hills, based on

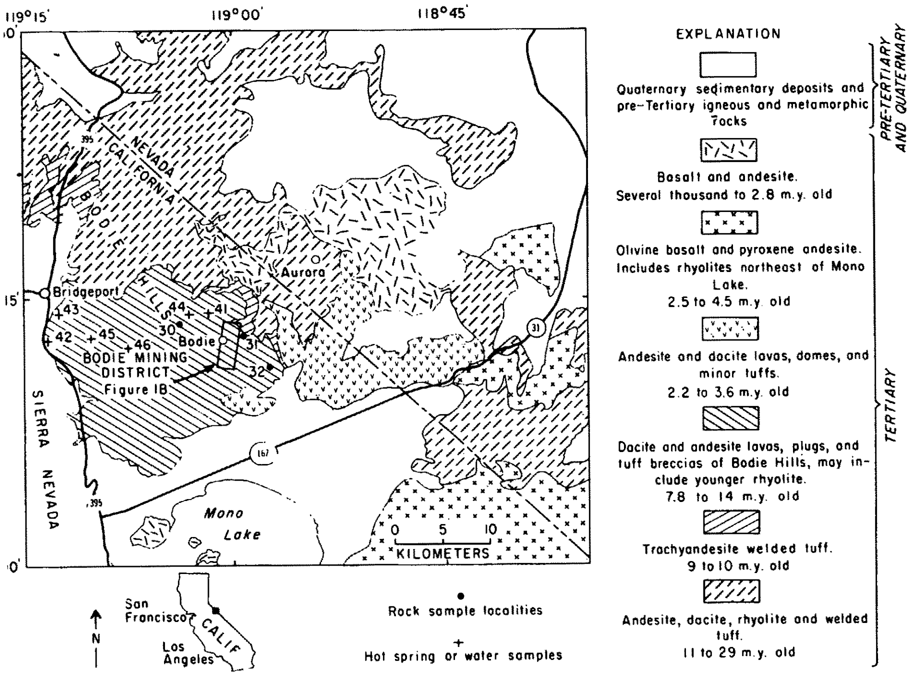


Figure 1. Regional geologic setting of the Bodie Hills and vicinity, California and Nevada, showing age and dominant composition of the Tertiary volcanic rocks (modified from Kleinhampl and others, 1975)

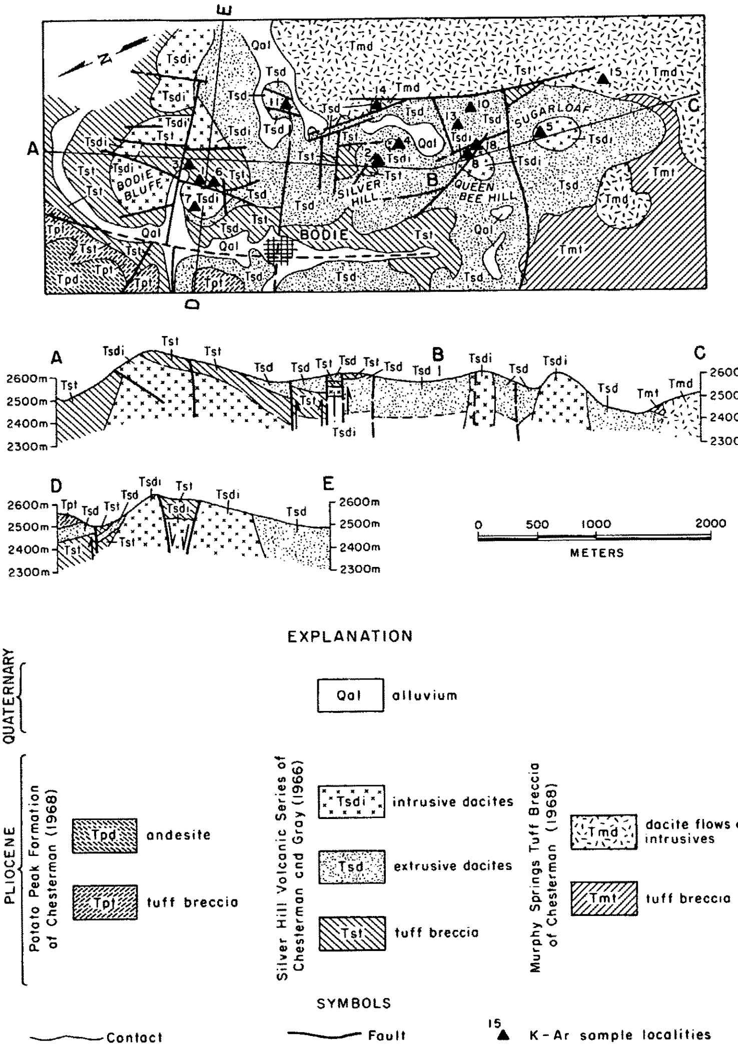


Figure 2. Generalized geologic map and cross sections of the Bodie mining district, Mono County, CA (modified from Chesterman and others, in press).

their proximity to eruptive centers which are characterized by complex structure and intrusive plugs. Many of the formations overlap each other in age as adjoining eruptive centers were frequently active at the same time. Hydrothermal alteration and mineral prospects are common, but the only major deposit located to date has been at Bodie. Although volcanic activity in the Hills spanned the time interval from 13.3 to 5.7 m.y. most of the eruptive material was emplaced between about 9.5 and 7.8 m.y.

The Bodie mining district is localized in dacite flows, tuff breccias and small intrusive plugs of the Silver Hill Volcanic series of Chesterman and Gray (1975), one of the volcanic formations of the Bodie Hills. The district is an eruptive center whose major structure consists of an irregular, faulted, north trending anticline (fig. 2) formed by intrusion and doming of the flows and tuff breccias by small plugs. The plugs occupy vents from which the extrusive volcanic rocks were erupted. Several sets of steeply dipping faults cut all units including the plugs. One prominent set strikes north to northeast, and another is normal to this (fig. 2). The major vein and fractures at Bodie also strike north to northeast parallel to one of the fault sets. Most of the production of the district comes from the vicinity of Bodie Bluff and Standard Hill in the north, in the vicinity of the graben of tuff breccia that was faulted down into the intrusive dacite during or shortly after emplacement (fig. 2).

The productive quartz veins cut both tuff breccia and intrusive rock. Several sets of quartz veins, which vary in thickness from about 1 to 90 ft are present, although most veins are not more than a few feet thick (Chesterman and others, 1983, in press). Adularia is a common constituent of the veins, sometimes forming crystals of up to 3 cm long coating open fractures. Ore minerals are principally native gold and silver, but argentite, pyrite, and sphalerite also occur. The latter increases with depth as the tenor of gold decreases. In the main productive zone near the graben, old records quoted by Chesterman and others (1983, in press) indicate that the ore averaged 1.7 opt (ounces per ton) Au and 3.1 opt Ag.

Wall rock alteration zoning at Bodie has not been studied in detail, although O'Neil and others (1973) reported on the isotopic and chemical effects of hydrothermal K-silicate alteration at Bodie Bluff. Chesterman and others (1983, in press) indicate that alteration zoning occurs both laterally and vertically. In the north, at Bodie Bluff, both the intrusive dacite and tuff breccia and flows are strongly silicified at the surface. Silberman (1982b) suggested that this silicified zone, a part of which has chalcedonic quartz vein stockworking represents a very shallow level in the system, probably just sub-surface. Below this near surface alteration, the rocks of the Bodie Bluff area are strongly K-silicate altered, largely recrystallized to the assemblage K-feldspar (adularia), K-mica (sericite) and quartz. This alteration also characterizes the wall rocks of the productive vein zone. To the south, argillic alteration occurs, and at least some zones of sericite alteration. Outside of the central part of the district, most of the volcanic rocks are strongly propylitized. At the lowest level of workings at Bodie Bluff accessible in recent years, about 700 ft beneath the top, the altered rocks still contain K-feldspar, but sericite and kaolinite are more abundant.

Age relationships

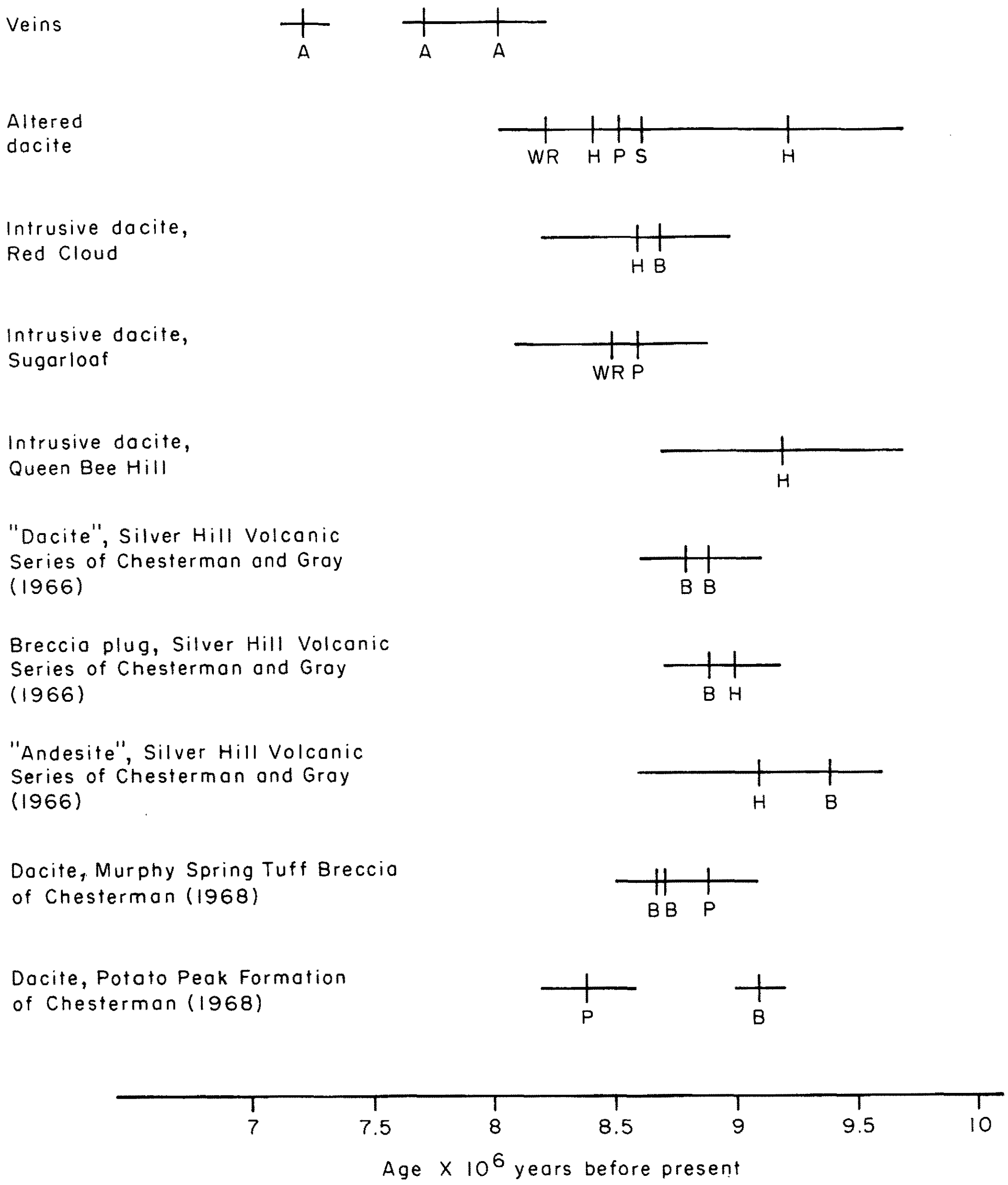
Sample descriptions and data for the age determinations at Bodie and surrounding region were published by Silberman and others (1972), Silberman and Chesterman (1972) and Kleinhampl and others (1975) and are summarized in table 1 and figure 3. The extrusive rocks of the Silver Hill volcanic series were emplaced between 9.4 and 8.8 m.y. The co-magmatic plugs were intruded between 8.6 and 9.4 m.y. Hydrothermal activity, as dated by K-Ar ages of sericite from altered tuff breccia in the southern part of the district, and K-sillicate altered Bodie Bluff intrusive dacite, started at 8.6 m.y., which was just about at the end stage of volcanic activity in the district. Three K-Ar ages from adularia separated from mineralized quartz veins are in the range 8.0 to 7.1 m.y., with the youngest age from a vein occupying a structure that cuts others that hosted veins in the northern part of the district.

Volcanic rocks were emplaced within the volcanic center between 9.4 and 8.6 m.y., about a 1 m.y. duration for the volcanic activity. Hydrothermal alteration commenced at the end of or immediately after volcanism and continued for 1 1/2 m.y., during which several sets ofcross cutting veins (Chesterman and others, 1983, in press) were emplaced and a major precious metal deposit was formed. The alteration-mineralization at Bodie was nearly the last stage of igneous-hydrothermal activity associated with the development of the Bodie Hills volcanic field. It was not until nearly 2 1/2 m.y. later that minor volcanism again occurred, west of the district. To the east, major volcanic activity commenced again at 3.6 m.y. (table 1; fig. 1).

Goldfield mining district

Geology of the mining district

The Goldfield mining district (fig. 4) in the Goldfield Hills of western Nevada is underlain by a complex sequence of Oligocene and Miocene volcanic rocks, which cover a pre-Tertiary basement composed of Ordovician sedimentary rocks and Jurassic granitic rocks. The older Oligocene volcanic rocks (Tov of fig. 4) are silicic flows and tuffs of local origin from a caldera whose ring fracture zone is outlined by the faulting and alteration patterns. The pre-Tertiary rocks are exposed in the core of this caldera. Approximately 4 to 8 m.y. years after cessation of the silicic volcanic activity, a new pulse of dominantly intermediate flows, tuffs, breccias, and domes were emplaced in the early Miocene from



Horizontal line represents analytical uncertainty

Letter refers to mineral used for K-Ar age determination

A = Adularia
S = Sericite
B = Biotite
H = Hornblende
P = Plagioclase
WR = Whole rock

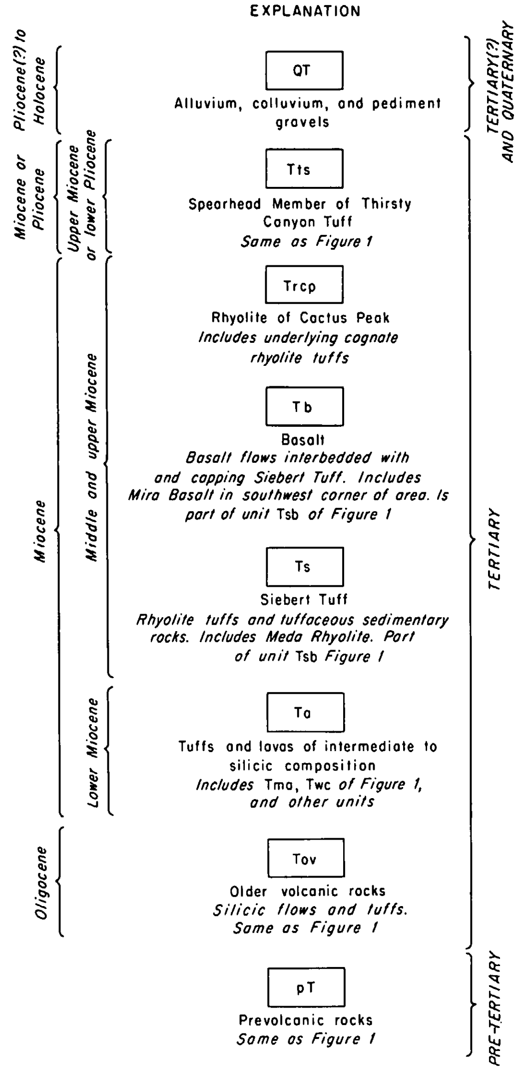
Plagioclase ages from Gilbert and others (1968)

Figure 3. K-Ar ages of volcanic rocks, altered volcanic rocks and quartz-adularia veins at the Bodie mining district and vicinity, Mono County, California (modified from Silberman and others, 1972).

Table 1. Range in Age of Veins and Volcanic Rocks in and near the Bodie Mining District, Bodie Hills, Mono County, California

Younger postore sequence (east of Bodie mining district)	3.6 m.y.-250,000 m.y.
Younger rhyolitic rocks, western Bodie Hills	5.7 m.y.-5.3 m.y.
Veins, Bodie mining district	8.0 m.y.-7.1 m.y.
Hydrothermal activity	8.6 m.y.-7.1 m.y.
Dacite intrusive rocks, Bodie mining district	9.2 m.y.-8.6 m.y.
Silver Hill Volcanic Series of Chesterman and Gray (1976), Bodie mining district	9.4 m.y.-8.8 m.y.
Murphy Spring Tuff Breccia of Chesterman (1968)	8.9 m.y.-8.7 m. y.
[1]Potato Peak Formation of Chesterman (1968)	9.1 m.y.-8.4 m.y.
Other basalts-andesites-dacites-rhyolites, western Bodie Hills	13.3 m.y.-7.8 m.y.

Modified from Silberman and others (1972). [1]Volcanic rocks of the Bodie Hills outside of the Bodie mining district.



Base from Goldfield and Mud Lake quadrangles, 1952.

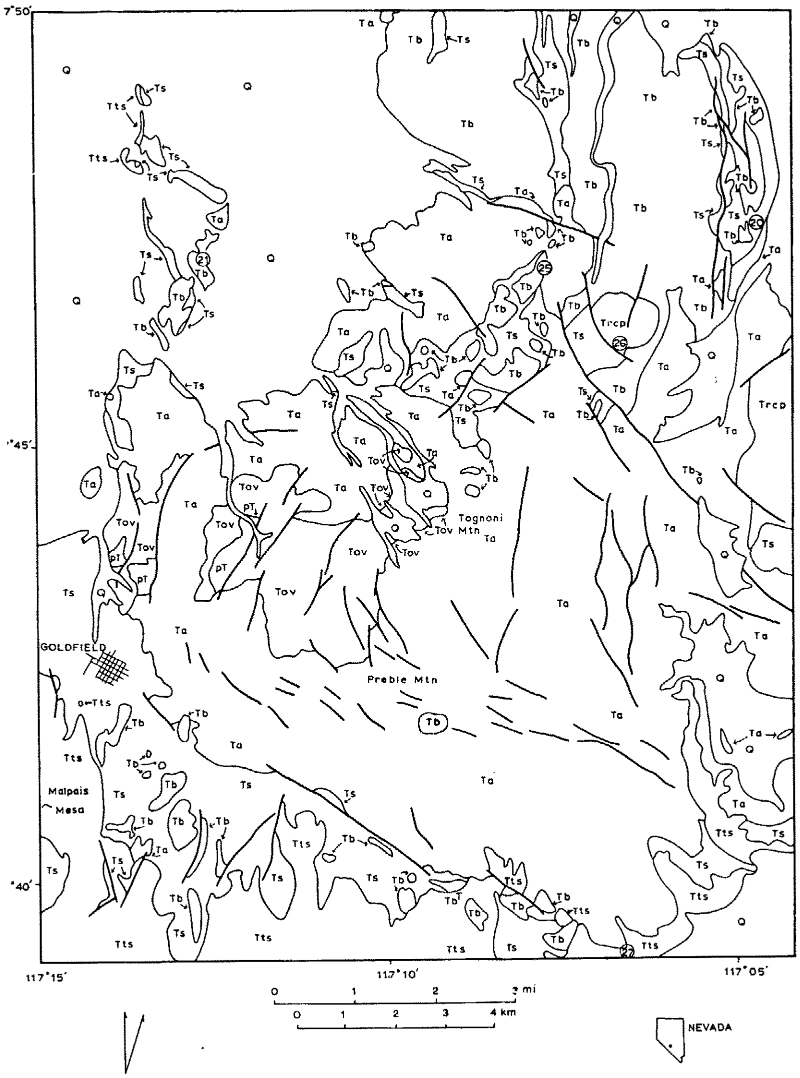
Geology generalized from unpublished mapping by R.P. Ashley, 1972.

SYMBOLS

Contact

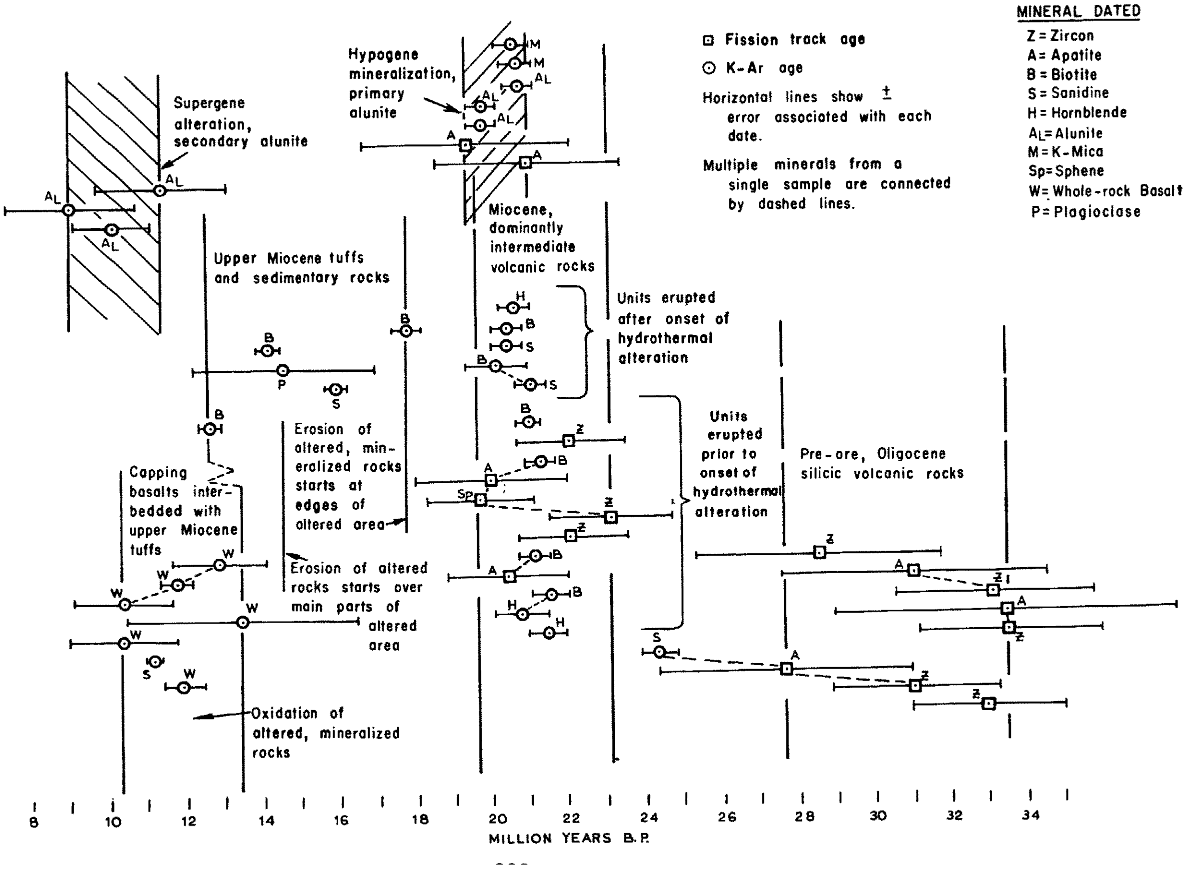
Fault

㉑ Sample locality, including locality number



◁ Figure 4. Simplified geologic map of the Goldfield mining district, Esmeralda and Nye Counties, Nevada (modified from Ashley and Silberman, 1976).

▽ Figure 5. Schematic summary of volcanic history and timing of alteration and mineralization at Goldfield (modified from Ashley and Silberman, 1976).



vents within and near the mining district (units Tma and Twc, fig. 4) (Ashley, 1974; Ashley and Silberman, 1976). Middle and upper Miocene sedimentary and volcanic rocks unconformably overlie the lower Miocene volcanics, and are largely from sources some distance away from the mining district (units Tsb and Tts, fig. 4), although some of the basalts in this younger sequence are erupted from local vents.

Hydrothermal alteration and mineralization at Goldfield are spatially and temporally associated with the dominantly intermediate Tma unit. Unit Twc was emplaced after onset of and during the hydrothermal alteration, but outside of the central part of the district (fig. 4). Mineralization at Goldfield occurs in silicified ledges consisting of prominent outcrops of fine grained quartz that occur throughout a 40 km^2 area of poorly exposed argillic and propylitic rocks. The ledges formed as replacement bodies along faults and fractures and may contain alunite, kaolinite, pyrophyllite and diaspore along with quartz. Limonite and pyrite (latter in unoxidized rocks) occur in all silicified zones. Productive mineralization in the ledges is restricted to a small area of 1.3 km^2, just north of Goldfield (fig. 4). Unoxidized ore formed open cavity fillings in brecciated silicified ledge material and consisted of varying proportions of native gold, and sulfide and sulfosalt minerals (Ashley, 1974). The overall average grade of ore at Goldfield was 0.54 opt (Albers and Stewart, 1972) but bonanza grades as high as 600 opt Au were reported (Ransome, 1909).

Alunite was an important hypogene constituent of the silicified ledges, including those hosting mineralization. It occurred as replacements of feldspar phenocrysts and pumice and as coarse hypogene veins cutting the silicified zones. Alunite deposition in the ledges persisted into early stages of mineralization (Ashley and Silberman, 1976). Supergene alunite occurs as fine grained veins cutting both oxidized silicified and argillized rocks. The zones peripheral to the quartz-alunite ledges were usually argillized, but at least in some areas, including the productive zone, quartz-sericite alteration mantles the ledges (Ashley and Silberman, 1976). The occurrence of the advanced argillic, alunite-containing and quartz-sericite alteration assemblages allowed the K-Ar ages of two alteration minerals to be determined.

Age relations

K-Ar ages of minerals from unaltered volcanic rocks, and from alunite and K-mica (sericite, $2M_1$ polymorph) were determined. In addition fission track ages from several units including the pre-Tertiary and older volcanic rocks (Tov) were obtained. The isotopic ages are summarized in figure 5 from Ashley and Silberman (1976). The older silicic units were propylitically altered and could not be dated by the K-Ar method. Zircon and apatites in these rocks were not affected by that alteration, and indicate emplacement ages of between 28 to 34 million years. The early Miocene host rocks were emplaced starting at about 22 m.y., and volcanism continued for about 1 to 2 m.y. Concordant K-Ar mineral ages and fission track ages were obtained for units of the early Miocene sequence (fig. 5). Post mineralization volcanic and sedimentary units formed between about 18 to 7 m.y. ago. Mineralization thus occurred between 22 and 18 m.y. ago.

K-Ar ages of replacement and hypogene vein alunites are between 21 and 20 m.y. Concordant results were obtained from the sericite samples from quartz-sericite zones near the ledges. Apatite fission track ages from pre-early Miocene units near altered zones gave ages of 21.0 and 19.6 m.y., concordant with the K-Ar results. The isotopic ages of alunite and apatite from Goldfield indicated that alunite provides accurate ages of mineralization in hydrothermal systems, and that apatite ages of rocks near (scale of meters) strongly altered zones also determined the ages of alteration. These results have been confirmed in other mineralized areas in epithermal systems (Morton and others, 1977; Lipman and others, 1976). In contrast, zircon and sphene fission track ages (some of which were collected from the same units as the apatite ages that were reset) are unaffected by proximity to this type of alteration (Ashley and Silberman, 1976).

The three supergene alunite K-Ar ages of about 10 m.y., represent oxidation of the sulfide bearing altered rocks some 10 m.y. after the hypogene mineralization. Fission track apatite ages demonstrate that no major thermal events affected the mineralized area after the early Miocene hydrothermal event. The middle and lower Miocene volcanic activity, apparently had no strong thermal effect here. Structural and stratigraphic data are in accord with erosion and oxidation starting to affect the mineralized area at about the time indicated by the supergene alunite ages. Thus at Goldfield, both hypogene hydrothermal alteration and supergene oxidation were dated by application of K-Ar analyses to alunites. The age relations of volcanic activity and alteration-mineralization at Goldfield are similar to those at Bodie. Several generalized conclusions can be drawn about the timing of igneous-hydrothermal activity from these studies.

(1) Hydrothermal alteration and mineralization starts late in and usually continues for some time after some significant local stage of volcanic activity. Pre- and syn-alteration volcanism lasts on the order of 1 m.y. or longer.

(2) The overall duration of hydrothermal activity indicated by the data at Bodie and Goldfield is 1 to 1.5 m.y. This is close to the average age of hydrothermal systems related to mineralization, as will be shown later.

(3) Volcanic activity can and does take place during and after hydrothermal mineralization, but generally outside of the zone of mineralization.

These generalizations have been confirmed by detailed study of other epithermal systems (Silberman and others, 1979; Noble and Silberman, 1983, in press).

DATA ON LIFETIMES OF HYDROTHERMAL SYSTEMS

A large amount of radiometric age data have become available on mineral deposits since the pioneering studies on porphyry copper deposits by Paul Damon and his associates (Damon and Mauger, 1966), and it is possible to compare the spans of hydrothermal activity at Bodie and Goldfield and their temporal relations to spatially associated igneous rocks with data from other hydrothermal mineral deposits and thermal spring systems. There are, unfortunately, few detailed studies on the chronology of hydrothermal systems, and even fewer that provide unequivocal estimates of the duration of hydrothermal activity.

Figure 6 summarizes data from a tabulation of geochronological studies of hydrothermal systems, including porphyry copper deposits, epithermal precious metal deposits and poly-metallic vein deposits (PM), and thermal hot spring systems (M. L. Silberman, unpubl. data, 1983).

Hydrothermal activity in porphyry copper deposits is generally found to have lasted about 1 m.y. or less, with the exception of the Bingham, Utah (Warnaars et al, 1978) and El Salvador, Chile (Gustauson and Hunt, 1975) systems, where I interpreted the data as indicated lifetimes on the order of 2 m.y. The few detailed studies of precious- and base-metal vein systems available suggest that hydrothermal activity commonly extends over periods of about 0.5 to 1.5 m.y. The longest-lived documented system is at Bodie, California (Silberman and others, 1972). The estimate of about 1.5 m.y. duration is relatively accurate, since the youngest age was obtained on vein material from a structure that cuts other mineralized structures and veins (Silberman and others, 1972). A similar lifetime is suggested for the Tui mine, New Zealand (Adams et al, 1974). Lifetimes of about 1, 0.7, and 0.5 are indicated for Goldfield and Divide, Nevada (Silberman and others, 1979b), and Summitville, Colorado (Mehnert and others, 1973), respectively. Data on other epithermal districts generally indicate a close association of igneous and hydrothermal activity, but are inadequate to infer the interval over which hydrothermal activity was taking place.

Figure 6 also depicts data on the lifetime of several active thermal spring systems. White (1955; 1974) has stressed the close similarity of many thermal springs and epithermal Au-Ag systems, and it now appears that several low-grade, large-tonnaged disseminated gold-silver deposits and prospects such as Round Mountain (Berger and Tingley, 1980), Borealis (Strachan and others, 1982), Sulfur (Wallace, 1980) and Hasbrouch Peak (Bonham and Garside, 1979) are fossil thermal spring systems. The age ranges for most of the thermal spring systems are the same as those for the porphyry and vein deposits, with the exception of Steamboat Springs, for which episodic activity appears to have been unusually long lived.

There do not seem to be significant differences in the lifetimes of these three types of systems, although the available data base is sparse. The average lifetime of hydrothermal activity based on this summary is 1.2 m.y., approximately the age of activity determined for Bodie and Goldfield.

PATTERNS OF GREAT BASIN MINERALIZATION

The relationship between the tectonic evolution of this region and the distribution of epithermal mineral deposits is well documented (Silberman and others, 1976).

Precious metal deposits are associated in space and time with several suites of volcanic rocks that were erupted in the Great Basin from mid to late Tertiary in response to interactions of the North American plate and various Pacific plates. The patterns of volcanic activity are thought to be related to variations in the dip of and the rate of convergence of the plates, and to transform faulting and migration of triple junctions (Atwater, 1970; Lipman and others, 1972; Christiansen and Lipman, 1972; Snyder and others, 1976). The distribution of volcanic rocks in the Great Basin in space and timed was summarized by Stewart and Carlson (1976). Figures 7 through 10 show simplified versions of the Stewart and Carlson maps along with locations of dated epithermal precious metal deposits (Silberman and others, 1976).

The entire pattern represented in figures 7 through 10 shows a generally outward, accurate progression of volcanic activity in time from the central Great Basin toward its margin. The figures also illustrate a similar pattern of outward migration for the hydrothermal mineral deposits. The overall distribution of dated hydrothermal Au-Ag deposits in the Great Basin is shown in figure 11. When the distribution and ages are considered in detail, several patterns and associations of interest are evident; the patterns differ in the northern and central Great Basin, and in the Walker Lane (western Great Basin).

Northern and central Great Basin

Figures 12 and 13 show dated ore deposits and their host rocks as well as the nature of volcanic activity that was taking place in the two regions of the Great Basin. The pattern for the central and northern Great Basin shows epithermal deposits associated with all stages of volcanic activity, with particularly vigorous hydrothermal activity immediately after the onset of crustal extension, in association with no strongly predominant host rock lithology. The area is characterized by a grouping of deposits in time, rather than with a host rock association. Of the 16 dated deposits in the northern and central area (figs. 11, 12) four formed during an early stage of intermediate volcanic activity and three during the period of

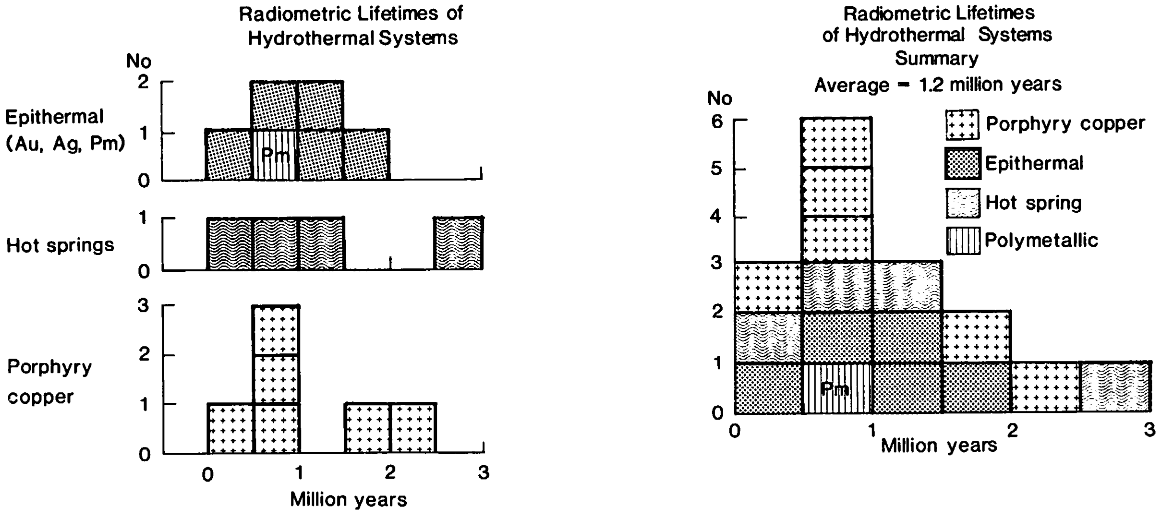


Figure 6. Histograms summarizing radiometric lifetimes of hydrothermal alteration-mineralization systems.

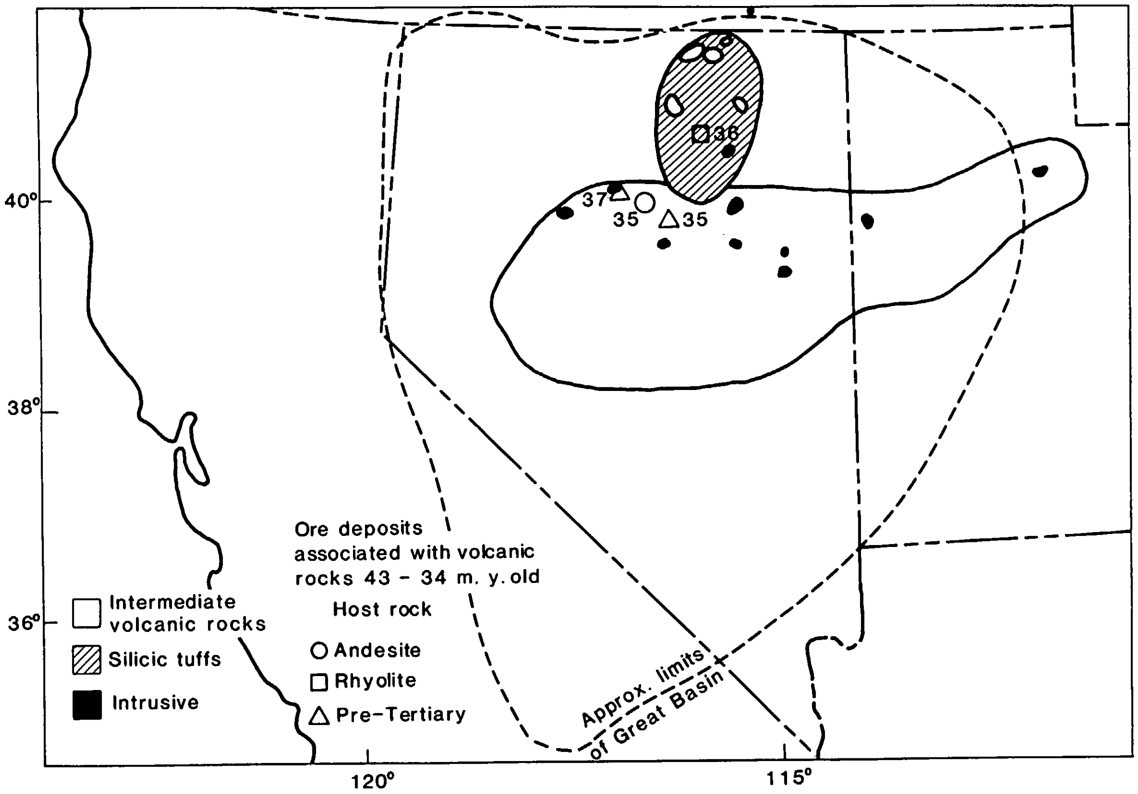


Figure 7. Distribution of volcanic rocks 43-34 m.y. old in the Great Basin and surrounding regions modified from Stewart and Carlson (1976). Location and age of ore deposits, and host rock lithologies are indicated.

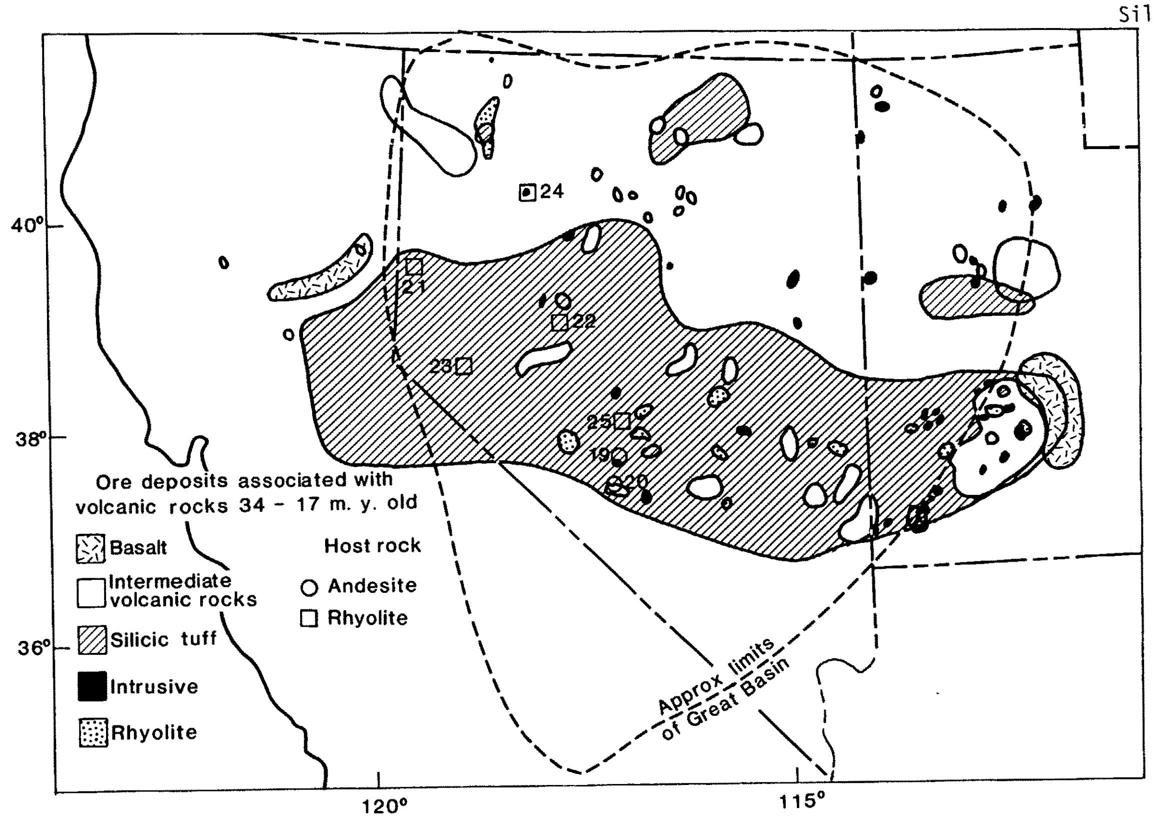


Figure 8. Distribution of volcanic rocks 34-17 m.y. old in the Great Basin and surrounding regions modified from Stewart and Carlson (1976). Location and age of ore deposits, and host rock lithologies are indicated.

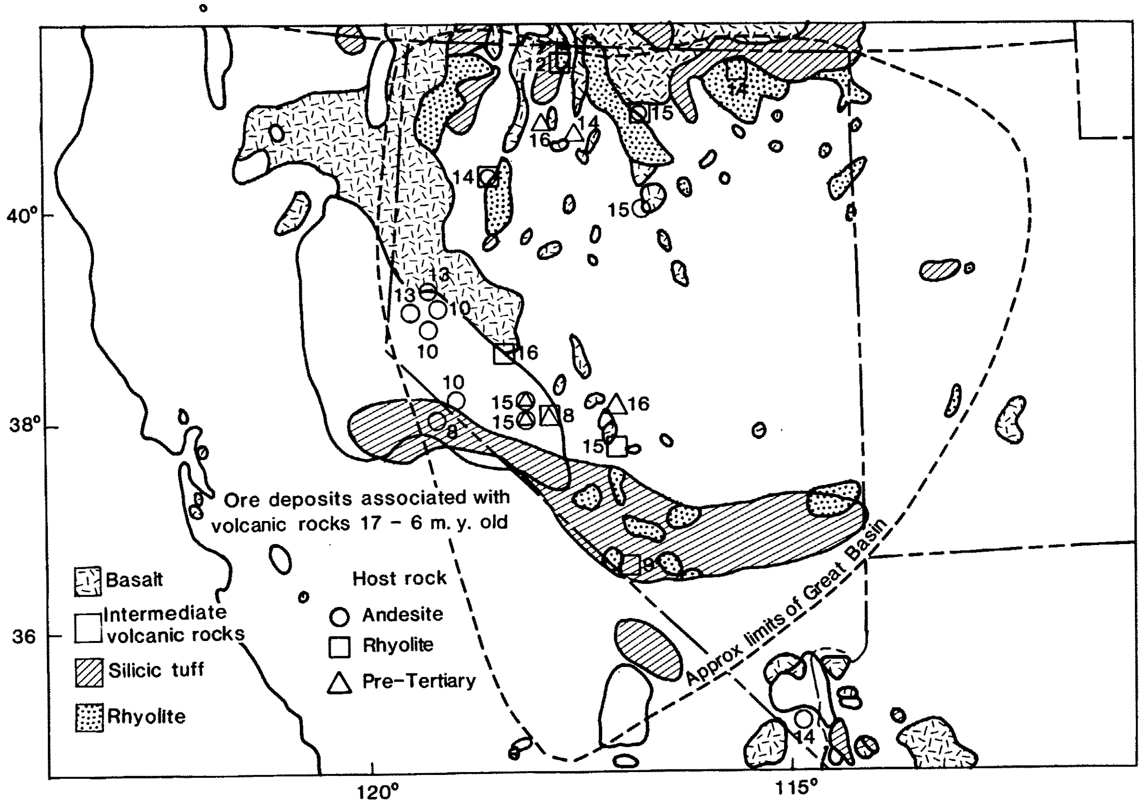


Figure 9. Distribution of volcanic rocks 17-6 m.y. old in the Great Basin and surrounding regions, modified from Stewart and Carlson (1976). Location and age of ore deposits, and host rock lithologies are indicated.

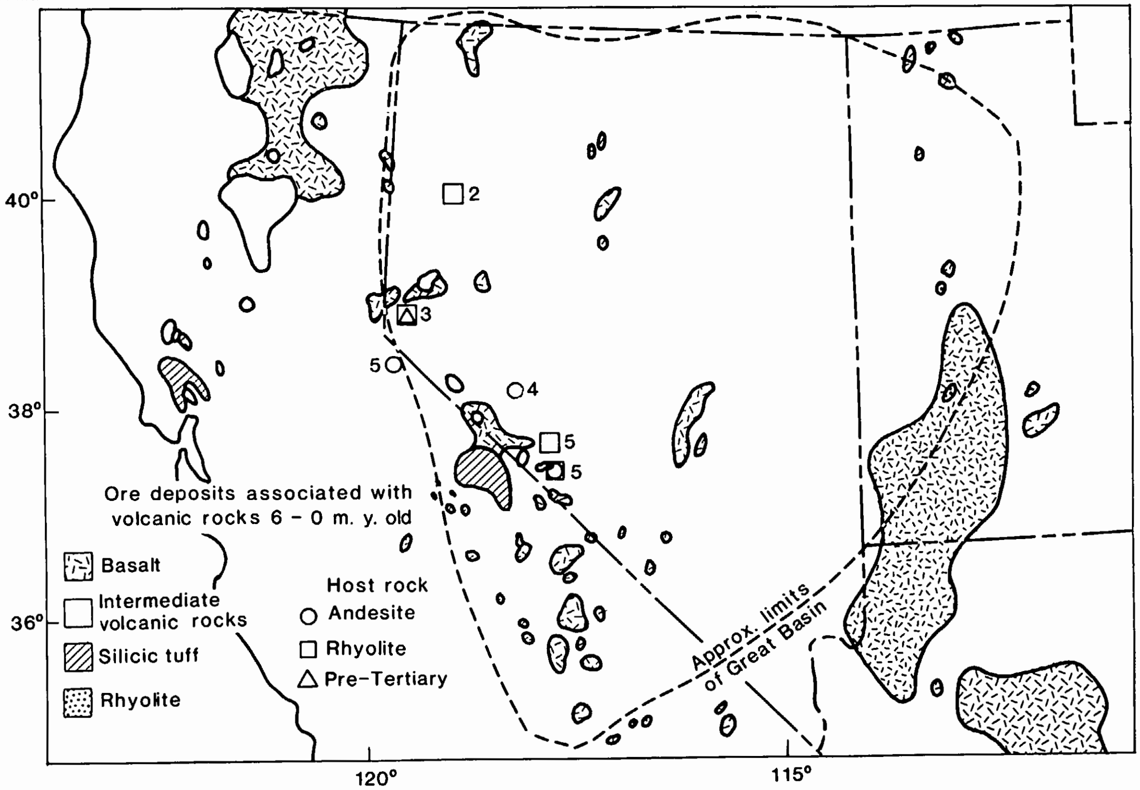


Figure 10. Distribution of volcanic rocks 6-0 m.y. old in the Great Basin and surrounding regions, modified from Stewart and Carlson (1976). Location and age of ore deposits, and host rock lithologies are indicated.

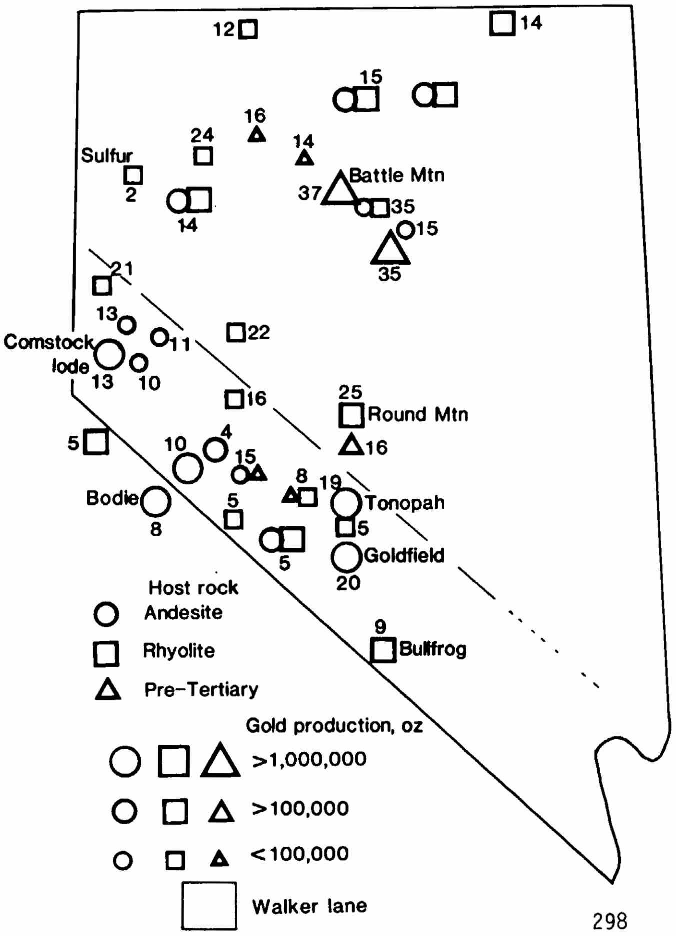


Figure 11. Distribution of ore deposits dated by the K-Ar method in the Great Basin, keyed to host rock lithology and approximate production of gold in troy ounces (modified from Silberman and others, 1976).

dominant ash flow-tuff eruption. All of these deposits are related to local intrusive or volcanic activity, and many are significant with production and or reserves of greater than 100,000 oz Au, and some with greater than 1,000,000 oz (e.g. Round Mountain and Cortez). A significant grouping of fissure vein deposits occurs between 12 and 16 m.y. ago, associated with the 17 and 6 m.y. mixed volcanic episode. Many of these are small deposits, less than 100,000 oz, and occur in faults or shear zones related to Basin and Range faulting, which followed the onset of crustal extension at 17 to 20 m.y. ago. The deposits are relatively independent of host rock type, and are not demonstrably related to local volcanic activity. Exceptions to this occur at Jarbidge and McDermitt, Nevada, where the deposits occur in voluminous volcanic sequences near the margins of the Great Basin. The two million year age on figure 11 and 12 is from the Sulfur prospect in northwest Nevada (M. L. Silberman and A. B. Wallace, unpub. data, 1980), and represents the youngest known Au containing system in the central Great Basin.

Walker Lane (western Great Basin)

The pattern of distribution of deposits along the Walker Lane is considerably different (fig. 13). There is no clear grouping in time, rather, mineral deposits occur throughout most of the time shown. Of 20 dated deposits, 9 are in andesitic host rocks, and 4 more are in the volcanic sequences that contain andesites as part of the host rock association. The major producers (greater than 1,000,000 oz Au) are all in andesites and include the Comstock Lode, Bodie, Aurora, Goldfield, and Tonopah. Production figures summarized in Silberman and others (1976) bear out the importance of andesites as a host rock for precious metal deposits in the Walker Lane. Most of the deposits are associated with local stages of volcanic or intrusive activity. Thus, the pattern for the Walker Lane shows no essential grouping in time, but a very strong association with a particular host rock lithology.

It is interesting to note that five deposits of 5 m.y. age or younger occur in the Walker Lane. The 2 m.y. old Sulfur deposit, although in the northern-central region, is close to the Walker Lane. Mineralization in the Great Basin has continued until nearly recent time, in spite of the fact that subduction affecting the area ended between 5 and 10 m.y. ago (Atwater and Molnar, 1973; Silberman and others, 1975).

TIMING OF STAGES OF ALTERATION-MINERALIZATION

None of the geochronological studies quoted above attempted to define the duration of a single stage of hydrothermal activity, or of a mineralizing event within an overall period of hydrothermal activity. There does appear to be a concensus developing among workers in epithermal systems that mineralizing events are short lived, transitory, and repetitive events within a longer context of hydrothermal activity (Silberman, 1982). Some evidence of this interpretation:

(1) Multiple stages of hydrothermal brecciation and stockwork veining, only some of which are associated with sulfide deposition and mineralization in bulk tonnage precious metal systems (Silberman, 1982; Berger and Eimon, in press).

(2) Banding of epithermal quartz veins in bonanza systems, with only a few of the bands containing sulfides. The banding and the brecciation referred to in (1) are believed to be related to boiling which occurs episodically in most systems (Buchanan, 1981).

(3) The occurrence of several alteration assemblages which succeed each other in a restricted area. In some systems, such as Bodie (Silberman and others, 1972; O'Neil and others, 1973) and Julcani (Noble and Silberman, 1983, in press; Peterson and others, 1977) mineralization occurs associated with one particular assemblage, and not others.

Epithermal mineral deposits are commonly found in close association with intrusive phases, where the heat of the crystallizing magma generates a convective hydrothermal system (White, 1974, 1981; Norton and Cathles, 1979). Cooling of the magma by conduction and convection, unless new sources of heat (magma) are provided will limit the period of time that the circulation of a hydrothermal system can occur. Factors such as permeability, salinity of the fluid, and recharge conditions (amount of fluid) will also affect this length of time. Norton and Cathles, (1979) suggest that permeability in hydrothermal systems is due to fracturing, and that cooling can be considered by a convective circulation model . Models of cooling plutons on the order of 2 km ± width suggests decay of a hydrothermal circulation cell well within about 100,000 years. This time period is short relative to the estimates discussed previously for overall hydrothermal lifetimes in epithermal systems. These observations suggest that magmatic bodies related to the generation of epithermal ore deposits are either much larger than the 1-3 km bodies frequently found at the present surface near such deposits (e.g. Bodie Bluff at Bodie; Mount Davidson at the Comstock Lode; rhyolite domes at Steamboat Springs, Nevada, etc.) or there must be successive, closely spaced pulses of magmatic influx that renew the sources of heat for the convective systems. In at least two areas, Steamboat Springs, Nevada (Silberman and others, 1979a), and Tonopah, Nevada (Silberman and others, 1979b), the presence of a regional batholith with several pulses of magma influx have been called upon to explain long lived, complex hydrothermal systems.

K-Ar data from the Julcani, polymetallic vein district of Peru, to be published shortly (Noble and Silberman, 1983, in press) support the interpretation that individual pulses of alteration and mineralization are short lived. K-Ar ages and geologic relationships at Julcani suggest that eight stages of interspersed volcanic and hydrothermal activity, including a pulse of

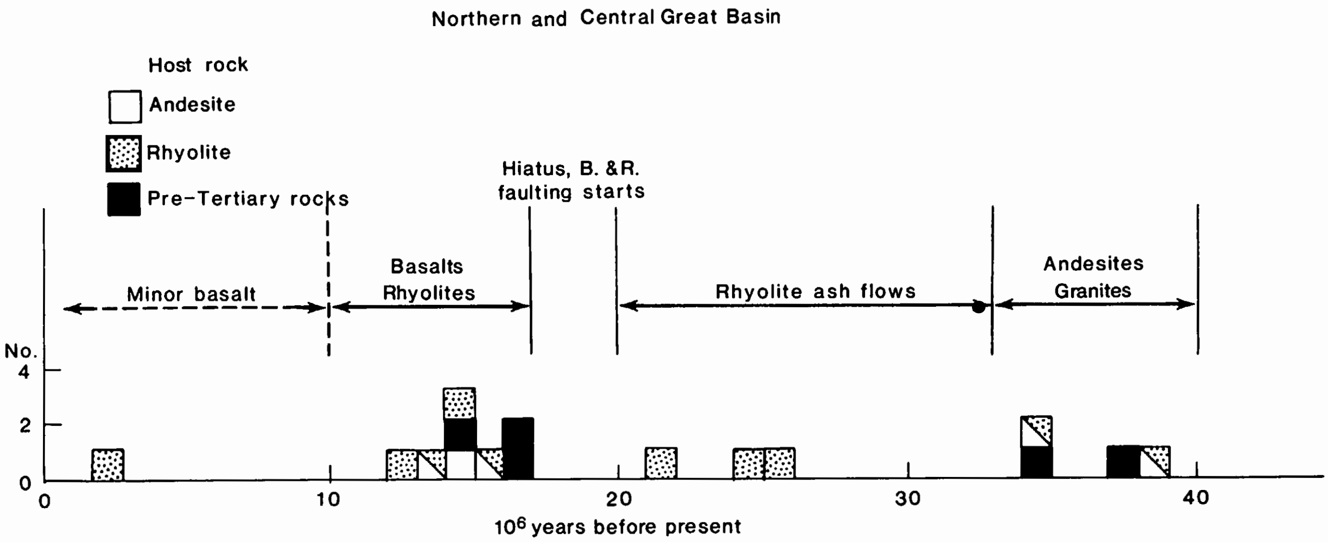


Figure 12. Histogram summarizing ages of ore deposits in the central and northern Great Basin with host rock lithology indicated.

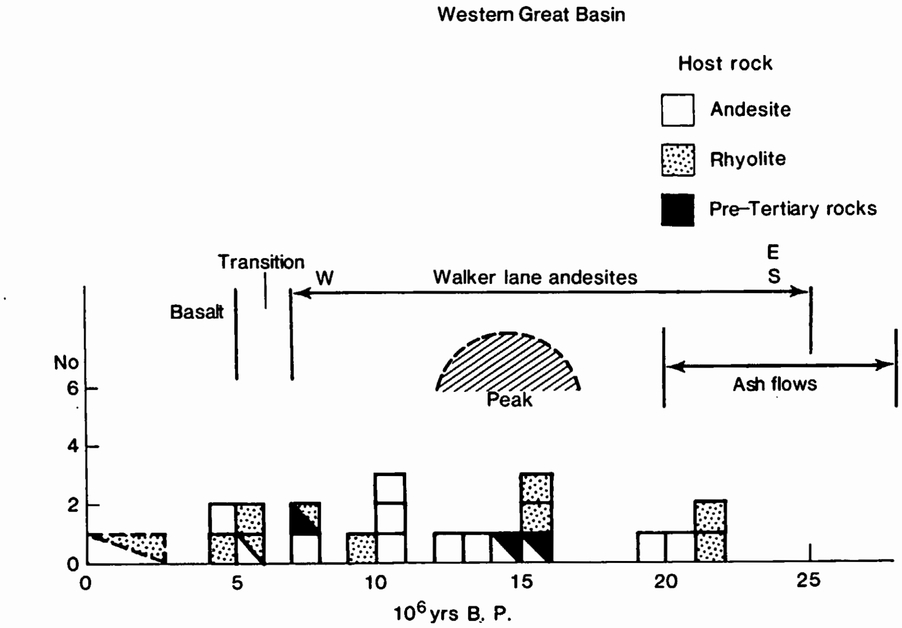


Figure 13. Histogram summarizing ages of ore deposits in the Walker Lane (western Great Basin) with host rock lithology indicated.

sulfide mineralization, occurred over a span of 700,000 years. Not all of the stages could be definitevely dated, but estimates of duration of the hydrothermal episodes range from 100,000 to 200,000 years. These time intervals are interestingly similar to the convective cooling periods for small plutons suggested by the Norton and Cathles (1979) models.

SUMMARY

This discussion of the geochronology of hydrothermal alteration and mineralization, particularly of the epithermal precious metal systems, has demonstrated the temporal relationships of hydrothermal processes to volcanic activity, and has suggested a range of timing of overall hydrothermal activity of 1/2 to 3 m.y. for many systems. It has also shown that regional patterns of hydrothermal mineralization occur, and that these patterns can be related to the timing of tectonic and volcanic evolution, although not always in a simple fashion. Finally, a start has been made in interpreting the timing of pulses of alteration and mineralization within a broader frame of overall hydrothermal activity. It is this topic that needs further investigation. Refinement of methods of isotopically determining the period of activity of alteration pulses and mineral deposition, and whether this fine scale tuning of the timing relationships has any correlation with the degree of mineralization (read economic significance) is yet to be accomplished.

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"This paper has not been edited for conformity with Geological Survey standards and nomenclature."