

Evaluation of Radioisotope Dating of Carlin-Type Deposits in the Great Basin, Western North America, and Implications for Deposit Genesis

G. B. AREHART,[†] A. M. CHAKURIAN,^{*} D. R. TRETBAR,^{**}

Department of Geological Sciences, University of Nevada, Reno, Reno, Nevada 89557

J. N. CHRISTENSEN,

Lawrence Berkeley National Laboratory, Lawrence Berkeley National Lab, 1 Cyclotron Road, Berkeley, California 94720

B. A. MCINNES,

CSIRO Ore Deposit Processes, Minerals Research Laboratories, North Ryde, New South Wales, Australia

AND R. A. DONELICK

Department of Geology and Geological Engineering, University of Idaho, Moscow, Idaho 83844

Abstract

A variety of techniques have been used in attempts to date the mineralization in Carlin-type deposits in the Great Basin, with highly variable results. These techniques and results are reviewed in this paper, along with presentation of two new dates, for the Rodeo deposit on the Carlin trend and for the Barneys Canyon deposit in Utah. Complete resetting of sericite by hydrothermal fluids of the temperature and duration of hydrothermal activity that form Carlin-type deposits is considered highly unlikely. Therefore, dates from sericite are generally of questionable value unless that sericite can be shown to have formed during the same hydrothermal event during which Au was deposited. For the deposits that have been investigated to date, sericite dates rarely, if ever, record the age of Au mineralization. However, sericite ages do appear to record pre-Au events in some districts. Such events may have contributed to ground preparation and, to a much lesser extent, to the tenor of the ore. Fission-track and U/Th-He techniques provide important age constraints on mineralization in some districts but also suffer from a less than clear association with Au. Rb-Sr dating of galkhaite, an Hg sulfosalt, provides the only direct age of mineralization, but galkhaite has been recognized in only a few locations (and dated in only two deposits). In a similar manner, adularia is contemporaneous with Au at Twin Creeks, but Twin Creeks is the only Carlin-type deposit where adularia has been reported. Several other techniques (U-Pb, Re-Os, Sm-Nd) have been used in attempts to date the deposits but with limited success.

The best available ages are those from preore and postore igneous events and those from galkhaite. Galkhaite from Getchell indicates a mineralization age of ~39 Ma and that from Rodeo (Carlin trend) indicates a mineralization age of 40 Ma. A new U/Th-He age (34 Ma) for apatite at Barneys Canyon suggests contemporaneity with the nearby Bingham porphyry Cu system. The most reliable data from several deposits and districts in the Great Basin indicate that Carlin-type mineralization occurred in a relatively narrow time interval, between 33 and 42 Ma. This interval coincides with the transition from a compressional to an extensional tectonic environment in the region. Although similar tectonic environments have existed at different times and places in western North America, no other Carlin-type mineralization is known to exist in the region. Therefore, although the age and tectonic environment of these deposits is now reasonably well constrained, it is clear that tectonic environment alone is insufficient to explain the genesis of Carlin-type deposits. Additional, perhaps unique, factors such as host rock geochemistry must have contributed to the development of these exceptional deposits.

Introduction and Deposit Description

CARLIN-TYPE deposits comprise extremely fine-grained disseminations of Au hosted by altered silty carbonate rocks. The majority of these deposits for which there are more than descriptive data available are located in the Great Basin of western North America (Fig. 1). The characteristics of many of these deposits are described in a series of papers in U.S. Geological Survey Bulletin 1646 (Tooker, 1985), by Arehart (1996), and by Hofstra and Cline (2000). However, additional

deposits that may be Carlin-type deposits are known from locations as diverse as southern China (Ashley et al., 1991; Mao, 1991), southeastern Asia (Sillitoe and Bonham, 1990; Garwin et al., 1995; Talusani, 2001), Iran (Mehrabi et al., 1999; Asadi et al., 1999), Africa (Hill, 1997), and Peru (Alvarez-A. and Noble, 1988).

Most Carlin-type deposits are characterized by high Au and/or Ag, by a geochemical association of Au, As, Sb, Hg, and locally Tl and Ba, and by a notable absence of base metal sulfide minerals. The most conspicuous alteration features are highly silicified zones, commonly known as jasperoids, and decarbonatization of the host rocks (Bagby and Berger, 1985; Tooker, 1985). Although high-grade portions of some of these deposits, such as at Getchell and Mercur, have been

[†]Corresponding author: e-mail, arehart@unr.edu

^{*}Present address: Geotrans, Inc., 17770 Cartwright Ave, Suite 500, Irvine, California 92614.

^{**}Present address: Barrick Goldstrike Mines, Inc., P.O. Box 29, Elko, Nevada 89803.

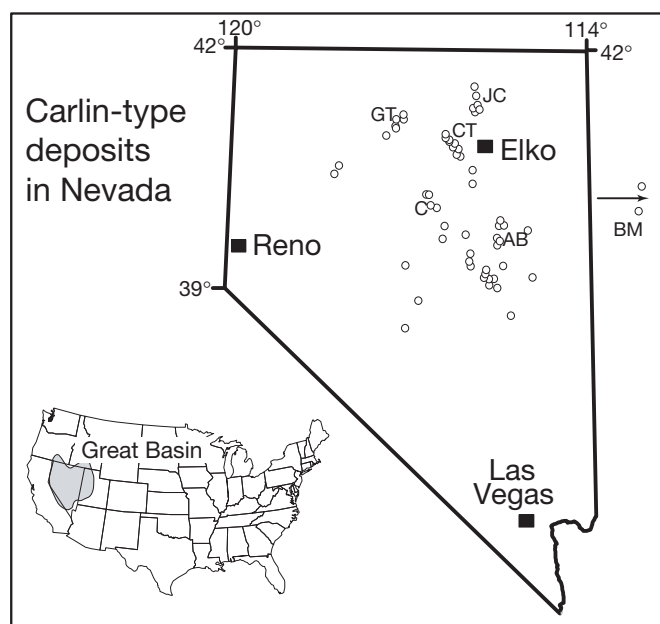


FIG. 1. Location map for Carlin-type deposits in Nevada. Deposits and major prospects are shown by circles. Deposit or district locations mentioned in the text are as follows: AB = Bald Mountain (includes Alligator Ridge and Bald Mountain); BM = Barneys Canyon (deposits in the Oquirrh Mountains including the Barneys Canyon, Bingham, Melco, and Mercur deposits in Utah, about 200 km east of the Utah-Nevada border); C = Cortez; CT = Carlin trend (includes Betze-Post, Carlin, Genesis-Bluestar, Rodeo); GT = Gatchell trend (includes Gatchell, Pinson, Twin Creeks); and JC = Jerritt Canyon (includes Murray, SSX).

mined sporadically since the late nineteenth century (Joralemon, 1951; Kornze, 1984), they were not recognized as a distinct class of ore deposit until the discovery and development of Carlin and Cortez as bulk tonnage mines in the mid-1960s (Hausen and Kerr, 1968; Wells et al., 1969). Carlin-type deposits did not become economically important until the mid-1970s, after the price of Au was freed from United States government price restrictions and allowed to rise to free market values. Since that time, Carlin-type deposits have become a major source of Au in the United States. The state of Nevada, the location of the majority of these deposits, contributes approximately 11 percent of global annual Au production (Dreisner and Coyner, 2001).

Early research on Carlin-type deposits consisted primarily of the development of geochemical exploration techniques and metallurgical extraction processes. Research into the origins of the deposits was frustrated by the scale of features necessary to elucidate origins and by the lack of good exposure of unoxidized ore. It has been only because of the discovery and exploitation of sulfidic ores of economic interest and recent developments in analytical capabilities that some of the complexities of these deposits are being unraveled to produce a better understanding of their origin.

This paper summarizes the available data on the age of Carlin-type Au deposits in the Great Basin and draws implications for the origin of these deposits. We review the dating techniques that have been used, along with their advantages and disadvantages, provide a discussion of the best available dates for deposits that are considered adequately dated, and

discuss some implications of those data. Several new ages are presented, including a new Rb-Sr age for galkhaite in the Carlin trend (40 Ma) and U/Th-He for apatite at Barneys Canyon (34 Ma). Galkhaite is the only mineral from a Carlin-type deposit that is clearly ore stage and that has been dated isotopically. The two Rb-Sr dates on galkhaite confirm the validity of the age of Carlin-type deposits determined from other minerals and techniques.

Hydrothermal alteration

Three major types of hydrothermal alteration have been recognized in Carlin-type deposits: decarbonatization, silicification (jasperoid formation), and argillization. The relative paragenetic position of these events and their relation to Au ore may vary between deposits or within a single deposit, probably reflecting fluctuations in each hydrothermal system through time or multiple episodes of mineralization. For example, penecontemporaneous decarbonatization and silicification have been documented at Carlin (Bakken and Einaudi, 1986) and Alligator Ridge (Ilchik, 1990); Au mineralization is strongest in moderately to completely decarbonatized and weakly silicified portions of these deposits. In contrast, significant portions of the ore at Jerritt Canyon (Hofstra et al., 1988) and Pinson (Madrid and Bagby, 1988) are in intensely silicified (nearly completely replaced) zones. In addition, pre-mineralization silicification has been described at Jerritt Canyon (Hofstra and Rowe, 1987; Northrop et al., 1987), and probably is present at other deposits as well.

Argillization related to Au mineralization is difficult to discern macroscopically except in areas of very intense alteration (usually the core of the system or in areas of igneous rocks). Peripherally, argillization takes the form of conversion of feldspars (both detrital and primary igneous minerals) to fine-grained phyllosilicate minerals, including what has been variously described as sericite, illite, and/or clay minerals. (The term sericite is used herein to refer to any fine-grained K-bearing, Fe-poor mica; generally it structurally is illite or muscovite). Because of the fine-grained nature of these phyllosilicates, it is unclear petrographically in many cases whether these minerals are of hydrothermal or nonhydrothermal (detrital) origin. Therefore, it is generally quite difficult or impossible to establish an Au-related origin for these minerals where they occur distal to ore. Attempts have been made at using crystallinity indices to outline the areal extent of hydrothermal phyllosilicates (Hauff et al., 1989), but in many cases it is unclear whether the more crystalline phyllosilicates are related to ore-related hydrothermal events or to preore metamorphic events, or if they are simply mature detrital materials. Near the center of the hydrothermal system (or systems) the intensity of sericitization increases, and the hydrothermal origin of these alteration minerals becomes somewhat more evident (Kuehn and Rose, 1992; Arehart et al., 1993b; Drews-Armitage et al., 1996), but it is still very difficult to relate these minerals to Au mineralization. In the core of the systems, sericite is replaced by a kaolinite-dominated phyllosilicate assemblage.

Of particular interest to dating efforts is the nature and timing of these K-bearing micas in alteration zones that may be used to date the deposits. The major questions, discussed in more detail below, are whether hydrothermal sericite is genetically related to Au mineralization, and whether preexisting K mica

was thermally reset during the course of hydrothermal events. In some districts (Jerritt Canyon), no secondary K micas appear to have formed (i.e., K content of the rocks decreased: Hofstra et al., 1999) whereas in other districts (Carlin trend: Bakken, 1990; Arehart et al., 1993a; Drews-Armitage et al., 1996) some K micas are interpreted to be hydrothermal in origin. The major issue in dating Carlin-type deposits using K micas is that of determining the relationship of these K micas to Au mineralization.

Mineral paragenesis and zoning

Figure 2 is a generalized paragenetic diagram for Carlin-type deposits of the Great Basin. Preore events (regional metamorphism, and possibly hydrothermal activity) resulted primarily in recrystallization and remobilization of preexisting minerals, including quartz (jasperoid), and calcite, pyrite, and barite from bedded barite deposits common in the Paleozoic rocks (Papke, 1984). Gold is closely associated with hydrothermal arsenian pyrite, pyrite, and locally arsenopyrite (Wells and Mullens, 1973; Arehart et al., 1993a). Temporally late in the Au stage are arsenic sulfide minerals (realgar and orpiment) that postdate alteration minerals such as kaolinite and quartz. Significantly later in the paragenetic sequence are barite, stibnite, and late calcite, which commonly are present as open fracture fillings. A wide variety of trace minerals, represented by galkhaite in Figure 2, including Tl-bearing minerals (e.g., Radtke, 1985; Tretbar, 2002) are associated temporally with the main Au-depositing event. Alunite, jarosite, crandallite $[\text{CaAl}_3(\text{PO}_4)_2(\text{OH})_5 \cdot \text{H}_2\text{O}]$ and a variety of other oxide minerals commonly are present in the supergene zone of the orebodies and locally extend to depths of 700 m along fractures. These minerals are oxidation products of the ores owing to weathering (Arehart et al., 1992).

Historical Perspective to ca. 1990

One of the major questions regarding Carlin-type deposits, recently answered for several deposits, was their age. Prior to discovery and exploitation of sulfidic ores in the early 1990s, most Carlin-type deposits being mined were oxidized. This oxidation complicated the interpretations of age, because many hypogene paragenetic relations had been obscured by weathering. A range of ages had been postulated for these de-

posits, on the basis of a variety of lines of reasoning. A regional study of altered shales and illite veins led Wilson and Parry (1990) to suggest that Mercur is Mesozoic in age. A Cretaceous age was espoused by a variety of workers on the basis of K-Ar dates on alteration minerals thought to be related to Au mineralization (Silberman and McKee, 1971; Silberman et al., 1974; Berger and Taylor, 1980; Bonham, 1985; Osterberg, 1990). Because most known deposits are located in the Great Basin, which experienced widespread igneous and hydrothermal activity through Tertiary time, others concluded that Carlin-type deposits are of Tertiary age (Joralemon, 1951; Wells et al., 1969; Radtke, 1985; Rota and Hausen, 1991). A pre-late Tertiary age was suggested by Bakken and Einaudi (1986) on the basis of structural evidence in the Carlin mine. A number of small jasperoid-hosted Au deposits were interpreted by Seedorff (1991) as mid-Tertiary on the basis of crosscutting and geologic relationships. He proposed a model that required regional crustal heating of suitable source rocks combined with development of the appropriate "plumbing" for migration of metamorphic-hydrothermal fluids. He considered that these conditions existed in early Eocene-Oligocene time, and he inferred that age for other large Carlin-type deposits. Miocene or younger ages were suggested by Radtke (1985) on the basis of igneous rocks thought to be the possible heat source for the Carlin deposit, by Birak and Hawkins (1985) on the basis of an absence of drop in ore grades across faults of Miocene age at Jerritt Canyon, and by Ilchik (1990), on the basis of K-Ar dates on alunite at Alligator Ridge. Unfortunately, none of these Miocene or younger ages have been determined on minerals or events that convincingly can be shown to have been related to the ore-forming event (or events).

Following discovery of the Betze-Post deposit in 1987, drilling and mining of hypogene ores opened up the possibility of more direct dating, because primary paragenetic relationships were more easily elucidated. Since that time, a large number of isotopic dates have been produced for different deposits, although different interpretations have been advanced for those dates.

Dating Techniques and Their Advantages and Disadvantages

Geologic constraints

Seedorff (1991) summarized geologic information on a number of small deposits and prospects in Nevada that he classified as Carlin-type deposits. At several of these localities, rocks of Tertiary age are reported to be altered and mineralized. Seedorff also noted the association of some of these mineralized zones with structures considered to be of mid-Tertiary age. He concluded that because the major structural control on alteration and mineralization in these occurrences is of Tertiary extensional origin, the deposits must be of a similar or younger age. In a like manner, Bakken (1990) described mineralized northeast-striking and north-northwest-striking structures at Carlin. On the basis of geologic arguments, she concluded that these structures and mineralization may have been related to pre-Basin and Range extension of mid-Tertiary (ca. 37 Ma) age. Because of the multiple movement history of some of these fault systems and the

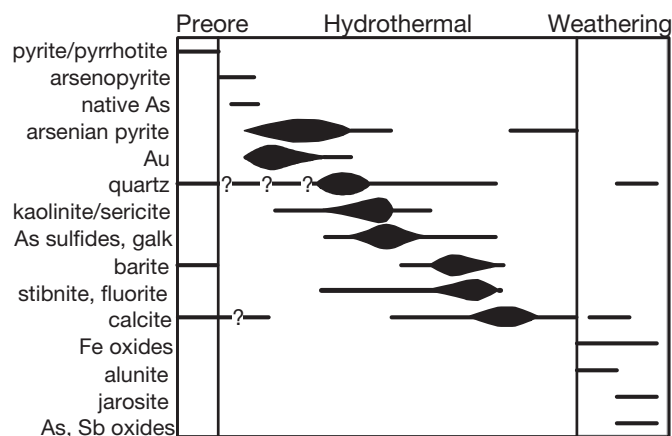


FIG. 2. Generalized paragenetic sequence for Carlin-type deposits. Modified from Arehart (1996). galk = galkhaite.

uncertainty associated with dating of tectonic events, these dates were only considered reasonable estimates or limits on the age of mineralization, and only for some deposits.

Geologic constraints also include application of indirect dating techniques, primarily crosscutting relationships, where the ages of the preore or postore rock units have been dated either by radioisotopic or other means. For Carlin-type deposits, these data fall into two major groups: ages of alunite minerals, and biotite, feldspar, and whole-rock crystallization ages. These data are unlikely to record events that are genetically linked to Au mineralization, but they can help place upper or lower age limits on the deposits. Dates for alunite range from ~27 Ma at Gold Quarry deposit to ~8 Ma at Betze-Post deposit (Arehart et al., 1992). In all cases, alunite in Carlin-type deposits has been demonstrated to be supergene and therefore unrelated to Au mineralization. However, these dates place lower limits on the age of Au-related hydrothermal activity.

The biotite, feldspar, and whole rock samples that have been dated comprise materials that are normally altered by hydrothermal activity associated with Carlin-type mineralization. Therefore, if these minerals and rocks are fresh enough to be dated, they are not reliable indicators of the timing of hydrothermal activity. However, if altered age-equivalent rocks are present, as is the case in some deposits, the crystallization and/or emplacement age of the igneous rocks provide an upper age constraint on mineralization. For example, at the Betze-Post deposit (Arehart et al., 1993b), the Goldstrike stock has a crystallization age of 156 Ma, implying that the mineralization is younger. In the Getchell trend, the Osgood stock (92 Ma) is altered and mineralized locally, requiring mineralization to be post 92 Ma. In a similar manner, crystallization ages for igneous units may place lower limits on the age if the igneous units are demonstrably younger than Au mineralization. Maher et al. (1993) described two Carlin-type occurrences in the Roberts Mountains on which they place minimum age constraints of 33 to 34 Ma. These limits are based on K-Ar dates on biotite and plagioclase in unaltered igneous rocks that postdate mineralization. At one of these deposits (Tonkin Springs), altered rocks that overlie the Au deposit give K-Ar dates of 37 Ma (biotite from fresh rock away from hydrothermal alteration), placing the age of the deposit between 37 and 33 Ma. In a similar manner, Ressel et al. (2000) were able to constrain the upper age of mineralization at the Beast deposit in the Carlin trend to younger than ~40 Ma through analyses of fresh equivalents of mineralized dikes. Arehart et al. (1993b) describe a postmineral dike in the Carlin trend having an age of 39 Ma; however, there is still some controversy over the timing of this dike relative to Au mineralization (Emsbo et al., 1996). At the Deep Star deposit in the Carlin trend, Heitt et al. (2003) describe a composite glassy rhyolite dike that apparently brackets mineralization. The oldest section of the dike is clearly altered and mineralized, whereas the younger segment is essentially fresh but contains fragments of mineralized rocks, making it clearly postore. Both segments of the dike yield analytically identical K-Ar ages of approximately 39 Ma. Felsic dikes in the Cortez trend are altered and mineralized on their margins. Fresh sanidine from the cores of the dikes and U-Pb dates on zircons yield similar ages of 34 and 35 Ma, respectively (Wells et

al., 1969; Mortensen et al., 2000). Unfortunately, there continues to be debate over the timing of mineralization relative to these dikes, and some advocate a preore age for dike emplacement (e.g., Wells et al., 1969), whereas others advocate a postore age for dike emplacement (McCormack and Hays, 1996).

In the Carlin trend, Miocene Carlin Formation has been reported to contain mineralized fragments of Carlin-type ore at Gold Quarry and near Betze-Post (Rota, 1987; Christensen et al., 1987; E. Lauha, oral commun., 2001). Tuffaceous units near the base of the Carlin Formation have been dated at 15 Ma (Fleck et al., 1998), which would limit Carlin-type formation to prior to that time.

In most other districts the appropriate preore and postore rocks that sharply bracket the mineralization have not yet been found or may not exist.

Potassium-argon systems in sericite

Phyllosilicates produced during alteration are important for direct dating of Carlin-type deposits because sericite can be dated by isotopic methods. An enormous effort has been put into dating these sericites and a large number of ages has been reported. Such dates are significant to the age of ore formation only if the sericite is clearly related to mineralization. Unfortunately, a clear determination of this relationship for all components of a given sample has not yet been demonstrated in any study. As described below, some useful age information can be obtained from isotopic measurements of sericite; however, all ages determined on sericites must be interpreted with extreme caution.

There are several possible origins of sericite in Carlin-type deposits: detrital grains in sedimentary host rocks; deuteric or magmatic minerals in igneous rocks; and hydrothermal (related or not related to Au) sericite. In addition, preore sericite has the potential for being reset to reflect hydrothermal activity, if the Au-related hydrothermal event was of sufficient temperature and duration. The analytical techniques for determining ages of these minerals are well developed; therefore, most analytical data are considered to be reliable. Potassium-argon systems (herein termed argon systems) include standard K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ dating techniques plus their modifications such as the encapsulation technique (e.g., Foland et al., 1992).

As noted above, two types of material may be considered for dating mineralization: new hydrothermal Au-related sericite and older (preore) sericite that has been raised to sufficient temperatures to have been reset to the time of Au mineralization. Although preore sericite is unlikely to have been held at sufficient temperatures for long enough time to have been reset during Carlin-type mineralization (Fig. 3), preore events may have been of sufficient duration and intensity to reset the Ar clock, as described below. Therefore, the only viable material that can be used for direct dating of Au mineralization is hydrothermal sericite formed at the time of Au mineralization. This fact presents the additional problem of separation of that sericite, if necessary, to obtain a hydrothermal age rather than a mixed age.

Some districts and deposits appear to have had K added to parts of the hydrothermal system, whereas in others K remained constant or decreased. Even if K has not been added

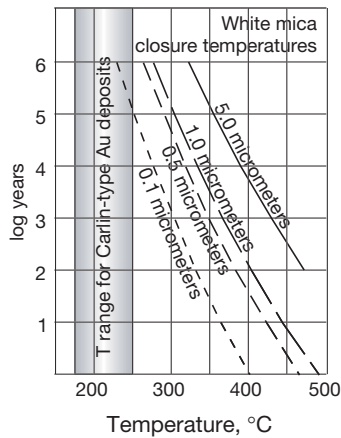


Fig. 3. Diffusion characteristics of white mica (sericite) in terms of closure temperature for various sizes of mineral grains. Only micas having a minimum dimension less than $0.5 \mu\text{m}$ diameter (in the a-b axial plane) are likely to be thermally reset by an event at the high-temperature limit of Carlin-type deposits and only after a very long duration. Diffusion in the c axial direction is negligible, so thickness of the mica is not important to these calculations. Calculations based on the equations of McDougall and Harrison (1988) and use the parameters $D_0 = 0.04 \text{ cm}^2/\text{s}$; $E = 52 \text{ kcal/mol}$; and $a = 27$ (cylindrical geometry) of Hames and Bowring (1994). Rock is assumed to cool by 150°C during the time period of the calculation.

on a large scale, if it has been remobilized locally, there is potential for generation of new hydrothermal sericite. In areas where no K has been added to any portion of the system (e.g., Jerritt Canyon: Hofstra et al., 1999), no new Au-related hydrothermal sericite has been formed, thus the deposit can not be dated by K-Ar methods. However, in other deposits, K has been increased at least locally and therefore holds the possibility of providing dates related to mineralization. Phyllosilicate zones in ore-hosting sedimentary rocks at Betze-Post (Arehart et al., 1993b) and Genesis-Bluestar (Drews-Armitage et al., 1996) comprise a core of kaolinite (i.e., sericite destruction zone) which grades outward into the hydrothermal assemblage kaolinite-sericite, where kaolinite is dominant over sericite. Similar phyllosilicate alteration zoning is present in igneous rocks, although the kaolinite zone is more restricted and hydrothermal sericite is more widespread, probably reflecting the increased availability of K in this part of the system owing to the presence of relatively large, preore igneous bodies of the Goldstrike stock. Particularly at Genesis-Bluestar, Drews-Armitage et al. (1996) report significant amounts of hydrothermal sericite. At Getchell, Cail and Cline (2001) document local sericite, indicating local mobility of K in this system. Similar K mobility is apparent in the Twin Creeks deposit (also in the Getchell trend), which hosts significant local concentrations of hydrothermal sericite and adularia (Hall et al., 2000). Mica polytype studies suggest preore sericite may have recrystallized or that new hydrothermal sericite may have formed (Hauff et al., 1991). This recrystallization would result in development of “new” sericite from the standpoint of argon systematics. Although this generation of “new” recrystallized sericite might be discernible using X-ray diffraction or reflectance spectroscopy techniques, it would likely be impossible to distinguish it optically from preexisting sericite, and therefore it would be impossible to separate the two generations of sericite for argon dating techniques.

Under conditions of high supersaturation, significant amounts of hydrothermal sericite may precipitate, as in some areas of the Carlin trend (Arehart et al., 1993b; Drews-Armitage et al., 1996). If this sericite is the only generation of sericite in the rocks and is shown to be Au-related, it could be dated to yield the age of Au deposition. Because most sedimentary and igneous rocks that host Carlin-type deposits contain at least some K feldspar, local mobility of K could also give rise to hydrothermal sericite. Such local K mobility generally will result in new sericite or an increase in size of some existing grains at the expense of dissolution of others (e.g., “Ostwald ripening”: Eberl and Sródon, 1988; Folger et al., 1996). Folger et al. (1996) undertook an extensive study of micas in sedimentary rocks at Jerritt Canyon and concluded that increasing crystallinity of micas reflects the Ostwald ripening process in these sedimentary rocks. Similar results are reported by Hauff et al. (1991) at Pinson. One result of the Ostwald ripening process is grains of mixed heritage, in which the cores represent the older generation of sericite and the rims represent the younger (hydrothermal) generation.

Measurement of K-Ar ages on such grains will result in mixed and meaningless ages because the grains are of composite heritage, in this case partially detrital and partially hydrothermal in origin. Similarly, it is essentially impossible to discriminate optically or physically between magmatic-deuteric and hydrothermal sericite in igneous rocks during the mineral separation procedures. Unless a sericite sample can be shown to be of a single generation, conventional K-Ar techniques will not be useful in obtaining a valid age. Unfortunately, it has yet to be shown definitively that such single-generation sericite is present in any sample from a Carlin-type deposit. Therefore, all K-Ar ages of sericite from Carlin-type deposits should be regarded with great suspicion.

An analytical technique by which one may perhaps separate generations of sericite (e.g., overgrowths of hydrothermal sericite on preexisting sericite) is that of $^{40}\text{Ar}/^{39}\text{Ar}$ step heating. Step heating sequentially releases Ar from different parts of a mineral grain; for example, from the margins to the core. For an ideal grain that has a core of prehydrothermal sericite (detrital or deuteric) and a rim of hydrothermal sericite, one might expect to obtain a step heating pattern that reflects these two ages: young ages in the first steps (rims) with older ages in the last steps (cores). In fact, step heating patterns that do not yield plateaus provide evidence for the multiple heritage of sericite grains, either as multiple generations or because of partial Ar loss during hydrothermal heating. Flat step heating spectra generally are considered to represent either a single generation of sericite or complete resetting of an earlier generation. Inasmuch as the temperature-time history of Carlin-type systems precludes resetting of sericites by hydrothermal activity (Fig. 3), a flat spectrum must reflect a single generation that is unlikely to be related to main-stage Au deposition.

The irradiation required for the $^{40}\text{Ar}/^{39}\text{Ar}$ step heating technique generates secondary ^{39}Ar (a proxy for K). If the grain being irradiated is too small, this ^{39}Ar will recoil out of the crystal as it is formed and be lost, resulting in an erroneously low value for K and a calculated age that is too old. In most Carlin-type systems, the sericite grains are sufficiently small (generally $<1 \mu\text{m}$ in thickness) to be below the threshold of

acceptability in terms of recoil. Fortunately, there are a few samples, usually in altered igneous rocks, where the grains are of sufficient size to mitigate the recoil problem. It is these samples that offer the most useful step heating data.

The step heating technique will only work where documented hydrothermal sericite is present, and then it may only provide upper and lower age limits. The assumption behind these determinations is that there are at least two generations of sericite present. If K is added to (or remobilized within) the system at least locally, there should be growth of new sericite through the process of Ostwald ripening. Because of the likelihood of mechanical breakage of the grains during sample preparation, irregular hydrothermal overgrowths, and a range of particle sizes, the step heating pattern is unlikely to provide “clean” results that can be attributed only to a single generation of sericite. Therefore, the results provide only some limits on the age of the two events. For example, Figure 4 shows a step heating spectrum from a sericite sample from Betze-Post. The higher-temperature portion of the curved step heat pattern represents the youngest possible age for the first generation of sericite (146 Ma). The sericite could have formed significantly earlier than this age indicates. In this sample, this portion of the spectrum probably represents a magmatic-deuteric alteration event that is close to the known ~150 Ma emplacement age of the dike. The low-temperature end of the spectrum represents the oldest possible age (110 Ma) for the second generation of sericite or for a thermal event that caused Ar loss. The true age of hydrothermal sericite or time of Ar loss could be significantly younger; i.e., this youngest step may still represent a mixture. This age is older than the known ~40 Ma age of the hydrothermal system (see discussion of the Carlin trend below), and in this case it is significantly older. Similar data from sericite at Carlin yielded an upper limit to hydrothermal alteration that is close to the age of mineralization established by Chakurian (2001). In addition, there may be additional generations of sericite of intermediate age present in this sample that are not distinguishable in the spectrum.

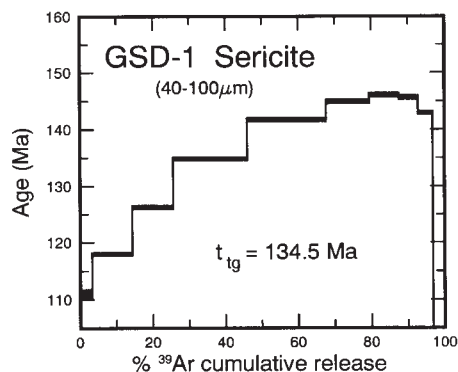


FIG. 4. Step heating analysis of a sericite from the Betze-Post deposit. The oldest age represents a minimum age of genesis of sericite, which is close to the crystallization age of the sample and probably represents magmatic-deuteric alteration. The youngest age represents the maximum age of a thermal event, possibly the hydrothermal event responsible for generating the deposit or perhaps some other thermal event younger than ~110 Ma. The total gas age (t_{tg}), which is equivalent to a K-Ar age, clearly is meaningless. Reproduced from Arehart et al., 1993a.

It is readily apparent that K-Ar dates will suffer similar mixed-heritage problems if multiple generations of sericite are present. Therefore, K-Ar dates will be valid only if it can be shown clearly that there is only a single generation of sericite present. $^{40}\text{Ar}/^{39}\text{Ar}$ step heating ages may provide some limits on the timing of sericite formation and degassing. However, only step heating experiments that yield data in the form of plateaus are likely to provide reliable single-event ages.

K-Ar Radioisotopic Age Data for Individual Deposits and Districts

Given the discussion above, it is clear that a large number of dates are present in the literature that must be evaluated with extreme care. With a few exceptions discussed here, K-Ar ages are not considered useful in constraining the age of Carlin-type deposits because the sericite is not clearly documented (in the literature) to be of single-generation hydrothermal origin for a given sample.

Carlin trend

In the Carlin trend, age limits are defined by preore and postore igneous events that are well dated by $^{40}\text{Ar}/^{39}\text{Ar}$ step heating techniques. The preore Goldstrike stock is 156 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$ on biotite, hornblende). Numerous dikes having K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ dates on both mineralized and unmineralized parts constrain Au mineralization to between ~40 and ~37 Ma (Arehart et al., 1993b, 2000; Mortensen et al., 2000; Ressel et al., 2000). At Deep Star, a composite rhyolite dike brackets Au mineralization at 39 Ma (K-Ar methods: Heitt et al., 2003). In addition, Au mineralization in part of the trend clearly is constrained to ~39 Ma by other techniques (see galkhaite discussion below). Arehart et al. (1993b) report ages of hydrothermal sericite associated with the Betze-Post deposit that have some scatter but cluster between 100 and 107 Ma. In the nearby Bluestar-Genesis deposit, Drews-Armitage et al. (1996) describe “pure hydrothermal sericite” from two samples in the intensely sericitized zone that yield ages of 94 and 98 Ma. Two samples of hydrothermal sericite from altered dikes at Carlin yielded $^{40}\text{Ar}/^{39}\text{Ar}$ step heating patterns with a number of steps near 120 Ma (Kuehn, 1989), similar to the Betze-Post dates. However, additional dating of sericite from Carlin (e.g., Fig. 4; Chakurian et al., 2003) yielded step heating patterns that step up from ~50 to ~140 Ma, having no plateaus.

In light of the discussion above regarding the limitations of sericite ages, coupled with dates obtained by other techniques (see below), it is clear that these data do not yield the age of the Au mineralization in the Carlin trend. However, given the description of many samples as only “hydrothermal sericite,” and the general clustering of ages near 100 Ma, it seems likely that a hydrothermal event took place in the Carlin trend at about this time, although the bulk, perhaps all, of the Au mineralization is significantly younger. It would be fortuitous if all these samples were of mixed heritage yet yielded similar ages. There are at least two igneous rocks that yield similar ages: the Richmond Stock (107 Ma by K-Ar methods: Evans, 1980) and a dike at the Mike deposit (107 Ma by K-Ar methods: Teal and Branham, 1997), therefore, it is not unreasonable to postulate hydrothermal activity associated with these magmatic events. In addition, hydrothermal K feldspar

in sedimentary rocks at the Mike Cu deposit yielded a K-Ar age of 111 Ma (Teal and Branham, 1997). Although these ages clearly do not reflect the timing of Au mineralization, they nonetheless suggest a significant hydrothermal event in the Carlin trend at ~100 Ma. Therefore, there appear to have been at least three major magmatic and hydrothermal events in the Carlin trend: ~160 to 150 Ma, associated with the intrusion of the Goldstrike stock and dikes; ~100 Ma, associated with the intrusion of the Richmond and Mike stocks; and ~40 Ma, associated with the majority of the Au mineralization.

Jerritt Canyon district

Isotopic data from the Jerritt Canyon district (Phinisey et al., 1996) encompass a wide range and include several dates similar to the Cretaceous ages described above for the Carlin trend. Sericite from an altered andesite dike gave a step heated age spectrum from 116 to 140 Ma. These dates were interpreted as reflecting a hydrothermal event not related to Carlin-type mineralization. A $^{40}\text{Ar}/^{39}\text{Ar}$ date from an unaltered basalt dike near the ore deposits yielded an age of 41 Ma; a similar dike is reported to be altered and locally ore grade nearby (Hofstra et al., 1999). A hornblende separate from a quartz monzonite dike that is interpreted to be postore, but is from 3 to 5 km from the ore zone, yielded a $^{40}\text{Ar}/^{39}\text{Ar}$ age of 39 Ma. From these data, Phinisey et al. (1996) and Hofstra et al. (1999) interpreted the age of Carlin-type mineralization at Jerritt Canyon to be between 41 and 39 Ma. Folger et al. (1996), in a companion study, evaluated the applicability of sericites to the dating of Carlin-type deposits. At Jerritt Canyon, they reported an age of 402 to 435 Ma for the 20 to 40 μm fraction of sericite, which is similar to the age of diagenesis. Finer-grained fractions (<1 μm) yielded younger ages (149 and 285 Ma), although still much older than the inferred age of mineralization (40 Ma). Folger et al. (1996) concluded that K-Ar ages of sericites from sedimentary rocks did not reflect the age of mineralization in the Jerritt Canyon district.

Getchell trend

Groff et al. (1997) reported the development of sericite in the preore igneous rocks at Getchell. Cail and Cline (2001) reported local K mobility indicated by destruction of K feldspar and formation of illite (sericite) in some ore zones in sedimentary rocks at Getchell. In the nearby Twin Creeks deposit, Hall et al. (2000) also reported extensive hydrothermal sericitization of the basalts there. Limited amounts of hydrothermal adularia are reported to be present at the Twin Creeks deposit (Groff et al., 1997; Hall et al., 1997), also indicating the action of K-bearing solutions. Groff et al. (1997) proposed that a major Au event at Getchell was associated with the development of their stage 3 sericite, two samples of which yielded step heating ages of 83 Ma (plateau age) and 81 Ma (total gas age, no plateau present). In contrast, Cline (2001) argued that, although there was some Au mineralization possibly associated with this ~82 Ma event, the major Carlin-type Au mineralization event is paragenetically later and occurred during the ~39 Ma hydrothermal event identified at Getchell. The presence of at least one sample having a plateau step heating pattern argues for development of a single generation of sericite at ~82 Ma in this location. However, the textural arguments of Cline (2001) suggest that, although there may have been a hydrothermal event,

it was not the event that generated Carlin-style mineralization. These observations are consistent with the relatively low temperature inferred for Carlin-type mineralization and a lack of significant resetting of the earlier sericite.

Twin Creeks is somewhat unusual, because basaltic host rocks are present in the ore zone. Hall et al. (2000) suggest that sericitization of abundant Fe chlorite in these basalts released Fe that was added to the carbonate minerals in adjacent sedimentary rocks. Subsequent sulfidation of the Fe carbonate was instrumental in causing Au deposition (Stenger et al., 1998). Hall et al. (2000) reported ages from a variety of sericite samples, four of which yielded step heating plateaus (or nearly plateaus) at 107 to 109 Ma. That these samples yielded plateaus indicates that the samples comprised essentially a single generation of sericite, and that sericite was not heated above its closure temperature (i.e., not reset) during subsequent events. These inferences are in agreement with the estimated temperatures reached by Carlin-type hydrothermal systems and systematics of sericite (Fig. 3). The data of Hall et al. (2000) also clearly indicate a major hydrothermal event near 110 Ma that resulted in generation of significant amounts of sericite. The close spatial overlap between Au and sericite of Cretaceous age is interpreted to represent either significant ground preparation at ~110 Ma or an Au event at that time, or possibly both. The limited distribution of adularia, found in only one restricted location at Twin Creeks, and not reported from any other Carlin-type system, is interpreted as possibly representing a relatively minor hydrothermal event overprinting a more significant Cretaceous Au-generative event. Hall et al. (2000) also note that the sericite ages represent a hydrothermal event significantly older than the oldest known intrusive rock in the area (Osgood stock, 92 Ma).

Oquirrh Mountains

A set of K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ dates from sericite samples from a number of locations in the Oquirrh Mountains, Utah, yielded ages ranging from 193 to 98 Ma (Wilson and Parry, 1990; Presnall, 1992; Parry et al., 1997). These dates are from samples from both mineralized zones as well as samples from many kilometers from known mineralization. A few of the K-Ar dates cluster near 155 Ma, but there is significant scatter. The age data have been interpreted to reflect regional hydrothermal fluid flow thought to have resulted in development of Carlin-type deposits at Mercur and Barney's Canyon (Wilson and Parry, 1990; Presnall and Parry, 1996). However, none of the samples that were dated have been demonstrated to be single-generation hydrothermal sericite; therefore the ages are considered suspect. $^{40}\text{Ar}/^{39}\text{Ar}$ dates presented by Parry et al. (1997) have plateaus or almost have plateaus, many of which cluster near ~170 Ma. Although these data suggest that many samples comprise single-generation sericite, and in the deposits there is a broad correlation between sericite and Au, no data presented in these studies make a compelling case for relating the timing of sericite development to that of Au precipitation. From this, we conclude that there most likely was a sericite-generating event at ~170 Ma, perhaps associated with regional events (Jurassic magmatism²), but the relationship to Au is equivocal. Clear field relations at Mercur indicate that Au mineralization postdates

the 32 Ma Eagle Hill rhyolite (Mako, 1997; Kerr, 1998), but no younger age constraints are available.

Summary

It is clear that sericite dates from Carlin-type deposits are unlikely to represent the major Au-depositing hydrothermal event. However, even given the caveats described above regarding the applicability of sericite dates, it is interesting to note that a significant number of the isotopic ages from sericites fall in a reasonably limited age range between 80 and 120 Ma. This coincidence of Mesozoic ages was interpreted by Folger et al. (1996) as related to Mesozoic plutonism and not to Carlin-type mineralization. However, plutonism of Mesozoic and other ages may have been instrumental in either generating precursor low-grade Au deposits that subsequently were remobilized and/or upgraded by younger hydrothermal systems or in providing critical "ground preparation" that focused Au deposition in subsequent hydrothermal events.

Fission-Track and U/Th-He Analyses

A second approach that has been used to constrain the ages of Carlin-type deposits includes fission-track and the related U/Th-He methods. Fission-track techniques have been employed on both zircon and apatite, and the U/Th-He method has been employed on apatite. Two types of samples have been analyzed: preore grains and hydrothermal grains.

Preore apatite and zircon have been analyzed because these minerals can be thermally reset by hydrothermal activity. As with sericites described above, fission-track ages from grains that have been reset are used only as indirect indicators of the age of mineralization. In fact, they represent only the last time the grains were held above their closure temperature for sufficient time to anneal the grain and effectively reset the clock. For zircons, the time-temperature requirements for complete resetting are generally outside the range thought to have been reached by Carlin-type hydrothermal systems (Fig. 5), although partial resetting, which depends on the composition of the grains, particularly their U and Th content, can occur. Apatites lie well within the window where resetting could occur in a Carlin-type hydrothermal system. The U/Th-He system in apatite, having a closure temperature near 75°C (Fig. 6), generally is thought to be reset completely by the temperature and duration of hydrothermal activity associated with Carlin-type mineralization.

There are few deposits where significant fission-track or U/Th-He work has been done. Arehart et al. (1993b) obtained data on several zircon samples in the Carlin trend and identified three major thermal events: 160 Ma, 110 Ma, and 40 Ma. Each of these events corresponds with a major pulse of igneous activity in the region, and the latter age also corresponds with the timing of hydrothermal activity that deposited Au. Arehart et al. (1993b) also reported an apatite fission-track age of 41 ± 4 Ma (1σ) for a postore dike in the core of the Betze-Post deposit. This age precludes hydrothermal activity that is significantly younger than ~40 Ma. Chakurian et al. (2003) undertook a further study of apatites in the Carlin trend. They identified three types of apatite: primary igneous, detrital, and hydrothermal. The majority of the apatite samples in and south of the Carlin deposit proper

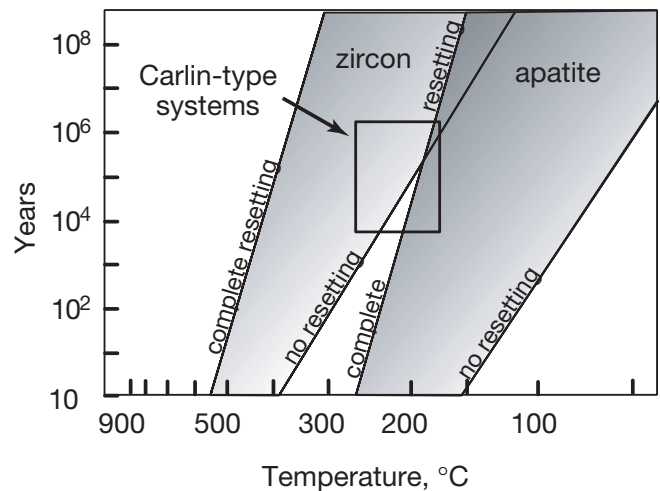


FIG. 5. Time-temperature annealing characteristics for fission-track dating of zircon and apatite. Zircons are likely to be only partially reset under the time-temperature conditions thought to be extant for Carlin-type deposits, whereas apatites are likely to be partially to completely reset. Modified from Hofstra et al. (1999) on the basis of the data of Harrison et al. (1979), Naeser (1981), Bal et al. (1983), and Naeser and Crowley (1989).

were reset completely at the time of mineralization (~40 Ma). Hydrothermal apatites that were probably generated at the time of Au mineralization as well as preexisting apatites in sedimentary and igneous rocks were reset. To the north of the Carlin deposit proper, apatite samples were only partially

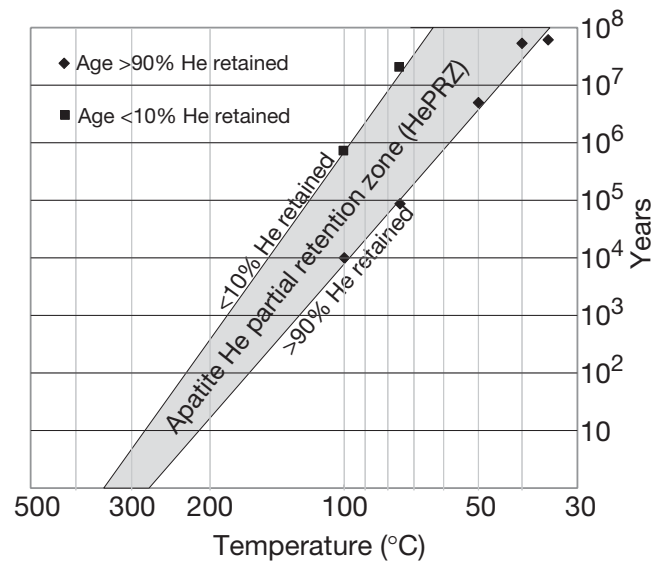


FIG. 6. Plot of retention time vs. temperature for the U/Th-He system in apatite. The apatite helium partial retention zone (HePRZ) is defined as the range of temperatures where helium ages lie between 10 and 90 percent of the steady-stage age (defined as the idealized situation where the thermal structure of the crust is defined only by the geothermal gradient, i.e., there is an absence of thermal, erosional, or tectonic events which might perturb the geothermal gradient). At hydrothermal temperatures of 100°C, 90 percent of He in apatite will be retained in the crystal when heated for 10,000 years and only 10 percent will have been retained in 700,000 years. For temperatures of formation at Barney's Canyon between 130° and 400°C (Presnell and Parry, 1996), the apatite chronometer would have been reset within time scales of 10 to 10,000 years.

reset. From these data it was concluded that the most recent hydrothermal activity of any areal significance took place at circa 40 Ma, and that the cause of hydrothermal circulation was, most likely, a pluton associated with a magnetic anomaly just northwest of Gold Quarry (Welches Canyon pluton: Chakurian et al., 2003).

Three apatite samples from the Carlin trend also were analyzed for U/Th-He by Chakurian et al. (2003). Two of these samples yielded analytically acceptable ages of 31.0 ± 1.9 (2σ , highly altered Main pit dike) and 21.4 ± 1.3 (2σ) Ma (visibly unaltered Goldstrike stock, 800 m depth). It is unclear what events these dates represent. There is known post-39 Ma hydrothermal activity in the vicinity of the Goldstrike stock sample, comprising minor epithermal(?) Hg mineralization of unknown age above the Rodeo deposit (Fleck et al., 1998; E. Lauha, oral commun., 2001). Additional U/Th-He data are required to fully assess the nature and extent of post-Carlin-type hydrothermal activity. However, given the lack of fission-track ages younger than ~39 Ma across the area, the areal extent of post-Carlin-type hydrothermal activity is minor.

There have been fission-track or U/Th-He ages reported for several other districts, usually derived from a single sample. Hofstra et al. (1999) report zircon and apatite fission-track ages from the Osgood stock (Getchell trend) that range from 91 to 66 Ma and 83 to 22 Ma, respectively. A single apatite sample from the Pinson deposit (Getchell trend) from a hydrothermal vug was analyzed by Berger (reported in Hofstra et al., 1999) and yielded an age of 42.7 ± 5.3 Ma. Although the sample is reported to be from ore-grade jasperoid, it is unclear how this apatite sample relates to Au mineralization. This date is clear evidence that there was essentially no moderate-temperature (>~150°C) hydrothermal activity after ~40 Ma, and it places a lower limit on the age of mineralization. This age also is similar to other ages determined for deposits in the Getchell trend by other techniques.

Five detrital zircon samples from sedimentary units in the Jerritt Canyon district yielded fission-track ages ranging from 571 to 261 Ma (Hofstra et al., 1999). As expected, given the closure characteristics of zircon (Fig. 5), all of these ages are interpreted as predating Au mineralization. Hutcherson (2002) reports an apatite fission-track age for hydrothermal apatite in an altered, mineralized dike at the Murray deposit in the Jerritt Canyon district. Her sample yielded a range of ages for individual grains (mean age for the population is ~20 Ma), but the oldest age for a single grain was 36 ± 8 Ma. This age was interpreted to be the age of mineralization; younger ages represent grains that had been partially or completely reset by Miocene thermal activity.

Two new dates are reported here for the Barneys Canyon and Bingham Canyon deposits (Table 1) and bear on the relative timing of Au mineralization in the peripheral zone and Cu-Mo mineralization in the core of the porphyry system. A U/Th-He age of 33.1 ± 1.6 Ma (2σ) was determined on apatite separated from a bleached sandstone unit from Au-bearing altered rock at the Barneys Canyon Au deposit. A quartz monzonite porphyry from the giant Bingham Canyon porphyry Cu-Mo-Au deposit located 8 km to the south returned an apatite U/Th-He age of 34.9 ± 1.8 Ma (2σ). These ages reflect the time the hydrothermal system (or systems) cooled below ~75°C and strongly suggest a temporal relationship between Au mineralization at Barneys Canyon and Cu-Mo-Au mineralization at Bingham Canyon. Reported ages for mineralization and igneous rocks at Bingham Canyon range from 37 to 40 Ma (Warnaars et al., 1978; Chesley and Ruiz, 1997; Kendrick et al., 2001; Parry et al., 2001). These Oligocene ages contrast with Jurassic K-Ar ages for sericite (see above), which Presnell and Parry (1996) interpreted as the probable age for Au mineralization at Barneys Canyon. As with the Pinson apatite fission-track age, the relationship of this sample to the Au mineralization event at Barneys Canyon is unclear, but the date clearly places lower limits on the timing of hydrothermal activity at this deposit. In light of the obvious heat source and metal zoning around Bingham, the apatite U/Th-He data seem to provide a geologically consistent age for Barneys Canyon.

Rb-Sr Ages of Galkhaite

Because the unusual sulfosalt mineral galkhaite [(Cs,Tl)(Hg,Cu,Zn)₆(As,Sb)₄S₁₂] contains large, singly charged elements such as Cs, Tl, and Hg, it was expected that it might also contain significant quantities of Rb or K, thus making it amenable to radioisotopic dating. At least four Carlin-type deposits have been reported to contain galkhaite (Getchell: Tretbar et al., 2000; Carlin: Dickson et al., 1979; Rodeo: this paper; and SSX: this paper). Of these, both the Getchell and Rodeo deposits have yielded sufficient galkhaite to make a mineral separate and obtain a date. Although galkhaite was reported at Carlin by Dickson et al. (1979), the locality for the mineral has been mined out and samples can no longer be obtained. At SSX, only a single grain (~10 μm across) has been found in a thin section.

Galkhaite is common at the Getchell mine but rare worldwide. At Getchell and Rodeo, mineral associations and detailed observations of its occurrence, distribution, and chemistry indicate that galkhaite is paragenetically late but still part of the Au stage and prerealgar (Fig. 2; Tretbar et al., 2000;

TABLE 1. U/Th-He Data from Barneys Canyon and Bingham, Utah

CSIRO ¹ number	Location	Descriptor	U (ppm)	Th (ppm)	He (ncc/g) ²	Ft ³	U-He age ± 2σ (Ma)
136029	Barneys Canyon	Altered sandstone	21	42	69,370	0.78	33.1 ± 1.6
136130	Bingham Canyon	Monzonite porphyry	5.8	10.8	27,500	0.79	34.9 ± 1.8

¹CSIRO = Commonwealth Scientific and Industrial Research Organization

²ncc = nanocubic centimeters

³Ft = alpha particle emission correction factor, which takes into account potential He loss from the U or Th located near the surface of the grains when decay occurs and is based on the size and morphology of each individual grain

Cline, 2001; D. Tretbar, unpub. data, 2002). Dickson et al. (1979) reported that galkhaite at Carlin occurred with cinnabar and in association with other Tl-bearing minerals; thus, it is probably of a similar paragenesis. From inductively coupled plasma-mass spectrometer analyses, the Rb concentration of the Getchell galkhaite was estimated to be on the order of 100 to 300 ppm. This concentration was determined on the basis of a comparison of the peak intensity for Rb with peak intensities for other elements of known concentration. Similar Rb concentrations were determined from the Rodeo galkhaite. Because galkhaite contains virtually no Sr, it is ideal for Rb-Sr dating.

Tretbar et al. (2000) reported the first age determination on galkhaite from Getchell. Because of the extreme Rb/Sr ratio, only a single datum is required to fix the age reasonably accurately. However, Tretbar et al. (2000) obtained measurements on four subsamples of galkhaite, yielding an isochron age of 39.0 ± 2.1 Ma. At the Rodeo deposit on the northern Carlin trend, galkhaite is associated spatially with ore and is most commonly found in silicified and vuggy rocks in a manner similar to Getchell. Detailed paragenetic studies, currently underway but not completed, show that galkhaite is intergrown with other late ore-stage minerals, cinnabar, and mercurian tennantite, and possibly with tvalchrelidzeite [$\text{Hg}_{12}(\text{Sb,As})_8\text{S}_{15}$]. New analytical data for a sample of galkhaite from the Rodeo deposit in the Carlin trend yield an age of 39.8 ± 0.6 Ma (Table 2).

Other Isotopic Dating Techniques

Several other isotopic dating techniques have been attempted on Carlin-type deposits. Hofstra et al. (1999) reported that attempts to use Re-Os on realgar, orpiment, and pyrite were unsuccessful, primarily because of the extremely low Re and Os contents of these minerals. Sm-Nd dating has been attempted on fluorite (J. Cline, oral commun., 2001), also unsuccessfully. We also have attempted Rb-Sr dating on sphalerite with no success to date because of the presence of relatively high-Sr contaminant phases.

U-Th-Pb techniques have been used on various minerals in Carlin-type deposits with mixed results. Hofstra et al. (2000) reported an age of fluorite at Getchell of 34 ± 11 Ma, which is consistent within errors of other dates. A sample of postore calcite from Meikle yielded an isochron age of ~ 2 Ma, although there were significant analytical problems reported with this sample (Hofstra et al., 2000). Attempts to use late ore-stage pyrite from Meikle yielded a pseudoisochron age of 159 ± 46 Ma, but field relations indicate that these pyrites can not be older than about 39 Ma (Hofstra et al., 2000). U-Pb techniques have been used on apatite, but unfortunately the uncertainties in measurements have been too large to obtain

good analytical ages (R.M. Tosdal, oral commun., 2000). In addition, this system is complicated by multiple types of apatite, as described above. These results suggest that U-Th-Pb techniques hold some promise in dating Carlin-type deposits, but that the samples must be selected and characterized carefully and analyzed accurately. In general, the low U and Th contents of most minerals in Carlin-type deposits will result in dates with relatively large uncertainties.

Paleoclimate Data

Hydrothermal fluids from which Carlin-type deposits were formed are dominated by meteoric fluids, and for most Carlin-type deposits those fluids have a δD signature that is low ($\sim -150\text{‰}$; Arehart, 1996). Hofstra et al. (1999) presented a curve for evolution of meteoric water through time in the western United States; the curve is based on the alunite curve of Arehart and O'Neil (1993) between 0 to 30 Ma and on data from various other sources to extend the curve from 30 to 170 Ma. There is good control on the isotopic composition of meteoric water back to ~ 50 Ma; before 50 Ma the data are sparse and the uncertainties increase. However, given the known ages of several deposits and their δD values, the available data from Carlin-type deposits are consistent with their formation during the time of lowest δD values for meteoric waters, that is, prior to ~ 30 Ma.

Summary of Mineralization Ages

Table 3 summarizes what we consider the best available ages for various Carlin-type deposits and/or districts. The two best-constrained districts are the Carlin trend and the Getchell trend. In the Carlin trend, mineralization took place at approximately 39 Ma, on the basis of dates from preore and postore igneous crystallization ages, step heated mixed-generation sericite, apatite fission-track data, and the single Rb-Sr age from galkhaite. The age of mineralization in the Getchell trend is constrained by $^{40}\text{Ar}/^{39}\text{Ar}$ ages of adularia (Twin Creeks), a single fission-track age from hydrothermal apatite (Pinson), and a single Rb-Sr isochron from galkhaite (Getchell), all of which yield mineralization ages near 40 Ma.

Ages of mineralization in other deposits are less well constrained (Table 3). In the Jerritt Canyon district, preore basalt dikes that are altered and/or mineralized in the ore zone limit mineralization to less than 41 Ma and apatite fission-track data from the Murray deposit have been interpreted to suggest mineralization is most likely $> \sim 39$ Ma. We consider that the best available age constraints for Mercur and Barney's Canyon are from the preore Eagle Hill rhyolite (32 Ma) and from an apatite U/Th-He age of 33 Ma respectively. Other districts have few age constraints. The Cortez district is clearly younger than the Mill Canyon or Gold Acres stocks (~ 160 Ma; McCormack and Hays, 1996). Altered dikes having a crystallization age of 35 Ma are present in the Cortez district, but it is unclear at present whether these dikes are preore or postore (Wells et al., 1969; McCormack and Hays, 1996). In several districts, supergene alunite provides the lower age limit to mineralization, which ranges from 9 to 27 Ma (Arehart et al., 1992). There are still other districts (e.g., Eureka, Taylor) for which the available data (see Table 3) provide only limits on the age of mineralization or are of

TABLE 2. Isotopic Data for Galkhaite from the Rodeo Deposit, Nevada

$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$	$^{87}\text{Rb}/^{86}\text{Sr}$	Apparent age ¹ $\pm 2\sigma$
1.6592	0.0024	1679	39.8 ± 0.6 Ma

¹Age calculated assuming an initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7095 ± 0.0020 , uncertainty in apparent age based on $^{87}\text{Sr}/^{86}\text{Sr}$, an uncertainty of 0.002 in assumed initial Sr, and a 1 percent error in $^{87}\text{Rb}/^{86}\text{Sr}$

TABLE 3. Summary of Best Available Age Constraints on Carlin-Type Deposits and Districts

District/deposit	Ma	Source material	System and reference
Carlin trend	37–39	Ore-stage galkhaite Preore and postore igneous rocks	Rb-Sr: This paper $^{40}\text{Ar}/^{39}\text{Ar}$: Arehart et al., 1993 Ressel et al., 2000 U-Pb: Mortensen et al., 2000
		Apatite fission-track	Arehart et al., 1993 Chakurian et al., 2003
Getchell trend	39–42	Ore-stage galkhaite	Rb-Sr: Tretbar et al., 2000
		Adularia associated with ore-stage orpiment	$^{40}\text{Ar}/^{39}\text{Ar}$: Groff et al., 1997 Hall et al., 2000
		Apatite (ore stage?)	Fission-track: Hofstra et al., 1999
Cortez	<150	Preore igneous rocks	K-Ar: Wells et al., 1969
	34	Igneous rocks interpreted as preore by Wells et al. (1969), as postore by McCormack and Hays (1996)	K-Ar, $^{40}\text{Ar}/^{39}\text{Ar}$: Wells et al., 1969 McCormack and Hays, 1996 U-Pb zircon: Mortensen et al., 2000
Gold Acres	<98	Preore igneous rocks	K-Ar: Hays and Foo, 1991
Eureka (Archimedes)	<110	Preore igneous rocks	K-Ar: Dilles et al., 1996
Jerritt Canyon District	~40	Preore igneous rocks	K-Ar, $^{40}\text{Ar}/^{39}\text{Ar}$: Phinisey et al., 1996 Hofstra et al., 1999
		Apatite in ore zone	Fission-track: Hutcherson, 2002:
Alligator Ridge	<45	Preore igneous rocks	$^{40}\text{Ar}/^{39}\text{Ar}$: Nutt, 1996 Nutt and Good, 1998
	>36.5	Postore igneous rocks	Nutt and Hofstra, 2003: $^{40}\text{Ar}/^{39}\text{Ar}$
Bald Mountain	<150	Preore igneous rocks; there is some question whether these are true Carlin-type deposits; see Nutt et al., 2000	K-Ar: Hitchborn et al., 1996 U-Pb zircon: Mortensen et al., 2000
Mercur	<32	Preore igneous rocks	K-Ar: Mako, 1997; Kerr, 1998:
Barneys Canyon/Melco	33	Preore igneous rocks	$^{40}\text{Ar}/^{39}\text{Ar}$: Deino and Keith, 1997
		Apatite in ore zone	U/Th-He: This paper
Tonkin Springs	33–38	Preore and postore igneous rocks	K-Ar: Maher et al., 1993
Windfall/Rustler	<35?	Preore igneous rocks	K-Ar: Wilson and Wilson, 1986

sufficient ambiguity that it is not possible to assess the age of Carlin-type Au mineralization with any certainty.

Gold mineralization of the majority of the Carlin-type deposits in the Great Basin occurred within a narrow time frame of 33 to 40 Ma. In addition to the age of Carlin-type Au mineralization, it is clear that there were preore hydrothermal events that may have contributed to the tenor of ore, or that provided important ground preparation that facilitated subsequent mineralization. In most districts, these events appear to be reflected in sericite ages that range generally between 80 and 120 Ma. An exception may be the somewhat older sericite ages (~160 Ma) in the Oquirrh Mountains of Utah. It should be noted that in some districts (Carlin trend, Bald Mountain, Cortez district), there is evidence for weak Au mineralization associated with Jurassic igneous rocks. This

mineralization also may have contributed to the Au endowment of some deposits, although the extent of that contribution is unclear at present.

Implications of the Ages

There has been debate over the past decade (or more) regarding the tectonic environment of Carlin-type deposits in the Great Basin. Although it is unclear why, all the well-dated deposits are approximately 33 to 40 Ma (Table 3), and the evidence favors a similar age for many other Carlin-type deposits. As noted by many researchers (e.g., Seedorff, 1991; Burchfiel et al., 1992; Christiansen and Yeats, 1992; Wernicke, 1992), this time corresponds with the transition from a compressional to an extensional tectonic environment in the Great Basin. It also is clear that this transition was accompanied by

fairly widespread magmatism across the Great Basin (Stewart, 1980; Seedorff, 1991).

Three models have been advanced regarding the genesis of Carlin-type hydrothermal activity. Seedorff (1991) argues for the release of metamorphic fluids, derived from Late Proterozoic rocks, during the transition from compression to extension in the Eocene. Ilchik and Barton (1997) argue that the high heat flow associated with extension and crustal thinning could have generated meteoric-hydrothermal systems capable of transporting sufficient quantities of Au to result in the observed Carlin-type deposits, without requiring any igneous activity. The major difference between these two models is the source of the fluids. An advantage of both of these models is that they can explain the development of Carlin-type deposits in areas where no concurrent igneous activity is known, such as the Getchell trend. As noted above, abundant igneous activity accompanied the inception of extensional tectonism across the Great Basin (e.g., Seedorff, 1991; Henry and Ressel, 2000) and in many districts that igneous activity was contemporaneous with Carlin-type mineralization (e.g., Carlin trend). The third major model is that of genesis of Carlin-type deposits as a direct product of magmatic activity (e.g., Sillitoe and Bonham, 1990). In those districts where contemporaneous igneous activity is known, most researchers argue for a genetic connection in which the magmatic events contributed at least thermal energy to the system and possibly contributed to the metal budget. The magmatic model presumes presently unexposed or unrecognized igneous rocks as the driving force for the genesis of some Carlin-type deposits where the spatial and temporal links between mineralization and magmatism are less well-developed.

Unfortunately, age data alone can not solve the question of whether Carlin-type deposits are generated solely by extensional tectonic processes and/or metamorphic processes, or whether magmatism reflected in igneous rocks, either hidden or cropping out at the present level of exposure, is a critical component. There are many districts in the Great Basin, spatially overlapping the area of Carlin-type deposits, where either or both extension and magmatism took place prior to and continued well beyond the time period for Carlin-type deposits. In these areas, porphyry and epithermal systems are present but no Carlin-type deposits of these ages are known. In addition, other areas of western North America underwent extension and magmatism at earlier or later times as part of an overall migration of extension and magmatism from north to south (Burchfiel et al., 1992; Christiansen and Yeats, 1992; Wernicke, 1992) without development of any (known) Carlin-type deposits. Therefore, given the relatively tight cluster of ages now known for Carlin-type deposits, it appears that there may be a unique environment or combination of events required for development of these deposits. Although the age data provide a critical piece of this puzzle, much additional work will be required to determine why Carlin-type deposits are nearly unique in the Great Basin in both time and space.

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