δD and $\delta^{18}O$ DATA FROM CARLIN-TYPE GOLD DEPOSITS- IMPLICATIONS FOR GENETIC MODELS

By Albert H. Hofstra *and* Robert O. Rye

ABSTRACT

δD and $\delta^{18}O$ data from quartz, clays, and inclusion fluids were used to characterize the isotopic composition of water in ore fluids. The hydrothermal fluids that formed most Carlin-type gold deposits had low δD_{H_2O} values (-116 to -164‰) and a wide range of $\delta^{18}O_{H_2O}$ values (-20 to 15‰) suggesting that ore fluids consisted of variably exchanged meteoric water. In contrast, fluids from Carlin-type deposits in the Getchell Trend had a much wider range of δD_{H_2O} values (-153 to -44 ‰) but a similar range of $\delta^{18}O_{H_2O}$values suggesting that ore fluids were magmatic or metamorphic in origin, although variably exchanged meteoric water was also present.

The δD_{H_2O} variation of meteoric water in this region over the past 170 Ma provides a means to discriminate between the various ages proposed for the deposits. The unusually low δD_{H_2O} values of the hydrothermal fluids agree with the δD_{H_2O} values of meteoric water in the mid-Tertiary (42 to 30 Ma) when the climate was cool, but are lower than those of meteoric water in the Late Jurassic and Cretaceous when the climate was warm.

The data suggest that Carlin-type deposits formed in the mid-Tertiary soon after the onset of extension and magmatism in northern Nevada and northwest Utah. The increased permeability and high heat flow in this setting may have provided the drive for deep circulation of meteoric water and development of Carlin-type deposits in fracture systems that focused fluid flow. In the Getchell Trend, these structures may have tapped metamorphic fluids generated in the middle crust or magmatic fluids released from deep intrusions or batholiths.

INTRODUCTION

This report is adapted from information in Hofstra and others (in review). The goal of this report is to use δD and $\delta^{18}O$ data from Carlin-type gold deposits to identify the source(s) of water in the ore fluids. This information is important because it can improve genetic models and constrain the age of the deposits. The age information results from temporal variations in the isotopic composition of meteoric water in response to changes in climate. Included in this report are new and previously published isotopic data from the Jerritt Canyon, Post/Betze, Carlin, Cortez, Gold Pick, Getchell, Twin Creeks, Alligator Ridge, and Mercur mines (Appendix A). The isotopic data are from quartz, clays, and inclusion fluids extracted from a variety of ore stage minerals.

Three different models have been proposed for the deposits with ore fluids derived from different sources: (**1**) the magmatic or distal-disseminated model where the deposits form from magmatic fluids in the distal parts of porphyry systems; (**2**) the meteoric water circulation model where the deposits form from rain water that evolved to become an ore fluid by deep circulation through sedimentary rocks; and (**3**) the metamorphic or shallow mesothermal vein model where the deposits form from metamorphic fluids expelled from shear zones at depth. Combinations of these end member models are also possible. It is important to point out that in each of these models a fluid from deeper levels displaces the local meteoric ground water at the sites of mineral precipitation. Therefore some of the isotopic data from each deposit is likely to reflect the isotopic composition of meteoric water at the time of mineralization.

ISOTOPIC CONSTRAINTS ON FLUID SOURCES

Figure 1 shows the δD and $\delta^{18}O$ values of water in Carlin-type ore fluids relative to some traditional references (see fig. 1 and Appendix A for sources of data). Fluids from most Carlin-type deposits have low hydrogen isotope values (< -116 ‰) and a wide range of oxygen isotope values that extend well away from the meteoric water line (fig.1). Variations in the temperature of deposition can only account for part of this range. The water-rock exchange curve shows how the isotopic composition of meteoric water would vary by progressive exchange with shaley marine limestones at a temperature of 300°C. The jasperoids with high $\delta^{18}O$ values can be explained if they precipitated from exchanged meteoric water that evolved by deep circulation through sedimentary rocks at elevated temperatures and low water-rock ratios. Jasperoids with low $\delta^{18}O$ values are representative of the relatively unexchanged meteoric ground water in the host rocks. At Jerritt Canyon, the jasperoids with the highest oxygen isotope values contain the most gold (fig. 1) suggesting that

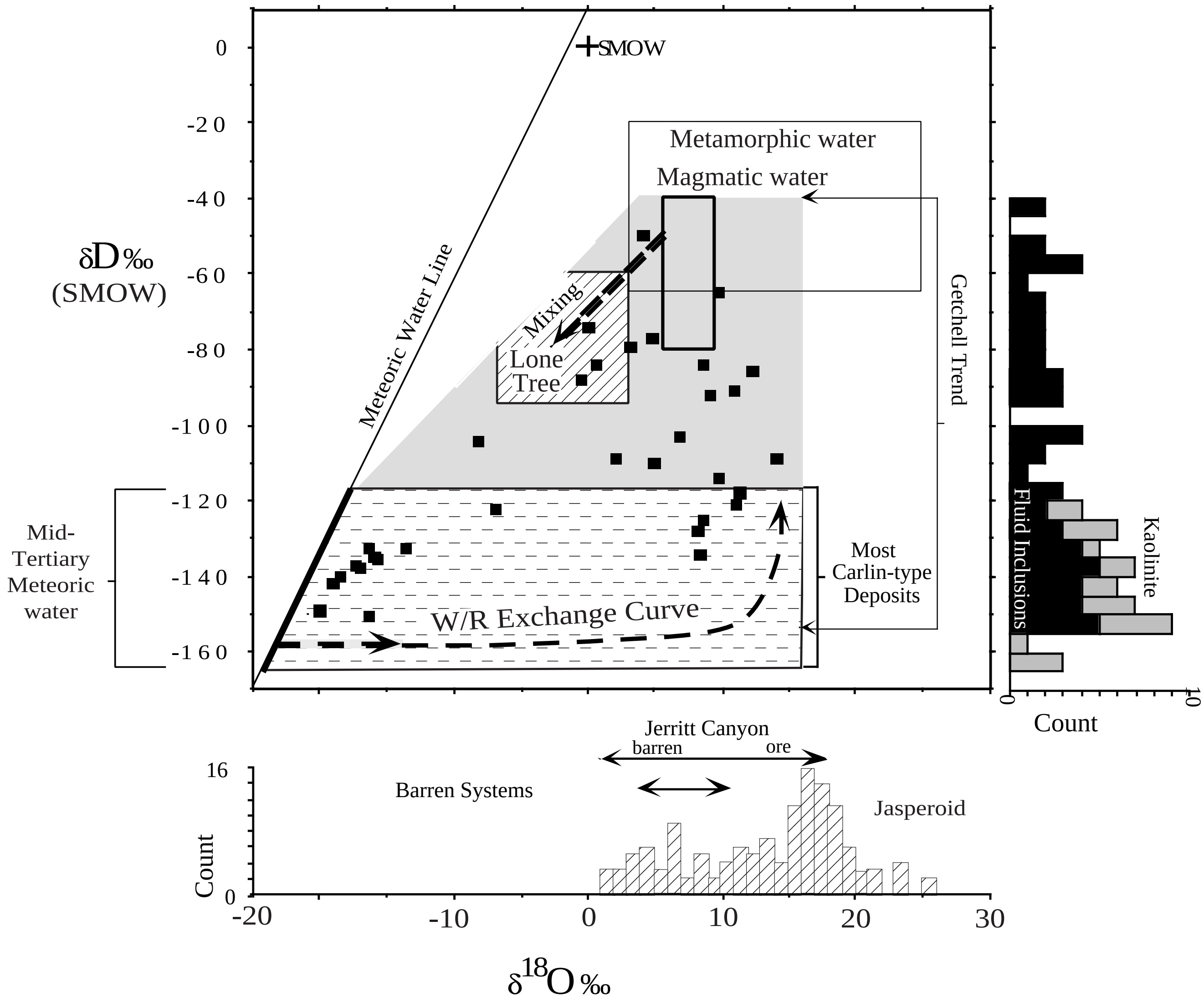

Figure 1. δD and $\delta^{18}O$ data from Carlin-type gold deposits. The black squares are samples for which there is both oxygen and hydrogen isotopic data. $\delta^{18}O$ data from jasperoids are shown on the x-axis (data from Hofstra, 1994; Ilchik, 1990; Holland and others, 1988; Radtke and others, 1980; Groff, 1996) and δD data from water in fluid inclusions and kaolinite are shown on the y-axis (see Appendix A for sources of data). The triangular field shows the calculated range of fluid compositions required by this data. Isotopic data from Lone Tree (diagonal rule pattern), a distal disseminated gold deposit, is shown for comparison (Howe and others, 1995; this study). See text for further description.

gold was transported by the isotopically exchanged fluid (Northrop and others, 1987; Hofstra and others, 1988). This observation is supported by evidence that jasperoids from barren systems (fig. 1) have low $\delta^{18}O$ compositions (Holland and others, 1988). Therefore, the large range of $\delta^{18}O$ values most likely reflects mixing between highly exchanged ore fluids and unexchanged meteoric ground water. Although it is possible that contributions from deep sources are present in these deposits and that the signal is masked by an overwhelming amount of meteoric water, there is a significant amount of data from Jerritt Canyon, Carlin, and Alligator Ridge that suggests the ore fluids consisted of exchanged meteoric water.

In contrast, samples from the Carlin-type deposits in the Getchell Trend have a much wider range of δD values (fig. 1) that extend from -153 to -44 ‰ but a similar range of $\delta^{18}O$ values (Cline and others, 1996, 1997; Groff, 1996). Samples representative of the main stage of gold mineralization have the highest δD values suggesting that gold was introduced by a magmatic or metamorphic fluid. The triangular range of values suggests that the deep sourced ore fluid mixed with both unexchanged meteoric water and exchanged meteoric water. Despite the evidence for a deep fluid source, the mineralogy, alteration, and geochemical signature of the deposits in the Getchell Trend are remarkably similar to Carlin-type deposits in the other districts. The most notable difference is the presence of small amounts of fluorite and adularia.

The Lone Tree deposit has a number of features that distinguish it from classic Carlin-type gold deposits and it is considered to be a distal disseminated deposit (Doebrich and Theodore, 1996). For example, it is located about 10 -15 km northwest of a group of mid-Tertiary porphyry systems in the Battle Mountain district and is younger than a 36.4 to 39.4 Ma rhyolite porphyry dike (Doebrich and others, 1995). It differs from most Carlin-type deposits in that most of the pyrite fills fractures rather than occurring as fine disseminations. It also contains traces of base metal sulfides and its Au /Ag ratios are lower than those in most Carlin type deposits. Mass transfer studies show that Fe was introduced rather than being immobile as in Carlin-types (this study). The introduction of iron suggests the presence of acidic, saline fluids and is consistent with the argillic alteration in the deposit and presence of halite daughter minerals in fluid inclusions (Kamali, 1996). The $\delta^{34}S$ systematics are also quite different from those typically found in Carlin-type deposits with bulk sulfur near 0 ‰ (Howe and others, 1995; Hofstra, 1997). The δD and $\delta^{18}O$ values of fluid inclusions in barite (Howe and others, 1995; this study) approach that of magmatic water (fig. 1). Collectively, this information suggests that gold was introduced by magmatic fluids.

In summary, the stable isotopic data from most Carlin-type deposits are consistent with the meteoric water circulation model, whereas, the data from the Getchell Trend are more consistent with the magmatic or metamorphic fluid models. The evidence from Lone Tree suggests that it formed from magmatic fluids, although it has a number of characteristics that distinguish it from most Carlin-type deposits. An important question then is whether deep sourced magmatic or metamorphic fluids are required to form Carlin-type deposits or whether the deposits in the Getchell Trend are unusual. Our current research is aimed at evaluating this possibility in other districts.

AGE CONTROVERSY

The age of Carlin-type deposits has been the subject of major debate and a variety of ages have been reported that range from the Late Jurassic to the Middle Tertiary (Emsbo and others, 1996; Hofstra, 1994, 1995; Hofstra and others, in review; Phinisey and others, 1996; Maher, and others, 1993; Silberman and others, 1974; Berger and others, 1975; Arehart and others, 1993; Wilson and Parry, 1995, 1991; Presnell and Parry 1992; Parry and others, 1997; and Drewes/Armitage and others, 1996). Figure 2 shows that the published ages for the deposits correspond to each of the major periods of magmatism in the region. The Late Jurassic and Cretaceous ages are based mainly on dates from white mica, or sericite, separated from mineralized sedimentary and igneous rocks and the mid-Tertiary ages are based mainly on cross-cutting relationships between gold ore and dated igneous rocks and a few dates on hydrothermal adularia and apatite. The age controversy revolves around whether one accepts the cross-cutting relationships or the sericite dates. While interpretation of the mid-Tertiary dates is straight forward, the sericitic alteration that is present in the deposits has generally not been shown to be related to the gold systems and in many cases is clearly related to pre-ore events. This is not too surprising given that the gold deposits are located along structural zones that contain intrusive rocks with a variety of ages. Furthermore, Folger and others (1996; this volume) have shown that older fine grained sericite in the host rocks is unlikely to be reset by Carlin-type hydrothermal systems.

δD CONSTRAINTS ON THE AGE OF CARLIN-TYPE DEPOSITS

Several recent studies have shown that the isotopic composition of the oceans and meteoric water on the continents have varied dramatically through time in response to global changes in climate (e.g. Emiliani, 1954,1966; Savin, 1977; Frakes and others, 1992; Francis and Frakes, 1993; Prothero, 1994; and references therein). The δD_{H_2O} variation of meteoric water on the continent provides a means to discriminate between the Mesozoic and mid-Tertiary ages proposed for the deposits. Since the ore fluids in many Carlin-type deposits consist largely of meteoric water, comparisons of the δD_{H_2O} values of the fluids with the δD-age record for

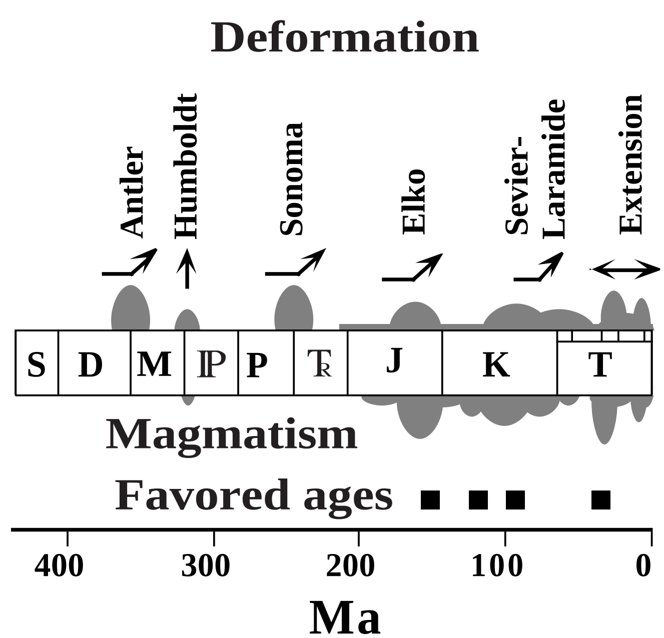

Figure 2. Major episodes of deformation and magmatism in the region and favored ages for Carlin-type gold deposits (Hofstra and others in review).

the region can be used to constrain the age of mineralization.

To date ore deposits from the δD_{H_2O} values of their ore fluids, it is necessary to construct a δD_{H_2O} versus age curve for meteoric water in the region (fig 3). Supergene alunites from the Great Basin provide a fairly continuous record of variations in the δD of meteoric water over the past 30 Ma (Arehart and O'Neil, 1993). Many of these supergene alunites are from Carlin-type gold deposits (Arehart and others, 1992). By combining the supergene alunite δD_{H_2O}-age curve with age and δD_{H_2O} data from older meteoric hydrothermal systems in the region (Appendix A), it is possible to construct a δD_{H_2O}-age curve for the past 170 million years as shown in figure 3. Prior to 170 Ma, this area was largely covered by sea water. The δD_{H_2O}-age curve constructed in this manner clearly shows that the δD of meteoric water in the region varied substantially over the past 170 Ma and that δD_{H_2O} values were lowest at about 30 Ma.

The δD_{H_2O}-age curve is consistent with the environmental factors that existed in the western U.S. over this time period and with global temperature curves. Isotopic patterns observed in continental precipitation today vary as a function of latitude, elevation, surface air temperature, amount of precipitation, and distance from the coast (Dansgaard, 1964). Each of these parameters affects the average degree of rainout of moisture from a given air mass as it moves from the source regions (mainly subtropical oceans) to the site of precipitation. Although paleolatitudes were as much as 7 degrees further south 150-m.y.-ago, for the past 100 m.y., they have been within 1 or 2 degrees of the present latitude (Lawrence and Meaux, 1993). Atmospheric circulation patterns would therefore have been dominated, as today, by west to east flow. Elevations varied in space and time in response to episodes of orogenic activity (Elko, Sevier, Laramide orogenies) but have probably been highest since the Laramide orogeny. Fossil flora and fauna from the continent suggest that the climate was distinctly warmer in mid-Jurassic to mid-Eocene time (Hallam, 1994; Francis and Frakes, 1993) and that cooler climates have prevailed ever since (Prothero, 1994). Although the western Cordillera (in eastern California and westernmost Nevada) has been an important highland (rainout area) since the mid-Jurassic, the δD of meteoric water (δD > -110 ‰) in mid-Jurassic to mid Eocene time (fig. 3) is consistent with the

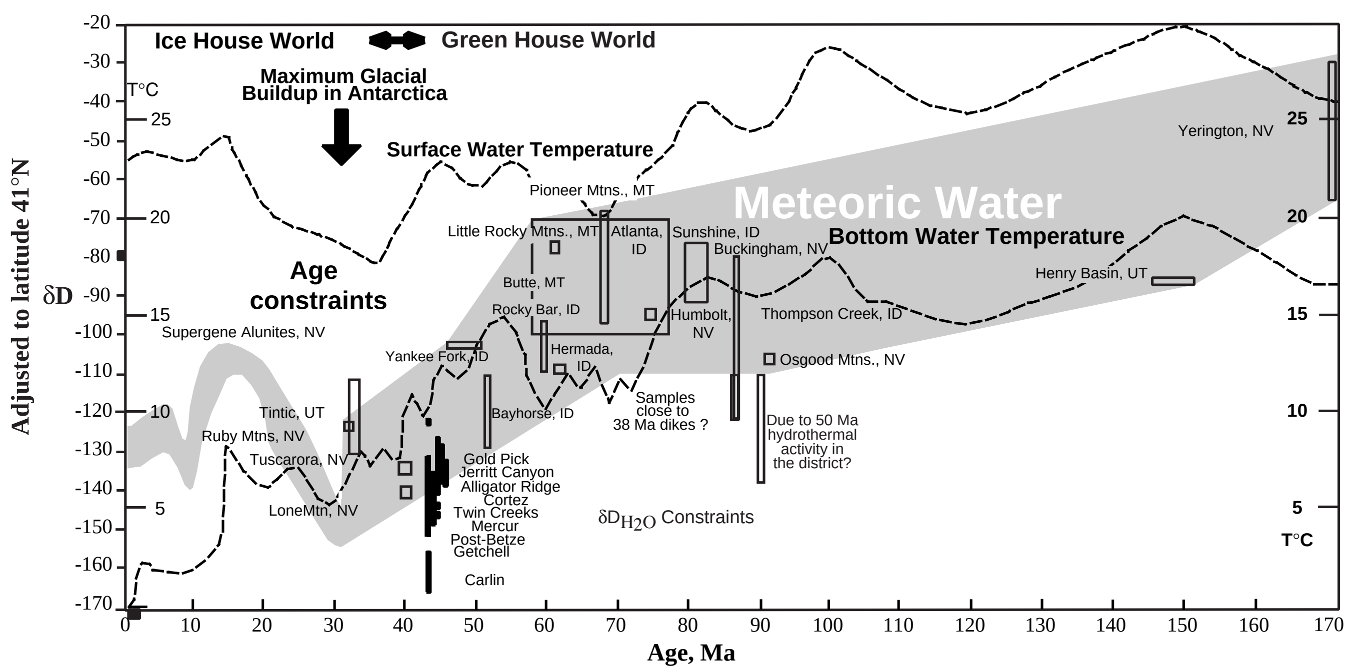

Figure 3. δD-Age curve showing variation in the isotopic composition of meteoric water over the past 170 Ma (constructed from information in Appendix A). The δD_{H_2O} values have been corrected to 41° North Latitude using a correction factor of 5 ‰ per degree latitude to be consistent with the alunite curve of Arehart and O'Neil (1993). In most respects the δD-Age curve agrees with knowledge of paleoclimates (see text). The δD-Age curve also corresponds well with paleotemperature curves for surface water and bottom water in the Pacific ocean (dashed lines) estimated from oxygen isotope analyses of calcareous microfossils (Douglas and Woodruff, 1981). The distinct minimum at about 30 Ma correlates with maximum glacial buildups in Antarctica and the maximum drop in sea level world wide. The unusually low δD_{H_2O} values from Carlin-type deposits (black bars) suggest that they formed near the low in curve when the climate was unusually cool. The δD_{H_2O} values agree well with the mid-Tertiary (42 to 30 Ma) age constraints on the deposits (bold rectangle) but are clearly at odds with the Jurassic and Cretaceous ages favored by some workers when the climate was much warmer. See text for further description. From Hofstra and others, in review.

relatively low elevation, warm climate, and close proximity to western (Pacific Ocean) and eastern (Carmel Sea-Cretaceous seaway) coastlines that characterized much of this period. The δD of meteoric water (δD < -110 ‰) since the mid Eocene is consistent with the higher elevations and cooler climatic conditions.

The δD_{H_2O}-age curve also mimics the global fossil foraminifera $\delta^{18}O$ pattern in the oceans (fig. 3), with relatively large δD_{H_20} values greater than -110 ‰ in Jurassic, Cretaceous, and early Tertiary time, when the world was in a “green house” state, and low δD_{H_2O} values of less than -110 and often as low as -140 to -160 in late Eocene and Oligocene time, when the world was in an “ice house” state. Most importantly, the δD_{H_2O} minimum at ~30 Ma correlates with maximum glacial buildups in Antarctica and the maximum drop in sea level world wide (Prothero, 1994). Although there are many uncertainties in the data used to construct the δD_{H_2O}-age curve, in most respects the curve is consistent with our knowledge of global temperature variations and environmental factors in the western United States over this time period. It is therefore reasonable to use the curve to estimate the age of Carlin-type deposits.

The δD_{H_2O} values of ore fluids from nine Carlin-type deposits range from -116 to -164‰. These values are unusually low for the latitude of the deposits and are generally less than present day meteoric water (fig. 3). For such widely separated deposits to have such similar isotopically light fluids, suggests that they formed at about the same time, near the low in the δD_{H_2O}-age curve (fig. 3), when the climate was unusually cool. Most important, the age estimates obtained from comparison of the ore fluid δD_{H_2O} values with the δD_{H_2O}-age curve agree with the mid-Tertiary (42 to 30 Ma) age constraints on the deposits (Maher and others, 1993; Hofstra, 1994, 1995; Phinsey and others, 1996; Emsbo and others, 1996; Groff et al, 1996; Hall and others, 1997). The low δD_{H_2O} values are clearly at odds with the Cretaceous and Jurassic ages (based on mica dates) favored by many workers (Silberman and others, 1974; Berger and others, 1975; Arehart and others, 1993; Wilson and Parry,1995, 1991; Presnell and Parry 1992; Drewes-Armitage, 1996; Groff et al, 1996; Parry and others, 1997) when the climate was much warmer.

The paleoclimate results provide compelling evidence that Carlin-type deposits in northern Nevada and northwestern Utah formed during a single metallogenic event in the mid-Tertiary. It is therefore important to consider the geologic setting at this time and the relation of mineralization to tectonics.

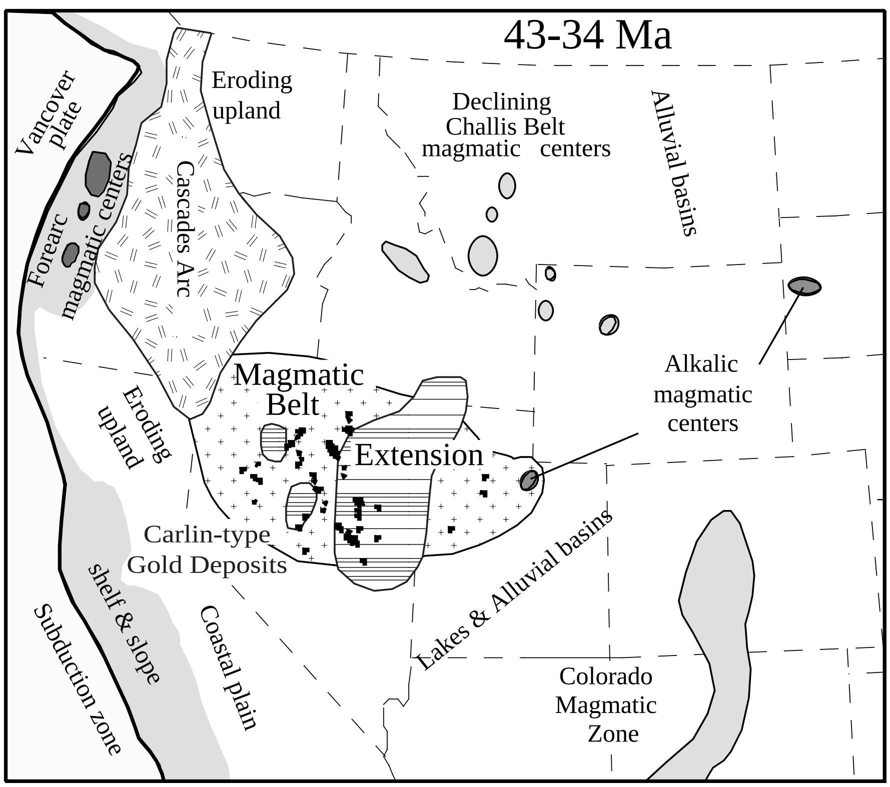

Figure 4. Paleogeography 43 to 34 million years ago showing the distribution of igneous activity, extensional tectonism (horizontal rule), and Carlin-type gold deposits (black dots). The increased permeability and high heat flow in this setting may have provided the drive for deep circulation of meteoric water and development of Carlin-type deposits in fracture systems that focused fluid flow. In the Getchell Trend, these structures may have tapped metamorphic fluids generated in the middle crust or magmatic fluids released from deep intrusions or batholiths. Modified from Christiansen and Yeats (1992).

GEOLOGIC SETTING IN THE MID-TERTIARY

Figure 4 shows the geologic setting in the western United States in the mid-Tertiary. The spatial correlation between Carlin-type deposits and areas undergoing magmatism and extension suggests that the deposits formed soon after the onset of this activity in northern Nevada and northwest Utah. The increased permeability and high heat flow in this setting may have provided the drive for deep circulation of meteoric water and development of Carlin-type deposits in fracture systems that focused fluid flow. In the Getchell Trend, these structures apparently tapped metamorphic fluids generated in the middle crust or magmatic fluids released from deep intrusions or batholiths. The results from Lone Tree indicate that distal disseminated deposits were forming at about the same time as classic Carlin-type deposits. Although gravity and magnetotelluric surveys (Grauch, and others, 1995; Rodriguez, 1997) suggest that deep penetrating structures and igneous intrusions are present below the Carlin Trend and Battle Mountain-Eureka Belt, thus far, there is no isotopic evidence for a deep fluid source in these districts. It is also important to note that Carlin-type deposits have not been recognized in similar tectonic settings to the north and south suggesting that additional factors were critical to their formation. This discussion points out the need for further studies to improve understanding of the source of ore fluid components, age of mineralization, and geologic framework of the deposits; information necessary to establish the relation between gold mineralization and tectonics.

REFERENCES CITED

Arehart, G.B., Foland, K.A., Naeser, C.W., and Kesler, S.E., 1993, $^{40}Ar/^{39}Ar$, K/Ar, and fission track geochronology of sediment-hosted disseminated gold deposits at Post/Betze, Carlin Trend, northeastern Nevada: Economic Geology, v. 88, p. 622-646.

Arehart, G.B. and O'Neil, J.R., 1993, D/H ratios of supergene alunite as an indicator of paleoclimate in continental settings: Climate Change in Continental Isotopic Records, Geophysical Monograph 78, p. 277-284.

Arehart, G.B., Kesler, S.E, O'Neil, J.R., and Foland, K.A., 1992, Evidence for the supergene origin of alunite in sediment-hosted micron gold deposits, Nevada: Economic Geology, v. 87, p. 263-270.

Berger, B.R., Silberman, M.B., and Koski, R.A., 1975, Discussion on K-Ar relations of granodiorite emplacement and tungsten and gold mineralization near the Getchell mine, Humbolt county, Nevada—A reply: Economic Geology, v.70, p. 1487-1491.

Boden, D.R., Struhsacker, E.M., and Wright, W.A., 1993, Volcanism, extension, and contrasting types of mineralization, Tuscarora mining district and vicinity, Nevada: Geological Society of Nevada, November Newsletter, 2 pgs.

Chesley, J.T., 1986, A combined $^{18}O/^{16}O$ and D/H isotopic study of molybdenite mineralization at Pear Lake and related areas in the Pioneer Mountains, southwest Montana: Corvalis, Oregon, Oregon State University, M.Sc. thesis, 91 p.

Christiansen, R. L., and Yeats, R.S., 1992, Post-Laramide geology of the U.S. Cordilleran region, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-3, pp. 261-406.

Cline, J.S., Hofstra, A.H., Landis, G.P., and Rye, R.O., 1997, Ore fluids at the Getchell Carlin-type gold deposit, northcentral Nevada, *in* Carlin-Type Gold Deposits Field Conference, Vikre, P., Thompson, T.B., Bettles, K., Christensen, O., and Parratt, R., eds., Society of Economic Geologist Guidebook Series, v 28, p. 155-166

Coats, R.R., 1987, Geology of Elko county, Nevada: Nevada Bureau of Mines and Geology, Bulletin 101, 112 p., 1 pl.

Criss, R.E., Fleck, R.J., and Taylor, H.P., Jr., 1991, Tertiary meteoric hydrothermal systems and their relation to ore deposition, northwestern United States and southern British Columbia: Journal of Geophysical Research, v. 96, no. B8, p. 13,335-13,356.

Dansgaard, W., 1964, Stable isotopes in precipitation: Tellus, v 16, p. 436-468.

Dilles, J.H., Solomon, G.C., Taylor, H.P., Jr., and Einaudi, M.T., 1992, Oxygen and hydrogen isotope characteristics of hydrothermal alteration at the Ann-Mason porphyry copper deposit, Yerington, Nevada: Economic Geology, v. 87, p. 44-63.

Doebrich, J.L., Wotruba, P.R., Theodore, T.G., McGibbon, D.H., and Felder, R.P., 1996, Field Trip H: Geology and ore deposits of the Battle Mountain mining district, *in* Geology and Ore Deposits of the American Cordillera Symposium, Field Trip Guidebook Compendium: Geological Society of Nevada, p. 327-376.

Doebrich, J.L., and Theodore, T.G., 1996, Geologic history of the Battle Mountain mining district, Nevada, and regional controls on the distribution of mineral systems, *in* Coyner, A.R and Fahey, P.L., eds., Geology and Ore Deposits of the American Cordillera: Geological Society of Nevada Symposium proceedings, Reno/Sparks, Nevada, April 1995, p. 453-483.

Douglas, R.G., and Woodruff, F., 1981, Deep sea benthic foraminifera, *in* Emiliani, C., ed., The Sea: New York, Wiley Interscience, p.1233-1327.

Drewes-Armitage, S.P., Romberger, S.B., Whitney, C.G.,1996, Clay alteration and gold deposition in the Genesis and Blue Star deposits, Eureka County, Nevada: Economic Geology, v. 91, p. 1383-1393.

Emiliani, C., 1954, Depth habitats of some species of pelagic foraminifers as indicated by oxygen isotope ratios: American Journal of Science, v. 252, p. 149-158.

Emiliani, C., 1966, Oxygen isotopes, oceanic sediements, and the ice ages: Transactions-American Geophysical Union, v. 47, no. 1, 44 p.

Emsbo, P., Hofstra, A.H., Park, D., Zimmerman, J.M., and Snee, L., 1996, A mid-Tertiary age constraint on alteration and mineralization in igneous dikes on the Goldstrike Property, Carlin Trend, Nevada: Geological Society of America Abstracts with Programs, v. 28, no. 7, p. A476.

Folger, H.W., Snee, L.W., Mehnert, H.H., Hofstra, A.H., and Dahl, A.R., 1996, Significance of K-Ar and $^{40}Ar/^{39}Ar$ dates from mica in Carlin-type gold deposits: Evidence from the Jerritt Canyon District, Nevada, *in* Coyner, A.R., and Fahey, P.L., eds., Geology and Ore Deposits of the American Cordillera: Geological Society of Nevada Symposium Proceedings, Reno/Sparks, Nevada, April 1995, p. 41-60.

Folger, H.W., Hofstra, A.H., Snee, L.W., and Eberl, D.D., (this volume), K-Ar and $^{40}Ar/^{39}Ar$ dating of illites from Carlin-type gold deposits-Nature of the problem and guidelines for future studies, *in* Tosdal, R.M., ed., Contributions to the gold metallogeny of northern Nevada: U.S. Geological Survey Open-File Report.

Frakes, L.A., Francis, J.E., and Syktus, J.I., 1992, Climate modes of the Phanerozoic: Cambridge University Press, 271 p.

Francis, J.E., and Frakes, L.A., 1993, Cretaceous Climates, *in* Wright, V.P., ed., Sedimentology Review, 1: Blackwell Scientific Publications, Oxford, p. 17-30

Grauch, V.J.S., Jachens, R.C., and Blakely, R.J, 1995, Evidence for a basement feature related to the Cortez disseminated gold trend and implication for regional exploration in Nevada: Economic Geology, v. 90, p.203-207.

Groff, J., 1996, $^{40}Ar/^{39}$ Ar geochronology of gold mineralization and origin of aurifereous fluids for the Getchell and Twin Creeks mines, Humboldt County, Nevada: Socorro, New Mexico, New Mexico Institute of Mining and Technology, Ph.D. Thesis, 291 p.

Groff, J.A., Heizler, M.T., McIntosh, W.C., and Norman, D.I., 1996, $^{40}Ar/^{39}Ar$ dating and mineral paragenesis for Carlin-type gold deposits along the Getchell Trend, Nevada: Evidence for Cretaceous and Tertiary gold mineralization: Economic Geology, v. 92, p. 601-622.

Hall, C.M., Simon, G., Kesler, S.E., 1997, Age of mineralization at the Twin Creeks SHMG Deposit, Nevada, *in* Vikre, P., Thompson, T.B., Bettles, K., Christensen, O., and Parratt, R., eds., Carlin-Type Gold Deposits Field Conference: Society of Economic Geologists Guidebook Series, v 28, p.151-154.

Hall, W.E., Schmidt, E.A., Howe, S.S., and Broch, M.J., 1984, The Thompson Creek, Idaho, porphyry molybdenum deposit - An example of a fluorine-deficient molybdenum granodiorite system: Proceedings of the Sixth Quadrennial IAGOD Symposium, E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany, p. 349-357.

Hallam, A., 1994, Jurassic climates as inferred from the sedimentary and fossil record, *in* Allen, JR.L., Hoskins, B.J., Sellwood, B.W., Spicer, R.A., and Valdes, P.J., eds., Paleoclimates and Their Modeling with Special Reference to the Mesozoic Era: London, Allen, The Royal Society, Chapman and Hall, p. 79-88.

Hofstra, A. H., Northrop, H.R., Rye, R.O., Landis, G.P., and Birak, D.J., 1988, Origin of sediment-hosted disseminated gold deposits by fluid mixing evidence from jasperoids in the Jerritt Canyon gold district, Nevada, U.S.A.: Bicentennial Gold '88, Oral Programme No. 22, Geological Society of Australia, p. 284-289.

Hofstra, A.H., 1994, Geology and genesis of the Carlin-type gold deposits in the Jerritt Canyon district, Nevada: Boulder, University of Colorado, Ph.D. Dissertation, 719 p.

Hofstra, A. H., 1995, Timing and duration of Carlin-type gold mineralization in Nevada and Utah—Relation to back-arc extension and magmatism: Geological Society of America Abstracts with programs, v. 27, no. 6, p. A-329.

Hofstra, A. H., 1997, Isotopic composion of sulfur in Carlin-type gold deposits: Implications for genetic models, *in* Vikre, P., Thompson, T.B., Bettles, K., Christensen, O., and Parratt, R., eds., Carlin-Type Gold Deposits Field Conference: Society of Economic Geologists Guidebook Series, v 28, p. 119-129.

Hofstra, A.H., Snee, L.W., Rye, R.O., Folger, H.W.,Phinisey, J.D.,Naeser, C.W., Stein, H.J.,Loranger, R.J.,Dahl, A.R., Lewchuk, M., in review, Age constraints on Jerritt Canyon and other Carlin-type gold deposits in the western United States — Relation to mid-Tertiary extension and magmatism: Economic Geology.

Holland, P.T., Beaty, D.W., and Snow, G.G., 1988, Comparative elemental and oxygen isotope geochemistry of jasperoid in the northern Great Basin; evidence for distinctive fluid evolution in gold-producing hydrothermal systems: Economic Geology, v. 83, p. 1401-1423.

Howe, S.S., Theodore, T.G., and Arehart, G.B., 1995, Sulfur and oxygen isotope composition of vein barite from the Marigold mine and surrounding area, north central Nevada: Application to gold exploration: Geology and Ore Deposits of the American Cordillera, Abstracts with Programs, p. A39.

Ilchik, R.P., 1990, Geology and geochemistry of the Vantage gold deposits, Alligator Ridge-Bald Mountain minning district, Nevada: Economic Geology, v. 85, p. 50-75.

Kamali, C., 1996, Characterization of ore fluids at the Lone Tree gold deposit, Humboldt County, Nevada: Socorro, New Mexico, New Mexico Institute of Mining and Technology, MSc. thesis, 137 p.

Kuehn, C.A., 1989, Studies of disseminated gold deposits near Carlin, Nevada: Evidence for a deep geologic setting of ore formation: Pennsylvania State University, Ph.D Thesis, 395 p.

Lawrence, J.R. and Meaux, J.R., 1993, The stable isotopic composition of ancient kaolinites in North America: Climate Change in Continental Isotopic Records: Geophysical Monograph 78, American Geophysical Union, p. 249-261.

Lewis, R.S., 1990, Geology geochemistry and mineral potential of Cretaceous and Tertiary plutons in the eastern part of the Soldier Mountains, Idaho: Corvalis, Oregon, Oregon State University, Ph.D. thesis, 214 p.

Maher, B. J., Browne, Q. J., and McKee, E. H., 1993, Constraints on the age of gold mineralization and metallogenesis in the Battle Mountain-Eureka mineral belt, Nevada: Economic Geology, v. 88, p. 469-478.

Norman, D.K., Parry, W.T., and Bowman, J.R., 1991, Petrology and geochemistry of propylitic alteration at southwest Tintic, Utah: Economic Geology, v. 86, p. 13-228.

Northrop, H.R., Rye, R.O., Landis, G.P., Lustwerk, R., Jones, M.B., and Daly, W.E., 1987, Sediment-hosted disseminated gold mineralization at Jerritt Canyon, Nevada, V-Stable isotope geochemistry and a model of ore deposition: Geological Society of America, Annual Meeting, Abstracts with programs, v.19, p. 791.

Northrop, H.R. and Goldhaber, M.B., 1990, Genesis of the Tabular-type vanadium-uranium deposits of the Henry Basin, Utah: Economic Geolgy, v. 85, p. 215-269.

Nutt, C., 1996, Cretaceous(?) to early Oligocene sedimentary and volcanic rocks at Alligator Ridge, Buck Mountain-Bald Mountain area, central Nevada, *in* Taylor, W.J. and Langrock, H., eds., Cenozoic structure andf stratigraphy of central Nevada: 1996 Field Conference Volume, Nevada Petroleum Society Inc., Reno, Nevada, p. 13-18.

Parry, W.T., Wilson, P.N., Presnell, R., 1997, Clay alteration and age of sediment-hosted diseeminated gold deposits in the Fold and

Thrust Belt, Utah, *in* Vikre, P., Thompson, T.B., Bettles, K., Christensen, O., and Parratt, R., eds., Carlin-Type Gold Deposits Field Conference: Society of Economic Geologists Guidebook Series, v 28, p. 185-192.

Phinisey, J.D., Hofstra, A.H., Snee, L.W., Roberts, T.T., Dahl, A.R., Loranger, R.J., 1996, Evidence for multiple episodes of igneous and hydrothermal activity and constraints on the timing of gold mineralization, Jerritt Canyon District, Elko County, Nevada, *in* Coyner, A.R and Fahey, P.L., eds., Geology and Ore Deposits of the American Cordillera: Geological Society of Nevada Symposium Proceedings, Reno/Sparks, Nevada, April 1995, p. 15-39.

Prothero, D.R., 1994, The Eocene-Oligocene Transition - Paradise Lost, Critical Moments, *in* Bottier, D.J. and Bambach, R.K., eds., Paleobiology and Earth History Series: New York, Columbia University Press, 291 p.

Presnell, R.D., 1992, Geology and geochemistry of the Barneys Canyon gold deposit, Salt Lake County, Utah, Salt Lake City, Utah, University of Utah, Ph.D. thesis, 363 p.

Presnell, R.D. and Parry, W.T., 1992, Argillic alteration at the Barneys Canyon gold deposit, *in* J.R. Wilson ed., Field Guide to geologic excursions in Utah and adjacent areas of Nevada, Idaho, and Wyoming: Utah Geological Survey and Geological Society of America, Miscellaneous Publication 92-3, p. 313-318.

Radtke, A.S., Rye, R.O., and Dickson, F.W., 1980, Geology and stable isotope studies of the Carlin gold deposit, Nevada: Economic Geology, v. 75, p. 641-672.

Rodriguez, B. D., 1997, Deep regional resistivity structure across the Carlin Trend, *in* Vikre, P., Thompson, T.B., Bettles, K., Christensen, O., and Parratt, R., eds., Carlin-Type Gold Deposits Field Conference: Society of Economic Geologists Guidebook Series, v. 28, p. 39-45.

Rye, R.O., Doe, B.R., and Wells, J.D., 1974, Stable isotope and lead isotope study of the Cortez, Nevada, gold deposit and surrounding area: U.S. Geological Survey Journal of Research, v. 2, p. 13-23.

Rytuba, J.J., 1985, Development of disseminated gold deposits of Cortez, Horse Canyon, and Gold Acres, Nevada, at the end stage of caldera-related volcanism: U.S. Geological Survey Circular 949, p. 47.

Savin, S.M., 1977, The history of the Earth's surface temperature during the past 100 million years: Annual Reviews of Earth and Planetary Science, v. 5, p. 319-355.

Seal, R.R., II, and Rye, R.O., 1993, Stable isotope study of fluid inclusions in fluorite from Idaho: Implication for continental climates during the Eocene: Geology, v. 21, p. 219-222.

Shepard, S.M.F., and Taylor, H.P., Jr., 1974, Hydrogen and oxygen isotope evidence for the origins of water in the Boulder Batholith and the Butte ore deposits, Montana: Economic Geology, v. 69, p. 9226-946.

Silberman, M.L., Berger, B.R., Koski, R.A., 1974, K-Ar age relations of granodiorite emplacement and tungsten and gold mineralization near the Getchell Mine, Hunbolt county, Nevada: Economic Geology, v. 69, p. 646-656.

Theodore, T.G., Blake, D.W., Loucks, T.A., and Johnson, C.A., 1992, Geology of the Buckingham stockwork molybdenum deposit and surrounding area, Lander County, Nevada: U.S. Geological Survey Professional Paper 798-D, 2 pls., 307 p.

Tilling, R.I., 1973, Boulder Batholith, Montana: A product of two contemporaneous but chemically distinct magma series: Geological Society of America Bulletin, v. 84, p. 3879-3900.

Wilson, M.R. and Kyser, Kurtis, 1988, Geochemistry of porphyry-hosted Au-Ag deposits in the Little Rocky Mountains, Montana: Economic Geology, v. 83, p 1329-1346.

Wilson, P. N. and Parry, W.T., 1990, Mesozoic hydrothermal alteration associated with gold mineralization in the Mercur district, Utah: Geology, v. 18, p. 866-869.

Wilson, P. N. and Parry, W.T., 1995, Characterization and dating of argillic alteration in the Mercur gold district, Utah: Economic Geology, v. 90, pp. 1197-1216.

Wickham, S.M., Peters, M.T., Fricke, H.C., and O'Neil, J.R., 1993, Identification of magmatic and meteoric fluid sources and upward and downward-moving infiltration fronts in a metamorphic core complex: Geology, v. 21, p. 81-84.

Appendix A. Age and δD of meteoric water ore fluids in Carlin-type gold deposits and other ore deposit types in the western United States. From Hofstra and others, in review.

Location	Deposit Type	Mineral(s)	Lat.(DMS)	Long.(DMS)	δD H2O, permil	δD H2O, 41°N	AGE (Ma)	REFERENCE(S)
Jerritt Canyon, NV	Carlin-type	Orpiment, realgar, kaolinite	412500	1160000	-129 to -143	-127 to -141	<40.8	this study
Twin Creeks, NV	Carlin-type	realgar	411500	1171000	-145	-144	42.0	Groff, 1996
Getchell, NV	Carlin-type	realgar	411000	1171500	-153 to -129	-152 to -130	?	Cline and others, 1996; Groff, 1996; this study
Post-Betze, NV	Carlin-type	orpiment, realgar	405800	1162230	-135 to -149	-135 to -149	<38.6	Emsbo and others, 1996; Groff, 1996; this study
Carlin, NV	Carlin-type	qtz,cal,bar,kaol	402000	1161000	-139 to -164	-143 to -167	?	Radtke and others, 1980; Kuehn, 1989
Mercur, UT	Carlin-type	calcite	401830	1121215	-144	-147.5	>31.6	Wilson and Parry, 1995; this study
Cortez, NV	Carlin-type	qtz, kaol	401000	1163500	-128 to -135	-132 to -139	>34.8	Rye et al, 1974; Rytuba, 1985; this study
Alligator Ridge, NV	Carlin-type	kaolinite	395000	1153000	-132 to -122	-138 to -128	>35.3	Ilchik, 1990; Nutt, 1996
Gold Pick(Gold Bar), NV	Carlin-type	orp, real	394500	1162200	-116	-122	?	this study
Sunshine mine, ID	Ag vein	quartz	473000	1160400	-118	-86	~80	Hofstra and Snee unpublished data
Little Rocky Mtn mines, MT	Epithermal Au-Ag vein	fluorite	473000	1093000	-110	-77.5	60	Wilson and Kyser, 1988
Butte-Boulder Batholith,MT	Porphyry Cu	sericite, qtz	460000	1123000	-110+ -15	-85±15	57 to 78	Sheppard and Taylor, 1974; Tilling, 1973
Pioneer Mtns, MT	Porphyry Mo	quartz	452500	1130000	-120 to -90	-97.5 to- 67.5	67	Chesley, 1986
Bayhorse district, ID	Epithermal F vein	fluorite	442730	1142000	-138±10	-121±10	51	Seal and Rye, 1993
Thompson Creek, Bayhorse dist., ID	Porphyry Mo	quartz	442000	1143500	-108 to -155	-91 to-138	89	Hall and others, 1984
Yankee Fork, So. Idaho Batholith, ID	Epithermal Au-Ag vein	quartz	442000	1144000	-120	-103	44 to 50	Criss and others, 1991; Lewis, 1990
Hermada, So. Idaho Batholith, ID	Epithermal Sb vein	sericite	440000	1150000	-124	-109	61	Criss and others, 1991; Snee unpublished data
Atlanta, So. Idaho Batholith,ID	Epithermal Au-Ag vein	sericite	434700	1150800	-123 to -87	-109 to -73	69	Criss and others, 1991; Snee unpublished data
Rocky Bar, So. Idaho Batholith,ID	Epithermal Au-Ag vein	qtz, sericite	434100	1151800	-124 to -114 qtz	-110 to -96	58	Criss and others, 1991; Snee unpublished data
Tuscarora, NV	Epithermal Au-Ag vein	quartz	411845	1161330	-134	-135.5	39	this study, Boden et al, 1993
Osgood Mtns, NV	Skarn and vein	quartz	411000	1171500	-107	-107	92	Taylor, 1976; Silberman and others, 1974
Lone Mountain, NV	Skarn and vein	quartz	410730	1165900	-140	-139	38	this study; Coats, 1987
Ruby Mtns, E Humboldt Range, NV	Core Complex	biotite	405000	1150500	-110 to -130	-111 to -131	> ~32	Wickham and others,1993 and refs. therein
Humbolt, NV	Epithermal Au-Ag	adularia	404000	1181500	-95	-97	73	O'Neil and Silberman, 1974
Buckingham, NV	Porphyry Mo	quartz	403615	1170300	-118 to -77	-120 to -79	86	Theodore and others, 1992
Tintic, UT	Epithermal Au-Ag vein	quartz	402000	1123500	-120	-123	~32	Norman and others, 1991
Yerington, NV	Porphyry Cu	sericite,chlorite	385800	1191500	-20 to -55	-30 to -65	169	Dilles and others, 1992
Henry Basin, UT	Sandstone U	chlorite,smectite	375500	1103000	-71	-86	150 to 144	

DMS-degrees, minutes, seconds