Spatial - temporal patterns in hydrothermal flow in Carlin-type Au-deposits in north-central Nevada mapped using apatite fission-track thermochronology;

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View of Pipeline open pit, Shoshone Mountains, Nevada

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Introduction

Carlin-type Au-deposits in northern Nevada form the world's third highest producing region after South Africa and Australia; being responsible for ~8% of the world's annual gold production (1997, 2002). The size and grade of the deposits makes them attractive exploration targets, but they typically have only a narrow alteration halo and lack an obvious distal chemical footprint that would act as a guide to exploration, particularly under pre-mineralization cover rocks. Because of the relatively limited geochemical footprint, other methods are required to help provide vectors toward deposits. As transport theory predicts that under certain circumstances, the thermal effect of hydrothermal fluid flow might be more far reaching than most chemical-mineralogical effects (Bickle and McKenzie, 1987; Cathles, 1997), including at the relatively low-temperatures of the auriferous hydrothermal fluids of 180-220° C estimated to have characterized the Carlin-type Au deposits (Hofstra and Cline, 2000). Consequently, being able to map such a thermal halo to the Carlin hydrothermal systems might provide the best distal indicator for use in exploration.

During hydrothermal fluid flow, heat is mainly transported by the egress of the liquid phase within the rock mass, and by conduction from the liquid into the surrounding rock (Bickle and McKenzie, 1987). The magnitude and penetration of a heat pulse that conducts into surrounding rock will depend primarily on the duration of fluid flow, the difference in temperature between the liquid and the rock, and the thermal diffusivity of the rock (Brady, 1988; Cathles et al., 2006). In view of the relatively low temperature for Carlin Au system, technics sensitive to these conditions will be required in order to map any thermal halo. Thermochronometers would be the preferred methodology as not only do they provide a temperature record but also a record of the time of the thermal resetting. Perhaps the most widely utilized, and the one chosen during this project is fission-tracks in apatite (AFT), which reset as apatite is heated above 60°C (Ketcham et al., 2007b). The extent of AFT resetting is a non-linear function of the duration and magnitude of the heating. As the magnitude and duration of conductive heating decreases outward from the hydrothermal fluid conduit, fission-tracks close to the conduit will be reset to a greater extent than those farther away. The pattern of AFT resetting will largely reflect the period and temperature of the fluid flow event that induced the conductive heating pulse.

Research Objectives

The main objectives of the USGS funded project are as follows.

1. What is the regional thermal history of the rocks hosting the deposits and what constraint does this place on the paleogeographic/tectonic framework of the deposits?
2. Are thermal anomalies defined by low-temperature thermochronometers associated with other clusters of Carlin-type Au deposits in the Cortez Range and Osgood Mountains and, if so, is it possible to infer a relationship between the scale of the thermal anomaly and that of gold endowment?
3. Are thermal anomalies uniquely associated with mineralization or is there some spatial association with Eocene intrusions that may have acted as the source of thermal energy responsible for resetting the AFT ages?
4. Is it possible to use the spatial-temporal pattern of AFT re-setting around Carlin-type deposits to constrain the time scale of hydrothermal flow responsible for mineralization?

Background to apatite fission-track thermochronology

Fission-tracks in apatite crystals are linear damage zones created by charged particles emitted during spontaneous fission of ^{238}U (Galbraith, 2005; Gallagher et al., 1998; Tagami and O'Sullivan, 2005; Wagner and Van den haute, 1992). They are metastable features that shorten, or anneal, over time. A measure of the magnitude of annealing is given by the reduced mean length, defined as l_m/l_0, where l_m is the mean observed c-axis parallel length, and l_0 is the initial track length of the same population of grains (Ketcham et al., 2007b; Ketcham et al., 1999). The rate of annealing is primarily a function of temperature (Carlson et al., 1999; Galbraith, 2005; Green et al., 1986; Wagner and Van den haute, 1992). The upper temperature bound, T_A, is the temperature at which a population of fission tracks formed at lower temperature fully anneals (l_m/l_0 ~0.55) during a linear heating path (Ketcham, 2005; Ketcham et al., 1999). The absolute value of T_A is proportional to the rate of heating or cooling. At sufficiently low temperatures, annealing becomes so slow that essentially all old and new tracks are retained. The temperature range between complete annealing and no effective annealing has been termed the partial annealing zone (PAZ) (Gallagher et al., 1998). The lower bound of the PAZ depends on the rate of cooling, and, on geological time scales (>10^6 yrs), a low level of near isothermal annealing (l_m/l_0 ~ 0.93) is inferred to occur at the earth's surface (Ketcham, 2005).

The rate of AFT annealing is also crystallographically controlled; fission tracks at a high angle to the c-axis have a mean length shorter than those at a low angle (Donelick, 1991; Galbraith, 2002; Galbraith and Laslett, 1988; Galbraith et al., 1990; Green et al., 1986). To account for this heterogeneity, re-projection techniques have been developed to convert initial (l_0) and measured fission track (l) lengths to equivalent c-axis parallel length, l_{c0} and l_c (Donelick et al., 1999; Ketcham et al., 2007a; Ketcham et al., 2009). The shortening of fission-tracks with progressive annealing is also known to vary in a complex way with anion (Cl, F, OH) and cation substitution (REE, Mn, Sr) in apatite (Barbarand et al., 2003; Carlson et al., 1999; Green et al., 2005; Hurford et al., 2005; Ketcham et al., 2007b; Ketcham et al., 1999). Fission-track length also correlate with the solubility of their host crystal in samples that have experienced >~70°C over geological time scales (Burtner et al., 1994). The metric of solubility has been termed D_{par} and it is the fission track etch pit diameter parallel to the crystallographic c-axis at the apatite surface (Donelick et al., 2005). D_{par} shows a general correlation with apatite fission track annealing kinetics and chemical composition (Barbarand et al., 2003; Carlson et al., 1999; Donelick et al., 2005; Ketcham et al., 2007b; O'Sullivan and Parrish, 1995), and serves as a physical proxy for integrated compositional variation in apatite. Small values of D_{par} (<~2.00 µm) are typical of fast-annealing, Ca-F-apatite, whereas large D_{par} values are typical of slow- to fast-annealing Ca (±Fe, Mn, rare earth elements)-F(±Cl)(±OH)-apatite. D_{par} is at least as reliable as Cl^- or $(OH)^-$ content as an indicator of the rate of apatite fission-track annealing (Donelick et al., 2005; Ketcham et al., 2007b; Ketcham et al., 1999).

Fission-tracks are produced at a constant rate and can be used for dating in the same manner as any other radioactive dating process. The density of naturally occurring, spontaneous, fission-tracks is used to determine the concentration of daughter product. Abundance of the ^{238}U parent can be calculated from the abundance of ^{235}U using the constant $^{238}U/^{235}U$ ratio observed in nature. The ^{235}U content is determined from the density of new fission-tracks induced by irradiating the sample with low energy thermal neutrons; the External Detector Method, EDM (Donelick et al., 2005; Galbraith, 2005; Gallagher et al., 1998; Tagami and O'Sullivan, 2005; Wagner and Van den haute, 1992). Alternatively the volume concentration of ^{238}U can be measured directly using LA-ICP-MS (Donelick et al., 2005; Hasebe et al., 2004).

An apatite fission-track (AFT) age for a rock sample is derived from a population of single crystal fission-track ages (Donelick et al., 2005; Galbraith, 2005; Tagami and O'Sullivan, 2005). All AFT ages in this study are reported as pooled ages. A pooled age assumes that all grains in the sample are derived from a single population with a *common* age reflecting a common time-temperature path through the apatite PAZ. The observed variation in single grain ages is then solely a product of the Poissonian probability of fission events occurring (Galbraith, 1981;

Galbraith and Laslett, 1993; Galbraith, 2005; Donelick et al., 2005). The pooled age is derived by summing the natural tracks (N_s) present in all the single crystals analyzed from the sample (including grains where N_s=0). The homogeneity of single crystal ages within a sample can be tested for Poissonian variation using the X^2 test. A X^2 probability, $p(X^2)$, of ≥ 0.05 is considered concordant with Poissonian variation and the common age model (Galbraith, 2005). Failure of the X^2 test at the at $p(X^2)$ < 0.05 - 0.01 indicates either that (i) there is insufficient data to provide a reliable test (single crystals have low N_s values), (ii) that there is a mixture of different AFT age populations (each with a different time-temperature history), or (iii) that the sample comprises crystals with inherently differing annealing kinetics (Galbraith, 2005; Galbraith and Laslett, 1993). For primary apatite in igneous rocks, and for detrital crystals heated above T_A, such kinetic variability can lead to a range in single crystal AFT ages greater than expected for Poissonian processes even though all the crystals followed the same time-temperature history. The precision of the common age estimate of the true age of the sample is encapsulated by the standard error (SE) of the pooled age. The standard error (SE) is a function of the number of natural fission-tracks present (largely reflecting the Poissonian uncertainty associated with the fission process) and the estimate of the ^{238}U concentration in the individual crystals (for the LA-ICP-MS method this is primarily analytical uncertainty; for the external detector method this results from both analytical uncertainty and Poissonian variation associated with the production of the induced fission-tracks) (Donelick et al., 2005; Galbraith, 2005; Ketcham, 2005; Tagami and O'Sullivan, 2005).

AFT age determinations and track length measurements were undertaken using procedures fully described by (Donelick et al., 2005). Most of the data had ^{238}U concentrations determined via LA-ICP-MS, for the rest the EDM was used (Table 1). Analytical uncertainty is reported as asymmetric 2SE values. Measurements of fission track etch pit diameter parallel to the crystallographic c-axis at the apatite surface (Dpar) were made on each apatite grain that yielded an age or a fission track length measurement. Measured track lengths were re-projected to equivalent c-axis lengths (l_c) using the technique of Ketcham et al (2007a). The annealing history of the samples analyzed in this study was assessed by inverse time-Temperature (t-T) modeling using the software package HeFTy v. 1.5.6 (Ketcham, 2005). This software is able to simultaneously model ages and track length distributions for multiple apatite populations exhibiting different Dpar values in a single sample also incorporates the c-axis re-projection technique of (Ketcham et al., 2007a).

General characteristics of Carlin Au-deposits in Nevada

The majority of gold in the Carlin type deposits of Nevada is disseminated in lower Paleozoic miogeoclinal carbonate rocks within the upper part of the footwall (lower plate) to the Roberts Mountains Thrust (RMT) (Arehart, 1996; Cline et al., 2005; Hofstra and Cline, 2000; Thompson et al., 2002). The hanging wall to the RMT (upper plate) largely comprises Lower Paleozoic eugeoclinal siliciclastic rocks that are not known to host any major gold deposits. Cross cutting relationships and direct dating of ore stage minerals constrain the main stage of hydrothermal activity and mineralization to the middle to late Eocene at ~42-37Ma (Arehart et al., 2003; Henry and Boden, 1998; Hofstra et al., 1999; Ressel et al., 2000; Tretbar et al., 2000). Gold deposition at this time occurred at <1 – 3 km depth and the hydrothermal fluid had temperatures of ~180°C to 220°C (Cline et al., 2005; Emsbo et al., 2003; Hofstra and Cline, 2000). Fluid inclusion analysis suggests the ore-stage hydrothermal fluids were reduced, of low salinity (2 – 4 wt%), and contained 2-4 mol% CO_2, <2 mol% CH_4 and <0.2 mol% H_2S (Hofstra and Cline, 2000). In addition to gold, the ore-stage hydrothermal fluids also carried As, Sb, Hg, Tl, W, Cu, and Te into the deposit (Barker et al., 2009; Cail and Cline, 2001; de Almeida et al., 2010; Emsbo et al., 2003; Hofstra and Cline, 2000; Yigit and Hofstra, 2003).

Gold is almost exclusively submicroscopic and concentrated in distinct trace-element rich zones several microns wide within the rim of fine-grained pyrite and marcasite (Barker et al., 2009; de Almeida et al., 2010; Muntean et al., 2011; Simon et al., 1999; Wells and Mullens, 1973). This ore-stage pyrite is believed to have formed via sulfidation of pre-existing Fe-silicate and Fe-carbonate minerals where bisulfide-complexed metals including gold were adsorbed on and incorporated into the precipitating Fe-sulfide (Hofstra and Cline, 2000; Hofstra et al., 1991; Kesler et al., 2003). Host rock alteration associated with Carlin-type mineralization is typically manifest as decarbonatization and sulfidation of the carbonate host rocks with variable argillization and silicification (Arehart, 1996; Hofstra and Cline, 2000; Hofstra et al., 1991; Stenger et al., 1998). In general, wall rock alteration in the typical calcareous host rock is quite subtle in all but the highest Au-grade areas. Nevertheless some degree of carbonate dissolution occurs with all gold mineralization although ore grades may not directly correlate with the intensity of the dissolution (Hofstra and Cline, 2000). This decarbonatization attests to the acidic nature of the hydrothermal fluid; the CO_2 content of the fluid suggesting a pH of just under 5.0 (Hofstra and Cline, 2000; Hofstra et al., 1991).

AFT Results

Northern Carlin trend

In previous studies summarized in the Year 1 report, AFT thermochronology identified a 50-25 Ma age thermal anomaly in close proximity to the Au-deposits of the northern Carlin trend (Fig. 1, Chakurian et al., 2003; Cline et al., 2005; Hickey, 2007; Hickey et al., 2005; Tosdal et al., 2003). Out beyond these zones, AFT ages are Cretaceous or older, reflecting the pre-mineralization regional cooling history (Fig. 1). Thermal modeling of the older AFT age cluster indicates that they last cooled from >100° C to <50° C during the Sevier orogeny at >60 Ma, with one major period of cooling at ~100-70Ma. The thermal effects of the Carlin hydrothermal systems were then superimposed on this regional pattern. The clusters of younger 50-25 Ma AFT ages are largely a product of one or more episodes of transient re-heating and rapid cooling between ~45 and 30Ma.

The spatial and temporal overlap of the young AFT ages with Au-mineralization is suggestive of a direct causative relationship (Fig. 1). Primary advection of heat by circulating hydrothermal fluids is indicated by the spatially heterogeneous nature of AFT resetting. This is most clearly illustrated in and around the 158Ma Goldstrike granodiorite stock on the northern Carlin trend (Fig. 1b). Samples from the weakly altered to unaltered core of the Goldstrike stock yield thermal histories consistent with only minor reheating at ~40Ma and preserve evidence for the regional Cretaceous cooling event. In contrast, AFT ages from highly altered and mineralized granodiorite from the northern edge of the stock were completely thermally reset at ~40Ma and preserve no part of the earlier cooling history seen in the core of the intrusion. The lower permeability (intrinsic and fracture-controlled) of pre-mineral intrusions like the Goldstrike stock restricted fluid flow through them, leading to no, or only partial, resetting of their AFT ages. Focused fluid flow on the margins of the stocks, however, resulted in complete thermal resetting in these regions.

Along the northern Carlin trend, AFT resetting is developed on a scale larger than the distribution of Au-deposits themselves. There is a central zone extending up to 6 km out from individual Au-deposits where all samples collected outside the large Jurassic stocks have young, thermally reset, AFT ages reflecting relatively pervasive upwelling of hot hydrothermal fluids. Up to another 6 km out from this central zone there are areas of mixed AFT ages that are fully reset, partially reset or not reset on a ~1 km scale (Fig. 1). This patchwork-like pattern is interpreted to be a product of heterogeneous (fracture-controlled?) fluid flow and heat transfer. The heterogeneous nature of thermal resetting combined with its overall spatial and temporal overlap with Carlin-type Au-deposits is consistent with the former being a product of syn-mineral hydrothermal fluid flow.

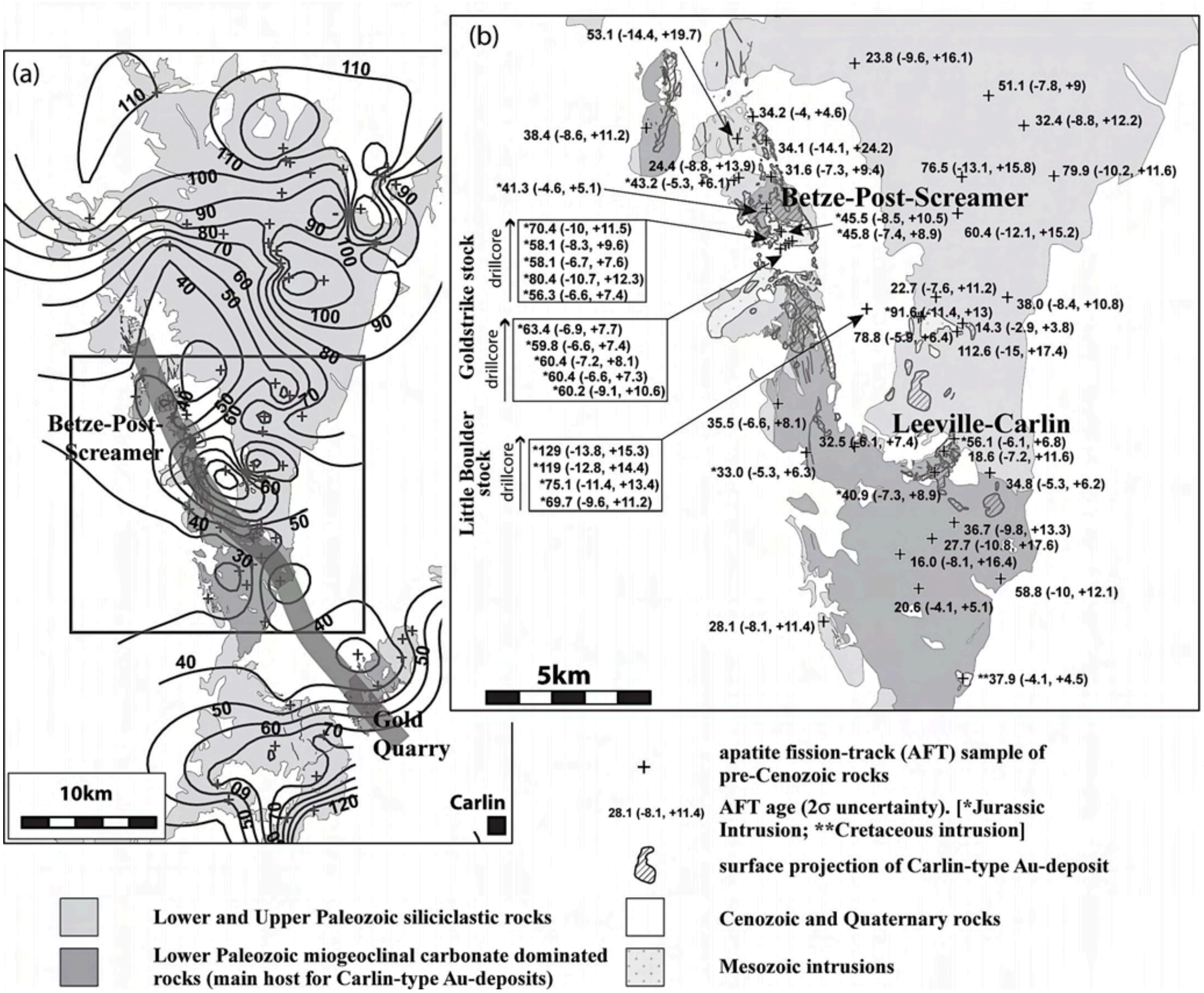


Figure 1. Pooled apatite fission-track (AFT) ages from samples of pre-Cenozoic rocks across and along the northern Carlin trend. (a) AFT ages contoured at 10 Ma intervals. Northern Carlin trend is shown by thick grey line. Note Cretaceous AFT ages distal to the Carlin trend. The latter ages reflect the regional cooling history onto which the thermal effects of the Carlin hydrothermal systems were then superposed. (b) Detail of AFT ages along the northern Carlin trend. Note concentration of 50-25 Ma ages coincident with Au.

Cortez and Shoshone Mountains

The northern and central Cortex Mountains are underlain principally by Jurassic felsic volcanic rocks and intrusions. The northern part of the range has unconformably overlying Cretaceous conglomerate-sandstone-mudstone alluvial sequence, with minor Eocene andesite and pyroclastic rocks and Miocene rhyolite flows. AFT ages from the central and northern part of the Cortez Mountains typically have

Cretaceous to Jurassic AFT ages that are >110 Ma (Fig. 2). Over most of the central and northern Cortez Mountains, thermal modeling of the AFT age and track length data yield cooling histories incompatible with any significant heating of apatite in the Eocene (max T <80-130° C on timescales of 10^6-10^4 yrs). Implicit in the results from this part of the range, we can conclude that the ~161 Ma intrusive rocks underwent their last major cooling between ~110 and ~70 Ma, when they cooled from ~80-30° C. This event, as in the northern Carlin trend, represents the effect of exhumation during the Sevier orogeny (~1.2 - 2.5 km). The modeling also suggests that in areas distal to Eocene mineralization in the southern Carlin trend, Jurassic intrusive rocks in the Cortez Mountains remained at low temperatures indicative of shallow depths (<~1 km) since the Cretaceous.

The AFT ages in the southern Cortez Mountains suggests a different history. Samples of Jurassic felsic intrusions and Paleozoic sedimentary rocks in the southern Cortez Mountains have largely Eocene and Oligocene AFT ages (Fig. 2). Thermal modeling of the AFT ages and track length data suggests these samples last cooled from a thermal high of >100° C beginning at ~40 Ma (Fig. 2). Given that Jurassic intrusions farther north along the Cortez range were typically at <30° C by 40 Ma and that there is no evidence for significant differences in the depth of post-Jurassic erosion south along the range, the Eocene cooling episode represents the re-equilibration of samples to background near-surface temperatures following a period of heating caused by buried Eocene intrusions and/or advective heat transfer associated with Eocene hydrothermal fluids.

The zone of thermal resetting in the southern Cortez Mountains encompasses several known Carlin-type deposits in lower plate Paleozoic sedimentary rock sequence, as well as fracture controlled Au-deposits in the Jurassic felsic intrusions of the Mill Canyon stock. The zone of thermal resetting extends into the Shoshone Range where it surrounds the Carlin type systems at Pipeline. On the west flank of the range, Miocene AFT ages reflect the effects of the younger Basin-and-Range normal faults. Miocene AFT ages are also encountered in the Mesozoic and Paleozoic rocks within and near to the Northern Nevada Rift, which crosses the southern Cortez Range to the immediate east of the Carlin-type Au deposits.

Osgood Mountains

The Osgood Mountains are underlain by Paleozoic sedimentary rocks intruded by the Cretaceous Osgood Mountains stock and temporally related dikes and sills (Fig. 3). Samples from the Osgood Mountains distal to known mineralization largely yield AFT ages between 50 and 90 Ma. Samples within or adjacent to the Cretaceous Osgood stock in the central and northern part of the range, west of the Getchell deposit, yield thermal models exhibiting rapid cooling from >~120° C to <30° C at ~95-75 Ma. The Osgood stock was emplaced at ~95 Ma (unpublished U-Pb SHRIMP age) and the rapid cooling either reflects cooling of the stock at shallow depths in the crust (~<1 km), and/or rapid exhumation during the Sevier orogeny. The age and track length data preclude any extensive Eocene heating (max T ~<20-30° C) and many samples have data consistent with paleodepths of <1 km through the Eocene.

There are numerous felsic Cretaceous plutons and dykes in the Osgood Mountains and these extend northeastward toward Twin Creeks. These samples have abundant apatite and produce well-constrained thermal models (Fig. 4). In the Getchell, Turquoise Ridge and Twin Creek deposits these dykes are heterogeneously affected by Eocene thermal resetting. Where mineralized, these intrusive bodies have Eocene AFT ages and underwent rapid cooling from >~100-120° C at~40 Ma. Unmineralized and apparently unaltered Cretaceous dykes and plutons in close proximity to mineralized examples (<1 km spacing) have Cretaceous AFT ages and were not strongly affected by Eocene re-heating. These samples underwent their last major period of rapid cooling to <~30° C at ~90-75 Ma.

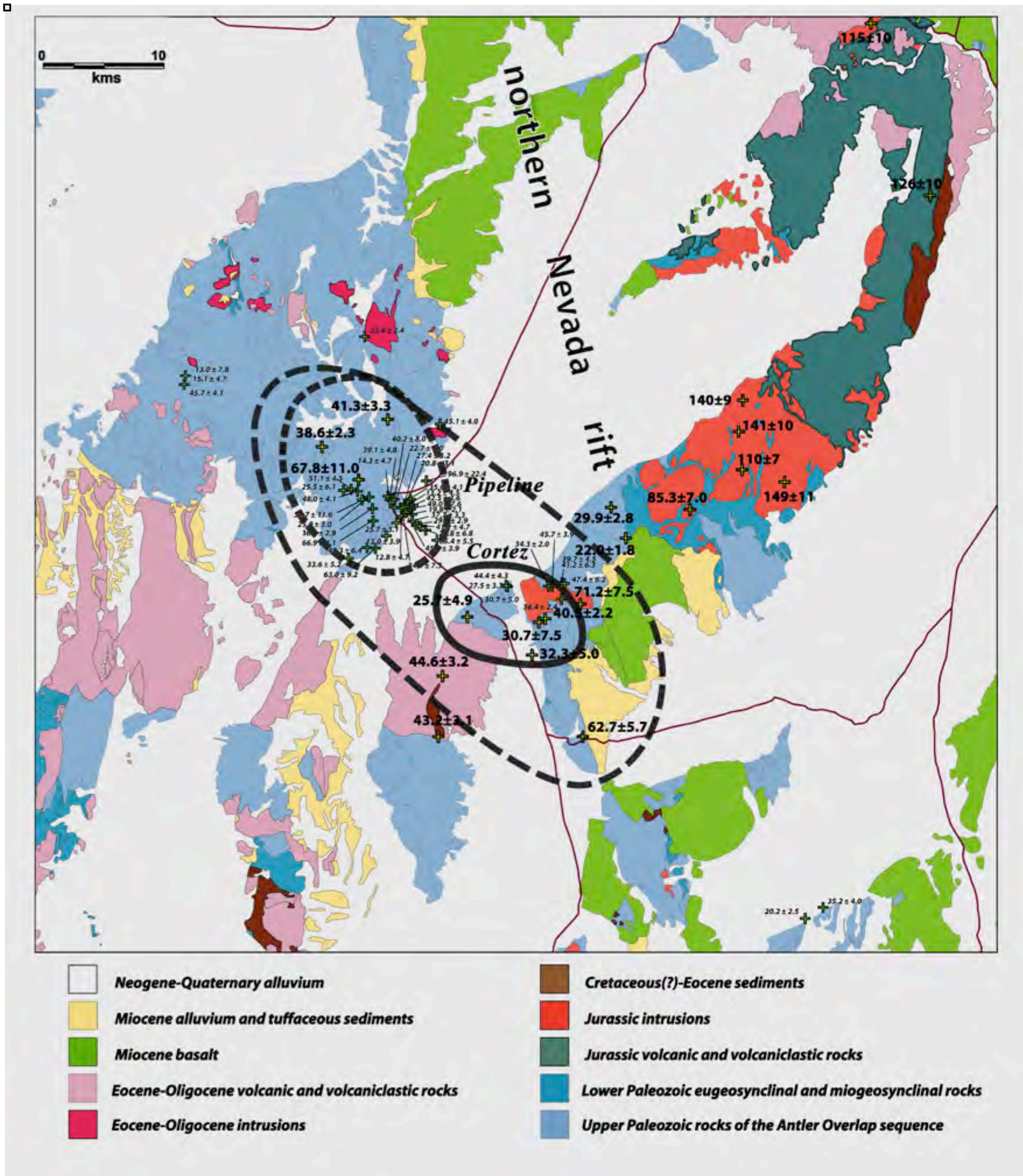
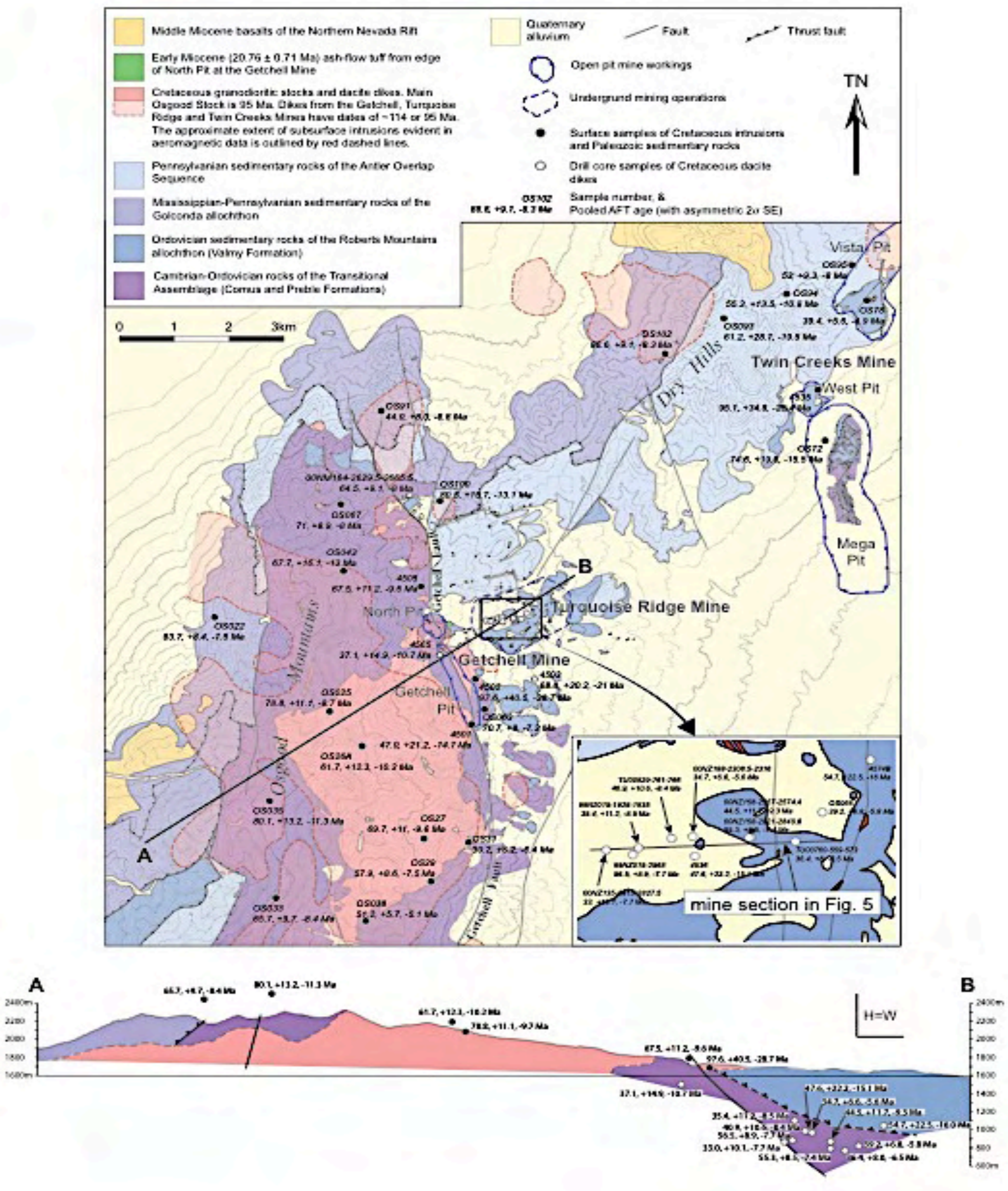


Figure 2. Pooled apatite fission trac (AFT) ages from samples of pre-Cenozoic rocks along the Cortez Mountains and around the Carlin-typre Cortez, Cortez Hills and Mule Canyon deposits.

Interpretation

Eocene thermal anomalies and Carlin-type Au-mineralization

In the area of the northern Carlin trend and southern Cortez Mountains, the zone of AFT resetting is developed on a scale larger than the distribution of Au-deposits themselves (Fig. 5). There is a central zone extending up to 6 km out from individual Au-deposits where all samples collected outside the large Jurassic stocks have young, thermally reset, AFT ages reflecting relatively pervasive upwelling of hot hydrothermal fluids. Up to another 6 km out from this central zone there are areas of mixed AFT ages that are fully reset, partially reset or not reset on a ~1 km scale (Fig. 1). This patchwork-like pattern is interpreted to be a product of heterogeneous (fracture-controlled?) fluid flow and heat transfer. The heterogeneous nature of thermal resetting combined with its overall spatio-temporal overlap with Carlin-type Au-deposits is consistent with the former being a product of syn-mineralization hydrothermal fluid



flow.

Figure 3. Geologic map of the northern Osgood Mountains showing the distribution in plan view of

apatite-fission track ages. Cross section **A – B** shows the changes in ages and the concentration of Eocene ages in the area of the Getchell Mine.

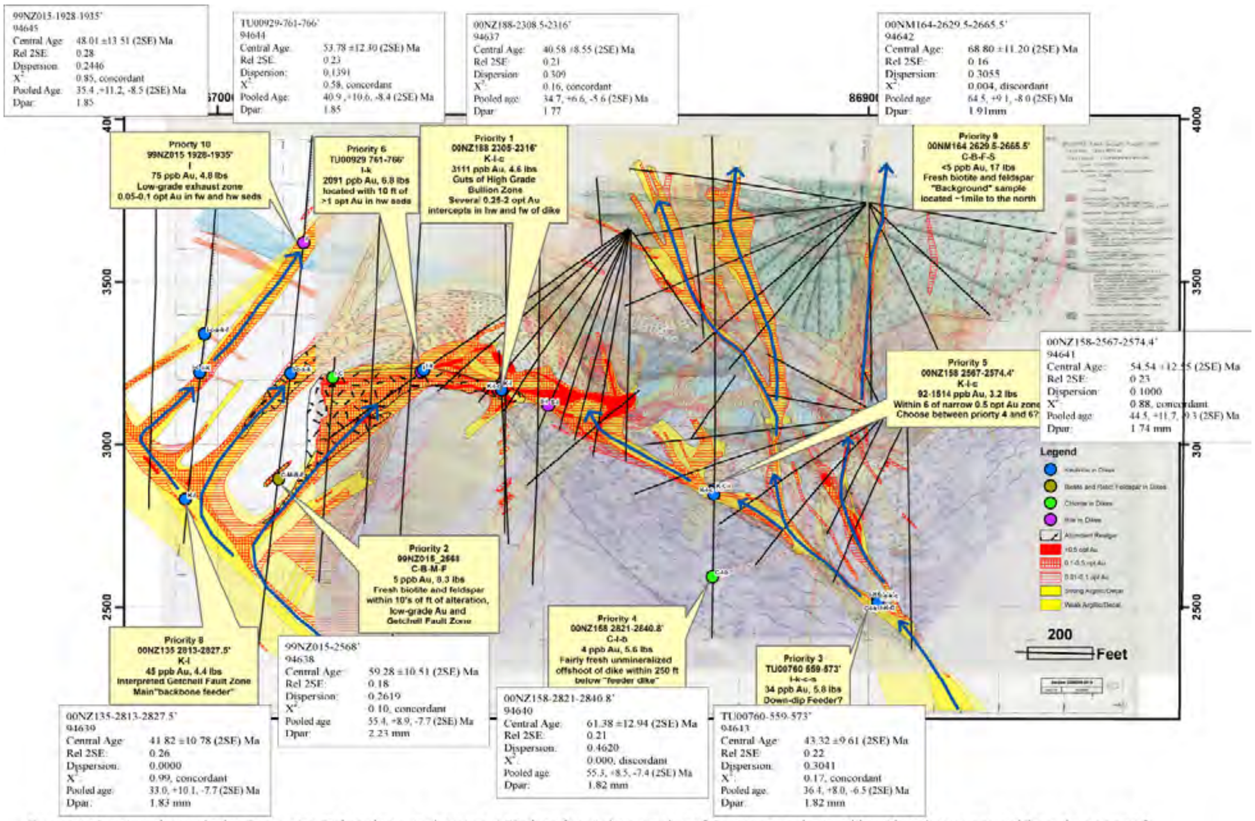


Figure 4. Cross section through the Turquoise Ridge deposit showing the AFT data for eight samples of Cretaceous dikes. Also shown are gold grade, zones of decalcification and argillization, zones of abundate realgar and interpreted flow paths.

In these areas there is a large zone of pervasive resetting where all samples analyzed have young, thermally reset, AFT ages. On the margin of this zone there are areas of mixed AFT ages that are fully reset, partially reset or not reset on a ~1 km scale. The zones of resetting in these two major clusters of Carlin-type Au deposits are approximately the same size. However, the known Au-endowment (production and reserves) is very different, at least based on current data. In contrast, the Getchell-Twin Creeks area lack the pattern of pervasive AFT age resetting on a regional scale, although the AFT resetting typifies most of the mineralized areas. Why there are differences in the AFT distribution between the two areas can be explained by their different geologic history.

It is clear that some of the Eocene thermal resetting particularly in the mineralized area is most likely to be a product of hydrothermal fluid flow for two reasons, and not some sort of large scale conductive cooling from an Eocene intrusion. One is the spatially heterogeneous distribution of fully reset, partially reset and non-reset apatite fission tracks at a scale <1 km in the Getchell-Twin Creeks area and on the margin of the northern Carlin trend. Two is the lack of near-surface Eocene intrusions capable of conductively heating the crust to temperatures of greater than >~100-120° C in rocks in Getchell-Twin Creeks areas that were at most only ~1-2 km below surface in the Eocene.

In contrast, a large Eocene intrusive complex on the southern margin of the northern Carlin trend has been inferred from aeromagnetic data, and Eocene volcanic rock dominate the outcrops to the immediate south of the region (Fig. 5). Three-dimensional geophysical inversion of a positive aeromagnetic anomaly south of the northern Carlin trend confirms the presence of a large subsurface intrusive body. The zone of reset AFT ages in the northern Carlin trend lies above and extends to the northwest parallel to the NW trending steep NE margin of this body. The intrusion is thought to be largely Eocene in age (Ressel and Henry, 2006; Ressel et al., 2000). The localization of AFT resetting to its NE margin suggests there may have been mechanically focused hydrothermal flow along this boundary. Furthermore, numerous Eocene dikes are present in the northern Carlin trend (Ressel and Henry, 2006), further confirming the input of magmatic heat into the AFT thermal anomaly.

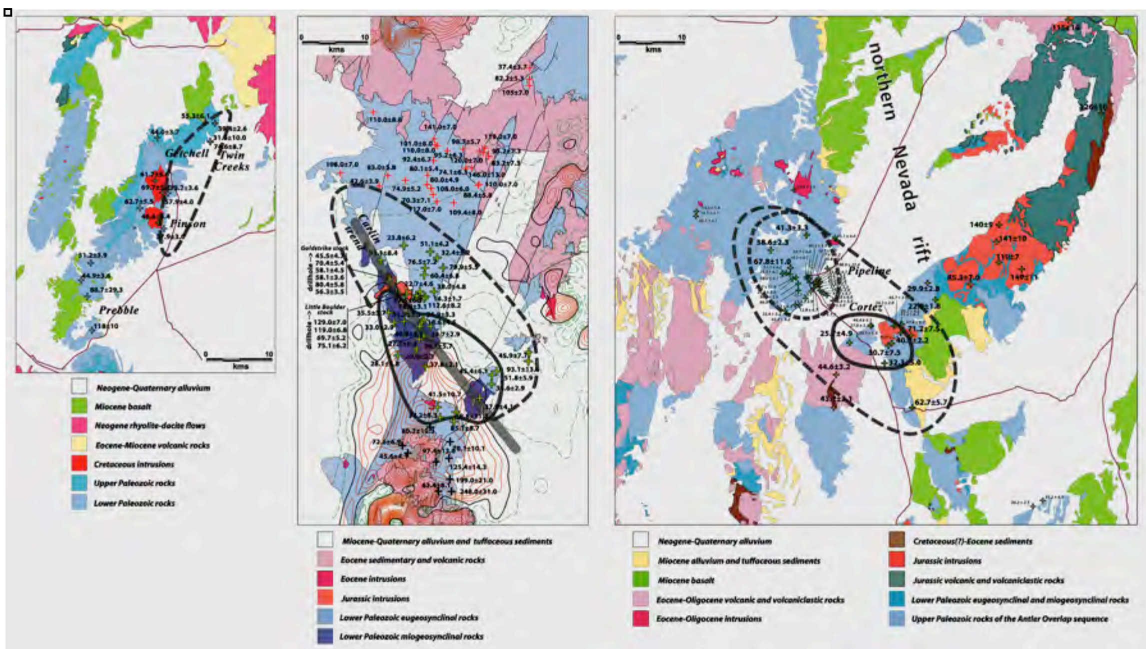


Figure 5. Comparison of zones of thermal resetting in the Cortez-Shoshone Mountains and northern Carlin trend. Areas of complete resetting are outlined by solid lines whereas area of partial resetting are outlined by dashed lines.

Numerous Eocene stocks outcrop in the Shoshone Range, but are generally absent from the Cortez Range. However, the size of the thermal anomaly and its internal coherence suggests that there may also be more Eocene magmatic rocks in the Cortez Range than previously recognized. To the immediate south in the southernmost Cortez Range, a slightly younger caldera has been inferred (John et al., 2008). It is possible that some of the size of the anomaly may be related to the superposition of conductive heat driven from that caldera forming event over the advective heat transferred by auriferous hydrothermal fluid that produced the Carlin type deposits.

Estimated duration of hydrothermal flow

The main ore-stage fluids responsible for mineralization in Carlin-type deposits had peak temperatures of 160-240° C (Hofstra and Cline, 2000). Late ore-stage fluids had temperatures of 120-180° C (Hofstra and Cline, 2000). Thermal modeling of AFT annealing kinetics suggests that for fluids of these temperatures, the rock must have been heated for periods of 10^{-1}-10^{3} years and 10^{2}-10^{5} years, respectively, before there was a significant reduction in the AFT age reflecting the Eocene hydrothermal system. These time scales suggest that thermal resetting need not have been a product of long-term pervasive fluid flow, but that transient pulses of hydrothermal flow, like that observed in modern geothermal centers, may have sufficed.

Some constraints on the duration of the thermal pulse associated with the Carlin-type deposits in the northern Carlin trend can be provided by thermal models of samples collected between 500 and 800 m into the Goldstrike Stock (Fig. 1). Using 2-sided heating models, estimates for the period of heating consistent with levels of annealing between Tl_{min} and Tl_{max} range from 5 to 10.4 k.y for a 220^{o}C fluid (50^{o}C background), increasing to 7 and 17 k.y for a 180^{o}C fluid. The small variation in the estimated period of heating clear reflects the influence of the starting temperature utilized. Using a 1-sided heating model, estimated periods of heating increase systematically inward into the stock, values for Tl_{min} and Tl_{max} ranging from 12 to 31 k.y. for 220°C fluids, and 18 to 60 k.y. for 180°C fluids. Decreasing the background temperature from 50°C to 30°C has little effect (~ 10-20%) on first-order estimates for the period of hydrothermal fluid flow. The thermal models and their duration of heating assume 100% conductive heating of the Goldstrike stock. Fluid flow together with advective heating derived by the hydrothermal fluid within the stock would reduce the maximum period of heating needed to explain the observed AFT data.

The AFT data from the stock better fit thermal models involving simultaneous heating on two sides rather than one-sided heating, even in multi-pulse models of hydrothermal activity, probably reflects; (i) a thermal history dominated by alternating and overlapping heat pulses propagating from more than one direction into the stock. (ii) In three dimensions our samples might lie more equidistant from major fluid conduits than represented by our simple one-dimensional models.

Genetic model of Au-mineralization, hydrothermal flow and AFT thermochronology

Results of previous studies suggest that the thermal resetting of apatite fission-tracks and Au-deposition overlapped in time with the ~40-37 Ma phase of rotational extensional faulting (Cline et al., 2005; Tosdal et al., 2003). Given this relationship, we consider a “2-fluid” model of hydrothermal flow (Fig. 6) to best explain the contrasting AFT patterns in the major clusters of Carlin type Au deposits. At the initiation of extension at ~40 Ma, strain in the pre-Eocene bedrock was largely accommodated by heterogeneous shear and tensional reactivation of older, variably oriented pre-Eocene structures. Extension enabled auriferous hydrothermal fluids from lower in the crust to flow upward along a dilating fracture mesh. Extension was initially concentrated along a limited number of structures. Fluid flow and Au-deposition was focused into these structures and along permeable carbonate horizons. With ongoing extension more pre-existing faults were reactivated and a greater number of new faults were initiated, increasing transient crustal permeability. Deeply circulating meteoric convection systems developed and swamped the earlier auriferous system (Fig. 6). It was largely this stage of hydrothermal flow that reset apatite fission-tracks at a scale larger than the known distribution of Au-deposits in the northern Carlin and the southern Cortez mountains (Fig. 6). The spatial and temporal coincidence of apatite fission-resetting with a large Eocene intrusion on the margin of the Carlin trend suggests magmatic thermal energy may have locally invigorated hydrothermal flow or that fluid flow may have been preferentially focused along their margins as a product of low mean stress or mechanical weakness.

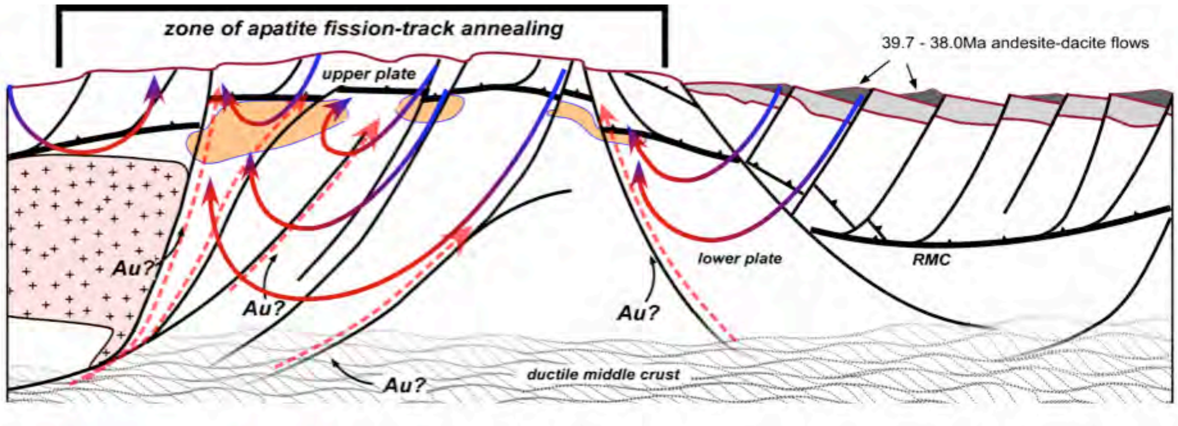


Figure 6. Schematic model of hydrothermal flow responsible for Au-mineralisation and AFT resetting in Carlin-type Au-deposits. See text for discussion. Carlin deposits are represented by orange polygons. Primary auriferous fluids shown by dashed red lines. Circulating meteoric fluid shown by solid lines with blue(cool)-red(hot) colour gradient. Eocene pluton is shown on left side of figure. Faults are shown in black.

In areas lacking Eocene intrusions (e.g., Osgood Mountains), the scale of fluid circulation was smaller and less pervasive. Thermal resetting of apatite fission tracks was more heterogeneously distributed and more closely reflected areas of Au-mineralization. The total Au-endowment was lower reflecting the smaller scale of hydrothermal circulation. The lack of coeval intrusion seems to have lead to less extensive meteoric fluid circulation; it being concentrated along many of the same fracture systems that carried the auriferous fluid.

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