Origin of gold in placer deposits of the Sierra Nevada Foothills, California

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ABSTRACT

The Sierra Nevada Foothills (SNF) region of northern California is one of the world’s premier gold provinces. Gold is present both in bedrock lode deposits and in major Tertiary, primarily Eocene, and Quaternary alluvial placer accumulations. Gold nuggets in the auriferous gravels of northern California traditionally have been interpreted to be masses of native gold released by physical weathering from underlying lode deposits and incorporated in the stream bed load. This interpretation has numerous problems. (1) Large gold nuggets are extremely uncommon in primary hydrothermal gold deposits, even within the orogenic gold-quartz veins of the SNF. (2) Historic lode gold production from the SNF has been about 35 million ounces, while Tertiary placer production exceeded 65 million ounces with yet another 50 million ounces of placer resource stranded by extraction restrictions. (3) A large part of the placer gold accumulation is situated upstream and uphill of the lode deposits. (4) Tertiary channel gold averages 920 fineness, whereas gold from primary veins is 600-900 fineness.

We suggest an alternative hypothesis that much of the placer gold in the SNF Tertiary gravels was sourced from the east, either from the great gold districts of Nevada or from districts long ago removed by erosion.

Gold in most primary hydrothermal deposits is widely disseminated in host rock at ppm-level concentrations within pyrite or other sulfide minerals. As demonstrated in modern tropical environments, the transformation of gold from trace concentrations in sulfide to grains or masses of native metal occurs primarily by supergene processes during intense chemical weathering in the soil profile. Gold is readily dissolved, mobilized and reprecipitated by chloride, bisulfate or organic-acid solutions, often with microbial mediation. These supergene processes significantly increase the fineness of the supergene gold grains relative to that of gold in the primary source.

The Paleogene climate of western North America was considerably warmer and wetter than present, much like modern tropical environments. Tertiary river channels were eroded into a surface of intense weathering, as evidenced by remnant laterite soil profiles throughout northern California. The lower Ione Formation, the distal marine equivalent of the proximal alluvial auriferous gravels, is comprised largely of kaolinite and quartz: the products of intense chemical weathering. Plant and animal fossils in Tertiary sedimentary rocks record a distinctly more tropical climate.

Multiple lines of evidence indicate that the Cretaceous to middle Cenozoic Sierra Nevada formed the steeper western flank of a gradually sloping high-elevation plateau - the Nevadaplano - that extended to central Nevada through the Oligocene time, and that the gold-bearing river channels extended from the Great Valley shoreline to head in what is now eastern Nevada.

We propose that gold nuggets, formed from by pedogenic processes during intense weathering of disseminated Eocene and older gold deposits in Nevada during a warmer and more humid Tertiary climate, were transported westward in great river systems.
draining the Nevadaplano, and were deposited in the Tertiary channels as stream gradients decreased at the foot of the range. The SNF auriferous gravels combine these distal nuggets with gold nuggets derived locally from intense weathering of the bedrock veins.
INTRODUCTION

Although the presence of gold in the area that became California had long been known to Native Americans and early Spanish settlers, the discovery and promotion of placer gold by James Marshall at Sutter’s Mill on the South Fork of the American River near Coloma, California, in 1848 sparked the largest voluntary migration in American history. The westward rush of Americans ensured that California became part of the United States, and the wealth generated by the California gold rush established California as an economic powerhouse for the next century (Walker, 2001).

The spirit of the event is wonderfully summarized by Waldemar Lindgren in his 1911 U.S. Geological Survey Professional Paper on the auriferous gravels of California.

“The peace of the wilderness was interrupted in 1849. An army of gold seekers invaded the mountains; at first they attacked the auriferous gravels of the present streams, but gradually the metal was traced to the old Tertiary river beds on the summits of the ridges and to the quartz veins, the primary source of all the gold in the Sierra Nevada. The Tertiary stream beds - the "channels," as they are called - proved rich but difficult to mine. New methods were devised; by hydraulic mining the gravel banks were washed down by the aid of powerful streams of water, and by drift mining the bottoms of the old stream beds were followed by tunnels underneath the heavy volcanic covering. Millions of dollars were annually recovered from these Tertiary channels…”

Exploitation of the extensive and rich placer deposits quickly progressed from hand panning to a variety of sluice-boxes to massive hydraulic washing of Tertiary river channels to drift mining paleochannels buried beneath younger Tertiary volcanic rocks. Hydraulic washing required massive amounts of water; the surface hydrology of the entire Sierra Nevada Foothills was quickly reconfigured by flumes, pipelines, ditches and dams.

The massive washing of stream beds and bank deposits choked the rivers with sediment, destroyed aquatic life, and soon threatened agriculture and communities downriver in the Great Valley of California. Parts of the valley were aggraded by as much as 2 meters, and a layer of sediment some 6 meters thick had accumulated in San Francisco Bay. The process of hydraulic mining, because of its introduction of sediment into the rivers of California, was banned in 1884 by court action - the Sawyer Decision - putting an end to the era of hydraulic mining (Peterson et al., 1968; Yeend, 1974).

Large-scale dredging of rivers in confined ponds began in the late 1890’s. During the 1930’s, there were as many as 12 dredges working the Yuba River valley. In total, some 1 billion cubic yards of gravel were disturbed. Elsewhere, conventional mining of Tertiary river gravels has continued intermittently, but at a much reduced level.
The geology of the Sierra Nevada Foothills placer gold deposits was intensively studied during the first decades of the 20th century. The best documentation was that of Lindgren (1911). Other important references are those of Yeend (1974) and Peterson et al. (1968). Classic historical references to the lode gold deposits are those of Knopf (1929), Ferguson and Gannett (1932), and Johnston (1940). Boyle (1979) provides a good summary of both lode and placer occurrences, notably within the context of gold deposits worldwide. More current important reviews of the gold province are those of Landefeld (1990), Bohlke (1999a, b), and Beirlein et al. (2008).

To identify the ultimate source of the placer gold, and the geological processes by which the gold grains and nuggets were formed, eroded, transported and deposited requires a solid understanding of the landscape and climate of western North America during the Tertiary time. In turn, these unique fluvial sediments can enhance our understanding of the topography, tectonics, and climate of western North America in the early Tertiary.

GEOLOGY AND GOLD DEPOSITS OF THE SIERRA NEVADA FOOTHILLS

Lode gold deposits

The Sierra Nevada Foothills gold province is host to some 13,000 mines and prospects that are distributed for some 300 kilometers throughout the northern and central Sierra Nevada Foothills metamorphic belt in California (Beirlein et al., 2008; Clark, 1970; Bohlke, 1999b) (Fig. 1). About 80-90% of the gold production, however, was concentrated within three districts: (1) the 195 km-long by 1.5 km-wide Mother Lode district, (2) the Alleghany district, and (3) the Grass Valley district (Goldfarb et al., 2008) (Fig. 2).

The Sierra Nevada Foothills metamorphic belt is part of the North American Cordillera that extends from Alaska to California and comprises a diverse collage of Paleozoic and Mesozoic turbidite terranes, island arc complexes, and backarc basins accreted to the North American continent. The terranes are bounded by a series of transcrustal faults and fault zones, traceable for hundreds of kilometers (Goldfarb et al., 2008; Snow and Scherer, 2006).

Extending along the entire length of the Sierra Nevada Foothills metamorphic belt, the Melones and Bear Mountain fault zones are mid-Jurassic structures that subsequently defined zones of failure between accreted terranes. The Melones fault zone exhibits first-order, province-scale, control over the location of much of the lode gold mineralization (Beirlein et al., 2008). In the northern Sierra Nevada Foothills metamorphic belt, the Melones fault zone comprises a 3.5 km-wide zone of serpentinite and mélangé. To the south, the fault narrows to a 1 km-wide shear of mylonite and phyllonite (Fig. 2).
Figure 1. Generalized geological map of California showing the distribution of principal terranes and basement rocks. The Sierra Nevada Foothills gold province is hosted within the Sierra Nevada metamorphic belt (after Wallace, 1990).
Figure 2. Generalized geology of the Sierra Nevada Foothills metamorphic belt showing locations of significant lode gold deposits and major districts. Terrane boundaries are from Snow and Scherer (2006).
Magmatism in the Sierra Nevada Foothills metamorphic belt was concentrated in two magmatic episodes that correspond to changes in the rate and angle of subduction between the North American and Farallon Plates. These episodes mainly pre-date and post-date the age of gold mineralization. The first magmatic episode was in Late Jurassic time with emplacement of isolated plutons across all tectonic terranes between 165 and 140 Ma (Goldfarb et al., 2008). The second magmatic episode, in Cretaceous time, resulted in the emplacement of the massive Sierra Nevada Batholith, located to the east of the Sierra Nevada Foothills gold districts, at about 120-80 Ma (Goldfarb et al., 2008).

The major gold deposits of the Sierra Nevada Foothills are classic examples of the style of gold deposits classified as Orogenic Gold Deposits (Goldfarb et al., 2005; Goldfarb et al., 2008; Groves et al., 2003). Orogenic gold deposits formed as an integral part of the evolution of subduction-related accretionary or collisional terranes in which the host-rock sequences were formed in arcs, back arcs, or accretionary prisms. Country rocks are regionally metamorphosed into belts with extensive greenschist to lower-amphibolite metamorphic-facies rocks. Mineralization formed synkinematically and invariably has a strong structural control involving faults, shear zones, or zones of competency contrast. Veins and vein zones have vertical dimensions of 1-3 kilometers with only subtle vertical metal zonation; in contrast, strong lateral zonation is typical within wall-rock alteration.

Although lode gold deposits occur along the length of the Sierra Nevada Foothills metamorphic belt, the northern and central portions of the belt were most productive. Towards its northern end, the Sierra Nevada Foothills gold province is about 12 km wide, and includes several important gold districts. By contrast, most of the significant districts in the 200-km long Mother Lode belt to the south occur within a <4 km-wide corridor centered on the Melones Fault Zone (Fig. 2).

Gold deposits occur within all rock types, including serpentinite, granitoids, mafic to felsic metamorphic rocks, and turbidite metasedimentary rocks. Host rocks are variably faulted and sheared, and range from greenschist to amphibolite metamorphic facies.

Dating of many of the foothills gold deposits has narrowed the age range of vein formation to about 125±10 Ma (Marsh et al., 2008). An age of 152±1.2 Ma in the Grass Valley district provides evidence of an older gold event in this one part of the gold province (Goldfarb et al, 2008).

The gold ore bodies are of two principal types: gold-quartz veins and gold-mineralized country rock (Knopf, 1929). The second type is more diverse as it includes auriferous greenstone (“gray ore”) and auriferous schist.

As might be expected, the quartz veins exhibit considerable variability in dimension and character. The veins are typically steeply-dipping tabular masses accompanied by both hanging-wall and footwall zones of quartz stringers; quartz is the dominant mineral; ankerite and albite occur very subordinately. Sulfide minerals vary between 1 and 2 per cent: pyrite predominates, followed in abundance by arsenopyrite and minor sphalerite,
galena, chalcopyrite and tetrahedrite. Alteration minerals in selvages surrounding the quartz veins include ankerite and sericite followed in abundance by albite, quartz, pyrite and arsenopyrite.

Within the quartz veins, gold is highly localized within ore shoots, which typically constitute a mere fraction of the vein volume, and, even within these ore shoots, the distribution of gold is highly irregular. The gold is mainly present as native gold of very small size. Grade control within most operating mines was, of necessity, by assay. Few mines had gold of sufficient size that high-grading by miners was possible or a problem (Knopf, 1929).

“Gray ore” was the name given to ankerite-altered greenstone that carried sufficient gold to be mined economically. The gray ore is comprised largely of fine-grained ankerite with more or less sericite, albite and quartz, and 3 to 4 per cent pyrite and arsenopyrite. The gray ore occurs in shoots that lie parallel to quartz fissure veins, with gradational margins to unaltered rock. Gold grade distributions are highly irregular; gold occurs as very fine grains of native metal.

Lode gold deposits throughout the Sierra Nevada Foothills gold province were mined to depths of more than 3 kilometers, with little change in the character of the deposits and no obvious decrease in resource potential at the deeper mining levels.

Of course there were some significant masses of gold discovered during mining. The largest mass of gold ever found in California came from Carson Hill. Found in 1854, it weighed 2340 troy ounces (72 kg). Several other nuggets weighing 6 to 7 troy pounds (2.2-2.6 kg) were found at the same locality. Notably, these nuggets were taken from a quartz vein, but within the zone of weathering immediately beneath surface outcrops (Knopf, 1929). A number of other significant gold masses and rich pockets were discovered during mining, particularly in the Alleghany District. While these were exciting discoveries, and certainly sparked enthusiasm during the early days of the Gold Rush, these large gold masses were exceptions to the observation that by far the greatest amount of gold in the Sierra Nevada Foothills lode gold deposits occurs as very small gold particles, often not visible to the unaided eye.

**Placer gold deposits**

The character of the Tertiary placer gold accumulations and the Tertiary river channels are described at length by Lindgren (1911), Haley (1923), Peterson et al. (1968), Clark (1970), and Yeend (1974). The channel-filling alluvial deposits are here called the Tertiary “gravels” following the historical use of this term when referring to the deposits. It should be emphasized, however, that the bulk of the alluvial sediment, particularly from upper stratigraphic levels, is not strictly gravel but is predominantly sand, silt and clay.
The sedimentary regime of the SNF Tertiary auriferous gravels consists of two components, which provide complementary evidence of the character of the fluvial system and its contained sediment load:

- The alluvial gravels localized within paleochannels of Tertiary river systems, representing a more proximal fluvial depositional environment; and
- the Ione Formation, fluvial-deltaic and marginal marine sediments representing a more distal depositional environment where the Tertiary rivers discharged their remaining sediment load into shallow marine waters.

The gold-bearing Tertiary gravels occur in paleochannels of once-great river systems that coursed down the western slope of the Sierra Nevada range and in deltas where these rivers met the sea that occupied the area that is now the Great Valley of California. The Tertiary channels are cut into the Paleozoic and Mesozoic rocks of the Sierra Nevada Foothills metamorphic belt, including the gold-quartz veins. The Tertiary gravels were in turn covered to a great extent by younger Tertiary volcanic and sedimentary rocks.

The Tertiary gravels accumulated over some considerable period of time during which time the form of the channels evolved, and the character, texture, and mineral composition of the alluvial sediments changed. The nature of the deposits and form of the paleochannels, as discussed by Lindgren (1911), is summarized in Figure 3.

In broad terms, the Tertiary gravels can be divided into Upper and Lower units. Although the units are lithologically and texturally distinct, the contact between the units is normally transitional and no distinct contact can be picked in the field (Lindgren, 1911; Yeend, 1974).

**Lower Gravels**

The deepest trough-shaped channels in the paleovalleys are filled to a depth of 15-60 meters by coarse gravel, which is normally well cemented: the so-called Lower or Channel Gravels. The Lower Gravels typically rest on a polished surface incised into metamorphic bedrock. Clasts range in size from pebbles to boulders as large as 2-3 meters in diameter, all well-rounded with polished surfaces. Clast lithologies are largely those of the regional metamorphic basement: slate, phyllite, greenstone and...
granodiorite. Quartz cobbles constitute part of the clasts but are not dominant. The abundance of quartz pebbles and cobbles increases up-section. There is also a notable increase in the angularity of cobbles and boulders up-section.

The fine matrix of the gravel is mainly sand-size. Claystone or siltstone beds are absent. While clay-size sedimentary material is sparse, the gravels contain significant amounts of clay minerals in the sand fraction, in the form of transported bedload kaolinite clasts, soil debris and altered saprock pebbles. The clay is dominantly kaolinite (Wood and Glasmann, 2013a, b).

The early miners divided the Lower Gravels into subunits based on coloration: deeper “blue gravel” and overlying “red gravel.” The coloration of the rock is a consequence both of the oxidation state of iron and differences in clast composition. Pyrite is common deeper in the Lower Gravels, restricted to zones beneath the water table. Authigenic pyrite formed by the reducing action of organic matter on sulfate carried in groundwater. In places, pyrite coats the surface of pebbles; assays of this pyrite frequently show it to contain low concentrations of gold. The immediately overlying gravel has a deep red color due to the later oxidation of pyrite. This, combined with the differing clast compositions – dark blue-gray lithic clasts at depth grading to more white quartz in the gravel above – contributes to the noted color change.

Upper Gravels

Covering the Lower Gravels, and attaining thicknesses to 100 meters, are the Upper or Bench Gravels. Deposits of the Upper Gravels occur both as channel fill incised into the Lower Gravel deposits and as sheets of alluvial sediment on a wide, gently sloping strath terrace. The terrace deposits reach widths of 3 km in places and occur on one or both sides of the underlying trough-shaped channel.

Attributes that distinguish the Upper Gravels from the Lower Gravels change gradationally. The Upper Gravels contain abundant silt and clay in the form of mudstone lenses. Lithic clasts, including slate, phyllite, hornfels, quartzite, greenstone and granodiorite, remain common but decrease in abundance up-section. The majority of the clasts represent a mixture of lithologies present within bedrock of the western Sierra Nevada slope, but some clasts have indicated provenance in Nevada (Slemmons, 1953; Bateman and Wahrhaftig, 1966; Yeend, 1974). The abundance of quartz, both as white quartz and quartzite, increases up-section, matched by a decrease in the abundance of lithic clasts and iron-oxide-stained soil debris.

The Upper Gravels are also distinguished by clasts of rhyolite, andesite and tuffaceous sediments at the top of the section. While the size of the clastic material within the Upper Gravels generally decreases downstream from east to west, the Upper Gravels locally contain enormous boulders up to 3 meters in diameter.

The clay mineralogy changes from dominantly kaolinite in the Lower Gravels to dominantly smectite in the Upper Gravels. In the Upper unit, the kaolinite component decreases until a ratio of smectite to kaolinite of about 70:30 is reached. This ratio is
similar to the ratio in paleosols preserved along the paleochannel margins and locally below the terrace gravels (Wood and Glasmann, 2013a, b).

The differences in the compositions and textures of the sediments between the Lower Gravels and the Upper Gravels record a dramatic change in sediment source, channel dynamics, and environmental conditions. The coarse boulder and cobble conglomerates with little fine sediment represent only a small fraction of the total sediment load that would have been transported within the Tertiary river systems. The rivers were actively eroding the land, cutting their channels, and carrying much of the sediment away. Large resistant rounded cobbles and boulders – and placer gold – remained as channel deposits, while finer sediment was moved down the channels to be deposited in lower energy depositional environments downstream. By contrast, the Upper Gravels were deposited by streams choked with sediment, meandering across broad floodplains and depositing much of their sediment load. This change could reflect a change in source area, climate and weathering, depth of erosion in the source area, tectonism, volcanism, or likely some combination of these influences. The transition from angular to well-rounded white quartz cobbles and boulders is indicative of gradually greater distances of transport. The decreasing abundance of lithic clasts of local derivation suggests that erosion of local terranes was minimal and that sediment was sourced further to the east.

The clay mineral composition of the auriferous gravels is distinctive. Quartz and kaolinite are the primary residual minerals in lateritic soil of warm-humid climates. Similarly, the kaolinite paleosols of this same composition that underlie Tertiary gravels throughout this region record the influence of warm-humid climatic conditions that prevailed during, or preceding, the period of erosion and deposition of the Tertiary gravels.

The Upper Gravels are overlain by rhyolite ignimbrite, tuffaceous paleosol horizons, and volcaniclastic fluvial sand generally referred to as the Delleker (northern Sierra) or Valley Springs (central Sierra) Formations (Bateman and Wahrhaftig, 1966; Wagner et al., 1981; Saucedo and Wagner, 1992). This unit reaches a thickness of 75 meters near Chalk Bluff (Fig. 11).

The Delleker Formation is unconformably overlain by andesite volcanic breccia, debris flows, and interbedded fluvial volcaniclastic sediments of the Miocene Mehrten Formation.

It was well known to the early miners that gold is not at all uniformly distributed within the gravels, and considerable effort was made to understand its distribution (Lindgren, 1911; Yeend, 1974). Conventional exploration wisdom was that the highest gold concentrations were located on and immediately above the bedrock surface (Fig. 4). Placer gold concentrations were found to wind from one side of the channel to the other, and were, as well, irregular and discontinuous along the lengths of the channels. The precise location of gold concentration in the ancient river systems depended upon the abundance of gold in the sediment load and the highly localized hydraulic and sedimentary regime present at the moment of deposition.
Although nuggets of gold receive much attention, the largest quantity of gold is of finer grain size. Most of the grains are flattened due to pounding of the particles by cobbles. At San Juan Ridge, Yeend (1974) documented that most of the gold grains in the lower gravels are 1-2 mm in diameter and 0.1-0.2 mm thick. The largest flake was 3 mm and the smallest 0.3 mm. Approximately 80% of the total gold weight was contained in grains of a diameter greater than 1 mm diameter. During more recent mining in the same locality, about 95% of the gold particles were less than 3.35 mm (6 mesh), with occasional particles up to 6 mm diameter (Pease and Watters, 1996).

Lindgren (1911) presented convincing documentation that the fineness of gold in the placer deposits – the purity of the gold expressed in parts per thousand - is always greater than that of the bedrock gold-quartz lode deposits in the nearby districts. The fineness of gold also varies considerably between different mineral districts. Figure 5 shows the range of fineness for lode and placer gold within six counties along the Sierra Nevada Foothills gold province. Gold fineness in the lode deposits ranges from about
600 to 900. Overall, the fineness of alluvial gold in the Tertiary channels averages about 920 (Lindgren, 1911). The distinct differences in gold grain chemistry between placer deposits and lode deposits in the same district indicate that the placer gold grains were not simply eroded from the bedrock lode source and deposited in the immediately overlying alluvial deposits.

Figure 5. Ranges in gold fineness for lode and placer gold deposits for six counties within the Sierra Nevada Foothills gold province. The fineness of the gold in placer concentrations is always greater than the fineness of gold in the nearby lode deposits. (Data from Lindgren, 1911)

Although Lindgren (1911) discounted the significance of supergene redistribution of gold within the placer gold deposits, he noted the well-documented occurrence of secondary gold crystals growing on particles of magnetite and ilmenite and documented that authigenic pyrite and marcasite in the Tertiary gravels are in places auriferous.

**Ione Formation**

The Ione Formation constitutes the western distal facies of the Tertiary fluvial depositional regime of the Sierra Nevada Foothills province. The Ione Formation is an Early to Middle Eocene sequence of clastic sedimentary rocks exposed discontinuously for 320 km along the western foothills of the Sierra Nevada (Fig. 9) (Creely and Force, 2007; Wood et al., 1995). The unit is characterized by kaolinite-rich sandstone and mudstone with interbedded lignite. These clay-rich sediments were deposited primarily in deltaic to lagoonal conditions at the western margin of a landscape of relatively low relief, with local coal swamps accumulating in quiet water.
The Ione Formation has been shown to consist of two end members separated by an erosional unconformity with as much as 40 meters of relief (Pask and Turner, 1952; Creely and Force, 2007). Sediments of the lower unit are compositionally more mature than the upper member (Pask and Turner, 1952). Allen (1929) correlated the upper 30 m feldspathic Ione sands with the Upper Gravels mapped by Lindgren (1911) and the lower 150-180 m of kaolinitic sands with the Lower Gravels.

The mineralogical composition of the lower Ione Formation is predominantly kaolinite and quartz. This distinctive clay mineral assemblage represents the climax mineral assemblage of intense chemical weathering, interpreted to have developed in response to a unique set of Tertiary conditions that included long-term continental stability associated with intense tropical weathering, followed by an erosional period initiated by tectonic activity and changing landscape drainage (Wood et al., 1995).

The clay mineral assemblage of upper Ione deposits contains more feldspar, biotite, and a clay mineral assemblage with significant amounts of smectite. The change in mineralogy within the Ione Formation is similar to that observed between the Lower Gravels and the Upper Gravels.

The Ione Formation itself was deposited upon a deeply weathered surface developed on crystalline basement rock with local relief of as much as 300 meters. The surface is characterized by a paleosol, 30 meters or more thick, with clearly preserved laterite and saprolite. Transported laterite, some containing as much as 44% iron, is interbedded in the basal Ione beds on the flanks of buried highlands (Bateman and Wahrhaftig, 1966). Both the thickness of this paleosol and the mineral suite present are evidence of the intensity and duration of chemical weathering prior to deposition of Ione sediments.

Wood (1994) and Wood et al. (1995) documented the pedogenic origin of the kaolinite in the Ione Formation. The mineral assemblage of the Ione Formation, and the thick laterite soil on which it rests, indicate a tropical climate with perhaps alterations of wet and dry seasons for the period of weathering that led to the formation of its sediments (Allen, 1929). During the early Tertiary, thick kaolinite-quartz-rich soil mantled a landscape of generally low relief with intense warm-humid weathering. In response to tectonism or changing erosional patterns, this extensive blanket of soil provided the source of kaolinite, carried down the Tertiary river channels to be deposited as the lower Ione Formation. The change in clay mineralogy within the Ione section suggests that the climate became less tropical or that an accelerated rate of erosion exposed and transported less-weathered material from the base of the source area weathering profile.

Age of the gold-bearing Tertiary gravels

The depositional age range of the Tertiary gravels, particularly the maximum age, has proven difficult to establish with certainty but is essential to evaluating potential sources of alluvial gold. The Lower or Channel Gravels contain neither fossil nor volcanic material that can be dated. The auriferous gravels, in general, are commonly correlated...
with the Ione Formation, which is in turn correlated with the marine, middle Eocene
Domengine Formation of the California Coast Ranges (Creely and Force, 2007;
Cherven, in press). Cherven (in press) places the Domengine astride the Early –
Middle Eocene boundary and indicates an age of ~50-47 Ma. Sullivan (in Creely and
Force, 2007) interprets “that the Ione is somewhat younger than the Domengine.” Data
presented here indicate that much of the “auriferous gravel” section is significantly
younger than Domengine Formation.

The stratigraphic section at Chalk Bluff north of I-80 in the Sierra Nevada Foothills is
representative of the region’s overall stratigraphy (Fig. 6). Lindgren divided this
sequence and many similar ones into, from youngest to oldest, a) andesite tuffs
(subsequently Mehrten Formation), b) rhyolite tuffs (Delleker or Valley Springs
Formation), c) Upper or Bench Gravels, and d) Lower or Channel Gravels (Fig. 3).
Placer gold occurs throughout the section but is primarily concentrated in the lower
gravels, with progressively decreasing concentrations in overlying units (Fig. 4). The
lower auriferous gravels lack fossils or isotopically dateable material, but the other units
have been dated either regionally or specifically at Chalk Bluff.

Intermediate to mafic lavas of the Mehrten Formation erupted from vents in what is now
the high Sierra Nevada and flowed variable distances down the paleochannels. Debris
flows commonly extended farther down these channels. The oldest dated flows or
debris deposits of the Mehrten Formation are 16 to 18 Ma, and they range to as young
as ~3 Ma (Wagner and Saucedo, 1990; Saucedo and Wagner, 1992; Cousens et al.,
2008).

Early KAr dating has, unfortunately, somewhat confused the age of the rhyolite tuffs, but
recent $^{40}$Ar/$^{39}$Ar dating demonstrates that the tuffs are, with one exception, no older than
31.5 to as young as 25.4 Ma near I-80, and from ~31.6 Ma to as young as 22.9 Ma
farther south near Valley Springs Peak (Henry and John, 2013 and unpublished data;
Figure 6). The early problematic KAr dates, which were of bulk samples of biotite,
sanidine, or plagioclase, suffered from two problems. Sanidine dates were commonly
too young because of incomplete extraction of radiogenic Ar (McDowell, 1983;
Hausback et al., 1990). An example is the lower tuff at Valley Springs Peak, for which
Dalrymple (1964) reported a sanidine date of 23.4 Ma and for which we find 28.95±0.01
Ma and correlate it with the tuff of Campbell Creek (Henry et al., 2012). Other samples
are probably too old because of contamination by xenocrysts from Mesozoic granites.
This interpretation probably applies to the 38.7±1.0 Ma biotite KAr age reported for tuff
from a drillhole at North Columbia (Yeend, 1974). Unfortunately, it is not currently
possible to resample and redate the North Columbia tuff.
Figure 6. Stratigraphic summary of the Tertiary gravels of the Sierra Nevada Foothills and associated formations with known and best interpreted ages.
The only tuff conclusively older than 31.5 Ma is a reworked dacite tuff at La Porte (Fig. 8), where a KAr plagioclase date is ~33.2 Ma (no reported ±; Evernden and James, 1964). Detrital zircons in sedimentary deposits below the La Porte tuff are as young as 33±2.6 Ma (Cassel et al., 2012; AJS). The La Porte dacite tuff is unlike the rhyolite tuffs that make up all other tuffaceous deposits (Garside et al., 2005; Cassel et al., 2012; Henry and John, 2013), may have been derived from intermediate volcanoes of the western Cascades far to the north, and has not been found anywhere else in the Sierra Nevada.

The sedimentary sequence that underlies the rhyolite tuffs can only be constrained to be older than ~31.5 Ma based on isotopic dating, except at La Porte, where it is ~33Ma and older. The upper gravels do contain floral and faunal data, which, unfortunately, have further confused the estimated age of the auriferous gravels. The best known work is that of MacGinitie (1941), who interpreted an Eocene age (~Capay: 52-49 Ma) for fossil leaves at Chalk Bluff based on correlation with a Capay-age marine unit near Oroville that MacGinitie thought equivalent to the Ione Formation. As pointed out by Schorn (2012), this correlation is incorrect. The Capay-age “Dry Creek” formation underlies Ione Formation near Oroville (Creely, 1965). MacGinitie’s incorrect correlation, however, has proliferated so that many subsequent publications assign the Chalk Bluff flora to late Early Eocene (~56-49 Ma; Wing and Greenwood, 1993; Fricke and Wing, 2004; Hren et al., 2010). As further pointed out by Schorn (2012), Wing and Greenwood (1993) estimated a MAT (mean annual temperature) for the Chalk Bluff flora that is ~14.5°C too cool for their latitude, coastal position, and inferred age. A reasonable conclusion is that the Chalk Bluff flora grew at a younger and cooler time.

General approximation of the age of clay-rich sediments is possible by correlation with the global climatic record. The clay mineral content of paleosols and sediment derived from weathering of soils is an integrated record of pedogenic processes at the time of formation. The Early Tertiary paleosols and sedimentary rocks in the Sierra Nevada Foothills record a change in the dominant clay mineral assemblage from kaolinite in lower units to smectite in upper units. This shift reflects a decrease in the intensity of the hydrolytic activity of weathering affecting regional soils, probably in the Mid- to Late-Eocene. Age estimation using soil mineralogy is imprecise; once formed, kaolinite-rich laterite soil remains largely unchanged until it is removed by erosion, which time interval cannot be determined.

The Chalk Bluff flora occur in mudstone beds enveloped by sandstone in the Upper Gravel section. These sandstone beds possess a matrix with a clay mineral assemblage that is a transition from the dominantly kaolinite assemblage typical of the Lower Gravel section to the dominantly smectite assemblage typical of the Upper Gravel. The smectite gravels are probably equivalent to the upper member of the Ione Formation (Fig. 6) (Allen, 1929; Pask and Turner, 1952). The smectite clay mineralogy indicates that these deposits were weathered during younger, cooler times than during the Early Eocene Climatic Optimum (~52-50 Ma) inferred from stable isotope and other data (Fig. 7) (Greenwood and Wing, 1995; Zachos et al., 2001, 2008; Hyland and Sheldon, 2013; Mudlesee et al., 2014). This clay mineralogy may also have been
derived from tuffaceous deposits, which typically alter to smectite, although the presence of a tuffaceous component in these deposits has not been confirmed. The maximum age of the upper gravels could have been sometime in the Late Eocene (~41-34 Ma).

![Figure 7. Chart of Cenozoic climate evolution based on the proxy of oxygen isotopic composition (δ18O) obtained from benthic foraminiferal shells found in marine sediment cores (from Mudelsee et al., 2014)](chart-image)

The age of the oldest, kaolinite-rich part of the gravels is still less constrained by direct dating. The best that can be done is to attempt to correlate sedimentary deposits and their mineralogy with the Eocene climatic record. We presume that the lower gravels are equivalent at least in part to the lower member of the Ione Formation as interpreted by Allen (1929) (Fig. 6). Climate underwent a long-term and mostly gradual cooling of ~12°C from the Eocene Climatic Optimum at ~52-50 Ma to the beginning of the Oligocene (~34Ma; Zachos et al., 2001, 2008; Hyland and Sheldon, 2013; Mudlesee et al., 2014) (Fig. 7). The Eocene-Oligocene boundary coincides with an abrupt cooling of another 4° to 6° C. The gradual Eocene-Oligocene cooling was interrupted by an abrupt warming of ~4°C during the Mid-Eocene Climatic Optimum.

Development of kaolinite-rich soils by extreme weathering probably would have been most intense during the 52-50 Ma Eocene Climatic Optimum. However, when the intensity of weathering transitioned from kaolinite-dominant to smectite-dominant is unclear. Neither is it known whether the transition was relatively abrupt or gradual over millions of years. The gradual climate record, along with the ~41 Ma Mid-Eocene Climatic Optimum, suggest a weathering continuum, possibly even with an episode of more intense weathering during the Mid-Eocene. Unfortunately, the length of time required to develop a climax kaolinite soil mineralogy is not known.
A similar Eocene transition from kaolinite-dominant weathering is recognized in the San Diego region of southernmost California and northernmost Baja California (Abbott et al., 1976; Peterson and Abbott, 1979; Link and Abbott, 1991). In that region, a thick kaolinite-rich paleosol is developed on an erosional surface that truncates all pre-Middle Eocene units. Middle and Upper Eocene units dominated by smectite clay overlie the paleosol, indicative of a climate beginning to cool and become dryer. This would place the kaolinitic paleosol as older than ~49 Ma and suggest it developed during the Early Eocene Climatic Optimum and the Paleocene – Eocene warming trend that preceded it.

If the southern California data are indicative of the age of the auriferous gravels, the Lower gravels of the Sierra Nevada Foothills could be mostly 49 Ma or older. The gravels could range to slightly younger, because they consist of transported kaolinite eroded from kaolinitic paleosols. How much younger is unknown.

Figure 6 gives our best assessment of the possible age(s) of the Lower and Upper gravels. Clearly, the timing is imperfectly known. Implications of the ages for the source of placer gold are discussed below.

**The Tertiary Climate of Western North America**

The Tertiary climate at the time the placer gold is proposed to have formed and the Tertiary auriferous gravels were deposited can be ascertained by the record of plant and animal fossils contained within. The classic documentation of the flora of the Tertiary gravels is that of MacGinitie (1941). A concise summary of the Tertiary climate record for the Sierra Nevada is that of Millar (1996), upon which the following summary is based. During the early Tertiary, warm-humid, subtropical to tropical conditions prevailed in the area now the Sierra Nevada. Among the trees, ginkgo (Ginkgo biloba), avocado (Persea), cinnamon (Cinnamomum), fig (Ficus), and tree fern (Zamia) were common. At the end of the Eocene - about 34 Ma - global climates changed rapidly from consistently warm to cool-seasonal temperate conditions. In response, vegetation also shifted to cool-dry-adapted conifers and hardwoods. This new flora contained many of the taxa now native to the Sierra, plus relicts from the subtropical forests of the earlier Tertiary. By the late Tertiary, in response to continued drying, winter cooling, and increasing summer drought, replacement of early Tertiary flora by modern taxa and associations had occurred.

Mammalian fossil remains recovered from the Tertiary gravels of California include species of rhinoceros and pachyderms, painting a similar paleoclimate picture.

Lindgren (1911) believed the consistent evidence from all the fossil localities showed that the climate of the region at the time the auriferous gravels were deposited was like that of the southern temperate zone of the Atlantic coast region today, with warmer temperatures and assuredly characterized by heavy rainfall.

Remnant Cretaceous-Tertiary lateritic paleosols preserved throughout the Sierra Nevada Foothills (Evans, 1981; Wood and Glasmann, 2013a, b; Wood et al., 1995)
provide qualitative confirmation of intense chemical weathering within a warm-wet climate regime. The paleoclimatic history interpreted for the Sierra Nevada is consistent with interpreted worldwide climate change (Fig. 7)

Gold endowment of the Sierra Nevada Foothills gold province

The Sierra Nevada Foothills gold province (Figs. 2 and 9), including both lode and placer gold deposits, is one of the world’s great gold provinces. Ascertaining exactly how much gold has been produced, however, is difficult. During the early years, gold was currency, the west was wild, and no one was keeping records. Important production estimates and database summaries of past production are those of Boyle (1979), Bohlke (1999b), Beirlein et al. (2008), Long et al. (1998), and Koschman and Bergendahl (1968) (Table 1).

Table 1. Estimates of California and Sierra Nevada Foothills historic gold production, in millions of ounces.

<table>
<thead>
<tr>
<th>Total California Gold Production</th>
<th>Total Production SNF</th>
<th>Placer Production SNF</th>
<th>Lode Production SNF</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>106</td>
<td>100</td>
<td>65.7</td>
<td>32.9</td>
<td>Koschmann and Bergendahl, 1968</td>
</tr>
<tr>
<td>106</td>
<td>66.8</td>
<td>66.8</td>
<td>39</td>
<td>Evans 1981</td>
</tr>
<tr>
<td>106</td>
<td>66.8</td>
<td>43</td>
<td>35</td>
<td>Clark, 1998</td>
</tr>
<tr>
<td>115</td>
<td>86</td>
<td>37.6</td>
<td>35</td>
<td>Long, 1998</td>
</tr>
<tr>
<td>128</td>
<td></td>
<td></td>
<td></td>
<td>Bohlke, 1999</td>
</tr>
</tbody>
</table>

Perhaps the most comprehensive source, Koschman and Bergendahl (1968), documented gold production in all of California from 1848 to 1965 of 106 million ounces (3297 t), of which 68 million ounces (2115 t) were from placer occurrences and 37.9 million ounces (1178 t) from lode production. Of this total California state production, the Sierra Nevada Foothills produced an estimated 65.7 million ounces (2043 t) of placer gold and 32.8 million ounces (1020 t) of lode gold.

The estimates in Table 1 differ considerably. We conclude that total lode gold production from the Sierra Nevada Foothills gold province was at least 35 million ounces (1088 t). Placer gold production from the same area likely exceeded 65 million ounces (2022 t).

As in most orogenic gold provinces, the majority of primary lode production came from a small number of deposits, with the 12 largest deposits accounting for almost 60% of the gold (Beirlein et al., 2008). The two largest lode gold deposits were the Empire and Idaho-Maryland deposits near Grass Valley (Fig. 2) with a combined production of 8.9 million ounces (275 t). Of 814 lode gold deposits in the database of Northover (2006), only 8 had gold production greater than 1 million ounces (31 t) (Fig. 9).
Haley (1923) reviewed the gold resource in Tertiary gravels stranded by the Sawyer decision, which ended large-scale hydraulic mining in 1884. His estimate considered both the total gold resource, and a smaller economic gold resource, reduced by that volume of material not then economic due to topography, elevation or lack of water. He estimated an “economic resource” of 30 million ounces (930 t) gold within a total remaining resource of 50 million ounces (1550 t) gold. Nearly as much placer gold remains in place today as was produced during more than a century of production!

We estimate that the total amount of gold contained within the Sierra Nevada Foothills gold placer deposits, combining past production and remaining resource, was greater than 115 million ounces (3,577 t).

However imprecise the historical gold production figures might be, several important observations can be made. First, the quantity of gold in either the lode or the placer deposits constitute a giant gold province, defined as a province containing more than 250 tonnes (~8 million ounces) of gold (Laznicka, 1999; Groves et al., 2003). Second, the quantity of gold contained within the placer deposits was more than three times as great as that within known lode deposits. This disparity in abundance makes it difficult to imagine the lode gold deposits to have been the source of the extensive overlying placer gold deposits.

ORIGIN OF GOLD IN THE PLACER DEPOSITS – AN ALTERNATIVE INTERPRETATION

The Sierra Nevada Foothills region of northern California is one of the world’s premier gold provinces. Gold is present both in bedrock lode deposits and in major Tertiary and Quaternary alluvial placer accumulations. Native gold in the auriferous gravels of northern California traditionally has been interpreted to be native gold released by physical weathering from underlying lode deposits and incorporated in the stream bed load. This interpretation has numerous problems. (1) Large gold grains and nuggets are extremely uncommon in primary hydrothermal gold deposits, even within the orogenic quartz-gold veins of the Sierra Nevada Foothills. (2) Historic lode gold production from the province has been about 35 million ounces, while Tertiary placer production exceeded 65 million ounces with yet at least another 50 million ounces of placer resource stranded by extraction restrictions estimated to remain. (3) A large part of the Tertiary alluvial placer gold accumulation is situated upstream and uphill of most of the lode deposits. (4) Tertiary channel gold averages 920 fineness, whereas gold from primary veins varies from 600-900 fineness.

We suggest as an alternative hypothesis that much of the placer gold in the Sierra Nevada Foothills Tertiary auriferous gravels was sourced from the great gold districts of Nevada. The native gold grains and nuggets formed through supergene weathering of primary hydrothermal gold deposits in a warm-humid environment on a tectonically stable high plateau. Subsequent accelerated physical weathering due to tectonism, climate change, or river incision, stripped the tropical soils with their contained gold from a large source area and transported it westward in large river systems. The dense gold
particles were deposited within the high-energy stream channel deposits at the base of the steep pre-Sierra slope, while the finer grained and less-dense, kaolinite-rich silicate soil minerals were carried westward to be deposited as the kaolinite-rich sedimentary units of the Ione Formation.

**Genesis of placer gold from chemical weathering primary gold deposits**

Few primary hydrothermal gold deposits anywhere in the world contain abundant masses of native gold that can be released by physical weathering to form the gold grains and nuggets found in alluvial placer deposits. In those few deposits in which masses of native gold are found, the coarse fraction constitutes but a minor part of the total gold resource. It appears highly unlikely that the orogenic quartz-gold veins of the Sierra Nevada Foothills gold province were the source for all or even most of the gold in the overlying placer gold deposits. So where did the gold come from? An examination of where gold nuggets are known to form in the modern environment can usefully inform this discussion.

Generally, placer gold deposits are considered to be of two types: eluvial and alluvial. Residual or eluvial gold placers are concentrations of gold that remain when other rock or soil material has been removed by chemical and physical weathering, leaving a near-surface residuum with abundant native gold. Gold grains from eluvial placers can in turn be eroded, physically transported, and deposited by water to form alluvial placers. Once formed, concentrations of placer gold may be repeatedly eroded, transported and redeposited (Henley and Adams, 1979). In North America, the well-known great placer gold fields of California, the Klondike, and Alaska are all alluvial placer gold deposits. It is important to appreciate, however, that the gold grains and nuggets in these alluvial deposits may have been formed, transported, and deposited in more than one cycle of erosion and deposition before coming to rest in their current locations. The ultimate source areas may have been distant from the locations where the alluvial concentrations now rest.

Elsewhere in the world, great quantities of gold are recovered from eluvial placer concentrations. There are thousands of residual placer gold deposits within the Amazon Basin, within the zone of tropical forested Africa, in Australia, and in Southeast Asia. These eluvial gold placer concentrations are typically restricted to the near-surface weathering profile and are often mined by artisanal miners using a variety of methods from simple panning to larger-scale hydraulic washing. The gold in these deposits occurs as grains to nuggets, which are recovered by gravity separation. In some occurrences, artisanal miners recover the gold underground, digging shafts down through the thick tropical soil profile, then tunneling along the soil-bedrock interface to recover the gold concentrated at the base of the soil profile.

The fact that some chemical elements can be chemically moved and concentrated by pedogenic processes within tropical soils is well known. Laterite concentrations are important ores for aluminum (bauxite), iron (direct-shipping hematite ores), and nickel (nickel laterite). The importance of intense chemical weathering in the formation of
many gold deposits has only been widely appreciated within the past decades. Although most modern eluvial gold deposits are found in tropical locations, Taylor et al. (1992) document the formation of cool climate laterite and bauxite weathering under conditions of high precipitation in New Zealand.


Soils can be described as geomembranes – open biogeochemical systems in which there is a dynamic redistribution of elements in response to changing physico-chemical conditions (Colin et al., 1992). The typical product of intense chemical weathering is a laterite soil (oxisol), marked by the progressive development of variations of saprolite, mottled zone, and laterite or ferricrete soil horizons (Fig. 8). Every chemical element is mobile to some extent; differences in element mobilities result in removal, residual concentration or secondary concentration of elements. Geochemical processes in the pedogenic environment are functions of primary lithology, geomorphology, biology, climate, hydrology and time.

Figure 8 summarizes common terminology for a deeply weathered regolith profile and summarizes typical mineralogy and major-element chemistry. Through chemical weathering processes, the chemistry and mineralogy of the soil profile is dramatically changed through time. In general, the oxides of iron, aluminum and titanium are least mobile and are concentrated in the residual soil. Alkali and alkali earth elements (Na, K, Ca, Mg) are highly soluble and readily moved away in groundwater. Notable for this discussion is the importance of the alumina-rich clay mineral kaolinite as a stable climax mineral in the laterite soil profile.

Although the concentration of silica decreases with weathering, some quartz remains as a residual mineral. Silica removed from the soil in groundwater may precipitate as crystalline quartz veins and fracture-fill in underlying bedrock, or may move laterally in groundwater to form silcrete beds or quartz overgrowths on quartz grains.
Gold is generally considered chemically inert under most weathering conditions, but may be chemically quite soluble and mobile where certain complexing ligands are present in soil and groundwater. Field evidence suggests that oxidation of primary gold-bearing sulfide minerals releases gold in an extremely fine-grained soluble state to the weathering environment. Significant chemical complexes for solubilizing gold are thiosulfate generated by pyrite oxidation, organic acids formed by the interaction of gold with organic matter, and halide complexes in saline soils (Butt, 1988). In tropical forests, organic acid complexes are an important ligand (Freise, 1931; Boyle, 1979), while in more arid terranes, such as present-day Australia, chloride complexes are dominant.

Once in solution, gold moves with groundwater. In continually wet environments, gold moves downward until it is precipitated by reduction, often by ferrous iron, at the weathering front. In tropical climates marked by wet and dry seasons, gold in groundwater may move also upward by capillary action during dry seasons to precipitate within the ferruginous laterite cover. Thus, two distinct modes of supergene gold concentration are distinguished: concentrations of native gold intergrown with iron-
oxides in near-surface laterite, and saprolite gold concentrations formed at the weathering front (Fig. 8).

Because silver is more soluble than gold, the two metals are parted during weathering and secondary concentration, removing silver in solution and leaving a gold-enriched residue behind (Jaireth, 1994; Mann, 1984).

As the weathering front progresses downward, supergene gold is repeatedly dissolved in the zone of oxidation, moved downward in groundwater, and precipitated at the redox boundary, only for the cycle to be repeated as the weathering front recedes. The morphology of gold grains observed in tropical soils around the world is quite consistent with this model. In the upper oxidizing horizon, gold occurs as corroded and pitted remnant grains, evidence of dissolution processes occurring in the unsaturated zone high in the weathering profile. Lower in the profile, in the zone of accretion, gold occurs as subhedral to euhedral crystals and crystal aggregates described as delicate euhedral, filamental or dendritic, evidence of grain growth in the supergene environment. (Santosh and Omana, 1991; Freyssinet, 1993, Wilson, 1984) The fineness of gold is almost always greater in these secondary crystals (Jaireth, 1994; Boyle, 1979, Mann, 1984).

It is common knowledge among placer miners that gold “grows” in placers, and modern studies confirm this (Freise, 1931; Boyle, 1979; Clough and Craw, 1989; Hughes et al., 1999). Alluvial gold placers, worked and thoroughly exhausted, may after a period of years once again be panned and yield a profitable amount of newly accumulated gold (Friese, 1931). Other evidence for chemical migration within alluvial placer deposits include crystalline gold overgrowths on abraded alluvial gold nuggets; the presence of gold in diagenetic pyrite that has replaced roots and branches in the alluvial placer deposits; occurrences of fine wire-gold within alluvial cobbles; fine crystalline gold crystals in moss mats; and gold impregnations of detrital wood and coaly material. Hughes et al. (1999) document widespread and abundant diagenetic pyrite in the sediments of paleoplacers, together with native copper and at least some perfectly crystalline diagenetic arsenopyrite. Schuster and Southam (2014) and Reith et al. (2010) have documented the importance of bacteria and biofilms in mediating the dissolution and precipitation of gold in weathering and sedimentary environments. In laboratory simulations, Lengke and Southam (2007) document the growth of millimeter-scale gold crusts on sedimentary grains during experiments as short as 150 days.

It is the conventional interpretation of many placer miners that gold grains and nuggets with delicate crystal forms have not traveled far from a bedrock vein source. Abundant evidence, however, suggests it more likely that often these delicate gold crystals were formed by supergene processes within a soil profile, or have recrystallized or grown in-situ within the alluvial environment in which they are found.

As gold nuggets are being formed today by pedogenic processes under conditions of intense chemical weathering, we propose that most of the gold nuggets within the Tertiary placer deposits of the Sierra Nevada Foothills gold province were formed by
weathering of primary gold deposits, supergene enrichment, and reconstitution of gold by pedogenic processes, likely with microbial mediation. Crystalline gold grains and nuggets were concentrated as eluvial placer deposits within the tropical soil mantle. In response to changing climate or topography, the gold nuggets were eroded from the source area, transported by large west-flowing river systems, to be deposited in the great Tertiary alluvial deposits of California. Some portion of the placer gold may have been formed by chemical weathering of the gold-rich terrane of the Sierra Nevada Foothills metamorphic belt to be locally redistributed by the Tertiary river systems (Evans, 1981).

Consider the sequential sediment yield from physical erosion of a plateau surface mantled by a thick auriferous laterite soil profile as in Figure 8. The early sediment load would contain abundant particulate gold with fine-grained kaolinite and quartz and few or no resistant lithic clasts. As erosion cuts deeper, the abundance of kaolinite would decrease, while that of smectite would increase. The abundance of gold, great during early erosion, would decline abruptly. As erosion reaches the unweathered bedrock surface, lithic clasts from the source area will enter the sediment stream. This is the general sequence of sediment composition noted up-section in the Sierra Nevada Tertiary gravels.

**Tertiary river channels, the Sierra Nevada, and Nevadaplano**

Early miners and geologists quickly appreciated the importance of following the Tertiary paleochannels, both at the surface and in the subsurface beneath younger cover. The channels were prospected and mapped (Lindgren, 1911). Lindgren recognized and documented that many of the major auriferous Tertiary channels are located uphill, and upstream of the major lode gold deposits from which they were assumed to have derived (Figs. 9 and 10). This evidence strongly suggests a yet more eastern source for the great alluvial accumulations with their contained gold.

As Lindgren (1911) and other early geologists sought the source of the placer gold, they were constrained by their understanding of the tectonic and topographic history of the Sierra Nevada. It was then accepted that the mountain range was generally symmetrical throughout Cretaceous time, with a crest located near to the current summit line. At some time at the end of the Cretaceous, the structure changed from a symmetrical uplift to a west-dipping monoclinal fault block, yet the location of the crest remaining largely unchanged. Constrained by this interpretation, the potential source area for all of the gold contained within the Tertiary gravels was restricted to the narrow slope between the crest of the Sierra Nevada and the location of the placer deposits.
Figure 9. Map showing the location of significant lode and placer gold deposits in the Sierra Nevada Foothills gold province. Note that many of the significant placer gold deposits are upstream and uphill from the major lode gold deposits. Outcrop occurrences of Ione Formation from Creely and Force (2007). Locations and gold production data are from Clark (1970) and Northover (2006).
More recently, the area that is now the Great Basin is widely interpreted to have been an erosional highland in the middle Cenozoic, following crustal thickening to as much as 70 km during Mesozoic–early Cenozoic shortening, batholith emplacement, and shallow slab subduction (e.g., Wolfe et al., 1997; Dilek and Moores, 1999; Ducea, 2001; Humphreys et al., 2003; DeCelles, 2004; Dickinson, 2006; Henry, 2008; Best et al., 2009; Cassel et al., 2009a, b, 2011, 2012, 2014; Colgan and Henry, 2009; Ernst, 2010; Henry and Faulds, 2010; Long, 2012). This highland, commonly referred to as the Nevadaplano based on an analogy to the Altiplano of the Andes (DeCelles, 2004), probably had maximum elevations of 3-4 km in east-central Nevada (Fig. 11). The Nevadaplano was maintained at high elevation until major extension and elevation loss began in the middle Miocene (Horton and Chamberlain, 2006; Colgan and Henry, 2009; Henry et al., 2011, 2012). Major paleoriver systems drained this highland both west to the Pacific Ocean, connecting to the Tertiary channels of this paper, and east to the Uinta Basin (Fig. 10; Henry, 2008; Cassel et al., 2009a, b, 2014; Henry and Faulds, 2010; Henry et al., 2012).
Despite this consensus, the absolute elevation and structural-topographic evolution of the Nevadaplano, particularly of what is now the Sierra Nevada, remain highly controversial (Wakabayashi and Sawyer, 2001; Mulch et al., 2006, 2008; Cassel et al., 2009a, b, 2014; Molnar, 2010; Wakabayashi, 2013). For most of the past century, the high topography of the northern Sierra Nevada was thought to be the result of uplift during the late Cenozoic, that the Sierra Nevada was a great uplifted and westward-tilted fault block like fault-block ranges of the Basin and Range (LeConte, 1886; Christensen, 1966; Huber, 1981; Unruh, 1991; Wakabayashi and Sawyer, 2001; Jones
et al., 2004; Wakabayashi, 2013). Recently, based on crustal thickness, stable isotope and organic molecule paleothermometry and altimetry, and detrital zircon geochronology, Wernicke et al., (1996); Horton et al. (2004), Mulch et al. (2006, 2008), Cassel et al. (2009a, b), Cecil et al. (2010), and Hren et al. (2010) interpreted that the Sierra Nevada initially uplifted during Late Cretaceous arc magmatism and, during the Eocene-Oligocene, was approximately the same elevation (ca. 2.5-3 km at the latitude of Lake Tahoe) as it is today. After cessation of Cretaceous magmatism at about 80 Ma, the present Sierra Nevada underwent significant erosion – as much as 5-8 km over about 30 million years creating a pre-Eocene erosional unconformity surface. This surface underwent significant chemical weathering due to the wet, warm Paleogene climate, leaving the surface, at least locally, covered by a thick lateritic soil profile (Evans, 1981; Wood et al., 1995). The auriferous gravels were deposited on the pre-Eocene erosional unconformity.

The Tertiary channels and their contained sedimentary deposits and gold are essential parts of the evidence for the “Nevadaplano” and bear on the evolution of elevation. For years, geologists have recognized that some clasts in the channels had to have come from farther east, in what is now the Great Basin of Nevada (Slemmons, 1953; Bateman and Wahrhaftig, 1966; Yeend, 1974). Our work has shown that these channels extended far to the east to an interpreted paleodivide extending across east-central Nevada (Faulds et al., 2005; Garside et al., 2005; Henry, 2008; Cassel et al., 2009a, b, 2012, 2014; Henry and Faulds, 2010; Henry et al., 2012; Fig. 11). Most notably, voluminous, mostly Oligocene (~34-19 Ma), rhyolite ash-flow tuffs erupted from calderas in central Nevada and flowed great distances down the paleochannels (Henry, 2008; Cassel et al., 2009a, b, 2012; Henry et al., 2012). The ash-flow tuffs and reworked tuffaceous deposits constitute part of the Tertiary gravel section. Several tuffs probably reached the former shoreline in what is now the Great Valley. The distribution of these tuffs demonstrates that the Sierra Nevada was a lower, western slope to the Nevadaplano to the east. Probably all of Lindgren’s (1911) named Tertiary rivers had headwaters in central Nevada, although they certainly had local tributaries restricted to the Sierra Nevada. Tuff distribution is also consistent with, but does not prove, the interpretation from stable isotope data of a 3-4 km high Nevadaplano (Cassel et al., 2014), because channelized tuffs can flow great distances even down low topographic gradients (Henry et al., 2012).

Possible sources of gold to the Tertiary Channels

Drainage of the Tertiary channels of the Sierra Nevada from much of the Great Basin allows for many additional possible sources of gold to the channels (Fig. 11). Indeed, the Great Basin contains one of the greatest gold endowments of the Americas (Sillitoe, 2008). Numerous major Mesozoic to late Cenozoic precious-metal deposits lie in the basins that drained through the Sierra Nevada Tertiary channels. This discussion mostly considers Eocene and older deposits, because younger deposits obviously could not contribute to the main auriferous gravels.
Garside et al. (2005) discussed numerous possible sources of Au in the easternmost Sierra Nevada and western Nevada. These include porphyry Cu mineralization at Lights Creek, Genesee, and Meadow Lake (Fig. 11). Hypabyssal quartz monzonite at Lights Creek is 178.1±3.9 Ma (Dilles and Stephens, 2011). Detrital zircons from sediments underlying the La Porte tuff are dominantly 160-180 Ma, which indicates that the Lights Creek intrusion or a similar age intrusion was exposed and shedding material into the Tertiary channels (Cassel et al., 2012). Numerous small “probably gold-bearing" quartz-tourmaline veins are scattered around western Nevada, but none had significant production of any metal. Garside et al. (2005) also pointed out that placer Au is found in paleovalleys in western Nevada below 27 Ma ash-flow tuffs in the Carson Range and near Yerington. The upper parts of the Jurassic porphyry copper system at Yerington could have been a source of gold to these placer deposits.

Probably Late Cretaceous, orogenic precious-metal veins are widespread in western to northwestern Nevada, particularly in the Humboldt Range (Fig. 11). Many are silver-rich, with Ag:Au ratios around 100:1 (Vikre, 1981, 2014; Crosby, 2012; Davis and Muntean, 2014a, b; Muntean and Davis, 2014), and mine production has been dominantly Ag. Nevertheless, Au production has been significant, recent exploration indicates major gold prospects, and the veins were major sources of Au to nearby Tertiary placer gold deposits (Johnson, 1973; Peters et al., 1996; Cheong et al., 2000).

The largest producer, the Couer Rochester mine in the southern Humboldt Range, has produced at least 130,000,000 ounces Ag and 1,500,000 ounces Au through 2012 and has total reserves and resources of 186.1 million ounces (5788 t) silver and 1.24 million ounces (38 t) gold (Coeur Mining, 2015; Davis and Muntean, 2014). The nearby gold-rich Spring Valley deposit has ~4 million ounces (~124 t) Au in the measured and indicated categories with no reported Ag (Midway Gold Corp., 2015). A Tertiary placer deposit at Spring Valley produced about 500,000 ounces Au, and one in the Sierra district to the northeast produced about 200,000 ounces (Fig. 11) (Johnson, 1973). The southern Humboldt Range underwent extensive early Tertiary erosion (Vikre, 1981).

Orogenic veins in the Humboldt Range are at least Late Cretaceous, ~70 Ma old, but have been difficult to date more precisely. Based on U-Pb zircon dating, host rocks are mostly Triassic (~249 Ma) volcanic rocks, and 92 and 94 Ma intrusions lie within 10 km of Rochester and Spring Valley in the southern Humboldt Range (Vetz, 2011; Crosby, 2012; Vikre, 2014). $^{40}\text{Ar}/^{39}\text{Ar}$ dating of hydrothermal minerals generally give disturbed spectra that suggest Late Cretaceous alteration (Cheong et al. 2000; Vikre, 2014). Disturbed $^{40}\text{Ar}/^{39}\text{Ar}$ and KAr dates of vein muscovite from Rochester scatter around 103-86 Ma, and all other KAr and $^{40}\text{Ar}/^{39}\text{Ar}$ dates of muscovite and alteration(?) K feldspar from the southern Humboldt Range range from 70 to 80 Ma (Vikre, 2014). Four of five samples of sericite associated with Au-quartz veins north of the Sonoma Range gave dates between about 90 and 107 Ma, and the fifth showed a maximum age of ~80 Ma with considerable Ar loss (Cheong et al., 2000).

Carlin-type gold deposits (CTDs) are the best known and largest producers of Au in Nevada with an identified gold endowment greater than 211 million ounces (6560 t) in
deposits concentrated within four linear belts in north-central Nevada (Fig. 11) (Sillitoe, 2008; Muntean et al., 2011; Cline et al., 2005). Despite the immense size of these deposits, their age, structural-stratigraphic setting, physical and mineralogical characteristics, and possibly location make their contribution to the “auriferous gravels” highly unlikely.

All reasonably well-dated Carlin-type deposits formed in the Eocene, between about 43 and 35 Ma (Fig. 11) (Cline et al., 2005; Ressel and Henry, 2006). Mineralization generally becomes younger southward, following the younging of Eocene magmatism, which was at least the heat source and possibly the source of fluids and metals to the deposits (Ressel and Henry, 2006; Muntean et al., 2011). If the deep channel gravels of the Sierra Nevada are older Eocene, ≥45 Ma, then CTDs could not have contributed to them. CTDs also would have been available to weathering only after the Eocene Climactic Optimum, when the climate was becoming cooler and dryer.

Carlin-type deposits are primarily hosted in largely carbonate, shelf- and slope-facies, Paleozoic sedimentary rocks in the lower plate of the Roberts Mountain allochthon, structurally below mostly siliciclastic, deeper-water, upper plate Paleozoic rocks that had been thrust over them. Lower-plate carbonate rocks are more favorable physical and chemical host rocks; upper-plate rocks often served as less-permeable caps. Upper-plate gold deposits are usually much smaller and of lower grade than lower-plate deposits. Although mineralization formed at relatively shallow depths, most exposure in the Eocene soon after gold deposit formation may have been restricted to upper plate rocks, so only a small part of the total mineralization was available for weathering, enrichment, or transport.

Gold in CTDs occurs as submicron substitution in arsenian pyrite, not as discrete Au grains (Cline et al., 2005). More recent oxidation of some deposits has generated extremely fine-grained free Au, but erosion and reworking of this Au into modern placer deposits has been minor. The “invisible Au” that is characteristic of CTDs meant that they were not discovered by early prospectors, in contrast to the discovery of most major gold deposits in Nevada and elsewhere. CTDs were only recognized as a distinct deposit type and large-scale mining undertaken in the 1960s.

CTDs are also the most distal potential sources to the “auriferous gravels” (Fig. 11). The Carlin trend and parts of the Battle Mountain-Eureka trend lie astride or even east of the inferred Tertiary drainage paleodivide. The precise location of the paleodivide and its evolution through time are uncertain, but many CTDs probably were in east-draining regions during Eocene and Oligocene time.

The paleodrainage network off the Nevadaplano probably lasted until the onset of major extension in the middle Miocene, ~17-16 Ma (Dilles and Gans, 1997; Wolfe et al., 1997; Horton and Chamberlain, 2004; Colgan and Henry, 2009). Deposits younger than that could not have contributed gold to Sierra Nevada gravels regardless of the influence of climate on Au mobilization. With the notable exception of the 26 Ma Round Mountain deposit (16 million ounces; 500 t Au), large deposits of Oligocene age are sparse in
Nevada (Henry et al., 1997). Some gold at Round Mountain is relatively coarse and includes high-grade veins that make exceptional sources for placer deposits. Quaternary placers were prominent producers during early mining in the district.

Precious-metal deposits of the Ancestral Cascade magmatic arc in what is now the Walker Lane belt of western Nevada range in age from ~22 to 4 Ma (John, 2001; Vikre and Henry, 2011). Only the oldest of these, e.g., the 20-22 Ma Goldfield (Ashley and Silberman, 1976; Vikre and Henry, 2011), 19-20 Ma Tonopah (Bonham and Garside, 1979), and 18-19 Ma Paradise Peak (John et al., 1989), could have contributed to upper parts of the Tertiary gravels.

We should further consider deposits that were likely present in the Cretaceous or Early Tertiary but that have been completely removed by erosion. It is an underlying premise of this paper that to understand the origin of the gold in the Tertiary placer deposits of the Sierra Nevada Foothills, we must imagine landscapes and climates different than those of today. At the end of the Cretaceous, the Sierra Nevada stood as the high volcanic arc of the North American Cordillera. We expect that the Cretaceous North American Cordillera presented geology and topography similar to that of the modern South American Andean Cordillera. By analogy with the younger Andean Cordillera, there likely could have existed within the North American volcanic arc, giant gold districts, which have been reduced and removed by tens of millions of years of weathering and kilometers of erosion.

The Cajamarca-Huaraz mineral district in Peru has a gold endowment of 86 million ounces (2675 t) in high-sulfidation epithermal and porphyry copper-gold deposits, and the El Indio-Maricunga mineral district in Chile has an endowment of 81 million ounces (2520 t) gold in high-sulfidation epithermal deposits. These two districts are among the largest gold systems in the American Cordillera (Sillitoe, 2008). Both districts are about 400 km long, stretching along the crest of the Andean magmatic arc. High-sulfidation gold deposits are hosted by voluminous long-lived volcanic systems of andesite-dacite-rhyolite composition. It is reasonable to consider that comparable districts once existed in the similar, but older, arc setting of the North American Cordillera. Weathering and erosion of even 3 kilometers of the uppermost volcanic arc would have completely reduced such deposits. Weathering of these deposits during warmer wetter Paleogene climate, under lush vegetative cover, may have released finely disseminated gold from auriferous sulfide minerals to be reconstituted as native gold particles and nuggets, accumulating as residual placer deposits. Near-surface supergene redistribution and concentration of gold is significant in some Andean gold deposits.

**Chemical Fingerprinting of Gold to Evaluate Sources**

The ability to chemically or isotopically fingerprint gold grains both in primary lode deposits and placer gold concentrations could greatly help evaluate sources, and a few attempts have been made in other districts. Knight et al. (1999) and Chapman et al. (2010a, b) used combined microchemical analysis and inclusion mineralogy of gold grains to connect placer accumulations in separate drainages with bedrock source areas elsewhere within the Klondike District, Yukon. Placer gold grains within individual
drainages have distinct ranges of composition and inclusion mineralogy, which can be correlated to lode gold centers within the district (about 2500 square kilometers area). The technique required analysis of thousands of individual gold grains by microanalytical techniques. Placer gold is typically an alloy of Au, Ag, Cu, Hg, and sometimes platinum group elements, and grains commonly exhibit significant chemical zonation from core to rim. In the Klondike studies, the chemistry of placer gold grains within any location exhibited significant variability, and it was only through analysis of large number of grains that compositional ranges could be defined.

The relative Re and Os concentrations in gold have been shown to be distinctive for deposits of different ages and geological settings and to reflect the degree of tectonic recycling of the gold (Frimmel et al., 2005, 2015).

For chemical fingerprinting to reliably identify the source(s) of gold grains in Sierra Nevada gravels, where potential source areas may be hundreds of kilometers distant, several requirements need to be met.

1) Different sources need to have distinct chemical or isotopic characteristics. There must be distinct chemical differences between, for example, Mesozoic lode gold deposits of the Sierra Nevada, epithermal deposits that may have existed on the North American Cordillera volcanic arc, and Carlin-type gold deposits of central Nevada. An immediate corollary is that a database of sufficiently representative analyses is required to determine the homogeneity and distinctiveness of gold alloy chemistry in these different deposit types. This data currently does not exist.

2) All or at least part of the distinct chemical signature of gold from the original lode deposits would need to be retained through the repeated supergene dissolution-precipitation process called upon here. It is well documented in references already cited that the fineness – the alloy chemistry - of gold is dramatically changed by supergene processes, both with and without microbial mediation. In the Klondike studies, Knight et al. (1999) concluded that such supergene modification was minor and restricted to thin rims in which Ag, Hg, and Cu were depleted. In other locations, chemical change is undeniable and this approach will not be reliable. Since heavy isotopes are not fractionated by low-temperature chemical processes, the lead isotopic composition should be preserved even if nuggets were chemically altered. Lead isotopes have been used extensively to identify crustal provinces and could correlate with the gold deposit areas.

3. Analytical methods with sufficient spatial resolution and analytical sensitivity are required, since placer gold grains exhibit significant chemical variability and frequently contain inclusion minerals. Knight et al. (1999) found that X-ray microprobe analysis of polished samples of lode and placer gold from the Klondike District, Yukon was practical only for Au, Ag, Hg, and Cu. Bulk analysis of individual grains is not likely to provide the chemical detail required for a reliable fingerprint.
We conclude that chemical or isotopic fingerprinting of placer gold might be possible but will require considerable effort just to test its potential. Until that technology is developed, the history of these nuggets is best interpreted from the geological context in which they are found, appreciating that the history thus interpreted may be only the latest chapter in a much longer geological history.

CONCLUSIONS

The discovery of gold in California in 1848 quickly led prospectors from modern river gravels to Tertiary river gravels to the bedrock orogenic gold-quartz vein deposits. Following a similar path, it has been the traditional interpretation that gold nuggets in modern alluvial gravels were derived from the auriferous Tertiary gravels, and all of the gold was ultimately sourced from the bedrock quartz-gold veins of the Sierra Nevada Foothills metamorphic belt.

This interpretation is difficult to accept for a number of reasons. 1) The amount of gold in the gravels greatly exceeds that known in the lode deposits by a factor of at least three. It would have required kilometers of erosion to expose that amount gold, which fortuitously would have remained atop the bedrock source. 2) Nuggets or grains of native gold are uncommon in most primary gold deposits, including the orogenic gold deposits of the Sierra Nevada Foothills. 3) Much of the gold in the Tertiary gravels occurs upstream, uphill, and laterally displaced from the major potential local bedrock lode gold sources. 4) The fineness of the placer gold is significantly greater than that of the underlying lode deposits – strong evidence for chemical reconstitution in the supergene environment.

Modern eluvial placer gold accumulations are found in environments with intense, commonly tropical, chemical weathering and thick laterite soil development. These deposits typically overlie bedrock containing geochemical enrichment in gold, but not necessarily over significant economic gold deposits. Over long periods of geologic time, gold has been concentrated by removal of other elements. As the weathering front advanced progressively downward with time, gold was repeatedly dissolved, mobilized locally within groundwater, and reprecipitated as the native metal. With time, widely dispersed gold was aggregated into grains and nuggets, often with delicate crystal forms and with increasingly higher fineness. Conditions favoring this process are a warm-wet climate, with lush vegetation, and tectonic stability.

The Late Cretaceous to mid-Tertiary climate of western North America was demonstrably warmer and wetter than present. The evidence is clear in the floral and faunal fossil record preserved in the upper Tertiary gravels. The interpreted climatic conditions mirror those interpreted for worldwide climatic conditions. Remnant laterite paleosols and the abundance of detrital kaolinite in the Ione Formation sediments indicate conditions of intense chemical weathering during deposition of the Lower Gravels, with moderating intensity of weathering during deposition of the Upper Gravels.

Most of the gold within the Tertiary channels is concentrated at the bedrock contact and within the immediately overlying few meters of gravel. This suggests that as incision of
the Tertiary channels began, there already existed in some source area, a large quantity of gold nuggets and grains, readily available for erosion, transportation and deposition within the Lower Gravels. An expansive plateau mantled by meters of laterite soil with eluvial placer gold is the landscape we imagine to have been the source.

Clay mineralogy tells a consistent story. The mineral assemblage kaolinite-quartz is the climax assemblage in a typical laterite profile. Early erosion of an auriferous laterite plateau carried a distinctive sedimentary assemblage containing abundant kaolinite, quartz, and native gold. The sediment load was carried within major west-flowing river systems heading in central Nevada. At the break-in-slope at the base of the western sierra, dense placer gold was concentrated among locally-derived boulders in the base of the channels, while the finer quartz and kaolinite sediment was carried along to be deposited in the littoral Ione Formations as the Tertiary rivers entered marine waters to the west.

It is now appreciated that the Sierra Nevada Foothills were the western slope of the high-elevation Nevadaplano that extended across the area that is now Nevada, with a drainage divide in central Nevada. The Tertiary channels, which contain the auriferous gravels in the Sierra Nevada Foothills, are known to have extended well into what is now the Great Basin. Some rock clasts identified in the Tertiary placers were demonstrably sourced in Nevada. In addition, the very well-rounded and polished durable cobbles and boulders in the Lower Gravels demonstrate long distance transport.

The age of the gravels is, unfortunately, poorly constrained. The Upper Gravels are demonstrably older than about 31.5 Ma. The Lower Gravels are estimated to be younger that about 50 Ma. This is too great an interval to be very useful, and certainly a question worthy of further investigation.

Although it is clear that the bulk of the gold contained within the Tertiary gravels was not sourced from the underlying quartz-gold veins and likely was sourced to the east of the Sierra Nevada, no specific source has been identified. The amount of gold contained within the placer deposits is greater than all but the largest of gold districts worldwide. It is possible that the source of the gold may have been the combination of numerous eluvial gold concentrations overlying a number of separate gold deposits across the broad area of the Nevadaplano.

Carlin-type gold deposits are the most significant bedrock gold deposit type in Nevada at the present time and current level of erosion. Most of these deposits formed at about 39 Ma. Although the age of the California Tertiary gravels is not well constrained, it is likely that the maximum gold concentrations in the Lower Gravels are older than this, and these CTDs are not likely bedrock sources.

A speculative possibility is that the gold was sourced from giant volcanic rock-hosted high-sulfidation gold districts over the North American magmatic arc, similar to gold districts presently exposed in the Andean Cordillera. Over millions of years, and kilometers of weathering of the Sierran arc, gold grains and nuggets may have formed by pedogenic processes to form eluvial or alluvial placers. Changes in topography,
tectonics, or climate may have accelerated physical erosion, stripping the laterite surface and flushing gold-rich gravel down the Tertiary river channels, to be deposited at the break-in-slope where we find the deposits today. The occurrence of the placer gold accumulations near to, and in some places overlying the lode quartz-gold veins, is likely fortuitous, not genetic.

The model proposed here brings together observations of sedimentology, volcanology, geochronology, paleoclimateology, clay mineralogy, ore deposits and tectonics in a broad framework explanation with few details. The Tertiary auriferous sediments of the Sierra Nevada Foothills have received surprisingly little careful study beyond the quest for gold. Numerous burning questions of geochronology, clast provenance, clay mineralogy, geomorphology and paleontology beg for further research. We emphasize the critical importance of understanding past climates and former landscapes to understanding the alluvial placer gold deposits of the Sierra Nevada Foothills, and other placer gold fields worldwide.

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Cretaceous - Eocene: Remnants of the Sierran magmatic arc remain with the high Nevadaplano behind. Intense chemical weathering in a tropical climate create residual gold placers over Carlin Type Deposits in Central Nevada, and perhaps over Volcanic-Hosted Epithermal deposits in Sierra arc volcanic rocks.

Eocene: Changing climate or tectonics result in increased physical erosion. Residual placer gold nuggets and underlying white quartz are eroded, transported westward in major rivers, and deposited at the slope break on the western flank of the Sierra. These are the Tertiary auriferous gravels.

Oligocene: Rhyolite volcanism in central Nevada spreads ignimbrite sheets as far as 200 km westward, filling Tertiary river valleys, and burying the auriferous gravels west of the Sierran crest.

Late Tertiary - Quaternary: Extensional collapse of the high Nevadaplano cuts westward drainage from Nevada. Erosion removes much of the volcanic cover from auriferous gravels. Modern streams erode and remobilize gold from Tertiary placer channels. No further development of residual gold nuggets in Nevada due to arid climate.