Gold Nuggets – Evidence of Past Climates and Former Landscape

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ABSTRACT

Placer gold deposits, alluvial or residual accumulations of metallic gold, might be considered the scattered skeletons of primary hydrothermal bedrock gold deposits. The enigma is that very few hardrock gold deposits actually contain grains of native gold. In most primary hydrothermal deposits, gold is widely disseminated throughout the rock at ppm-level concentrations as an atomic impurity within pyrite or other sulfide minerals. The transformation of gold from impurity in rock to chunks of native metal occurs principally in the weathering environment. Accumulations of placer gold preserve fascinating evidence of past climates and former landscapes.

Normally, we think of gold as being a nearly insoluble element. Under conditions of intense chemical weathering, however, as for example exist today in Brazil, Africa and Australia, the mobility of many elements including gold may be significantly enhanced. Soils have been described as geomembranes – open biogeochemical systems in which there is a dynamic redistribution of elements in response to changing physical and chemical conditions. Where tropical soils have developed over gold-enriched rock, gold is commonly concentrated both with iron-oxide in near-surface laterite and at the redox boundary in saprolite at depth. Field evidence suggests that oxidation of primary gold-bearing sulfide minerals releases gold in a chemically active state to the weathering environment. There it is solubilized as a chloride or thiosulfate or humate complex, and moves with groundwater until reprecipitated by chemical reduction. As the chemical weathering profile progresses downward, gold continues to be remobilized and increasingly concentrated near the base of the weathering profile.

The morphology of gold grains in tropical soils show evidence of this continuous process. In the upper oxidizing soil horizon, gold occurs as corroded and pitted remnant grains – evidence of dissolution. Lower in the profile, in the zone of accretion, gold occurs as subhedal to euhedral grains and grain aggregates, often with quite delicate form – clear evidence of grain growth in the supergene soil environment. The fineness of the gold, that is the ratio of gold to silver in the metal, is progressively greater in the secondary crystals. It is quite well established that gold nuggets "grow" in the weathering environment; they are not simply chunks of gold physically weathered from a gold vein.

As tropical soils are stripped by physical weathering, the accumulations of particulate residual gold become alluvium: eroded, transported, and deposited as sediment by rivers, glaciers or even on beaches. In the near-surface environment, gold is indeed both physically and chemically durable. Once formed, placer gold concentrations may be repeatedly redistributed during sequential erosional cycles through geological time. Interpretation of the origin of placer gold concentrations, then, requires an appreciation of changing geological landscapes and climate through time.

Gold nuggets in the auriferous gravels of northern California have traditionally been interpreted simply to be chunks of gold released by physical weathering from underlying lode deposits. An alternative interpretation is that most nugget gold in the Tertiary auriferous gravels was sourced from the great gold districts of Nevada. Multiple lines of evidence indicate that the northern Sierra Nevada was the steep western flank of a gradually sloping high-elevation plateau – Nevadaplano – that extended to central Nevada through Oligocene time, and that drainages extended from what is now eastern Nevada to the Great Valley shoreline. The Paleogene climate was considerably warmer and wetter, as recorded in remnant early Tertiary soil and sedimentary rock. Native gold nuggets formed in soil during intense chemical weathering of disseminated gold deposits in Nevada, were transported westward in great river systems draining the Nevadaplano, and deposited in the Tertiary channels of California as gradients decreased near the shore. A very similar interpretation explains the great gold placers of the Klondike, now an area of relatively low relief and arctic climate, developed tens of millions of years ago when the climate and topography were different than today.

NOTES TO ACCOMPANY POWER POINT

These notes are intended to supplement the Power Point presentation.

Slide 1. I first presented this topic in November 2013 to the Four Corners Geological Association in Farmington New Mexico, then again to the Geological Society of Nevada in February 2014. The presentation stimulated considerable interest with the GSN group, many of whom are minerals geologists familiar with the lode and placer gold deposits of the Sierra Nevada foothills gold belts. I am a minerals exploration geologist and do explore for gold, but strictly hardrock gold. My attention to placer gold is as a geological pathfinder and component of the natural environment - a record of geologic history. The photo on the title slide shows recreational gold panners on the Rhein River in Switzerland, where I have been working the past three years.

Slide 2. Gold is atomic number 79, with a specific gravity of 19.32. With this density, a gram of gold has about the volume of a drop of water. Gold occurs with the so-called coinage elements – Cu, Ag, Pt, Pd, Hg – and exhibits similar, but not identical, geochemical behavior. Gold is the noble metal because if does not react readily with oxygen or chlorine. It does form chemical combinations reluctantly, with a valence of +1 or +3.

Slide 3. Gold geologists are experts with coordinate conversion, having to deal with metric and imperial units, as well as the arcane troy ounce. Important figures to note are that a typical grade for large-tonnage gold deposits is about 1 ppm Au. Large gold deposits are those containing more than 3.2 million ounces; giant gold deposits (occurrence of just a few such deposits per continent) contain more than 32 million ounces. For comparison, the total gold production for the USA in 2013 was 7.7 million ounces, of which 5.5 million ounces was from Nevada. An interesting factoid: the total world gold production to date is 193,000 tonnes, which would form a cube 22 meters on a side. A similar cube for all silver is 55 meters.

Slide 4. Gold nuggets come in all sizes and shapes. Probably the largest nugget ever found was the Welcome Stranger, found in Australia, weighing 2284 troy ounces or 71 kg. The largest nugget found in California was 1593 ounces or 49.5 kg. Nuggets typically contain between 83-92% gold, with the remainder silver, copper or other metals.

Slide 5. The conventional interpretation is that gold nuggets in alluvial placer deposits have been shed to the sediment by physical weathering of lode gold deposits – chunks of gold that have simply been released from veins by physical weathering. In gold exploration, the presence of gold nuggets in a stream is, of course, a piece of evidence requiring attention. I have gone to the field with many prospectors or promoters and heard the pitch: "there is so much gold in this river that they must be a giant bedrock gold deposit within this valley". It is a pathfinder idea that rarely works, and as we shall see is overly simplistic.

Slide 6. The second piece of seeming common sense is that well-worn and rounded nuggets come from far away, while those exhibiting crystal faces or containing quartz are proximal to their bedrock source. Simple and obvious. And probably wrong.

The enigma is that the presence of gold as the native metal in quartz veins is very uncommon. In most large hypogene bedrock gold deposits, gold occurs as a trace impurity in other minerals, or if present as the metal, occurs in very small particles. In North America, there are but a handful of districts from which specimens of native gold have been or can be recovered: Red Lake Ontario, Round Mountain Nevada, Sleeper Nevada, Allegheny District California. Even in these mines, specimen gold is the exception rather than the rule.

Where is the source? My answer is that the earth has a long history; the landscape we see today is far different from the landscape of a million or ten million years ago; and the climate of the earth has changed through time. I make the case that most gold nuggets formed by cold-temperature near-surface supergene reconstitution of gold, originally disseminated in primary bedrock deposits. In oversimplified terms, gold nuggets have an origin similar to that of carbonate concretions; or silica concentrations (chert nodules, quartz geodes, petrified wood); or pyrite or barite nodules in sedimentary rocks; or the masses of native silver over the sulfide veins of the great silver deposits of Creede or Cerro Rico.

TALK OUTLINE: Here is where I will go in this talk. First, let me talk about the two greatest gold rushes in North America and the placer deposits that drove them. Then I will talk a bit about bedrock gold deposits, which must be the sources of the gold which occurs in placer gold nuggets. Then I will describe the chemical and physical processes that connect primary and secondary gold deposits. Finally, I will return to the alluvial gold fields to see what the deposits tell us about geologic history.

Slide 7. At the large scale, there are two types of placer gold deposits. Residual or eluvial placers represent concentrations of gold that remain when other rock or soil material has been removed, leaving a residual gold concentration. Gold in residual placers can be transported and moved by water to create alluvial placers. These are the most commonly known deposits – the gold that is recovered by panning streams, or by the dredges from the Yuba River or the beaches of Nome.

Slide 8. Historically, there have been spectacular accumulations of placer gold that played a major part in world history. Although the presence of gold had been long known in California by native Americans and early Spanish settlers, the discovery and promotion of gold by James Marshall at Sutters Mill on the South Fork of the American River near Coloma California in 1848, sparked the largest voluntary migration in American history. There were an estimated 300,000 people in California by 1850 – approximately 1 in 9 Americans was in California!

Slide 9. I think the spirit of the event is wonderfully summarized by Waldemar Lindgren in his 1911 USGS 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…"*

And so it progressed, from panning modern rivers to hydraulic washing Tertiary channels to drift mining the buried channels. Hydraulic washing required massive amounts of water; the surface hydrology of the entire Sierra foothills was reconfigured by flumes, pipelines, ditches and dams.

The massive washing of stream beds and bank deposits, of course, choked the rivers with sediment, destroyed aquatic life, and soon threatened the agriculture and communities downriver in the Great Valley. Parts of the valley were aggraded as much as 7 feet, and a layer of sediment about 20 feet thick was deposited in San Francisco Bay. The process of hydraulic mining and the introduction of sediment into the rivers of California was banned by law (the Sawyer Decision) in 1884, putting an end to that era.

Yuba River was aggraded up to 100 feet, and would breach its banks and flood the area. Dredging began in 1893 to restore the land by stacking the gravel on the banks. This changed to dredging the river for gold. In the 1930's, there were as many as 12 dredges working the Yuba river valley, churning through some 25 million cubic yards per year. Since 1981, there has been one dredge working intermittently; it is currently down for repairs. In total some 1 billion cubic yards of gravel has been disturbed. These scenes are near Marysville California.

Slide 10. Let's return to the Tertiary channels. This shows a section from Lindgren of the auriferous gravels in channels on eroded bedrock and overlain by Oligocene rhyolite and andesite. The greatest gold concentrations are found in the deep gravels in channels scoured into bedrock. The deep channels are overlain by bench gravels. The auriferous alluvial gravels were in turn covered by Oligocene and Pliocene volcanic rocks. Malakoff Diggings State Park is a great place to see the impact of hydraulic mining and view the auriferous gravels.

Slide 11. These are photos of the coarse auriferous gravel in a drift mine on the Ruby Channel of the paleo-Yuba River in Sierra County (this from a presentation by Gary Clifton to the January 2013 GSN meeting). The gravel channels are cut into footwall slates. These are dynamic fluvial systems!

Slide 12. This map, from Lindgren's 1911 USGS Professional paper, shows the location both of the Tertiary auriferous channels and modern rivers. Perhaps it is worth noting the obvious that the placer gold deposits of California are at least as old as Tertiary, and the gold in today's streams has recycled from earlier stream channels that are not coincident with today's drainages and drainage basins. To find the source of the gold in today's streams, we need to follow the Tertiary channels. On Lindgren's map, we see that many of the Tertiary channels bear only a general relationship to the present stream channels and that in many cases, cross the latter at a large angle.

Also on this map is shown the general trace of the Sierra Nevada foothills lode gold deposits, from south to north the Mother Lode district, the Grass Valley district, and the Allegheny district that extend in a zone about 300 km long by 4 km wide. The lode deposits are dominantly quartz-gold veins hosted within metamorphic rocks along the length of the plate suture marked by the Melones Fault Zone. Lindgren, like almost every geologist who has written about the Sierra Nevada foothills placer gold deposits considered the source to be the lode gold deposits with which they are so closely associated. This interpretation has difficulties.

Consider that a total of some **<u>55 million ounces</u>** of placer gold was won from the rivers during the California gold rush (Boyle p.365). This is an enormous amount of gold – the equivalent of about two giant gold deposits or 7 years of current total gold production of the USA! The total historic gold production from all of the mines of the foothills gold districts was about **<u>32 million ounces</u>**, this from hundreds of mines, some as deep as 1.6 kilometers, mined for more than a century. It is difficult to imagine how these veins could have been physically weathered to release this much gold to river gravels. Even then, most of the gold in the veins is fine-grained, and the veins do not contain masses of gold equal to the size of nuggets found in the gravels.

Slide 13. The second difficulty is that the placer deposits extend upstream from the lode deposits; indeed remnants of many of the stream channels can be mapped over the top of the Sierra Nevada into western Nevada. Clearly a source other than the Mother Lode is required for the 1700 tonnes of gold in the California placer deposits – the equivalent to all of the gold in two GIANT deposits.

Slide 14. I thank Jim Wood for this slide. On Yeend's map of the Tertiary channels of the ancestral Yuba River, Jim has highlighted the auriferous alluvial gravels in yellow and mapped channels and flow directions in red. Three important points: (1) the auriferous gravels are uphill and upstream of the Grass Valley Mining District – the often-considered bedrock source of the gold; (2) there are NO significant gold deposits higher up in the Sierra Nevada; all of the major gold deposits are localized along the suture zone marked by the Melones Fault system; and (3) the ancestral Yuba River was a major fluvial system, larger than the current river systems of the region.

So let's leave that thread hang for a while…..

Slide 15. The other great North American gold rush was that to the Yukon in 1998-99. An estimated 100,000 people streamed north to the Yukon when rich placer deposits were discovered near the confluence of Klondike Creek and the Yukon River, at Dawson City. Despite the colorful history, the boom was short-lived. The easy river placers were quickly staked, and recovering gold from the frozen bank gravels was challenging. The weather is brutal and the area lacks the abundant high-gradient streams to facilitate hydraulic washing. Waves of prospectors left the area in 1899 when news of gold on the beaches of Nome reached the frozen interior. Historically some **<u>20 million ounces</u>** of placer gold have been recovered in the district.

Slide 16. A cross-section through these auriferous channels looks stunningly like the California channels. The deep white gravel channels have the highest grades. Boyle has calculated that the White Gravels contained a total of **60 million ounces** of gold (again as much as 2 giant gold deposits). So where did all the gold come from?

Slide 17. As in California, the initial rush was to gold in modern streams, but this gold is simply being recycled from auriferous Tertiary gravels. Modern rivers are exhuming Tertiary river channels, carved into Klondike schist bedrock. For years, no significant bedrock gold deposits have been found within the area. Within the past decade, a number of modest-size bedrock gold deposits have been discovered in the White Gold district. Notably, the gold in these bedrock deposits occurs with sooty sulfide mineralization within shear zones – no giant lumps of gold to be mechanically released to form placers. It is difficult to imagine that these local deposits can be the source of the great placers. As in California, we have extremely large concentrations of gold in Tertiary gravels without an identified bedrock source?

And we will let that thread hang for a while….

What do giant bedrock gold deposits look like?

Slide 18. Northeastern Nevada is the most significant gold province in North America. Sedimentary-rock-hosted disseminated bulk-mineable gold deposits are by far the most important type of gold deposits. These are the so-called "Carlin-type" gold deposits, named for the town of Carlin in northeastern Nevada. Twin Creeks is one of these deposits, and this is a typical view. Host rocks are Paleozoic shelf carbonate and clastic lithologies. On this photo, or on the ground, there are neither significant quartz veins nor visible gold to be seen. For scale, these are 20-foot benches, and the vehicles are 240 short-ton capacity trucks.

Side 19. Carlin-type gold ore is characterized by the occurrence of gold as an atomic impurity in trace-element-rich pyrite which is widely disseminated in very ordinary sedimentary rocks. The gold is rarely visible. Most of the prospectors headed to the goldfields of California followed the Humboldt River across Nevada and walked right across giant outcropping gold orebodies. When these were first recognized in the 1960's, they became known as "microscopic gold" or "no-see-um" gold deposits. The gold is not visible, there is little quartz veining, and the deposits do not, in Nevada, shed placer gold deposits.

The forms of the individual orebodies reflect the local porosity and permeability of the host rock, that is, the influence of local lithology and structure. (Fluid paths and puddles) Indeed many of gold orebodies exhibit features similar to hydrocarbon traps: anticlines, debris-flow carbonate units, brecciated zones between rock units of differing competence, contacts of sedimentary rock units with igneous intrusions.

These are epigenetic hydrothermal gold deposits. The gold is introduced into rock well after its lithification by hydrothermal fluids. Gold is carried in solution as a bisulfide complex. Gold precipitation may occur through various physical or chemical changes, such as boiling or reaction of the fluid with the rock. The most common mechanism is through a process of "sulfidation" in which the sulfur in solution reacts with iron in the host rock to precipitate pyrite, breaking the gold complex and including gold as an atomic impurity in pyrite. The solutions are acidic; the most common wall-rock alteration associated with these gold deposits is carbonate dissolution and alteration of detrital aluminosilicate minerals (like feldspar) to clay minerals.

Slide 20. Gold occurs most frequently within arsenical rims on microscopic pyrite. The pyrite is commonly so fine-grained as to appear like soot, not its brassy yellow color.

Slide 21. The gold is mostly so fine it cannot be seen even with an optical microscope. Most people who work in these mines, including geologists, never see gold until the final product is poured. As the deposits weather and erode in Nevada, the fine gold is washed away and no placers are formed. Gold is hosted in a variety of stratigraphic units of various ages, although impure carbonate units – silty limestone and calcareous siltstone – is the most favorable lithology.

Slide 22. To date, some 60 million ounces have been produced from the Carlin Trend and 50 million ounces from the Battle Mountain Eureka Trend. Northern Nevada is truly one of the world's most significant gold provinces. **For comparison, recall that the California placer deposits yielded about 55 million ounces – the total life-to-date production of the Carlin or Battle Mountain trends - while the bedrock mines of the Sierra Nevada foothills districts produced only about 32 million ounces. I think this informs the question of provenance.**

Slide 23. A bit of cultural trivia – a map of the California Trail. None of the CTD of Nevada have significant associated placer deposits. For this reason they were missed by the early prospectors. The X marks on the map mark the locations of a few of the giant gold deposits in Northern Nevada.

Slide 24. Jumping North. I said earlier that no giant gold deposits exist within the Klondike District. So where might the gold come from? It is only in the past few years that giant gold deposits have been discovered in the Yukon. In the central Yukon, along the Nadaleen and Rackla Rivers, recent exploration, primarily by ATAC Resources and now other companies, has discovered Carlin-type gold mineralization, some 200 km east of the Klondike. As in Nevada, the gold occurs as microscopic particles or in atomic substitution in arsenical pyrite. The host rocks are Proterozoic; the age of mineralization is not known. The setting of the district is very similar to that of northern Nevada – the boundary between the McKenzie carbonate platform to the north and the Selwyn Basin to the south. The stratigraphy has been deformed and imbricated by compressional faulting, focused at that shelf-slope break.

Slide 25-26. Rock alteration is dominantly carbonate dissolution. Elements added include mainly S, As, Au and Tl. These deposits have all the signatures of Carlin-type gold mineralization. Resources have yet to be published, but be assured that these are giant deposits. There is no placer gold associated with these deposits.

Where are nuggets forming today?

Slide 27. So, we have seen what placer gold deposits look like, and we have seen what giant bedrock gold deposits look like. Let's look at environments where we believe gold nuggets are forming today. To understand the alluvial gold deposits of California, let's start with residual or eluvial gold placers elsewhere - that is, to look at residual concentrations of gold that have not been transported by water.

There are thousands of residual gold deposits in the Amazon Basin. These are mined by hand, or using mechanical equipment, or hydraulic washing. Most are only a few tens of meters deep, washing the laterite soil profile to recover residual gold. The gold in saprolite occurs as grains to nuggets, which are recovered by gravitational separation through an amazing assortment of contraptions. Unfortunately, mercury is widely used to capture fine gold, and released to the environment. These scenes are in Brazil, but they could be in Surinam or Peru or Congo or Thailand or Indonesia.

Slide 28. One of the most fascinating districts in which I have worked is near the city of Ouro Preto in the State of Minas Garais, Brazil. This was an opulent Portuguese colonial city. Founded in the 17th century, the city had 100,000 residents by 1700. (For comparison, the anglo population of what would be the USA was 275,000 with New York at 5000). The buildings were as fine as any structure in Lisbon; many of the richly guilded soapstone churches remain. The landscape surrounding the city looks like a field of giant collapsed prairie dog diggings. Rich concentrations of gold are found at the base of saprolite weathering. To get to the gold, garimpeiros dig shafts through the soil – typically some 10 meters deep, then burrow along the top of bedrock to extract the gold-rich material. The importance of this for our story is that here we find gold highly concentrated at the base of a tropical soil profile. Concentrations in bedrock are too low to be economically interesting.

Slide 29. The fact that chemical elements can be greatly concentrated within tropical soils has, of course, been known for centuries. Laterite concentrations are important ores for aluminum (bauxite), iron (direct-shipping hematite ores), and nickel (nickel laterite). Appreciation of the importance of laterite weathering in the formation of many gold deposits has only been widely appreciated within the past decades; yet there remain those who stick hard to the idea that gold is a chemically inert element and do not accept the story.

Let's review some very simplified soil terminology for lateritic soils. The ferruginous upper part of a lateritic weathering profile – lateritic gravel or a duricrust – is an iron-rich layer in which all textural evidence of the original bedrock has been destroyed. This ferruginous layer is a common feature in lateritic terrains, covering thousands of square kilometers in South America and Africa. It caps mesas; it makes great roads and landing strips; it is nearly sterile for agriculture. Underlying the ferruginous layer is a clay-rich zone, typically kaolinite, some tens of meters thick, resulting from intense weathering and leaching of bedrock. Where rock fabric is at least partly preserved despite intensive weathering, the term saprolite is used. The term saprock applies where bedrock is only slightly weathered.

Some years ago I came across the description of soils as a geomembrane filter. Rock, water, soil gas, and biological agents interact in soils to develop complex biogeochemical weathering systems, which undergo continuous physical and chemical evolution. This creates distinct fractionation of minerals and chemical elements. Some elements are concentrated as residual elements (Al, Fe, Ti) while others are removed in groundwater discharge (Na, K, Ca, Si). Others, like gold, are redistributed within the profile: depleted in one location to be concentrated in another. Soil environments are marked by sometimes extremely different conditions of local chemical equilibrium, sometimes at the microscopic level of grain boundaries.

Slide 30. It turns out that gold is also redistributed within the weathering profile, leached from the weathering rock to be reconcentrated elsewhere. Two styles of gold enrichment are distinguished:

Laterite supergene gold deposits are nearly flat-lying enrichment zones coincident with a ferricrete or mottled zone. Gold is usually fine-grained, but nuggets are found. Gold may occur as complex intergrowths in ferruginous duricrust.
Saprolite supergene gold deposits are deeper and may form more than one sub-horizontal layer, often near bedrock. Euhedral gold crystals are common

It is laterite gold nuggets that prospectors find with metal detectors near-surface in Australia. Saprolite concentrations were mined at Ouro Preto.

Just how gold is mobilized and redistributed in soil processes depends upon the nature of the original rock material, the climate and topography of the location, and the climate and soil history.

Slide 31-32. This illustration of the Hannan South gold deposit in Western Australia could be repeated for dozens of deposits. A primary bedrock gold deposit has been enriched by supergene concentration, and there is a marked blanket of gold enrichment at the redox front. The gold occurs as the native metal. Dozens of similar gold deposits have been or are being mined in Western Australia. Photomicrographs of the secondary gold in saprolite reveals euhedral crystal forms.

Slide 33. A polished section of a laterite gold nugget shows the intimate intergrowth of native gold with iron oxide.

Slide 34. Laterite profiles in the Niambur gold prospect of southern India contain grains and nuggets of supergene gold. Chemical rounding and corrosion cavities characterize the gold grains in the upper zones of intense weathering, while lower less-weathered horizons contain grains with jagged contours and few etch pits. SEM images reveal a variety of growth patterns of secondary gold, including spongy, filimental, and dendritic patterns. Spectacular examples exist of "painted" gold with bright luster precipitated over dull primary grains. While the original gold grains have fineness 825, secondary grains have fineness 991-999. The textural and compositional evidence testify to a distinct low-temperature process of chemical dissolution, migration and reprecipitation of gold progressively downward during tropical weathering.

Slide 35. In fact, gold is very mobile in the natural environment. The various reactions show the mobility of gold with chloride and thiosulfate ligands. Organic soil acids are also effective. Note that silver is slightly more soluble than gold, and during repeated dissolution/reprecipitation, silver and gold are parted, leaving a gold-enriched residue. In a loose sense, the supergene enrichment is similar to that of copper, which leaches to the redox boundary.

Slide 36. What happens when auriferous pyrite oxidizes? The gold impurity is left without a home, in an extremely fine-grained unstable configuration. First it accretes to form "micronuggets", which have been documented at the Carlin deposit and represent about the end product in these Nevada deposits in the present weathering environment. With more intense chemical weathering, gold moves in solution. Common sites of precipitation include pyrite, larger gold nuggets, and fractures or corners on quartz.

Slide 37 summarizes some of the chemical transfer in soils. Al and Fe are fixed. Na, Mg, K and such are removed in solution. Ca may be removed or reconcentrated during alternating wet-dry cycles to form calcrete: gold often follows Ca to concentrate in the laterite. Alternatively, Au may move downward in oxidizing, acidic waters to precipitate at the redox base of oxidation. Si is leached, either to leave the system in groundwater, <u>or to be redeposited as white quartz veins at depth below the weathering zone.</u>

Slides 38 explains itself. Worth noting that (1) the limit of oxidation is not planar and can extend great distances down fractures, and (2) that gold concentrations in oxidized fractures may represent material introduced to the "vein" from above.

Slide 39. The most well-known garimpo, of course, is Serra Pelada, in Parà. Discovered in 1979, the occurrence was quickly overrun by garimpeiros, with up to 100,000 people thought to be present at the peak – the largest mine in the world at the time. The prize for the garimpeiros were substantial nuggets of gold, some measuring many kilos in weight (the largest reported was 6.8 kg). Interesting and a bit unique for Serra Pelada was the occurrence of wire platinum (ouro preto) with the gold. Digging through the weathered saprolite with hand tools, all the material was carried out manually. The pit measured about 400 meters x 300 meters and reached a depth of about 100 meters. When the miners reached the base of oxidation – the base of weathering and the base of the saprolite – the nuggets were gone and only much lower grade gold remained. In total, the pit produced some 2 million ounces of gold, plus contained Pt and Pd.

Slide 40. In time, the garimpeiros went away and companies have drilled to explore the depths of the system, and the picture revealed has been incredible. We see a central zone of so-called "red siltstone", surrounded by decalcified marble out to unaltered marble. Mineralization is concentrated at the weathering front. The colors indicate gray – carbon; blue – inner silicification; yellow – argillic; pink – outer silicification; gold intercepts shown as red on the drill traces. In those high-grade intervals are found native gold and wire metallic platinum. The geometry of alteration and metal enrichment is striking like that of roll-front uranium deposits.

Slide 41. Summarize: gold is indeed mobile in the natural environment. Laterites cover 1/3 of the current land surface; over geologic time what happens in the soil environment is indeed important.

Slide 42. So what happens if a Carlin-type deposit is exposed to conditions of intense chemical weathering? Newmont had just such a property with the Mesel deposit on the North Arm of the island of Sulawesi in Indonesia. Mesel is considered a CTD because the petrology, mineralogy and geochemistry of the ore is indistinguishable from Nevada ore. The deposit is situated on an active volcanic island. Around the margins of the island are carbonate lagoons and reefs, which occasionally are buried and incorporated into the volcanic edifice. The Mesel deposit is hosted within one of these Miocene-age carbonate packages, at the reactive contact between underlying limestone and overlying andesite tuff.

Slide 43. The mineralized package grades from limestone, to decalcified limestone with pyrite, to silicified limestone, to black goopy pyritic insoluble residue from decalcified limestone, to sulfidized andesite, up to fresh rock. Gold occurs as an impurity in rims on arsenical pyrite.

Slide 44. The deposit outcropped to daylight, so we could walk from primary ore, through the weathering edge, to footwall rock where the deposit has now been removed. When this high-sulfide deposit weathers, it rains sulfuric acid, which dissolved the underlying limestone. The weathered remnants of the deposit are clasts of silicified rock and grains of metallic gold. Some lay on the surface; some accumulated in cave fill; some washed down the river.

At Mesel, as soon as Newmont started exploration and drilling, the locals discovered the residual placer gold accumulations, and the area was overrun by some 10,000 artisanal miners. The company lost the oxide placer part of the deposit, but was able to produce the sulfide.

Slide 45. The cave-fill is fascinating in that it contains pieces of silicified limestone and lots of other surface debris, grains of native gold, and it is cemented by calcite and open-space-filling white quartz.

There are a couple of small gold deposits in eastern Nevada that exhibit similar relationships.

Slide 46. Interesting observations include the occurrence of gold grains in anthracite; the occurrence of crystalline gold in moss mats; secondary growth of gold in placer deposits, and jacutinga in hematite deposits (like 67% Fe, compared to less than 30% in BIF). The jacutinga represents the gold impurity in the chemical sediment BIF, which was mobilized to aggregate as native gold within fractures during the long weathering of the BIF to form specularite ore. (This is on the shield, which has experienced no tectonic or intrusive activity for 1 billion years). I hope I have convinced you that gold is indeed mobile under conditions of intense chemical weathering, and that gold nuggets form in this environment. Recalling that 1/3 of the present surface of the continents is covered by tropical soil, this is an important geologic process.

Slide 47. Return to California. Among the challenging questions of California geology are 1) the origin of the gold in the auriferous gravels, and 2) the origin, uplift and evolution of the northern Sierra Nevada and western Basin and Range. For most of the past century, the high topography of the SN has been thought to be the result of a uplift during the late Cenozoic. As a student, I learned that the SN was a great uplifted westward-tilted fault block, similar to so many other fault block ranges of the Basin and Range. Multiple lines of evidence show that the Sierra Nevada was part of a high topographic feature throughout the Cenozoic, with a broad high-elevation plateau extending to the east. This region of high topography – Nevadaplano – was present from late Eocene through Miocene. Drainages extended from what is now eastern Nevada to the oceanic shoreline in what is now the Great Valley. The river systems depositing alluvium in the Sierra Nevada foothills were sourced in north-central Nevada.

Slide 48. After cessation of Cretaceous magmatism at 80 Ma, the region now the Sierra Nevada underwent significant erosion (5-8 km), over something like 30 million years, creating a pre-Eocene erosional unconformity surface. This surface underwent significant chemical weathering due to a wet, warm Paleogene climate, leading to the development of lateritic soils and intensely weathered basement. On this slide, the north-south color bands outline basement domains of Paleozoic and Mesozoic metamorphic and magmatic rocks. These are unconformably overlain by Tertiary and Quaternary rocks.

Slide 49. The Eocene auriferous fluvial gravels were deposited on the sub-Eocene unconformity. The Eocene auriferous gravels are in turn overlain by Oligocene rhyolite ignimbrite and volcaniclastic fluvial sediments. The Ione Formation is the coastal equivalent of the Tertiary fluvial gravels.

Slides 50-52. Researchers have completed significant sedimentological work on the auriferous gravels. I want to highlight four key observations:

1. The auriferous gravels contain clasts of lithologies that do not occur on the west slope of the Sierra Nevada, but are consistent with sources in western Nevada.
2. The auriferous gravels exhibit alteration characteristic of extreme chemical weathering, both before transport and after deposition; (Slide 50)
3. Detailed chemical, petrological and geochronological study indicates the rhyolite ignimbrites were sourced further east in what is now central Nevada, over 200 km distant. We know that ignimbrites form

high density flows that ramp against rather than overflow topographic barriers; there was no topographic barrier between central Nevada and Western California in Oligocene (Slide 51)

4. Hydrated volcanic glass from these ignimbrites preserves δD of Oligocene meteoric water, and meteoric water carries the isotopic signature of elevation. This measure shows a steep elevation gradient from west to east across the SN, with a lower gradient to the east across Nevada. (Slide 52)

Slide 53. We still do not know the precise source of the alluvial gold, but the possible connection to the great gold province of Northern Nevada opens possibilities. Confirmation of the tropical weathering environment at the time of erosion and deposition provides a mechanism to create nuggets of gold from disseminated microscopic gold in Nevada. These may have been Carlin-type deposits, or perhaps there were once volcanic rock-hosted gold deposits such as Yanacocha or Pierina over the Cretaceous arc.

Slides 54-55 present my simplified conceptual model for the development of the auriferous gravels of northern California in four time periods. The setting of the California Tertiary placers at the base of the Nevadaplano, is the mirror image of the gold placers of the Madre de Dios or Tipuani regions of Peru and Bolivia on the eastern base of the Altiplano.

Slide 56. Shifting north, we can imagine a similar history for the Yukon. This is now an area of Arctic climate, in which physical weathering is far more significant than chemical weathering. In the Tertiary, however, the climate was much warmer and humid. Alaska, of course, exports coal of Cretaceous- and Tertiary age. The vegetation in the coal is largely coniferous, so the interpreted climate was not tropical, but this was an area of intense chemical weathering beneath lush vegetation.

In many locations in Alaska and the Yukon, there are remnant auriferous alluvial deposits now stranded on high ridges and drainage divides that are being eroded and recycled into the modern streams. The morphologies of the paleochannels demonstrate much different drainage patterns than presently exist. Again – one cannot casually assume that the presence of placer gold in a stream is a reliable indication that the current drainage basin contains a primary bedrock gold deposit. But I can also tell you that I have told this story to many geologists in Alaska, and many do not believe me. Even as geologists, we have a difficult time imagining this cold mountainous terrane with lush warm-weather vegetation. The weathered residue has been largely removed by glaciation or physical weathering.

Slide 57. It is the unique chemical behavior of gold that has permitted formation of placer deposits. The most noble of metals is mobile in the local chemical conditions of the soil biogeomembrane: widely dispersed gold can aggregate to form nuggets during chemical weathering. Once released to the surface environment, however, these nuggets are both chemically and physically stable, and can be recycled in alluvial or beach environments through multiple erosion cycles. The earth has a long history – the landscape and climate have changed and continue to change. That is the story that gold nuggets tell.

The gold deposits in California are there because the hydraulics of the Tertiary streams favored deposition – the suture zone was also the break-in-slope at which the streams dropped their coarse sediment. One can make the same argument for the Yukon, except that post-Tertiary deformation has been so significant that it is difficult to reconstruct past topography.

Slide 60. Now there are some nuggets to think about…..