Laurentian SEG Student Chapter International Field Trip 2018:

Southwestern USA

February 15th-28th, 2018
Field Guide

Organized by Natascia Zuccarelli (LU-SEG President) and
Dylan J. McKevitt (LU-SEG Vice President)

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List of Participants

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Daniel Kontak	Canadian	Professor, Laurentian University

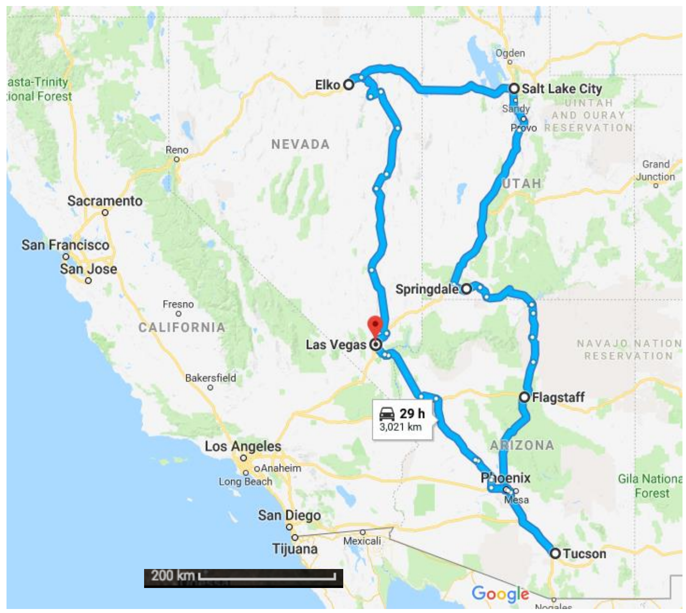
Itinerary

Day 1 (Feb 15):
Travel from Toronto to Las Vegas, NV (Night in Las Vegas)

Day 2 (Feb 16):
Travel to Carlin Trend, Geology stops en route (Night in Elko)

Day 3 (Feb 17):
Tour of Cortez Hills Mine, Barrick Gold (Night in Elko)

Day 4 (Feb 18):
Tour Leeville Mine, Newmont (Night in Elko)



Day 5 (Feb 19):
Tour of Gold Quarry Mine, Newmont.
(Night in Salt Lake City)

Day 6 (Feb 20):
Day in the Tintic District, University of Utah prof, Dr. Erich Petersen
(Night in Salt Lake City)

Day 7 (Feb 21):
Tour of Bingham Canyon, Rio Tinto
(Night in Salt Lake City)

Day 8 (Feb 22):
Travel to Springdale, UT. Bryce Canyon en route (Night in Springdale)

Day 9 (Feb 23):
Day in Zion National Park (Night in Springdale)

Day 10 (Feb 24):
Travel to Flagstaff, AZ. Grand Canyon en route (Night in Flagstaff)

Day 11 (Feb 25):
Travel to Tucson. Geology stops en route (Night in Tucson)

Day 12 (Feb 26):
Tour of Ray Mine, Asarco (Night in Tucson)

Day 13 (Feb 27):
Tour of Kartchner Caves (Night in Tucson)

Day 14 (Feb 28):
Travel from Tucson to Las Vegas (Night in Las Vegas). March 1st morning flight to Toronto.

Contact Numbers

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Feb 15th Flight: Toronto-Detroit (DL6211), Detroit-Las Vegas (DL1490)
March 1st Flight: Las Vegas-Salt Lake City (DL0926), Salt Lake City-Toronto (DL2797)

Canadian Embassy: **Washington (**1-844-880-6519**), Denver (**1-844-880-6519)

Hotels

Luxor Hotel (Las Vegas, NV)
3900 S Las Vegas Blvd, Las Vegas, NV 89119, USA (+1 702-262-4000)

Best Western Elko (Elko, NV)
1930 Idaho St, Elko, NV 89801, USA (+1 775-738-8787)

Metropolitan Inn (Salt Lake City, UT)
524 S W Temple, Salt Lake City, UT 84101, USA (+1 801-531-7100)

Holiday Inn Springdale (Springdale, UT)
1215 Zion – Mount Carmel Hwy, Springdale, UT 84767, USA (+1 435-772-3200)

Comfort Inn Lucky Lane Flagstaff (Flagstaff, AZ)
2480 E Lucky Ln, Flagstaff, AZ 86004, USA (+1 928-774-7701)

Riverpark Inn (Tucson, AZ)
777 W Cushing St, Tucson, AZ 85745, USA (+1 520-239-2300)

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Sponsors

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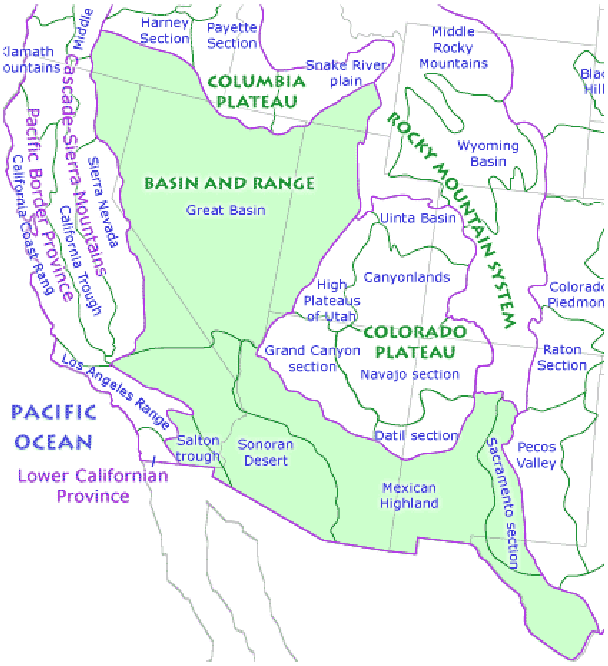
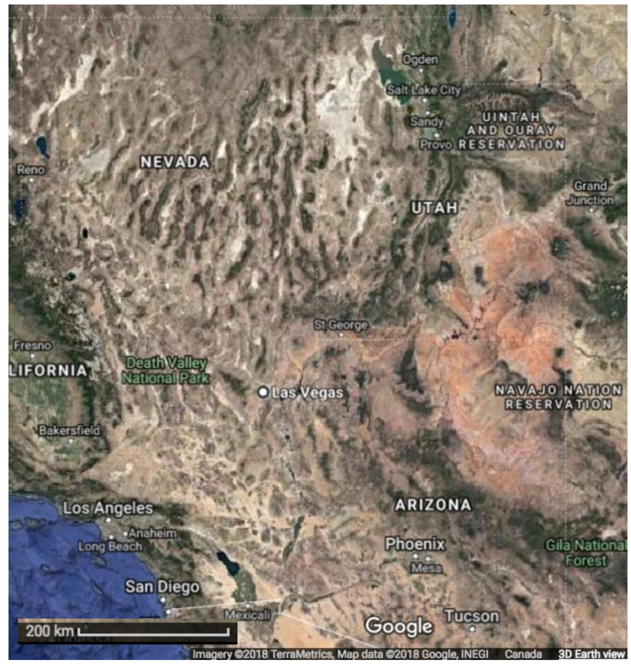
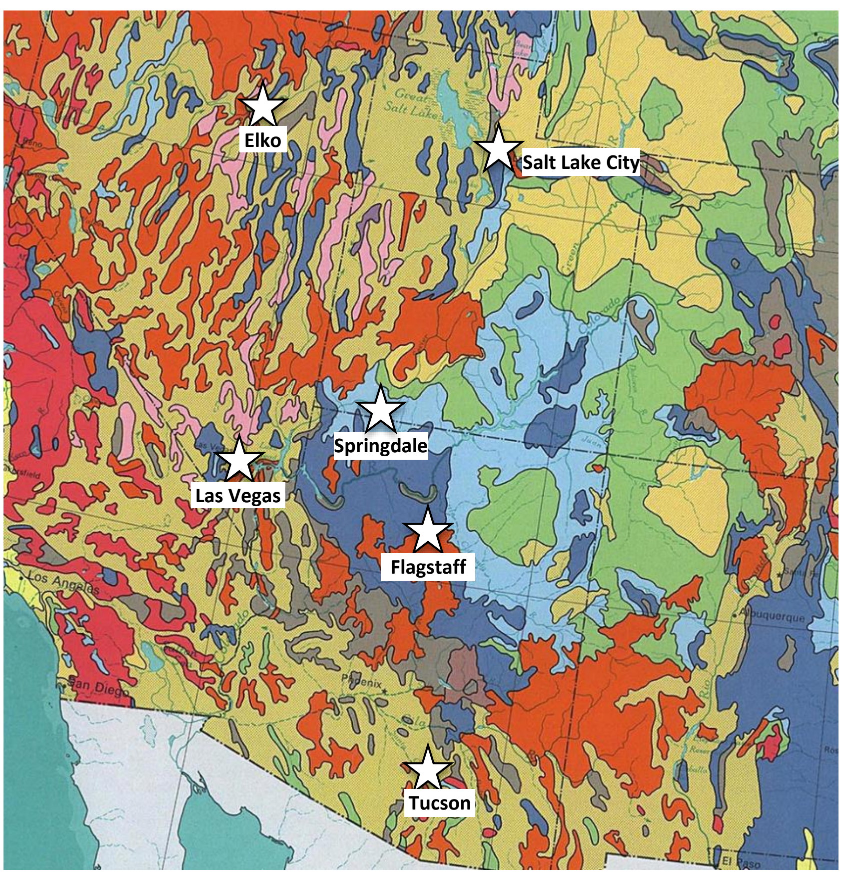
Overview Maps

Major Geological Provinces of the SW USA/Satellite image of SW USA

(USGS, 2018/Google Earth, 2018)

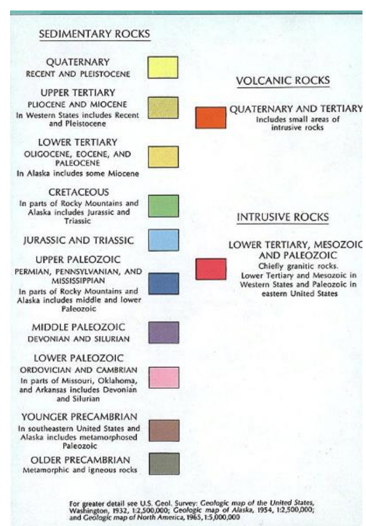






Geologic Map: SW USA

(USGS. 1966)



Geologic History of the SW USA

(From Ronald C. Blakey, 2013. *Paleography of Southwestern North America*. Deep Time Maps map series. Colorado Plateau Geosystems Inc.)

1. **Early Paleozoic passive margin of Western North America** — the edge of the continent ran north-south through central Nevada; ocean crust lay to the west.

2. **Devonian incursion of fast-moving arc systems, possibly from both the SW and NW;** these arcs transported exotic terranes originally sourced from Gondwana, Baltica, and the Caledonian region of the Iapetus Ocean.

3. **Late Devonian-Mississippian terrane accretion (Antler orogen)** and evolution of Western North America into an active tectonic margin.

4. During the **late Paleozoic and early Mesozoic, a series of arcs, probably both west- and east-facing, were along the western margin of the continent;** some of these arcs, with both exotic and peri-North American terranes, accreted to the western margin during the Permo-Triassic Sonoman orogen.

5. **Triassic establishment of Cordilleran magmatic arc — along the southern margin of the continent, the arc was built on Proterozoic North American crust —** an Andean-style arc. Farther north, the arc was built on fringing terranes as one or more complex island arcs.

6. The exotic **greater Wrangellia terrane (aka Insular Superterrane) drifted towards North America from the west and initially collided and amalgamated with the fringing island arcs in the Middle and Late Jurassic.** The resulting block, commonly referred to as Baja BC, then accreted to the western margin of the continent in the Late Jurassic and Early Cretaceous. Some of these events were responsible for the Late Jurassic Nevadan orogen and perhaps initiated the Cretaceous Sevier Orogen.

7. The ensuing **plate reorganization and renewed subduction beneath western North America resulted in the oblique, left-lateral subduction of the oceanic Farallon Plate.** The left-lateral **transpression drove Baja BC southward along the Pacific margin.** The model presented in these maps follows a moderate translation interpretation in which the southern margin of Baja BC reached the approximate lattitude of Central California by the Late Cretaceous.

8. **During the Cretaceous, huge portions of the Farallon Plate were subducted below SW North America. The great batholiths of the Peninsular Ranges, Sierra Nevada, Idaho Batholith, and Coast Plutonic Complex were generated.** Resulting compression formed the Sevier Thrust Belt and caused significant compression of the western continent.

9. **Between 85 Ma and 70 Ma, a large fragment of an inactive ocean ridge was subducted beneath the southern portion of the map region.** The resulting reorganized subduction shifted to right-latteral transpression. The subducted and thickened ocean crust wrecked havoc with SW North America and eventually **shut down normal Cordilleran subduction and replaced it with shallow subduction, generated widespread regional metamorphism and uplift, and caused uplift of the Central and Southern Rocky Mountains and Colorado Plateau.** These events persisted well into the Neogene.

10. In the **mid Cenozoic, the western margin of the Farallon Plate, the East Pacific Rise, drifted towards SW North America.** As collision and subduction occurred, the resulting shift in plate dynamics caused right-lateral transform faulting and extension of SW North America. **During the Neogene, these complicated events generated the Basin and Range, resulted in widespread volcanism, created the San Andreas Fault system, and resulted in capture and NW translation of parts of the margin of the continent by the Pacific Plate**. These tectonic conditions persist into the present.

PART ONE: The Geology of Northern Nevada (February 15th-19th)

February 15th-16th: The Basin and Range

(USGS, 2018)

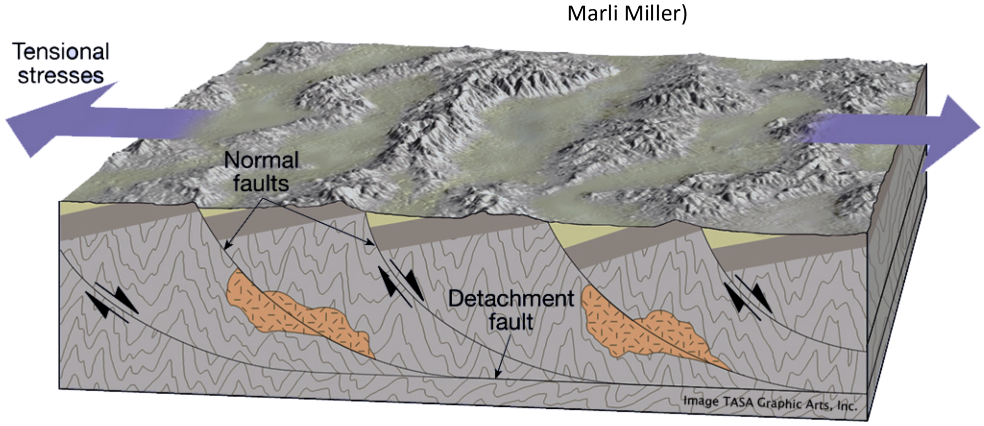
The Basin and Range province has a characteristic topography. Steep climbs up elongate mountain ranges alternate with long treks across flat, dry deserts. This basic topographic pattern extends from eastern California to central Utah, and from southern Idaho into the state of Sonora in Mexico. The forces which created this distinct topography lie deep beneath the surface.

Within the Basin and Range Province, the crust (and upper mantle) has been stretched up to 100% of its original width. The entire region has been subjected to extension that thinned and cracked the crust as it was pulled apart, creating large faults. Along these roughly north-south-trending faults mountains were uplifted and valleys down-dropped, producing the distinctive alternating pattern of linear mountain ranges and valleys of the Basin and Range province.

Although there are other types of faults in the Basin and Range province, the extension and crustal stretching that have shaped the present landscape produce mostly normal faults. The upthrown side of these faults form mountains that rise abruptly and steeply, and the down-dropped side creates low valleys. The fault plane, along which the two sides of the fault move, extends deep in the crust, usually an angle of 60 degrees. In places, the relief or vertical difference between the two sides is as much as 10,000 feet.

As the rocky ranges rise, they are immediately subject to weathering and erosion. The exposed bedrock is attacked by water, ice, wind and other erosional agents. Rock particles are stripped away and wash down the mountain sides, often covering young faults until they rupture again. Sediment collects in the adjacent valleys, in some places burying the bedrock under thousands of feet of rock debris.

Aerial view of the basin and range province. (Photo taken by Marli Miller)



Geology of the Basin and Range province (TASA Graphic Arts for the USGS, 2014)

February 17th-19th: The Carlin Trend

(From "Carlin-type gold deposits of Northern Nevada" - SEG Carlin Trend SFT Field Guide, 2017, Guidebook Vol. 56 by Jean Cline and John Muntean, Borden Putnam, Rael Lipson, and Ryan Taylor)

General Geology

Geologic History of the Carlin Trend

The Carlin Trend is located along the **rifted western margin of North America as defined by initial Sr 0.706 isotope isopleth of Mesozoic and Tertiary igneous rocks (Elison et al., 1990).** Rifting during the Neoproterozoic caused passive margin formation of a westward thickening sequence comprising an eastern assemblage of terrigenous clastic rocks with overlying miogeoclinal carbonate rocks and a coeval western assemblage of eugeoclinal siliciclastic rocks to the west.

During the early Mississippian Antler orogeny, pre- and coeval Mississippian eugeoclinal rock sequences in the west were thrust to the east, overriding the eastern facies miogeoclinal rocks forming the Roberts Mountains thrust fault. **Contraction continued in response to additional compressional orogenic events during late Paleozoic and Mesozoic time with related deformation providing important structural preparation of potential host rocks.** Structural studies along the Carlin Trend have identified an early extensional phase of deformation along the North American passive cratonic margin, followed by three compressional events:

1. **Antler Orogeny:** The Roberts Mountains thrust fault, which formed by eastward-directed thrusting inversion during Mississippian times.

2. **Paleozoic and Jurassic age folding** associated with west- to west-northwest–dipping reverse faults, probably formed during east- to southeast-directed deformation.

3. **Late Mesozoic or early Tertiary Laramide-style deformation** and later Cenozoic events forming upright north-to northwest-trending folds and northwest-trending reverse faults by reactivation of the early extensional structures.

Tectonism changed in the late Eocene, related to interactions at the western North American plate boundary and changes in crustal plate tectonic motions, with the long-term E-W compressional regime transitioning to a west-northwest–directed tension such that north-northeast and approximately north-south striking faults and fractures were opened along the Carlin Trend.

Interpretations of the plate tectonic history of the western North American plate boundary suggest that **subduction of the Farallon plate and its associated spreading ridge changed the western US continental margin from simple compression to a transpressional regime** with development of right-lateral faulting along the North American plate boundary (San Andreas fault, etc.) and inboard widespread extension in the western US and Basin and Range, in particular (Atwater, 1970; Irwin, 1990; Wallace, 1990). Atwater has proposed the possibility that **the entirety of the western US may have acted as a broad transform fault/ transtensional accommodation zone, along the lines of ideas first put forth by Carey (1958), Wise (1963), Hamilton and Myers (1966), and Hamilton (1989). At about the same time, a belt of calc-alkaline magmatism swept through Nevada, from northeast to the southwest, in response to the foundering of the Farallon plate.**

Eocene extensional faulting followed these contractional events and is associated with gold mineralization. Mineralization ages determined for Carlin deposits show they are synchronous with this southwest sweep of magmatic activity and initial extension.

The net result of this tectonostratigraphic history is an ideal structural geometry in which **ore fluids were channeled into favorable stratigraphy and stratigraphic/formational contacts via structural culminations by multiple generations of major structures dipping away from a central fault network in the core of the Carlin Trend**, promoting fluid-rock reaction in receptive lower-plate rocks. Mineralization was particularly enhanced at intersections of all features that increase porosity and permeability, including ideal host rocks and structures, particularly those striking north-northwest and northeast, silicified zones, dike contacts, sedimentary contacts, bedding, and lithologic contacts within beds.

Carlin-type Gold Deposits

Carlin-type gold deposits are largely replacement bodies with visually subtle alteration dominated by decarbonatization and silicification of silty carbonate host rocks, and they contain Au in solid solution or as submicron particles in disseminated pyrite or marcasite. The deposits occur in clusters and along trends, are generally stratiform and conform to bedding of altered units, but exhibit both structural and stratigraphic controls. High-angle faults acted as feeders for ore fluids to access favorable (permeable and reactive) stratigraphy and stratigraphic traps (aquitards provided by less permeable facies above unconformities, thrust faults. Three environments of sedimentation are favored for deposition/creation of favorable facies and sequence stratigraphy:

1. **Unconformities** which cap sea-level lowstand sedimentary sequences are favored, where variably karsted tops (dolines) on carbonate sequences are first overlain by receptive, fine-grained, calcareous and noncalcareous wackestones and mudstones as sea level rises (Cook, 2015; Smith and Cook, 2015). Where present, the karst itself may not be extensively mineralized, though it clearly played a role in fluid flow; hydrothermal dissolution collapse breccias are increasingly found associated with mineralization in many deposits.

2. **In sediments from deeper water settings** where carbonate debris flows and turbidites shed off the carbonate platform/reef margin were deposited during high stand conditions.

3. **Where fine-grained calcareous and noncalcareous siltstone** and mudstones overlie the downslope mass-transported units in lowstand environments—both the debris flows and turbidites and the overlying fractured fine-grained facies are potential host rocks.

The “classic” Carlin-type gold deposits are the stratigraphically controlled end-member of a broad spectrum of occurrence types which includes large collapse breccia-hosted deposits, formed by extensive decarbonatization of favorable host rocks adjacent to structural conduits (e.g., Betze-Post, Goldbug, and Genesis) and replacement deposits in fine silty calcareous units resting atop unconformities. Carlin- type deposits can be seen to be opportunistic; ore-forming fluids make almost passive use of high- and low-angle structures and unconformities as conduits for their passage, moving into structural highs—fault blocks or anticlines—and reacting there with receptive facies forming replacement deposits within host strata. This spectrum of deposit types produces remarkable contrasts in orebody geometry, tonnage, grade, host rock, structural orientation, hydrothermal alteration, geochemistry, metallurgy, hydrology, and ground conditions, and has wide-reaching implications for exploration, mining, and processing.

Carlin Trend Stratigraphy and Mineralization

Disseminated gold deposits along the Carlin Trend are hosted in the north by lower-plate carbonate strata of the Devonian-Silurian Roberts Mountains Formation, Devonian Popovich Formation, and Rodeo Creek Formation and in the south by the Devonian-

Mississippian transitional Web Formation. Host rocks are composed of silty limestone with intercalated biogenic debris that were deposited along the western margin of ancestral North America. Late Silurian to Middle Devonian biohermal to carbonate shoal accumulation (Bootstrap limestone) occurred over a period of 50 to 100 million years in the northernmost Carlin Trend. Subaerial exposure and erosion shed bioclastic debris with fan-like geometry, producing thick sequences of proximal, upper slope fossiliferous debris flows that are mineralized in the Meikle, Goldbug, and Betze-Post deposits, and mid-slope silty facies at the Blue Star-Genesis and Carlin deposits. Bioturbated wavy ("wispy") laminated silty limestone of the upper Roberts Mountains Formation provides the most favorable host rock on the northern Carlin Trend, containing 65% of the gold resource in about 400 ft (120 m) of the stratigraphic section.

Gold deposits of the northern Carlin Trend are predominantly exposed near the fault-bounded margins of the uplifted Lynn and Bootstrap structural windows. Flanking these Paleozoic windows are deep, northerly trending basins filled by post-mineral Tertiary volcaniclastic sediments and gravels. Tectonic uplift and erosion have exposed autochthonous carbonate strata beneath the Roberts Mountains thrust.

The central portion of the northern Carlin Trend is intruded by a large, Late Jurassic granodiorite intrusion (Goldstrike stock) and numerous Eocene rhyolite to dacite dikes. Two of the highest-grade gold deposits on the Carlin Trend, Deep Star and Deep Post, occur along the sheared margins of the Goldstrike stock, and most of the gold deposits occur within 2 mi (3 km) of the stock along the dike-filled Post-Gen fault zone. It is inferred that Eocene magmatism is the major process that drove hydrothermal circulation forming Carlin gold deposits. Gold deposits represent a continuum of styles from stratiform, permeability- controlled end members (e.g., Carlin, West Leeville, Pete, and Tara) to shear zone-hosted end members (e.g., Deep Star, Deep Post, and Meikle).

Carlin Trend Mineralization Process

Carlin mineralization formed by sulfidation when bisulfide-complexed Au in acidic ore fluids reacted with and dissolved receptive carbonate host rocks, exposing available reactive Fe and pyrite. Sulfur in the ore fluid reacted with available Fe, forming pyrite rims on exposed preexisting pyrite cores. Gold ions and other trace element cations in solution were attracted to the locally negatively charged pyrite surfaces exposed in host rocks and were "captured" by rapidly precipitating ore pyrite rims.

Deuterium and oxygen isotope studies of minerals and fluid inclusions at the Getchell deposit have identified a deep magmatic or metamorphic ore fluid. However, similar studies at other deposits on other trends and districts have identified only meteoric fluids, although some isotopic studies of alteration minerals there have identified magmatic/metamorphic fluids.

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Smith, M.T., and Cook, H.E., 2015, Carlin on the Shelf? A Review of Sediment-Hosted Gold Deposits and Their Settings in the Eastern Great Basin [abs.], in Pennell, W.M., and Garside, L.J., eds., New Concepts and Discoveries: Reno, NV, Geol. Soc. of Nevada Conference Volume, May 2015.
Teal, L., and Jackson, M., 2002, Geologic Overview of the Carlin Trend Gold Deposits, in Thompson, T.B., Teal, L., and Meeuwig, R.O., eds., Gold Deposits of the Carlin Trend: Nevada Bureau of Mines and Geology, v. 111, p. 9–19.

February 17th: Geology of the Cortez Hills Mine (Barrick Gold)

The geological setting of the Cortez District is identical to that of the northern Carlin Trend – more so than that of any other Carlin-type deposits worldwide. It is identical in both its geographic location and geological history of formation.

Cortez Hills is near the historic center of the Cortez District, adjacent to the exhausted Cortez open-pit mine. **The deposit consists of three zones of mineralization: the open-pit breccia zone; the underground Lower zone; and the Pediment zone resource, comprised of transported eroded breccia zone mineralization which was deposited in recent pediment gravels.** Across Crescent Valley from Cortez Hills is the Pipeline open pit mine, adjacent to the historic Gold Acres mine. Combined, the Cortez Hills and Pipeline contain proven and probable reserves of 151 Mt grading 2.11 g/t Au for 10.2 Moz; measured and indicated resources total an additional 31 Mt grading 2.12 g/t Au for 2.1 Moz.

Jurassic igneous activity in the district variably altered and mineralized the Silurian-Devonian Roberts Mountains and Devonian Wenban Limestone prior to the Carlin-style mineralization event. Late Basin-and-Range faulting has juxtaposed the formations in the Cortez Canyon. **The Mill Canyon stock was important in generating widespread Ag and base-metal mineralization and alteration in mantos** and less important fissure veins, forming one of the earliest bonanza-Ag mining camps in Nevada. Associated alteration related to this early mineralizing phase includes tremolite porphyroblasts that are widespread and abundant in Cortez Hills host rocks. A ~104 Ma quartz monzonite intrusion has been identified only in drill holes, and sits ~4 km west of the Cortez Hills breccia body.

Carlin-type mineralization in the Cortez District occurs at **many positions throughout the stratigraphic column, where porosity and permeability are enhanced and within receptive (reactive) facies**; the Wenban and Horse Canyon Formations are correlative with the Popovich and Rodeo Creek Formations, respectively, along the Carlin Trend. The Cortez Hills breccia zone contains high-grade ore within a widening-upward funnel-shaped breccia pipe which has an interior of high-grade polylithic breccia with juxtaposed clasts that have highly varied alteration, grade, and degree of oxidation, and a central zone of rotated breccia developed within an outer monolithic crackle breccia. **Gold grade is generally highest in the central breccia zone.** Breccia clasts range from micron scale to blocks of micrite 20 m in size. Most of the rocks in the breccia zone are oxidized to hematite, goethite, jarosite, and other unidentified oxide and arsenate minerals.

Observations of orebody characteristics during mining are consistent with a carbonate dissolution and collapse brecciation event with upward stoping of the brecciation through the calcite-rich Devonian Wenban Formation, up to the Upper Devonian Horse Canyon formation contact which contains less carbonate to react with the dissolution fluids. Mineralization in the

Carlin Trend General Overview: Figures

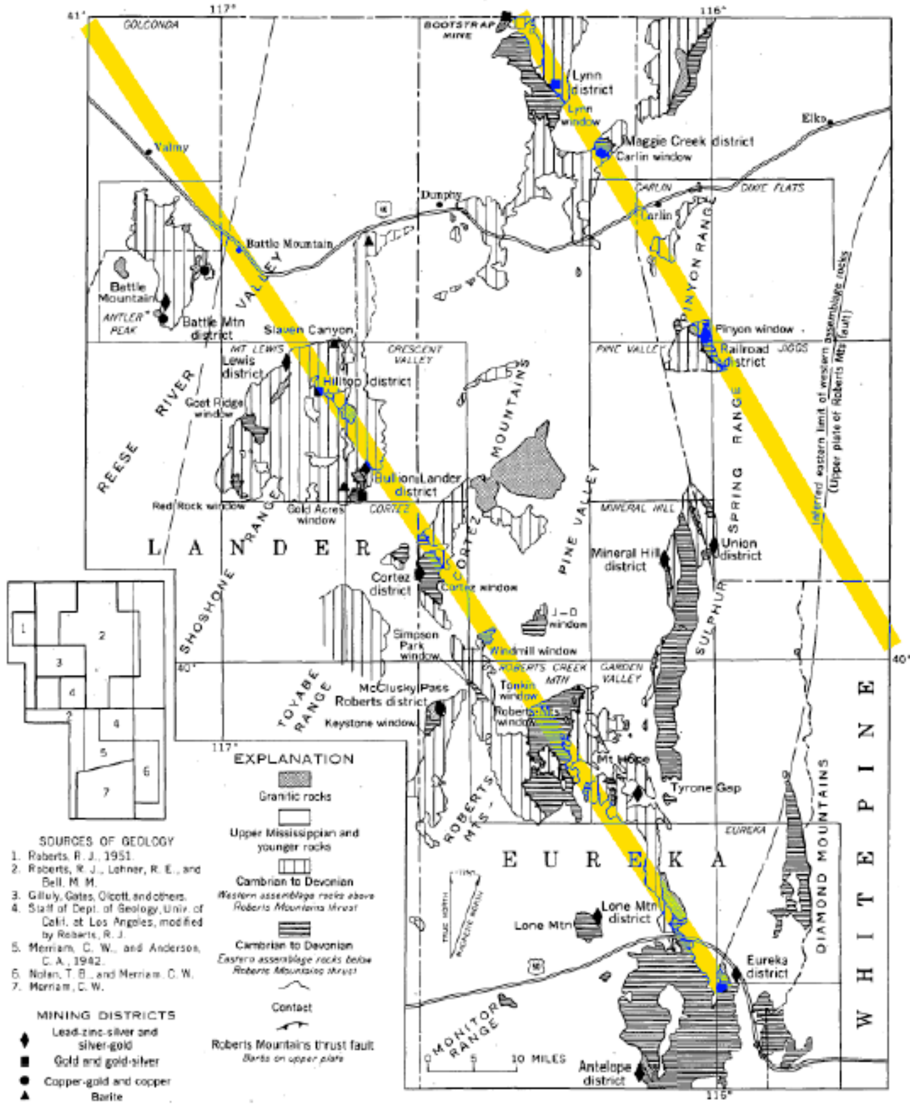

Figure 1-3. Map showing northwest alignment of mineral districts, distribution of Paleozoic facies and granite rocks in north central Nevada (*modified after* Roberts, 1960). Carlin (right) and Cortez (left) Trends shown.

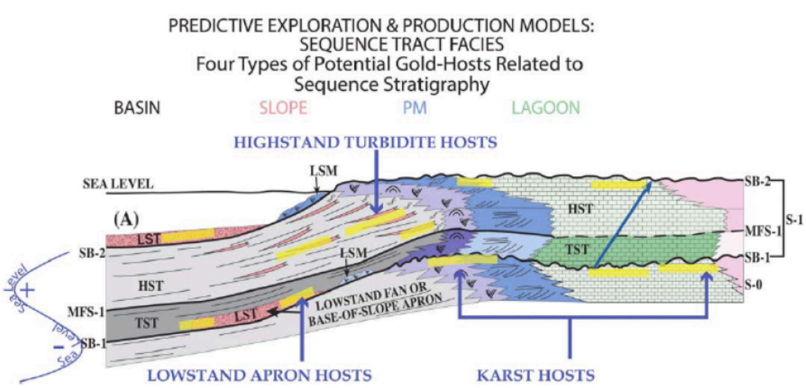

Figure 1-15. Predictive exploration and production carbonate gold host models utilizing carbonate sequence stratigraphy principles (Cook, 2015).

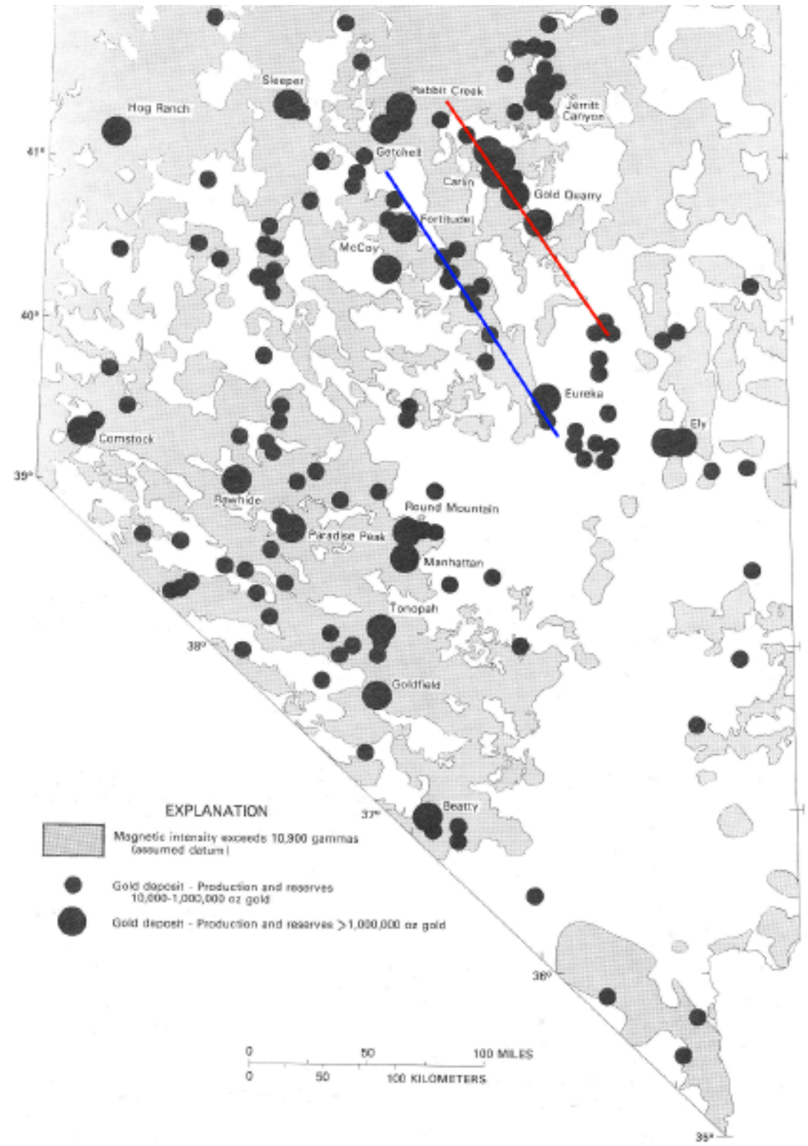

Figure 1-1. Map of Nevada showing distribution and relative size of significant gold deposits, and areas of magnetic intensity greater than 10,900 gammas (*modified after* Shaw, 1990). Carlin Trend is shown in RED; Cortez (Battle Mountain-Eureka) Trend in BLUE.

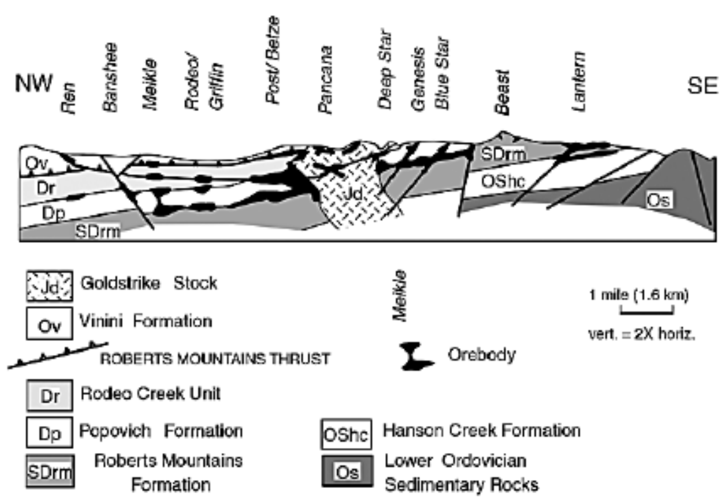

Figure 1-11. Simplified long-section (northwest-southeast) of the northern Carlin Trend, showing Carlin-type deposits, Jurassic Goldstrike stock, cap rocks (Rodeo Creek unit and Vinini Formation), major structures, favorable stratigraphy (Popovich and Roberts Mountains Formations), and absence of deep roots below the deposits (Hofstra and Cline, 2000).

breccia zone is primarily in The Devonian Wenban Formation, with some ore in underlying Silurian Devonian Roberts Mountains Formation. Ore in the Lower zone occurs along the low-angle Ponderosa duplex fault zone that duplicates much of the stratigraphic section in thin thrust slices. Mineralization is localized where this faulting intersected a steeply dipping rhyolite dike swarm in Ordovician Hanson Creek Dolomite and Silurian Devonian Roberts Mountains Formation to the base of the Wenban Formation.

The Cortez Hills deposit formed in response to fluid-rock reaction at temperatures <260ÅãC during a single heating and cooling event coincident with regional magmatism, and over a relatively short geologic timeframe. As the hydrothermal system collapsed and cool meteoric water infiltrated the deposit, the ore stage transitioned to the late-ore stage, which contains significantly decreased gold in pyrite with modified trace element chemistry. Late-ore stage pyrites no longer consistently contain gold and they exhibit less strongly associated Tl, Hg, and Cu, but contain relatively abundant Pb and Sb (Table 6-4). Sulfosalt minerals appear during this stage and initially include relatively uncommon aktashite and christite, Cu-Hg– and Tl-Hg–rich sulfosalt minerals, respectively. These minerals formed as late-ore fluid temperatures declined and sulfide mineral stability gave way to stable sulfosalt minerals. Over time, as available Cu, Hg, and Tl diminished, realgar became the dominant sulfosalt mineral that both replaced some earlier- formed aktashite and christite as well as precipitated in open space.

Geologic relationships and mineral and geochemical analyses at Cortez Hills indicate that the breccia zone and late ore stages formed in response to the following sequence of geologic events and processes:

1. **Burial diagenesis and low-grade contact metasomatism** related to the intrusion of either the Jurassic Mill Canyon stovk and/or the poorly exposed Cretaceous 104 Ma quartz monzonite produced an assemblage of minerals in Silurian-Devonian Roberts Mountains and Devonian Wenban Formation host rocks that include dickite, tremolite, clinochlore, sphalerite, chalcopyrite, marcasite, and pyrite containing trace As, Pb, Sn, Co, Bi, and S, and recrystallized calcite.

2. During the Eocene, **ore fluids accessed the Voodoo fault,** reacted with and sulfidized silty limestone in the Roberts Mountains, Wenban, and Horse Canyon Formations and produced Au-bearing pyrites that generally contain relative abundances as follows: As >> (Tl, Hg, Cu) > Au >> Ag in the Cortez Hills breccia zone. Ore fluids also replaced host-rock minerals, including dickite, calcite, dolomite, tremolite, and clinochlore, with an ore assemblage consistently composed of jasperoid, illite, and ore pyrite.

3. **Illite replaced dickite, tremolite, and clinochlore**, and minor illite precipitated in open space primarily between ~227Åã and 277ÅãC, consistent with accepted temperatures of deposit formation.

4. Where mineralization was intensely developed, the **ore fluids altered the host rocks and formed local replacement breccia with a matrix of illite, jasperoid, and pyrite** which contains “clasts” of non-interconnected jasperoid crystals and relict calcite. Less intensely altered and mineralized rock contains greater relict host carbonate rock.

5. The **cooling and collapse of the hydrothermal system initiated the late-stage mineralization** and accelerated decalcification and collapse breccia formation owing to the coupled effects of cooling by meteoric water incursion and the retrograde solubility of calcite, which combined to form a dissolution collapse breccia.

6. **The collapse of the hydrothermal system coincided with initial precipitation of Evolved**

Ore Pyrites (EOP) which contain variable to no measurable Au, elevated and associated Pb and Sb, elevated Cu, and less well correlated Tl, Hg, and Cu.

7. **System cooling drove the mineral stability transition** from sulfide to sulfosalt with initial localized precipitation of aktashite ($Cu_6Hg_3As_4S_{12}$) and christite ($TlHgAsS_3$) that, as Tl, Hg, and Cu from the hydrothermal fluid and rock package were consumed, evolved to realgar-dominant precipitation.

8. Over time, and as the concentrations of Au, Tl, Hg, and Cu in the ore fluids diminished**, realgar partially replaced christite and aktashite. Calcite and realgar partially cemented the hydrothermal dissolution collapse breccia, and brecciation ceased by the end of the late ore stage** as the chemistry of the final hydrothermal fluid was dominated by As.

9. Ore and alteration mineral textures and chemistries demonstrate that the Cortez Hills breccia formed during a **single hydrothermal heating event, coincident with local magmatism at ~35.8 to 35.4 Ma, followed by cooling and system collapse.** This observation is consistent with a potentially brief duration of deposit formation of less than ~45,000 to 15,000 yrs, as suggested by numerical modeling for the giant Betze-Post deposit on the Carlin Trend.

10. **Late or post-ore precipitation of calcite-only veins signaled the end of the precipitation of sulfide- bearing minerals.**

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February 18th: The Geology of Leeville Mine (Newmont)

The Lynn District

In 1907, small-scale gold placer mining began along Lynn Creek, which ultimately led to discovery of **a series of narrow auriferous quartz veins approximately 1 mile north of the present-day Carlin orebodies**. These veins were developed as the Big Six Mine, located just east of Leeville and achieved maximum annual production of about 500 oz Au between 1935 and 1936.

The main Carlin orebodies to the south were discovered in 1962 and were mined until 1987. In **1992 and 1993, Newmont identified the Leeville Corridor, a zone along 340Åã azimuth of favorable structure and stratigraphy extending approximately 1.5 miles northwest from the Carlin deposit** which hosts an extensive zone of high-grade gold mineralization at depths of 1,500 to 2,000 ft. Additionally, Newmont recognized that N10ÅãE striking faults, such as the Hardie and Lynn faults, are important controls to mineralization.

The West Leeville deposit is **bound to the west by the West Bounding fault,** which dips 60Åã west and marks the western boundary of the Leeville Corridor. In 2002, the deposit contained a drill indicated resource of 3.2 Moz of Au, in 7.3

Cortez Hills Mining District: Figures

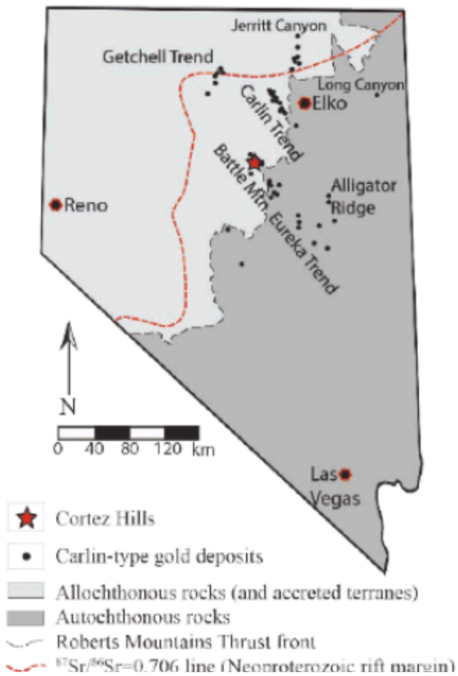

Figure 6-2. Location of major Carlin-type gold trends and districts in Nevada, western United States. Shaded in greys are allochthonous (western facies), and autochthonous (eastern facies) rocks of the Roberts Mountains thrust. Location of the Cortez District is shown with a red star (Maroun et al., 2017).

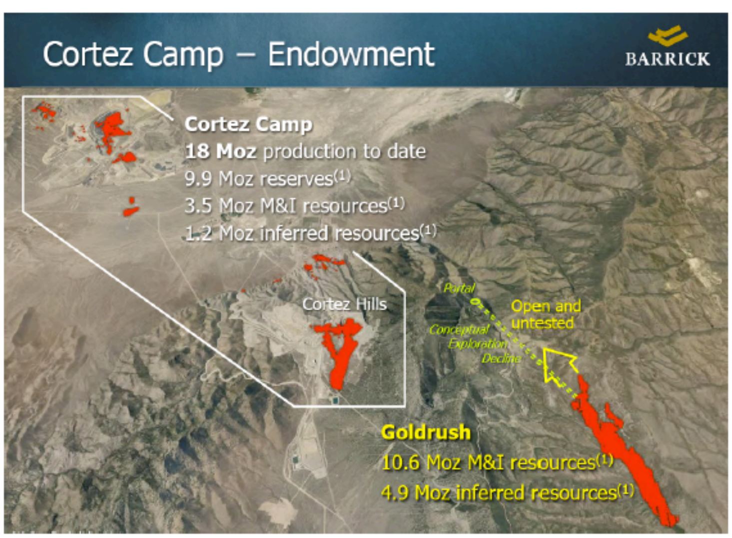

Figure 6-13. Cortez Camp – endowment (Barrick, 2015)

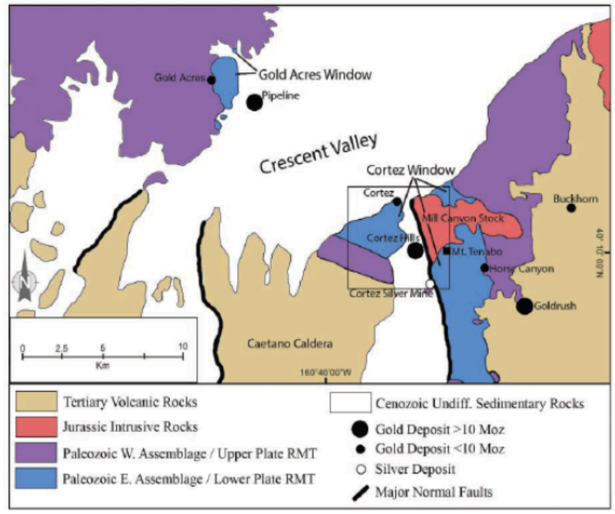

Figure 6-3. General geology of the Cortez District, showing locations of gold and silver deposits, and the lower- and upper-plates of the Roberts Mountains thrust (Maroun et al., 2017). Black frame is the area of Fig. 6-6.

Table 6-1. Cortez complex Reserves and Resources (Barrick, 2017).

Barrick Gold - Reserves and Resources

2016		Tonnes (x1000)	Grade, Au (g/t)	Ounces (x1000)
Cortez Hills and Pipeline (100%)				
Reserves	Proven	16,196	1.52	793
	Probable	134,806	2.18	9,427
	P+P	151,002	2.11	10,220
Resources	Measured	2,199	2.04	144
	Indicated	29,137	2.13	1,999
	M+I	31,336	2.12	2,143

Reserves calculated using the following gold prices: US$1,000 (2017-2020); US$1,200 (2021-onwards)
Reserves calculated using the following silver prices: US$13.75 (2017-2020); US$16.50 (2021-onwards)
Various cut-off grades are used depending upon the type of mine, its maturity, and ore type
Resources calculated using US$1,500 gold price, and US$18.75 silver price
Mineral resources are in addition to mineral reserves (exclusive)
(Barrick, 2017)

Reconciliation of 2016 to 2015 Declarations

		Tonnes (x1000)	Grade, Au (g/t)	Ounces (x1000)
Cortez Hills and Pipeline (100%)				
2016	P+P	151,002	2.11	10,220
2015	P+P	153,232	2.26	11,129
Net (Depletions)/Revisions		(2,230)	(12.42)	(909)
Relative change, %		-1%	-7%	-8%

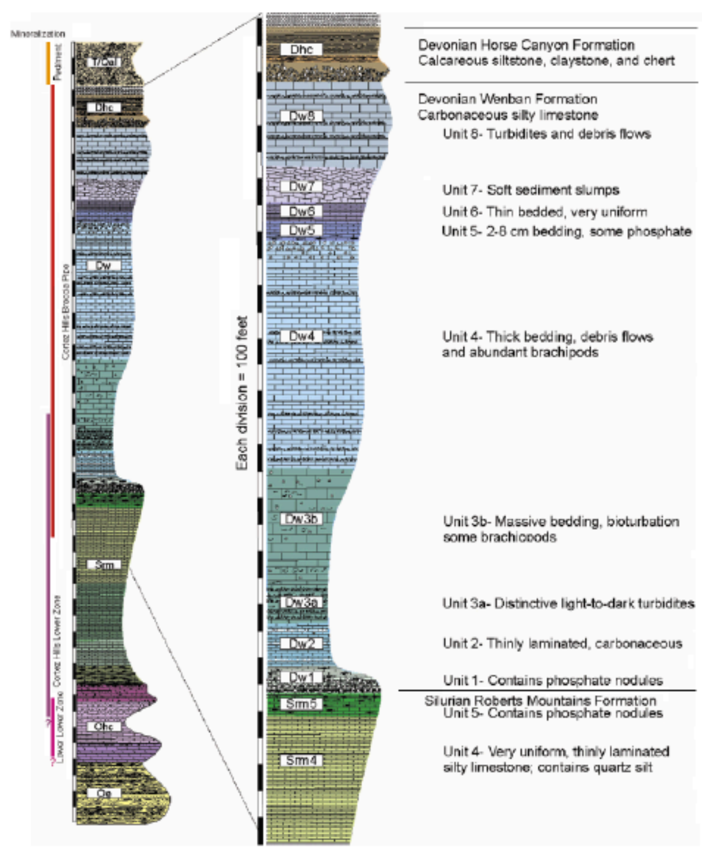

Figure 6-6. Stratigraphic column, Cortez Window (after Arbonies et al., 2011).

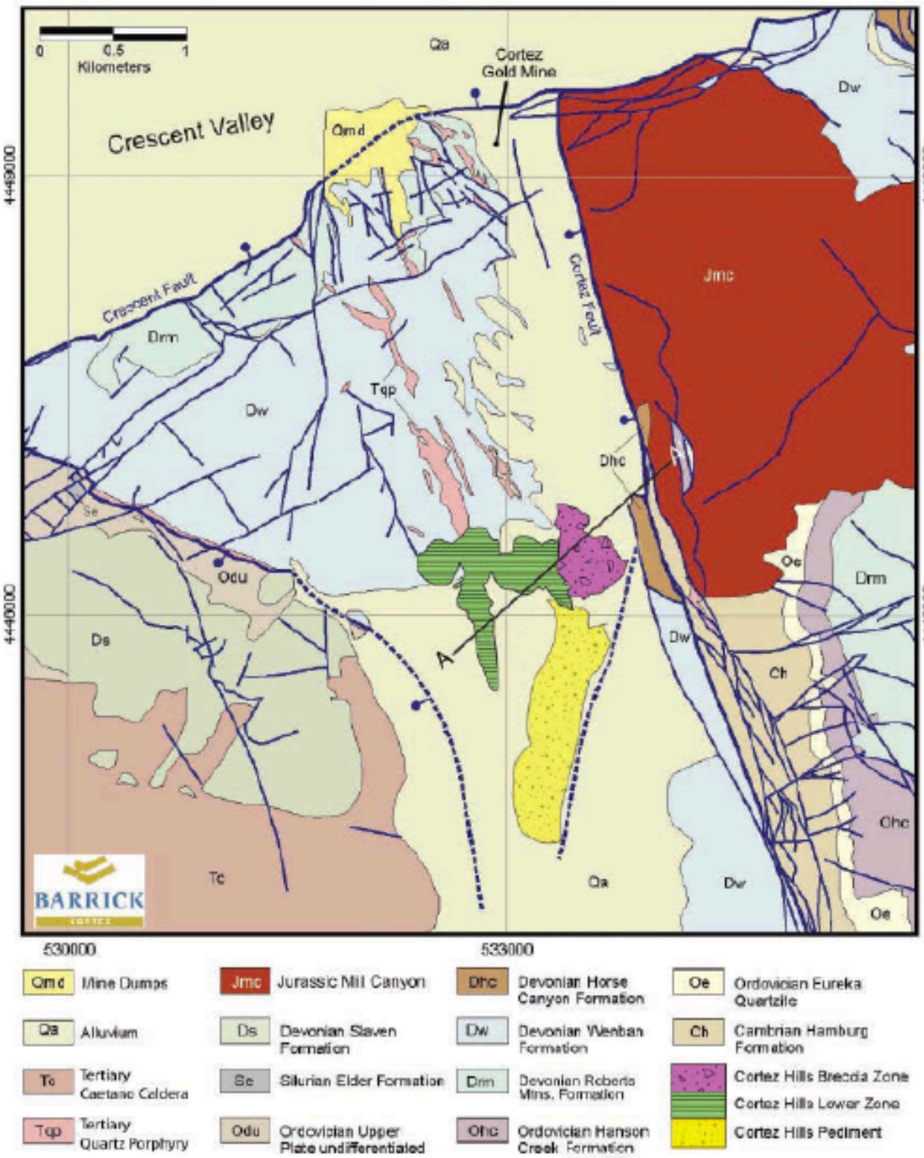

Figure 6-5. General geology of Cortez Hills, showing: Projection of the Cortez Hills breccia zone (purple); Cortez hills lower zone (green); the Pediment deposit (yellow); faults (blue; Maroun et al., 2017). A-A' marks cross-section shown in Fig. 6-7.

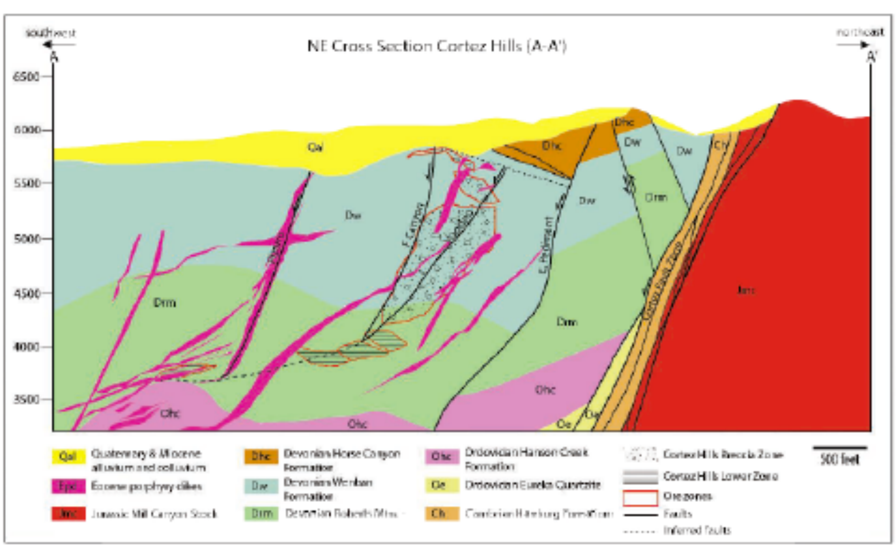

Figure 6-7. Simplified geologic cross-section along A-A' displayed in Fig. 6-5. This vertical slice is 100-ft thick – all features are projected up-to 50 ft from in-front of, and from-behind, the cross-section line. Many small-scale structures and stratigraphic offsets are not shown. Elevations AMSL in feet (Maroun et al., 2017).

Mst grading an average of 0.436 oz/st Au. At year-end 2016, Newmont declared Carlin Trend proven plus probable reserves of 13.670 Moz Au and measured plus indicated resources of 4.340 Moz Au.

The Leeville Deposit (Newmont)

The West Leeville deposit occurs within the upper Devonian-Silurian Roberts Mountains Formation ("DSr,") in a northwest-trending horst of highly decalcified limestone. The deposit exhibits stratabound mineralization similar to the Carlin deposit and appears to have formed by ore-forming fluids moving up high-angle faults into reactive host rocks. Although West Leeville is generally considered an example of stratigraphically controlled mineralization, grade-thickness contours reflect the influence of the intersection of the West Bounding and 315Åã azimuth Rodeo Creek faults as key structural ore controls.

The high-grade mineralization is **largely stratabound (conformable with bedding)** and localized in two facies zones within three of the uppermost DSr units, DSr2, 3, and 4 as follows:

1. **Upper zone mineralization contains about 70% of the gold at West Leeville and is located along the DSr2/DSr3 contact.** The mineralization is in calcarenite-rich facies which grades down section into underlying rhythmically-bedded bioclastic debris flows and calcarenites at the top of DSr3. This zone is strongly decalcified and moderately silicified. The upper zone lies along a contact with upper calcarenite and underlying bioclastic debris flows and calcarenites. This zone is sandwiched within a package of "wispy-laminated silty limestone."

2. **Lower zone mineralization formed along the DSr3/DSr4 contact along a transitional contact of bioclastic-rich DSr3**, with most mineralization in the underlying decalcified planar-laminated DSr4. Below this zone, the rock is largely unaltered, although crosscut by abundant calcite veining. Locally, alteration and some mineralization extend up into the overlying Popovich Formation which is unconformably overlain by the informally named Devonian Rodeo Creek Formation (Drc). Drc is the immediate structural footwall of the Roberts Mountains thrust (Fig. 3-4); Ordovician Vinini Formation comprises the upper plate of the thrust.

Jackson et al. (2002) explain the location of mineralization as follows (paraphrasing): **The stratabound gold zones occur above and below the relatively bioclastic interbed-rich DSr3 unit.** These interbeds and their contacts with surrounding wispy silty limestone had relatively higher permeability and were probably zones of high fluid flow. However, the bioclastic beds were not the preferred site for gold deposition perhaps because they are relatively pyrite poor and less susceptible to sulfidation (Hofstra et al., 1991). Also, if the bioclastic beds were silicified early (pre-gold) in the development of the system, then later gold-bearing fluids may have moved peripheral to these zones of silicification and deposited gold in surrounding, more reactive wispy-laminated silty limestone.

Alteration at West Leeville includes decalcification (removal of calcite but not dolomite), silicification, and argillization. These processes produced quartz, dolomite, and kaolinite with <4 wt % pyrite. Although up to 50% of rock calcite was removed, there is little evidence of volume loss or collapse, probably owing to the presence of the detrital quartz silt component of the rock.

Silicification, if concurrent with decalcification, may also have helped maintain rock integrity. Silicification is variably accompanied by mineralization and ranges from being coincident with high-grade Au to being barren, perhaps depending on relative timing of the mineralization and silicification events. Silicified and mineralized faults are interpreted as important ore fluid conduits. Kaolinite, the dominant clay alteration mineral, coats fractures and replaced silty limestones/ intrusive rocks.

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February 19th: The Geology of Gold Quarry Mine (Newmont)

The Maggie District

Gold Quarry is located in the Maggie Creek subdistrict, central Carlin Trend and is one of the two largest Carlin-type deposits ever discovered. As with many deposits, its discovery and ownership have taken many turns along the way. The first claims in the mine area were staked in 1925 by A. Berning, who leased the property to Cuba Consolidated Mines Company, which, during 1936, shipped 60 st of ore averaging 0.417 oz/st Au and 0.882 oz/st Ag. Newmont leased the Maggie Creek property in 1962 and conducted a drilling program during 1963–64 in the vicinity of what is now the northern limit of the Gold Quarry Pit. Drilling was centered southwest of the jasperoid outcrop, from which the 60 st of ore was mined. Further drilling prior to 1970 delineated 340,000 st grading 0.12 oz/st. However, Newmont dropped the lease in 1970 due to low gold prices and discouraging metallurgical test work.

During 1971, Newmont's continuing metallurgical work and X-ray fluorescence–X-ray diffraction (XRF-XRD) studies of drill cuttings suggested the mineralization was possibly open ended and metallurgically treatable. Consequently, they again leased the property but were forced to accept a 10% gross royalty to owners Thornton and Ash (Guzzardi Jr, 1982)—typical royalties range from 2% to a maximum of about 5%. The lease agreements were kept short by the owners and each renewal was subject to increasing rates until the final lease agreement held a 16.5% gross royalty—an astronomical burden on Newmont's ability to mine profitably.

The Gold Quarry Mine (Newmont)

The Gold Quarry deposit is largely hosted in relatively unreactive Devonian Rodeo Creek Formation siliciclastic rocks, yet the total resource has exceeded 25 Moz Au (Powell, 2010). The Gold Quarry mineralization was localized by the interplay of a complex set of structures. The relatively poor siliciclastic host rock has likely resulted in grades being lower than for comparable local deposits hosted in more receptive, silty carbonate rocks. **Gold Quarry and nearby deposits occur where the Mesozoic (”passive”) northwest-striking Good Hope fault and parallel folds are intersected by Eocene (“active”) north-northeast–striking faults**, as indicated by ore grades in excess of 0.1 oz/st. Major Carlin type deposits are typically developed where these active structures intersect bodies of rock prepared earlier by passive structures (Powell, 2010).

Gold production began in the early 1980s following discovery in 1979 under about 250 ft of Tertiary Carlin Formation. The Deep Sulfide Feeder and Chukar Footwall underground zones were discovered in 1991 and 1997, respectively. Cumulative production through 2009 from the Maggie Creek subdistrict, including Gold Quarry, Mac, and Tusc, was 17.310 Moz Au (GSN Guidebook 1, 2010). Reported production up to 2009 was 7.7 Moz Au at a grade of 0.057 oz/st (GSN Guidebook 1, 2010).

Mineralization occurs in an upper structural stockwork zone and a lower zone of stratabound replacement mineralization. The more recently discovered Chukar Footwall zone occurs at depth in Devonian Popovich Formation. High gold grades here occur along the hinge of the Chukar anticline. Alteration associated with ore includes intense silicification and decalcification, lesser argillization, and formation of barite in the Chukar Footwall. Visible gold present in the Chukar Footwall zone

Leeville and Gold Quarry Mining Districts: Figures

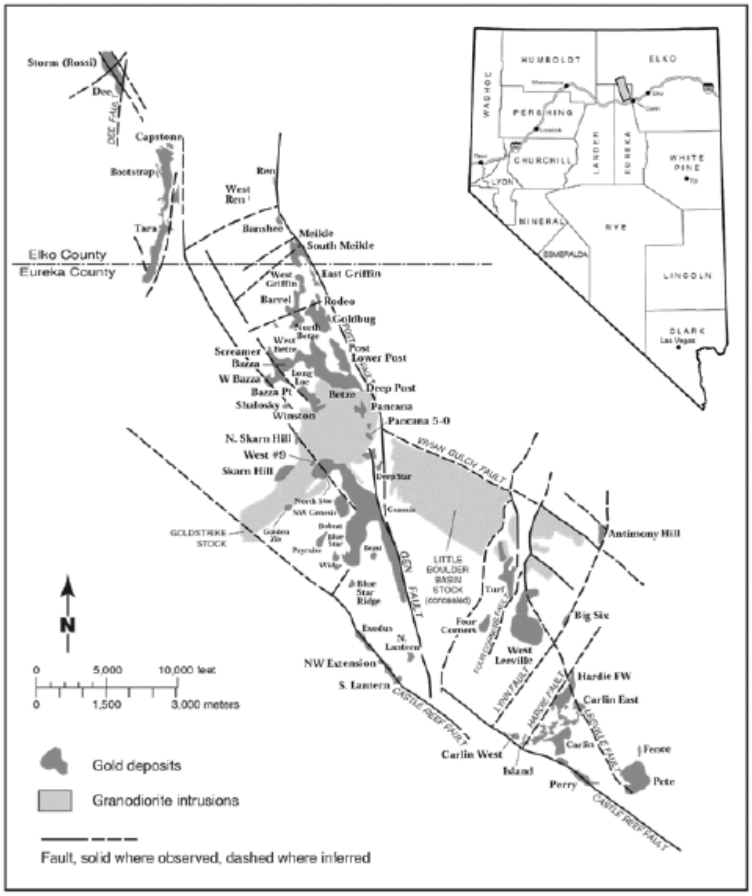

Figure 3-1. Gold deposits on the northern Carlin Trend (Teal and Jackson, 2002)

Table 3-1. Newmont Carlin Area Underground and Open-pit Reserves and Resources: Leeville (shaft access) and Chukar, Pete Bajo and Exodus (portal access) underground mines. Emigrant, Gold Quarry, and Silverstar Open-pit mines (100% Newmont, 2017a,b)

Newmont Mining - Reserves and Resources

2016		Tons (x1000)	Grade, Au (oz/st)	Ounces (x1000)
Carlin Underground: Leeville, Chukar, Pete Bajo and Exodus (100%)				
Reserves	Proven	12,000	0.299	3,580
	Probable	6,600	0.240	1,590
	P+P	18,600	0.278	5,170
Resources	Measured	900	0.201	180
	Indicated	2,300	0.231	540
	M+I	3,200	0.223	720

2016 and 2015 Reserves calculated using US$1,200 gold price
Cut-off grade not less than 0.044 oz/st
2016 and 2015 Resources calculated using US$1,400 gold price
Resources are reported exclusive of reserves.
(Newmont, 2017a,b)

Reconciliation of 2016 to 2015 Declarations

		Tons (x1000)	Grade, Au (oz/st)	Ounces (x1000)
Carlin Underground:				
2016	P+P	18,600	0.278	5,170
2015	P+P	23,000	0.266	6,100
Net (Depletions)/Revisions		(4,400)	(0.215)	(930)
Relative change, %		-19%	5%	-15%

2016		Tons (x1000)	Grade, Au (oz/st)	Ounces (x1000)
Carlin Open-pits: Emigrant, Gold Quarry and Silverstar (100%)				
Reserves	Proven	67,900	0.058	3,960
	Probable	187,400	0.024	4,540
	P+P	255,300	0.033	8,500
Resources	Measured	33,800	0.049	1,670
	Indicated	66,500	0.029	1,950
	M+I	100,300	0.036	3,620

2016 and 2015 Reserves calculated using US$1,200 gold price
Cut-off grade not less than 0.044 oz/st
2016 and 2015 Resources calculated using US$1,400 gold price
Resources are reported exclusive of reserves.
(Newmont, 2017a,b)

		Tons (x1000)	Grade, Au (oz/st)	Ounces (x1000)
Carlin Open-pits: Emigrant, Gold Quarry and Silverstar (100%)				
2016	P+P	255,300	0.033	8,500
2015	P+P	258,300	0.036	9,350
Net (Depletions)/Revisions		(3,000)	(0.291)	(850)
Relative change, %		-1%	-8%	-9%

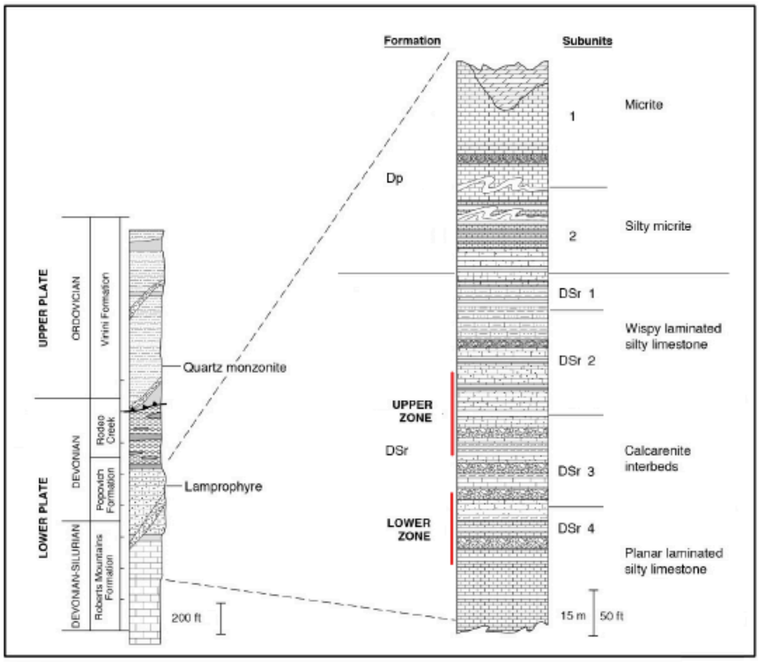

Figure 3-2. Stratigraphy of West Leeville (after Jackson et al., 2002)

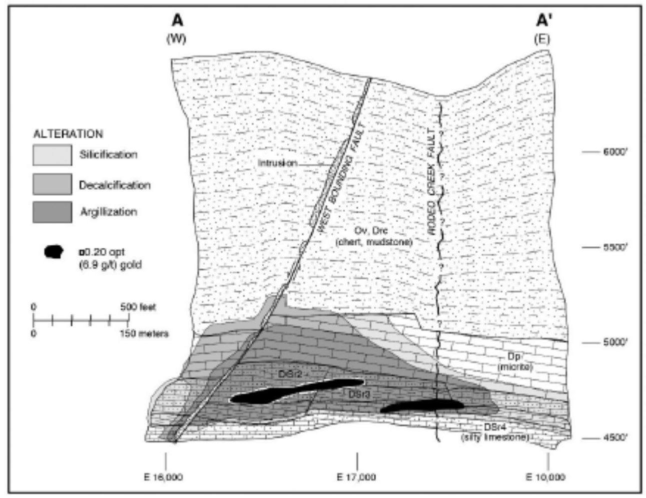

Figure 3-3. West Leeville cross-section A-A' (Jackson et al., 2002)

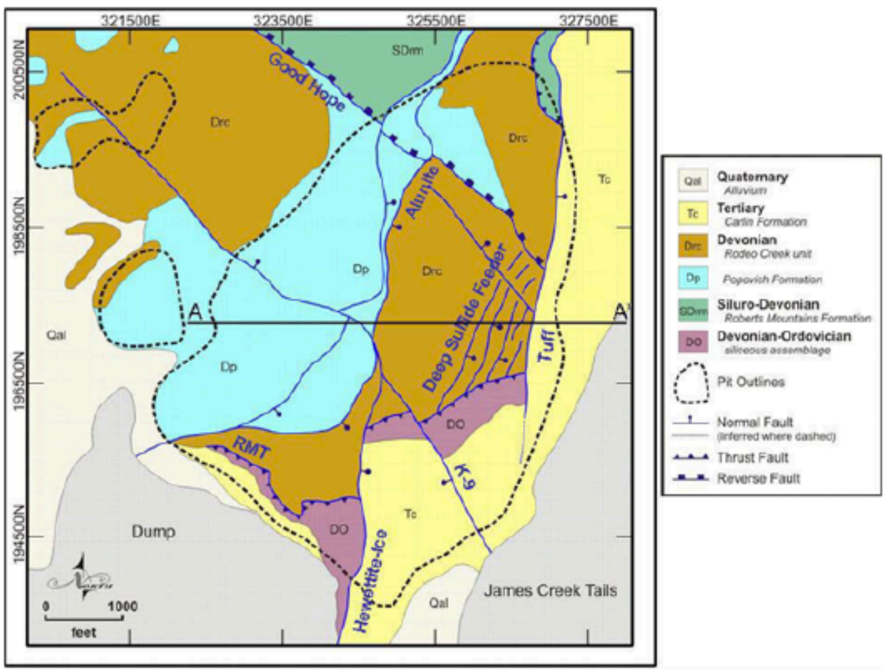

Figure 3-7. Simplified geologic map of Gold Quarry (Powell, 2010)

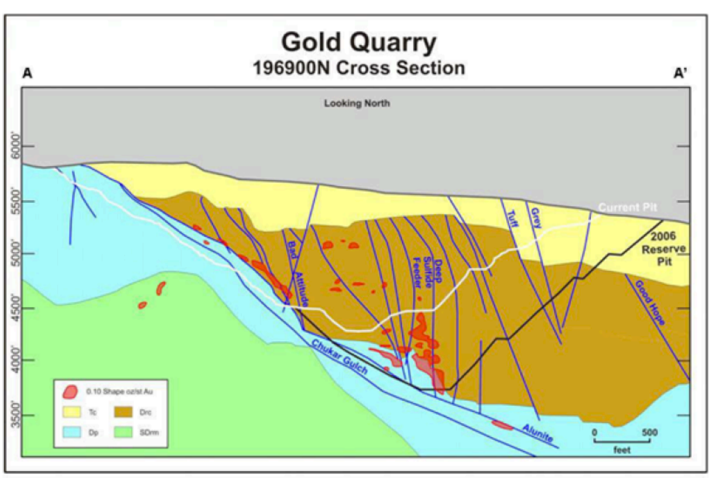

Figure 3-8. East-west cross-section of Gold Quarry (Powell, 2010)

is spatially associated and co-precipitated with barite from meteoric water that descended into open structures.

It is thought that four structural events contributed to formation of Gold Quarry (Cole, 1995). Structures developed during the Paleozoic Antler orogeny formed the Roberts Mountain Thrust and associated low-angle reverse faults, recumbent fold, and duplexes. The poorly understood Mesozoic northwest-striking Good Hope fault is a major district-scale control of mineralization, and is interpreted as a reverse fault with Roberts Mountains and Popovich Formation in the hanging wall and Rodeo Creek Formation in the footwall. Recently, the fault has been interpreted as part of a regional system of compression- related folding and localized development of reverse faults, probably related to Mesozoic tectonism (Powell, 2010).

Similar folds with west-northwest– and north-northwest–trending axes extending to the northern Carlin Trend are thought to be penecontemporaneous. These major structures likely provided important structural preparation of the host rocks. Cenozoic-aged north-northeast–striking normal faults control mineralization and were probably open and facilitated ore fluid flow during the gold mineralizing event. Normal offset along these faults is no more than 500 to 600 ft. Miocene to present Basin and Range faulting produced largely north-south striking, steeply east dipping normal faults that down-dropped stratigraphy and gold mineralization to the east.

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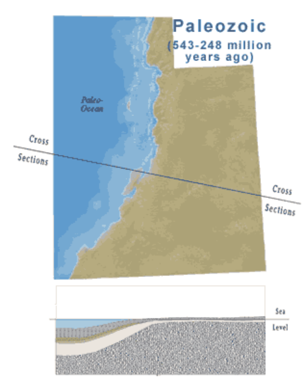
PART TWO:
The Geology of Northern Utah (February 19th-21st)

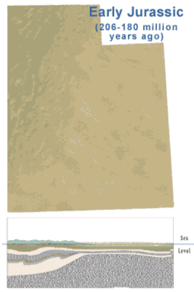
General Geology

(from Utah Geologic Survey, "Utah: A Geologic History")

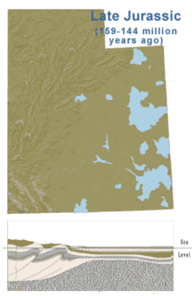
In Northern Utah, three major geologic provinces meet: to the east, the Basin and Range, centrally the Colorado Plateau, and to the northwest the Rocky Mountain range. These provinces reveal vastly different geological processes, but also contain vast amounts of mineralization that have been mined historically and in the present day. The geologic history of the state is as follows:



Paleozoic: During this era Utah was at the western edge of North America. The eastern portion of the state was a low plain with little relief at about sea level. What little sediment did reach the ocean was well washed quartz sand. Coral reefs, now exposed as thick limestones in the Wasatch Mountains, marked shallow seas that led to deep oceans in the west.



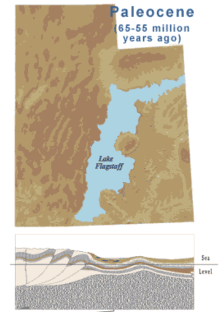
Early Jurassic: Cut off from moisture-laden ocean winds by rising mountains to the west, desert sands were blown into Utah from the north and northwest. These blowing sands formed dunes which eventually turned into rock and are preserved in what is now called the Navajo Sandstone. These ancient dunes are well exposed at Checkerboard Mesa in Zion National Park and on the San Rafael Swell.

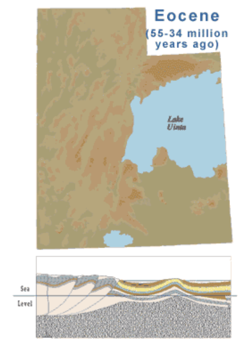


Late Jurassic: At this time Utah was a hot, swampy lowland with mountains and volcanoes to the west and northwest. Meandering rivers and lakes abounded, while dinosaurs roamed the land. Their fossilized bones are preserved and can be seen at famous sites such as the Cleveland-Lloyd Dinosaur Quarry and Dinosaur National Monument.

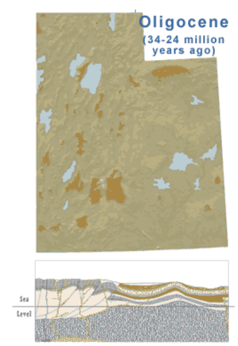
Late Cretaceous: Pressure from continental collisions with the Pacific Plate to the west produced high mountains in western Utah. The eastern portion of the state was covered by an inland sea that stretched from the Gulf of Mexico to the Arctic. The costal plain between these two areas advanced and retreated as sediment filled the sea and the basin sank. Coal swamps formed behind barrier islands while dinosaurs continued to rule.

Paleocene: Erosion wore down the mountains to the west and sediments filled the inland sea to the east. Continued pressure from the Pacific Plate caused both the Uinta Mountains and the Colorado Plateau to uplift. The Colorado Plateau warped as it rose, making the beginning of predominate swells and depressions now found in Utah (such as the San Rafael Swell). A large freshwater body, called Lake Flagstaff, occupied a depression in what is now central Utah.



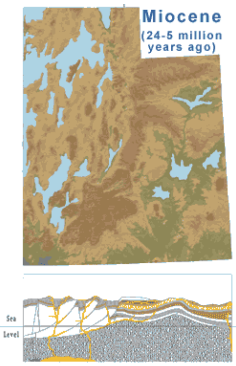


Eocene: After spending nearly 500 million years near sea level, Utah continued its rise to nearly a mile high in elevation. Continued warping of the Colorado Plateau produced basins for lakes such as Lake Uinta. Organic-rich accumulations in the bottom sediments include well-preserved fish fossils and oil shales. The western mountains were reduced to relics.



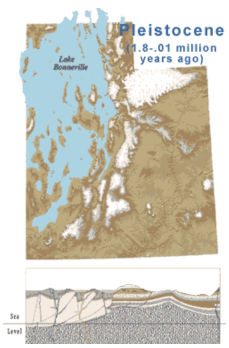
Oligocene: On the Colorado Plateau the lake basins were filled in and broad plains separated mountain uplifts. The beginning of modern rivers ran across these plains. The continental divide passed through northeastern Utah so the Green River in Wyoming drained to the Mississippi River. With the beginning of extension in western Utah, which would eventually lead to the Basin and Range, extensive volcanic activity started to occur.

Miocene: Whereas previous compression had moved the site of San Francisco closer to Salt Lake City, extension was now moving the two apart. This extension separated uplifted mountain blocks from down-dropped basins

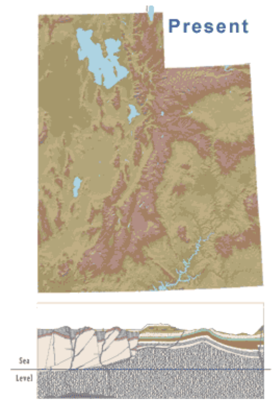


forming the Basin and Range. **Volcanic activity continued forming three great metallic mineral belts. From north to south they are: Park City-Oquirrh, Deer Creek-Tintic, and Wah Wah-Tushar. The Colorado Plateau continued to rise and tilt northeastward.**

Pleistocene: The geography of Utah was very close to what it is now. Mountains, canyons, and rivers were all well in place. The climate at this time was wetter and colder and as a result glacial activity took place. Canyons were carved and expanded in the Uinta Mountains as well as in several other mountain ranges throughout the state. A giant fresh-water body called Lake Bonneville also formed, stretching from the Wasatch Mountains to Nevada and from the Utah-Idaho border nearly down to Cedar City in southern Utah.

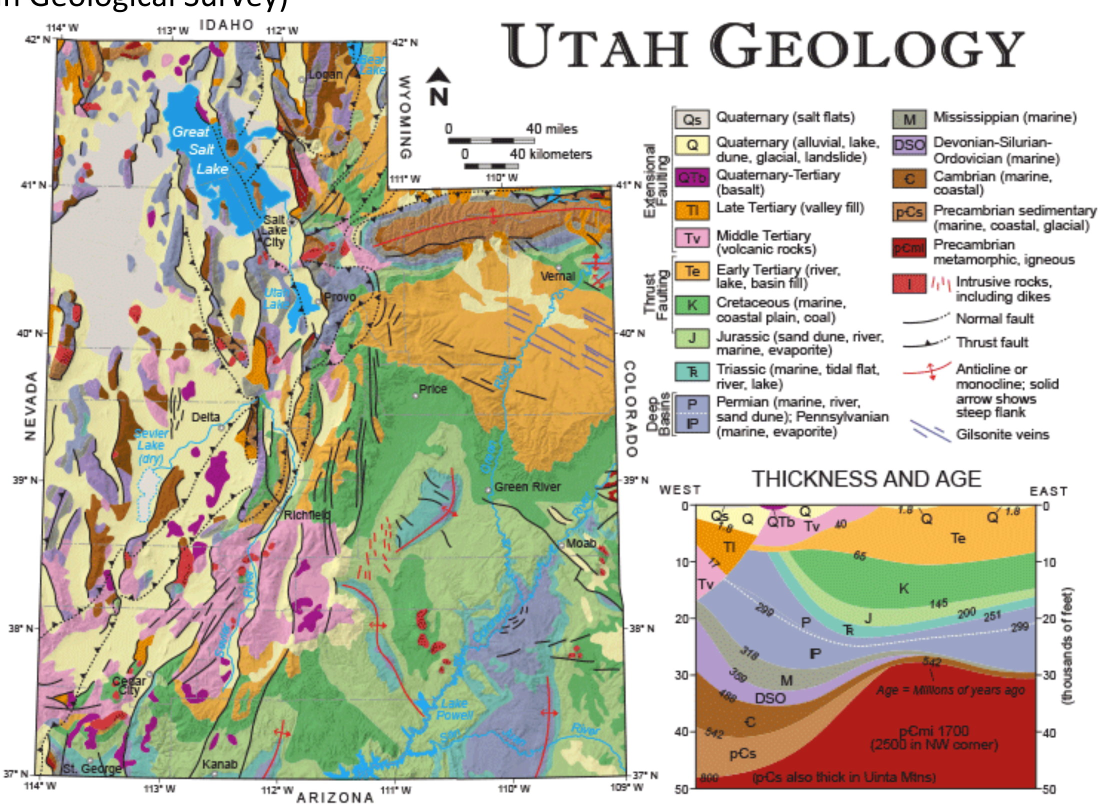


Present: The geologic history of Utah has left an indelible mark on the state. It explains why the rocks to the east are brightly colorful while those to the west have somber colors, why there are spectacularly massive canyons on the Colorado Plateau while much of the Basin and Range has no external drainage, and why a high mountain chain, the Wasatch, runs down the middle of the state. This history determines the location of settlements, industry, and recreation sites.



<u>Geologic Map of Utah</u>

(Utah Geological Survey)



February 20th: The Tintic Mining District with Dr. Erich Petersen (University of Utah)

(Taken from: "History, Geology, and Production of the Tintic Mining District: Juab, Utah, and Tooele Counties" by Ken Krahulec and David F. Briggs, Utah Geological Association, 2006).

The Tintic mining district, located roughly 60 miles south of Salt Lake City, is the **second most productive district in Utah.** The initial discovery in the Tintic district occurred in 1869. With the arrival of the railroad in 1878, the mining operations expanded rapidly making **Tintic the most productive district in Utah by 1899.** Although district production peaked during the first half of the twentieth century, exploration activities from 1940 to 1970 continued to make significant discoveries under volcanic cover in areas peripheral to the Main Tintic subdistrict. Production declined significantly with the **closure of the Burgin mine in 1978, sputtered in the 1990s, and finally came to an end in March 2002 with the closure of the Trixie mine. The district is currently idle except for sporadic exploration activities.**

Figure 1. Location map for the Tintic mining district, Juab, Utah, and Tooele Counties.

Geologically, the Tintic district is underlain by a **thick section of Paleozoic strata that have been strongly folded into north-south trending, asymmetrical anticlines and synclines that have been cut by northeast-trending, right-lateral strike-slip faults.** These sedimentary rocks were uplifted, eroded, and covered by early Oligocene calc-alkaline volcanics emanating from a large caldera just to the south of the district. Continuing magmatism resulted in the intrusion of monzonite stocks, plugs, dikes, and sills with associated hydrothermal alteration and mineralization. The **area was uplifted on the west during the Basin and Range orogeny, resulting in slight eastward rotation and continuing erosion of the East Tintic Mountains.**

The Tintic mining district can be broken down into four subdistricts based on geology, location, and ore occurrence**: Main Tintic, East Tintic, Southwest Tintic, and North Tintic. The majority of the production has been derived from sub-vertical copper-gold-silver chimneys and sub-horizontal, carbonate-hosted, lead-zinc-silver ore runs (replacement deposits) of the Main Tintic subdistrict (Morris, 1968).** The bulk of the remaining metal production has been derived from the structurally complex ore bodies of the East Tintic subdistrict. The

Southwest Tintic subdistrict hosts a **large, subeconomic porphyry copper system, which has seen minor production from peripheral high-sulfidation, copper-silver-lead veins.** In the North Tintic subdistrict, limited production of zinc-rich replacement ores have been derived from the Scranton and other small mines.

Total district production is nearly 20 million tons, which at current metal prices would translates to well over three billion dollars. Roughly 90 percent of this production has come from irregular, precious metal-rich polymetallic base metal replacement ores. Silver (42 percent at modern metal prices) has been the most valuable product in the district followed by significant gold (29 percent) and lead values (17 percent) with lesser contributions by copper (6 percent) and zinc (6 percent). Not included in these figures, is the production of well over one million tons of halloysite clay, mainly from the Dragon mine.

February 21st: The Geology of Bingham Canyon (Rio Tinto)

History, Size and Processes of the Mine

(From "Kennecott's Utah Copper's Bingham Canyon Teacher Guide, 2011)

Mine History

Bingham Canyon was settled in 1848 by the Bingham brothers, Thomas and Sanford, who were ranchers with no mining experience. In 1863, soldiers stationed at Fort Douglas in Salt Lake City explored the canyon and discovered lead ore. Utah's first mining district was created in the Bingham Canyon area that same year.

In 1893, Daniel Jackling, a metallurgical engineer, and Robert Gemmell, a mining engineer, studied the deposit and **recommended developing the ore body through a revolutionary open-pit mining method and processing the ore through a large-scale industrial process.** The miners and their families lived near Bingham Canyon in places called Highland Boy, Copper Heights, Copperfield, Carr Fork, Heaston Heights, Telegraph, Dinkeyville, Terrace Heights, Greek Camp and Frog Town. At one point, the population in the area approached 20,000 people. **In 1903, the Utah Copper Company was formed to develop the mine, based on the recommendations of Mr. Jackling and Mr. Gemmell.** In 1906, the first steam shovels began mining away the waste rock that covered the ore body. The ore was found in a part of the mountain that divided the main canyon.

Size of the Mine

Kennecott Utah Copper's (KUC) Bingham Canyon Mine has produced more copper than any mine in history — about 19 million tons. The mine is 2¾ miles across at the top and ¾ of a mile deep. You could stack two Sears Towers (now known as the Willis building), on top of each other and still not reach the top of the mine.

If you stretched out all the roads in the open-pit mine — some 500 miles of roadway — you'd have enough distance to reach from Salt Lake City to Denver. KUC mines about 55,000,000 tons of copper ore and 120,000,000 tons of overburden per year. You could lay the soccer field at Rio Tinto Stadium in Sandy, Utah, end to end more than 38 times across the top of the Bingham Canyon Mine before it would reach both sides. The elevation of the Bingham Canyon Mine drops from 8,040 feet above sea level to 4,390 feet above sea level.

Mine Processes

1. **Bingham Canyon Mine:** This is where the mining process begins. Every day, Kennecott Utah Copper mines about 150,000 tons of copper ore and 330,000 tons of overburden. The ore containing copper, gold, silver and molybdenum is hauled and deposited in the in-pit crusher and sent to the Copperton

2. **Concentrator (Copperton Concentrator):** From the mine, ore is transported on a five-mile conveyor and stockpiled at the Copperton Concentrator. There the ore is ground into fine particles. The smaller pieces are then combined with air, water and chemical reagents to separate the valuable minerals from the waste rock. The mineral bearing concentrate is then transported to the smelter through a pipeline.

3. **Tailings** are sent through a pipeline from the Copperton Concentrator to the tailings impoundment area north of the town of Magna where they are stored.

4. **Smelter:** At the smelter, the copper concentrate is transformed into liquid copper through a flash smelting process. The copper matte is processed in the furnace to produce 99.5 percent blister copper. From there, the 750 pound copper plates, called anodes, are sent to the refinery.

5. **Refinery:** At the refinery, anodes are lowered into electrolytic cells containing a stainless steel blank and acidic solution. For 10 days, an electric current is sent between the anode and the cathode, causing the copper ions to migrate to the steel sheet. The other impurities, including gold and silver, fall into the bottom of the cell and are recovered in the Precious

6. **Metals plant**: This process forms a plate of 99.99% pure copper. The copper is separated from the steel sheet and sent to market.

Overview of Geology

(Taken from “The Bingham Canyon Pit”, M. Dane Picard, Journal of Geoscience Education, v. 47, 1999, p. 369-373)

Geology and Mineralization

At the center of the Bingham district is the Eocene porphyry-copper deposit containing primarily copper, gold, silver and molybdenum. On average, a ton of ore at Bingham Canyon contains 10.6 pounds of copper. During the Eocene epoch (39.8 to 38.8 Ma) porphyritic magmas intruded the sedimentary sequence of the Oquirrh Mountains (Late Paleozoic) and crystallized at depth, forming a stock (intrusion with <100 km^2 surface area). The fluids associated with these intrusions initiated a major mineralization event.

The Bingham district - though clay is in the center and not the outside - closely exemplifies the classic alteration and mineralization zoning expected in a porphyry-copper deposit. The ores are in five overlapping zones: a low-grade core, then a molybdenum zone, followed by a copper zone, an iron ("pyrite halo") zone, and finally a lead-zinc-silver zones. Copper is found mainly as small disseminated grains or in veinlets spread through the outer shell of the intrusion and, to less extent, in the nearby sedimentary rocks.

From 39 to 33 Ma, volcanoes in centers close to where the porphyry-copper deposits occur erupted flows that were chemically similar in make-up to the intrusions. The eruptions occurred at about 38.5 Ma (older volcanic suite), 37.7 Ma, and 32 Ma (younger volcanic suite). Work by **Waite et al. (1997) show in a cross section a hypothetical stratovolcano structure over the Bingham canyon deposit.**

Structure

In the mine, the **dominant structure is the northwest-trending Bingham syncline. The Bingham stock intruded the axis of the Bingham syncline.** North of the Bingham syncline is a fold that is convex upward with the oldest lithologies at the center, the Copperton anticline, the only other major fold in the area. The anticline trends north and is separated from the Bingham syncline by the Midas thrust fault where older strata have been thrust on a shallow plane over younger strata.

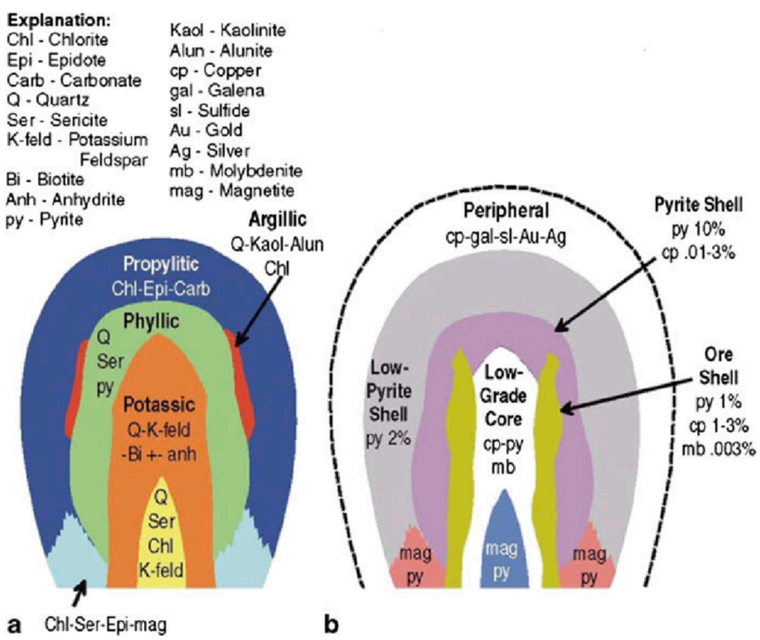
Ore veins dominantly strike northeast and dip steeply westward; there is little displacement on them. They fill nearly parallel faults and fissures. In the area, other northwest striking faults are only weakly mineralized.

Associated Skarn Deposits and Other Base Metal Mineralization

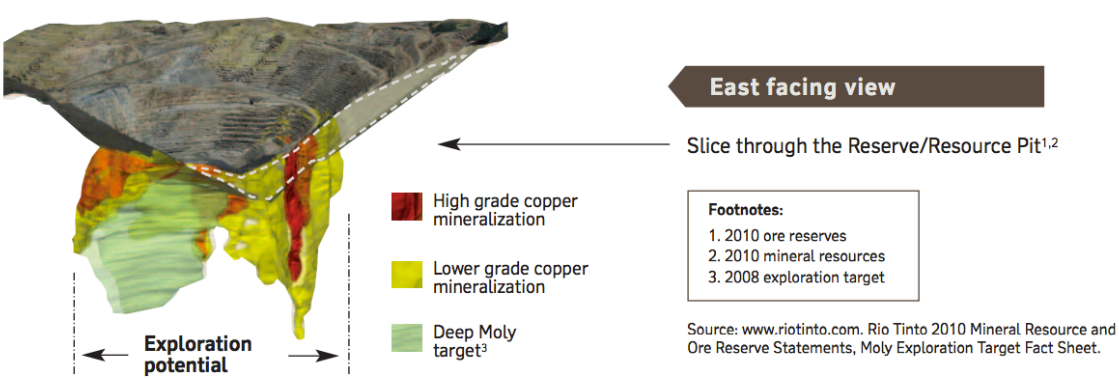
Major copper-gold skarn deposits flank the Bingham copper-ore body on the west (Carr

Fork Deposit) and north (North Ore Shoot Deposit). Such deposits usually form where hydrothermal solutions pass from granitic porphyries (at Bingham the monzonite porphyries) into limestone or dolomite. Generally, the solutions are acidic, dissolving the carbonate rocks and replacing the carbonate minerals with silicate minerals, sulfides of iron, copper, zinc, lead, and silver; with oxides of iron, tin, and tungsten; and with gold. Present output of these skarns is about **310,000 tons of copper, 3.5 million ounces of silver, and 350,000 ounces of gold each year.**

Vein and replacement lead-zinc-silver ores found in a halo around the Bingham mine itself have yielded 28 million tons of other base metals at an average grade of 8.6 percent lead, 6.6 percent zinc, 5.0 ounces per ton silver, and 0.039 ounces per ton gold.



Idealized porphyry deposit model (Beiranvnd Pour et al. 2011)



Bingham Canyon Mine Resources and Reserves. 2011 (Rio Tinto)

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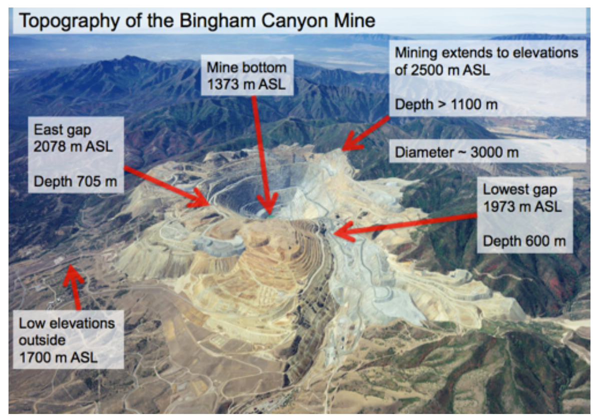
Waite, KA., Keith, J.D., Christiansen, E.H., Whitney, J.A., Hattori, Keiko, Tingey, D.G., and Hook, C.J., 1997, Petrogenesis of volcanic and intrusive rocks associated with the Bingham Canyon Porphyry Cu-Au-Mo deposit, Utah: in John, D.A., and Ballantyne, G.H., editors, Geology and Ore Deposits of Oquirrh and Wasatch Mountains, Utah, Guidebook Prepared for the Society of Economic Geologists, v. 29, p. 69-90.



Overview of Bingham Canyon Mine (Kennecott Mines)

Geology of Bingham Canyon: Figures

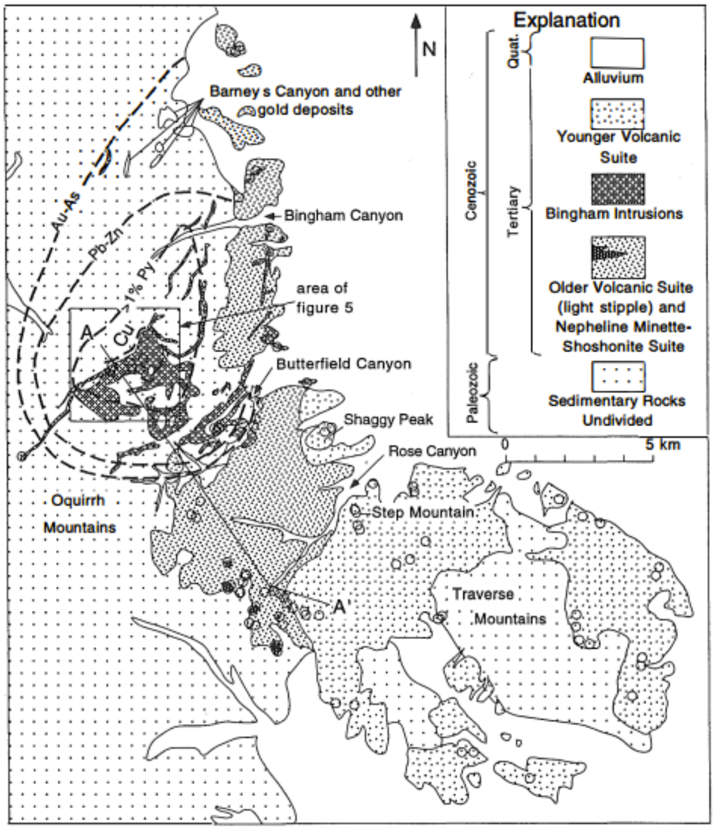
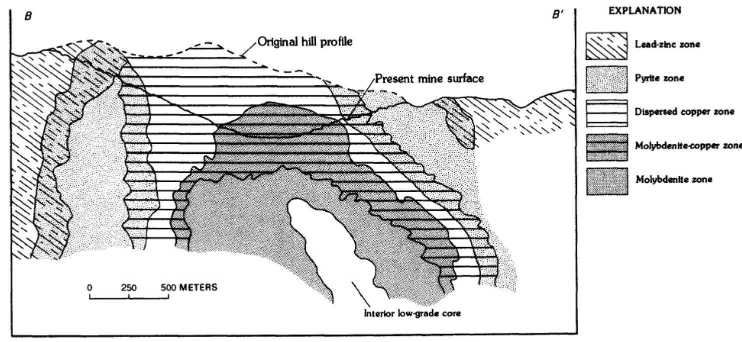
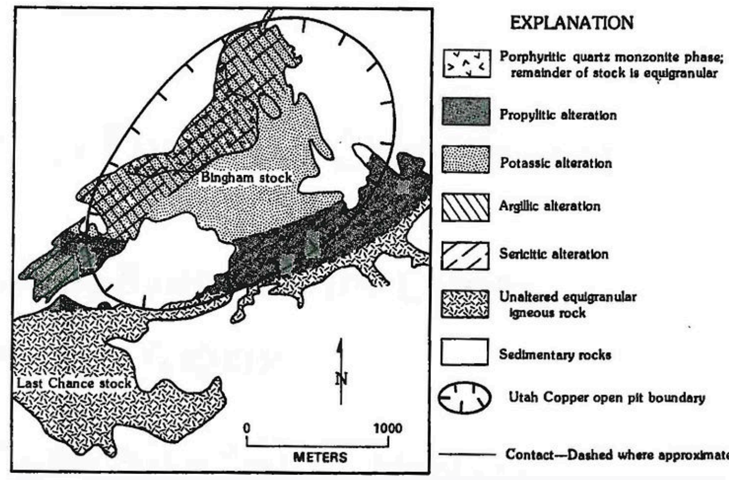


FIG. 2. Simplified geologic map of the west flank of the Oquirrh Mountains, Utah. Small circles represent sample locations. Dashed lines outline the limits of the Bingham Canyon copper orebody and associated mineralized halos as labeled (Babcock et al., 1995). Boundary between older and younger volcanic suites is approximated from the data of this study; other geologic contacts are compiled from Smith (1961) and Babcock et al. (1995).





Top: Bingham Canyon cross-section sulfides. **Bottom:** Sketch geologic map of the Bingham Canyon copper deposit, Utah, USA, showing **bedrock type and alteration zones.** ("Gold in the Bingham district, Utah" in US Geological Survey, Bulletin 1857-E, p.E11, 1990)

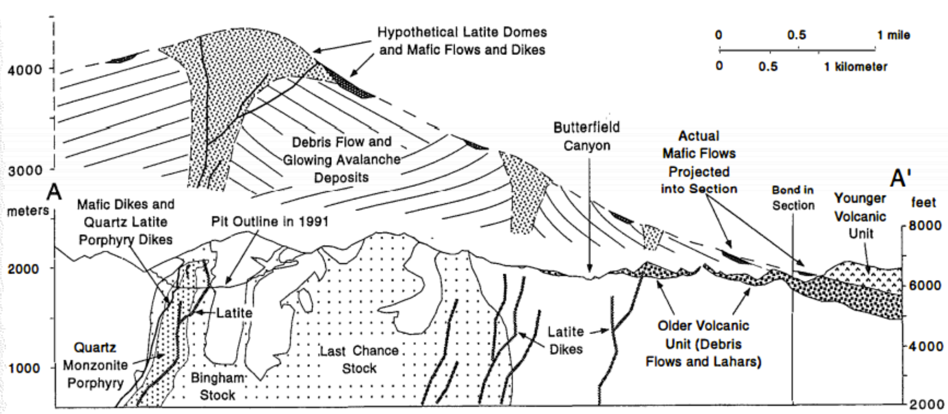
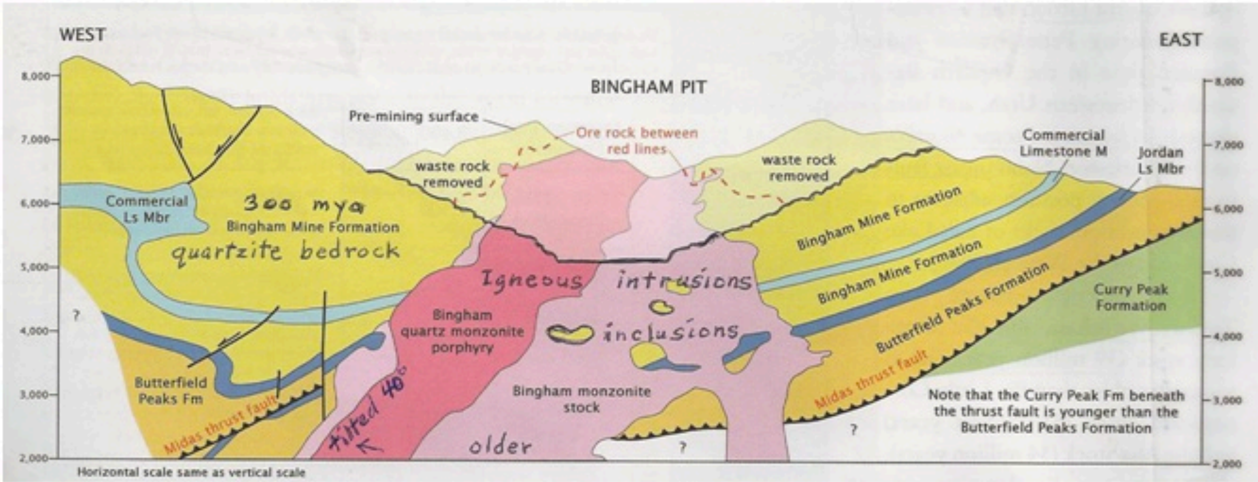


FIG. 3. Cross-section A-A' (Fig. 2) depicting a hypothetical volcanic edifice over the Bingham Canyon porphyry copper deposit. The reconstructed cover infers that some of the Bingham intrusions vented to form domes that decrepitated to form the existing debris avalanche deposits. Note the occurrence of mafic dikes within the pit. Geologic contacts compiled from Babcock et al. (1995) and unpublished Kennecott maps.

Top: Simplified geology of the Bingham Canyon region. **Bottom:** Simplified geology of Bingham Canyon with hypothetical now-eroded volcanic edifice over the deposit. (Waite et al., 1997)



Age		Formation	Thickness in feet	Lithology and fossils
Quaternary		Alluvium & Lake Bonneville deposits	0–1,000	stream-laid sand and gravel, and Bonneville lake beds
Pliocene — Miocene		Salt Lake valley-filling deposits	3,000	pre-Bonnevill alluvial and lake deposits; Sale Lake Formation is exposed in Jordan Narrows and in road cuts near Magna where it is a white ash of glassy shards
	The Oquirrh Mts area began separating from the Wasatch Mts area (neither mountain range existed as such at that time) about 17 million years ago with the inception of rifting along the Wasatch fault, starting the creation of the Salt Lake Valley. Before that time the Oquirrh area was much closer to the Wasatch area than it is today.			
Oligocene		Shaggy Peak rhyolite plug		light gray; pitted cavernous surface
		Latitic volcanic rocks of the West Traverse Mountains	3,000–4,000	33–30 million years old; volcanic breccias and ash flows; youngest at South Mtn near Herriman; at Step Mtn has large columnar joints
				5-million-year gap in record
Eocene		Latitic volcanic rocks of Bingham Canyon	3,000	39–38 million years old; eruptive equivalent of Bingham stock, their source at depth under a very large stratovolcano
		Bingham quartz monzonite porphyry		contains about 25% quartz; hydrothermally altered; ore-bearing; 39 million years old; intrudes the stock
		Bingham monzonite stock		a fine-grained rock; contains plagioclase, K-feldspar, lesser dark minerals and quartz; this altered rock hosted much of Bingham's copper ore
Cretaceous	During the Late Cretaceous Sevier orogony, Bingham's Oquirrh Group rocks, along with older and younger strata, were moved southeastward some tens of miles on the Charleston–Nebo thrust. At depth, beneath Bingham, they may rest on Jurassic strata.			
Permian	OQUIRRH GROUP	Freeman Peak Formation	2,400	thick-bedded, tan, calcareous quartite with thin interbeds of calcareous sandstone and shale; *Swagerina*
		Curry Peak Formation	2,500	tan calcareous siltstone, sandstone, and orthoquartzite; contains "worm trails" and Permian fusulinids
Pennsylvanian		Bingham Mine Formation	6,500	principal sedimentary ore host rock; mostly quartzite; more calcareous and silty in the lower half; two cherty limestone beds, the Jordan and the Commercial, hosted copper-gold and lead-zinc-silver ores; contains *Triticites* (fusulinid), corals, bryzoans, and brachiopods
		Commercial Ls M	100–200	
		Jordan Ls Mbr	100–300	
		Butterfield Peaks Formation	9,000	the upper 2,000 feet is mostly tan quartzite with some interbeds of cherty limestone and calcareous sandstone; the middle 3,800 feet is cyclic interbeds of cherty limestone and calcareous orthoquartzite; the lower 3,300 feet is cyclic interbeds of limestone, quartzite, sandstone, siltstone, and some shale; bryozoan, coral, and brachiopod fossils are abundant in limstones
		West Canyon Limestone	1,100	gray limestone with interbeds of shale; contains brachiopods and other marine invertebrate fossils

Cross section and stratigraphic column of Bingham Canyon Mine (Kennecott Mines, 1991)

PART THREE:
The Grand Staircase of Southern Utah / Northern Arizona (February 22nd-24th)

Background

Initially, we will drive south from Salt Lake City along the eastern edge of the Basin and Range Province (with the Rocky Mountains to the east) (see Appendix A). Then, in southwestern Utah, we will head east up onto the Colorado Plateau and to the top of the "Grand Staircase" (Appendix B). The Grand Staircase-Escalante National Monument was designated a U.S. national monument in 1996. This area in southern Utah initially spanned 7,610 km^2, but in 2017 was ordered to be reduced to 4,062 km^2. It is one of the most remote regions (and the last to mapped) in the contiguous United States. This leg of our field trip will lead "downstairs". The steps are composed of (in descending order) the Pink, Grey, White, Vermillion, and Chocolate Cliffs. Each derives its unique color from different geologic formations – see the red dots on Appendix B Fig. B-1, and also Appendix C. Stops at Bryce Canyon and Zion National Parks will showcase, respectively, the upper and middle parts of the staircase; further travel south will bring us to the bottom step near the UT-AZ border.

Continuing south into Arizona, we will gradually increase in elevation across the Arizona Strip (the area between the Utah border and the Colorado River) as we drive onto the uplifted Kaibab Plateau (part of the larger Colorado Plateau). The Arizona Strip, along with some land just south of the Grand Canyon, hosts breccia pipe style uranium mineralization (see Appendix D for a detailed description). This region was explored extensively in the 1970s and '80s following a 1950 discovery along the Grand Canyon's south rim (in the Orphan copper mine), and mining through the 1980s produced over 8600 tonnes of U3O8 from seven mines. Although the ore grades of 0.4-1% are much less than those of the Athabasca Basin unconformity style deposits, the mining costs of these Arizona deposits are significantly lower. Indeed, this allowed exploration and mining even during periods of low yellowcake price; in 1982, total production cost for breccia pipe uranium was about $10/lb ($24 in 2007 US dollar terms) U3O8 concentrate, and it was sold for around $40/lb. Considering average ore reserves of 3.5 million pounds (about 1590 tonnes) per pipe, with an average grade of 0.6% U3O8, a mineralized pipe was worth around $105 million in 1982 (over $225 million in 2007 US dollars). Mine shafts 300-490 m long are usually required, but declines can be used where mineralized pipes occur near canyons. In 2007 (before the 2011 Fukushima disaster and resulting U market crash), over 500 breccia pipe targets in the Arizona Strip were being explored by 11 exploration companies. However, in 2012 the government issued a ban on new uranium claims and mines in the Grand Canyon region (existing mines were excluded). One of these pre-existing mines – Canyon Mine – is located about 10 km south of the Rim. It was approved in 1986, but a drop in U prices in the early 1990s forced it and other mines around the Canyon (including Kanab Point, Pinenut, and Arizona One) to go on standby. In December 2017, a U.S. federal appeals court ruled to allow the Canyon Mine to reopen, despite ongoing opposition from environmental campaigners and Native American groups.

In addition to uranium, the Colorado Plateau hosts all of Arizona's other energy resources – including coal from Black Mesa in the eastern part and oil from the Navajo Reservation in the northeastern part of the state.

February 22nd: Salt Lake City – Springdale, UT. Bryce Canyon National Park

Bryce Canyon National Park features the hematite-stained Pink Cliffs and "hoodoos" of the Claron Formation. During the Cretaceous, this area was submerged under a seaway that deposited hundreds of meters of sediment to form the lowest and oldest gray-brown rocks – the Dakota Sandstone (which hosts abundant petrified wood, oyster beds, and coal), which is overlain by the Tropic Shale (perhaps the most fossil-rich rocks in the area, featuring straight and curled ammonites). Later regression of the Cretaceous Seaway deposited the shales and sandstones of the Straight Cliffs Formation, followed by Wahweap, Kaiparowits, Canaan Peak, and Pine Hollow Formations. Subsequent uplift and compression of the Laramide orogeny from the late Cretaceous until the early Paleocene formed the up to 5° dipping Bryce Canyon Anticline. The formations lying above the Straight Cliffs (and including part of it) were eroded from the anticline's crest. Then, in the Tertiary, erosion of highlands to the west deposited limy, iron-rich sediments in freshwater basins as the Claron Formation, forming an angular unconformity with the underlying Straight Cliffs Fmn.

Hoodoos are rock pillars / spires resulting from differential erosion by water and ice (Fig. 3.1). Around 10-15 Ma, the Paunsaugunt Plateau was caught and lifted by the Colorado Plateau. The resulting joints now provide space for snowmelt to run into and freeze. This frost-wedging facilitates gully, slot canyon, and hoodoo formation. Limestone, dolomite, and siltstone provide the hoodoo's caprock, while mudstone is gradually eroded during rainfall. The moistened mud runs down the rock sides, forming *mud stucco* – effectively a protective coating against wind erosion.

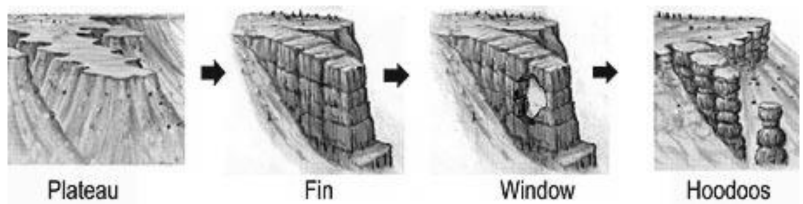


Figure 3.1: Progression of hoodoo formation in Bryce Canyon. Public Domain image, from https://commons.wikimedia.org/wiki/File:Hoodoo_formation-Big.jpg.

February 23rd: Zion National Park

The narrow canyons, mesas, rock towers and plateaus of the Zion and Kolob canyons area represents the middle step in the Grand Staircase (Appendices B-C). Zion Canyon was cut by the North Fork of the Virgin River during Tertiary uplift. At Zion National Park, formations dip gently eastward, and the oldest strata is exposed along the Virgin River in Zion Canyon, while the youngest occurs in the Kolob Canyons. The plateau is bounded by two fault zones; the Sevier on the east and the Hurricane on the west.

Cherty, fossil-rich Kaibab Limestone – the oldest formation at Zion – is the youngest exposed at the Grand Canyon. The youngest formation at Zion – the Dakota Sandstone – forms the oldest strata exposed at Bryce Canyon. Seven other formations compose the stratigraphic section at Zion. Of special interest is the Upper Triassic Chinle Formation (containing the Petrified Forest Member, along with uranium ore, Fe-Mn oxides and Cu sulfides) and the Mid-Jurassic Navajo Sandstone (displaying sweeping cross-beds composed of 98% rounded quartz grains).

February 24th: Springdale, UT – Flagstaff, AZ. Grand Canyon National Park

See Appendix C for the Grand Canyon's stratigraphy.

The Grand Canyon (the 15th U.S. National Park and also a UNESCO World Heritage Site) is 446 km long, up to 29 km wide, and 1.6 km deep. The North Rim is closed during the winter; thus, we will visit the South Rim and the most popular viewing sites. If time permits, we will hike the Grandview Trail onto Horseshow Mesa, viewing the ruins of the historic Grandview Mine and Last Chance Mine en route. Located about 1 km below the canyon rim, these copper mines were first staked in 1890 and operated from 1892-1907. High grade ore (sometimes exceeding 70% Cu) was hauled out daily along the Grandview Trail by a string of mules. The trail from Grandview point to Horseshoe Mesa was built by the miners for the mule teams; you may note steep sections of the trail that are paved with stone to improve the mules' footing. As with other deposits in the Grand Canyon region (see *Background* above), mineralization is hosted in breccia pipes. This is the type locality for Grandviewite – $Cu_3Al_9(SO_4)_2(OH)_{29}$, just one of the many secondary copper minerals found here. Bat-friendly gating of the unstable adits was funded by Freeport-McMoRan in 2009.

Another mine – the Orphan Mine – was located a few km west of today's Grand Canyon Village. It operated from 1953-1969 as one of the most productive uranium mines in the region, producing around 1930 tonnes of uranium oxide (estimated at $40 million), 3030 tonnes of copper, 50 tonnes of silver, and 1.5 tonnes of vanadium oxide.

While at the Rim, try to spot the Great Unconformity. Within the Grand Canyon, this global unconformity that separates Cambrian strata with abundant fossil evidence from Precambrian, fossil-poor rocks represents from 250 to 1200 million years of "missing time" (e.g., erosion). Depending on your location in the Canyon, you will see 525 Ma Tapeats Sandstone overlying 1.85-1.65 Ga Vishnu Schist (pervasively intruded by Zoroaster Granite) or some part of the 1200-800 Ma Grand Canyon Supergroup (composed of the 1.1 Ga Unkar Group (Bass limestone, Hakatai shale, Shinumo quartzite), Chuar Group, Nankoweap Fmn, and Cardenas lavas. Although we won't make it to the bottom of the Canyon to actually touch the Unconformity, there will be a couple opportunities for that later in this trip!

PART FOUR: Southern Arizona (February 25th-28th)

Background

As we leave Flagstaff and drive south off the Colorado Plateau into the Sonoran Desert (back into the Basin and Range Province), we will cross the Mogollon Rim. This escarpment forms the southwestern edge of the Colorado Plateau, running for about 320 km. Most land south of the Mogollon Rim lies at 1200-1500 m above sea level; the escarpment is about 2400 m in elevation. Lava flows cap the Rim in many places. Interstate 17 bisects the Mogollon Rim (between Flagstaff and Phoenix). One of our stops en route – Sedona – lies near the Rim.

Continuing into the Sonoran Desert of southeastern AZ, we will encounter a series of high valleys and mountain ranges with topographic relief spanning valleys at 1525 m elevation to mountain peaks at 3050 m. Later, as we drive back to Las Vegas on the desert's western boundary, maximum relief will decrease (ranging from sea level to 915 m).

Although mines on the Colorado Plateau did produce copper and other metals in the past, now all of the large, open pit porphyry copper mines and others that yield Arizona's metal production lie in the Basin and Range Province.

From Rasmussen (2012):

Arizona is known as the Copper State because about two-thirds of the copper produced in the U.S. comes from Arizona each year. This copper is produced from the large porphyry copper deposits that were created during the middle Laramide mountain building phase (66-55 Ma) in the early Tertiary period. These disseminated copper deposits are associated with porphyritic granitic intrusions. Examples of the Laramide porphyry copper deposits include mines in the Tucson area: the Pima district (Twin Buttes, Sierrita- Esperanza, Rosemont, and Mission-Pima mines) south of Tucson, the Silver Bell mine northwest of Tucson, and the historic Ajo mine west of Tucson. The open pit copper mines also include mines in central Arizona: Ray, Miami, Pinto Valley, Carlota, Superior, and Resolution mines east of Phoenix; the Morenci and Safford mines of eastern Arizona; and the Bagdad and Mineral Park mines of northwestern Arizona. The porphyry copper systems are extremely large, covering most of any mountain range. These mining districts commonly have other types of deposits in a bulls-eye pattern outward from the copper-rich core in this sequence: copper-zinc, zinc-lead-silver-gold, and silver-manganese at the outer zones. Skarn deposits occur near the plutons. Oxidation and secondary enrichment have converted the primary copper mineral of chalcopyrite into richer copper secondary minerals of chalcocite, and the leachable 'copper oxide' minerals of azurite and malachite, and chrysocolla.

February 25th: Flagstaff – Tucson, AZ.

Our first stop en route to Tucson will either be in Sedona or Jerome. Both are popular tourist destinations. Jerome, a historic copper mining town once known as the wickedest town in the west, features a smaller "ghost-town" feel, fine historic museums, and abandoned Cu-Au-Ag mines that worked VMS deposits formed along a caldera ring fault. Sedona boasts a larger population and excellent hiking trails (most notable, the Lizard Head and Brins Mesa trails). Hematite staining in the Permian Schnebly Hill sandstone (located between the lower Hermit and higher Coconino Formations) is responsible for Sedona's picturesque red cliffs.

Great Unconformity near Payson, AZ

Located just a few km north of Payson along Highway 87 (as it curves southward into Payson) is a roadcut offering excellent exposure of the Great Unconformity, 525 Ma Tapeats Sandstone overlies 1.7 Ga Payson Granite. Other fine exposures are located in the area, including one less than 10 km north of Payson where Highway 87 crosses the East Verde River.

Superstition Mountains

As we continue south-southeast towards Tucson, we will pass the Superstition Mountains which stand roughly 60 km east of Phoenix. They are composed of welded tuff, breccia, rhyolite and granite, dacite, and conglomerate. A few gold deposits occur nearby. Around 25 Ma, explosive volcanic eruptions from three volcanic centers – "supervolcanoes" each 16-19 km across – yielded rhyolite flows and extensive ash deposits followed by caldera collapse, and then a final period of resurgence as renewed magma pressure forced the caldera interior upwards to form a resurgence dome. Later erosion produced thick alluvial fans radiating outwards from the dome.

February 26th: Porphyry-Cu Mineralization: Ray Mine (ASARCO)

ASARCO (the American Smelting and Refining Company), part of Grupo Mexico (one of the world's major copper producers), is a fully integrated miner, smelter, and refiner of copper in the US. Its domestic mines annually produce 350-400 million pounds of copper, with the significant mines all in Arizona (the open-pit Ray, Mission, and Silver Bell mines). The Ray and Silver Bell mines produce a solvent extraction / electrowinning product, and ASARCO operates a copper smelter in Hayden, AZ.

The open-pit Ray Mine (Fig. 4.1) has been in production since 1911, and has produced over 4.5 million tons of Cu (as of 1998). Underground mining (including block caving and shrinkage stope methods) were used until 1955, when most production was recovered from sulfide ore by concentrating and smelting. Since 1969, significant production has come from leaching and solvent extraction-electrowinning of silicate and oxide ores. Published reserves (as of 1992) were 1.1 billion tons at 0.6 % Cu.

Figure 4.1: Aerial view of the Ray Mine porphyry copper deposit. Photo courtesy of ASARCO, from Rasmussen, 2012 (Figure 9).

Porphyry copper (and lesser Ag-Au-Mo-Pb-Zn) mineralization is hosted in Pinal Schist, Granite Mountain Porphyry, Pioneer Shale (Apache Group), and Dripping Spring Quartzite (Fig. 4.2). Primary ore control is the intersection of NW and NE fault zones, permeability, and host rock. Ore has been concentrated and upgraded via secondary enrichment. Alteration includes sericitic, propylitic, biotite-clay, chloritization, and epidote.

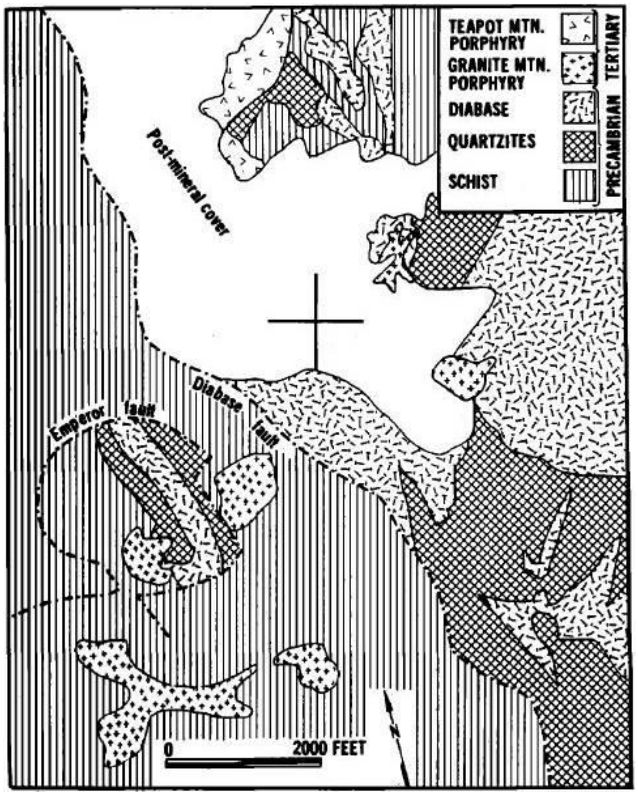


Figure 4.2: Generalized geologic map of the Ray copper deposit. Cross at center corresponds to the cross in Fig. xx. From Phillips, Gambell & Fountain (1974; Fig. 2).

Ray geology is complex due to faulting, two episodes of tilting, a complicated enrichment history, hypogene and supergene alteration, and removal of a large part of the original ore shell. This sulfide system developed in various Precambrian rocks and Laramide orogeny-related intrusives (Fig. xx). The oldest is the Pinal Schist, a sequence of metamorphosed shale, siltstone, sandstone and conglomerate with plutons or flows of rhyolitic porphyry. Precambrian Ruin Granite (quartz monzonite) intrudes the schist but postdates metamorphism. Tuffaceous mudstone to arkosic conglomerate of the Pioneer Formation and Dripping Spring Quartzite (upper Precambrian Apache Group) overlie the Pinal and Pioneer. A series of Laramide intermediate-felsic dikes and stocks intrude all older rocks; these include the Tortilla Quartz Diorite, Teapot Mountain Porphyry (qtz monzonite), and the Granite Mountain Porphyry. These are likely the source of hypogene Cu mineralization and alteration of the surrounding wall rock. Two large faults cross-cut the orebody: the Diabase Fault (displacement of around 460 m) and the Emperor Fault (displacement of over 900 m). The deposit's sulfide mineral zoning includes a central portion of low total sulfide and high ratio of chalcopyrite-pyrite, surrounded by a "doughnut"-shaped high copper zone of chalcopyrite to pyrite mix (Fig. 4.3).

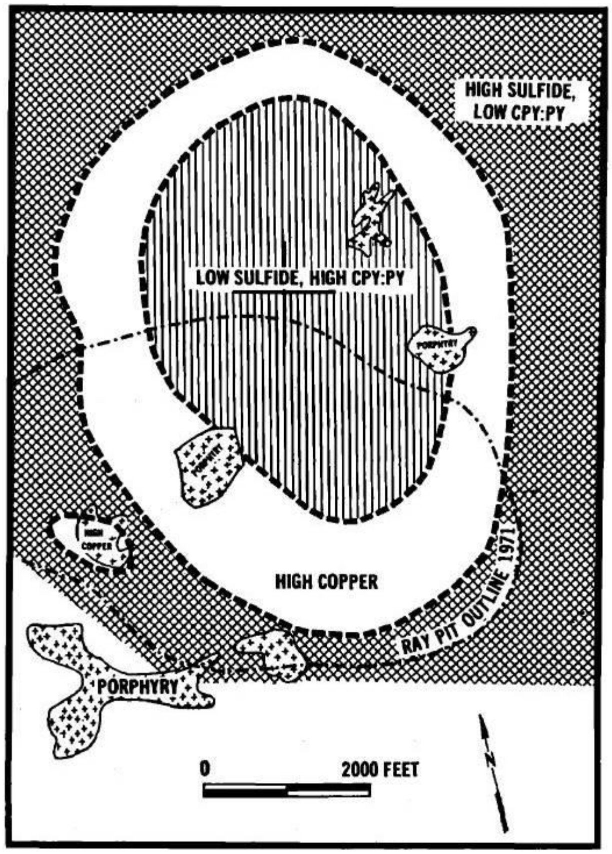


Figure 4.3: Generalized zoning of hypogene sulfides in the Ray deposit. Granite Mountain Porphyry shown. From Phillips, Gambell & Fountain (1974; Fig. 3).

February 27th: Kartchner Caverns

Abstract from Jagnow (1999):

Kartchner Caverns is developed entirely within the Mississippian Escabrosa Limestone in an isolated fault block along the east flank of the Whetstone Mountains in southeastern Arizona. Seven black to dark-gray marker beds throughout the lower Escabrosa section… [function as] key organic-rich marker beds. More than 60 mapped faults cut Kartchner Caverns and probably date to the Miocene emplacement of the Kartchner block… Kartchner Caverns developed near the 1408 m msl base level, and then stoped upwards along faults to resistant ceiling beds. Kartchner Caverns has been stable in its development for >50Ka.

February 28th: Tucson, AZ – Las Vegas, NV.

Great Unconformity at Frenchman Mountain

Frenchman Mountain stands along the eastern side of Las Vegas. Around 6-10 million years ago, extension and listric faulting in this part of the Basin and Range moved Frenchman Mountain eastwards an estimated 80 km from its original position, consequently tilting the strata about 50° to the east (Fig. 4.4). Present-day Lake Mead occupies the gap between the untilted strata of the Grand Canyon region and the dipping Frenchman Mountain block. At this stop, the Great Unconformity is well exposed; 1.7 Ga Vishnu Group schist and granite lie in sharp contact with 500 Ma Tapeats Sandstone. The "missing time" represents ¼ of earth's history! Walking eastwards, one would move up-section from the Cambrian Tapeats Sandstone (present at the base of the Phanerozoic section of the Grand Canyon) through to the Triassic Moenkopi Formation.

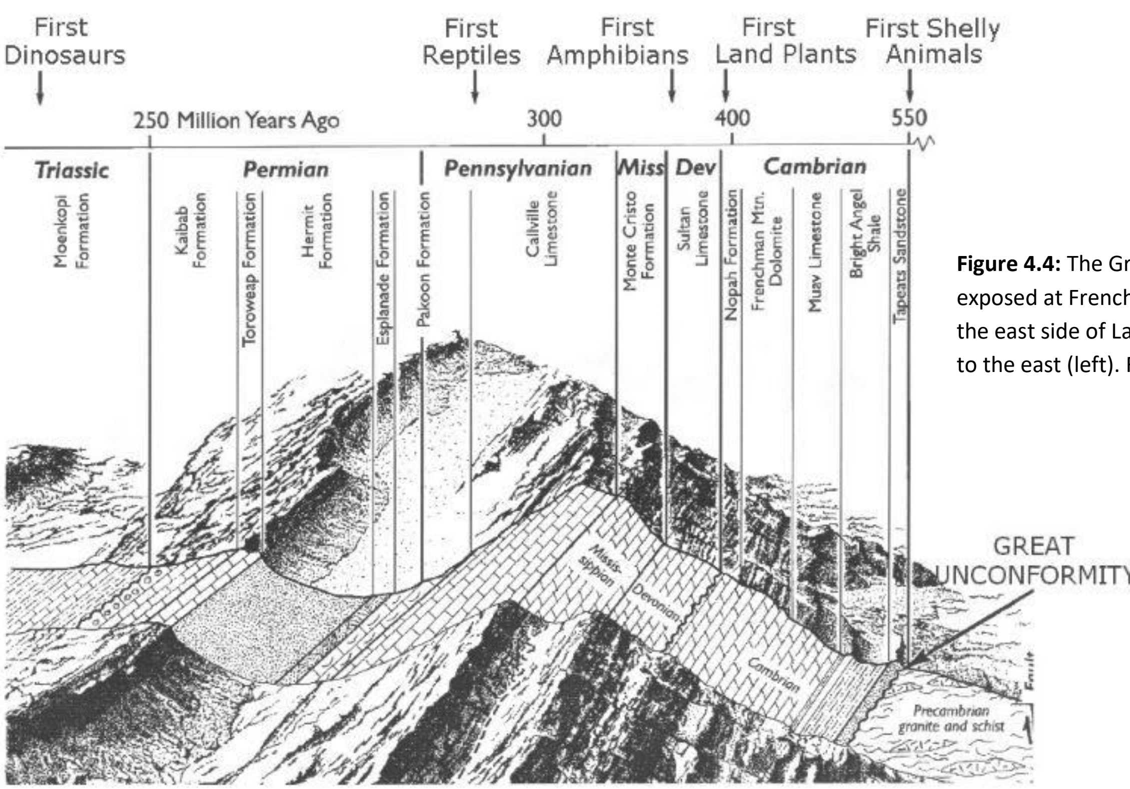


Figure 4.4: The Great Unconformity exposed at Frenchman Mountain on the east side of Las Vegas. Strata dips to the east (left). From Roland (n.d.).

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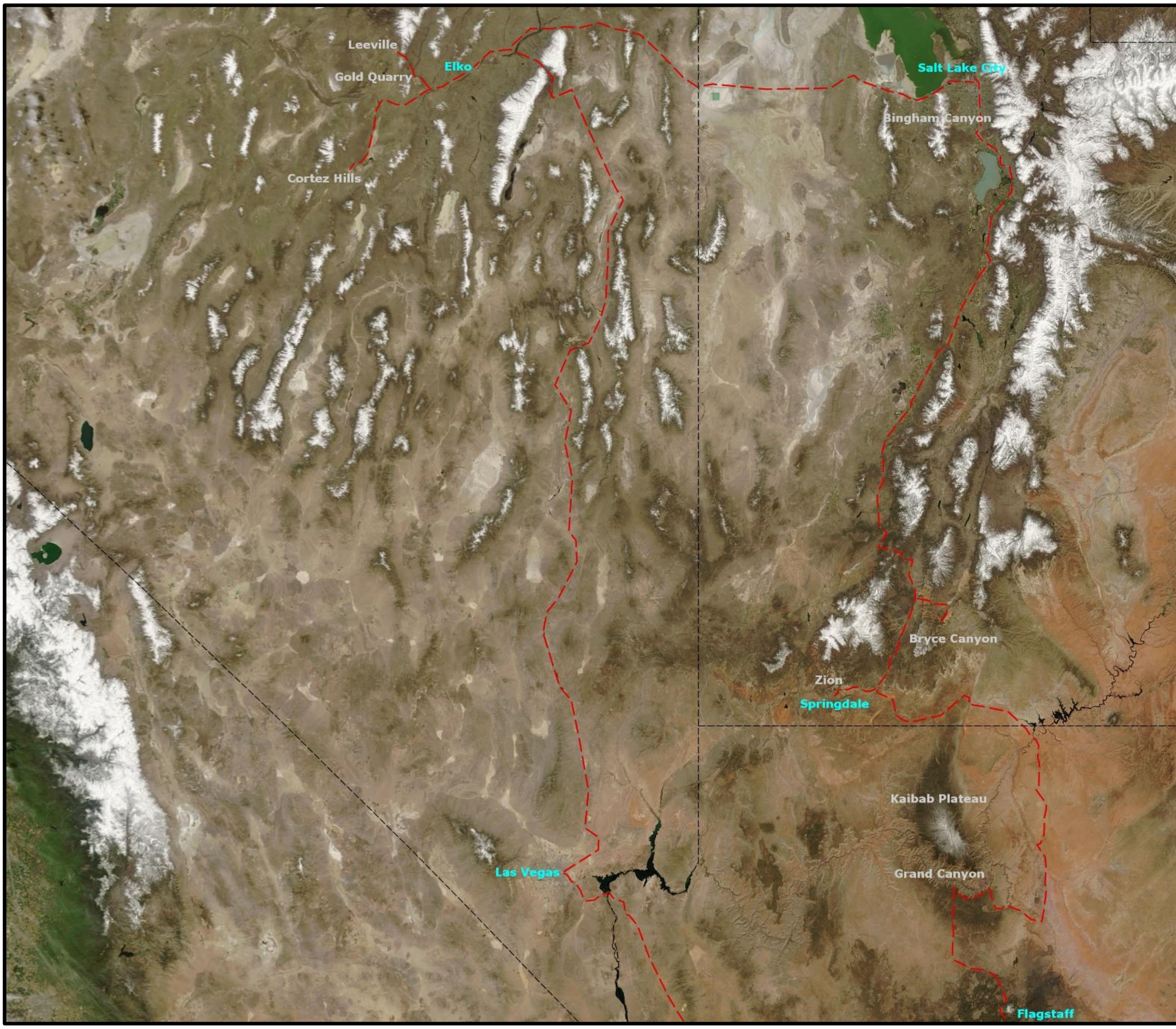


Appendix A: Overview map of this field trip Parts 1-3 (Part 4 – Southern Arizona – is not shown). Cities we will stay in (light blue) and mines / parks we will visit (gray) are noted; dashed red line delineates our route. Note the physiographic regions: we will be in the Basin and Range as we drive north from Las Vegas and cross from the Sonoran Desert into more mountainous terrain near Elko. After visiting the Carlin Trend, we will drive east to Salt Lake City and into a "transition zone" on the edge of the Colorado Plateau to the southeast (with the Rocky Mountains immediately to the east-northeast). Then, driving south towards Springdale, we will remain in this "transition zone" until climbing upwards to Bryce Canyon and Zion National Parks on the Colorado Plateau, which we will stay on until travelling south past Flagstaff during Part 4. MODIS 250 m satellite image.

Appendix B: Stratigraphy of the Grand Staircase

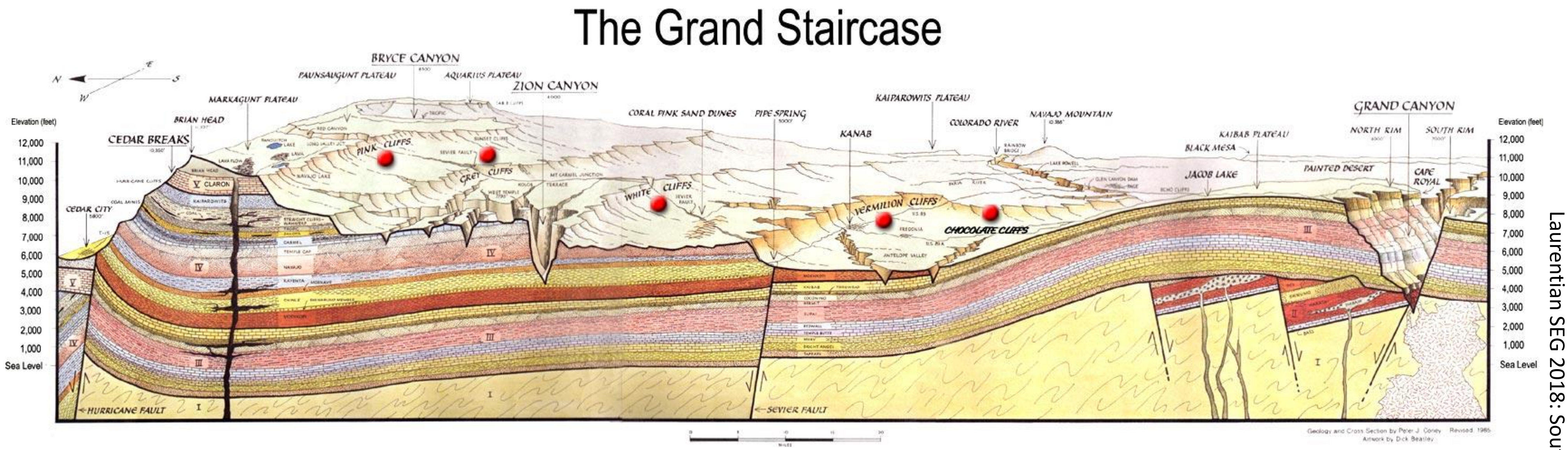
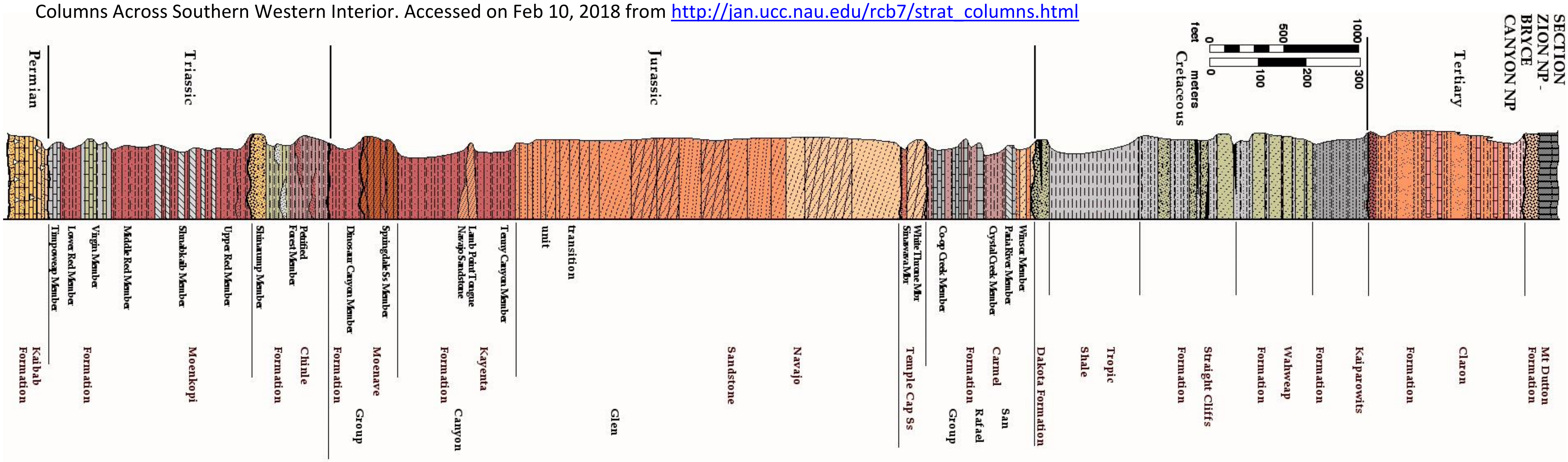


Figure B-1: Stratigraphy from Bryce Canyon south to the Grand Canyon. Red dots mark the five “steps” (cliffs) of the Grand Staircase. From left to right (north-south): Pink, Grey, White, Vermillion and Chocolate Cliffs. Geology and cross-section by Peter J. Coney; artwork by Dick Beasley. Revised 1985. Obtained from Wikimedia Commons at https://commons.wikimedia.org/wiki/File:Grand_Staircase-big.jpg

Figure B-2: Stratigraphic section of Bryce Canyon and Zion National Parks. Image from Blakey, R. (n.d.). Stratigraphic Columns Across Southern Western Interior. Accessed on Feb 10, 2018 from http://jan.ucc.nau.edu/rcb7/strat_columns.html



205-145 Ma: Nevadan orogeny; granitic intrusions in southeast AZ created porphyry Cu-Au deposits; volcanic ash and Petrified Forest Member of Chinle Fmn; Aztec / Navajo Sandstone

250-205 Ma: Pangea formed, breaks-up; US west coast became leading edge of westward-moving North American continent; subsequent volcanic and plutonic activity from subduction fueled mineralization that moved eastward across CA-AZ.

140-89 Ma: Sevier orogeny (in CA); subduction zone stable (did not flatten), so no vein-related mineralization in AZ. Sandstones and shales deposited in northern AZ; coal deposits in northeast.

89-43 Ma: Laramide orogeny, subduction zone flattens, volcanism migrates eastward, overprinting previous mineralization; caldera collapse in supervolcanoes of southern AZ creates ring and radial fractures for hydrothermal fluids to deposit Ag-Pb-Zn veins (Santa Rita Mountains, Tombstone Hills); granitic intrusions create large porphyry-Cu deposits (e.g., Ray mine); late granite / pegmatite intrudes deep in the crust during flat subduction / underthrusting towards the northeast under the CO Plateau, uplifting the Plateau.

42-15 Ma: Massive volcanic eruptions and resulting ash flow tuff-dominated mountain ranges (e.g., Superstition mountains); widespread volcanism, granitic intrusions; Au-Cu veins associated with dyke swarms, and Ag-Pb-Zn skarns along contact zones associated with caldera systems; uranium, secondary Cu, industrial mineral deposits in local basins.

5-0 Ma: CO Plateau eroded

542-251.5 Ma: AZ on trailing edge of eastward-moving continent; stable, passive margin; orogenies in eastern US (Taconic, Acadian, Alleghenian) fed sediments – sandstone and siltstone – with limestone deposited between transgressions / regressions.

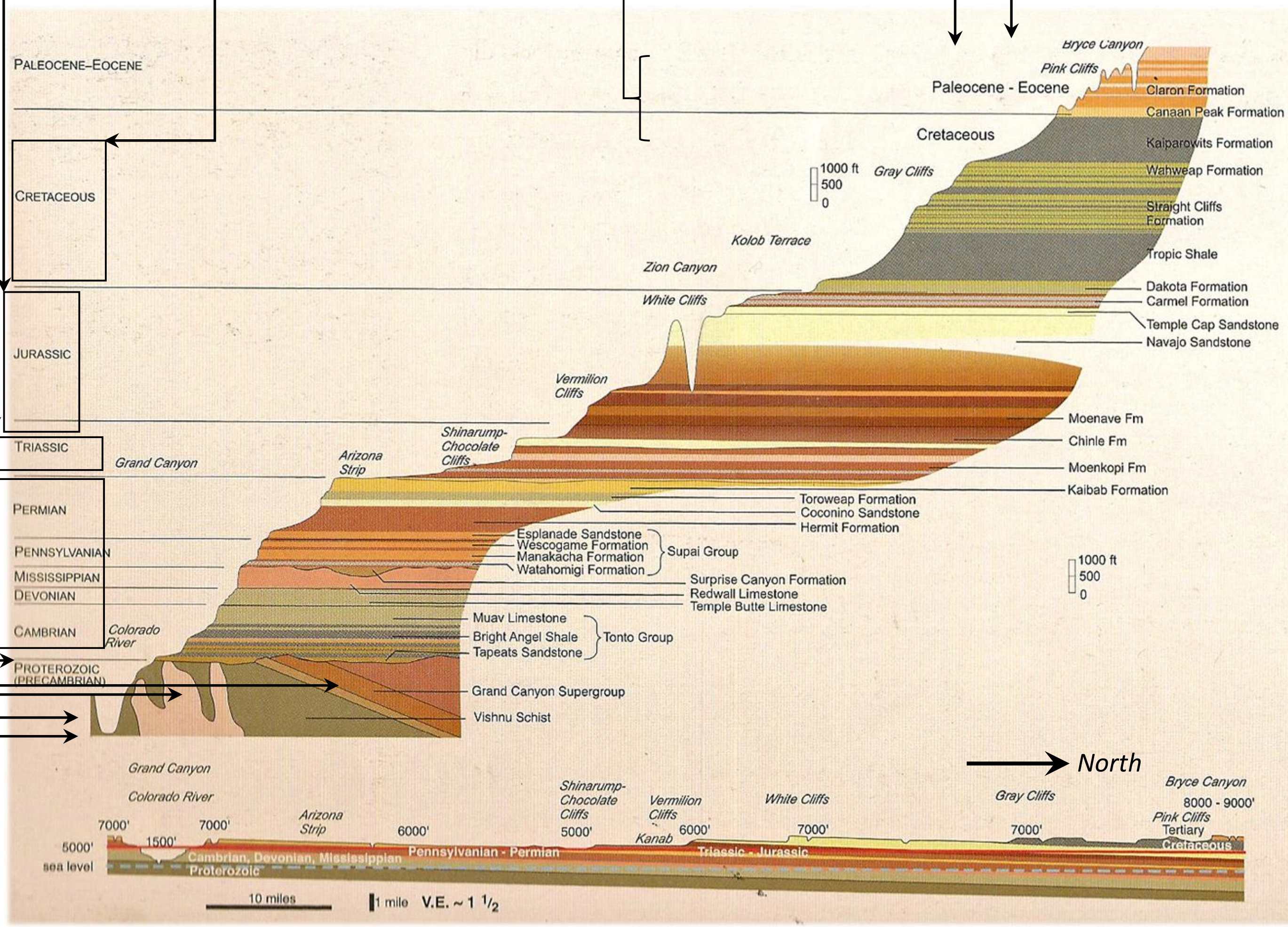
The Great Unconformity (representing a gap of up to 900+ million years - 350 million years of erosion - in Grand Canyon).

1200-1000 Ma: Grenville orogeny; sedimentary strata deposited in basins (Apache Group, Unkar Group in Grand Canyon, overlain by 850 Ma Chuar Group and Sixtymile Fmn).

1450-1400 Ma: orthoclase phyric granite intrusions (including Oracle Granite of Tucson area, Ruin Granite in Ray-Superior area, Zoroaster Granite in Grand Canyon); exotic Be-Li-Ta-Nb-Bi-U-W minerals in veins; NW-trending "Texas Zone" of faults / fractures, which act as later mineralizing fluid pathways.

1700-1615 Ma: Mazatzal orogeny; Pinal Schist and granite-granodiorite intrusions.

1800-1740 Ma: Yavapai orogeny; oldest Precambrian rocks in northern AZ (metamorphosed volcanic and sedimentary rocks, including Verde district Cu-Zn VMS at Jerome).



Appendix C: Representative stratigraphic section of northern-central Arizona. Descriptions apply to some locations beyond the extend of this strat section; placement of events is approximate. Image by Blakey and Ranney (2008); image obtained from http://written-in-stone-seen-through-my-lens.blogspot.ca/2011/01/grand-staircase.html. Descriptions from Rasmussen (2012).

Appendix D: Descriptive Model of Solution-Collapse Breccia Pipe Uranium Deposits

Warren I. Finch, USGS

Note: *References and text have been retained as published; for complete references, visit https://pubs.usgs.gov/bul/b2004/html/bull2004 breccia_pipe_uranium_deposits.htm*

BRIEF DESCRIPTION

Synonym: Collapse breccia pipe deposits, sedimentary breccia pipe deposits, Orphan Lode-type deposit.

Description: Uraninite and associated sulfide, arsenide, sulfate, and arsenic-sulfosalt minerals as disseminated replacements and minor fracture fillings in distinct bodies in near-vertical cylindrical solution-collapse breccia pipes, 30-175 m in diameter and 1,000 m in length. Pipes located in flat-lying upper Paleozoic and Triassic rocks restricted to the Grand Canyon region in the southwestern part of the Colorado Plateau.

Typical Deposits: Orphan Lode (Chenoweth, 1986; Gornitz and others, 1988), EZ-2 (Krewedl and Carisey, 1986), Pigeon (Schafer, 1988) all in Arizona.

Relative Importance: One of two dominant high-grade sources of United States uranium production in 1987; expected to be major source of future uranium production within the United States.

Commodities: U

Other Commodities: ± Cu± V± Ag± Au

Associated Deposit Types (*suspected to be genetically related): *Sandstone uranium; supergene enrichment of Cu and V and depletion of U in deeply eroded and weathered pipes--typical example, Ridenour, Arizona (Chenoweth, 1988); Apex germanium- and gallium-bearing breccia pipe nearby in Basin and Range province (Wenrich and others, 1987).

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic Setting: Pipes found within and along the southwest margin of the Colorado Plateau, in a stable block existent since the Precambrian and resistant to tectonic forces acting on the western part of the North American plate. Wall rocks of pipes were deposited on a stable marine platform. Pipes apparently originated along and at intersections of N. 50° E.- and N. 45° W.-trending joint or fracture sets (Wenrich and Sutphin, 1989), roughly parallel to orthogonal Colorado River (N. 45° E.), Zuni (N. 45° W), and related lineaments shown by Green (1988, fig. 4) that developed in the Precambrian and rejuvenated in later periods. No igneous rocks are found in the pipes.

Regional Depositional Environment: Breccia pipes developed from solution collapse within the thick Mississippian Redwall Limestone (0-210 m) beginning in the Late Mississippian and propagated upward into overlying strata of carbonate-cemented sandstone, siltstone, limestone, and conglomerate for at least 1,000 m, apparently only where the Redwall is >15 m thick. Stoping was intermittently active and reached the lower members of the Chinle Formation in Late Triassic time.

Age Range: Host wall-rocks for pipes: Late Mississippian to Late Triassic. Ores: 260-200 Ma (Ludwig and Simmons, 1988).

LOCAL GEOLOGIC ATTRIBUTES

Host Rocks: Karst-collapse breccia. Breccia clasts as wide as 10 m across, consisting mainly of sandstone (~90 percent) and siltstone (~10 percent), occur in a matrix of quartz grains that is commonly well-cemented with carbonate minerals. Minor claystone and limestone clasts.

Associated Rocks: Unbrecciated flat-lying sandstone, siltstone, and limestone.

Ore Mineralogy: Principal ore minerals: uraninite ± roscoelite + tyuyamunite* + torbernite* + uranophane * + zeunerite* + chalcopyrite + bornite* ± chalcocite* ± malachite* + azurite * + brochantite * + volborthite + naumannite. Associated base-metal minerals: ± sphalerite ± galena ± bravoite ± rammelsbergite + stibnite + molybdenite + skutterudite. An asterisk indicates sugergene origin. Pre-uraninite mineral assemblages resemble those of Mississippi Valley-type deposits. Unusual complexity of mineralogy shown in appendix E.

Gangue Minerals: Pyrite + marcasite + calcite + dolomite + barite + anhydrite ±s iderite ± hematite ± limonite ± goethite ± pyrobitumen (see app. E).

Texture And Mineral Zoning: Orebodies occur as discontinuous pods mainly in the core of the breccia pipe but some are also found in the annular-ring structure and may occupy as much as a 200-m vertical interval (fig. 20). Mainly replacement and sparse open-space filling. Pyrite/marcasite and base-metal sulfides, locally associated with pyrobitumen, form a discontinuous "massive sulfide cap" above the uranium deposits in many pipes. Uranium, vanadium, and copper roughly zoned within some deposits.

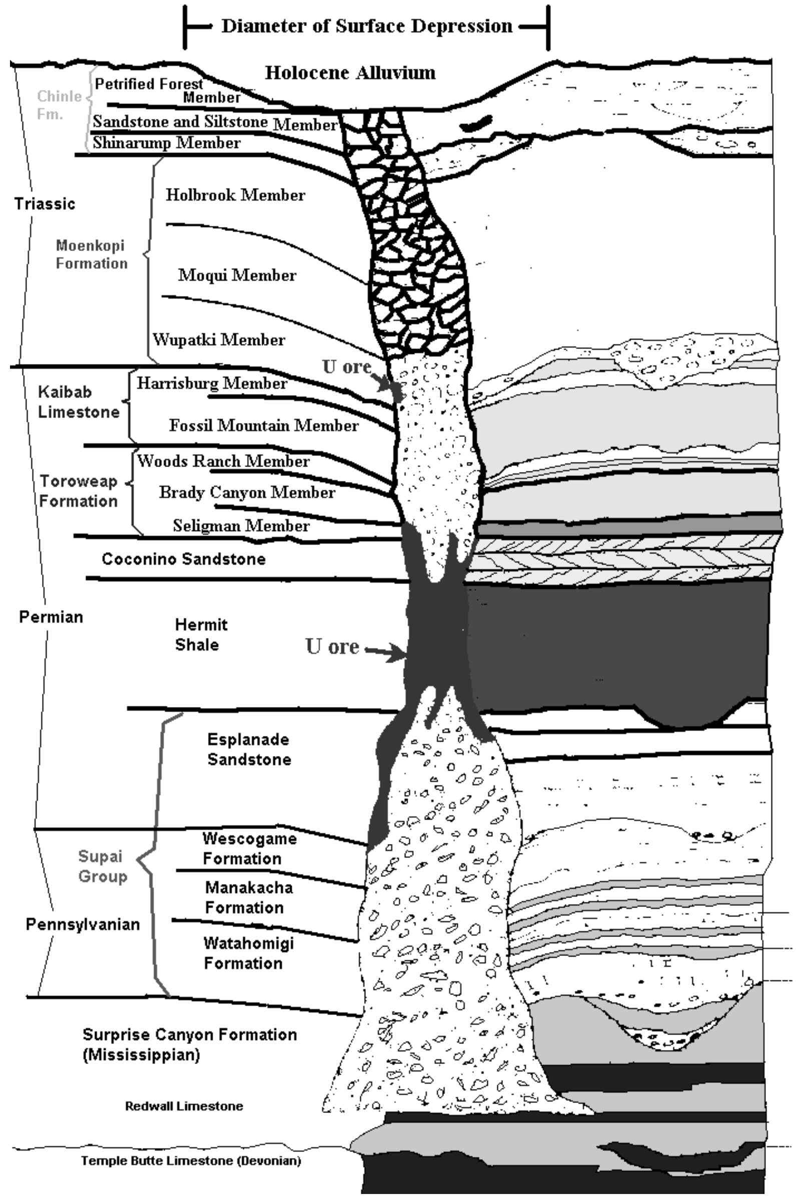


Figure 20. Schematic cross section of a solution-collapse breccia pipe in the Grand Canyon region, showing the general distribution of uranium ore within the pipe (stratigraphic section modified after Van Gosen and Wenrich, 1989). [Because of limitations on the reproduction of the original figure, the figure shown here does not contain all of the detail of the original.]

Ore Controls: Fractured, permeable rock within breccia pipe. Nearly all primary ore confined to the breccia pipe: rarely, a little uranium ore is reported in relatively undisturbed beds outside the ring structure. Vertically, most primary ore is below the Coconino Sandstone and at the level of the Hermit Shale and the Esplanade Sandstone of the Supai Group (fig. 20).

Isotopic Signatures: See Age Range above.

Fluid Inclusions: Fluid-inclusion-filling temperatures of 80-173°C for ore-related sphalerite, dolomite, and calcite. Salinities (in weight percent NaCl equivalent) are for sphalerite, [= or >] 9, for dolomite, [= or >] 17, and for calcite, [= or >] 4 (Wenrich, 1985; Wenrich and Sutphin, 1988).

Structural Setting: All ore associated with solution-collapse breccia pipes.

Ore Deposit Geometry: Orebodies develop in annular-ring structures and in the core (fig. 20). At Orphan Lode, orebodies in core range from 15 to 60 m in diameter and from 30 to 90 m high; annular-ring orebodies are 5-20 m wide, and a few tens of meters high, and extend variably part way around ring circumference (Chenoweth, 1988).

Alteration: Characteristic bleaching by reduction (some extends locally outward into wall rocks as much as 30 m); common carbonate recrystallization and calcification, local dolomitization and kaolinization, some weak silicification. Calcified rock extends outside boundary shears, completely surrounding the Orphan Lode pipe. Malachite, azurite, goethite, and other secondary minerals on surface outcrops of eroded pipes.

Effect of Weathering: Leaching of U and enrichment of Cu and V, particularly in those pipes deeply weathered. "Massive sulfide cap" apparently prevented oxidation prior to erosion and exposure.

Effect of Metamorphism: Not applicable.

Geochemical Signatures: Enrichment of Ag, As, Ba, Cd, Co, Cr, Cs, Cu, Hg, Mo, Ni, Pb, Sb, Se, Sr, U, V, Y, Zn, Zr, and REE; indicator elements are Ag, As, Co, Cu, Ni, Pb, and Zn (Wenrich, 1985).

Geophysical Signatures: Electrical conductivity and magnetic properties of the pipes are significantly greater than for unbrecciated rocks; diagnostic differences in conductivity shown by scalar audiomagnetotelluric (AMT) and E-field telluric profile data for one pipe (Flanigan and others, 1986). Ground magnetometer surveys show subtle low magnetic values over several pipes (Van Gosen and Wenrich, 1989).

Spatial Exploration Guides: Collapse features recognized by concentrically inward-dipping beds, circular concave topography, circular patches of brecciated and (or) bleached or iron-stained rock (related to "massive sulfide cap") and differences in vegetation. In well-exposed areas of the Marble Plateau, collapse breccia pipe densities are 0.11 pipes per square kilometer. Marked tendency for pipes to occur in clusters as small as 3 km2 in diameter. The presence of one pipe indicates a high probability for other pipes nearby.

Other Exploration Guides: For a new area outside of the Grand Canyon region, a thick (>15 m) flat-lying, karst-forming limestone overlain by a thick sequence of predominantly carbonate-cemented sandstone and siltstone within a perpetually stable cratonic environment and a post-pipe formation volcanic source for uranium. Preexisting Mississippi Valley-type Cu-Co-Ni-Pb-Zn sulfide-rich ore may be required as a reductant for uranium deposition.

Overburden: Favorable area on Coconino Plateau (fig. 20): depths to mineralized portion of pipes are 150-600 m. Area exposed on Esplanade surface (fig. 20): depths are 0-120 m. Additional cover by basalt, 0-100 m thick, around San Francisco and Mt. Floyd volcanic fields. Quaternary and Tertiary sediments, 0-50 m thick, cover a few areas.

Other: Tectonic stability required for preservation. "Massive sulfide cap" prevented and delayed oxidation of some breccia pipe ores. Goethite possible pathfinder mineral for recognition of concealed pipe.