

Arizona Minerals through Geologic Time

Copper , Bisbee



200 Ma (million years ago)

Silver, Lucky Cuss m.



75 Ma



Gold, Gold Basin,
Mohave Co., AZ

69 Ma

by Jan C. Rasmussen, Ph.D.

www.janrasmussen.com/research

Assisted by Stanley B. Keith

Orogenies in AZ

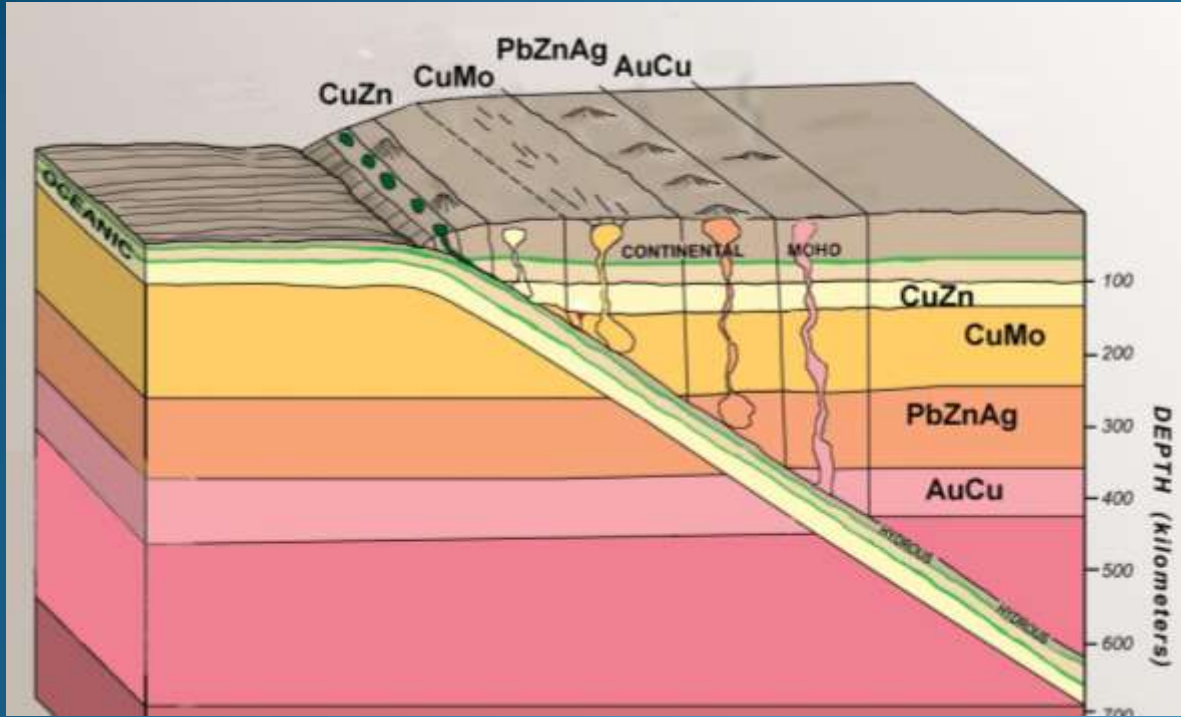
Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
San Andreas	Late	2.6 - 0.012	olivine; gypsum	Peridot Mesa, Camp Verde	Olivine, glauconite; gypsum;
	Early	13-2.6	Zeolites, salt	San Francisco volcanics, Luke salt	Clinoptilolite, hectorite; halite
Galiuro	Late	28-10	Mn, U, Au-Ag	Artillery Mts., Anderson, Oatman, Mammoth	Mn oxides, camotite, gold, Tiger suite, specularite
	Middle	28-15	PbZnAg(AuCu)	Ash Peak, Red Cloud, Aravaipa	Cassiterite; silver, galena, sphalerite
	Early	30-21	Au (CuWAg)	Kofa, South Mountain, Gila Bend Mountains;	Gold, todorokite, chalcophanite, pyrolusite
Laramide	Late	65-29	Actinolite, garnet	Cemetery Ridge, Garnet Ridge	Actinolite, serpentine group, pyrope garnet
		70-35	Au	Gold Basin, Vulture	gold, kyanite
		60-40	W	Blue Bird	wolframite group, scheelite
	Middle	65-55	Cu-Mo-Ag	Ajo, Ray, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci	chalcocopyrite, molybdenite, pyrite, bornite, epidote, garnet
	Early	75-65	Ag,Pb-Zn	Tombstone, Glove, Empire, Ruby, Salero	galena, sphalerite, alabandite, tetrahedrite, silver, enargite
	Earliest	89-75	Cu-Au-Ag	Old Yuma, Mexican Hat, Golden Rule	gold, galena, cerussite, mottramite, wulfenite, vanadinite
Sevier	Late	93-91	U	Black Mountain (U)	carnotite; tyuyamunite, hewettite
	Middle	100-89	Coal, fire clay	Dakota Ss, Deer Creek coal	Coal, kaolinite
	Early	135-110	calcite flux	Paul Spur	calcite
	Early	154-135	U-V-Cu (Ni-Co)	Orphan, Hermit, Arizona 1, EZ-2, Pigeon	pyrite, uraninite, bravoite, sphalerite, chalcocopyrite, galena
Nevadan	Late	175-155	Au	Nogales	gold
		175-155	W veins	Las Guijas, Juniper Flat	wolframite group, hübnerite, scheelite
		160-155	Kyanite	Tung Hill	dumortierite, rutile, scheelite
	Middle W AZ	173-155	Pb-Zn-Ag	Comobabi Mts., Cababi (Mildren-Steppe Mine)	galena, sphalerite, tetrahedrite
		189-155	AuCu (AgWPb)	La Cholla, Sugarloaf (Big Bertha), Jaeger	quartz, pyrite, gold, chalcocopyrite, specular hematite
	Early SE AZ	191-175	Pb-Zn-Ag(CuAu)	Gleeson (South Turquoise), Hartford	galena, sphalerite, tetrahedrite, cerussite, wulfenite
		201-191	Cu-Au, PGE	Warren (Bisbee), Turquoise (Courtland)	chalcocopyrite, bornite; azurite, malachite, cuprite, copper
Early N AZ	237-201	U-V-Cu (Ni-Co)	Orphan , Grandview; Monument Valley	uraninite, chalcocopyrite, galena, torbernite; camotite	
Ouachita	Pangea	318-271	NaCl, K, salt	Holbrook salt, potash	sylvite, carnallite, polyhalite, halite, gypsum, anhydrite
Antler (NV)	Laurentia	380-357	oolitic iron	Payson "diamond quartz"; Ranch Cr. Fe	'Herkimer habit' quartz, oolitic hematite
Keweenawan	failed rifting	1104-1035	asbestos; U (Cu)	Sierra Ancha, Hope	chrysotile asbestos, lizardite; uraninite, pyrite
Elzevirian	Arc	1360-1240	hematite	Apache Iron, Chediski Iron	hematite, apatite, muscovite, chert
Picuris	Late	1460-1370	Be, Li, Ce, Ta-Nb	White Picacho; Wagon Bow, Tungstona	spodumene, lepidolite, scheelite, beryl, wolframite group
	Early	1470-1420	Fe, amethyst	Four Peaks Amethyst	amethyst, hematite, fluorapatite
Mazatzal	Late	1630-1610	Au (Ag Pb Cu Bi)	Yellowstone	Gold, quartz, baryte, bismuth minerals, tourmaline, zircon
	Early	1630-1590	W, Be, F, LREE;	Black Beauty, Kingman Feldspar	scheelite, beryl, allanite-Nd, bastnaesite; microcline
	Middle	1680-1630	Au	Roosevelt, Spring Creek, Prescott, Thumb Butte	gold
	Early	1702-1680	Be, F	Breadpan Fm., Gordon Creek pyrophyllite	acicular beryl, tourmaline, topaz; pyrophyllite
Yavapai	Late	1715-1690	W(Be)	Boriana, Money Maker-North Star	scheelite, beryl, hübnerite, wolframite, microcline, quartz,
	Early	1770- 1715	Hg;Au(Ag);MoCu	Phoenix Mts. Hg; Groom Creek; Squaw Peak	cinnabar, kyanite, tourmaline; gold, quartz;molybdenite
	Early	1750-1720	Zn-Cu-Ag VMS; Fe-Si BIF,	VMS Jerome, Antler; Pikes Peak Fe-Si	VMS (pyrite, chalcocopyrite, sphalerite, galena, cubanite, arsenopyrite, pyrrolite; chert-hematite (magnetite);
Mohave		1820-1780	None	None	muscovite, garnet, feldspar

1840 Ma

Jan C. Rasmuss

Alkalinity and Minerals

In oxidized crust (Arizona)



Modified from:
Keith, 1978

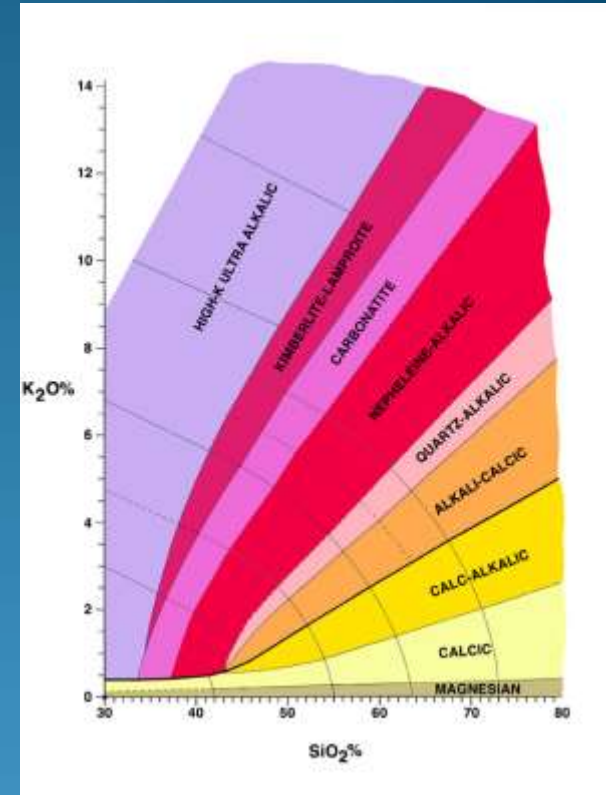
Pink = AuCu

Orange = PbZnAg

Yellow = CuMo

Pale yellow = CuZn

Overprinting of different magma chemistries from different mantle layers and crustal sources give Arizona a variety of mineral signatures through time



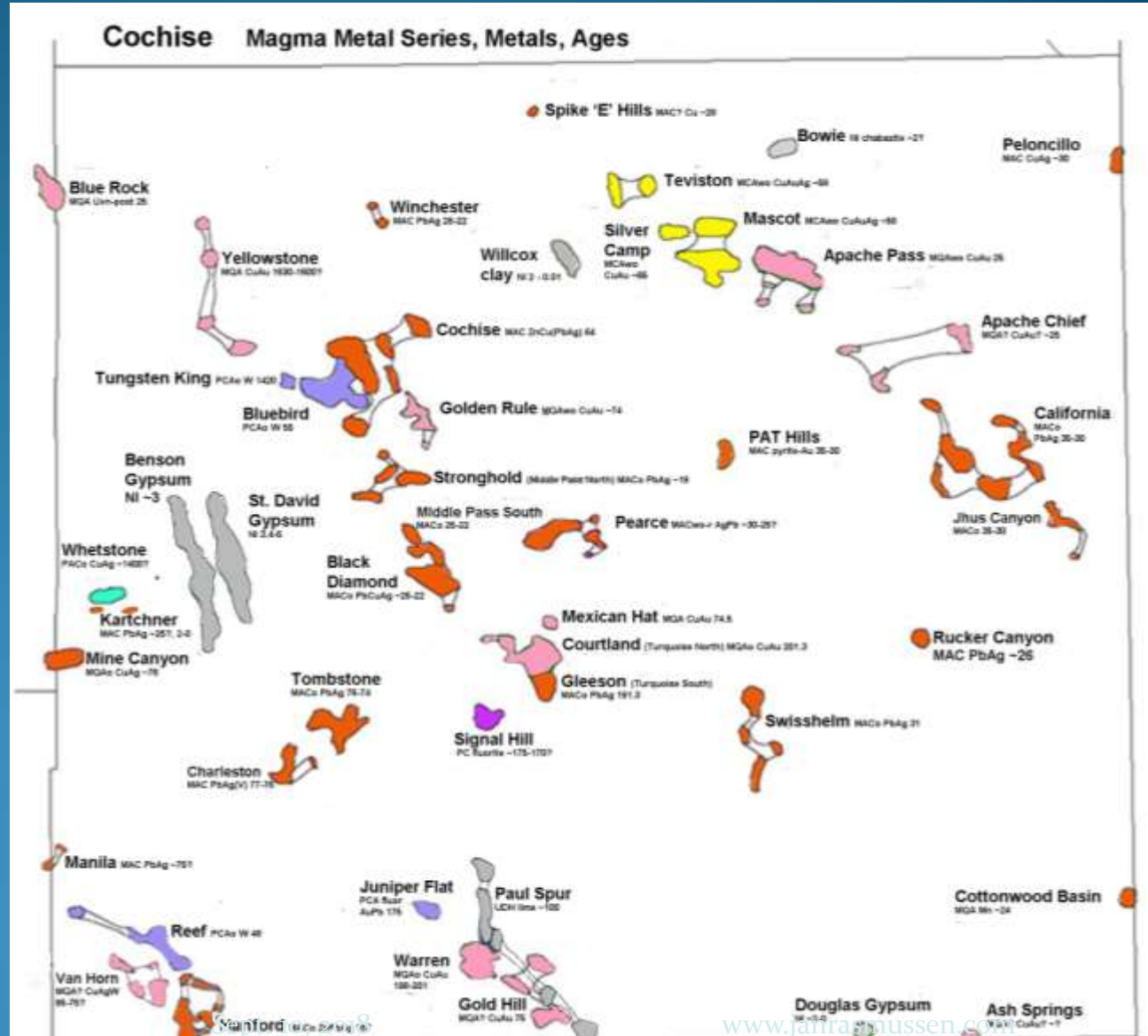
K₂O vs SiO₂ variation diagram with alkalinity fields for whole rock geochemistry of associated igneous rocks

Very complex, overprinted mountain building cycles bring new minerals

Re-organization events in between, allow oxidation of the sulfides into collectible minerals.

Example of Mineral District map

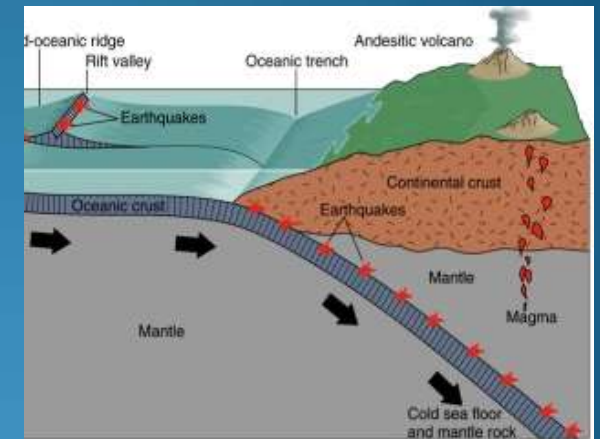
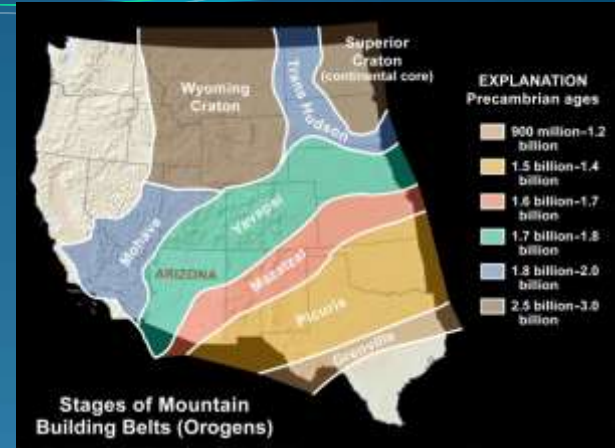
To be in 4th edition of Mineralogy of Arizona, 2020



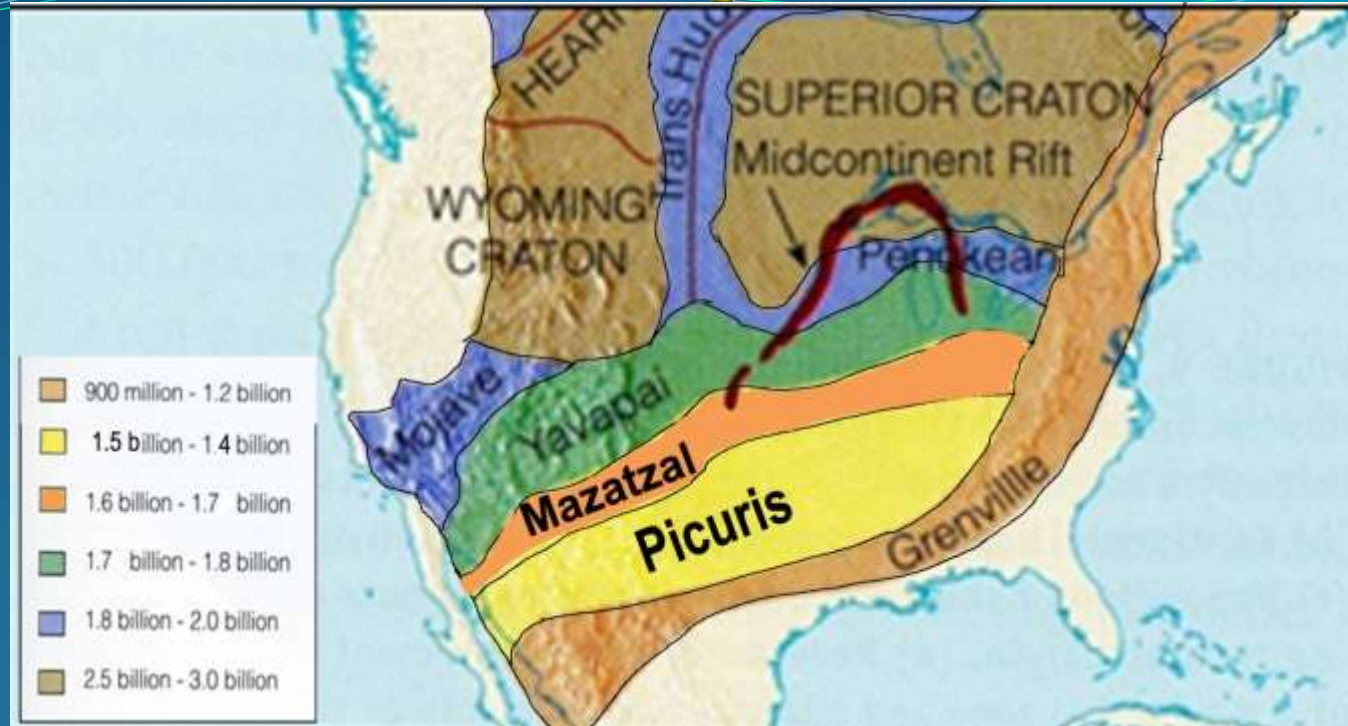
Arizona Mineralization through Geologic Time

Mineralization is related to mountain building episodes

- **Precambrian = orogenies added to fringes of continent**
- **Paleozoic = AZ on trailing edge**
- Eastern orogenies - **no metals**
- **Mesozoic-Cenozoic = AZ on leading edge = Cordilleran orogeny - many metals**
- **Latest Cenozoic = subduction cutoff by San Andreas transform margin - no metals**



Precambrian Orogenies in Arizona



Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Elzevirian	Arc	1360-1240	hematite	Apache Iron, Chediski Iron	hematite, apatite, muscovite, chert
Picuris	Late	1460-1370	Be, Li, Ce, Ta-Nb	White Picacho; Wagon Bow, Tungstona	spodumene, lepidolite, scheelite, beryl, wolframite group
	Early	1470-1420	Fe, amethyst	Four Peaks Amethyst	amethyst, hematite, fluorapatite
Mazatzal	Late	1630-1610	Au (Ag Pb Cu Bi)	Yellowstone	Gold, quartz, baryte, bismuth minerals, tourmaline, zircon
	Early	1630-1590	W, Be, F, LREE;	Black Beauty, Kingman Feldspar	scheelite, beryl, allanite-Nd, bastnaesite; microcline
	Middle	1680-1630	Au	Roosevelt, Spring Creek, Prescott, Thumb Butte	gold
	Early	1702-1680	Be, F	Breadpan Fm., Gordon Creek pyrophyllite	acicular beryl, tourmaline, topaz; pyrophyllite
Yavapai	Late	1715-1690	W(Be)	Boriana, Money Maker-North Star	scheelite, beryl, hübnerite, wolframite, microcline, quartz.
	Early	1770- 1715	Hg, Au(Ag), MoCu	Phoenix Mts. Hg; Groom Creek; Squaw Peak	cinnabar, kyanite, tourmaline; gold, quartz; molybdenite
	Early	1750-1720	Zn-Cu-Ag VMS; Fe-Si BIF;	VMS Jerome, Antler; Pikes Peak Fe-Si	VMS (pyrite, chalcopyrite, sphalerite, galena, cubanite, arsenopyrite, pyrrotite; chert-hematite (magnetite);
Mohave		1820-1780	None	None	muscovite, garnet, feldspar

Yavapai - Jerome VMS (1.8 – 1.7 Ga)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Yavapai	Early	1770-1775	Pg, Au, Ag, Mo, Cu	Phoenix Mts., Ing., Groom Creek, Squaw Peak	Chalcopyrite, pyrite, sphalerite, galena, quartz, molybdenite
	Early	1750-1720	Zn-Cu-Ag VMS; Fe-Si BIF	VMS Jerome, Antler; Pikes Peak Fe-Si	VMS (pyrite, chalcopyrite, sphalerite, galena, cubanite, arsenopyrite, pyrrhotite; chert-hematite (magnetite));



Volcanogenic Massive Sulfide (VMS)

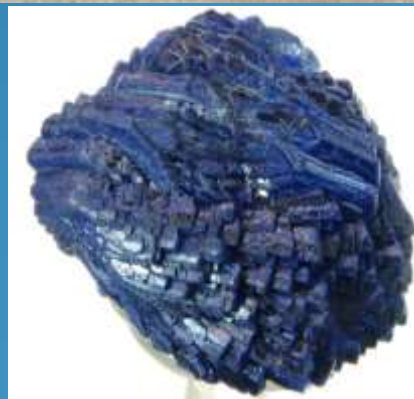
Pyrite, chalcopyrite, sphalerite, galena, cubanite, arsenopyrite, mackinawite, pyrrhotite, magnesian chlorite

Zn-Cu-Ag

chalcopyrite



Chalcocite, Rock Currier MinDat
Jan C. Rasmussen, Ph.D., R.G.

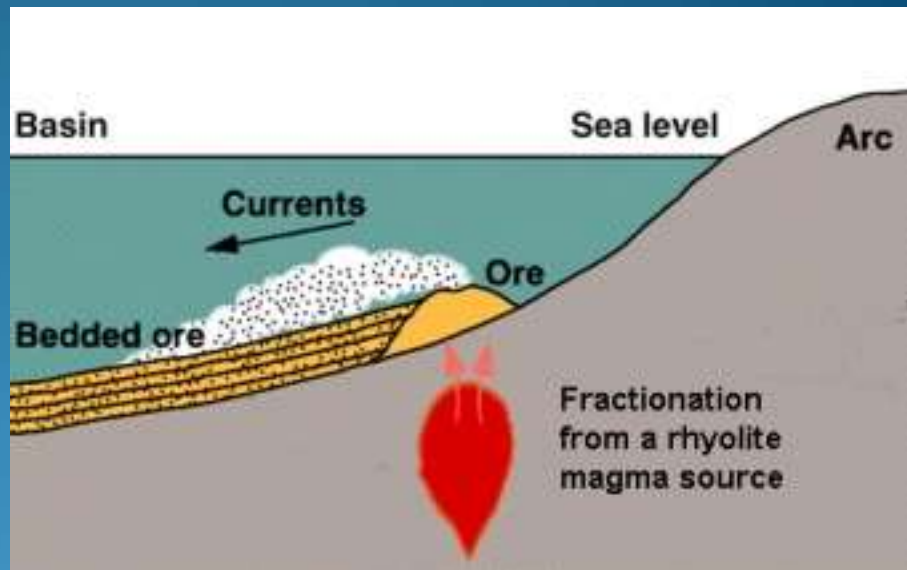


Azurite, Roger Sedgewick photo, MinDat
Sept. 10, 2018



Yavapai - Jerome VMS (1735 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Early	1750-1720	Zn-Cu-Ag VMS; Fe-Si BIF;	VMS Jerome, Antler; Pikes Peak Fe-Si	VMS (pyrite, chalcopyrite, sphalerite, galena, cubanite, arsenopyrite, pyrrhotite; chert-hematite (magnetite));



Deposition of Volcanogenic Massive Sulfide ore

Black smoker, modern seafloor

Middle Yavapai Orogeny (1.77-1.71 Ga)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Yavapai	Early	1770- 1715	Hg;Au(Ag);MoCu	Phoenix Mts. Hg; Groom Creek; Squaw Peak	cinnabar, kyanite, tourmaline; gold, quartz;molybdenite

Cinnabar, kyanite, andalusite, pyrophyllite, tourmaline



cinnabar



Kyanite, Piestewa Peak,
Ray Grant, K. Nash MinDat

Cinnabar (mercury sulfide) Sunflower dist., Maricopa Co.



Piestewa Peak,
Phoenix Mts.



Piemontite, Piestewa Peak, Peter Cristofono photo MinDat
Jan C. Rasmussen, Ph.D., R.G. Sept. 10, 2018

Late Yavapai Orogeny (1.71-1.69 Ga)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Late	1715-1690	W(Be)	Boriana, Money Maker-North Star	scheelite, beryl, hübnerite, wolframite, microcline, quartz,

Boriana Tungsten

Scheelite, beryl, wolframite group, fluorite, microcline, quartz, muscovite, chalcopyrite, pyrite, apatite, zircon, molybdenite, andalusite



Scheelite, Harvard collection



Scheelite, Mark Hay collection



Molybdenite, Cleator, owner Chuck Cominski



Andalusite, Bradshaw Mts., Rob Lavinsky, MinDat

Early Picuris Orogeny (1470-1420 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Picuris	Late	1460-1370	Be, Li, Ce, Ta-Nb	White Picacho; Wagon Bow, Tungstona	spodumene, lepidolite, scheelite, beryl, wolframite group
	Early	1470-1420	Fe, amethyst	Four Peaks Amethyst	amethyst, hematite, fluorapatite

amethyst, hematite, fluorapatite



Amethyst, Four Peaks mine, Mazatzal Mts., Maricopa Co., MinDat photo



Late Picuris Orogeny (1460-1370 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Picuris	Late	1460-1370	Be, Li, Ce, Ta-Nb	White Picacho; Wagon Bow, Tungstona	spodumene, lepidolite, scheelite, beryl, wolframite group



White Picacho, Wagon Bow, Tungstona



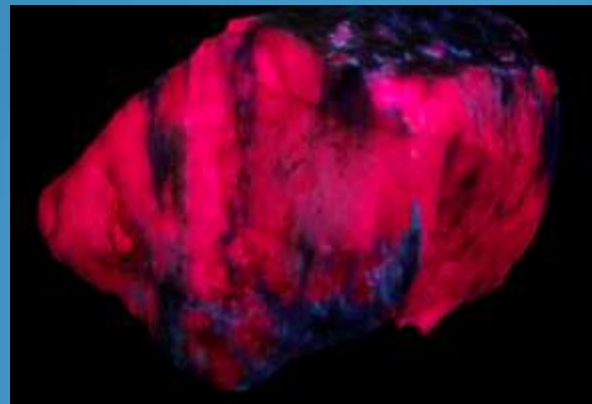
Oracle Granite, Santa Catalina Mts.

Euxenite $Y, Ca, Ce, U, Th(Nb, Ta, Ti)_2O_6$
White Picacho pegmatites



beryl

spodumene, lepidolite, scheelite, beryl, wolframite; albite, cassiterite, epidote, hematite, microcline, monazite-Ce, quartz, rutile, xenotime-Y, quartz



Eucryptite, White Picacho, Chris Clemons, MinDat



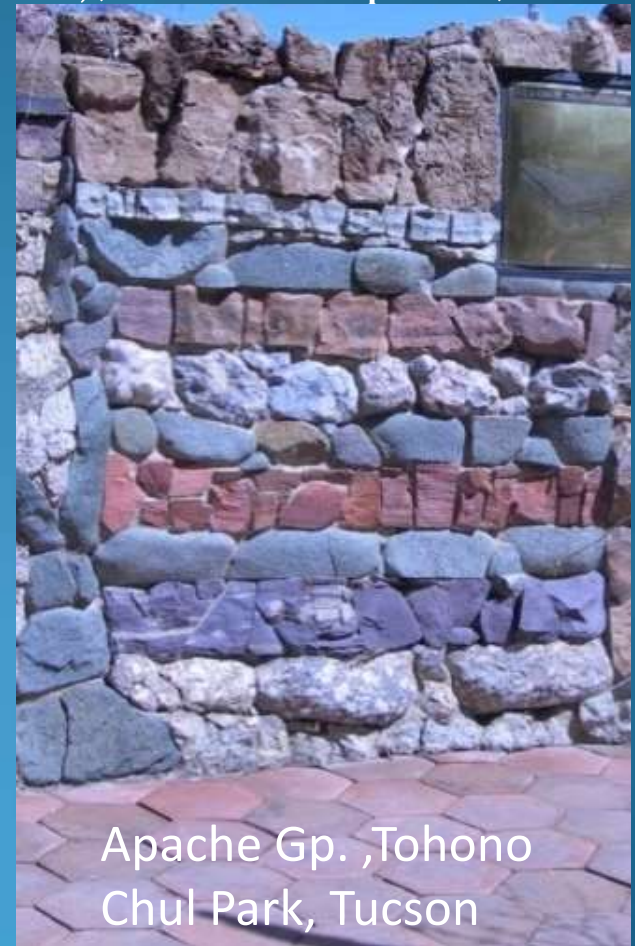
Beryl, White Picacho

Beryl, White Picacho

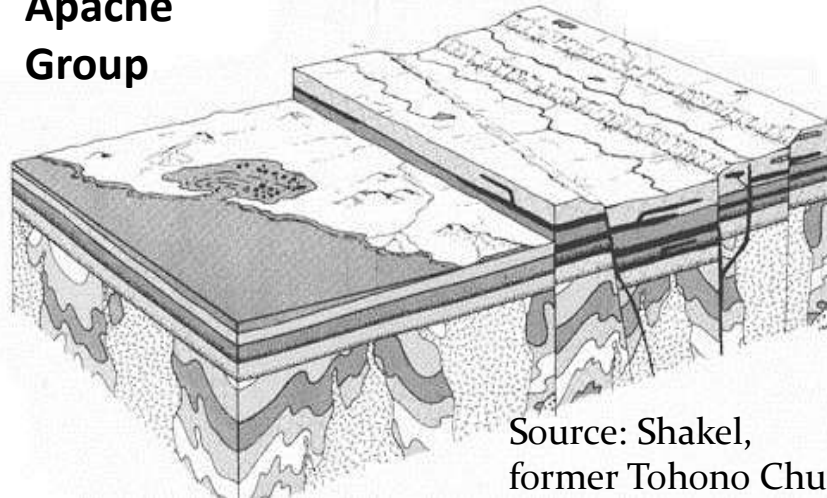
Keweenawan (1104-1035 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Keweenawan	failed rifting	1104-1035	asbestos; U (Cu)	Sierra Ancha, Hope	chrysotile asbestos, lizardite; uraninite, pyrite

Grand Canyon supergroup
(Unkar Gp. (incl. Cardenas basalt - 1070 Ma Rb-Sr), Nankoweap Fm., Chuar Gp.)



Apache Group



Source: Shakel, former Tohono Chul

Apache Gp. ,Tohono Chul Park, Tucson

Keweenawan (1104-1035 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Keweenawan	failed rifting	1104-1035	asbestos; U (Cu)	Sierra Ancha, Hope	chrysotile asbestos, lizardite; uraninite, pyrite

Apache Gp., chrysotile asbestos, lizardite

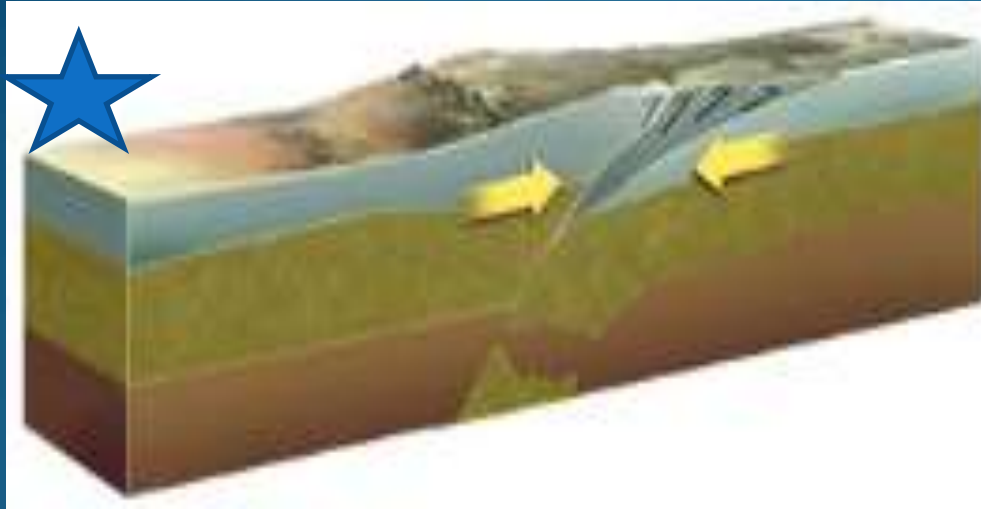


Diabase in Apache Gp. ,Tohono Chul Park, Tucson

Diabase in contact with Mescal Limestone made marble and serpentine chrysotile asbestos

Paleozoic Orogenies (540-251 Ma) – E US

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Antler (NV)	Laurentia	380-357	oolitic iron	Payson "diamond quartz"; Ranch Cr. Fe	'Herkimer habit' quartz, oolitic hematite



Collisions of eastern N.A. with Europe or Africa made large mountain ranges.

Arizona mostly had seas go in and out (transgression/regression).

Arizona was on the western, trailing edge of North America

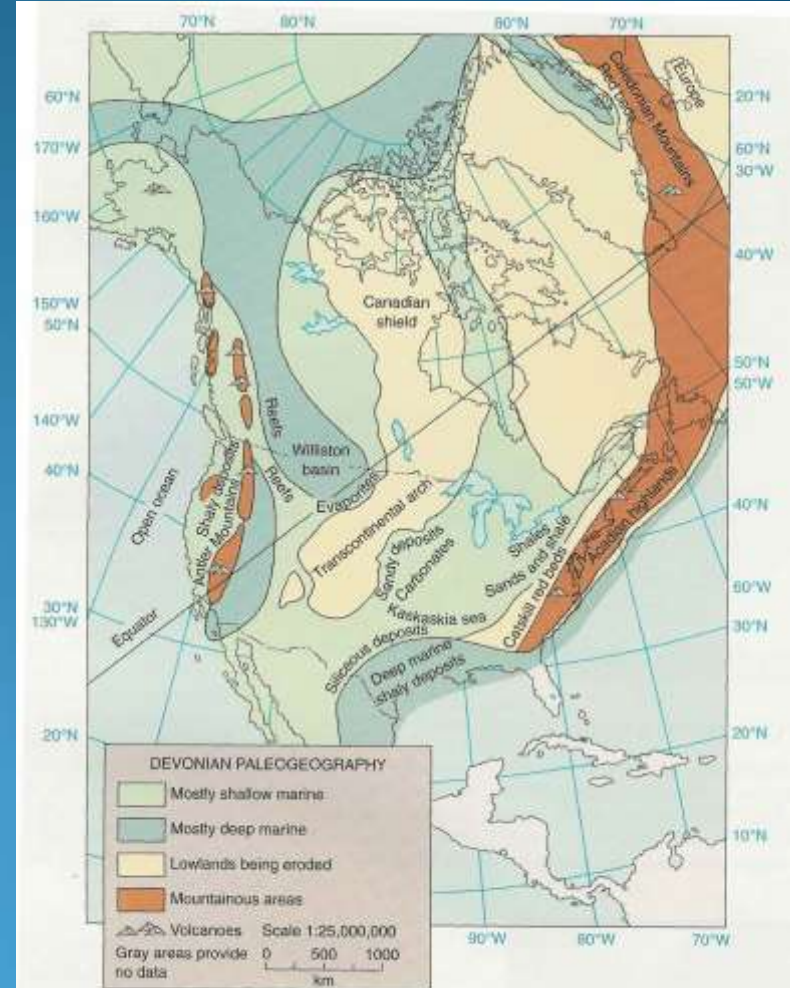


FIGURE 9-4 Paleogeography of North America during the Devonian Period.

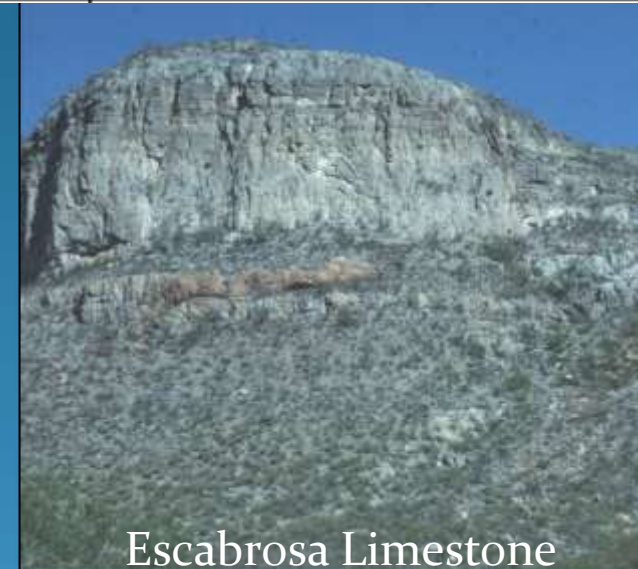
Lull - Mississippian Limestones in Arizona

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Lull between Acadian & Alleghenian		355-330		Limestone	Redwall Ls., Escabrosa Ls.



Redwall Limestone

Rillito Cement plant



Escabrosa Limestone



Clarkdale Cement plant

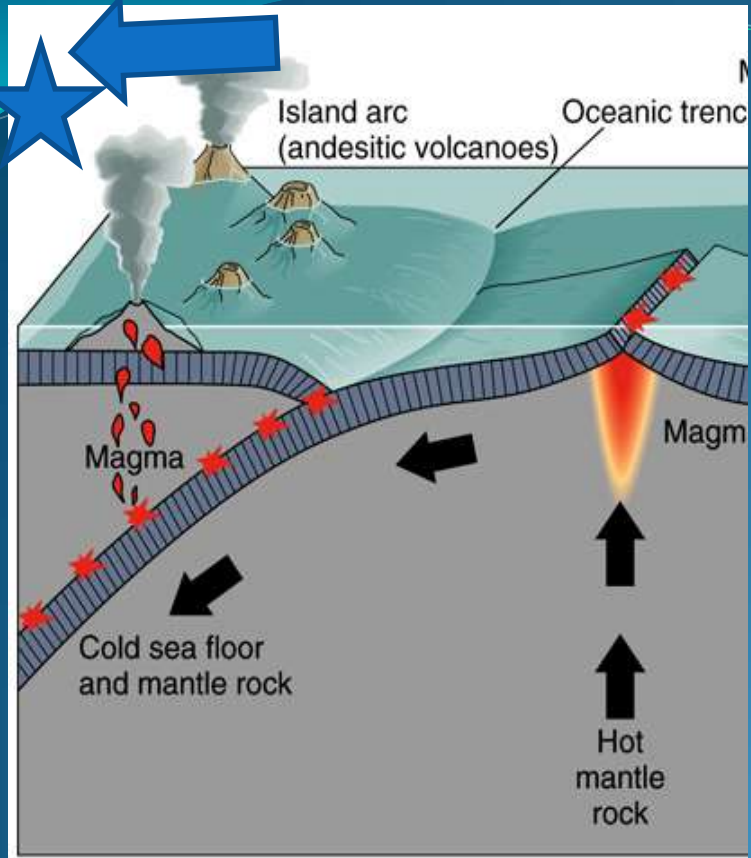


Calcite marble



Sahuarita Marble

Arizona's position switched with respect to plate tectonics after Paleozoic

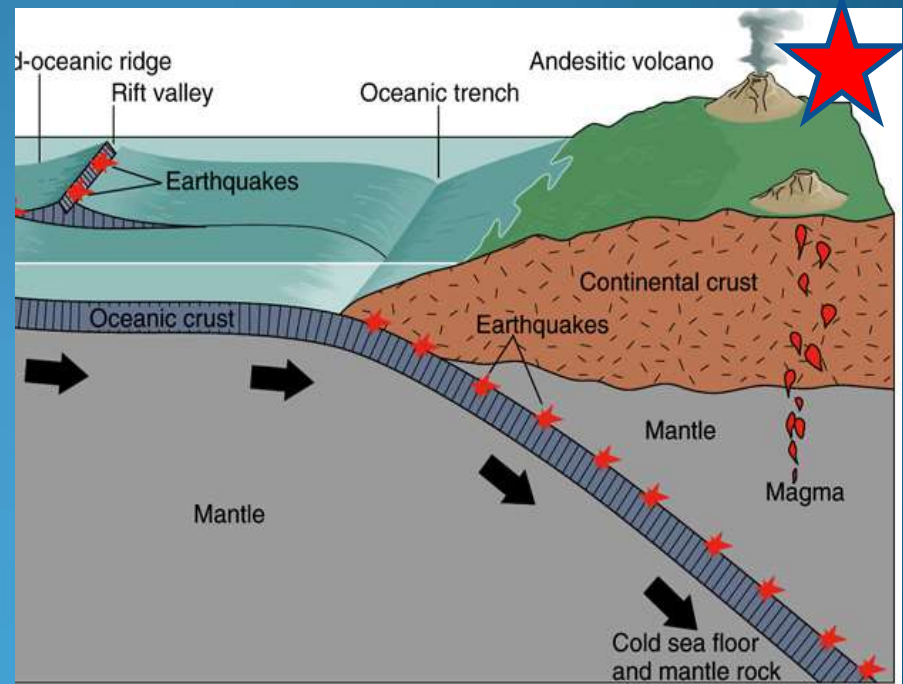


Big changes at 252 Ma



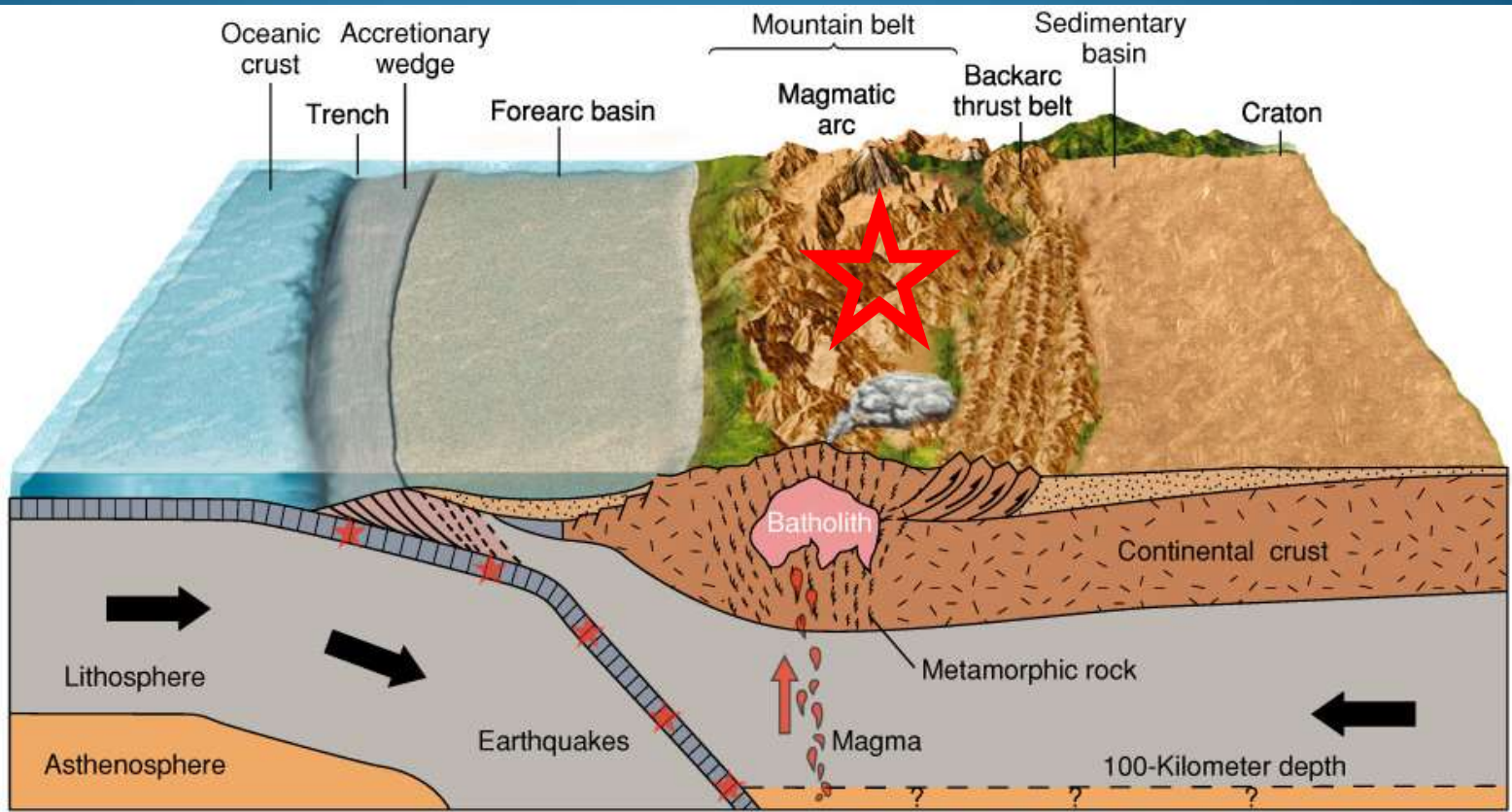
Mesozoic -
Arizona switched to the leading edge of N. American continent = mountain building, volcanoes, earthquakes, igneous intrusions, metal deposits

Paleozoic -
Arizona was on trailing edge of N. American continent = calm seaways = no metals



Nevadan (Tri-Jurassic) Orogeny (237-155 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Nevadan	Late	175-155	Au	Nogales	gold
		175-155	W veins	Las Guijas, Juniper Flat	wolframite group, hübnerite, scheelite
		160-155	Kyanite	Tung Hill	dumortierite, rutile, scheelite
	Middle W AZ	173-155	Pb-Zn-Ag	Comobabi Mts., Cababi (Mildren-Steppe Mine)	galena, sphalerite, tetrahedrite
		189-155	AuCu (AgWPb)	La Cholla, Sugarloaf (Big Bertha), Jaeger	quartz, pyrite, gold, chalcopyrite, specular hematite
	Early SE AZ	191-175	Pb-Zn-Ag(CuAu)	Gleeson (South Turquoise), Hartford	galena, sphalerite, tetrahedrite, cerussite, wulfenite
		201-191	Cu-Au, PGE	Warren (Bisbee), Turquoise (Courtland)	chalcopyrite, bornite; azurite, malachite, cuprite, copper
	Early N AZ	237-201	U-V-Cu (Ni-Co)	Orphan , Grandview; Monument Valley	uraninite, chalcopyrite, galena, torbernite; carnotite



Early Nevadan Orogeny (237-205 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Early N AZ	237-201	U-V-Cu (Ni-Co)	Orphan, Grandview; Monument Valley	uraninite, chalcocopyrite, galena, torbernite; carnotite

215-210 Ma



Auracarioxylon arizonicum



Petrified
Forest
Member,
Chinle Fm.,
Petrified
Forest
National
Park

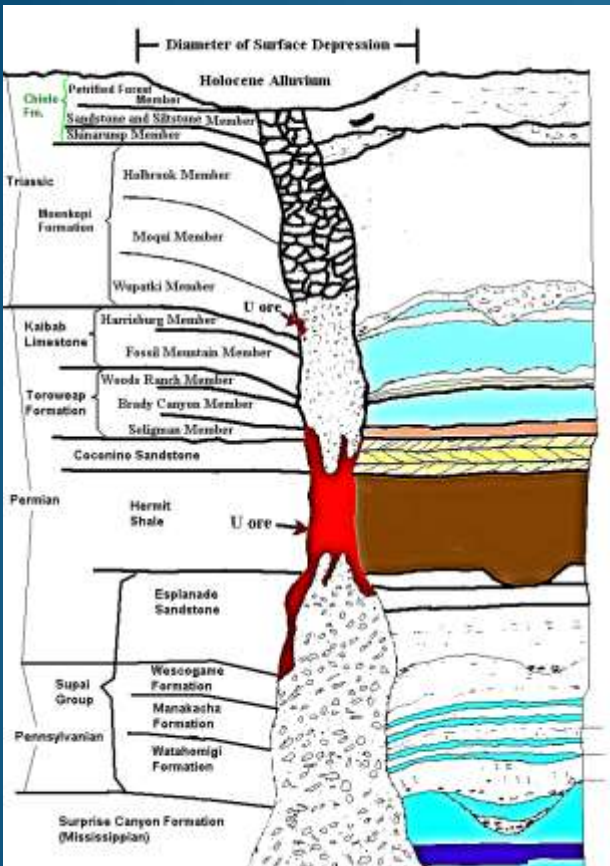


Coelophysis



Early Nevadan (Jurassic) (230-180 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Early SE AZ	201-191	Cu-Au, PGE	Warren (Bisbee), Turquoise (Courtland)	chalcopyrite, bornite; azurite, malachite, cuprite, copper
	Early N AZ	237-201	U-V-Cu (Ni-Co)	Orphan, Grandview; Monument Valley	uraninite, chalcopyrite, galena, torbernite; carnotite



Source: Karen Wenrich



Uranium Breccia pipe in Grand Canyon

Early Nevadan Orogeny (230-180 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Early N AZ	237-201	U-V-Cu (Ni-Co)	Orphan, Grandview; Monument Valley	uraninite, chalcocopyrite, galena, torbernite; carnotite

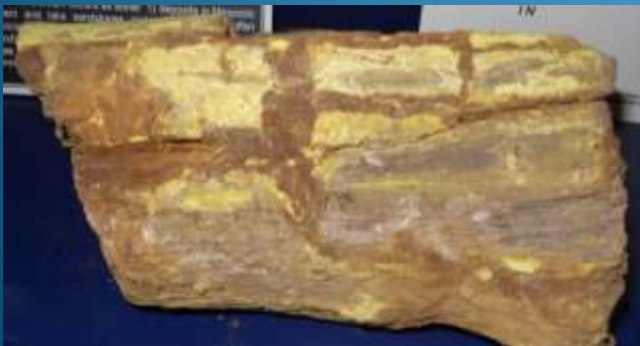


**Grandview mine; cyanotrichite
on antlerite**
AzMMM specimen



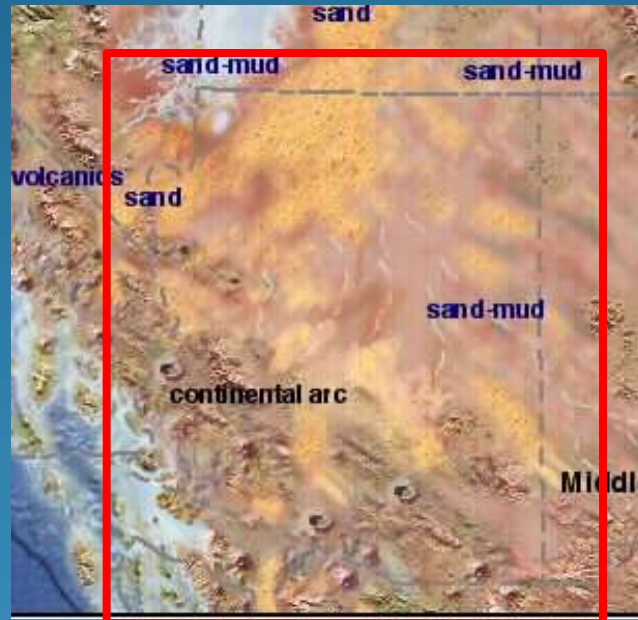
**Carnotite in
petrified
wood,
Coconino
Co.**
AzMMM specimen

Ridenour mine; tyuyamunite, $\text{Ca}(\text{UO}_2)_2(\text{V}_2\text{O}_8) \cdot 5-8\text{H}_2\text{O}$
Wenrich photo



Middle Jurassic volcanic arc (201-155 Ma)

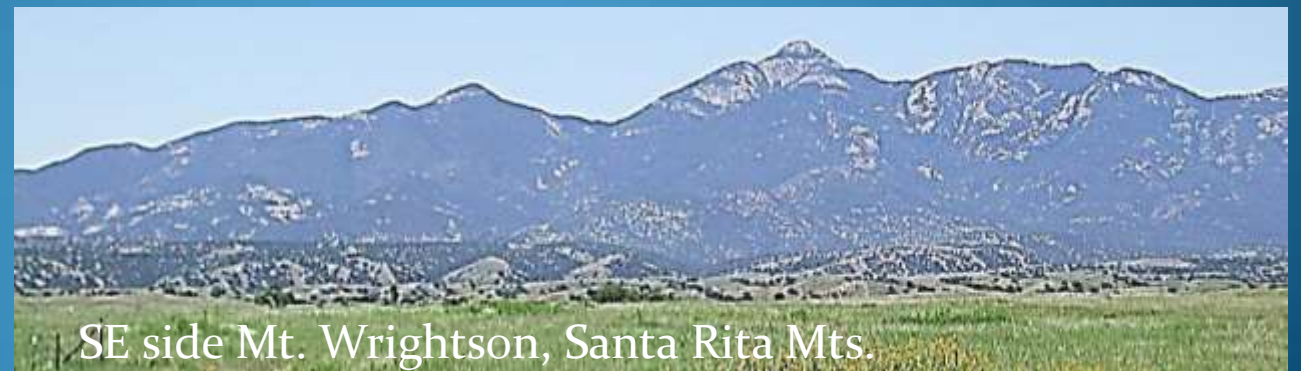
Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Nevadan	Middle W AZ	173-155	Pb-Zn-Ag	Comobabi Mts., Cababi (Mildren-Steppe Mine)	galena, sphalerite, tetrahedrite
		189-155	AuCu (AgWPb)	La Cholla, Sugarloaf (Big Bertha), Jaeger	quartz, pyrite, gold, chalcocopyrite, specular hematite
	Early SE AZ	191-175	Pb-Zn-Ag(CuAu)	Gleeson (South Turquoise), Hartford	galena, sphalerite, tetrahedrite, cerussite, wulfenite
		201-191	Cu-Au, PGE	Warren (Bisbee), Turquoise (Courtland)	chalcocopyrite, bornite; azurite, malachite, cuprite, copper



All paleogeographic paintings from Blakey & Ranney



S. Mustang Mts., SE AZ



SE side Mt. Wrightson, Santa Rita Mts.

Middle Nevadan – Bisbee (201-191 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Early SE AZ	201-191	Cu-Au, PGE	Warren (Bisbee), Turquoise (Courtland)	chalcopyrite, bornite; azurite, malachite, cuprite, copper

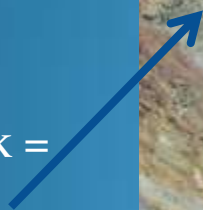


Campbell shaft



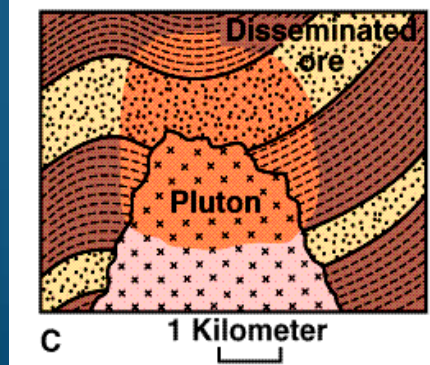
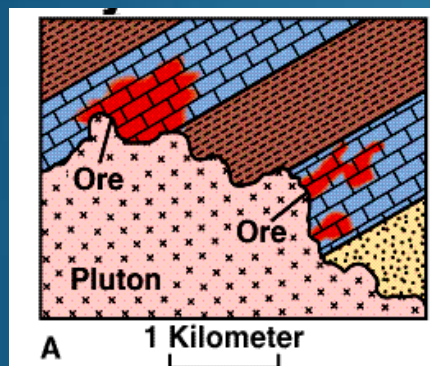
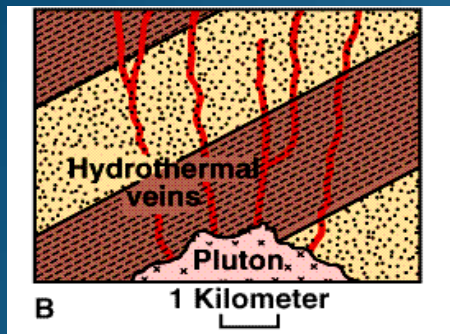
Lavender Pit, Bisbee

Sacramento Stock =
200 Ma MQA



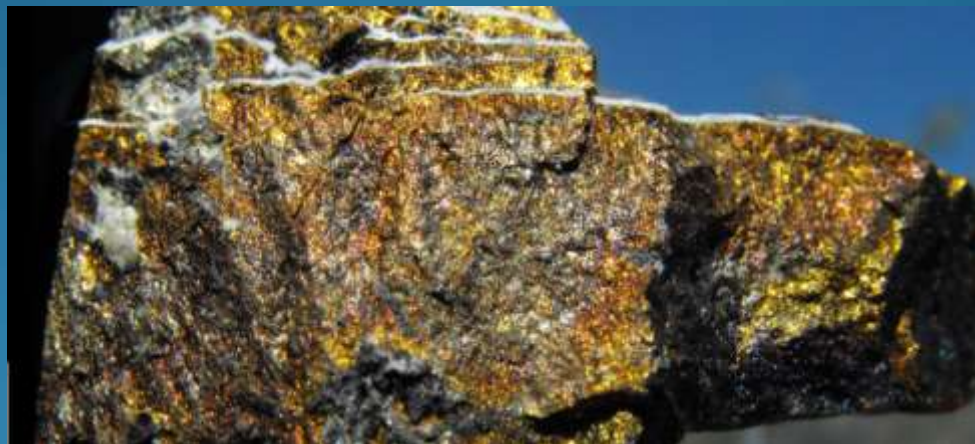
Bisbee (200 Ma) primary minerals

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Early SE AZ	201-191	Cu-Au, PGE	Warren (Bisbee), Turquoise (Courtland)	chalcopyrite, bornite; azurite, malachite, cuprite, copper



Bisbee

Primary: Chalcopyrite, bornite, galena, specularite, sphalerite, chalcocite



Chalcopyrite,
Lavender Pit,
Luetcke photo,
MinDat.org



Bornite, from mine dumps
Patricia Renz photo MinDat.org
Sept. 10, 2018



Chalcocite, G. Ciccolini, MinDat

Bisbee (200 Ma) secondary minerals

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Early SE AZ	201-191	Cu-Au, PGE	Warren (Bisbee), Turquoise (Courtland)	chalcocite, bornite; azurite, malachite, cuprite, copper



azurite



chalcocite

azurite, malachite, chrysocolla,
chalcocite, copper, cuprite,
hematite, calcite, aragonite,
hemimorphite, turquoise,



turquoise

cuprite, photo by Doug Graeme



bisbeeminingandminerals.com



malachite



copper

bisbeeminingandminerals.com

S. Turquoise district – Gleeson (191 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Early SE AZ	191-175	Pb-Zn-Ag(CuAu)	Gleeson (South Turquoise), Hartford	galena, sphalerite, tetrahedrite, cerussite, wulfenite



Silver Bill mine, wulfenite, AZMMM



Defiance mine, wulfenite, AZMMM Donor: Les Presmyk



Rosasite, Silver Bill m.
Rob Levinsky, MinDat.org



Aurichalcite, Silver Bill mine

Bruce Murphy, MinDat.org

Gleeson Quartz Monzonite =
191.3 Ma

Jan C. Rasmussen, Ph.D., R.G.

Laramide Orogeny - (89-35 Ma)

Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Late	65-29	Actinolite, garnet	Cemetery Ridge, Garnet Ridge	Actinolite, serpentine group, pyrope garnet
	70-35	Au	Gold Basin, Vulture	gold, kyanite
	60-40	W	Blue Bird	wolframite group, scheelite
Middle	65-55	Cu-Mo-Ag	Ajo, Ray, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci	chalcopyrite, molybdenite, pyrite, bornite, epidote, garnet
Early	75-65	Ag,Pb-Zn	Tombstone, Glove, Empire, Ruby, Salero	galena, sphalerite, alabandite, tetrahedrite, silver, enargite
Earliest	89-75	Cu-Au-Ag	Old Yuma, Mexican Hat, Golden Rule	gold, galena, cerussite, mottramite, wulfenite, vanadinite

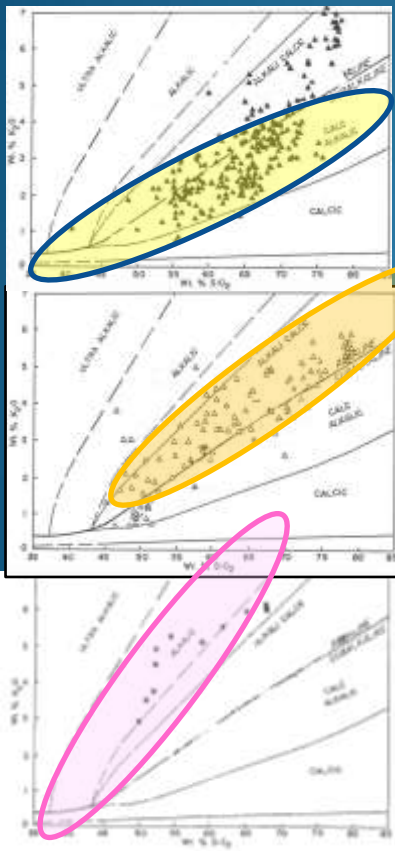
Production for Laramide assemblages (as of 1986)

assemblage	Wilderness Gold Basin	Wilderness Wilderness	Morenci	Tombstone	Hillsboro
facies	Gold Basin	Wilderness			
alkalinity	PC	PCA	MCA	MAC	MQA
Cu (kg)	334,187	545,779	22,253,000,000	7,655,000	6,753,800
Pb	1,455,606	1,437,061	273,800,000	48,690,000	456,169
Zn	307,333	210,257	1,292,000,000	17,130,000	
Mo	0	0	172,640,000		
W		1,742,651	-		
Au	34,702	170	125,600	12,400	5,632
Ag	29,335	10,212	5,960,000	1,197,000	22,489
Ag:Au		41:1	47:1	96:1	4:1
Cu:Au		3210:1	180,000:1	620:1	1199:1
Cu:(Pb+Zn)		1:3	14:1	1:9	15:1
Zn:Pb		6.8:1	5:1	1:3	

MCA
CuMo

MAC
PbAg

MQA
CuAu



Earliest Laramide (~80) Old Yuma Mine

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Earliest	89-75	Cu-Au-Ag	Old Yuma, Mexican Hat, Golden Rule	gold, galena, cerussite, mottramite, wulfenite, vanadinite

- Anglesite
- Calcite
- Cerussite
- Chrysocolla
- Descloizite
- Fornacite
- Galena
- Hematite
- Malachite
- Minium
- Mottramite
- Plattnerite
- Quartz
- Tetrahedrite
- Vanadinite
- Willemite
- Wulfenite



Vanadinite, $Pb_5(VO_4)_3Cl$, owner Les & Paula Presmyk, TGMS 2012 display

vanadinite



Cerussite, $(PbCO_3)$ 1" bar, Rock Currier, H. Oboda collection, mindat.org



Vanadinite, owner Tony Potucek



Minium, $(Pb^{2+}_2Pb^{4+}O_4)$ 6 mm FOV, photo by Michael C. Roarke, mindat.org
www.janrasmussen.com

N. Tucson Mts. Evidence of epeiric uplift & erosion = Eocene erosion surface above flat subduction zone

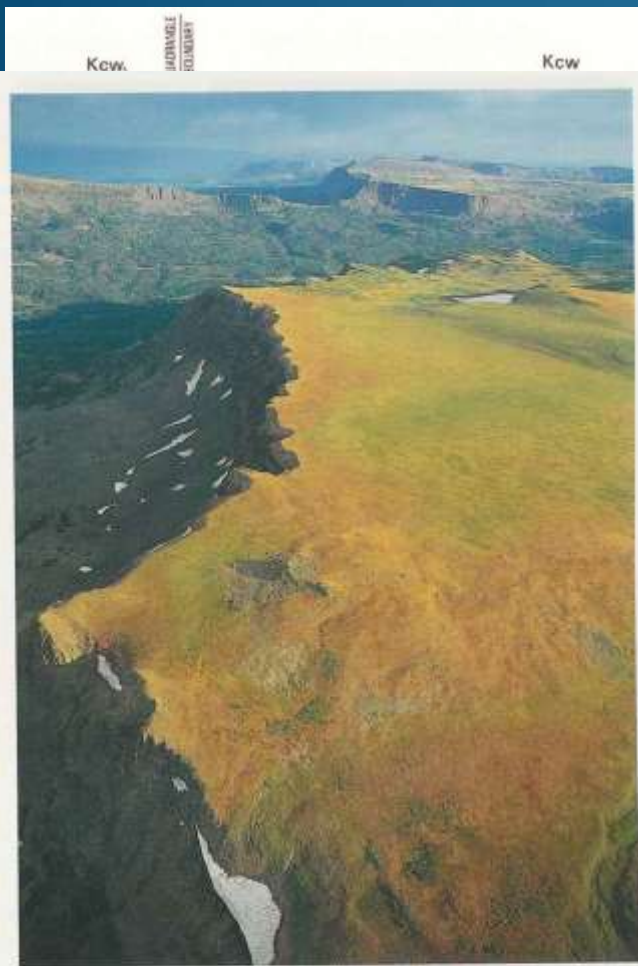
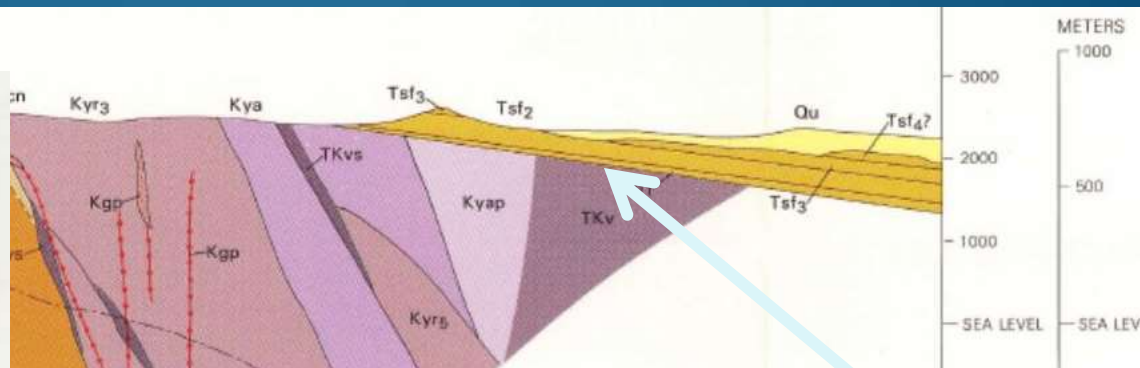
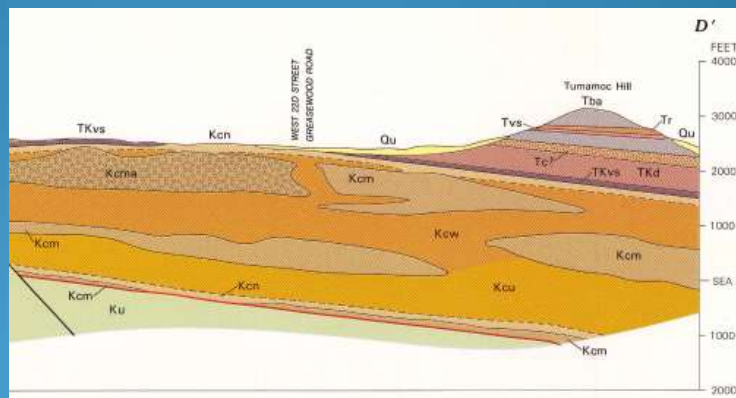


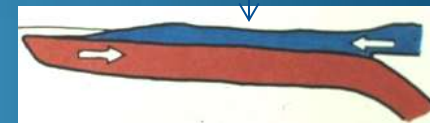
Figure 18-25 The subsummit surface formed by the flat-topped Rocky Mountains. This surface, seen here near Derby Peak, Colorado, formed near the end of the Eocene Epoch and has since been uplifted and dissected by erosion. (Michael Collier.)



Angular unconformity between Late Cretaceous Yuma Mine volcanics and mid-Tertiary volcanics of Safford Peak



Eocene erosion surface



Unconformity under Tumamoc Hill mid-Tertiary overlying Twin Hills Dacite and Cat Mtn. Rhyolite (Late Cretaceous)

Wulfenite – Old Yuma Mine

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Earliest	89-75	Cu-Au-Ag	Old Yuma, Mexican Hat, Golden Rule	gold, galena, cerussite, mottramite, wulfenite, vanadinite



Owner Jim & Gail Spann



Owner Frank Sousa



Owner John & Karen Cesar

Owner Stan Keith



Owner Paul Harter



Owner Les & Paula Presmyk

Early Laramide (Tombstone) (75-65 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Early	75-65	Ag,Pb-Zn	Tombstone, Glove, Empire, Ruby, Salero	galena, sphalerite, alabandite, tetrahedrite, silver, enargite

Thick ignimbrite (ash) flows



Tucson Mts. - Cat Mountain Rhyolite

Mt. Pinatubo, Philippines, 1991



Tombstone Hills – Uncle Sam Tuff

Early Laramide (76-74) Tombstone - silver

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Early	75-65	Ag,Pb-Zn	Tombstone, Glove, Empire, Ruby, Salero	galena, sphalerite, alabandite, tetrahedrite, silver, enargite

Alabandite MnS



Alabandite
Mn²⁺S
Tombstone, Cochise Co.
AMNH# 52023



Arizona Mineral Treasures
Emmonsite
300' level, Empire Mine,
Tombstone, Cochise County
Owner: Peter Mepaw



Wulfenite
Tough Nut mine, Tombstone
Cochise Co. Arizona



Arizona Mineral Treasures
Silver
Lucky Cuss Mine Tombstone,
Cochise County
Owner: Philip Mineral Foundation

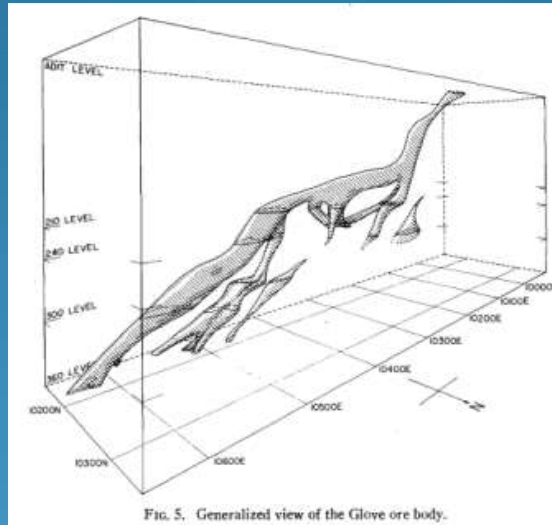


Single jockers working in a mine in the Gouldenough Mine, circa 1890
Marie Devere Collection

Early Laramide (~75 Ma) Glove Mine

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Early	75-65	Ag,Pb-Zn	Tombstone, Glove, Empire, Ruby, Salero	galena, sphalerite, alabandite, tetrahedrite, silver, enargite

- Argentiferous galena, sphalerite, small amounts of pyrite, chalcopyrite & quartz
- Extensive solution by hydrothermal fluids of the limestone and deep oxidation concentrated cerussite, anglesite, wulfenite, and smithsonite



Hydrothermal cave



Middle Laramide - Morenci (65-55 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Laramide	Middle	65-55	Cu-Mo-Ag	Ajo, Ray, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci	chalcopyrite, molybdenite, pyrite, bornite, epidote, garnet



Silver Bell



Bornite

Porphyry copper-molybdenum mines



Chalcopyrite



Sierrita



MoS₂



Middle Laramide – porphyry Cu (65-55 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Laramide	Middle	65-55	Cu-Mo-Ag	Ajo, Ray, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci	chalcocopyrite, molybdenite, pyrite, bornite, epidote, garnet

Morenci mine – photo from Freeport



Ray mine – photo from ASARCO (Grupo)



Jan C. Rasmussen, Ph.D., R.G.

copper



S

chalcocopyrite



www.janrasmussen.com

Middle Laramide (65-55 Ma) Magma Mine

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Laramide	Middle	65-55	Cu-Mo-Ag	Ajo, Ray, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci	chalcocite, molybdenite, pyrite, bornite, epidote, garnet

stromeyerite, Magma
Magma Cu. Co. donor



Pyrite
A bed,
Michael
Cline,
MinDat



Barite, A bed, Magma,
Chris Whitney-Smith, MinDat

tennantite



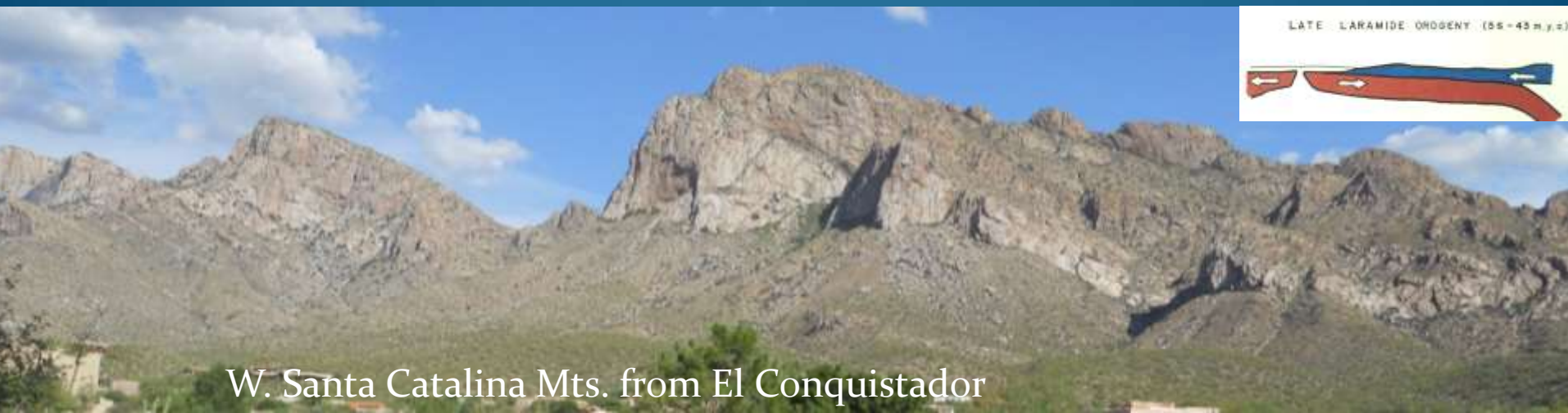
hematite



bornite

Latest Laramide – Wilderness (55-43 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Laramide	Late	65-29	Actinolite, garnet	Cemetery Ridge, Garnet Ridge	Actinolite, serpentine group, pyrope garnet
		70-35	Au	Gold Basin, Vulture	gold, kyanite
		60-40	W	Blue Bird	wolframite group, scheelite
				Ajo, Ray, San Manuel, Mineral Park, Pima, Pinal, ...	



W. Santa Catalina Mts. from El Conquistador



HUEBNERITE
Manganese Tungstate
Mn²⁺WO₄
Dragoon Mts., Cochise Co., AZ
Donor: Lewis A. Smith
850123



Garnets Lemmon Rock

Sept. 10, 2018



www.janrasmussen.com

Latest Laramide (Wilderness) (55-43 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
		65-29	Actinolite, garnet	Cemetery Ridge, Garnet Ridge	Actinolite, serpentine group, pyrope garnet
	Late	70-35	Au	Gold Basin, Vulture	gold, kyanite



Gold, Gold Basin,
Mohave Co.



Wulfenite, Shelby m., Gold Basin,
Douglas Merson photo, MinDat.org

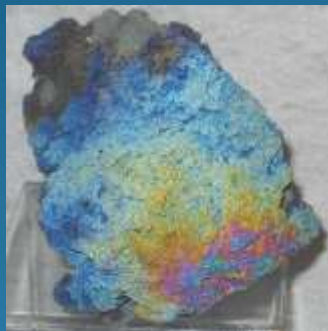


Rolf Luetcke
specimen and
photo,
MinDat.org

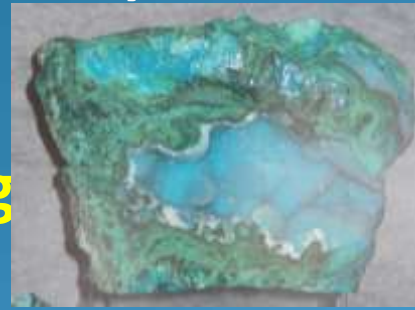
Re-organization – Secondary Enrichment

(45-35 Ma)

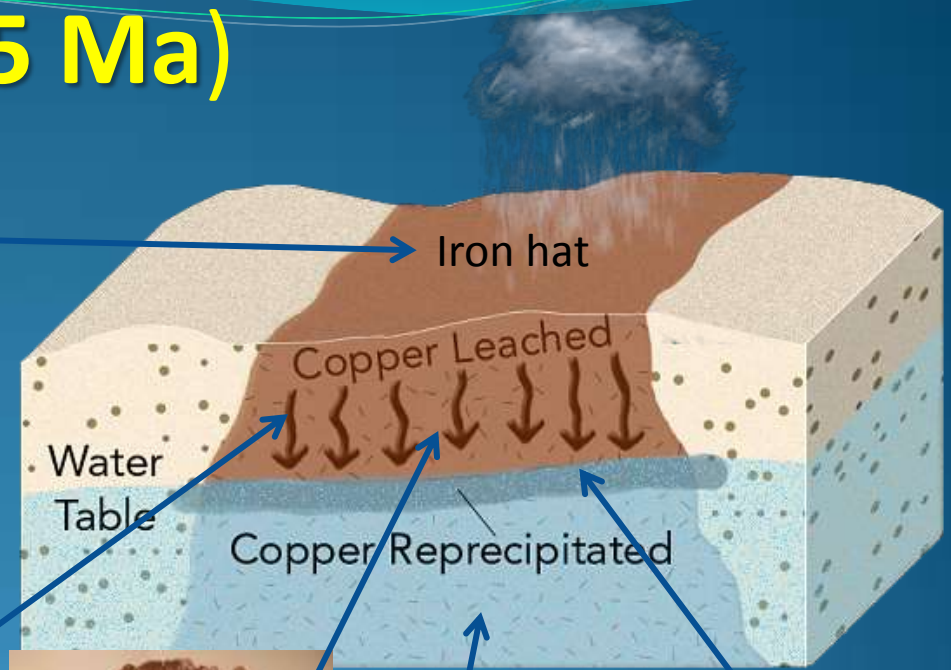
Weathering leaches copper from top, leaving them reddish colored. Copper is precipitated at the water table, enriching the deposit with chalcocite, copper, azurite, malachite, chrysocolla



Hematite/turgite, Ray, Flagg Min. Col.



Chrysocolla, malachite, Inspiration, Flagg Min Col.



Copper Ray

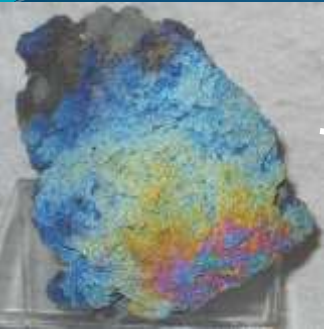


Chalcocite, Morenci Rolf Luetcke



Chalcopyrite, Ray

Eocene Erosion and Plate Re-organization – Secondary Enrichment of Porphyry Copper Deposits (45-35 Ma)



Hematite/turgite,
Ray, Flagg Min. Col.



Chrysocolla on malachite,
Inspiration, Flagg Min Col.



Malachite
on Azurite
Ajo
Photo by Dan
Weinrich
In Mindat.org



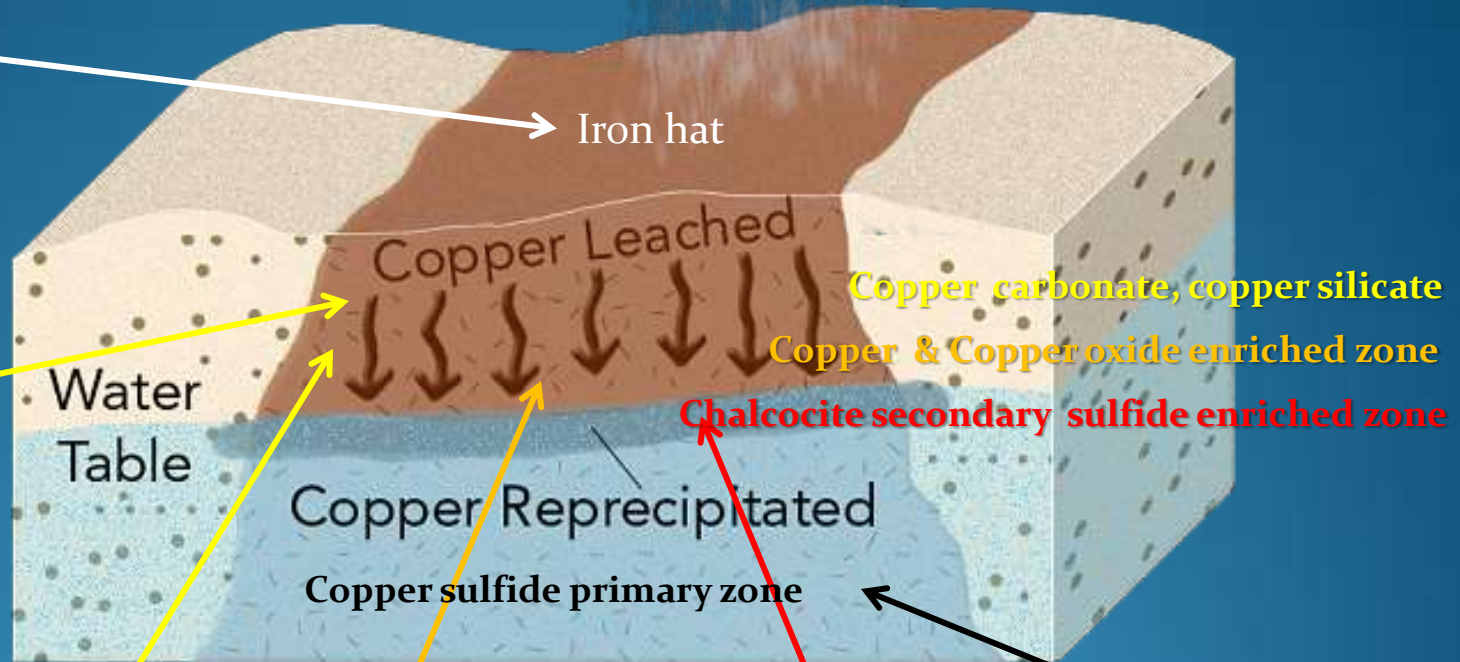
Cuprite on Copper Ray
Larry Maltby photo Mindat



Chalcocite, Morenci
Rolf Luetcke photo Mindat



Chalcopyrite, Ray



Oxidation of later Pb-Zn portions of Porphyry Coppers

• 79 mine



Oxidation of Cu skarn portions of Porphyry Coppers

- Christmas mine



Galiuro Orogeny - mid-Tertiary (43-13 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
Galiuro	Late	28-10	Mn, U, Au-Ag	Artillery Mts., Anderson, Oatman, Mammoth	Mn oxides, carnotite, gold, Tiger suite, specularite
	Middle	28-15	PbZnAg(AuCu)	Ash Peak, Red Cloud, Aravaipa	Cassiterite, silver, galena, sphalerite
	Early	30-21	Au (CuWAg)	Kofa, South Mountain, Gila Bend Mountains;	Gold, todorokite, chalcophanite, pyrolusite



Chiricahua Mts. Ash flow tuffs



Vanadinite



Mimetite

Red Cloud Mine



N. Tucson Mts.



Wulfenite

Late Galiuro orogeny (28-10 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Late	28-10	Mn, U, Au-Ag	Artillery Mts., Anderson, Oatman, Mammoth	Mn oxides, carnotite, gold, Tiger suite, specularite



Collins Cut, Mammoth St. Anthony Mine, Tiger



Moss mine, Oatman, mindat.org, USGS Bull.



Gold,
Mammoth-St.
Anthony mine,
M. Cline,
MinDat



Fluorite, Oatman

Late Galiuro – Mammoth-St. Anthony M.

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Late	28-10	Mn, U, Au-Ag	Artillery Mts., Anderson, Oatman, Mammoth	Mn oxides, carnotite, gold, Tiger suite, specularite



vanadinite



cerussite



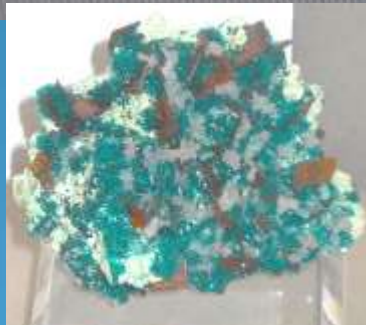
diableite



boleite



Wulfenite, mimetic
Mammoth-St. Anthony
Pinal Co., Ariz.



diopside



hemimorphite

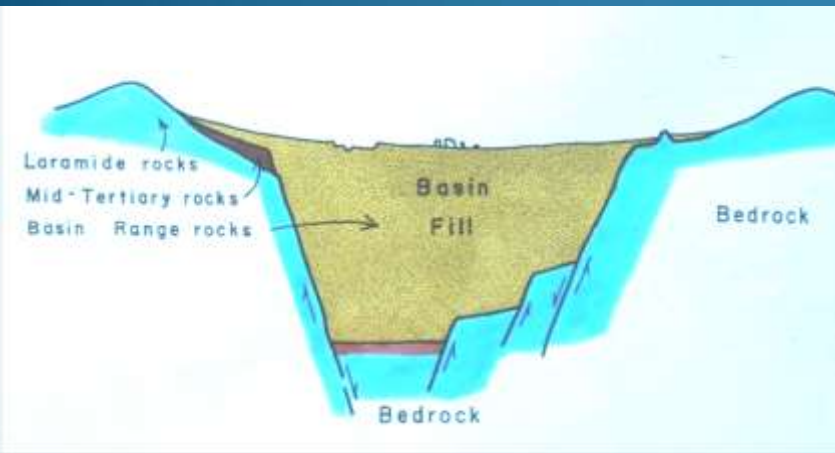


caledonite

San Andreas – Basin & Range (13-0 Ma)

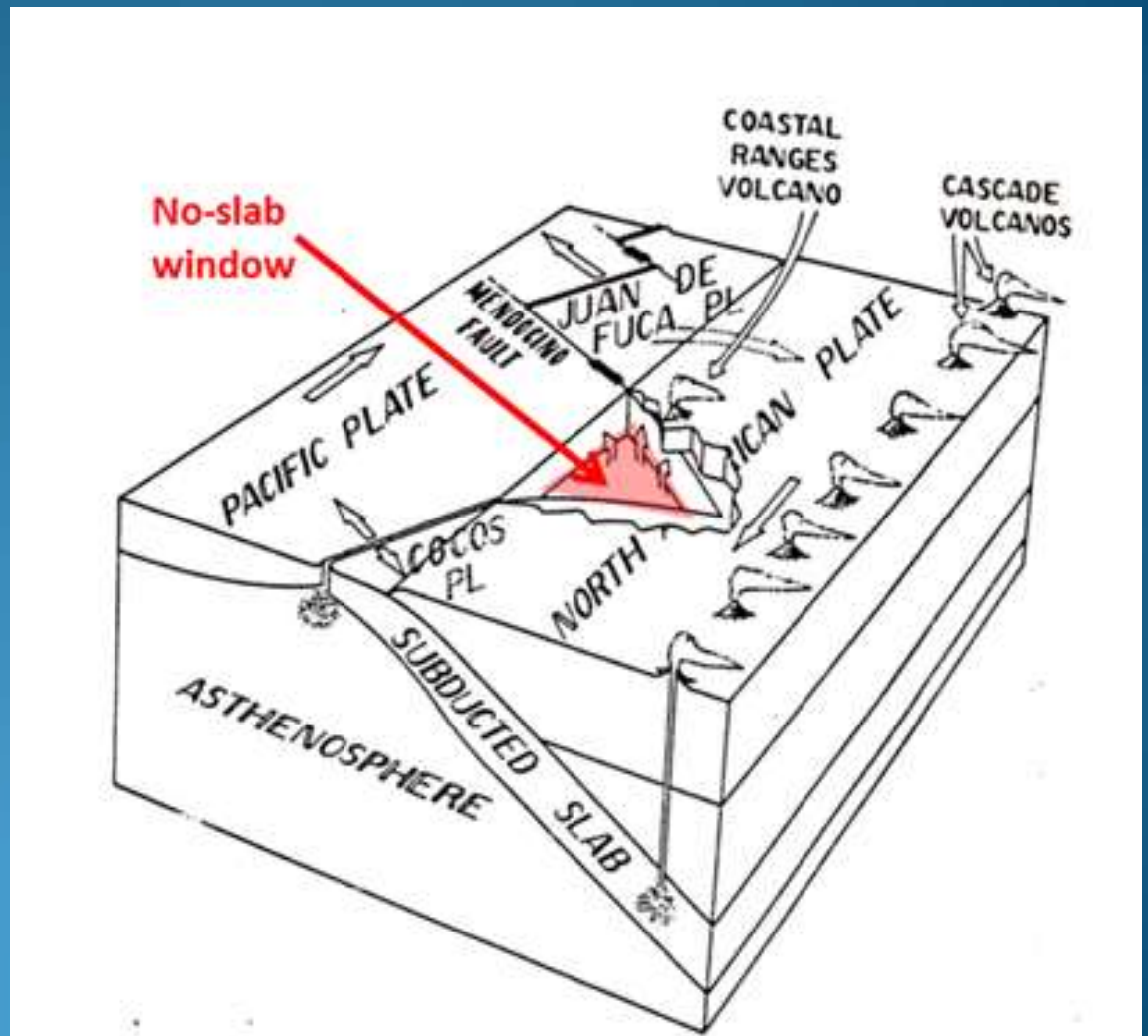
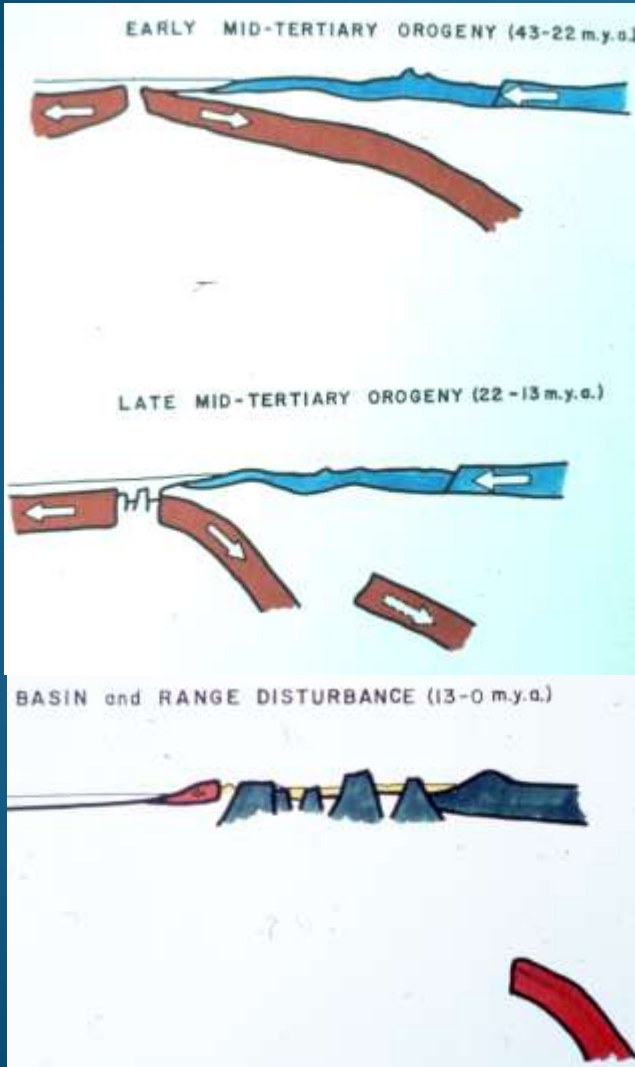
Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
San Andreas	Late	2.6 - 0.012	olivine; gypsum	Peridot Mesa, Camp Verde	Olivine; glauberite; gypsum;
	Early	13-2.6	Zeolites, salt	San Francisco volcanics, Luke salt	Clinoptilolite, hectorite; halite

Basin and Range Valleys filled with sand, gravel, clay, gypsum, & salt - true extension



San Andreas fault cuts off eastward-subducting slab

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
	Late	28-10	Mn, U, Au-Ag	Artillery Mts., Anderson, Oatman, Mammoth	Mn oxides, carnotite, gold, Tiger suite, specularite



San Andreas – volcanism (13-0 Ma)

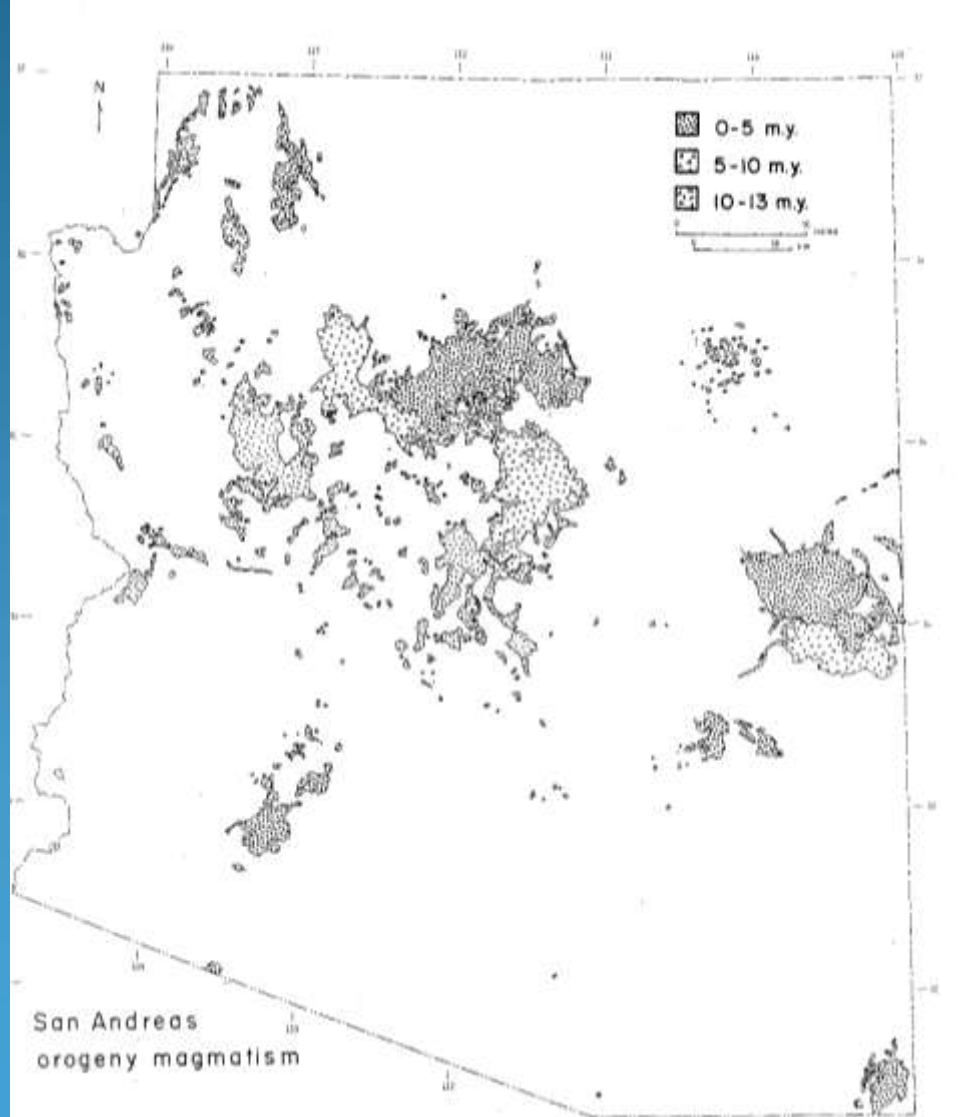
Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
San Andreas	Late	2.6 - 0.012	olivine; gypsum	Peridot Mesa, Camp Verde	Olivine, glauberite; gypsum;
	Early	13-2.6	Zeolites, salt	San Francisco volcanics, Luke salt	Clinoptilolite, hectorite; halite



San Francisco Peaks, Flagstaff



Natrolite,
Horseshoe Dam,
donor Stan Celestisn



San Andreas
orogeny magmatism

San Andreas – Basin & Range (13-0 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
San Andreas	Late	2.6 - 0.012	olivine; gypsum	Peridot Mesa, Camp Verde	Olivine, glauberite; gypsum;
	Early	13-2.6	Zeolites, salt	San Francisco volcanics, Luke salt	Clinoptilolite, hectorite; halite



Olivine in basalt, San Carlos

No metals



Cinder cone along I-40 near Flagstaff



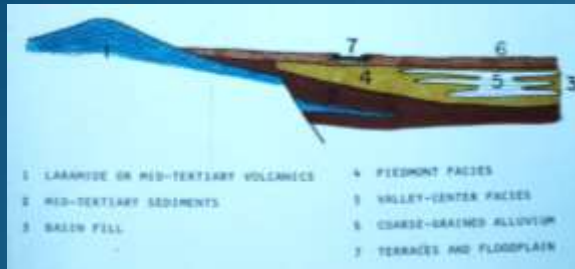
cinders



Olivine necklace, San Carlos

San Andreas (13-0 Ma) rifting - basins

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
San Andreas	Late	2.6 - 0.012	olivine; gypsum	Peridot Mesa, Camp Verde	Olivine, glauberite; gypsum;
	Early	13-2.6	Zeolites, salt	San Francisco volcanics, Luke salt	Clinoptilolite, hectorite; halite



Rillito ~ 21 Ma



Willcox Playa

San Andreas – zeolites in basalt (14 Ma), saline minerals from young basins (5-0 Ma)

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
San Andreas	Late	2.6 - 0.012	olivine; gypsum	Peridot Mesa, Camp Verde	Olivine, glauberite; gypsum;



Natrolite, Horseshoe Dam,
donor Stan Celestisn



calcite after glauberite, Camp Verde
salt mine, Rock Currier, MinDat

San Andreas – Basins (14-0 Ma)

Industrial minerals from young basins

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
San Andreas	Late	2.6 - 0.012	olivine; gypsum	Peridot Mesa, Camp Verde	Olivine, glauberite; gypsum;



Sand & gravel



Kalamazoo Clay - 1987

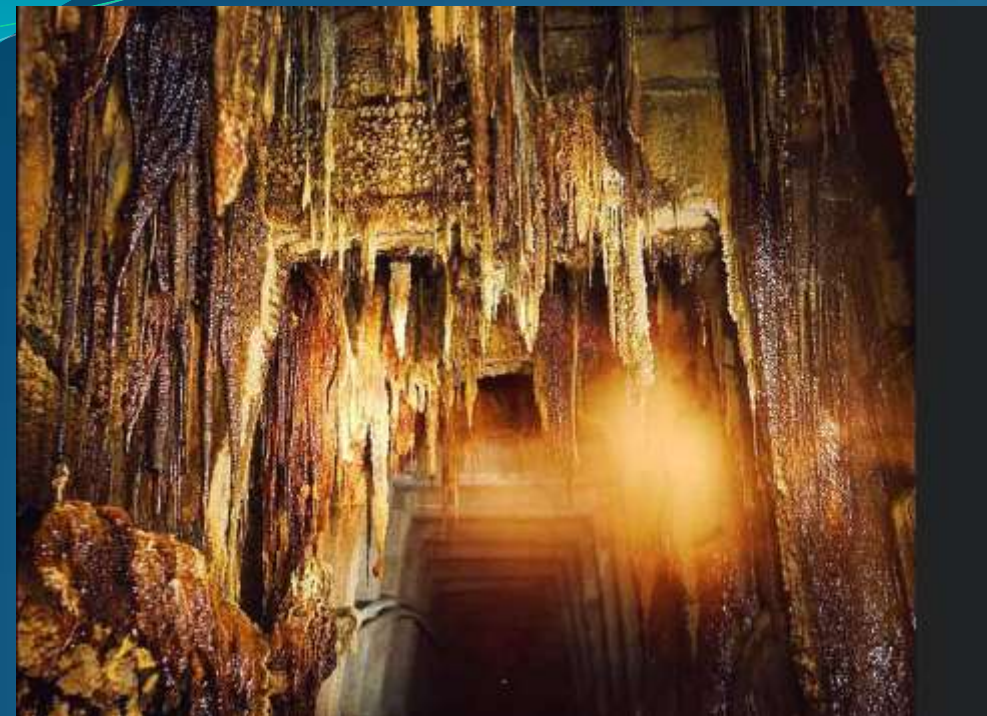


Gypsum rose – St. David



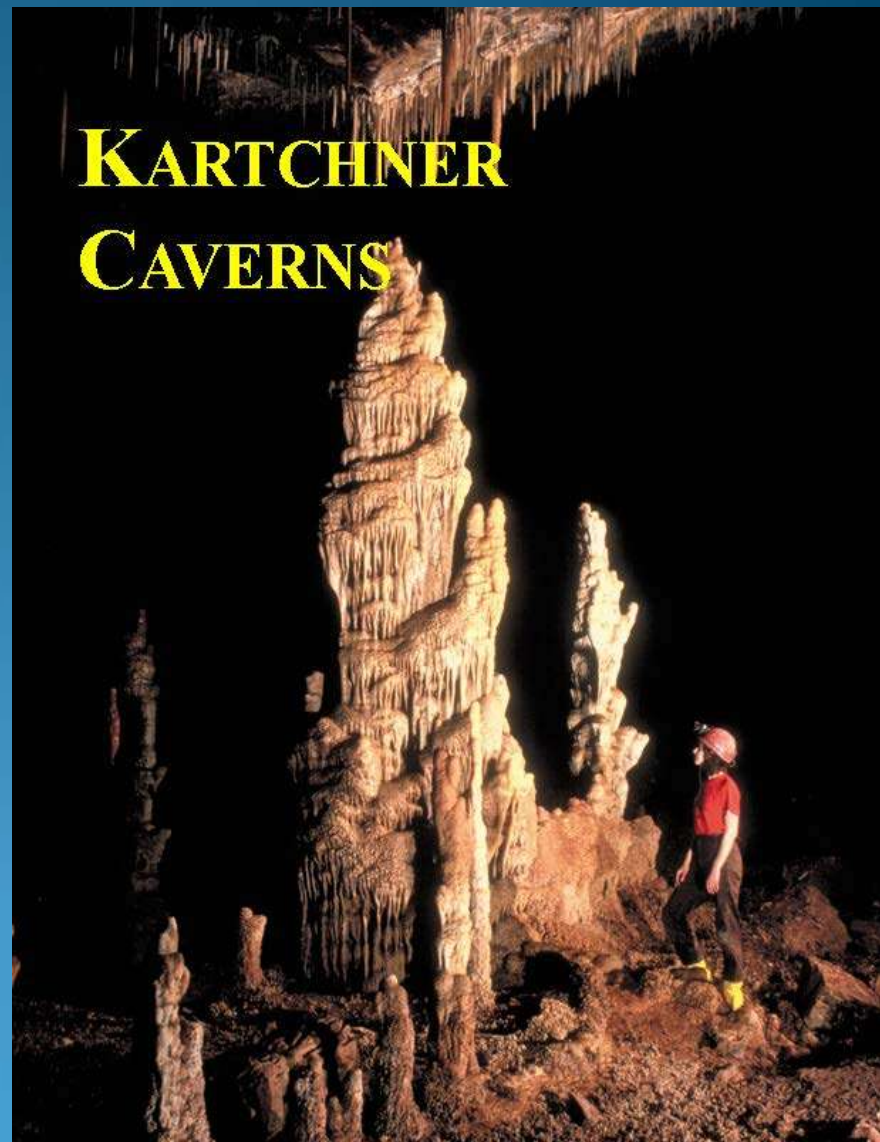
Salt - Picacho Basin – UnoCal photo

Modern Minerals Are Still Forming



Bisbee , post-mining iron hydroxides and melanterite coating mine timber on the 2833 level of the Campbell Mine, Graeme, BisbeeMiningandMinerals.com

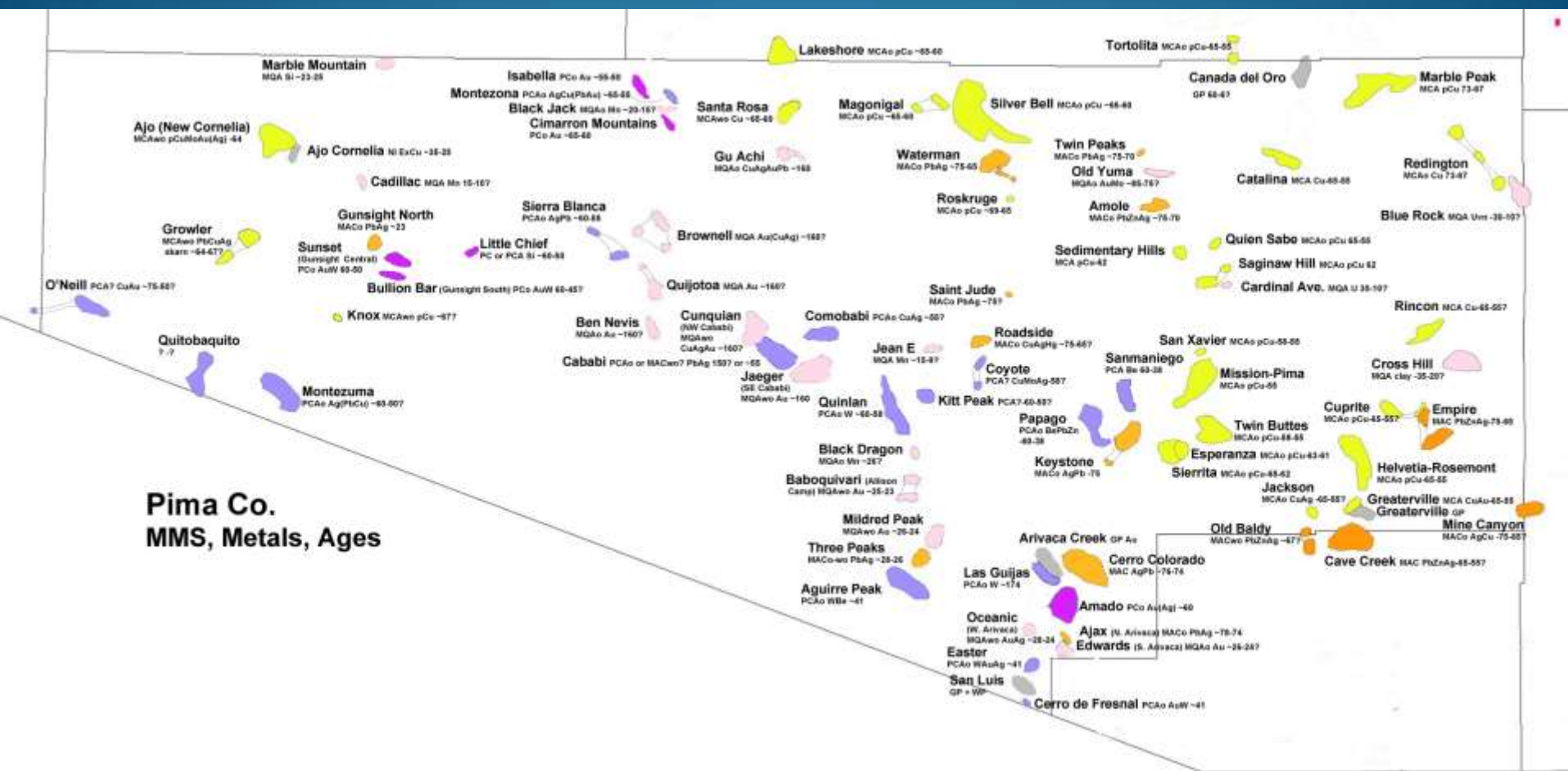
Copper replacing wood, Inspiration Mine



**KARTCHNER
CAVERNS**

Very complex, overprinted mountain building cycles bring new ore minerals

Re-organization events between mountain building episodes, allow oxidation of the sulfides into collectible minerals.



Arizona Minerals through Geologic Time

+ Complex

+ Repeated intrusions

+ Bring new minerals

+ Overprints

+ Oxidation during re-organization

Result:
+ Many beautiful minerals to collect & love

Orogeny	Phase	Age (Ma)	Resources	Mineral districts/ systems	Minerals
San Andreas	Late	2.6 - 0.012	olivine, gypsum	Peridot Mesa, Camp Verde	Olivine, glauberite, gypsum
	Early	13-2.6	Zeolites, salt	San Francisco volcanics, Luke salt	Clinoptilolite, hectorite, halite
Galluro	Late	26-10	Mn, U, Au-Ag	Artillery Mts., Anderson, Oatman, Mammoth	Mn oxides, carnotite, gold, Tiger suite, specularite
	Middle	26-15	PbZnAg(AuCu)	Ash Peak, Red Cloud, Aravaipa	Cassiterite, silver, galena, sphalerite
	Early	30-21	Au (CuWAg)	Kofa, South Mountain, Gila Bend Mountains	Gold, todorokite, chalcophanite, pyrolusite
Laramide	Late	95-29	Actinolite, garnet	Cemetery Ridge, Garnet Ridge	Actinolite, serpentine group, pyrope garnet
		70-35	Au	Gold Basin, Vulture	gold, kyanite
		80-40	W	Blue Bird	wolframite group, scheelite
	Middle	65-55	Cu-Mo-Ag	Ajo, Ray, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci	chalcopyrite, molybdenite, pyrite, bornite, epidote, garnet
	Early	75-65	Ag, Pb-Zn	Tombstone, Globe, Empire, Ruby, Salero	galena, sphalerite, alabandite, tetrahedrite, silver, enargite
Earliest	89-75	Cu-Au-Ag	Old Yuma, Mexican Hat, Golden Rule	gold, galena, cerussite, mottramite, wulfenite, vanadinite	
Sevier	Late	93-91	U	Black Mountain (U)	carnotite, tyuyamunite, hewettite
	Middle	100-89	Coal, fire clay	Dakota Sh., Deer Creek coal	Coal, kaolinite
	Early	135-110	calcite flux	Paul Spur	calcite
	Early	154-135	U-V-Cu (Ni-Co)	Orphan, Hermit, Arizona 1, EZ-2, Pigeon	pyrite, uraninite, bravoite, sphalerite, chalcopyrite, galena
Nevadan	Late	175-155	Au	Nogales	gold
		175-155	W veins	Las Guijas, Juniper Flat	wolframite group, hübnerite, scheelite
		180-155	Kyanite	Tung Hill	dumortierite, rutile, scheelite
	Middle W AZ	173-155	Pb-Zn-Ag	Comobabi Mts., Cababi (Midren-Steppe Mine)	galena, sphalerite, tetrahedrite
		169-155	AuCu (AgWPb)	La Cholla, Sugarloaf (Big Bertha), Jaeger	quartz, pyrite, gold, chalcopyrite, specular hematite
	Early SE AZ	191-175	Pb-Zn-Ag(CuAu)	Gleeson (South Turquoise), Hartford	galena, sphalerite, tetrahedrite, cerussite, wulfenite
		201-191	Cu-Au, PGE	Warren (Bisbee), Turquoise (Courtland)	chalcopyrite, bornite, azurite, malachite, cuprite, copper
Early N AZ	237-201	U-V-Cu (Ni-Co)	Orphan, Grandview, Monument Valley	uraninite, chalcopyrite, galena, torbernite, carnotite	
Quachita	Pangea	318-271	NaCl, K, salt	Holbrook salt, polish	sylvite, carnallite, polyhalite, halite, gypsum, anhydrite
Antler (NV)	Laurentia	360-357	oolitic iron	Payson "diamond quartz"; Ranch Cr. Fe	"Herkimer habit" quartz, oolitic hematite
Keweenawan	failed rifting	1104-1035	asbestos, U, Cu	Sierra Ancha, Hope	chrysotile asbestos, lizardite, uraninite, pyrite
Elzevirian	Arc	1580-1240	hematite	Apache Iron, Chediski Iron	hematite, apatite, muscovite, chert
Picuris	Late	1460-1370	Be, U, Ce, Ta-Nb	White Picacho, Wagon Bow, Tungstona	spodumene, lepidolite, scheelite, beryl, wolframite group
	Early	1470-1420	Fe, amethyst	Four Peaks Amethyst	amethyst, hematite, fluorapatite
Mazatzal	Late	1630-1610	Au (Ag Pb Cu Bi)	Yellowstone	Gold, quartz, baryte, bismuth minerals, tourmaline, zircon
	Early	1630-1590	W, Be, F, LREE	Black Beauty, Kingman Feldspar	scheelite, beryl, allanite-Nd, bastnaesite, microcline
	Middle	1680-1630	Au	Roosevelt, Spring Creek, Prescott, Thumb Butte	gold
	Early	1702-1680	Be, F	Breadpan Fm., Gordon Creek pyrophyllite	acicular beryl, tourmaline, topaz, pyrophyllite
Yavapai	Late	1715-1690	W(Be)	Boriana, Money Maker-North Star	scheelite, beryl, hübnerite, wolframite, microcline, quartz
	Early	1770-1715	Hg, Au(Ag), MoCu	Phoenix Mts. Hg, Groom Creek, Squaw Peak	cinnabar, kyanite, tourmaline, gold, quartz, molybdenite
	Early	1750-1720	Zn-Cu-Ag VMS, Fe-Si BIF	VMS Jerome, Antler, Pikes Peak Fe-Si	VMS (pyrite, chalcopyrite, sphalerite, galena, cubanite, arsenopyrite, pyrrotite); chert-hematite (magnetite);
Mohave		1820-1780	None	None	muscovite, garnet, feldspar