Arizona Mineralization through Geologic Time

Copper , Bisbee

Gold, Gold Basin, Mohave Co., AZ

It's not all copper!

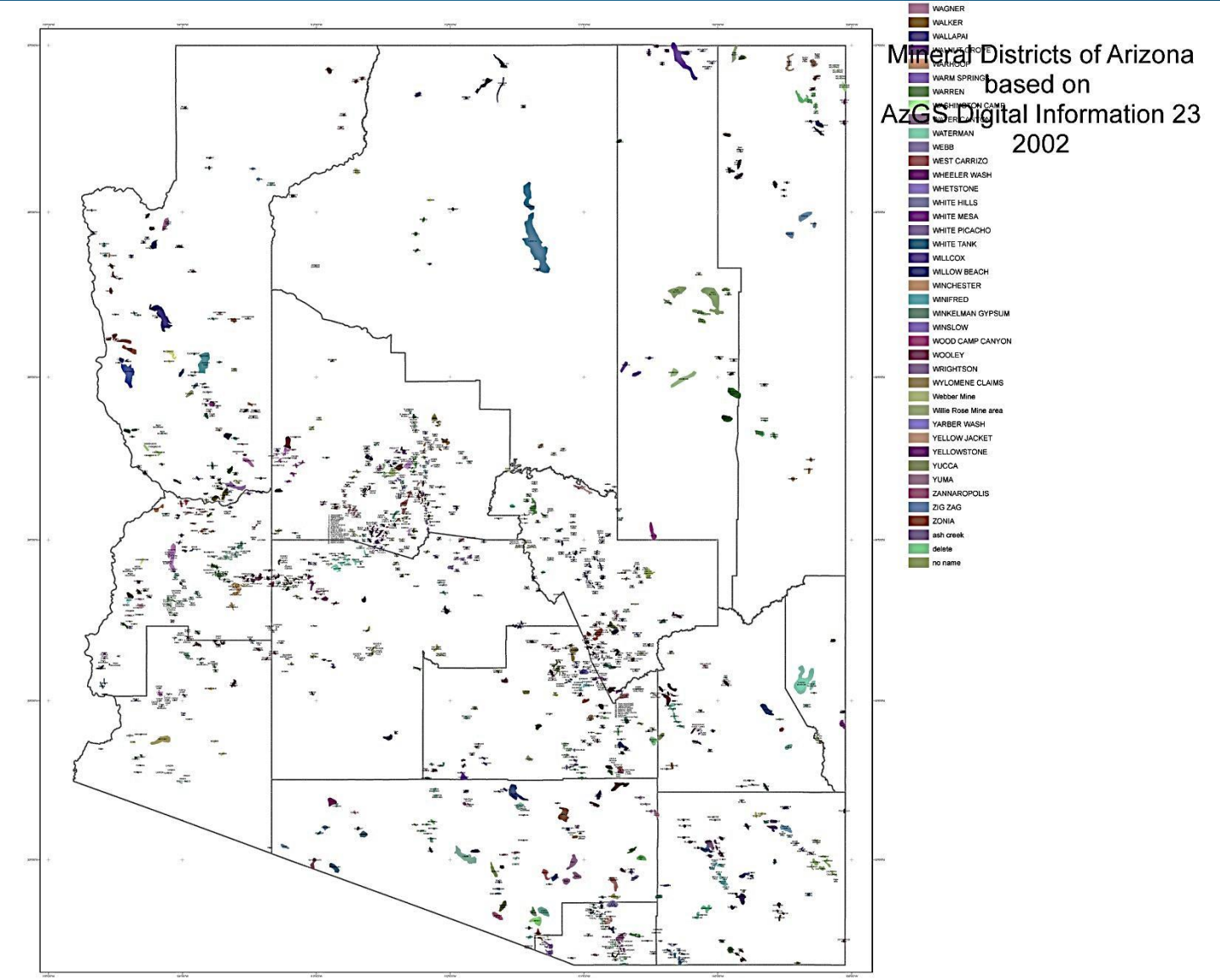
by Jan C. Rasmussen
Consulting Geologist

Arizona Mining Districts

>800 districts/ subdistricts

Very rich mineral heritage

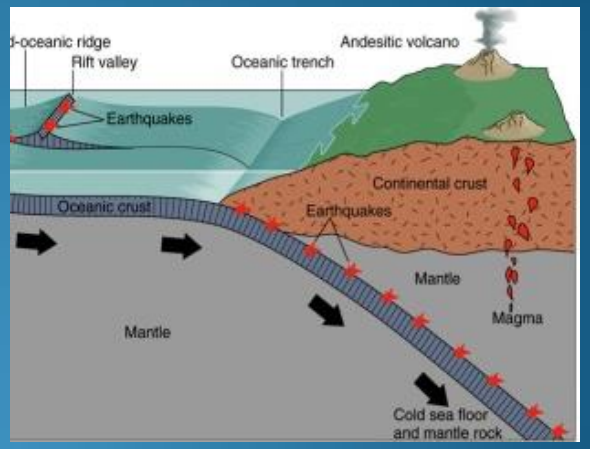
Copper deposits were made only 3 times in AZ geologic history

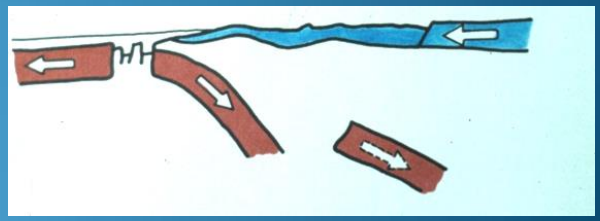


Arizona Mineralization through Geologic Time

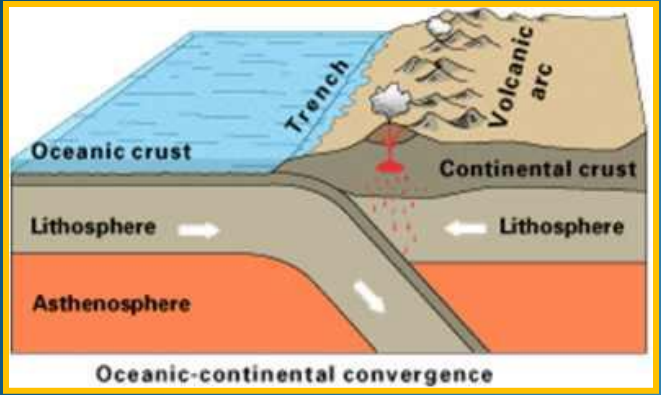
Mineralization is related to mountain building episodes

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

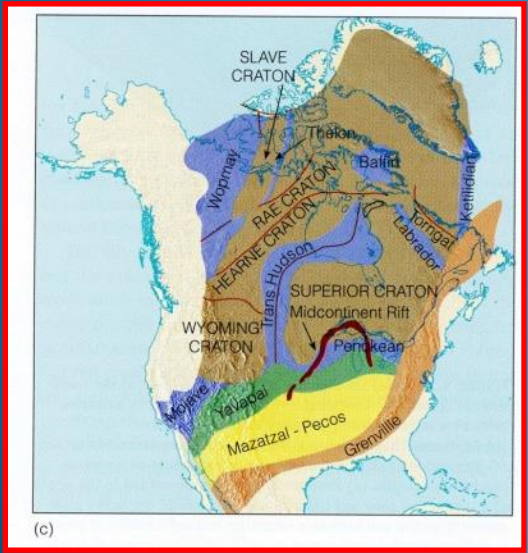




Orogenies in Arizona

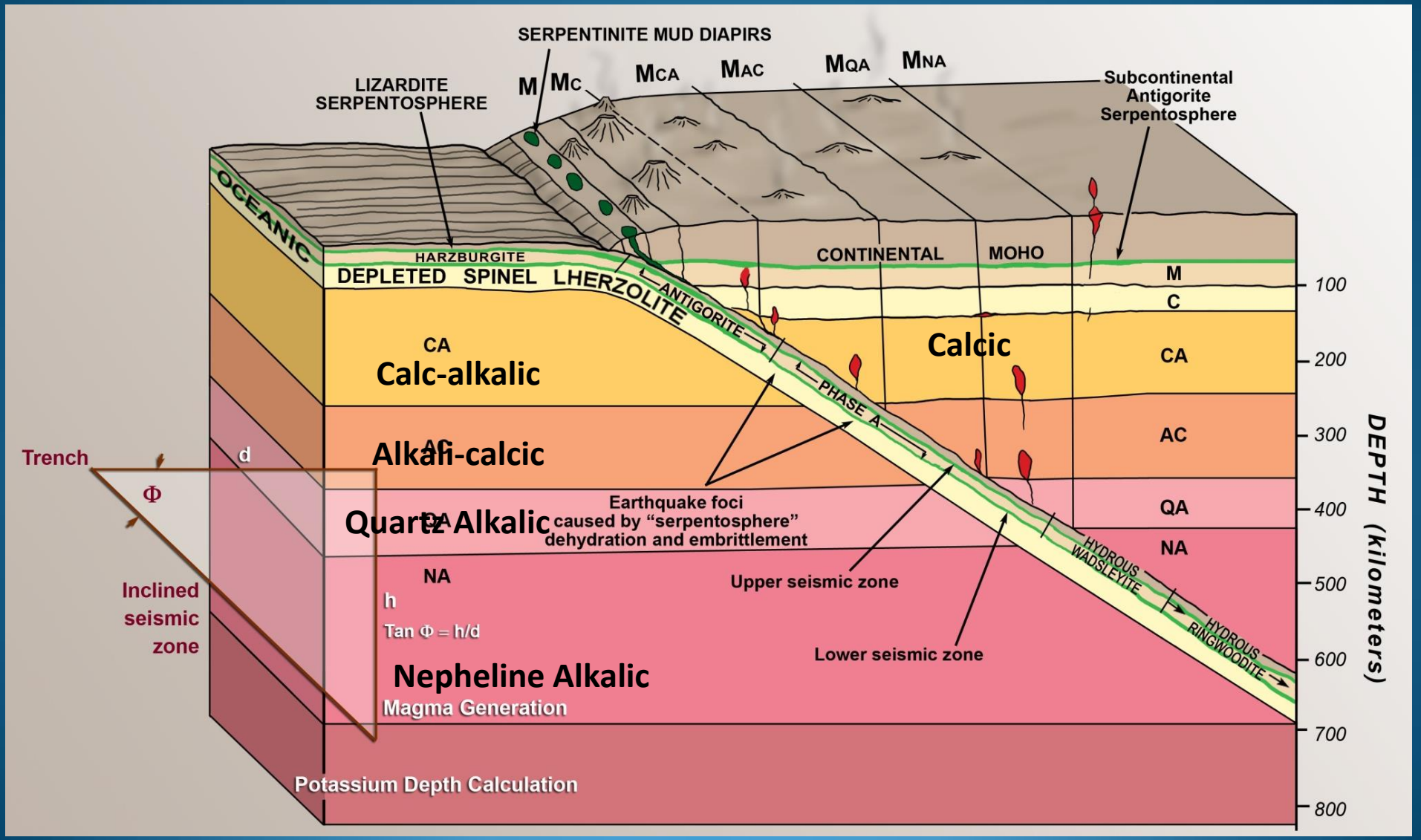


Oceanic-continental convergence



Orogeny	Phase	Age (Ma)	Alkalinity	Resources	Mining districts
San Andreas	Basin & Range	13-0	M A	Sand, gravel, salt, zeolites, gypsum	San Francisco volcanic field, San Carlos olivine, Emerald Isle
Galiuro	Late)	18-13	M QA	Cu-Au-Ag in veins; epithermal Au-Ag veins	Oatman, Mammoth, Rowley
	Middle	28-18	M AC	Pb-Zn-Ag F veins, replace.; epithermal	Silver (Red Cloud m.), Castle Dome, Stanley, Aravaipa
	Early	30-22	M CA	Au +/- Cu-W veins & disseminated	Little Harquahala, Kofa
	Earliest	38-28	-	Uranium, clay, exotic copper	Ajo Cornelia, Copper Butte (from Ray)
Laramide	Late	55-43	P C, CA	Au dissem. & qtz veins; W veins,	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin, Copperstone
	Middle	65-55	M CA	large disseminated porphyry Cu systems, local skarns & veins, fringing Zn-Pb-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior
	Early	85-65	M AC	Pb-Zn-Ag veins & replacement deposits	Tombstone, Tyndall (Glove), Washington Camp, Salero
	Earliest	89-85	M QA	Cu-Au hydrothermal	Hillsboro, NM
Sevier		145-89		Sedimentary rocks	Bisbee Group sediments
Nevadan	Late	160-145	P		
	Middle	205-160	M QA	porphyry Cu-Au at Bisbee, Gleeson	Warren (Bisbee mine), Turquoise (Courtland-Gleeson)
	Early	230-205	M AC, A	Uranium, vanadium, copper	Orphan, Grandview, Monument Valley
Alleghenian (Ouachita)		325-220	-	U in sed. rocks	Payson uranium
Acadian/ Caledonian		410-380	-	Limestone	
Taconic.		490-445	-		
Grenville		1200-900	M QA	Serpentine asbestos	Sierra Ancha uranium Chrysotile (Salt R. Canyon)
"Oracle/Ruin"		1440-1335	P C AC	Pegmatites & greisens – Be, Li, Ta-Nb, U & W	White Picacho, Tungstona, Four Peaks
Mazatzal		1750-1600	M C	Cu-Zn-Ag VMS	Old Dick (Bruce)
Yavapai		1800-1775	M C	Cu-Zn-Au VMS, Cu-Zn-Ag	Big Bug (Iron King), Verde (Jerome)
Penokean/ Hudsonian		2000-1800	M C	BIF (Banded iron formation)	Pikes Peak iron

Alkalinity in mantle layers

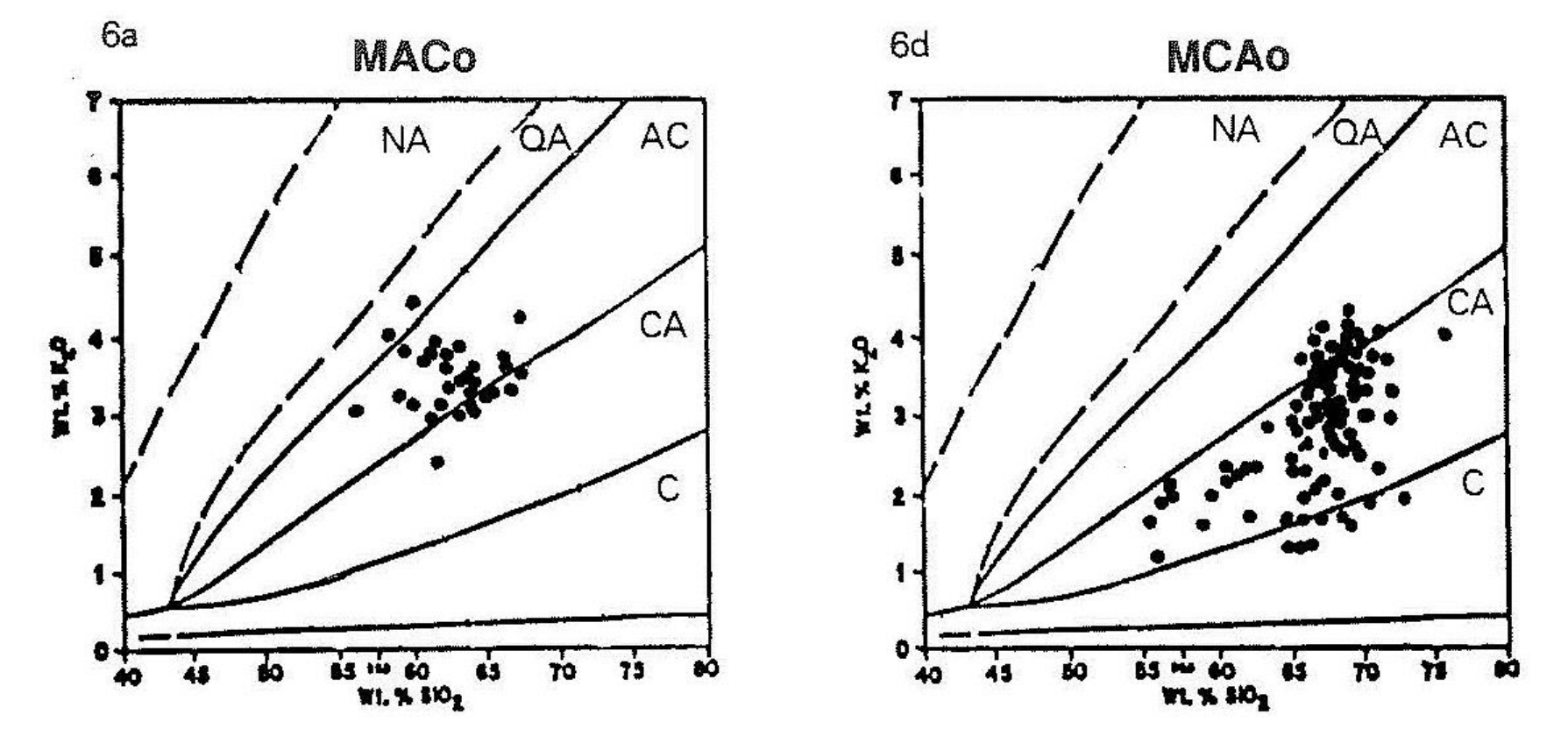


Alkalinity in mantle layers

Alkalinity (Metaluminous)	Metals (oxidized)	Metals (reduced)
Calcic	Cu>Zn-Au-Ag	Au>Ag
Calc-alkalic	Cu* Zn-Pb-Ag>>Au-Mo-Mn	Au*
Alkali-calcic	Pb-Zn-Ag	Ag (Sn)
Quartz Alkalic	Cu-Au-Fe-U-LREE	Au-Cu-Ni-Co
Nepheline Alkalic	Al,LREE-Zr-U-Th-Y	Au>Ag

Alkalinity (Peraluminous)	Metals (oxidized)	Metals (reduced)
Calcic	Au-Ag	Au>Ag
Calc-alkalic	W-Be-Pb-Zn-Ag	W-Pb-Zn-Ag
Alkali-calcic	U-W	Sn-W-Cu-U-Pb-Zn-Ag-Li-C

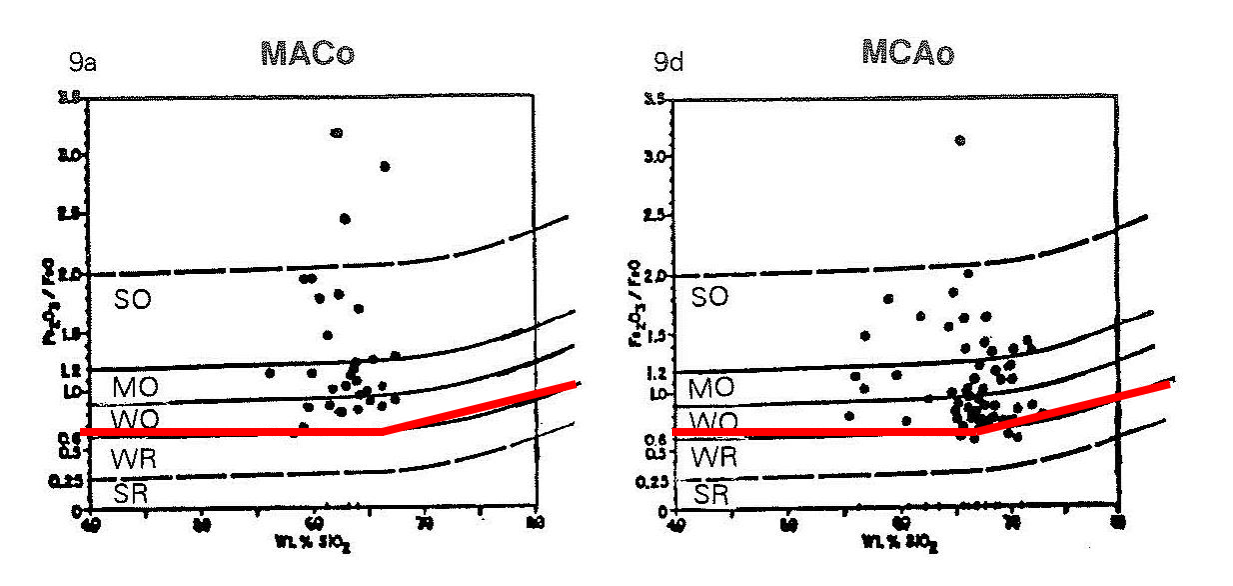
Alkalinity on K_2O vs. SiO_2 plots



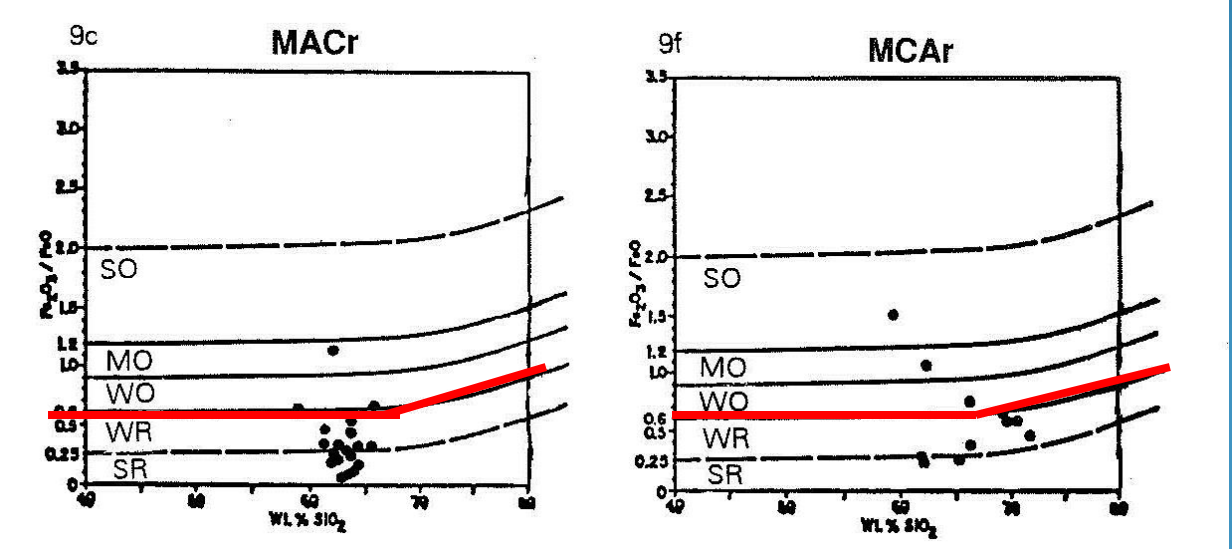
Alkali-calcic = MAC

Calc-alkalic = MCA

Oxidized and Reduced plots



Oxidized = base metals



Reduced = precious metals

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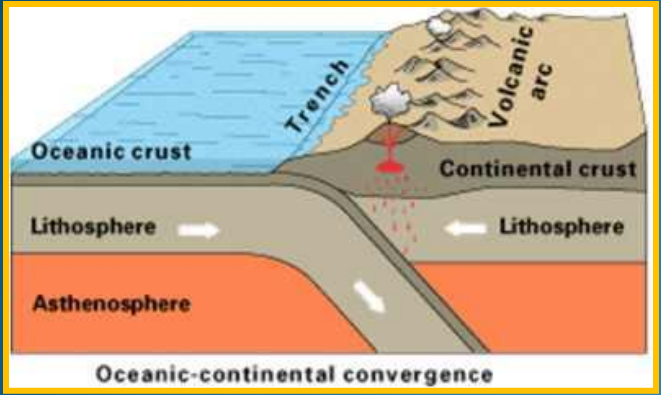

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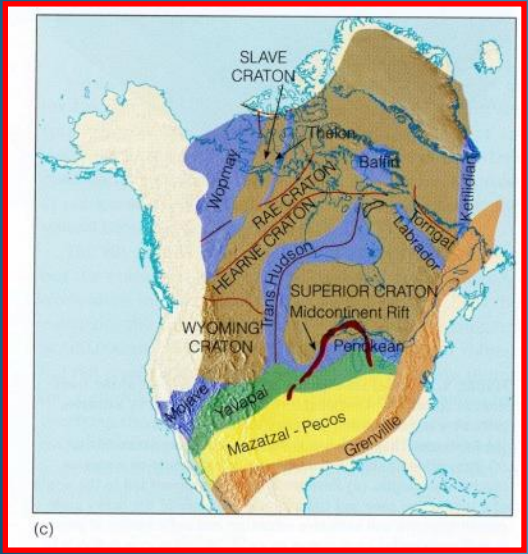

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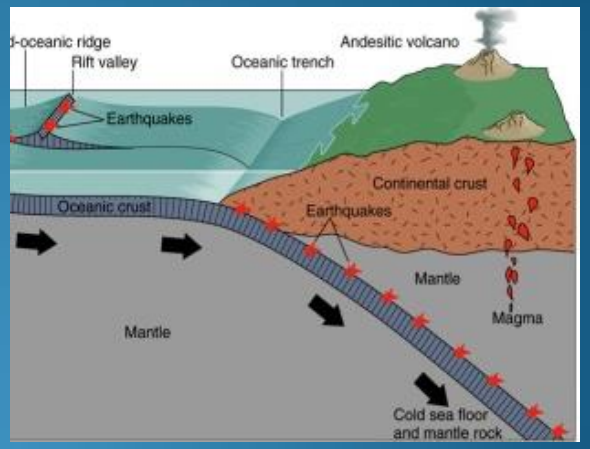

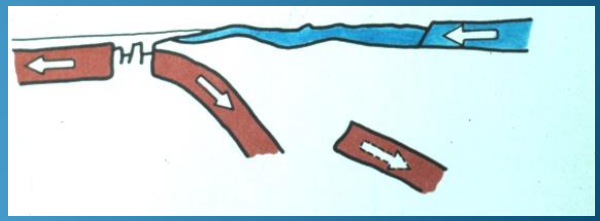

Precambrian Orogenies in Arizona

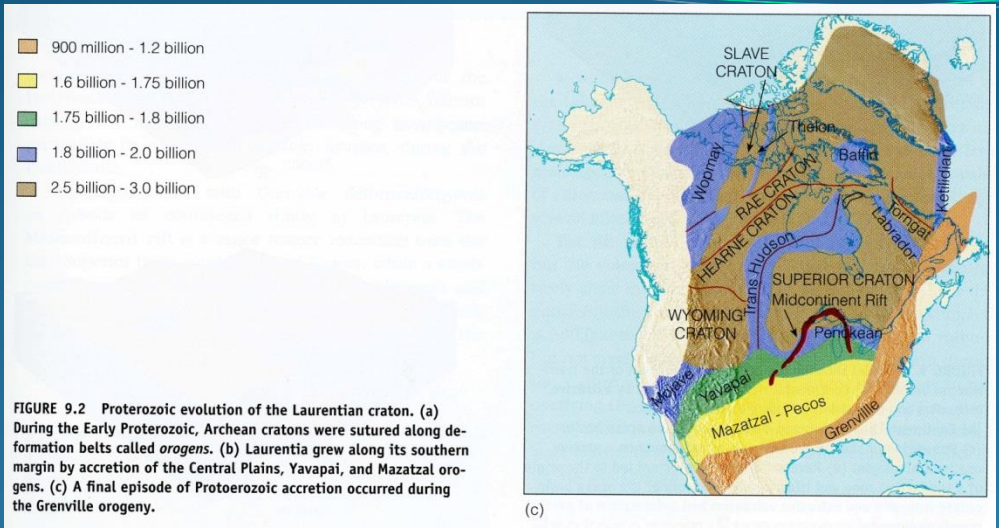

FIGURE 9.2 Proterozoic evolution of the Laurentian craton. (a) During the Early Proterozoic, Archean cratons were sutured along deformation belts called *orogens*. (b) Laurentia grew along its southern margin by accretion of the Central Plains, Yavapai, and Mazatzal orogens. (c) A final episode of Protoerozoic accretion occurred during the Grenville orogeny.

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Grenville		1200-900	Late Middle Proterozoic – Early Late Proterozoic	basalt flows, diabase dikes	Metalum. Alkalic	Serpentine asbestos	Sierra Ancha uranium Chrysotile (Salt R. Canyon)
"Oracle/Ruin"		1440-1335	Middle Proterozoic	K-feldspar megacrystic or porphyritic granites	Peralum. Calc-alkalic, Alkali-calcic	Pegmatites & greisens – Be, Li, Ta-Nb, U & W	White Picacho, Tungstona, Four Peaks
Mazatzal		1750-1600	Late Early Proterozoic	Basalt & rhyolite metavolc., schist	Metalum. Calcic	Cu-Zn-Ag VMS	Old Dick (Bruce)
Yavapai		1800-1775	Late Early Proterozoic	Andesite, schist, metarhyolite	Metalum. Calcic	Cu-Zn-Au VMS, Cu-Zn-Ag	Big Bug (Iron King), Verde (Jerome)
Penokean/ Hudsonian		2000-1800	Middle Late Proterozoic	Schist, banded cherty iron formation	Metalum. Calcic	BIF (Banded iron formation)	Pikes Peak iron

Hudsonian/Mohave Orogeny (2 – 1.8 Ga)

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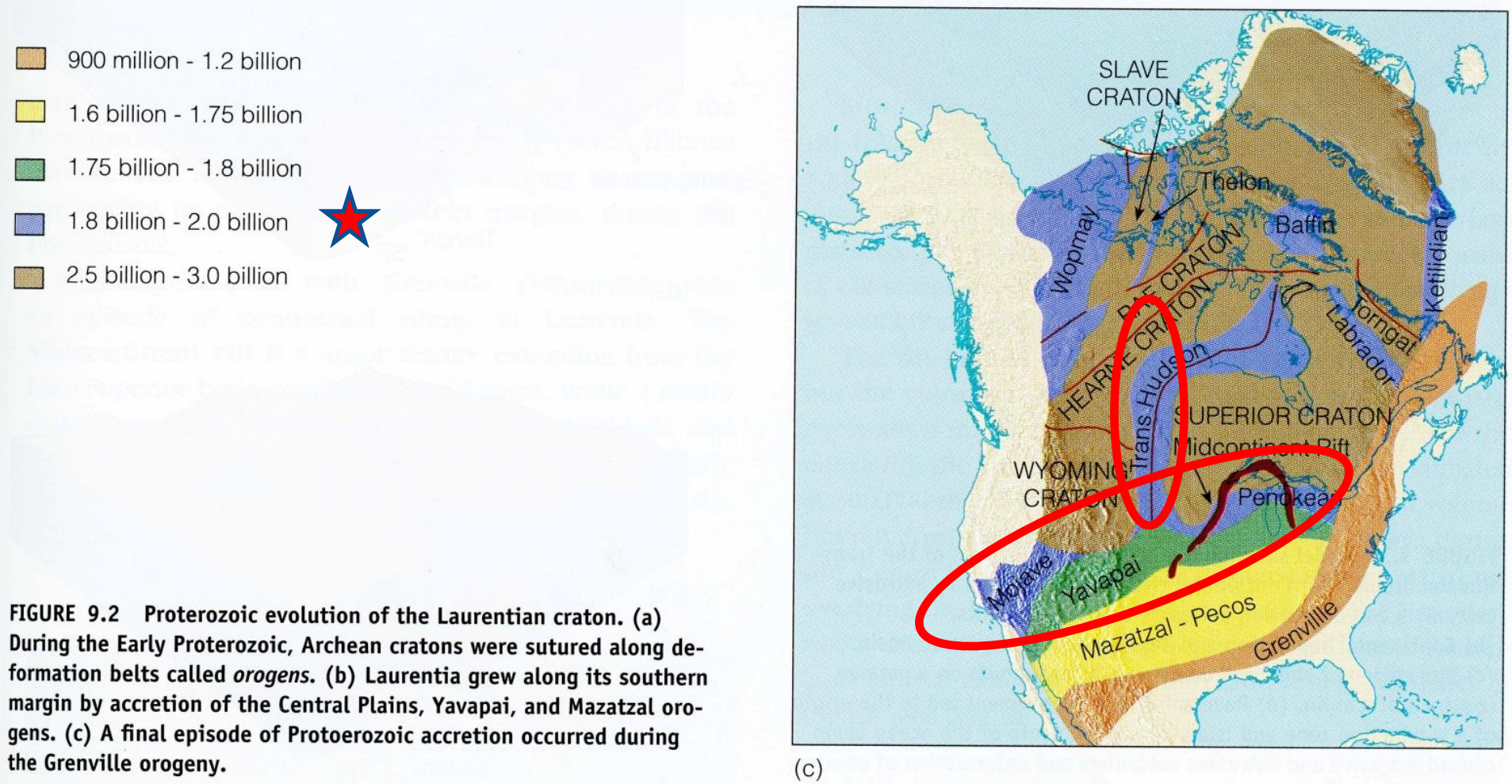

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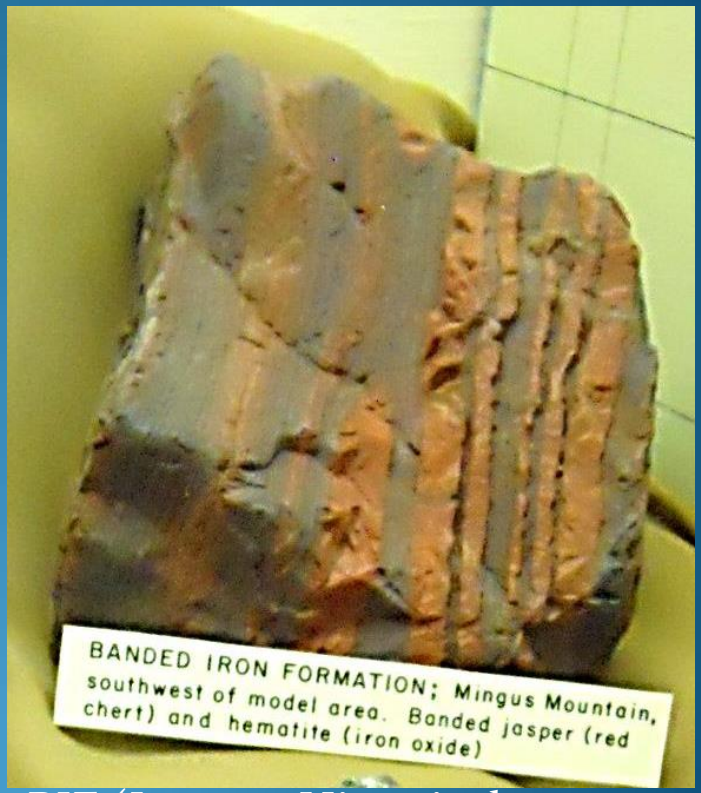
Mohave Orogeny – Pikes Peak BIF Banded Iron Formation

Hieroglyphic Mountains (Pikes Peak) hematite-magnetite taconite, north-central Maricopa County - Iron Age, Pig Iron, and Bessemer mines

FIGURE 22. - Taconite-Like Hematite-Magnetite Iron Formation, Hieroglyphic Mountains, T 6 N, Rs 1 and 2 W, Maricopa County, Ariz. Note banded, laminated structure.



BIF (Jerome Historical museum) Paul Lindberg sample

Yavapai - Jerome VMS (1.8 – 1.775 Ga)

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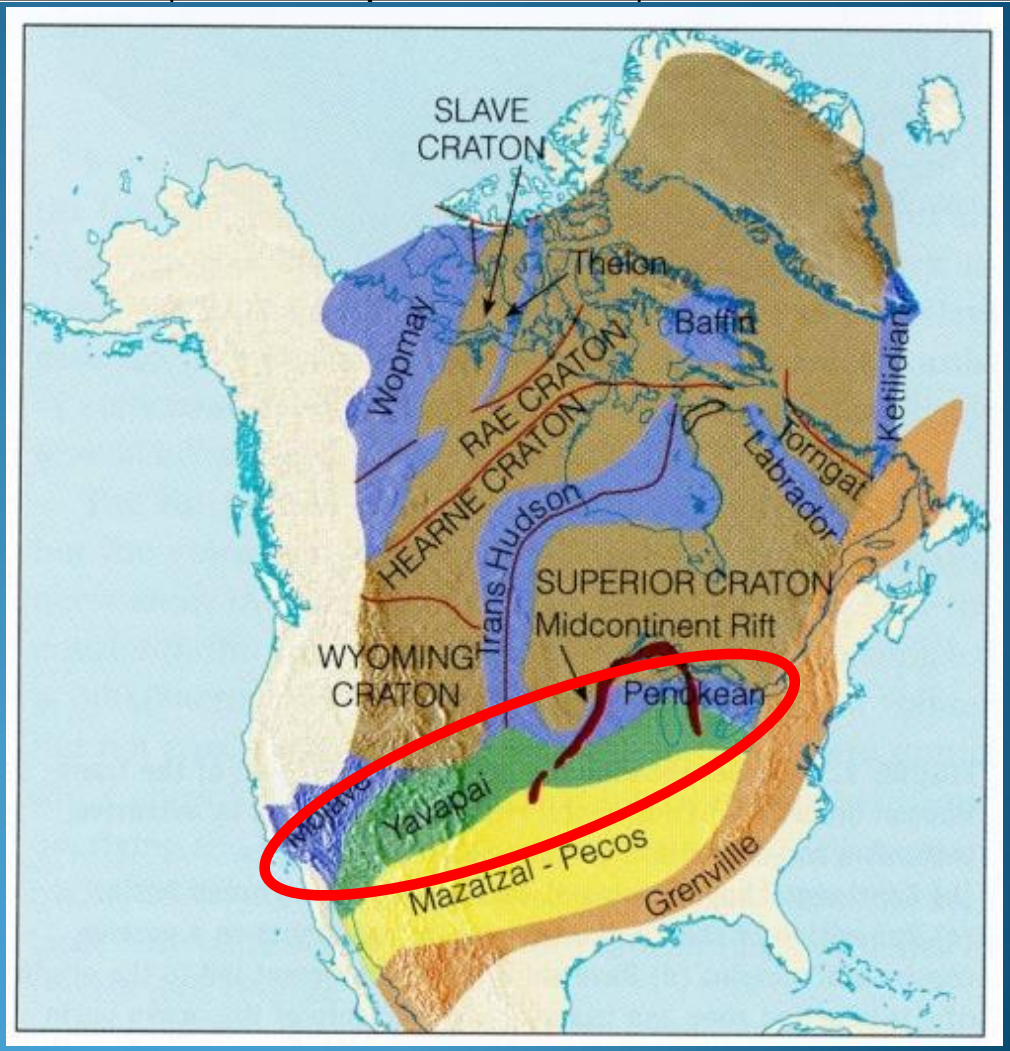

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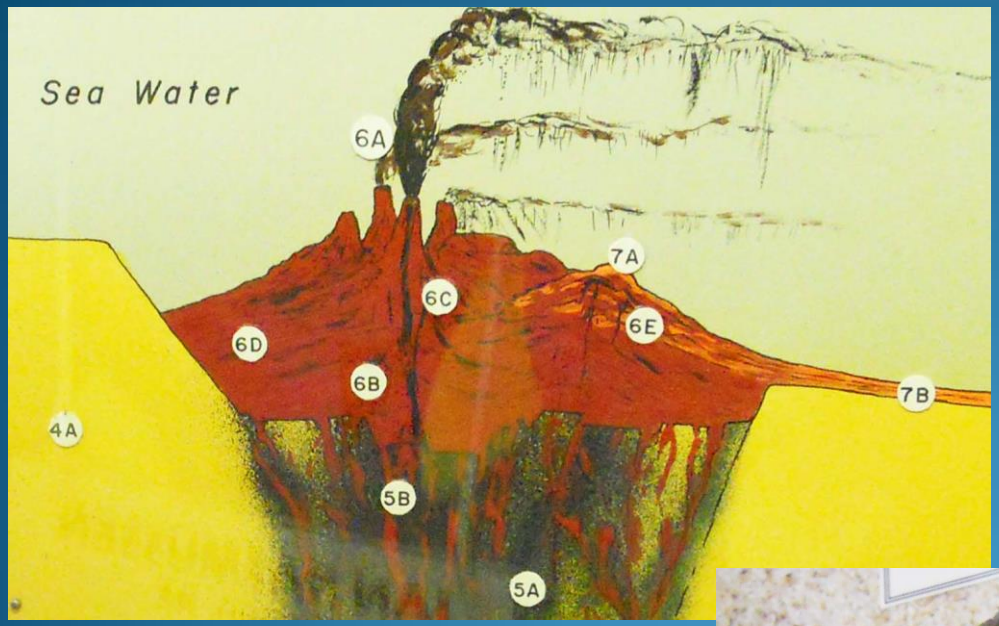

Bornite, chalcopyrite
Copper iron sulfides
United Verde mine,
Jerome, AZ
AzMMM sample

3D model of Verde deposit by Paul Lindberg, Jerome Historical museum

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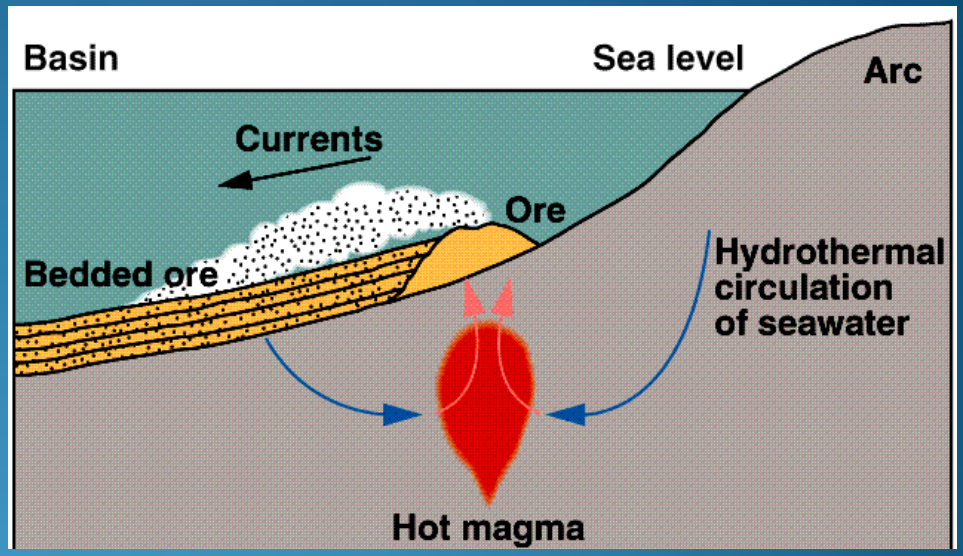
Black smoker, modern seafloor



Deposition of Volcanogenic Massive Sulfide ore

Jerome (Verde m.d.) (1800 – 1775 Ma)

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Chalcopyrite, copper iron sulfide, United Verde mine, Jerome, AZ, AzMMM specimen

Tennantite, chalcopyrite - Copper iron sulfides - United Verde mine, Jerome, AZ, AzMMM sample

Yavapai - Big Bug – Iron King VMS

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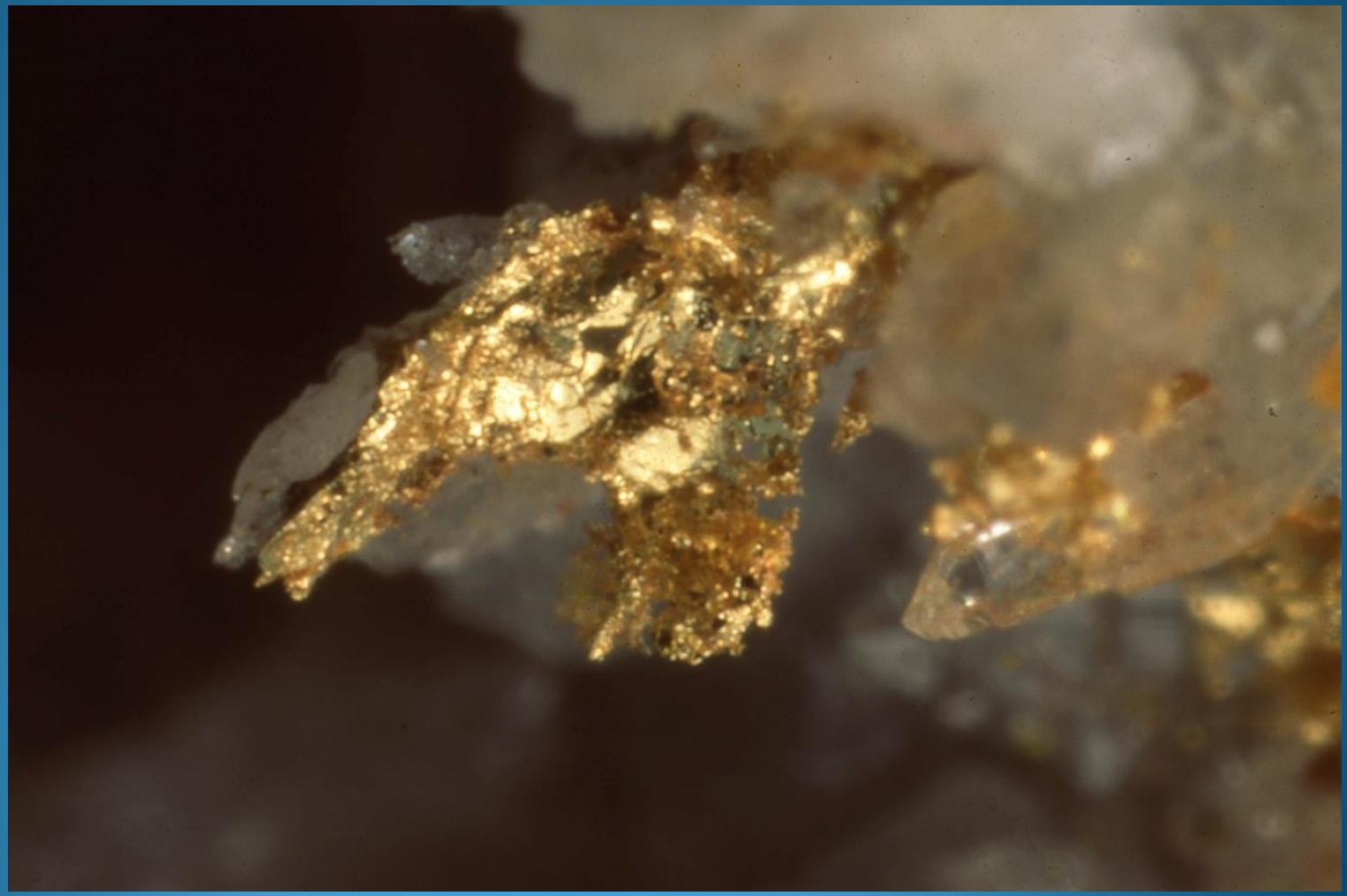
Gold from Big Bug mine –

Sugar White photo, Ed Huskinson sample



Mazatzal Orogeny (1.75-1.6 Ga)

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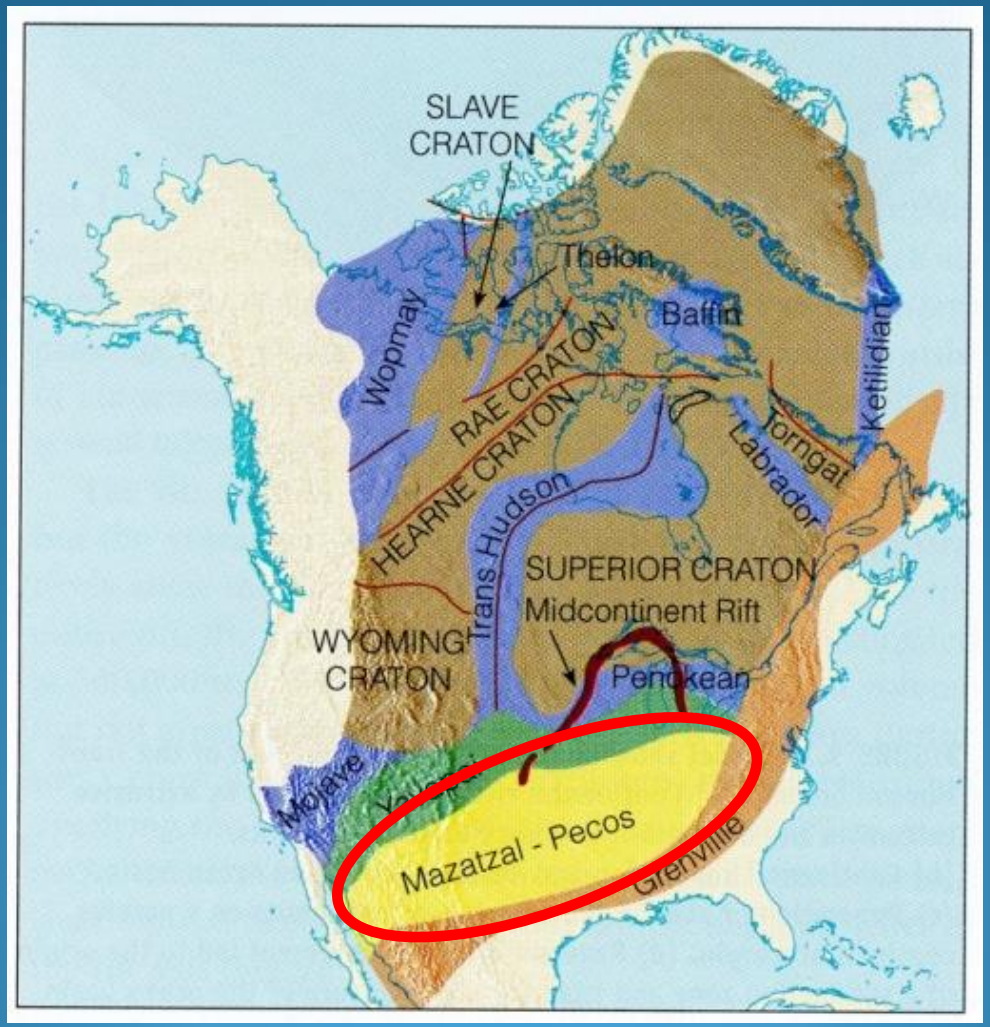

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The Old Dick (Bruce) mine is a

- former underground Zn-Cu-Ag-Au-Pb-As-Co-Cd mine
- located 2¾ miles SSW of Bagdad.
- volcanogenic massive sulfide deposit
- stratiform ore bodies hosted in the Brindle Formation and the Dick Rhyolite

Hillside mine, Eureka dist., Yav. Co.; source: Baird, mindat.org

The Old Ore lenses consist of resinous yellowish-brown and black sphalerite

- pyrite concentrated in irregularly spaced, narrow bands
- chalcopyrite in minute stringers and wide
- galena in local pods , sphalerite in veinlets
- disseminated tiny euhedral arsenopyrite crystals
- some gold and silver Information source: MinDat.org

Oracle "anorogenic" Orogeny (1.44-1.335 Ga)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
"Oracle/Ruin"		1440-1335	Middle Proterozoic	K-feldspar megacrystic or porphyritic granites	Peralum. Calc-alkalic, Alkali-calcic	Pegmatites & greisens – Be, Li, Ta-Nb, U & W	White Picacho, Tungstona, Four Peaks

Euxenite
White Picacho pegmatites

Oracle Granite, Santa Catalina Mts.

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

Grenville Orogeny (1200-900 Ma)

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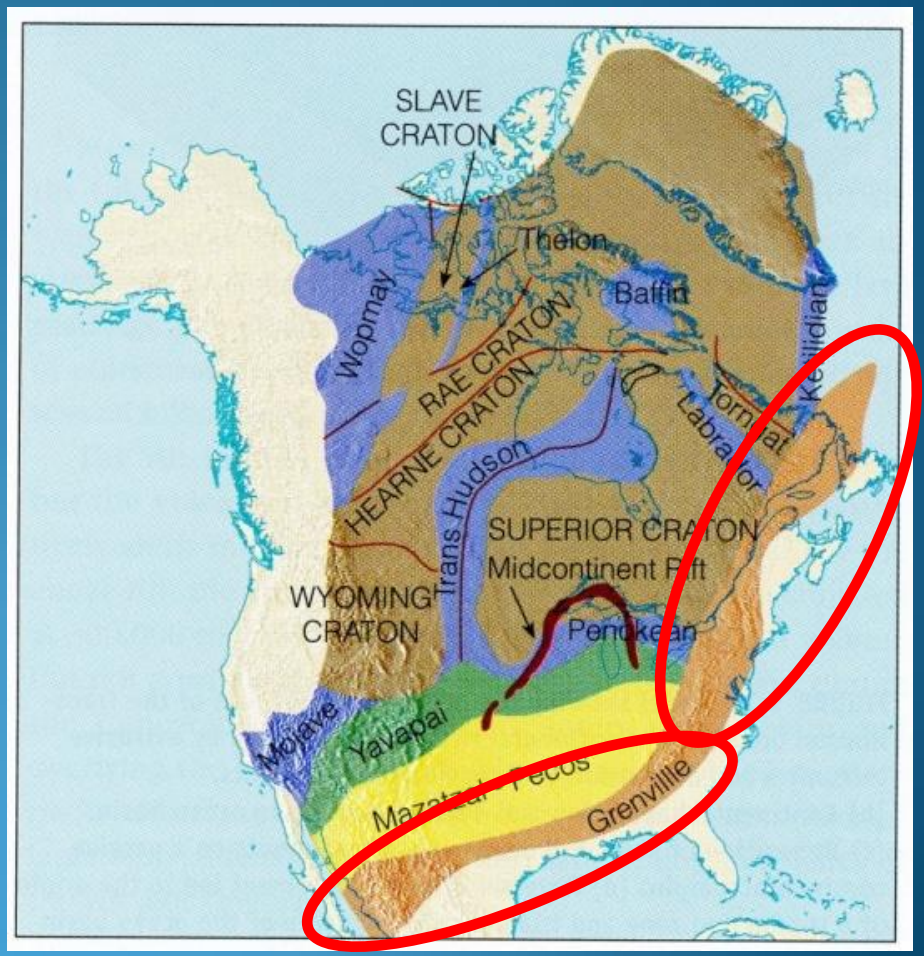
Grand Canyon supergroup (Unkar Gp. (incl. Cardenas basalt - 1070 Ma Rb-Sr), Nankoweap Fm., Chuar Gp.)



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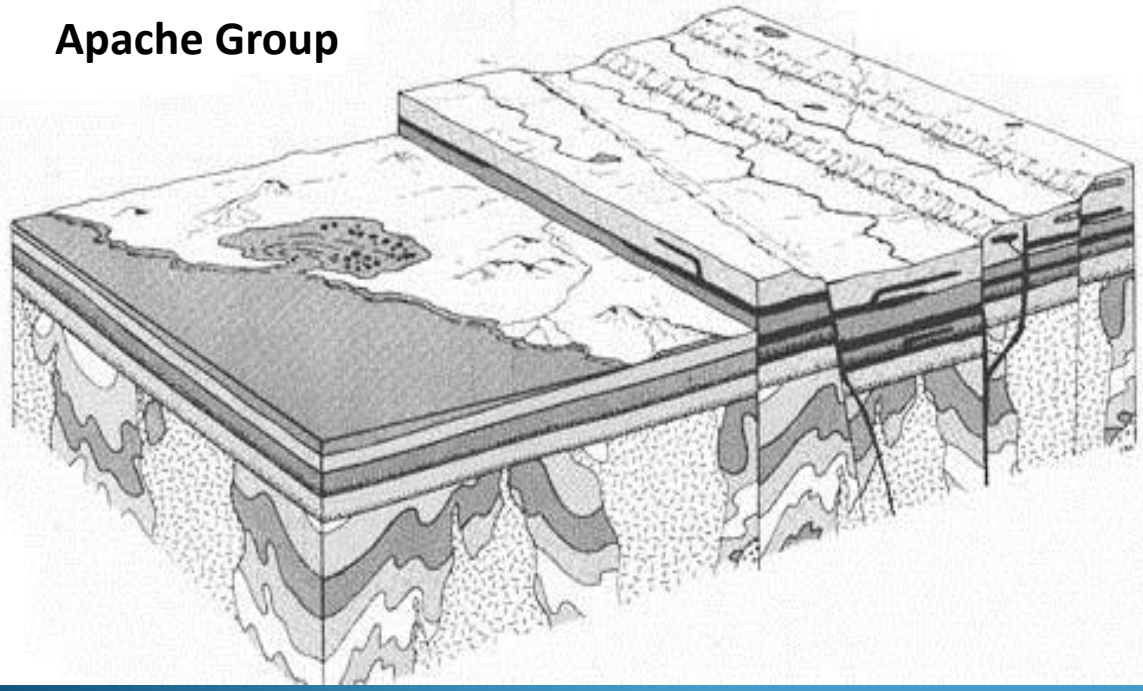
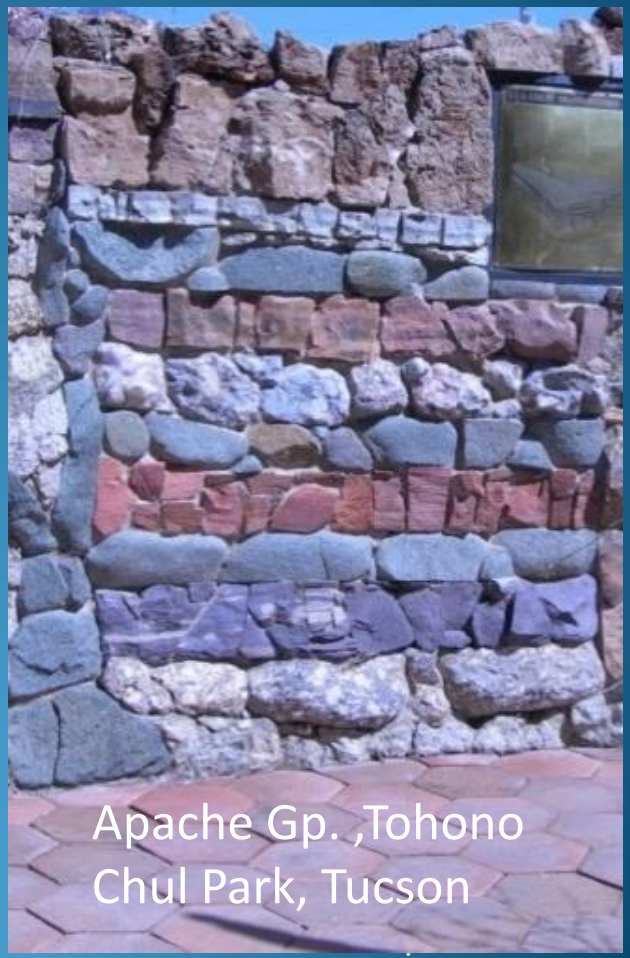
Apache Group





Apache Gp. ,Tohono Chul Park, Tucson

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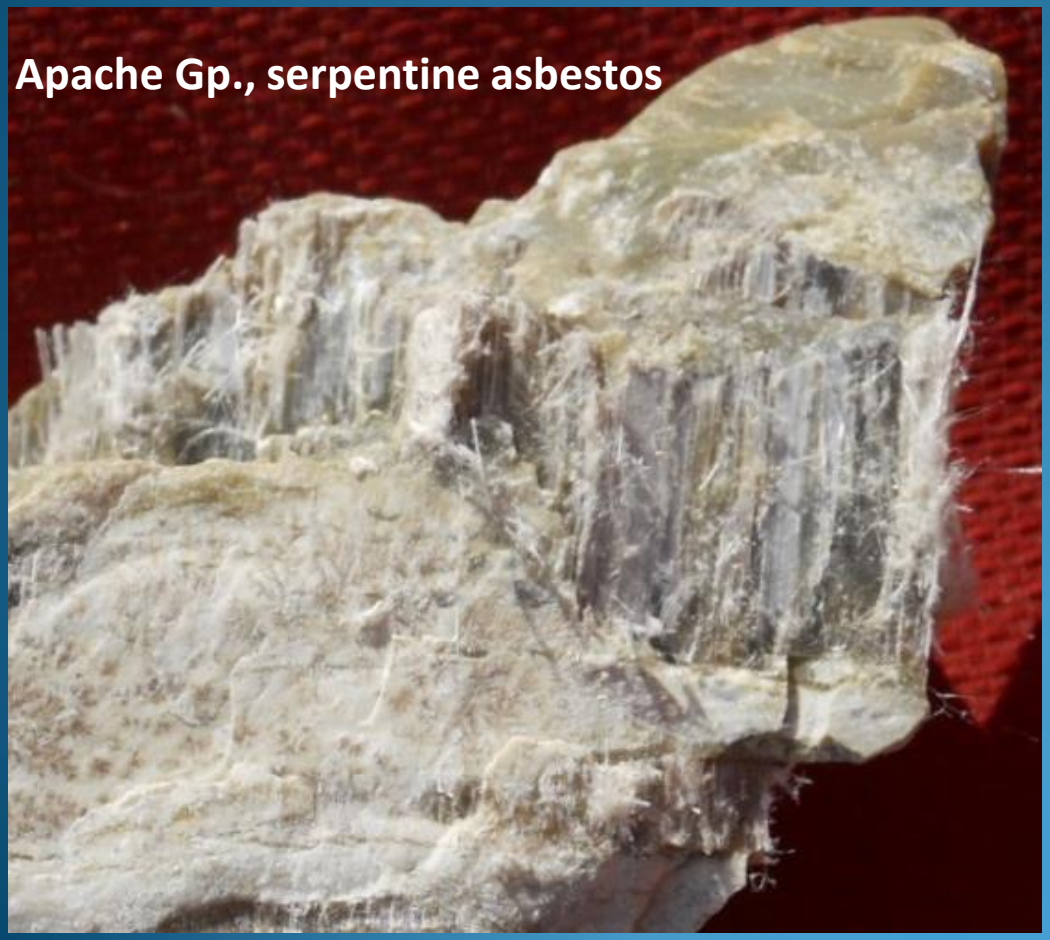
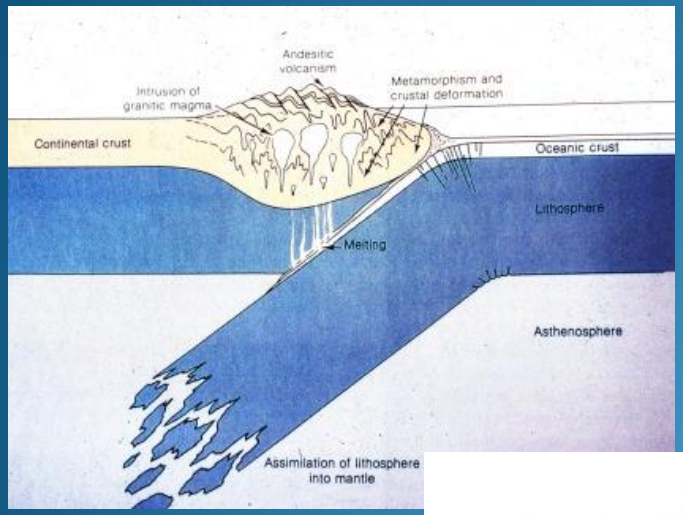
Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Grenville		1200-900	Late Middle Proterozoic – Early Late Proterozoic	basalt flows, diabase dikes	Metalum. Alkalic	Serpentine asbestos	Sierra Ancha uranium Chrysotile (Salt R. Canyon)

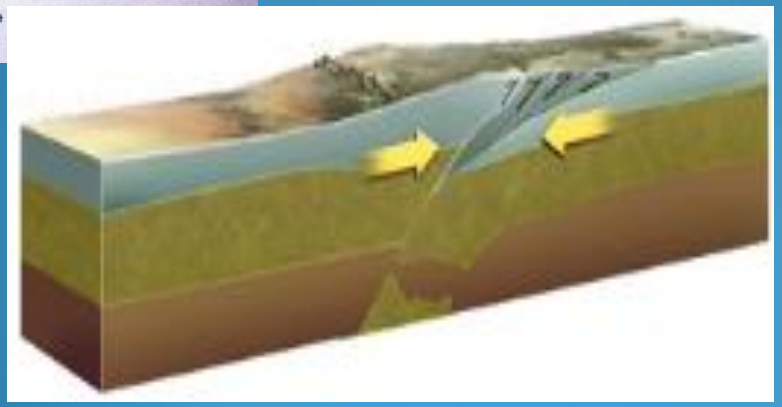


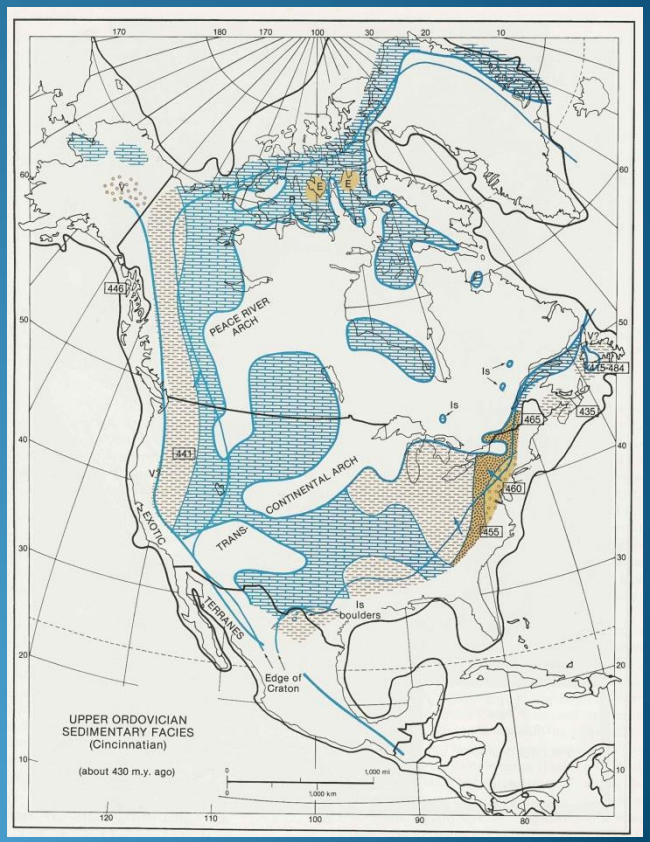
Diabase in Apache Gp. ,Tohono Chul Park, Tucson

Paleozoic Orogenies in eastern U.S.

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Alleghenian (Ouachita)		325-220	Miss. – Triassic	None	-	U in sed. rocks	Payson uranium
Acadian/ Caledonian		410-380	Devonian	None	-	Limestone	
Taconic.		490-445	Cambrian – Ord.	None	-		







Paleozoic cratonic sequences

Unconformity bounded
Continental assembly

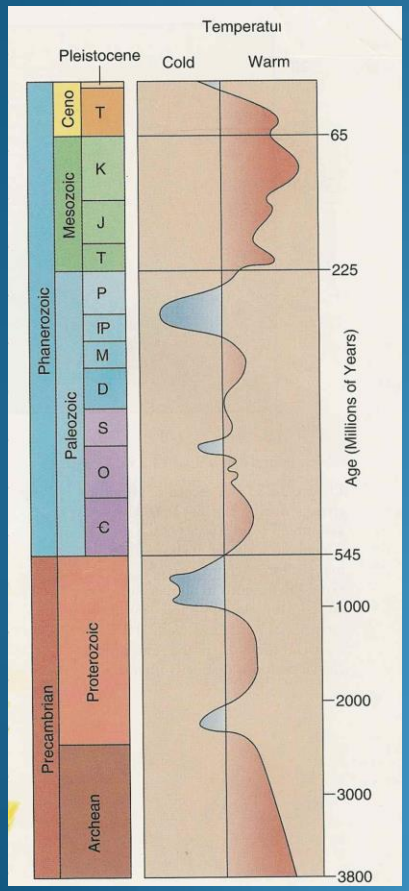


TABLE 8-1 Cratonic Sequences of North America*

Geologic Time		Cratonic Sequences: Center of craton / Margin of craton	Orogenic Events	Biologic Events	Ice Ages
CENOZOIC		Tejas	Himalayan / Alpine	Age of mammals	
MESOZOIC	Cretaceous	Zuni	Laramide / Sevier	*Massive extinctions* First flowering plants Climax dinosaurs and ammonites	
	Jurassic		Nevadan	First birds Abundant dinosaurs and ammonites	
				First dinosaurs First mammals	
LATE PALEOZOIC	Permian	250 m.y.a. Absaroka	Sonoma	Abundant cycads *Massive extinctions* (including trilobites) Mammal-like reptiles	
	Pennsylvanian		Alleghenian	Great coal forests Conifers First reptiles	
	Mississippian	Kaskaskia	Antler	Abundant amphibians and sharks Scale trees Seed ferns	
	Devonian			*Extinctions* First insects First amphibians First forests First sharks	
EARLY PALEOZOIC	Silurian	410 m.y.a. Tippecanoe	Acadian–Caledonian	First jawed fishes First air-breathing arthropods	
	Ordovician		Taconic	*Extinctions* First land plants Expansion of marine shelled invertebrates	
	Cambrian	Sauk		First fishes Abundant shell-bearing marine invertebrates Trilobites	
LATE PROTEROZOIC		540 m.y.a.		Rise of the metazoans	

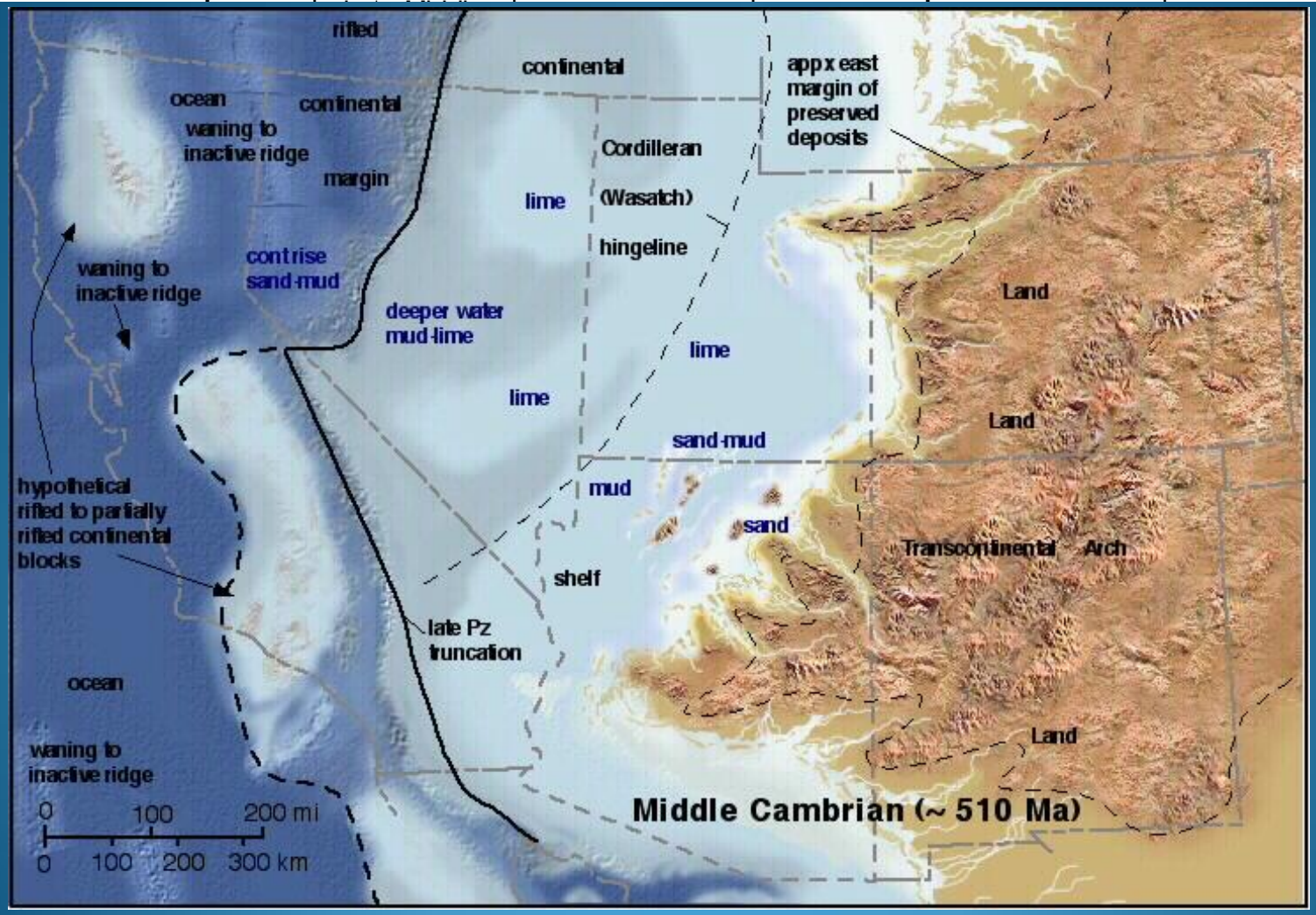
Laramide orogeny
Nevadan orogeny
Alleghenian orogeny
Caledonian orogeny
Taconic orogeny

*The green areas represent sequences of strata. They are separated by major unconformities, indicated in yellow. Note that the rock record is most complete near cratonic margins, just as the time spans represented by unconformities are greatest near the center of the craton. Major biologic, orogenic, and glacial events are added for reference. (Cratonic sequence model after Sloss, L. L. 1965. *Bull Geol. Soc. Amer.* 74:93–114.)

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

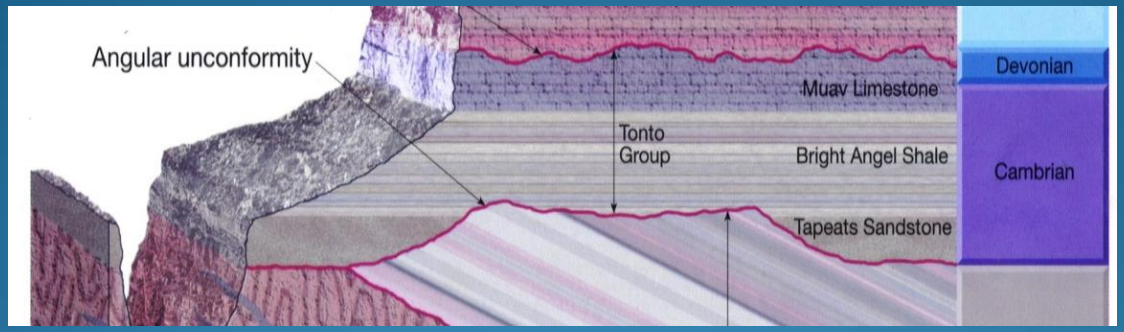
Taconic sedimentation in Arizona

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Taconic.		490-445	Cambrian – Ord.	None	-		



Taconic sedimentation in Arizona

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Taconic.		490-445	Cambrian – Ord.	None	-		



Tonto Group, Grand Canyon (Tapeats Ss. Ledge, overlain by Bright Angel Shale slope, and Muav Ls. Ledge)

Taconic sedimentation in Arizona

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Taconic.		490-445	Cambrian – Ord.	None	-		

Bolsa Quartzite on skyline, Rosemont Copper, Santa Rita Mts.

Acadian/Caledonian sedimentation in Arizona

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Acadian/ Caledonian		410-380	Devonian	None	-	Limestone	

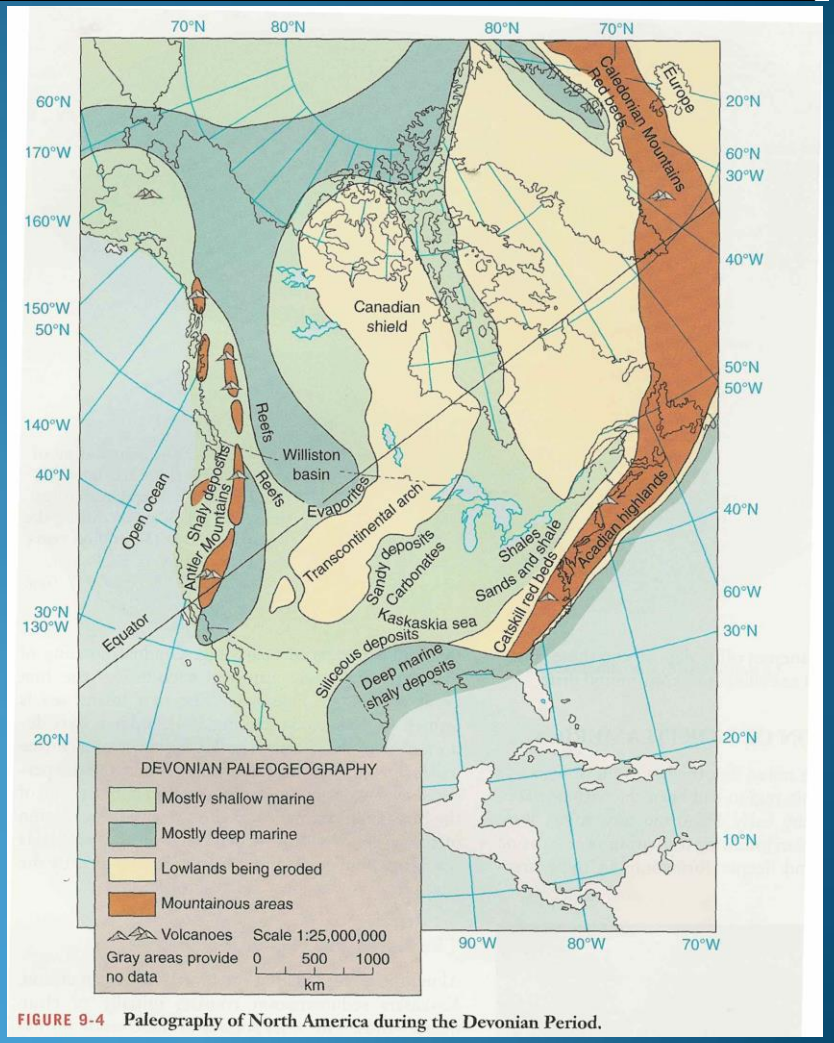
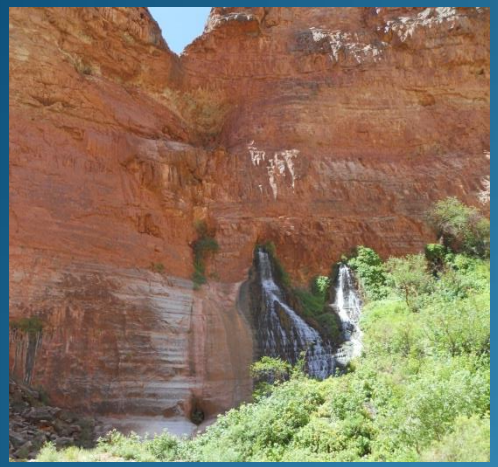


FIGURE 9-4 Paleography of North America during the Devonian Period.

All paleogeographic paintings from Blakey & Ranney

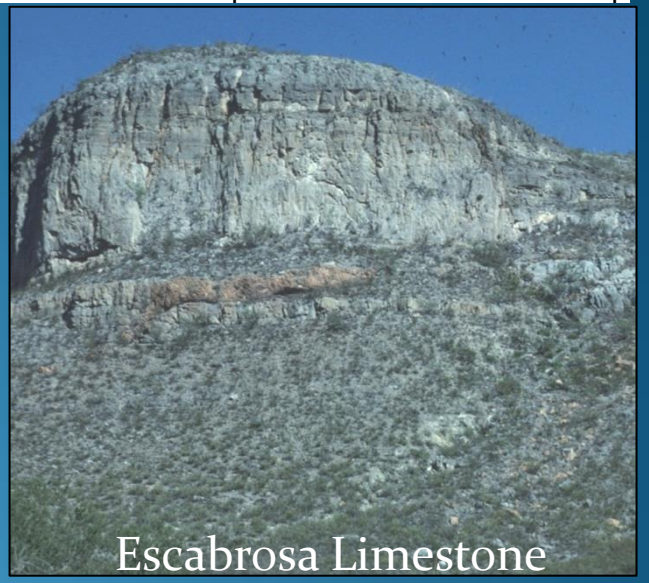
Lull - Mississippian Limestones in Arizona

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Alleghenian (Ouachita)		325-220	Miss. – Triassic	None	-	U in sed. rocks	Payson uranium
Acadian/ Caledonian		410-380	Devonian	None	-	Limestone	



Redwall Limestone

Rillito Cement plant



Escabrosa Limestone

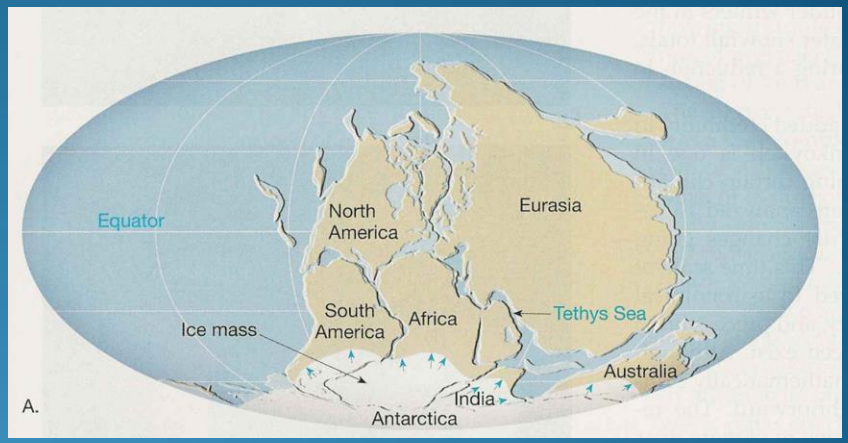
Clarkdale Cement plant

Sahuarita Marble

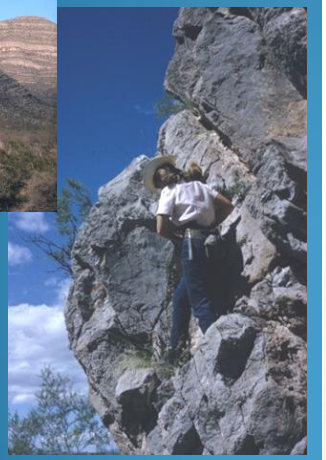
Alleghenian sedimentation in Arizona

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Alleghenian (Ouachita)		325-220	Miss. – Triassic	None	-	U in sed. rocks	Payson uranium


Sedona – Supai Group




Government Butte, S. of Tombstone


Jan on Permian Colina Ls. 1967

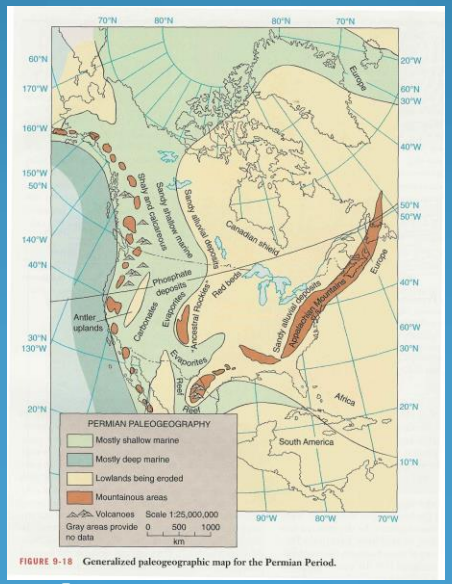
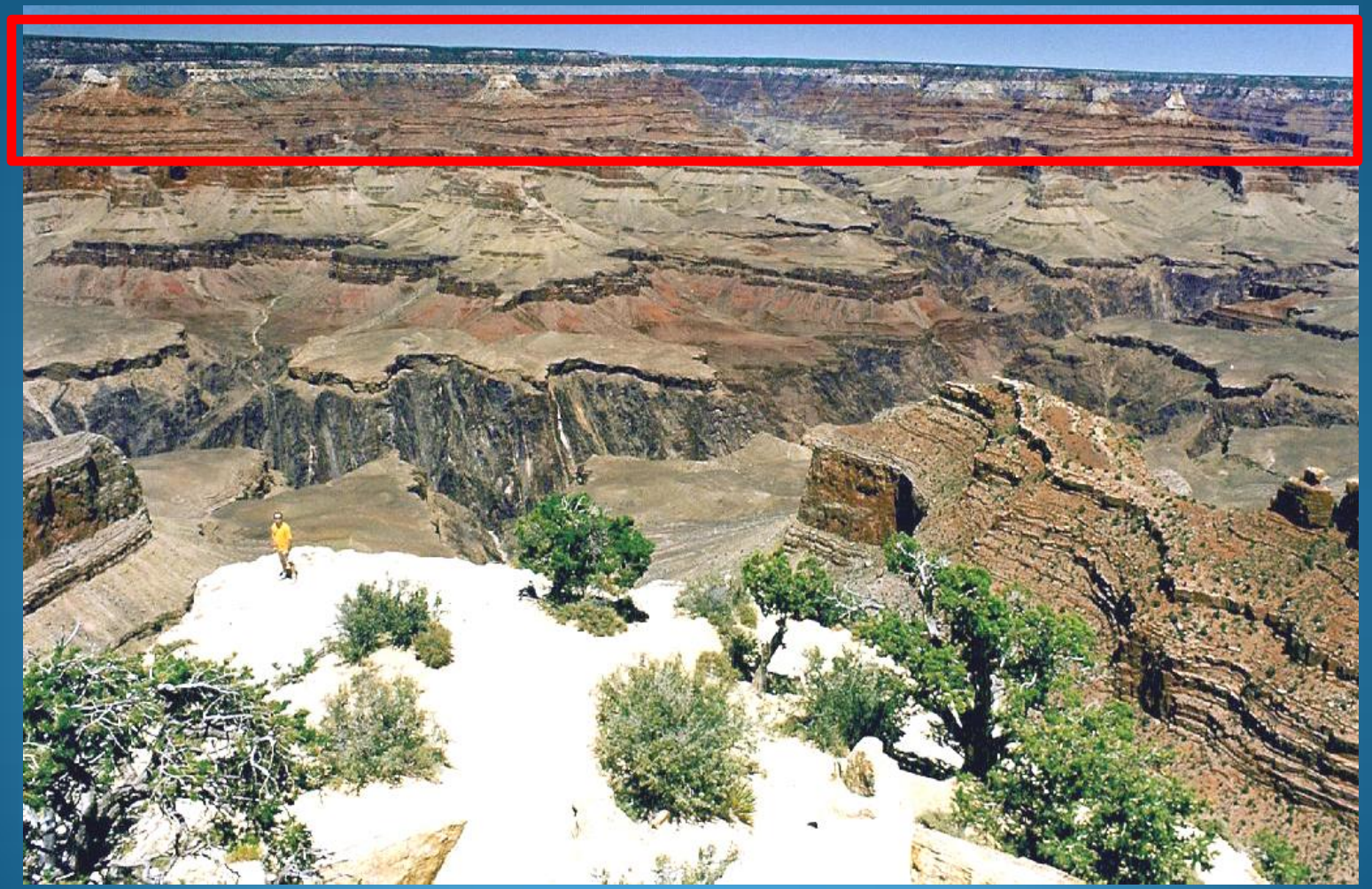


FIGURE 9-18 Generalized paleogeographic map for the Permian Period.

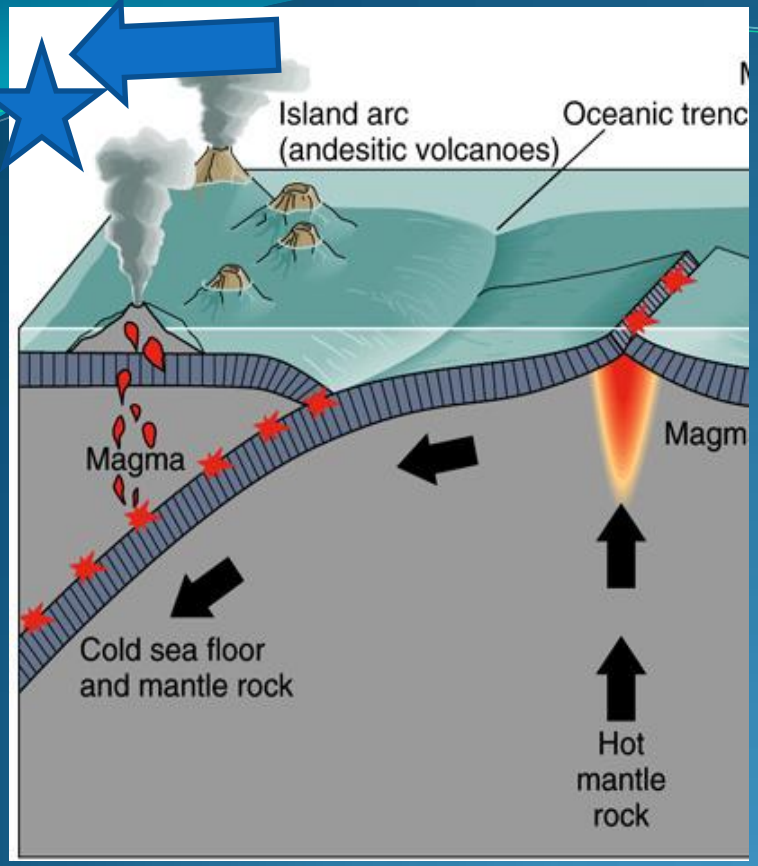

Goosenecks of the San Juan R., Hermosa Fm.

Alleghenian sedimentation in Arizona

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Alleghenian (Ouachita)		325-220	Miss. – Triassic	None	-	U in sed. rocks	Payson uranium

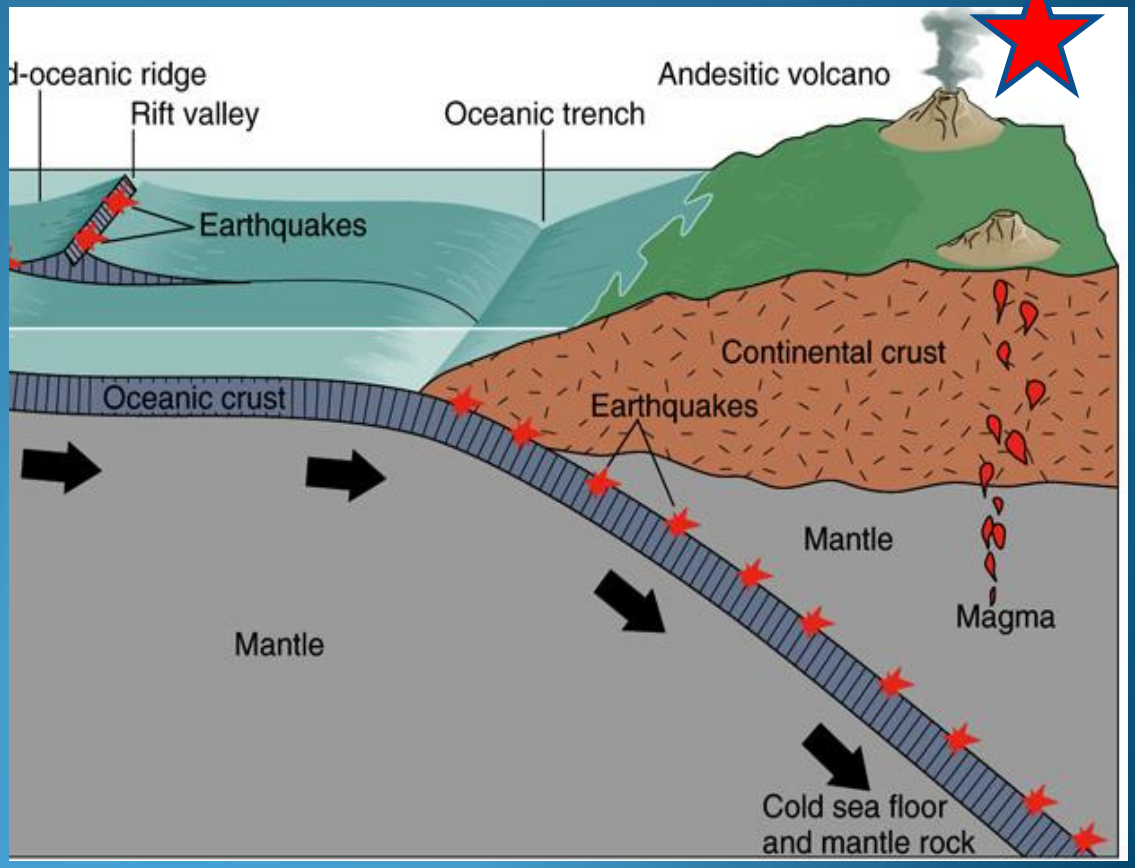


Arizona's position with respect to plate tectonics in Paleozoic vs. Mesozoic

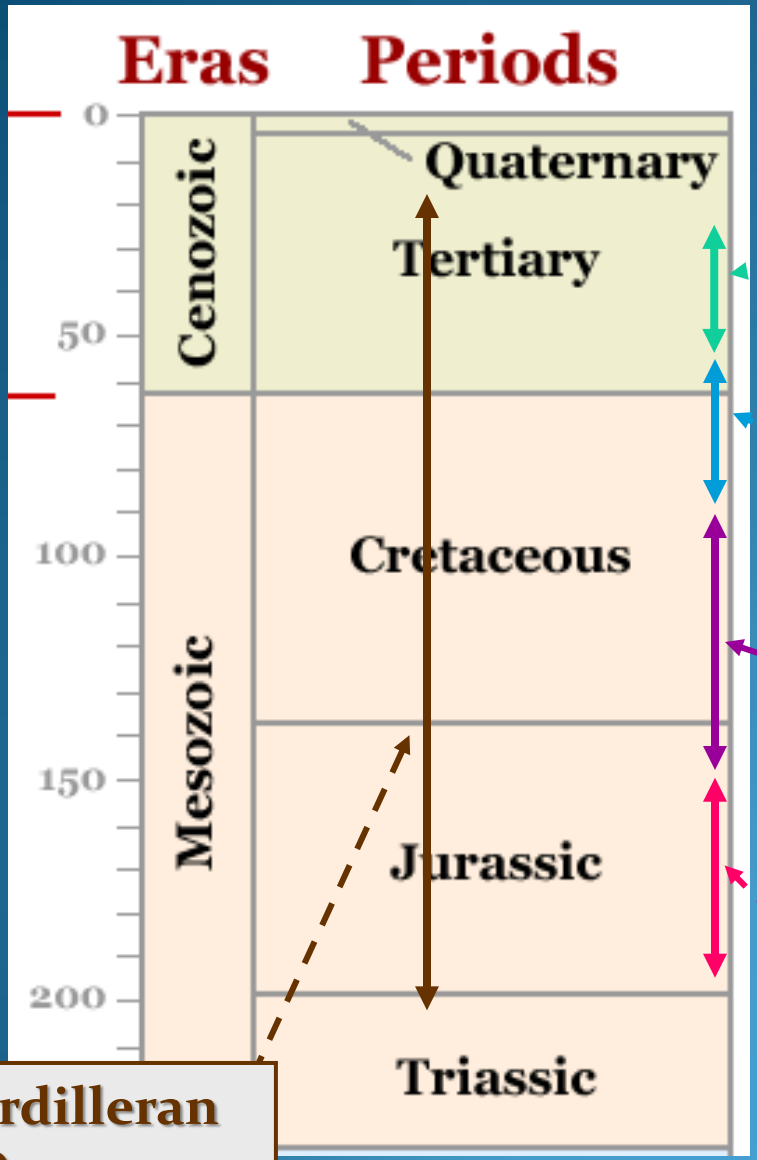


Paleozoic – Arizona was on trailing edge of N. American continent = calm seaways

Mesozoic – Arizona was on leading edge of N. American continent = mountain building, volcanoes, earthquakes, igneous intrusions



Cordilleran orogenies



Galiuro Orogeny (38 – 15 Ma) sinking slab,

Laramide Orogeny (89 – 40 Ma) thick-skinned thrust faulting, formation of Rocky Mts., magmatism, ore deposits

Sevier Orogeny (~145 – 89 Ma) magmatism & thin-skinned thrust faulting

Nevadan Orogeny (~200 – 145 Ma) arc collision, magmatism & minor thrust faulting

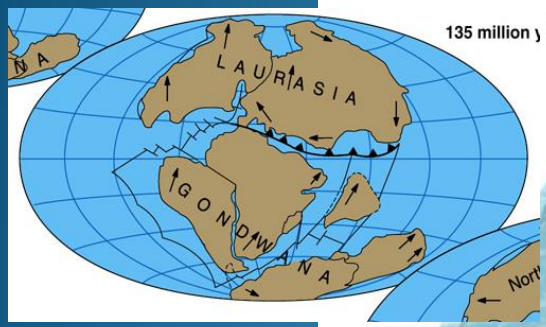
Cordilleran Orogeny (200 – 15 Ma)

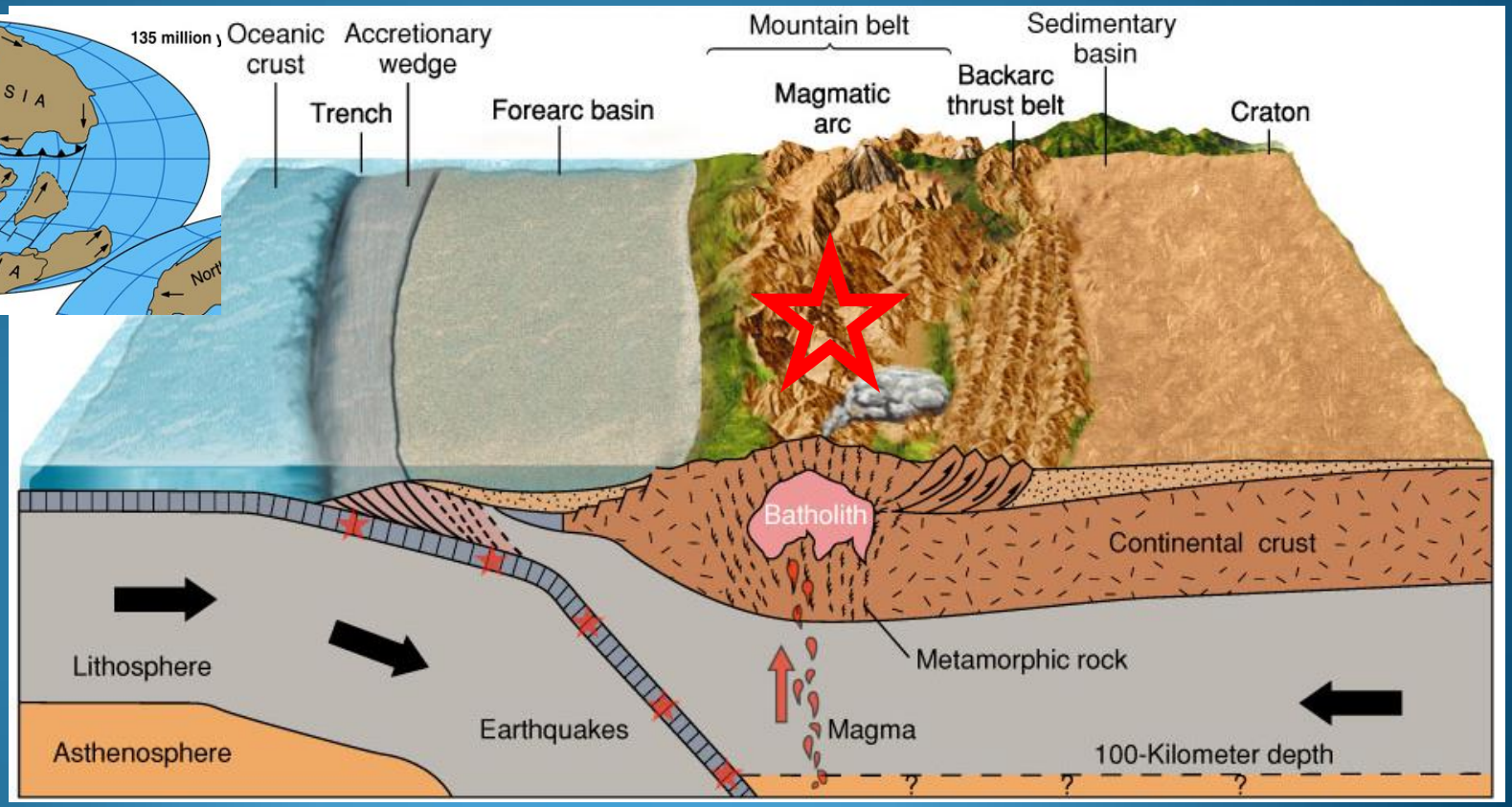
Mesozoic – Cenozoic Orogenies

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
San Andreas	Basin & Range	13-0	Latest Tertiary	anhydrous basaltic volcanism	Metalum. Alkalic	Sand, gravel, salt, zeolites, gypsum	San Francisco volcanic field, San Carlos olivine, Emerald Isle exotic Cu
Galiuro	Late (Whipple)	18-13	Late Tertiary	volcanics & local epizonal stocks	Metalum-inous Alkalic	Cu-Au-Ag in veins; epithermal Au-Ag veins	Oatman, Mammoth, Rowley,Swansea
	Middle (Datil)	28-18	Mid-Tertiary	alkali-calcic ignimbritic volcanics & plutons	Metaluminous Alkali-calcic	Pb-Zn-Ag F veins, replace.; epithermal	Silver (Red Cloud), Castle Dome, Stanley, Aravaipa
	Early (South Mountain	30-22	Mid-Tertiary	calc-alkalic volcanics & plutons	Metalum. Calc-alkalic	Au +/- Cu-W veins & disseminated	Little Harquahala, Kofa
	Earliest (Mineta)	38-28	Mid-Tertiary	mostly within 'volcanic gap"	-	Uranium, clay, exotic copper	Ajo Cornelia, Copper Butte (from Ray)
Laramide	Late (Wilderness)	55-43	Early Tertiary	2-mica, garnet-muscovite granitic stocks, sills, dikes	Peralum. Calcic, Calc-alkalic	Au dissem. & qtz veins; W veins,	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin, Copperstone
	Middle (Morenci)	65-55	Cretaceous-Tertiary	granodiorite - quartz monzonite porphyry stocks, NE to ENE-striking dike swarms	Metaluminous Calc-alkalic	large disseminated porphyry Cu systems, local skarns & veins, fringing Zn-Pb-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior
	Early (Tombstone)	85-65	Late Cretaceous	qtz. monz. porph. stocks; ash flows	Metalum. Alkali-calcic	Pb-Zn-Ag veins & replacement deposits	Tombstone, Tyndall (Glove), Washington Camp, Salero
	Earliest (Hillsboro)	89-85	mid-Cretaceous	Volcanics, small stocks	Metalum. Alkalic	Cu-Au hydrothermal	Hillsboro, NM
Sevier		145-89	mid-Cretaceous			Sedimentary rocks	Bisbee Group sediments
Nevadan	Late	160-145	Late Jurassic	volcanics			
	Middle	205-160	Late & Middle Jurassic	Canelo Hills volcanics; plutonic rocks	Metalum. Alkalic	porphyry Cu-Au at Bisbee, Gleeson	Warren (Bisbee mine), Turquoise (Courtland-Gleeson)
	Early	230-205	Late Triassic	Fluid flow thru sedimentary rocks	Metalum. Alkalic	Uranium, vanadium, copper	Orphan, Grandview, Monument Valley

Nevadan Orogeny (230-145 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Nevadan	Late	160-145	Late Jurassic	volcanics			
	Middle	205-160	Late & Middle Jurassic	Canelo Hills volcanics; plutonic rocks	Metalum. Alkalic	porphyry Cu-Au at Bisbee, Gleeson	Warren (Bisbee mine), Turquoise (Courtland-Gleeson)
	Early	230-205	Late Triassic	Fluid flow thru sedimentary rocks	Metalum. Alkalic	Uranium, vanadium, copper	Orphan, Grandview, Monument Valley





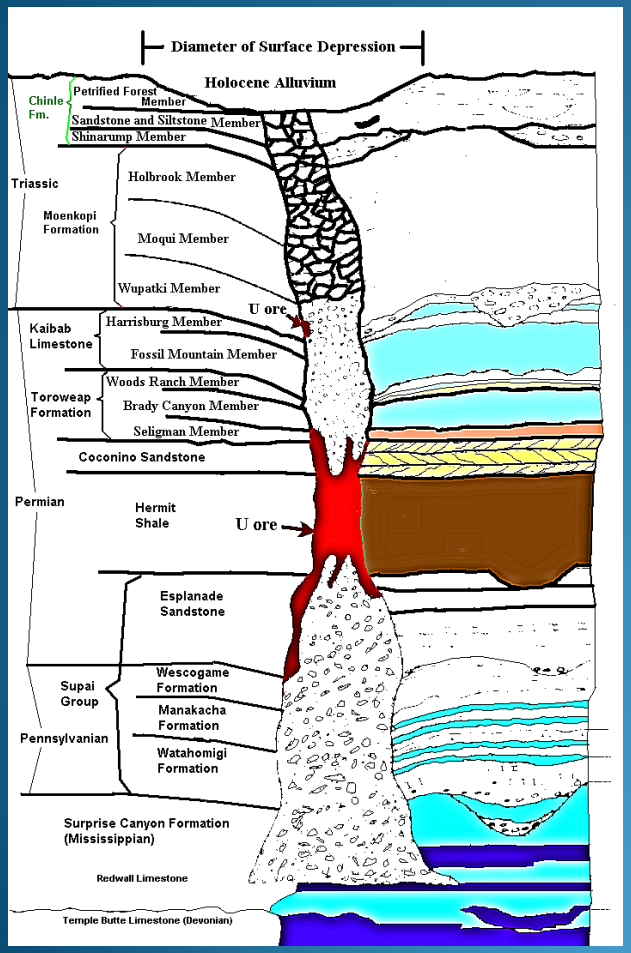
Early Nevadan Orogeny (230-205 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Nevadan	[illegible]	160	[illegible] Jurassic	[illegible] plutonic rocks	Alkalic	[illegible] Gleeson	[illegible] Gleeson)
	Early	230-205	Late Triassic	Fluid flow thru sedimentary rocks	Metalum. Alkalic	Uranium, vanadium, copper	Orphan, Grandview, Monument Valley

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

Early Jurassic [Nevadan Orogeny] (230-200 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Early	230-205	Late Triassic	Fluid flow thru sedimentary rocks	Metalum. Alkalic	Uranium, vanadium, copper	Orphan, Grandview, Monument Valley

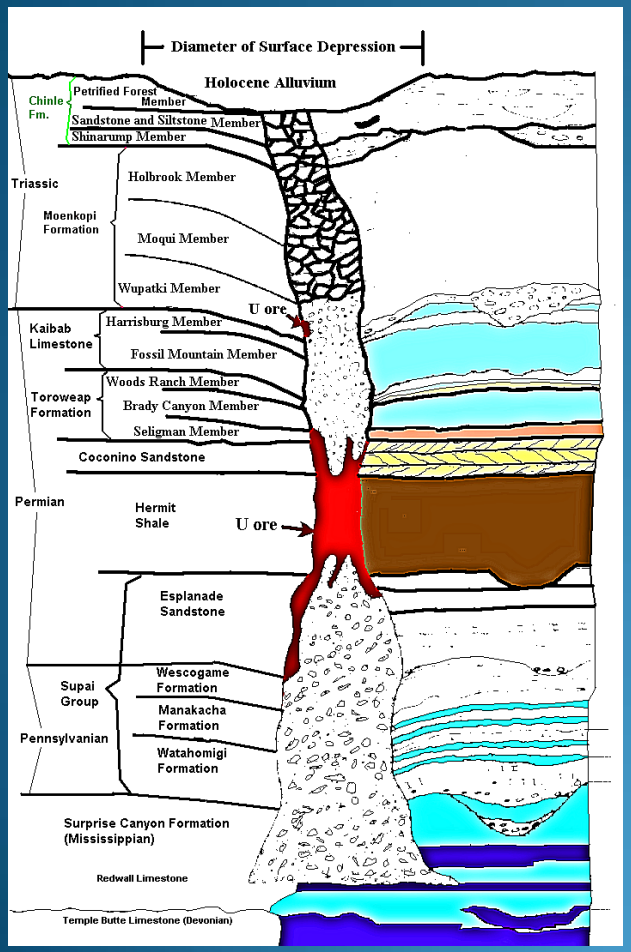


Source: K. Wenrich

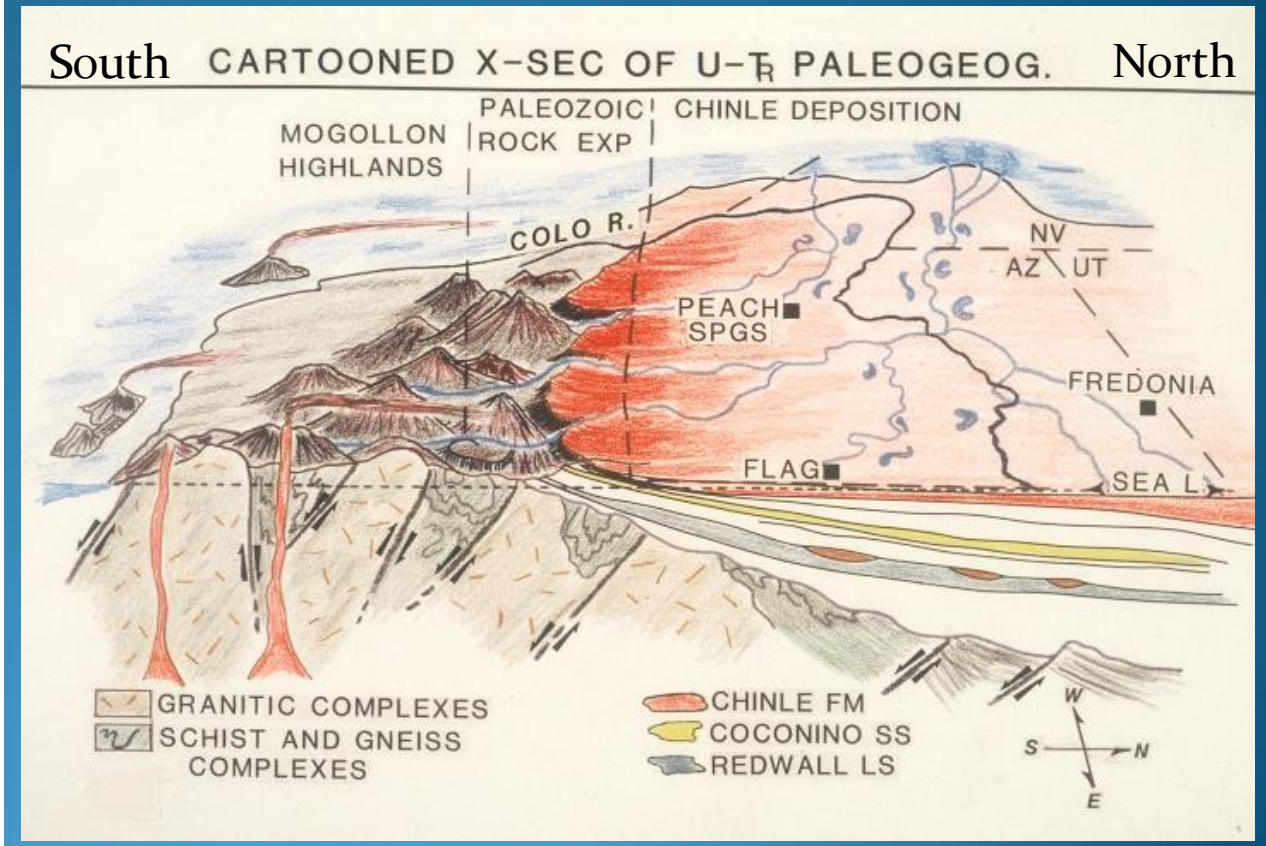
Breccia pipe in Grand Canyon

Early Jurassic [Nevadan Orogeny] (230-200 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Early	230-205	Late Triassic	Fluid flow thru sedimentary rocks	Metalum. Alkalic	Uranium, vanadium, copper	Orphan, Grandview, Monument Valley



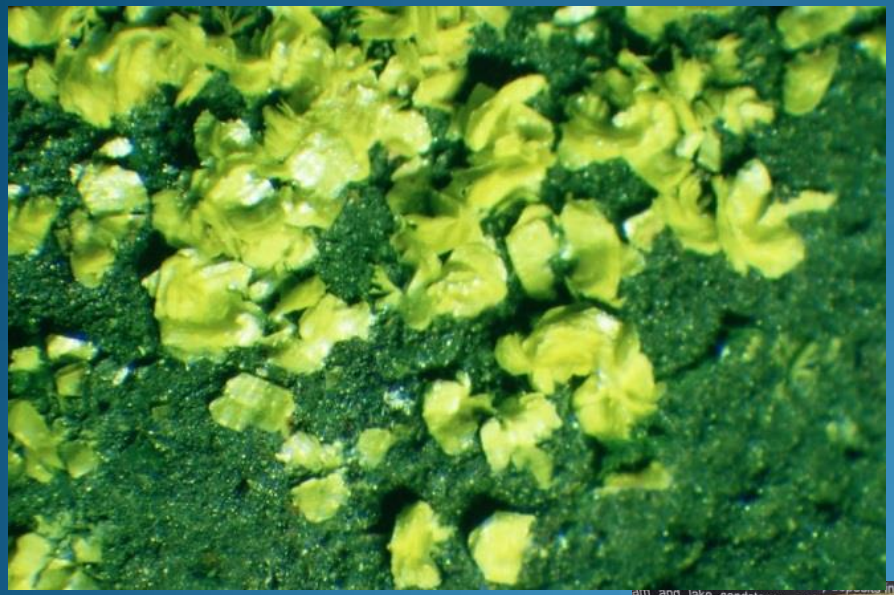
Source: Wenrich



Source: Wenrich

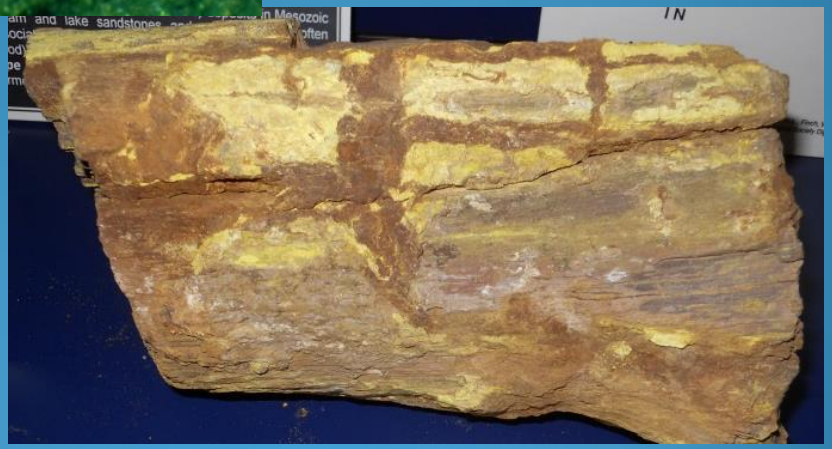
Early Jurassic [Nevadan Orogeny] (230-200 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Early	230-205	Late Triassic	Fluid flow thru sedimentary rocks	Metalum. Alkalic	Uranium, vanadium, copper	Orphan, Grandview, Monument Valley



Ridenour mine; tyuyamunite, Wenrich photo

Grandview mine; cyanotrichite on antlerite AzMMM specimen



Carnotite in petrified wood, Coconino Co. AzMMM specimen

Jurassic arc magmatism

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Nevadan	Middle	205-160	Late & Middle Jurassic	Canelo Hills volcanics; plutonic rocks	Metalum. Alkalic	porphyry Cu-Au at Bisbee, Gleeson	Warren (Bisbee mine), Turquoise (Courtland-Gleeson)

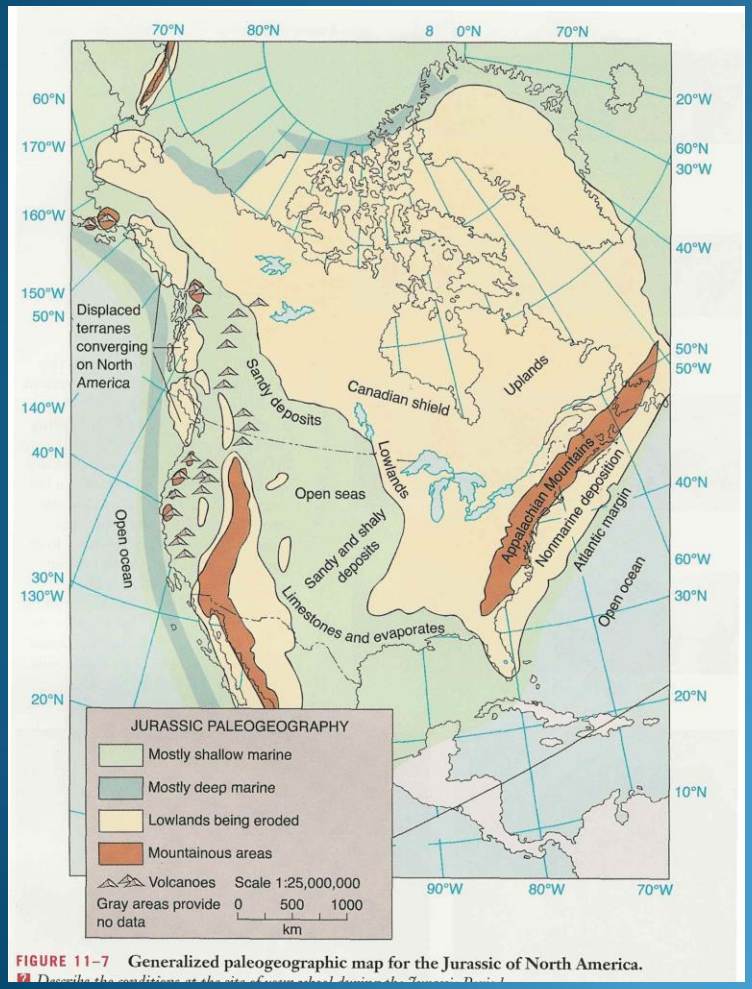
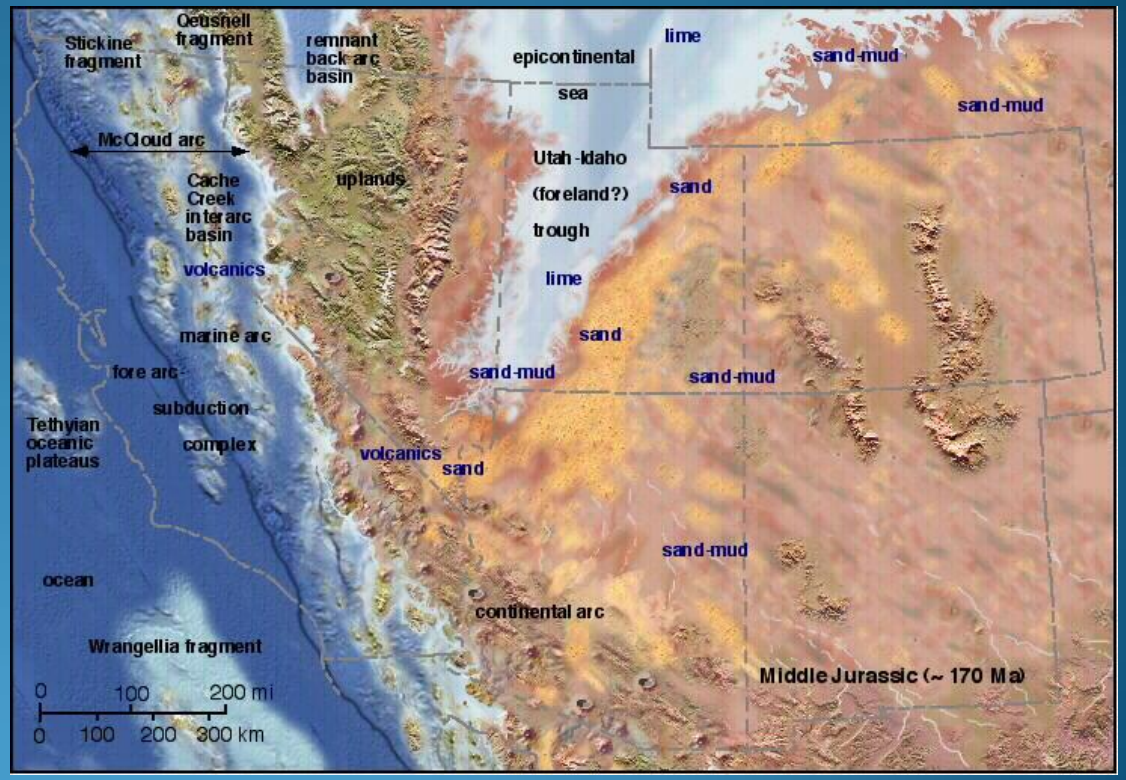


FIGURE 11–7 Generalized paleogeographic map for the Jurassic of North America.



All paleogeographic paintings from Blakey & Ranney

Jurassic arc magmatism

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Nevadan	Middle	205-160	Late & Middle Jurassic	Canelo Hills volcanics; plutonic rocks	Metalum. Alkalic	porphyry Cu-Au at Bisbee, Gleeson	Warren (Bisbee mine), Turquoise (Courtland-Gleeson)

Santa Rita Mts., Mt. Wrightson

South end of Mustang Mts.,
East of Sonoita, AZ

Middle Nevadan - Warren m.d. (Bisbee)

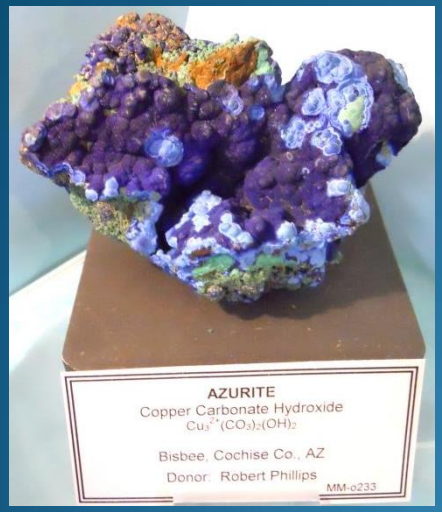
Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Nevadan	Middle	205-160	Late & Middle Jurassic	Canelo Hills volcanics; plutonic rocks	Metalum. Alkalic	porphyry Cu-Au at Bisbee, Gleeson	Warren (Bisbee mine), Turquoise (Courtland-Gleeson)

Porphyry Cu-Au

Sacramento Stock = 190 Ma MQA
Juniper Flat granite = 160-165 Ma MAC

Warren district (Bisbee) azurite

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Nevadan	Middle	205-160	Late & Middle Jurassic	Canelo Hills volcanics; plutonic rocks	Metalum. Alkalic	porphyry Cu-Au at Bisbee, Gleeson	Warren (Bisbee mine), Turquoise (Courtland-Gleeson)



Bisbee azurite - copper carbonate; turquoise

Warren district (Bisbee) secondary

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Nevadan	Middle	205-160	Late & Middle Jurassic	Canelo Hills volcanics; plutonic rocks	Metalum. Alkalic	porphyry Cu-Au at Bisbee, Gleeson	Warren (Bisbee mine), Turquoise (Courtland-Gleeson)

chalcocite

copper

copper

cuprite

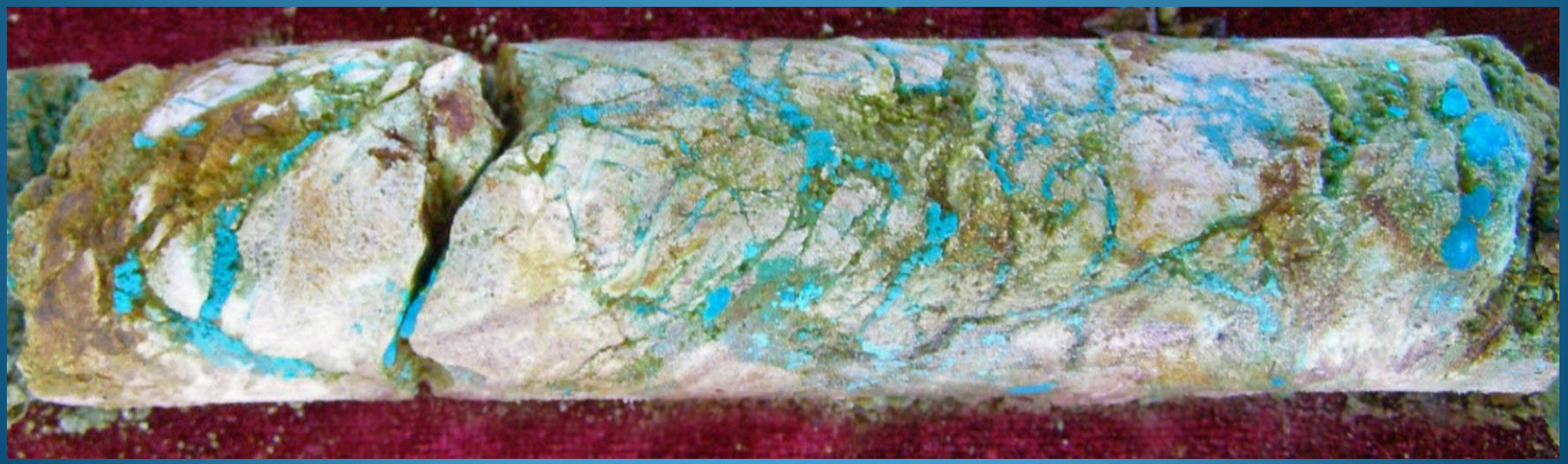
malachite

Jurassic mineralization - Western Arizona – Yuma King

Strong possibility for additional Bisbee type porphyry copper gold deposits in western Arizona

Quartz Monzonite - Re-Os on Molybdenite – 190 Ma (Keith pers. comm.)

Spiderweb Turquoise



Turquoise district – Courtland-Gleeson

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Nevadan	Middle	205-160	Late & Middle Jurassic	Canelo Hills volcanics; plutonic rocks	Metalum. Alkalic	porphyry Cu-Au at Bisbee, Gleeson	Warren (Bisbee mine), Turquoise (Courtland-Gleeson)

Early and Middle Jurassic age dates

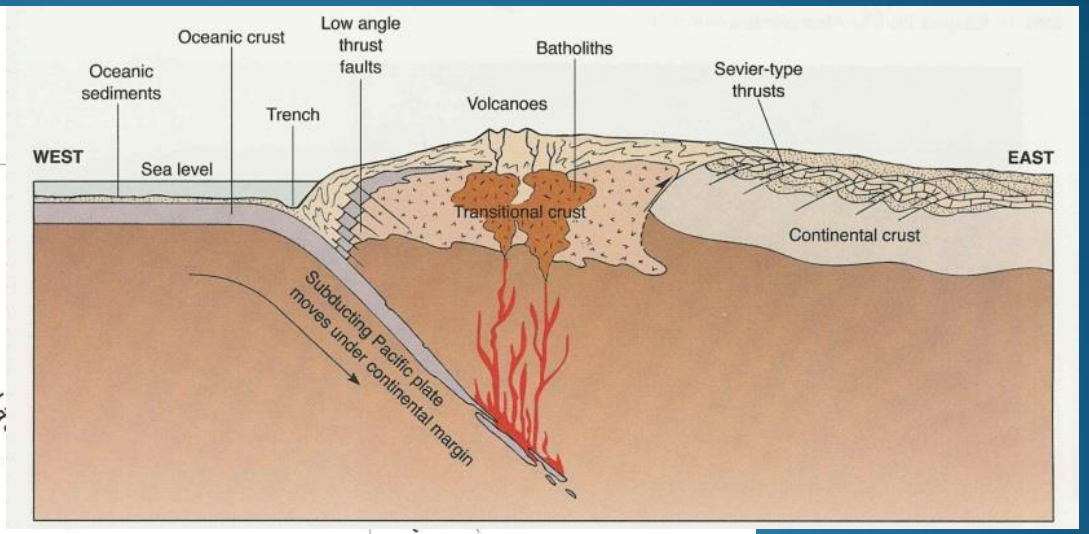
Silver Bill mine, wulfenite

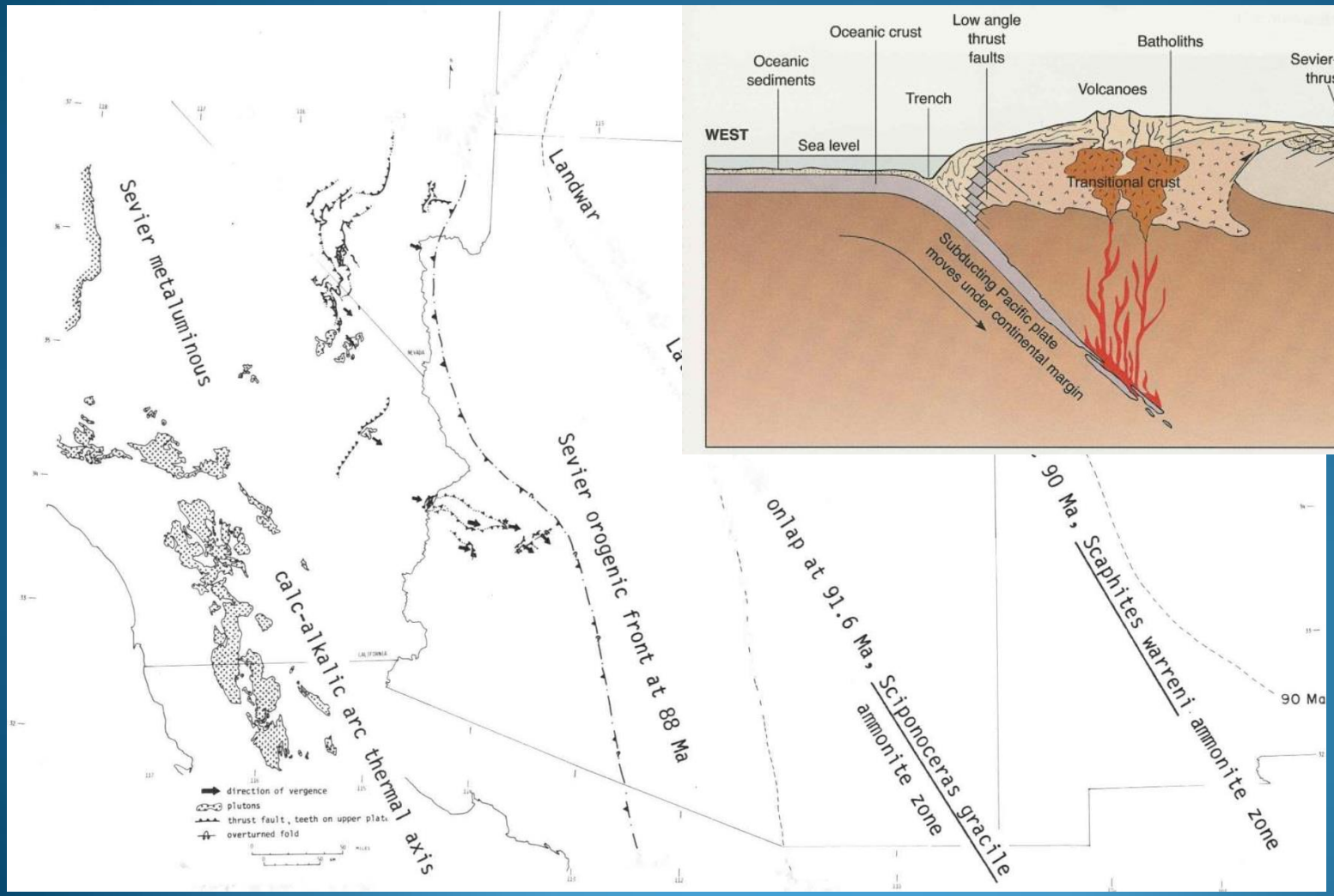
Defiance mine, wulfenite, Donor: Les Presmyk

Courtland area = 180 Ma - possible Quartz Alkalic;
Gleeson Ridge = 165-170 Ma - possible Alkali-calcic

Sevier Orogeny (145-89 Ma)

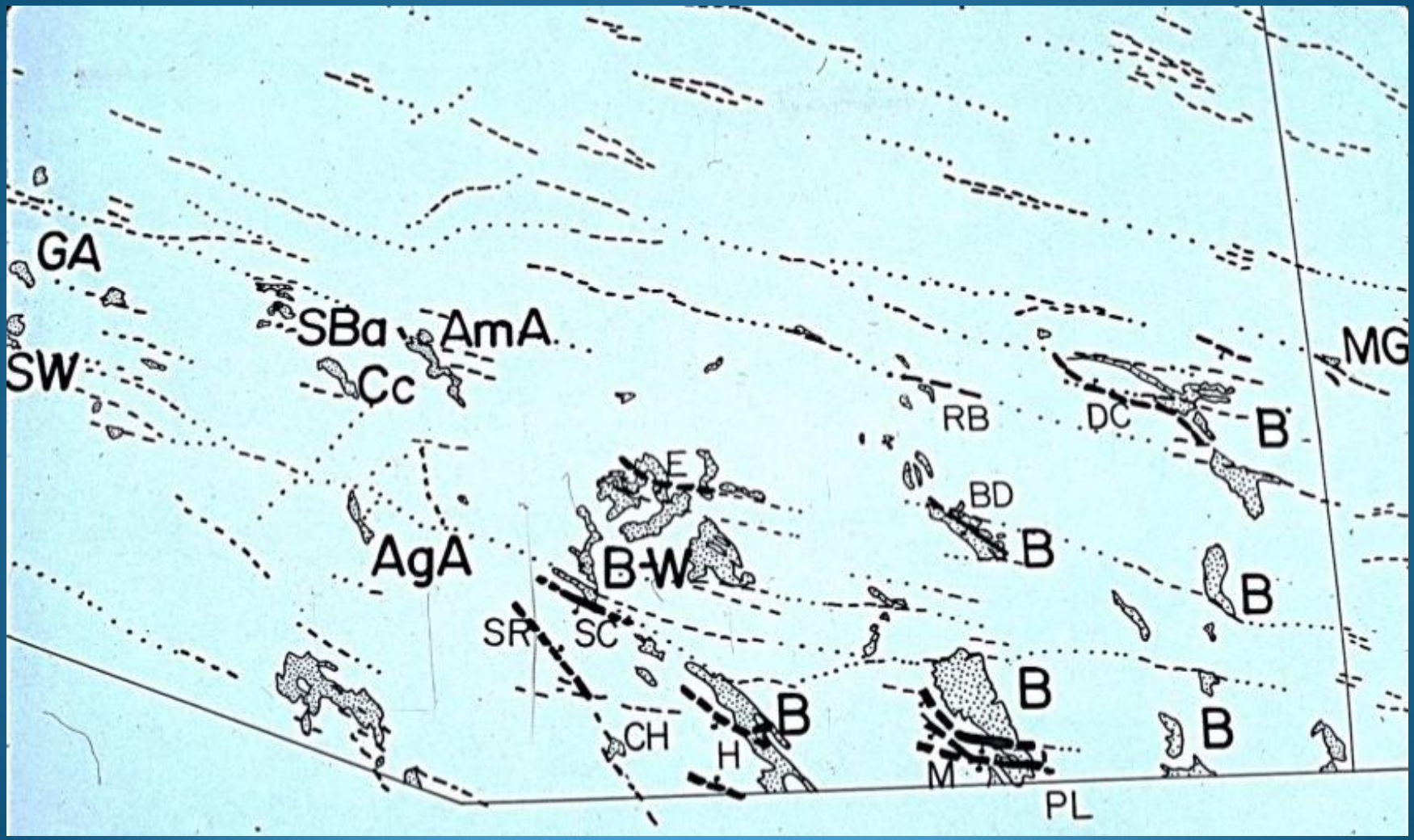
Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Sevier		145-89	mid-Cretaceous			Sedimentary rocks	Bisbee Group sediments





Sevier Orogeny (145-89 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Sevier		145-89	mid-Cretaceous			Sedimentary rocks	Bisbee Group sediments



Sevier Orogeny (145-89 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Sevier		145-89	mid-Cretaceous			Sedimentary rocks	Bisbee Group sediments

Sevier Orogeny (145-89 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Sevier		145-89	mid-Cretaceous			Sedimentary rocks	Bisbee Group sediments

Mural Ls. (Bisbee Group) E. of Bisbee

Limestone mined at Paul Spur, near Douglas

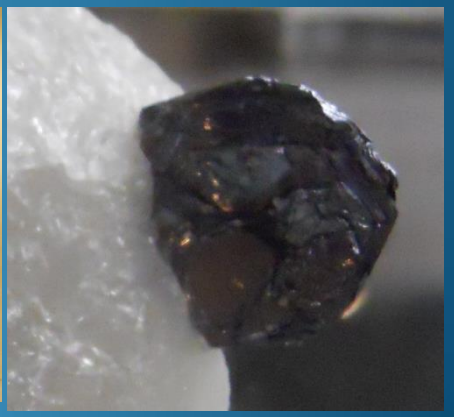
Laramide Orogeny (89-35 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Laramide	Late (Wilderness)	55-43	Early Tertiary	2-mica, garnet-muscovite granitic stocks, sills, dikes	Peralum. Calcic, Calc-alkalic	Au dissem. & qtz veins; W veins,	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin, Copperstone
	Middle (Morenci)	65-55	Cretaceous-Tertiary	granodiorite - quartz monzonite porphyry stocks, NE to ENE-striking dike swarms	Metaluminous Calc-alkalic	large disseminated porphyry Cu systems, local skarns & veins, fringing Zn-Pb-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior
	Early (Tombstone)	85-65	Late Cretaceous	qtz. monz. porph. stocks; ash flows	Metalum. Alkali-calcic	Pb-Zn-Ag veins & replacement deposits	Tombstone, Tyndall (Glove), Washington Camp, Salero
	Earliest (Hillsboro)	89-85	mid-Cretaceous	Volcanics, small stocks	Metalum. Alkalic	Cu-Au hydrothermal	Hillsboro, NM

Chalcopyrite Pima m.

Chalcocite Bisbee m.

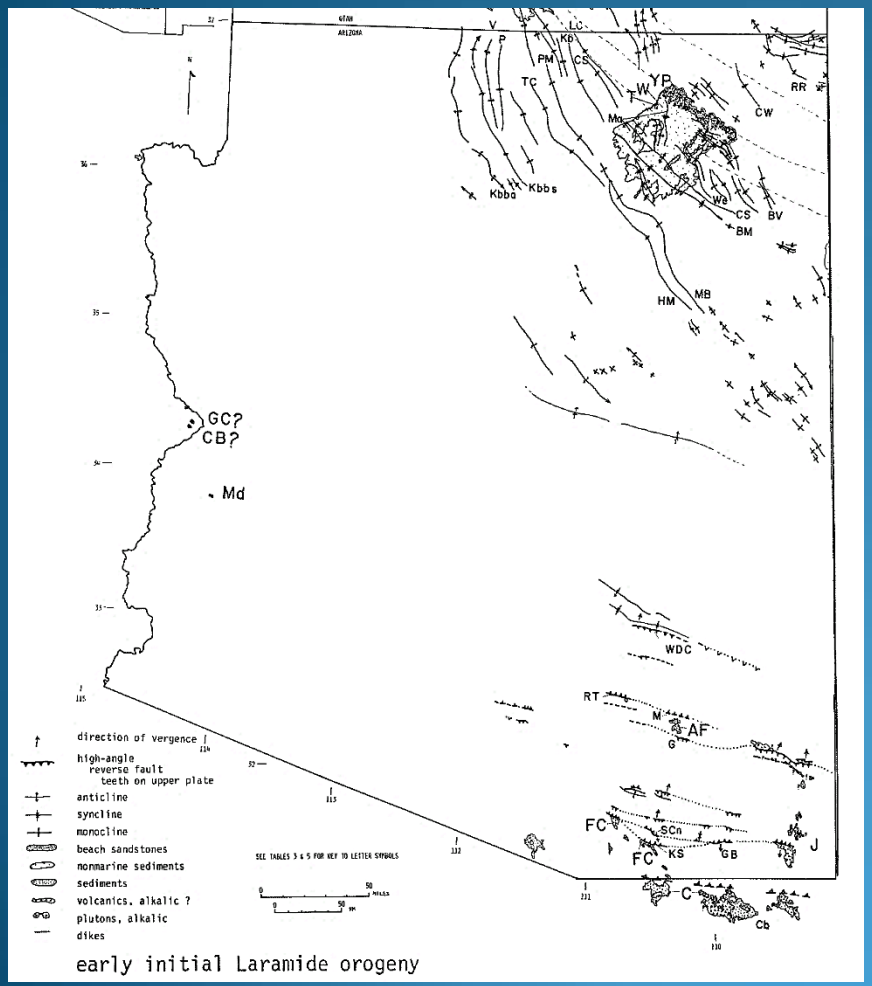
Bornite Magma m.



Molybdenite Cleator

Earliest Laramide -Hillsboro (89-85 Ma)

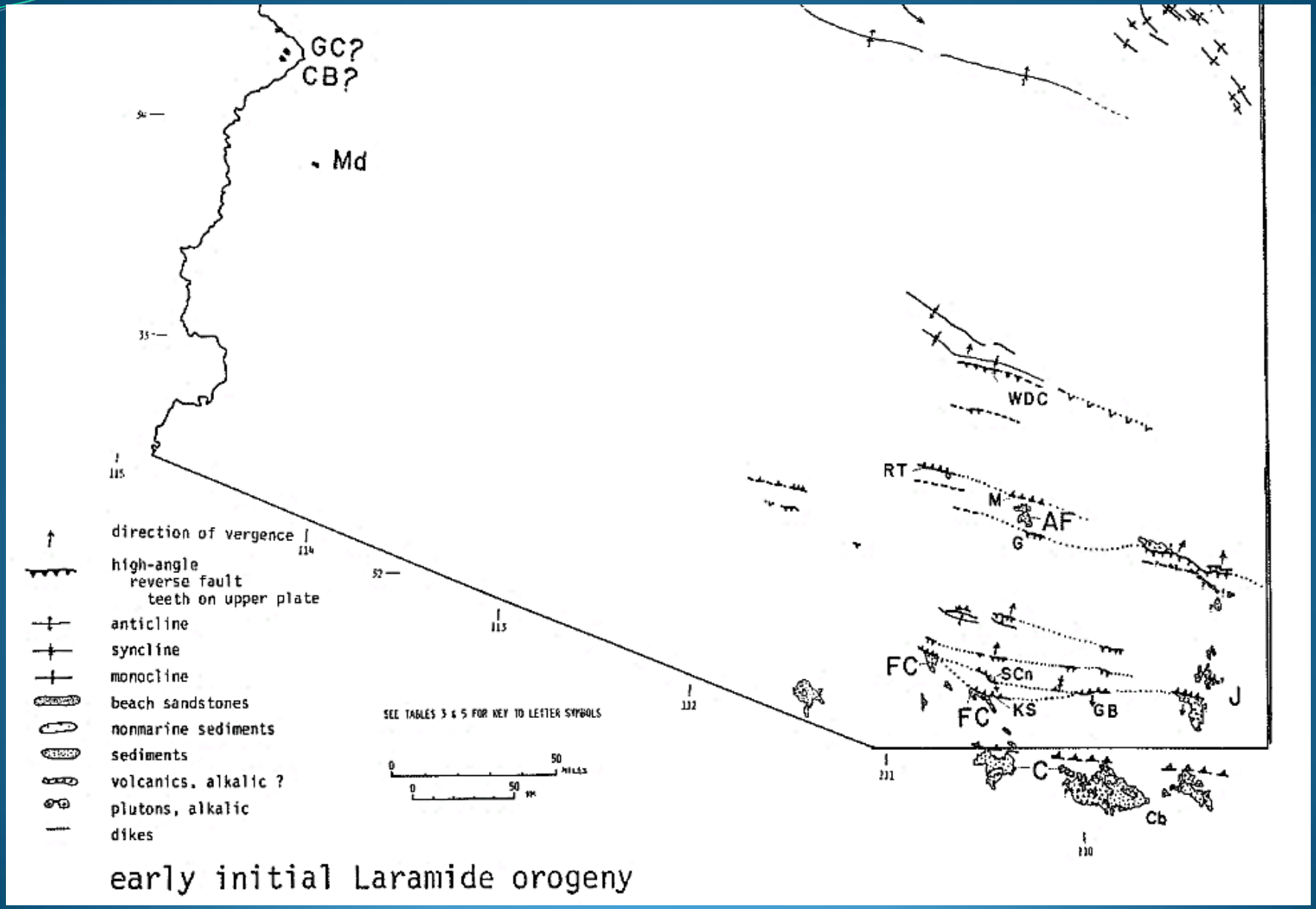
Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Earliest (Hillsboro)	89-85	mid-Cretaceous	Volcanics, small stocks	Metalum. Alkalic	Cu-Au hydrothermal	Hillsboro, NM



N Arizona – coal in Wepo Fm. at Black Mesa

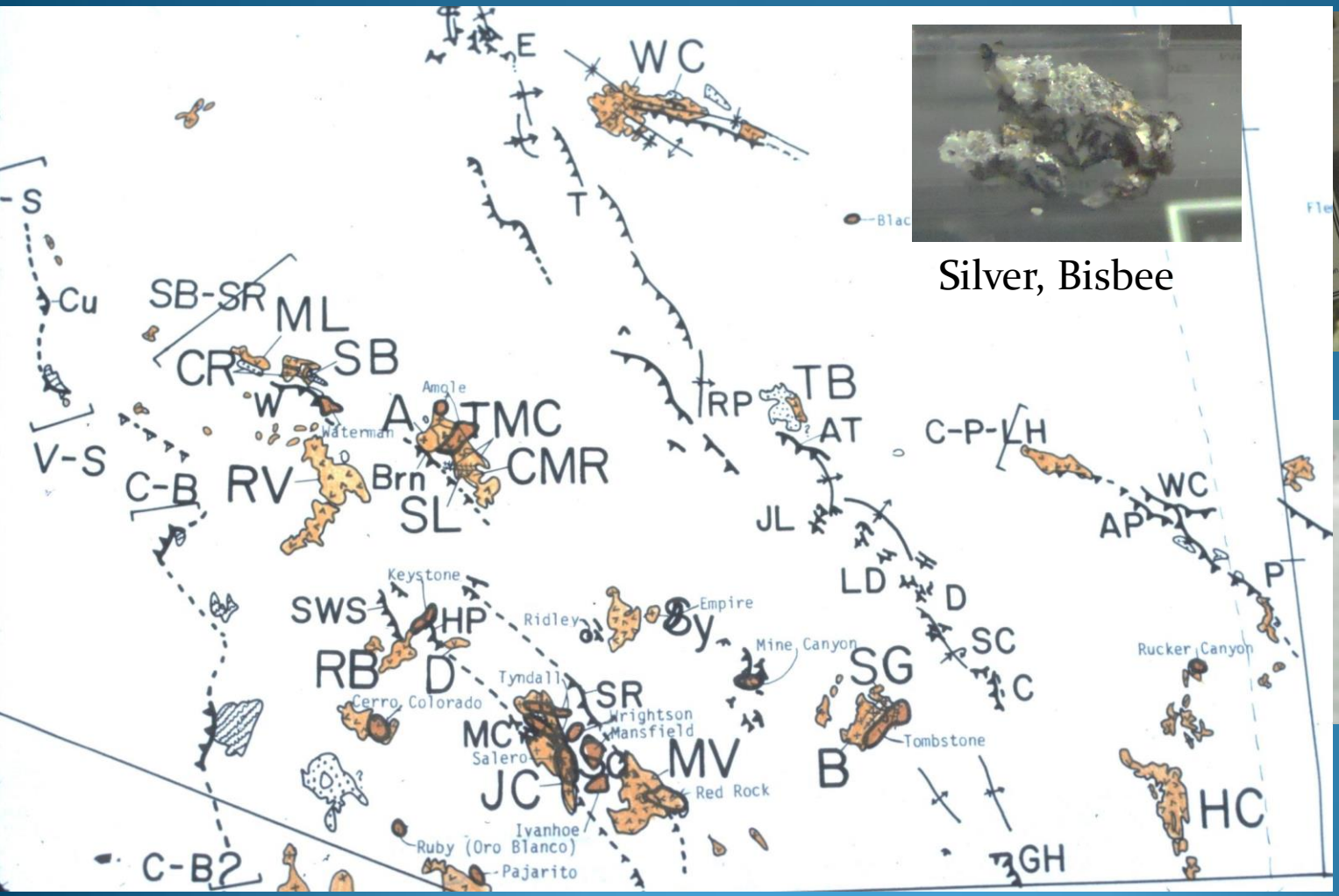
Photo from Peabody Coal (Freeport-McMoran)

Earliest Laramide -Hillsboro (89-85 Ma)

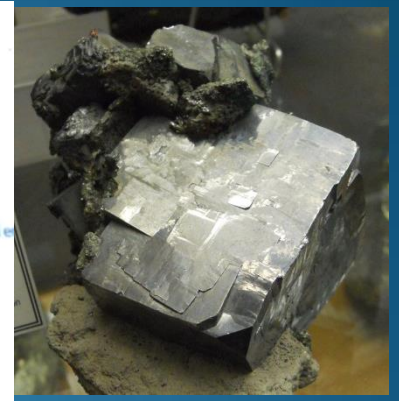


Early Laramide (Tombstone) (85-65 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Early (Tombstone)	85-65	Late Cretaceous	qtz. monz. porph. stocks; ash flows	Metalum. Alkali-calcic	Pb-Zn-Ag veins & replacement deposits	Tombstone, Tyndall (Glove), Washington Camp, Salero



Silver, Bisbee



Galena, Missouri

Sphalerite, Kansas

Early Laramide (Tombstone) (85-65 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Early (Tombstone)	85-65	Late Cretaceous	qtz. monz. porph. stocks; ash flows	Metalum. Alkali-calcic	Pb-Zn-Ag veins & replacement deposits	Tombstone, Tyndall (Glove), Washington Camp, Salero

Mt. Pinatubo, Philippines, 1991

MAC = thick ignimbrite (ash) flows

Early Laramide (Tombstone) (85-65 Ma)

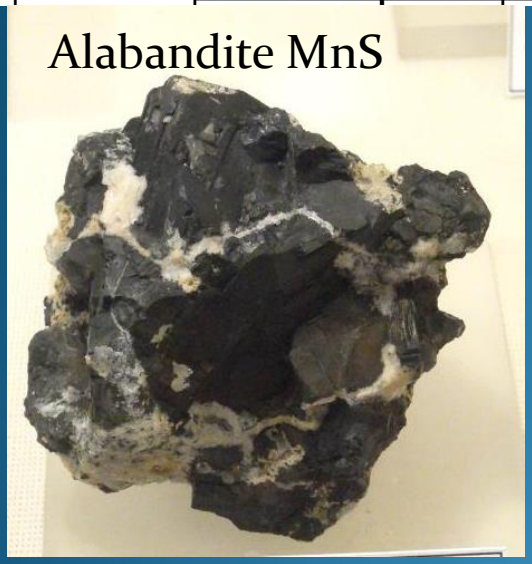
Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Early (Tombstone)	85-65	Late Cretaceous	qtz. monz. porph. stocks; ash flows	Metalum. Alkali-calcic	Pb-Zn-Ag veins & replacement deposits	Tombstone, Tyndall (Glove), Washington Camp, Salero

Tombstone Hills – Uncle Sam Tuff

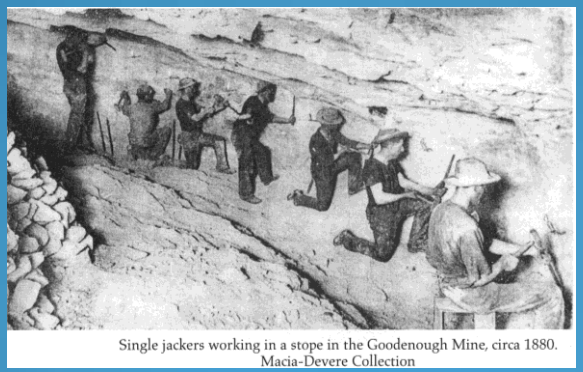
Tucson Mts. - Cat Mountain Rhyolite – 74 Ma ignimbrite (rhyolite ash flows)

Tombstone silver mines

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Early (Tombstone)	85-65	Late Cretaceous	qtz. monz. porph. stocks; ash flows	Metalum. Alkali-calcic	Pb-Zn-Ag veins & replacement deposits	Tombstone, Tyndall (Glove), Washington Camp, Salero



Emmonsite, Empire m.



Single jackers working in a stope in the Goodenough Mine, circa 1880.
Macia-Devere Collection

Glove Mine wulfenite, Santa Rita Mts.

- Argentiferous galena, sphalerite, small amounts of pyrite, chalcopyrite & quartz
- Deposited in permeable zones at the intersection of a bedding plane fault and favorable beds in Permian Naco Limestone
- Extensive solution of the limestone and deep oxidation concentrated cerussite, anglesite, wulfenite, & smithsonite in the leached caverns as sand carbonate ore

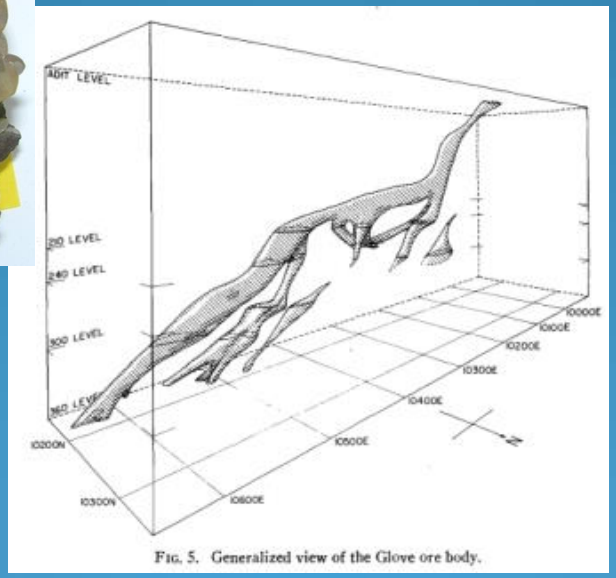
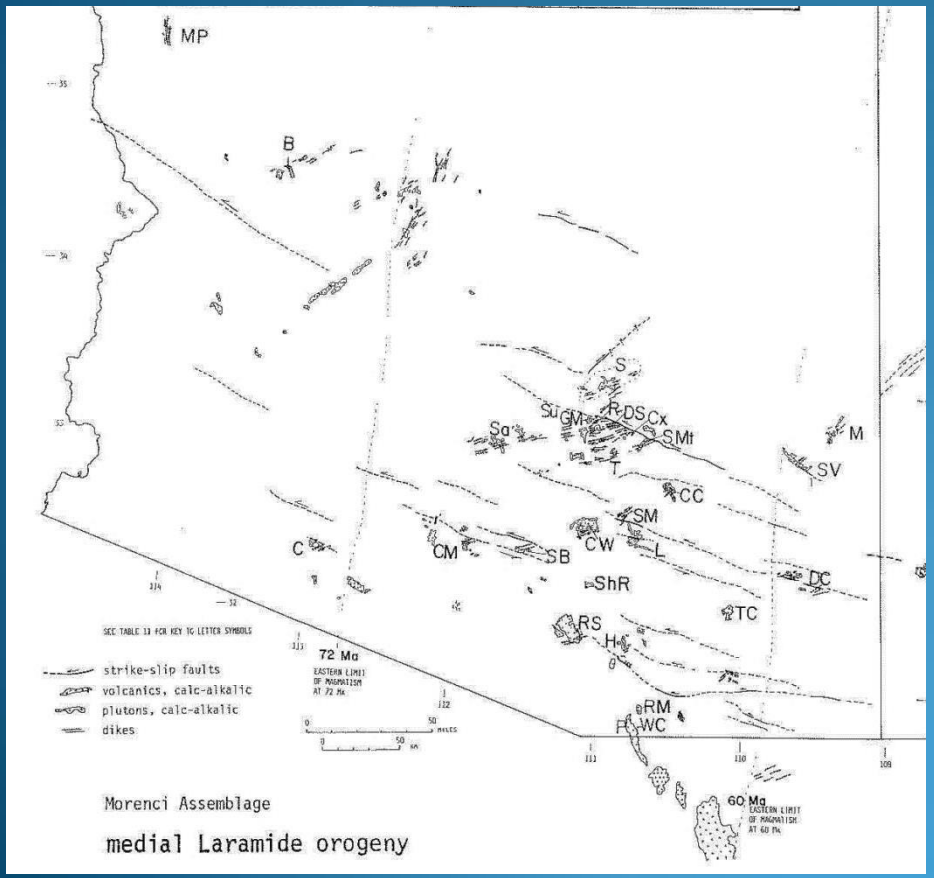


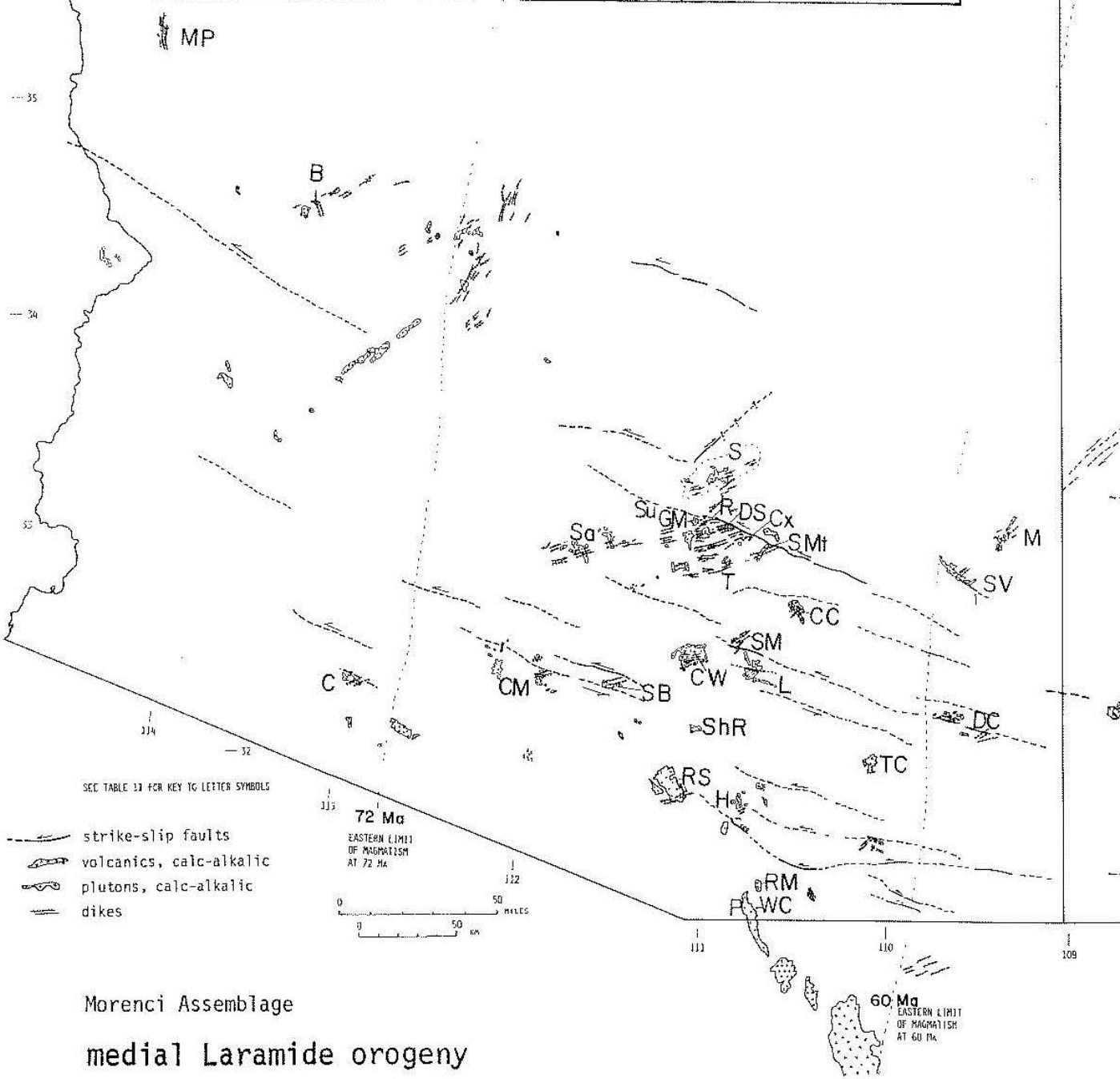
FIG. 5. Generalized view of the Glove ore body.

Middle Laramide - Morenci (65-55 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Laramide	Middle (Morenci)	65-55	Cretaceous-Tertiary	granodiorite - quartz monzonite porphyry stocks, NE to ENE-striking dike swarms	Metaluminous Calc-alkalic	large disseminated porphyry Cu systems, local skarns & veins, fringing Zn-Pb-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior



Middle Laramide - Morenci (65-55 Ma)



Middle Laramide - Morenci (65-55 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Laramide	Middle (Morenci)	65-55	Cretaceous-Tertiary	granodiorite - quartz monzonite porphyry stocks, NE to ENE-striking dike swarms	Metaluminous Calc-alkalic	large disseminated porphyry Cu systems, local skarns & veins, fringing Zn-Pb-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior

Ajo

San Manuel

Miami-Globe

Bagdad

Ray

Morenci

Tucson Gem & Mineral Show 2012

Laramide – Mission, Silver Bell mines

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Laramide	Middle (Morenci)	65-55	Cretaceous-Tertiary	granodiorite - quartz monzonite porphyry stocks, NE to ENE-striking dike swarms	Metaluminous Calc-alkalic	large disseminated porphyry Cu systems, local skarns & veins, fringing Zn-Pb-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior

Mission mine

Silver Bell mine

Photos courtesy of ASARCO (Grupo)

Laramide - Ray mine – porphyry Cu

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Laramide	Middle (Morenci)	65-55	Cretaceous-Tertiary	granodiorite - quartz monzonite porphyry stocks, NE to ENE-striking dike swarms	Metaluminous Calc-alkalic	large disseminated porphyry Cu systems, local skarns & veins, fringing Zn-Pb-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior

Ray shovel, haul truck
Dave Briggs photos

Photo courtesy of ASARCO (Grupo)

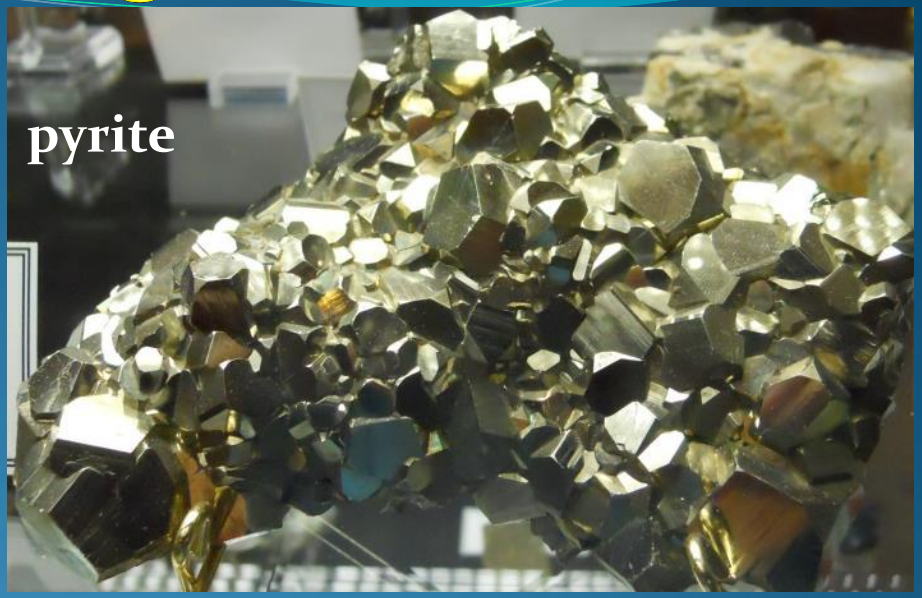
Pima district (Mission m.) porphyry copper deposits

Bornite – peacock copper – copper iron sulfide

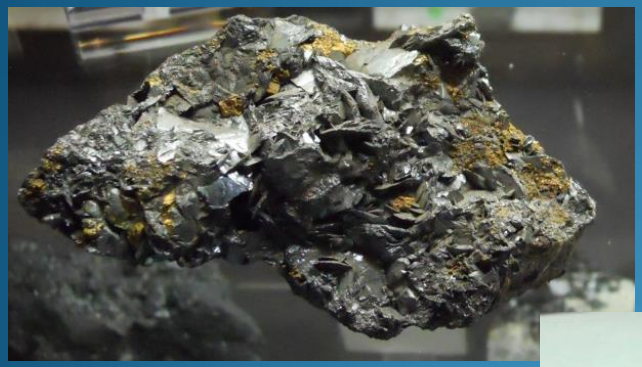
Chalcopyrite – copper fools gold
Copper-iron-sulfide

Superior – Magma mine

stromeyerite



pyrite



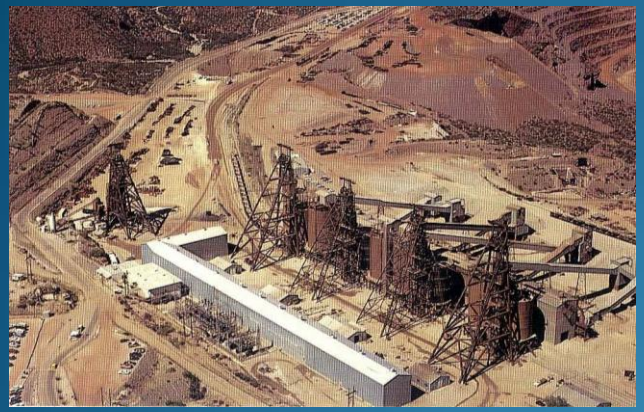
hematite

tennantite

bornite

San Manuel mine

San Manuel mine 1998



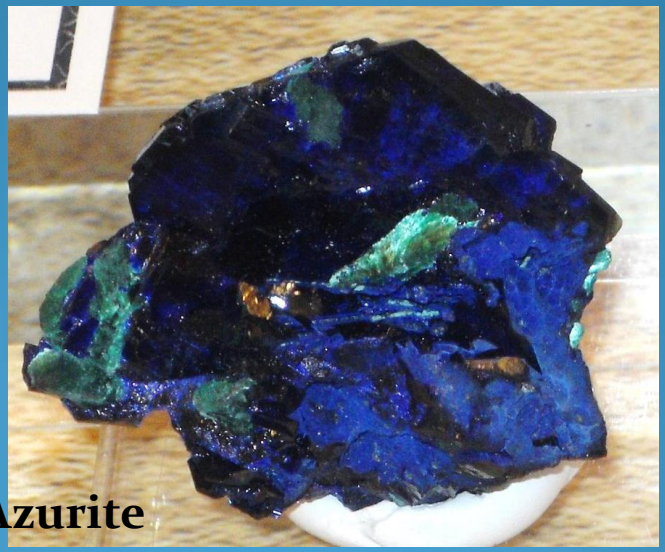
San Manuel tailings Covered, regraded 2006

San Manuel mine

Malachite

Quartz on Chrysocolla

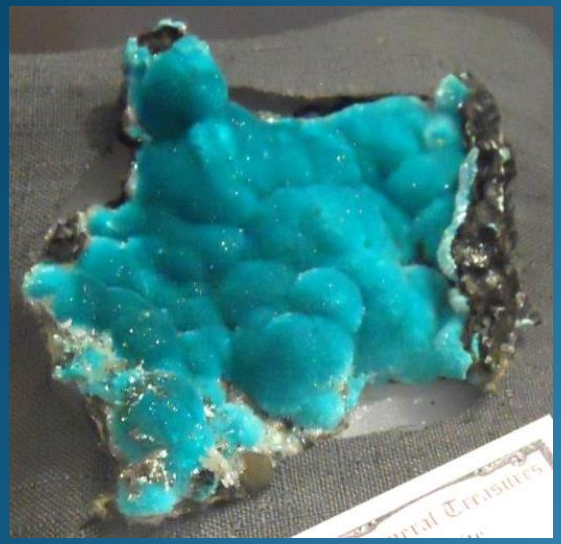
Pyrite



Azurite

Outer Pb-Zn zones of Porphyry Copper deposits

79 mine



aurichalcite

cerussite

tsumebite

smithsonite

wulfenite

Outer Pb-Zn zones of Porphyry Copper deposits

Christmas mine

rosasite

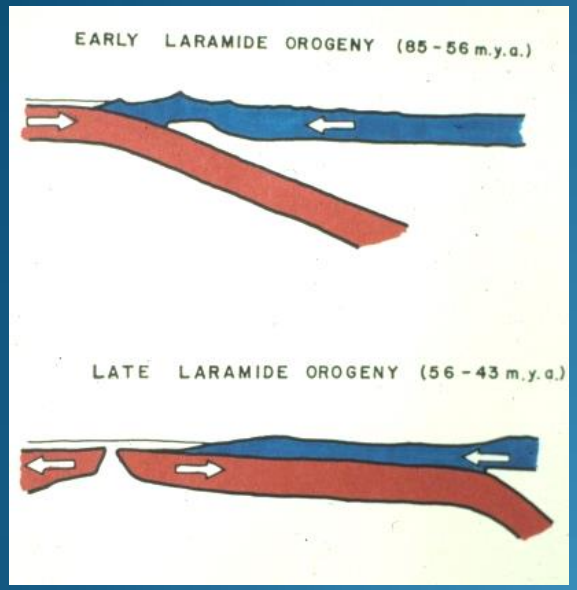
Copper on apophyllite

kinoite

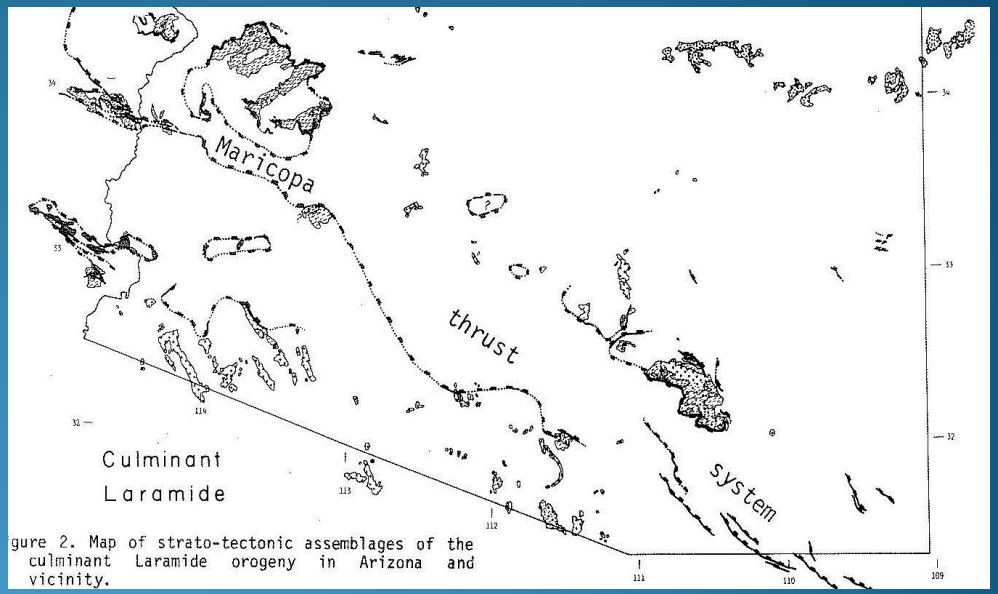
dioptase

Latest Laramide – Wilderness (55-43 Ma)

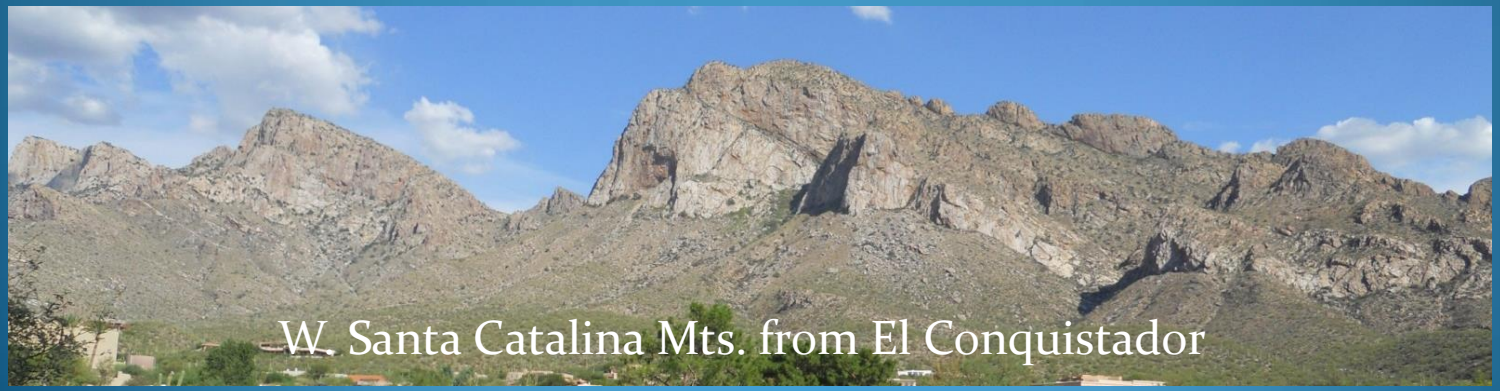
Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Late (Wilderness)	55-43	Early Tertiary	2-mica, garnet-muscovite granitic stocks, sills, dikes	Peralum. Calcic, Calc-alkalic	Au dissem. & qtz veins; W veins,	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin, Copperstone



Flat subduction

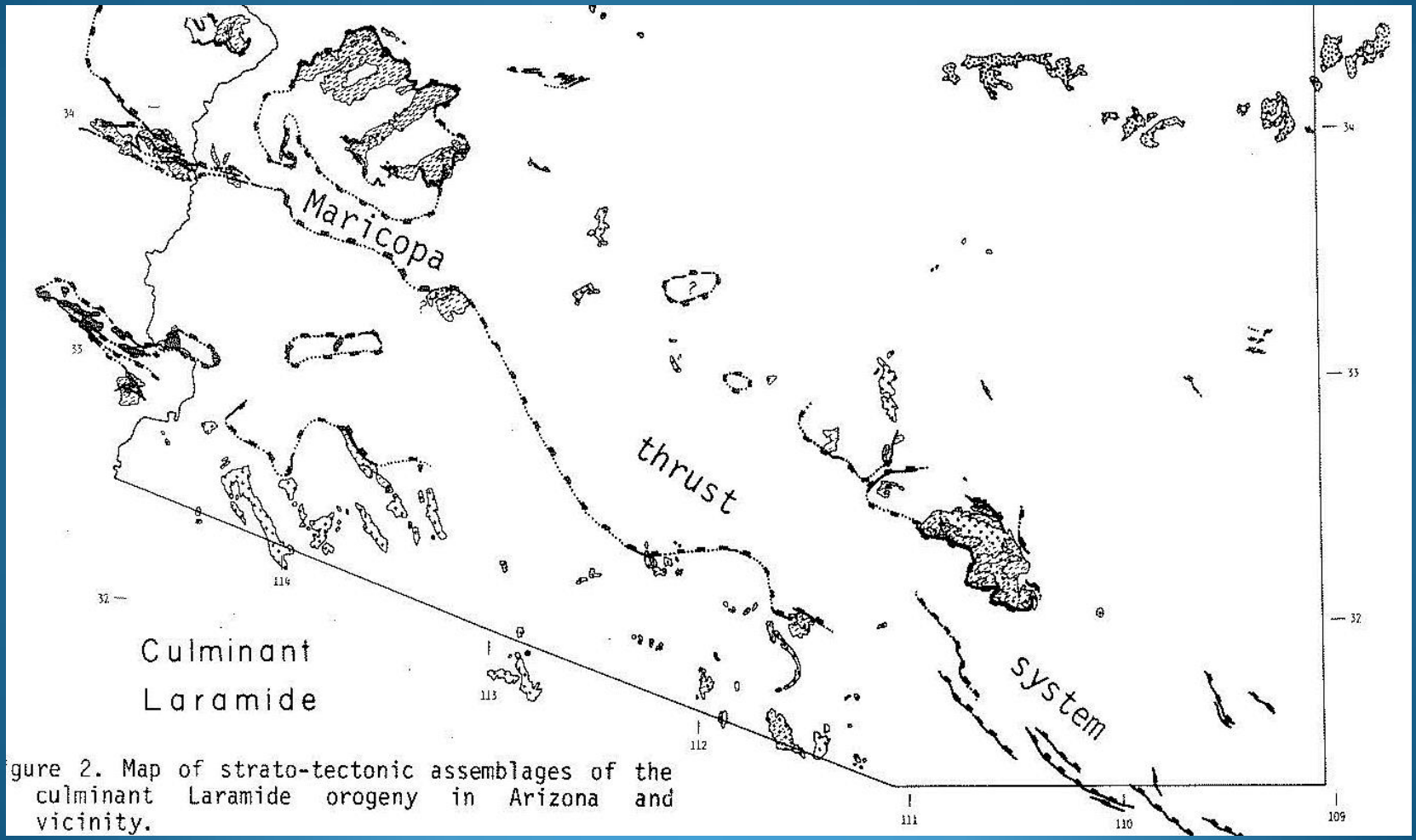


gure 2. Map of strato-tectonic assemblages of the culminant Laramide orogeny in Arizona and vicinity.


W. Santa Catalina Mts. from El Conquistador

Latest Laramide – Wilderness (55-43 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Late (Wilderness)	55-43	Early Tertiary	2-mica, garnet-muscovite granitic stocks, sills, dikes	Peralum. Calcic, Calc-alkalic	Au dissem. & qtz veins; W veins,	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin, Copperstone



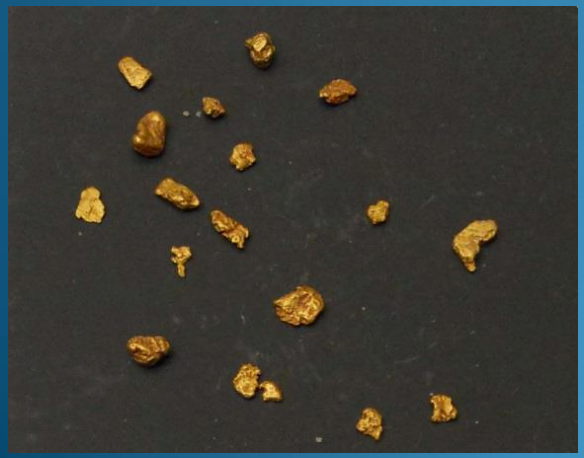
igure 2. Map of strato-tectonic assemblages of the culminant Laramide orogeny in Arizona and vicinity.

Latest Laramide (Paleocene) mining districts

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Late (Wilderness)	55-43	Early Tertiary	2-mica, garnet-muscovite granitic stocks, sills, dikes	Peralum. Calcic, Calc-alkalic	Au dissem. & qtz veins; W veins,	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin, Copperstone

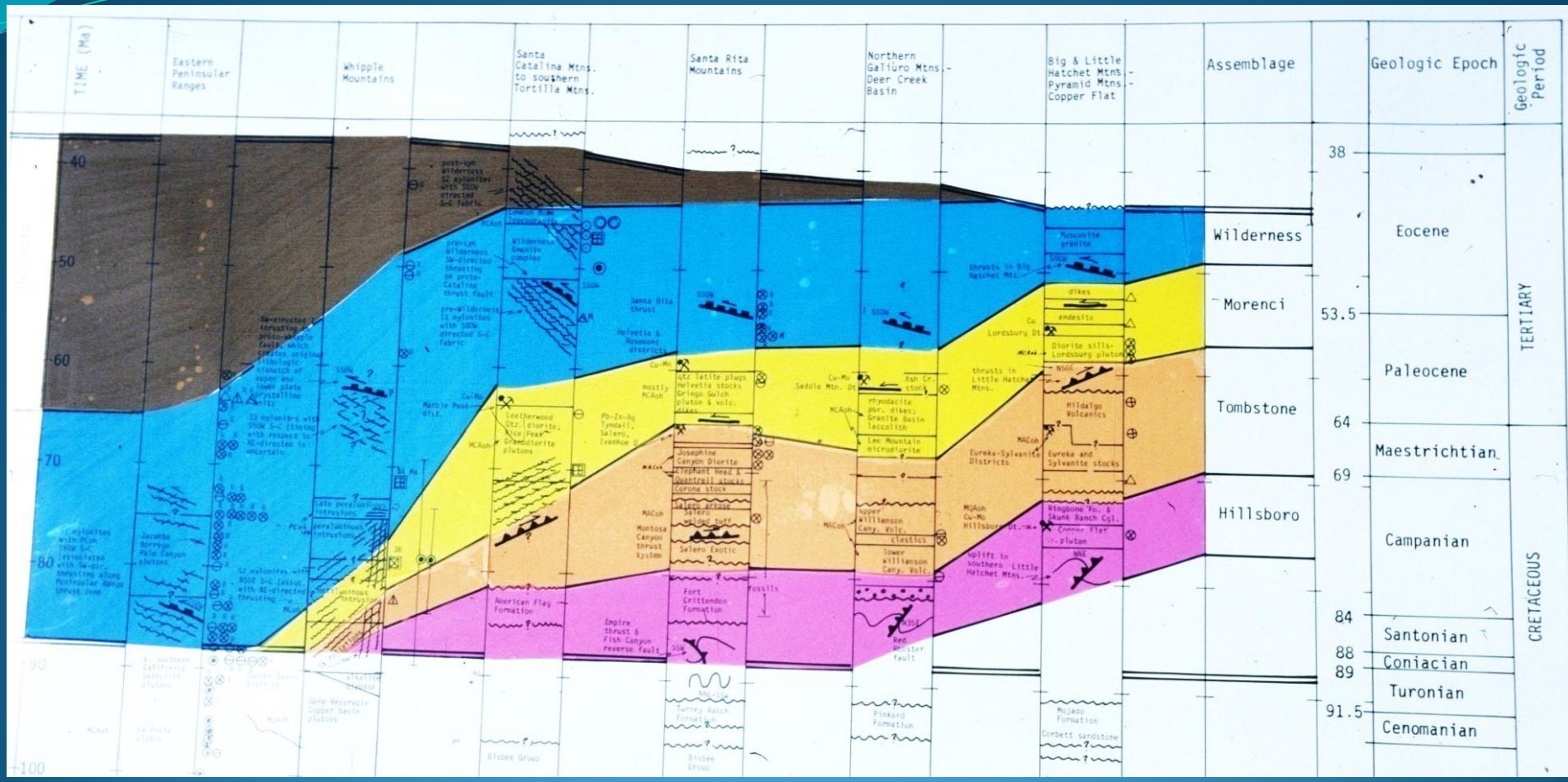
Gold, Gold Basin, Mohave Co., AZ

Copperstone Gold mine, La Paz Co.



Gold, Las Guijas, Pima Co. AZ

Laramide 'transgression' of magmatism



Eastward migrating magmatism of Metaluminous QA, AC, and CA, then Peraluminous

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

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Galiuro	Late (Whipple)	18-13	Late Tertiary	volcanics & local epizonal stocks	Metalum-inous Alkalic	Cu-Au-Ag in veins; epithermal Au-Ag veins	Oatman, Mammoth, Rowley,Swansea
	Middle (Datil)	28-18	Mid-Tertiary	alkali-calcic ignimbritic volcanics & plutons	Metalumin ous Alkali-calcic	Pb-Zn-Ag F veins, replace.; epithermal	Silver (Red Cloud), Castle Dome, Stanley, Aravaipa
	Early (South Mountain	30-22	Mid-Tertiary	calc-alkalic volcanics & plutons	Metalum. Calc-alkalic	Au +/- Cu-W veins & disseminated	Little Harquahala, Kofa
	Earliest (Mineta)	38-28	Mid-Tertiary	mostly within 'volcanic gap"	-	Uranium, clay, exotic copper	Ajo Cornelia, Copper Butte (from Ray)

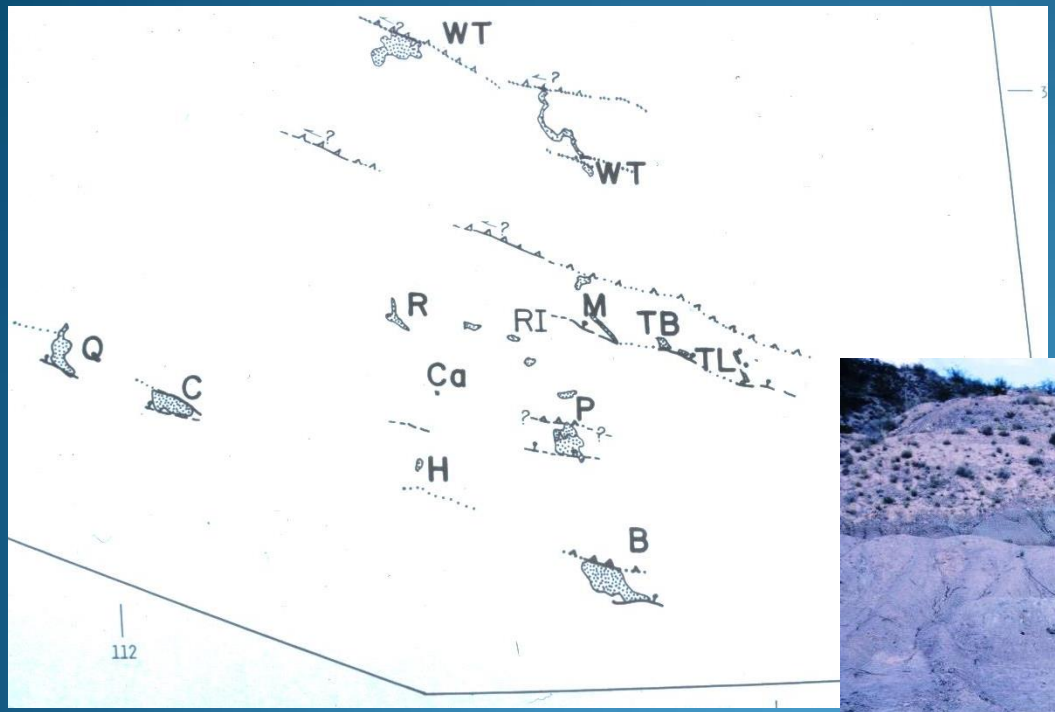
Chiricahua Mts. Ash flow tuffs

N. Tucson Mts.

Organ Pipe volcanics

Early Galiuro – Mineta (38-28 Ma)

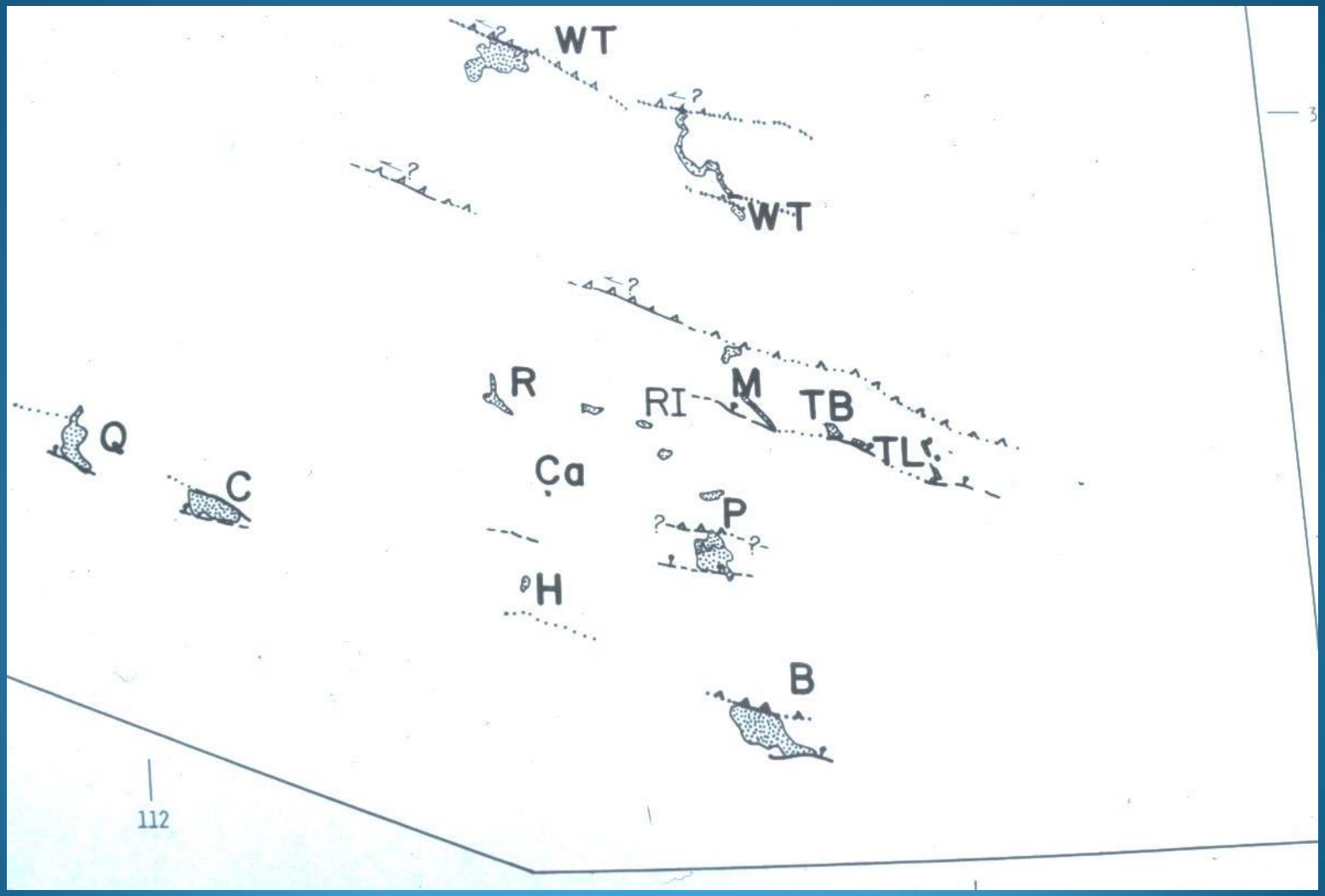
Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Earliest (Mineta)	38-28	Mid-Tertiary	mostly within 'volcanic gap"	-	Uranium, clay, exotic copper	Ajo Cornelia, Copper Butte (from Ray)



Pantano Clay, East Tucson - 1987

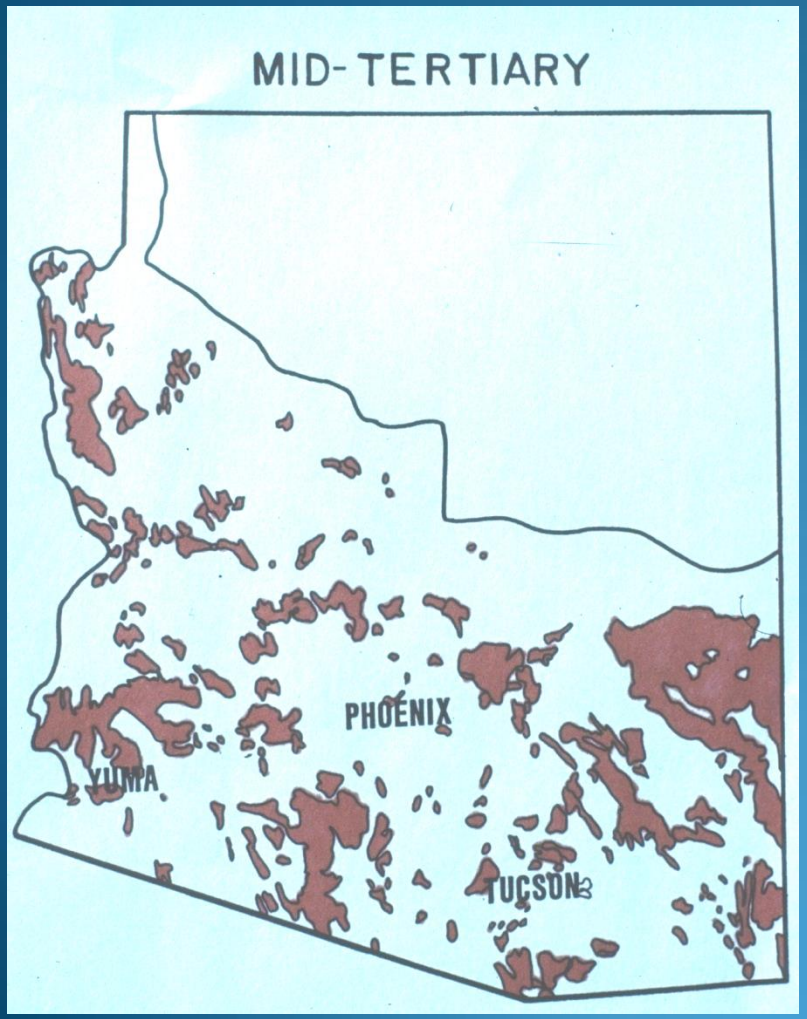
Early Galiuro – Mineta (38-28 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Earliest (Mineta)	38-28	Mid-Tertiary	mostly within 'volcanic gap"	-	Uranium, clay, exotic copper	Ajo Cornelia, Copper Butte (from Ray)



Middle Galiuro – South Mtn. (30-22 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Early (South Mountain	30-22	Mid-Tertiary	calc-alkalic volcanics & plutons	Metalum. Calc-alkalic	Au +/- Cu-W veins & disseminated	Little Harquahala, Kofa



South Mountain, south Phoenix

Middle Galiuro – Datil (28-18 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Galiuro	Middle (Datil)	28-18	Mid-Tertiary	alkali-calcic ignimbritic volcanics & plutons	Metaluminous Alkali-calcic	Pb-Zn-Ag F veins, replace.; epithermal	Silver (Red Cloud), Castle Dome, Stanley, Aravaipa

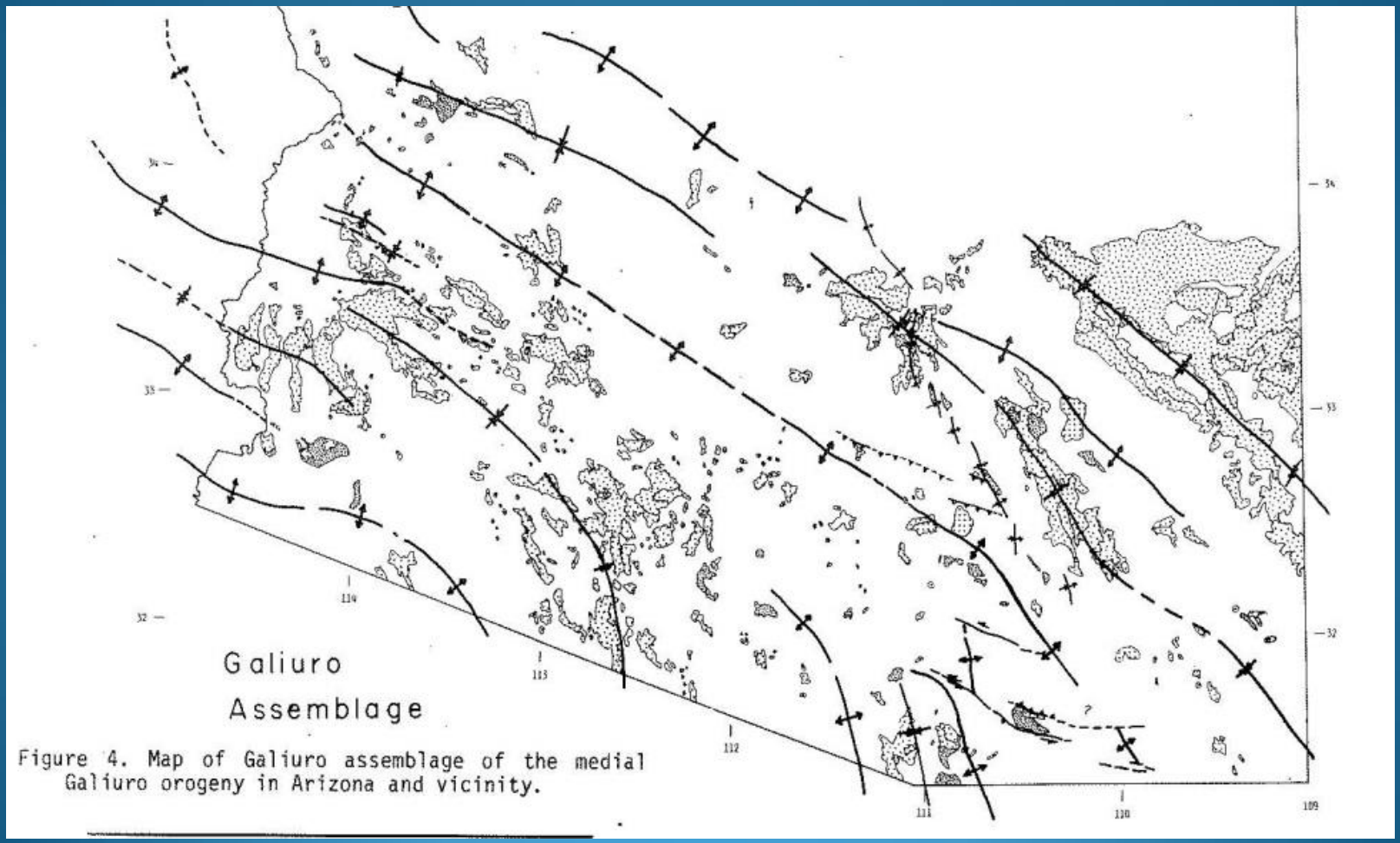


Figure 4. Map of Galiuro assemblage of the medial Galiuro orogeny in Arizona and vicinity.

Middle Galiuro – Datil (28-18 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Galiuro	Middle (Datil)	28-18	Mid-Tertiary	alkali-calcic ignimbritic volcanics & plutons	Metaluminous Alkali-calcic	Pb-Zn-Ag F veins, replace.; epithermal	Silver (Red Cloud), Castle Dome, Stanley, Aravaipa

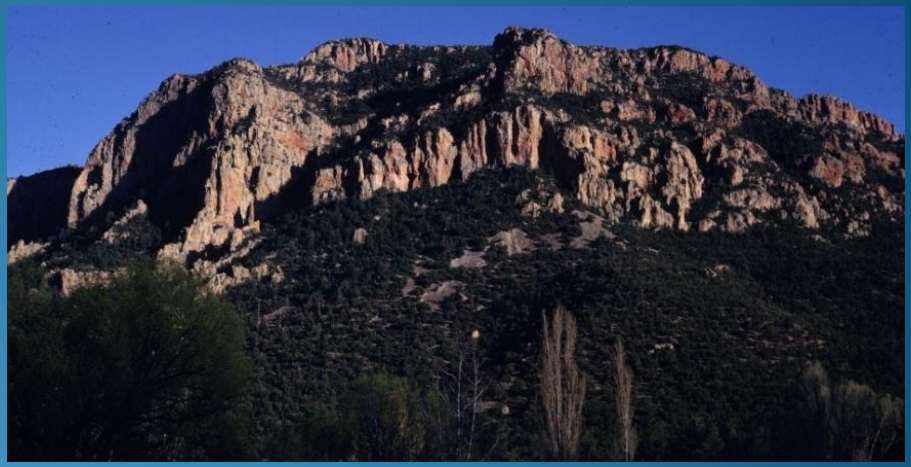
Superstition Volcanics

Galiuro Volcanics

Middle Galiuro – Datil (28-18 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
Galiuro	Middle (Datil)	28-18	Mid-Tertiary	alkali-calcic ignimbritic volcanics & plutons	Metaluminous Alkali-calcic	Pb-Zn-Ag F veins, replace.; epithermal	Silver (Red Cloud), Castle Dome, Stanley, Aravaipa

N. Tucson Mts.



Chiricahua Mts. Ash flow tuffs

A Mountain Tucson Mts.

Organ Pipe volcanics

Red Cloud Mine

Vanadinite

Late Galiuro – Whipple (18-13 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Late (Whipple)	18-13	Late Tertiary	volcanics & local epizonal stocks	Metalum-inous Alkalic	Cu-Au-Ag in veins; epithermal Au-Ag veins	Oatman, Mammoth, Rowley,Swansea

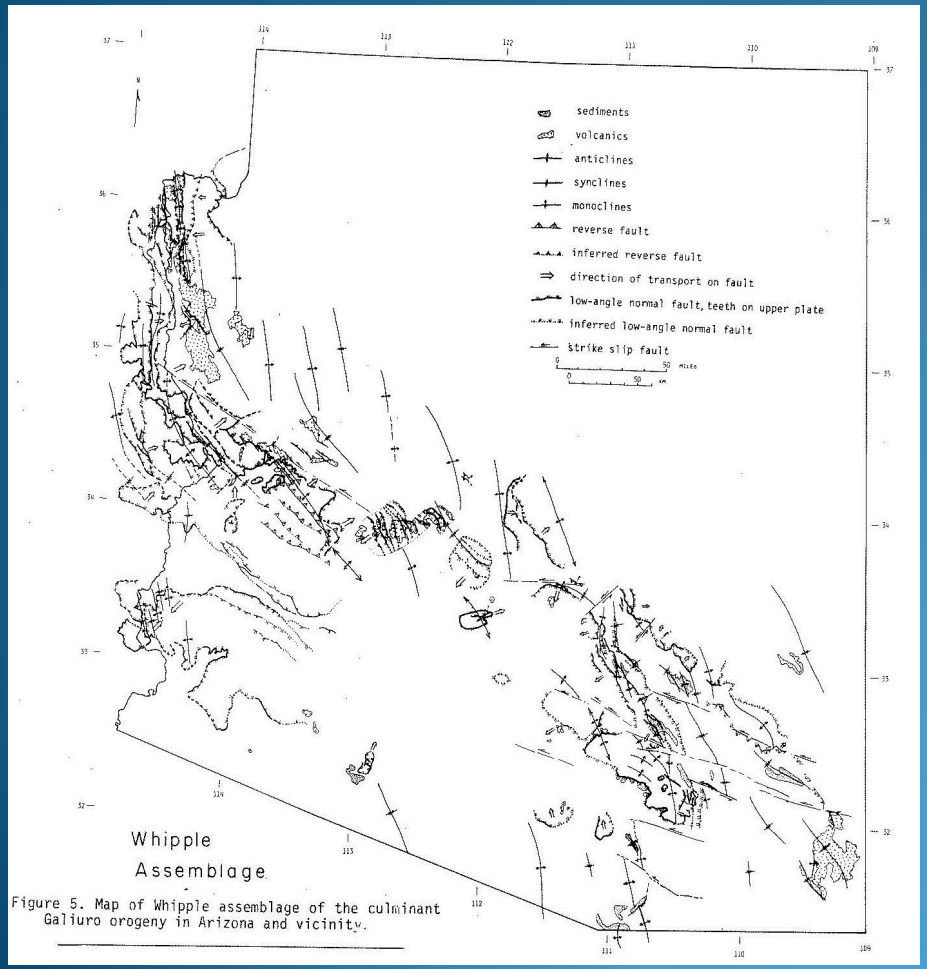


Figure 5. Map of Whipple assemblage of the culminant Galiuro orogeny in Arizona and vicinity.

Fluorite, Harquahala Mts.

Late Galiuro – Whipple (18-13 Ma)

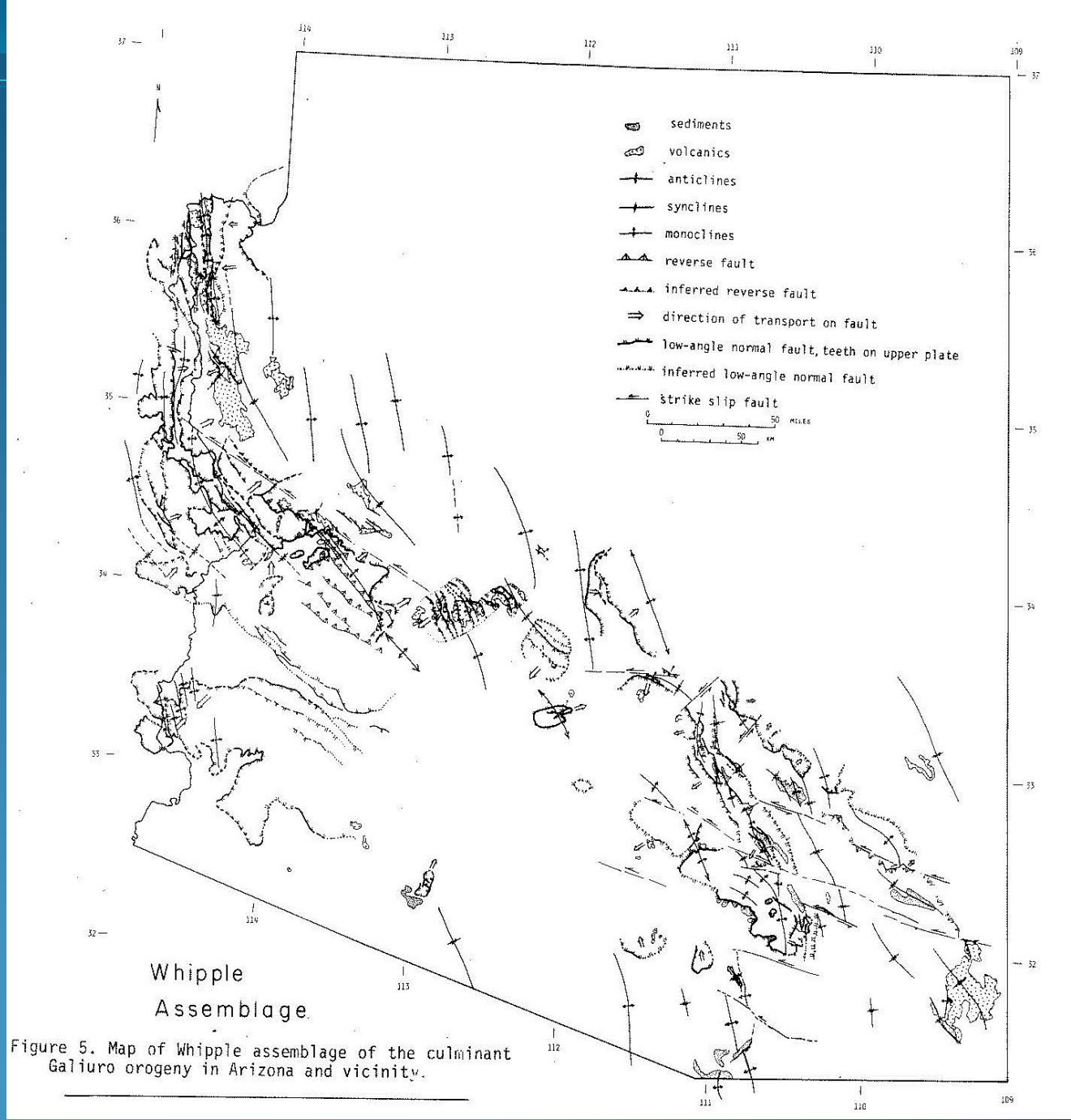
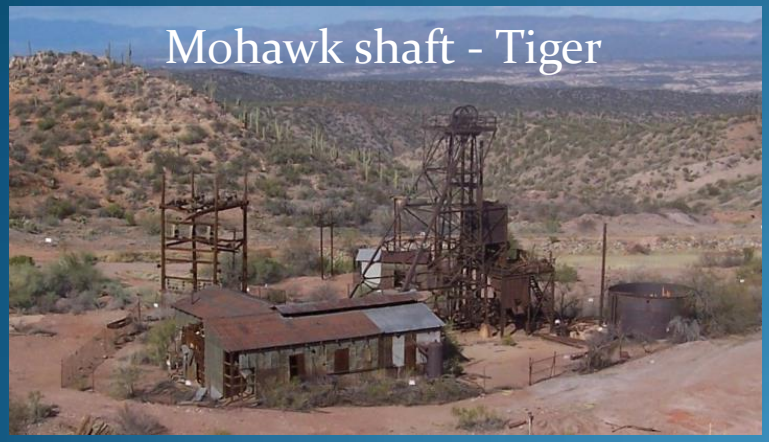


Figure 5. Map of Whipple assemblage of the culminant Galiuro orogeny in Arizona and vicinity.

Mammoth-St. Anthony mine (Tiger)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
	Late (Whipple)	18-13	Late Tertiary	volcanics & local epizonal stocks	Metalum-inous Alkalic	Cu-Au-Ag in veins; epithermal Au-Ag veins	Oatman, Mammoth, Rowley,Swansea



Aerial photo courtesy of BHP Billiton, 2006

Mid-Tertiary – Santa Catalinas - Tiger – Mammoth-St. Anthony mine

vanadinite

cerussite

diaboleite

boleite

dioptase

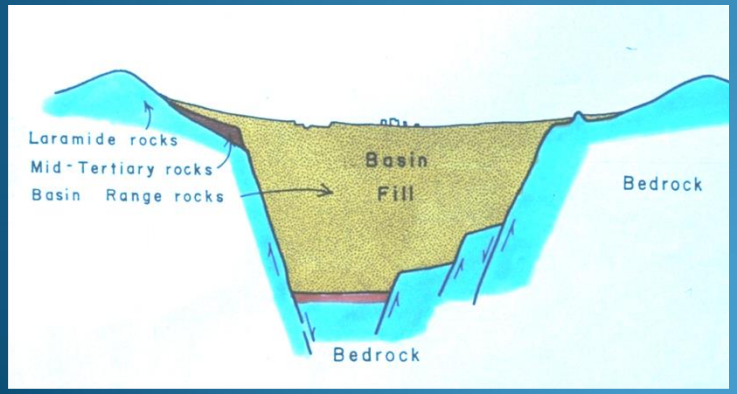
hemimorphite

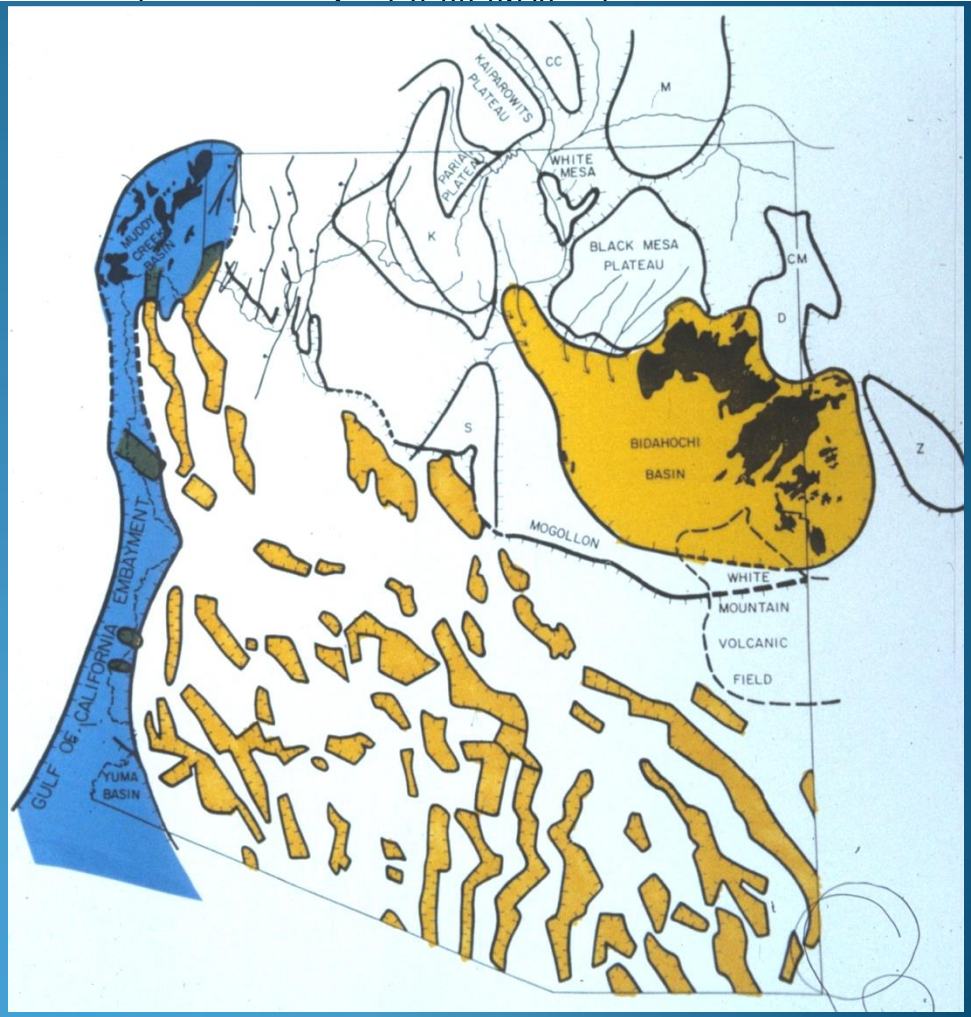
caledonite

San Andreas – Basin & Range (13-0 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
San Andreas	Basin & Range	13-0	Latest Tertiary	anhydrous basaltic volcanism	Metalum. Alkalic	Sand, gravel, salt, zeolites, gypsum	San Francisco volcanic field, San Carlos olivine, Emerald Isle exotic Cu

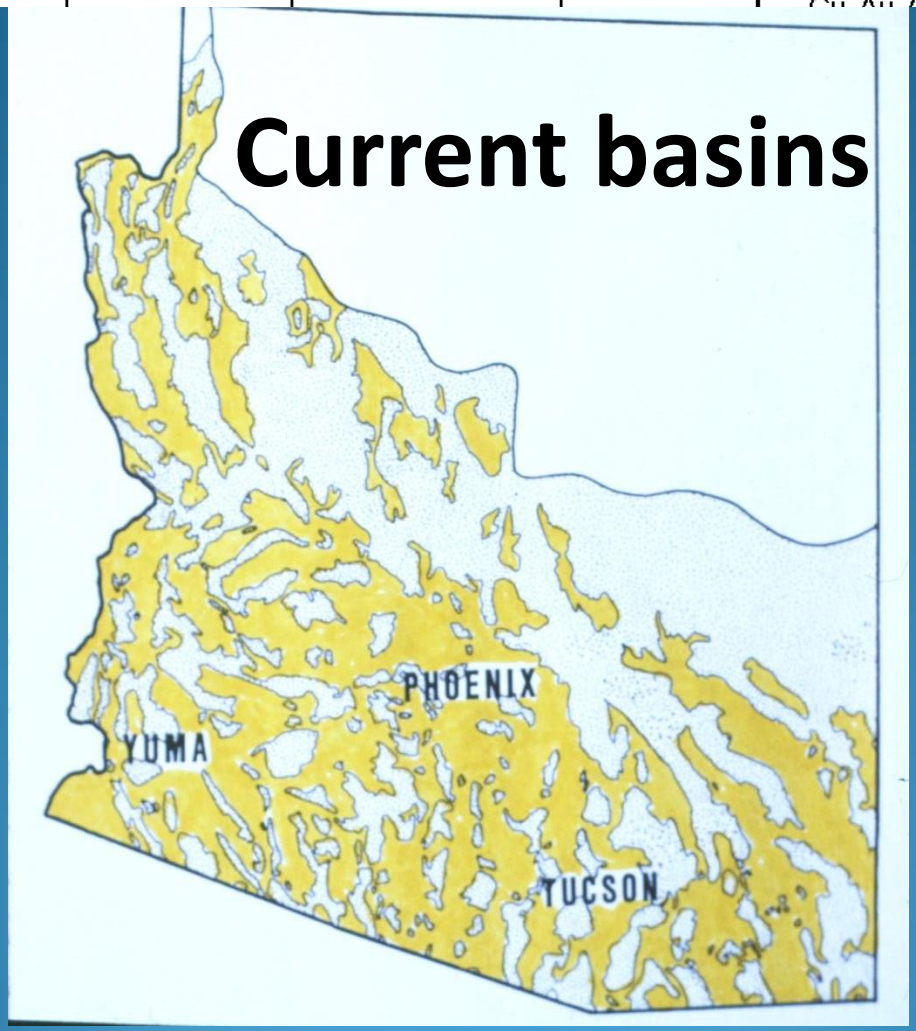
Basin and Range
Valleys filled with sand, gravel, clay, gypsum, & salt





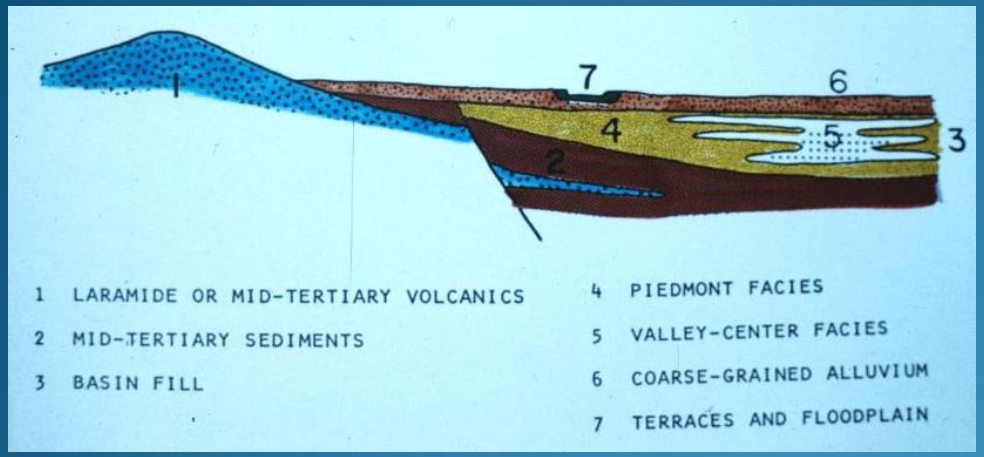
San Andreas – Basin & Range (13-0 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
San Andreas	Basin & Range	13-0	Latest Tertiary	anhydrous basaltic volcanism	Metalum. Alkalic	Sand, gravel, salt, zeolites, gypsum	San Francisco volcanic field, San Carlos olivine, Emerald Isle exotic Cu



Basin & Range Disturbance (13-0 Ma)

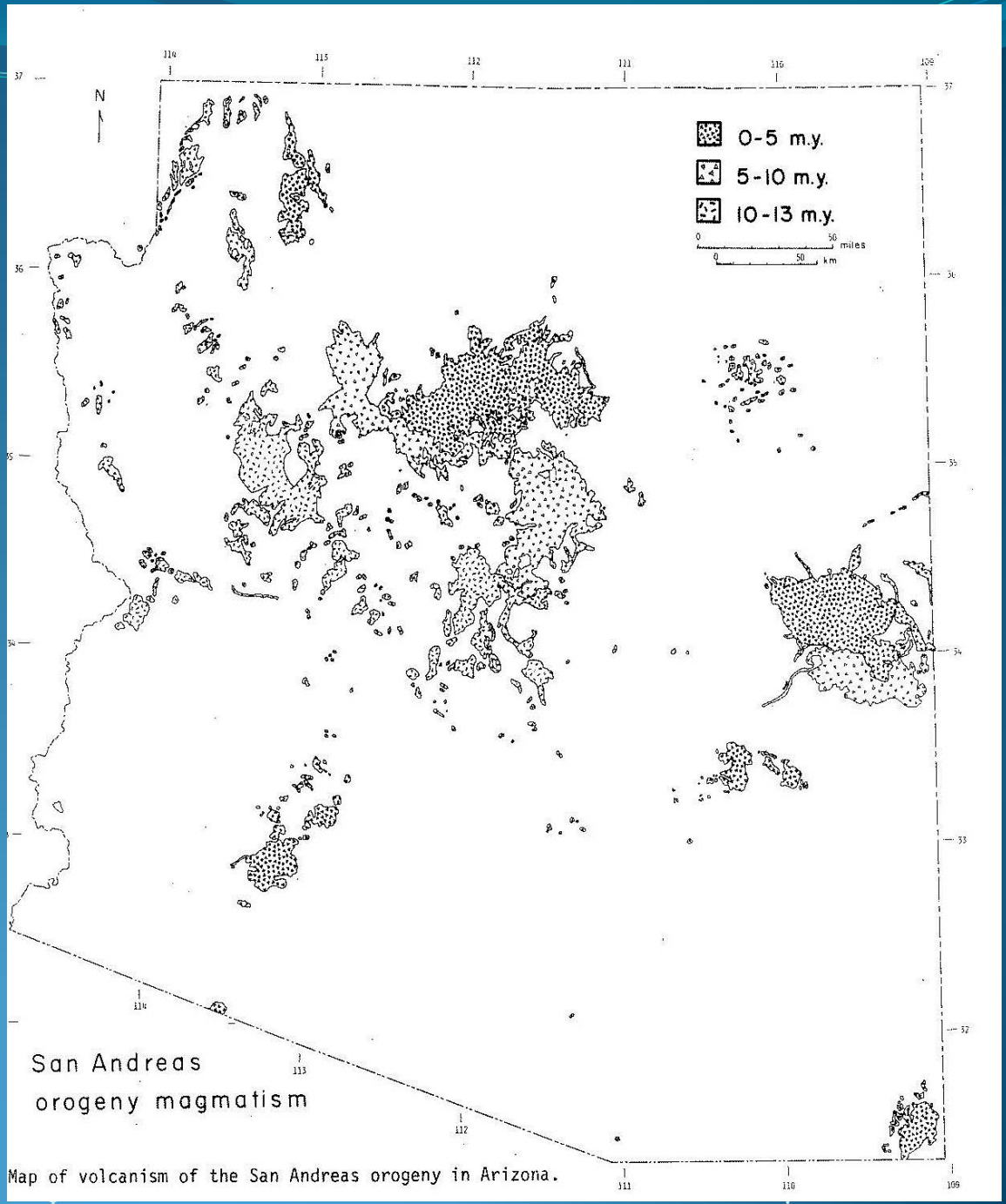
Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
San Andreas	Basin & Range	13-0	Latest Tertiary	anhydrous basaltic volcanism	Metalum. Alkalic	Sand, gravel, salt, zeolites, gypsum	San Francisco volcanic field, San Carlos olivine, Emerald Isle exotic Cu




Rillito II - ~ 21 Ma

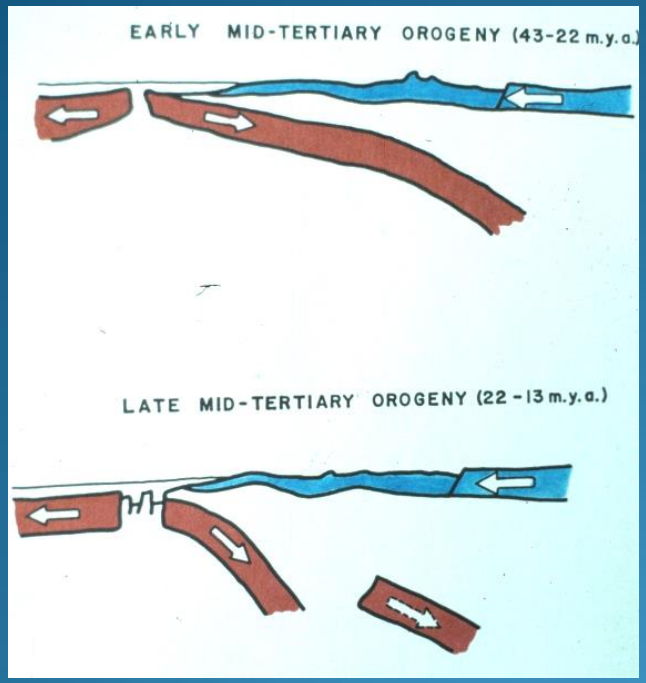
Willcox Playa

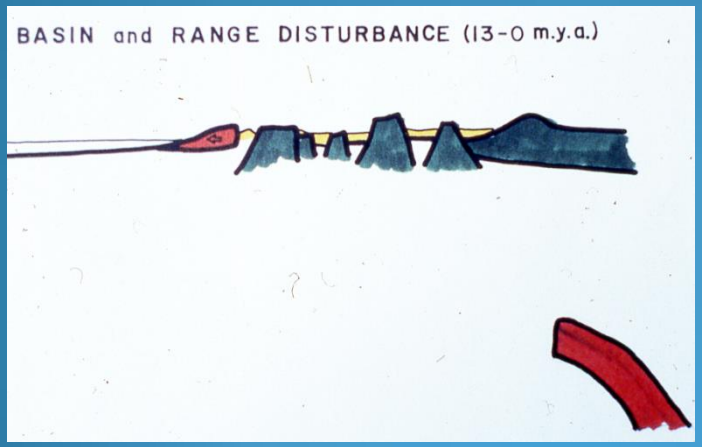
San Andreas – Basin & Range (13-0 Ma) volcanism

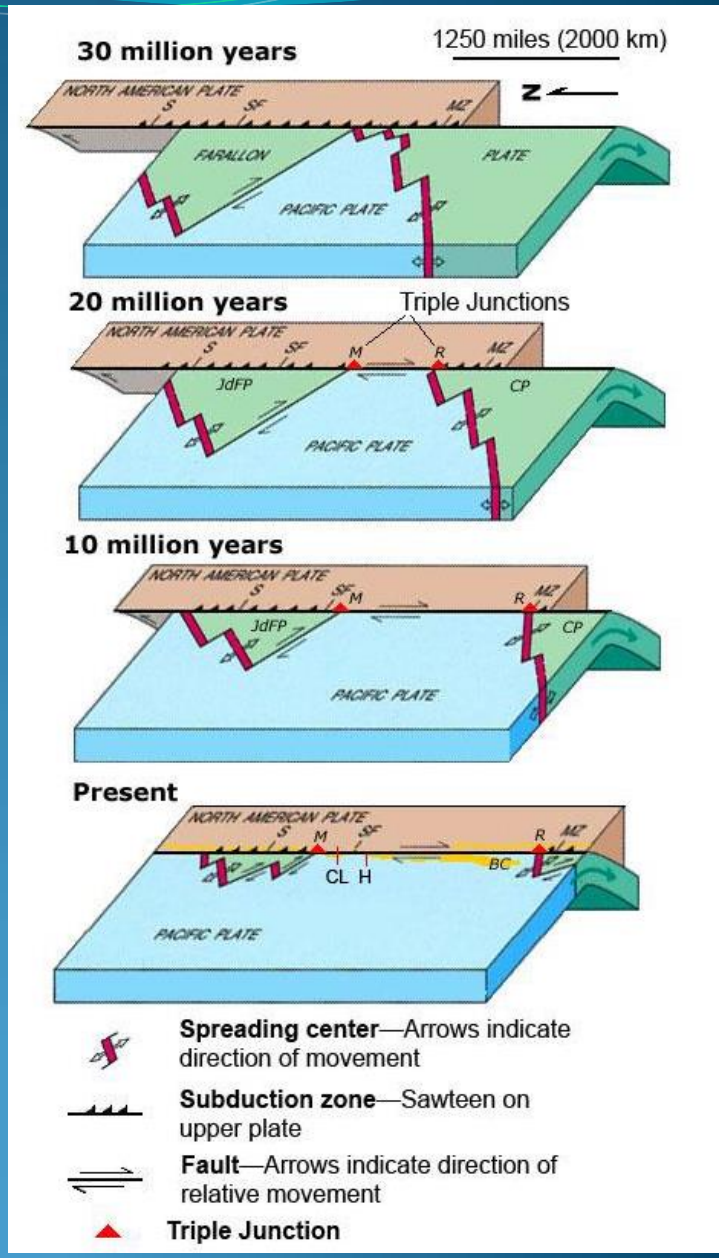


Map of volcanism of the San Andreas orogeny in Arizona.

San Andreas fault cuts off eastward-subducting slab







San Andreas orogeny = true extension – rifting – basalt volcanos

San Francisco Peaks, Flagstaff, AZ

San Andreas – Basin & Range (13-0 Ma)

Late Cenozoic volcanics

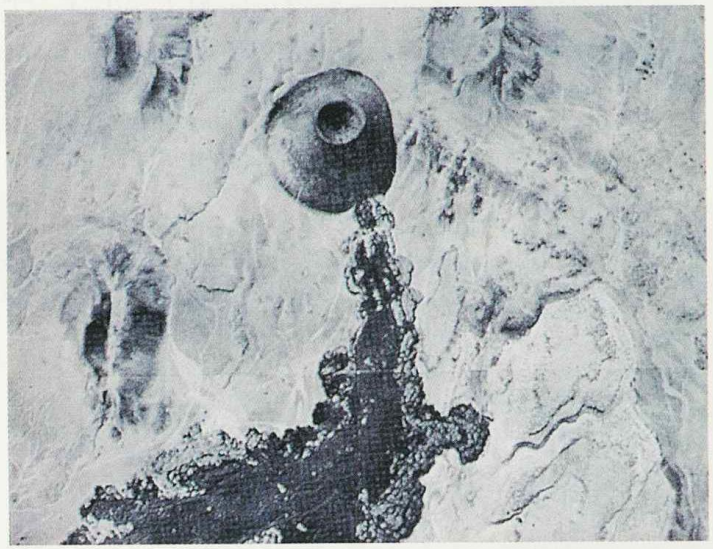
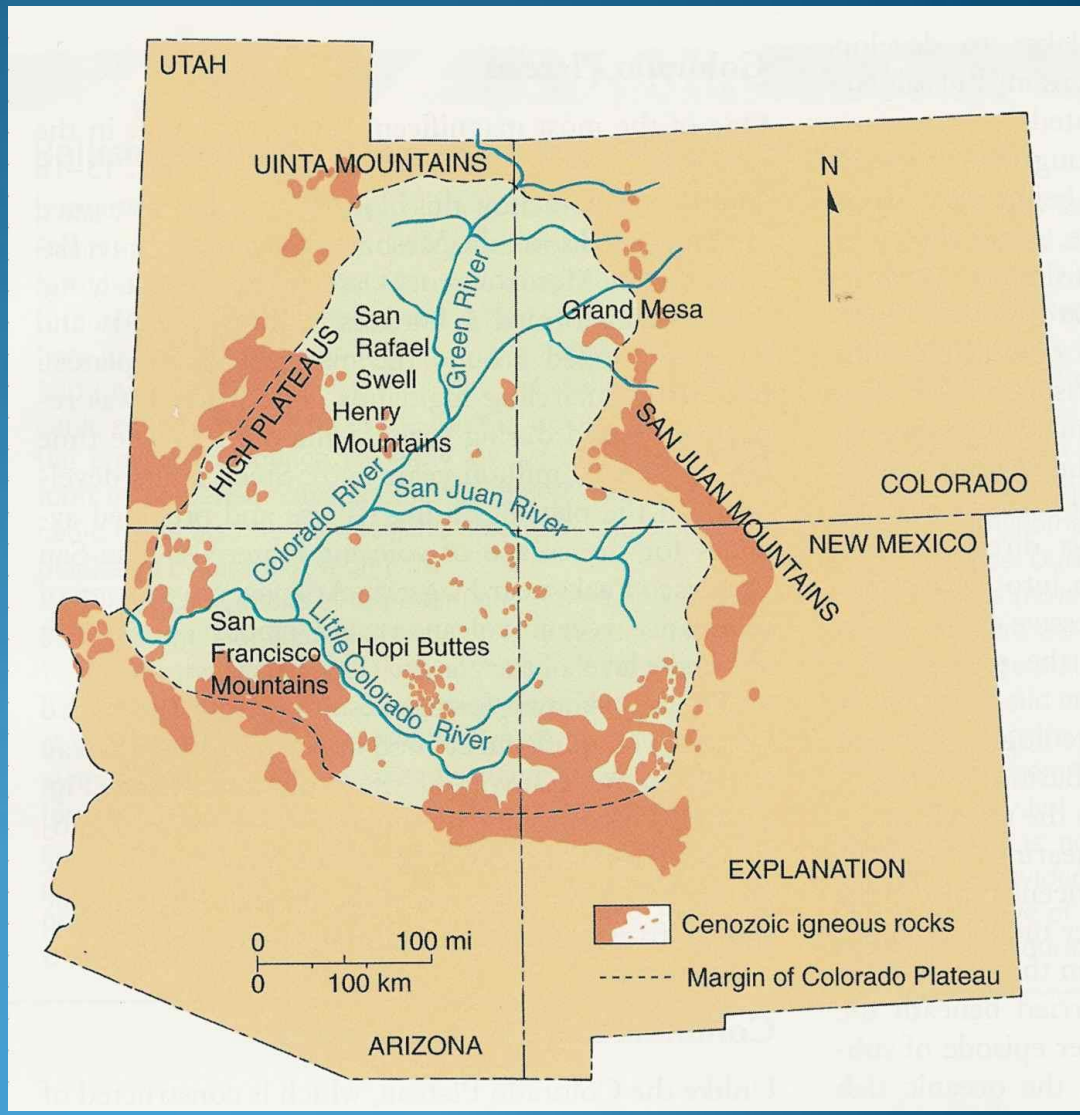


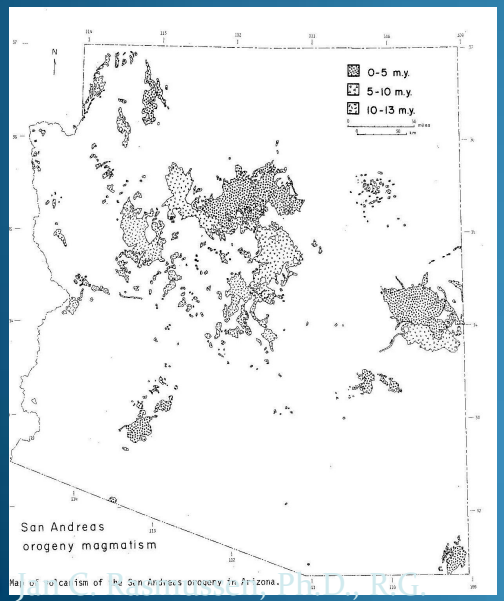
FIGURE 13-20 **Vertical aerial photograph of a large cinder cone in the San Francisco volcanic field of northern Arizona.** The solidified flow issuing from the cone is 7 kilometers long and more than 30 meters thick.



San Andreas – Basin & Range (13-0 Ma)

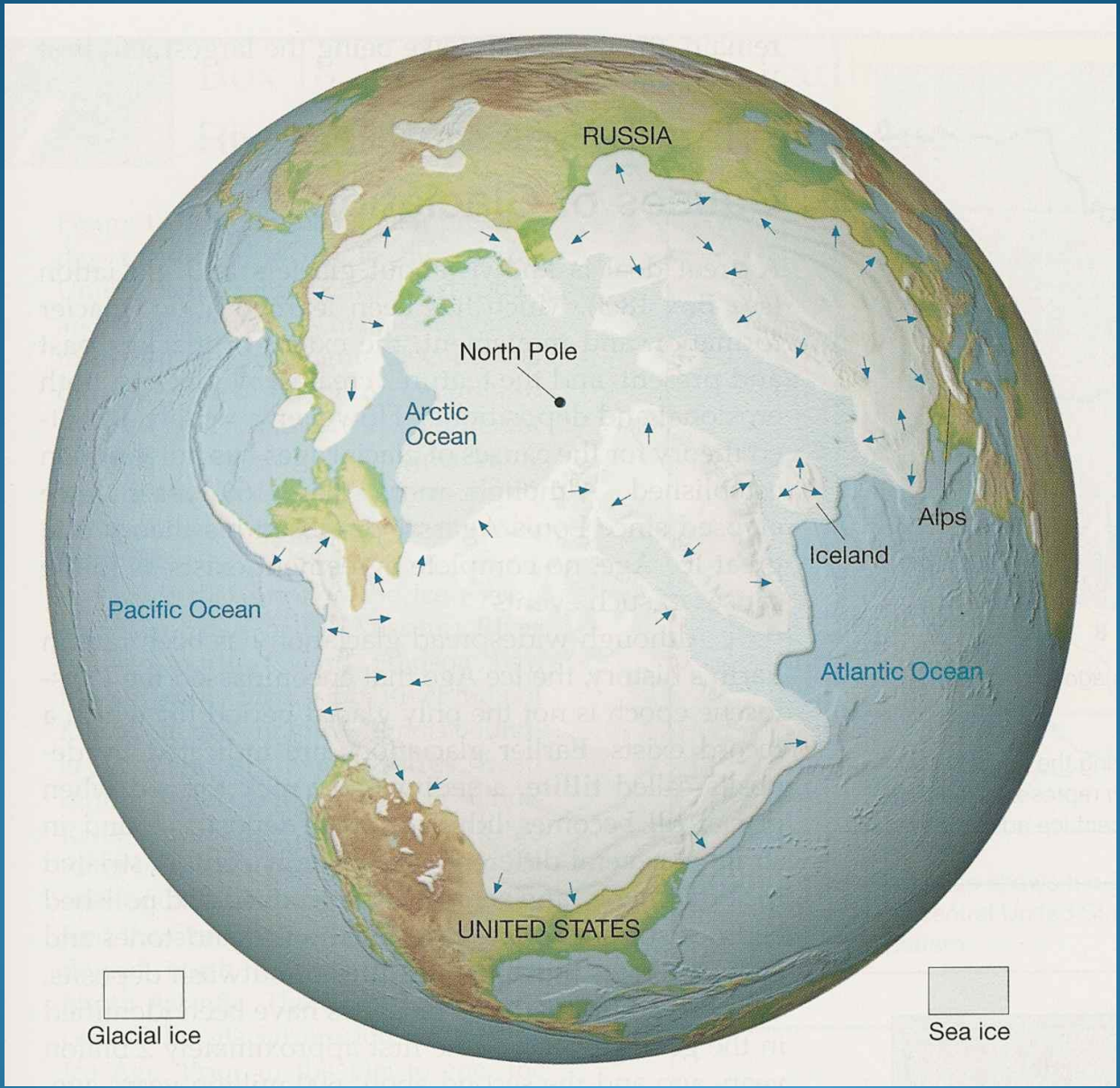
Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Resources	Mining districts
San Andreas	Basin & Range	13-0	Latest Tertiary	anhydrous basaltic volcanism	Metalum. Alkalic	Sand, gravel, salt, zeolites, gypsum	San Francisco volcanic field, San Carlos olivine, Emerald Isle exotic Cu

cinders



San Francisco Peaks, Flagstaff

Pleistocene maximum glaciation – 18,000 years ago



San Andreas – Basin & Range (13-0 Ma)

Industrial minerals from basins

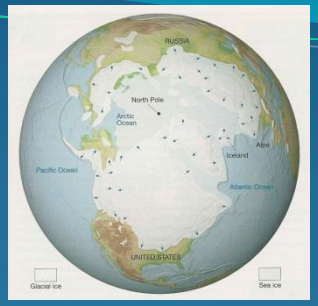
Sand & gravel

Kalamazoo Clay - 1987

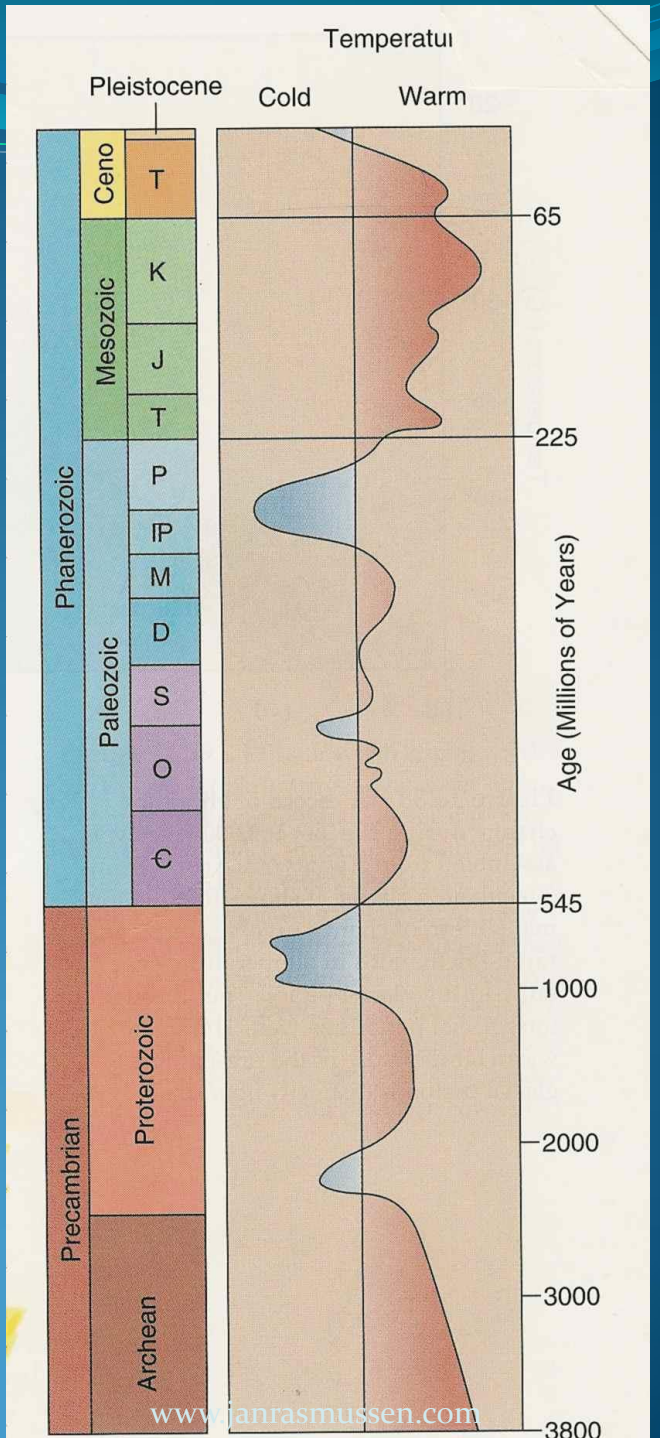
Gypsum rose – St. David

Salt - Picacho Basin – UnoCal photo

Glaciation through Geologic time



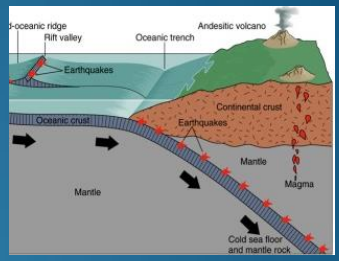
- Depends on plate tectonics through geologic time
- Continental collisions (continents massed closing oceanic circulation) = ice ages
- Big environmental changes through geologic time – but mostly warm
- Ice ages ~ every 250 million years

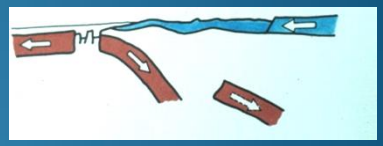


Arizona Mineralization through Geologic Time

Mineralization is related to orogenic episodes

- **Precambrian = orogenies added to fringes of continent = metals**
- **Paleozoic = AZ on trailing edge - Eastern orogenies – AZ calm seas - limestone**
- **Mesozoic-Cenozoic = AZ on leading edge – Cordilleran – subduction = metals**
- **Latest Cenozoic = subduction cutoff by San Andreas – no metals; industrial minerals**





- **It's not all copper!**
- **Presence of other metal deposit types indicate the crust is not the source of copper**