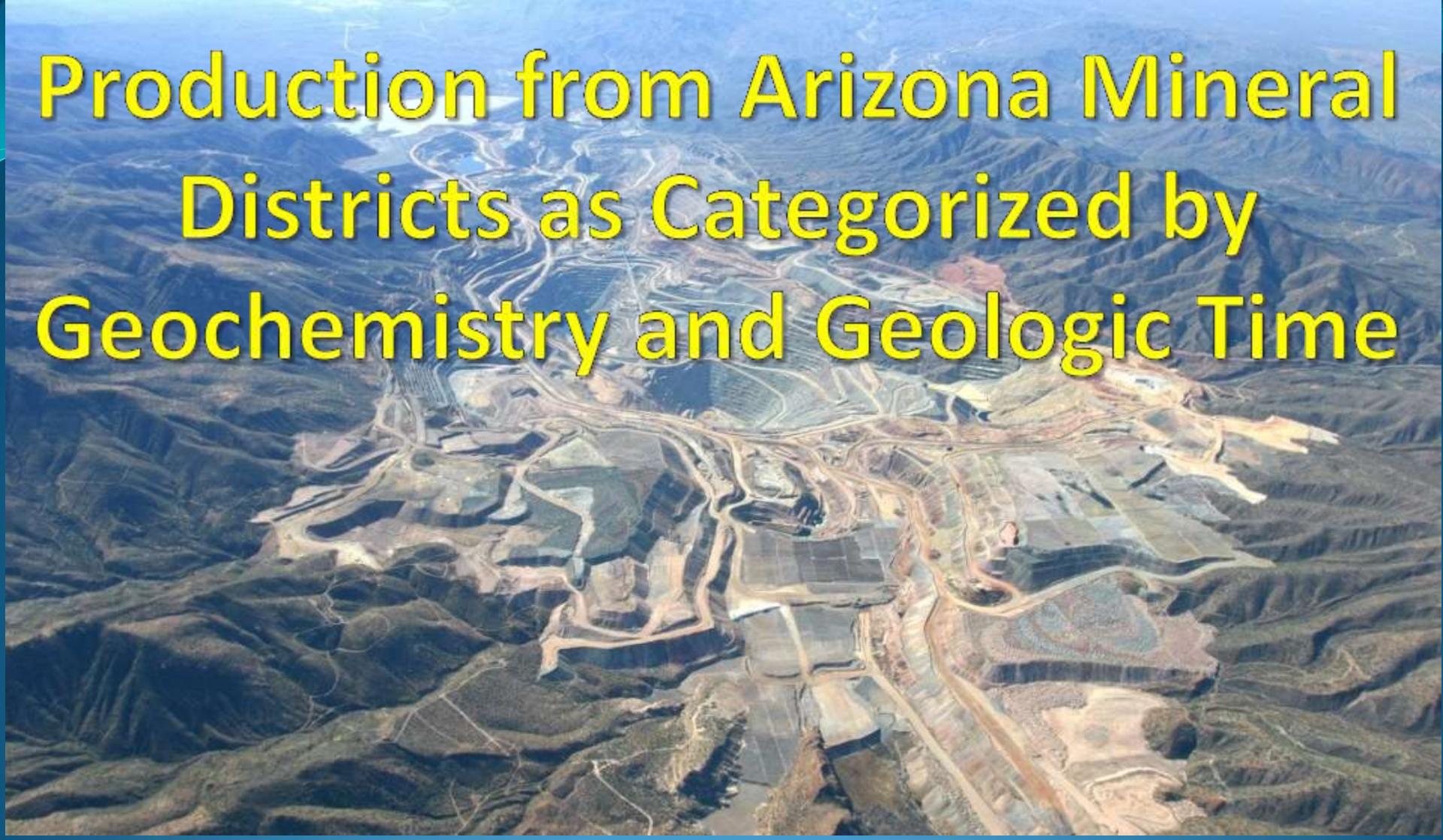
Production from Arizona Mineral Districts as Categorized by Geochemistry and Geologic Time



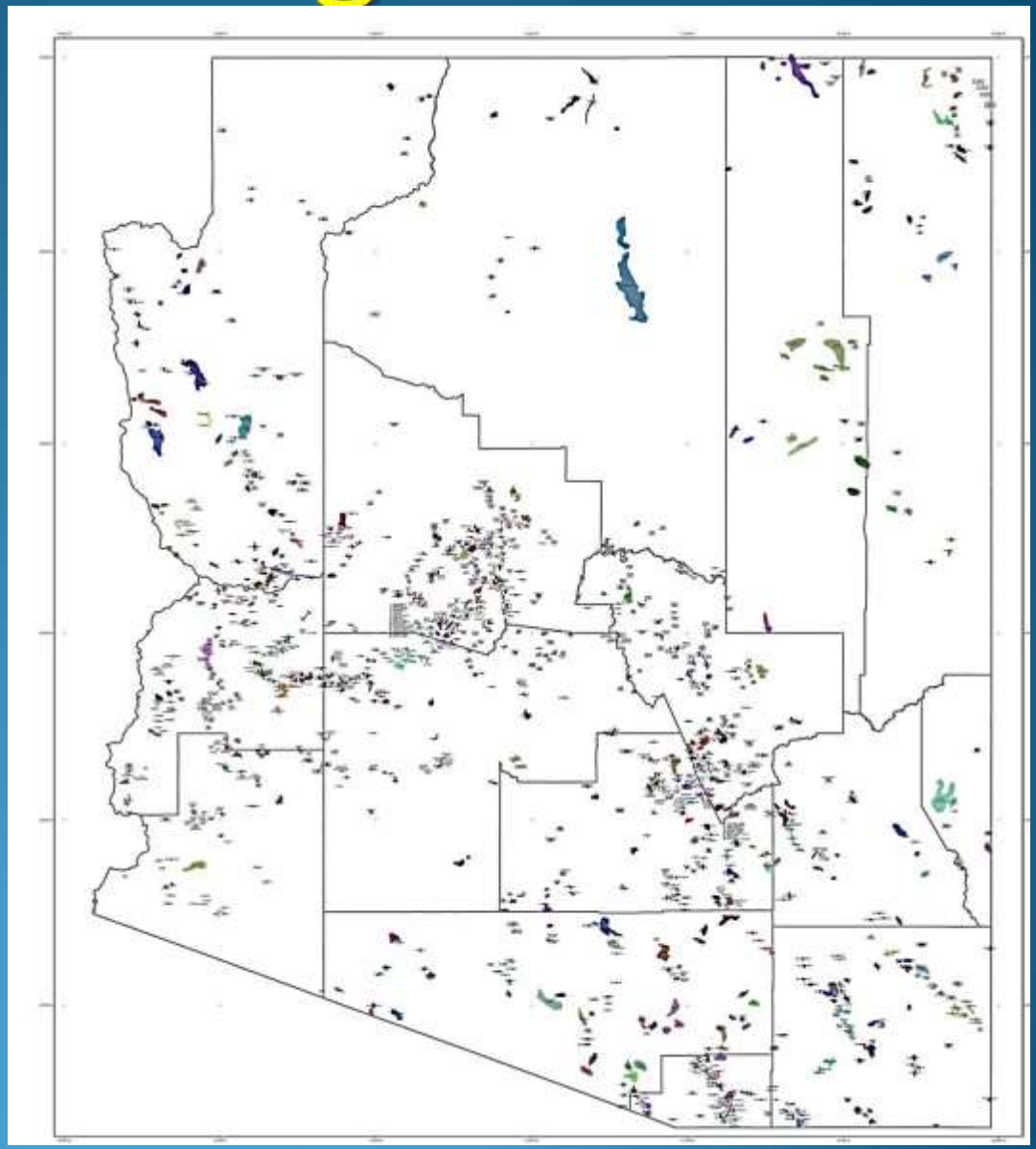
by **Jan C. Rasmussen, Ph.D., SME R.G.**

and **Stanley B. Keith, MagmaChem Exploration**

Ray mine – photo courtesy of ASARCO (Grupo)

Arizona Mining Districts

- ~ 450 districts
- Copper deposits were made only 2 times in AZ geologic history – Jurassic and Laramide
- Other 14 ore deposit intervals produced: Au, Ag-Pb-Zn, W-Be, Hg, Mn
- Crust is not the source of copper

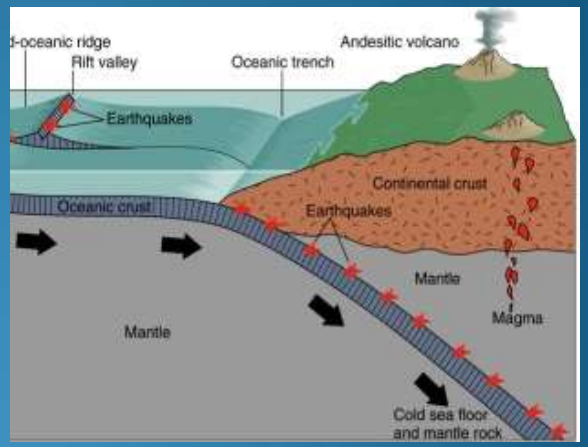


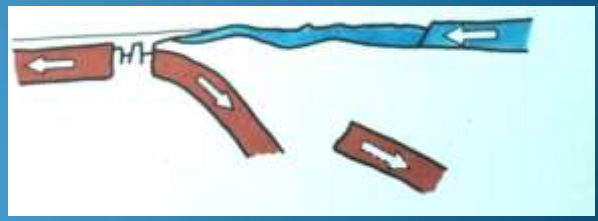
Map – from AzGS

Arizona Mineralization through Geologic Time

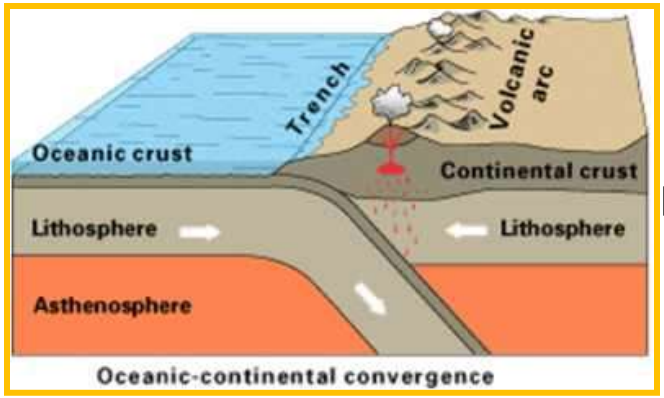
Mineralization is related to mountain building episodes (orogenies)

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





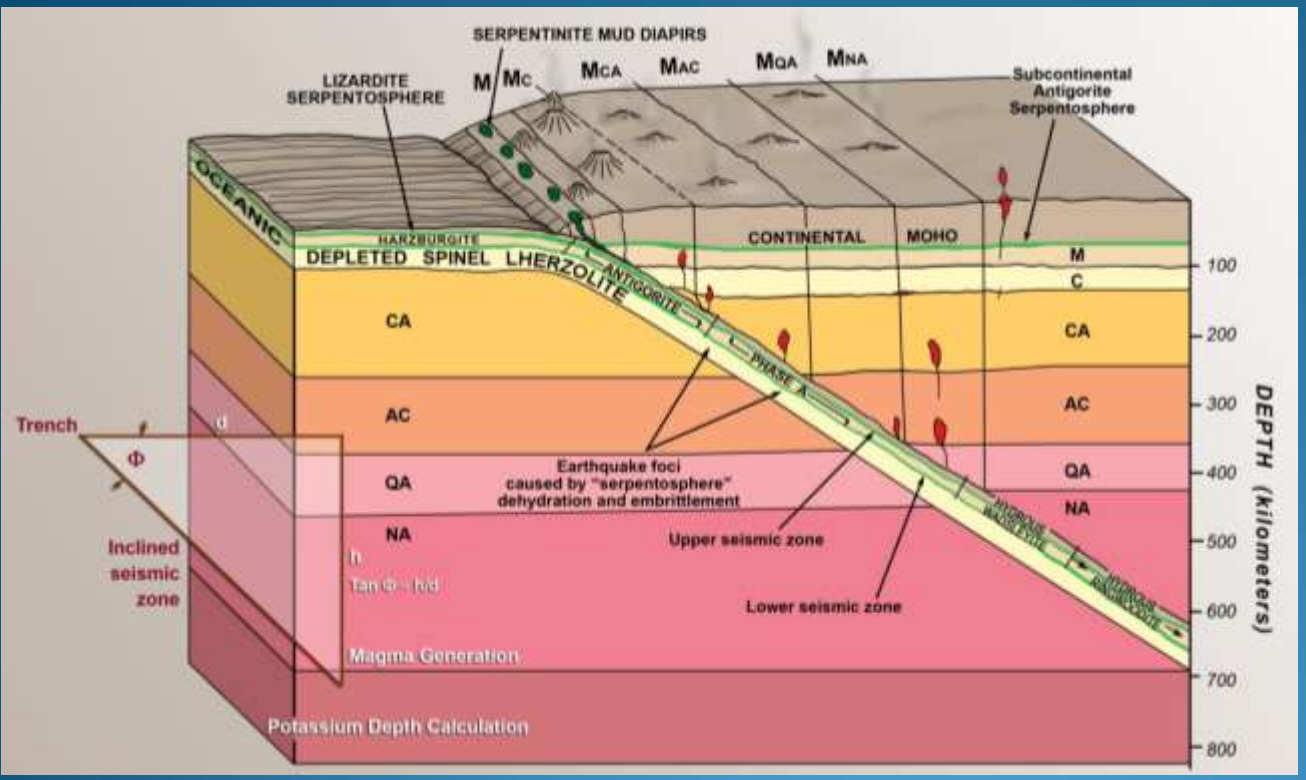
Orogenies in Arizona



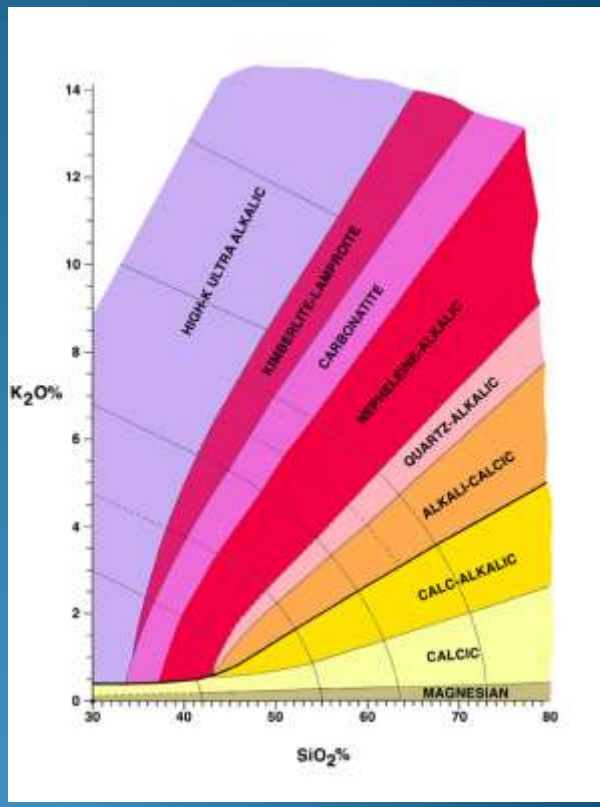
Oceanic-continental convergence

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
San Andreas	Basin & Range	13-0	MQA	Sand, gravel, salt, zeolites, gypsum	San Francisco volcanic field, San Carlos olivine, Emerald Isle
Galiuro	Late (Whipple)	18-13	MQA	Au-Ag (Cu) F, U, Mn	Oatman, Mammoth, Rowley, Tiger
	Middle (Datil)	28-18	MAC	Pb-Zn-Ag F	Silver (Red Cloud), Castle Dome, Stanley, Aravaipa
	Early (South Mountain	30-22	MCA	Au +/- (Cu, W)	Little Harquahala, Kofa
	Earliest (Mineta)	38-28	-	U, clay, exotic Cu	Ajo Cornelia, Copper Butte (from Ray)
Laramide	Late (Wilderness)	55-43	PC; PCA	Au, W (Be)	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin
	Middle (Morenci)	65-55	MCA	porphyry Cu-Mo-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior
	Early (Tomb-stone)	85-65	MAC	Pb-Zn-Ag	Tombstone, Tyndall (Glove), Washington Camp, Salero
	Earliest (Hillsboro)	89-85	MQA	Cu-Au-Ag (Pb, Zn)	Hillsboro, NM
Sevier		145-89	-	Bisbee Group sedimentary rocks (113-100 Ma)	Limestone (Paul Spur near Bisbee)
Nevadan	Latest	155-145	MCA	Not yet recognized in AZ	Yerington, NV
	Late	170-155	MAC	Pb-Zn-Ag	Turquoise (Gleeson)
	Middle	205-180	MQA	porphyry Cu-Au	Warren (Bisbee mine), Turquoise (Courtland), Yuma King
	Early	230-205	MQA	U, V, Cu	Orphan, Grandview, Monument Valley
Alleghenian (Ouachita)		325-252	-	U, NaCl, K_2CO_3	potash
Lull between Acadian & Alleghenian		355-330		Limestone	Redwall Ls., Escabrosa Ls.
Acadian/ Caledonian/ Antler (NV)		410-370	-	UltraDeep Hydrocarbon?	Percha black shale
Grenville		1200-900	MQA	Serpentine asbestos, U, (Cu)	Sierra Ancha U, Chrysotile (Salt R. Canyon)
"Oracle/Ruin"		1440-1335	PCA; PAC	Be, Li, Ta-Nb, U & W	White Picacho, Tungstona, Four Peaks
Mazatzal		1750-1600	MC	Hg, Au, Sn	Mazatzal Mts., Phoenix Mts., Green Valley
Yavapai		1800-1775	MC	Zn-Cu-Au VMS, Zn-Cu-Ag VMS, BIF	Big Bug (Iron King), Verde (Jerome), Old Dick (Bruce), Pikes Peak Fe
Penokean/ Hudsonian		2000-1800	MC	gneisses	western Grand Canyon

Alkalinity and Potassium-Depth Ratios



Source: Keith, 1978

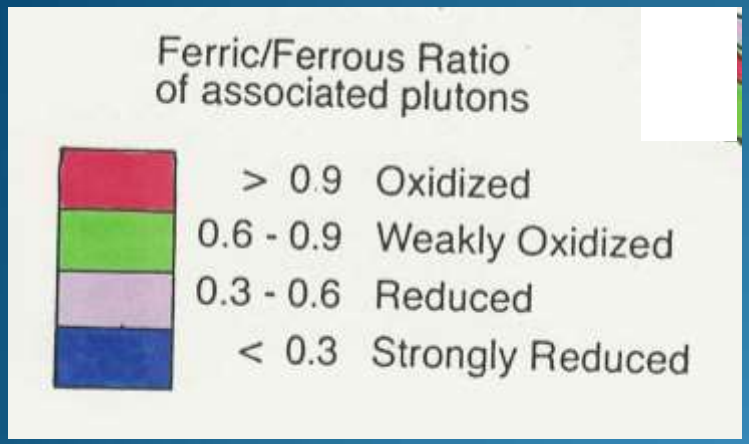


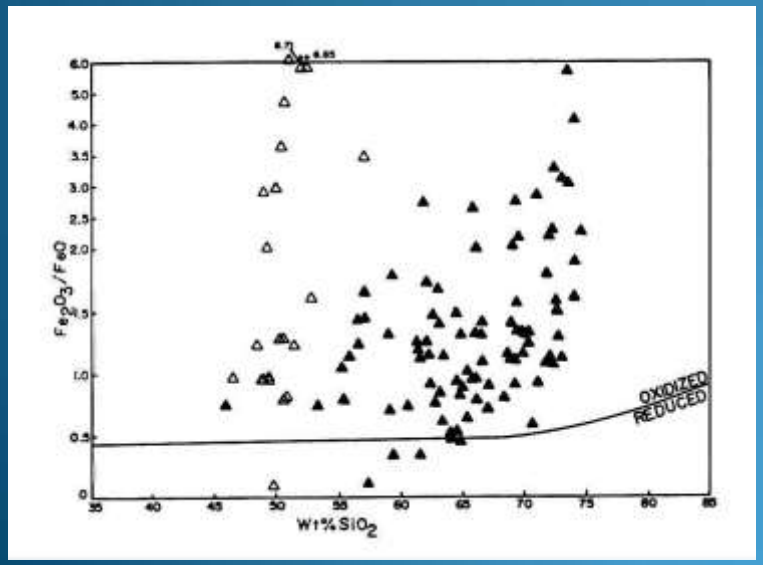
K2O vs SiO2 variation diagram with alkalinity fields – unaltered whole rock geochemistry

QA = Quartz alkalic = pink
AC = Alkali-calcic = orange
CA = Calc-alkalic = yellow
C = Calcic = pale yellow

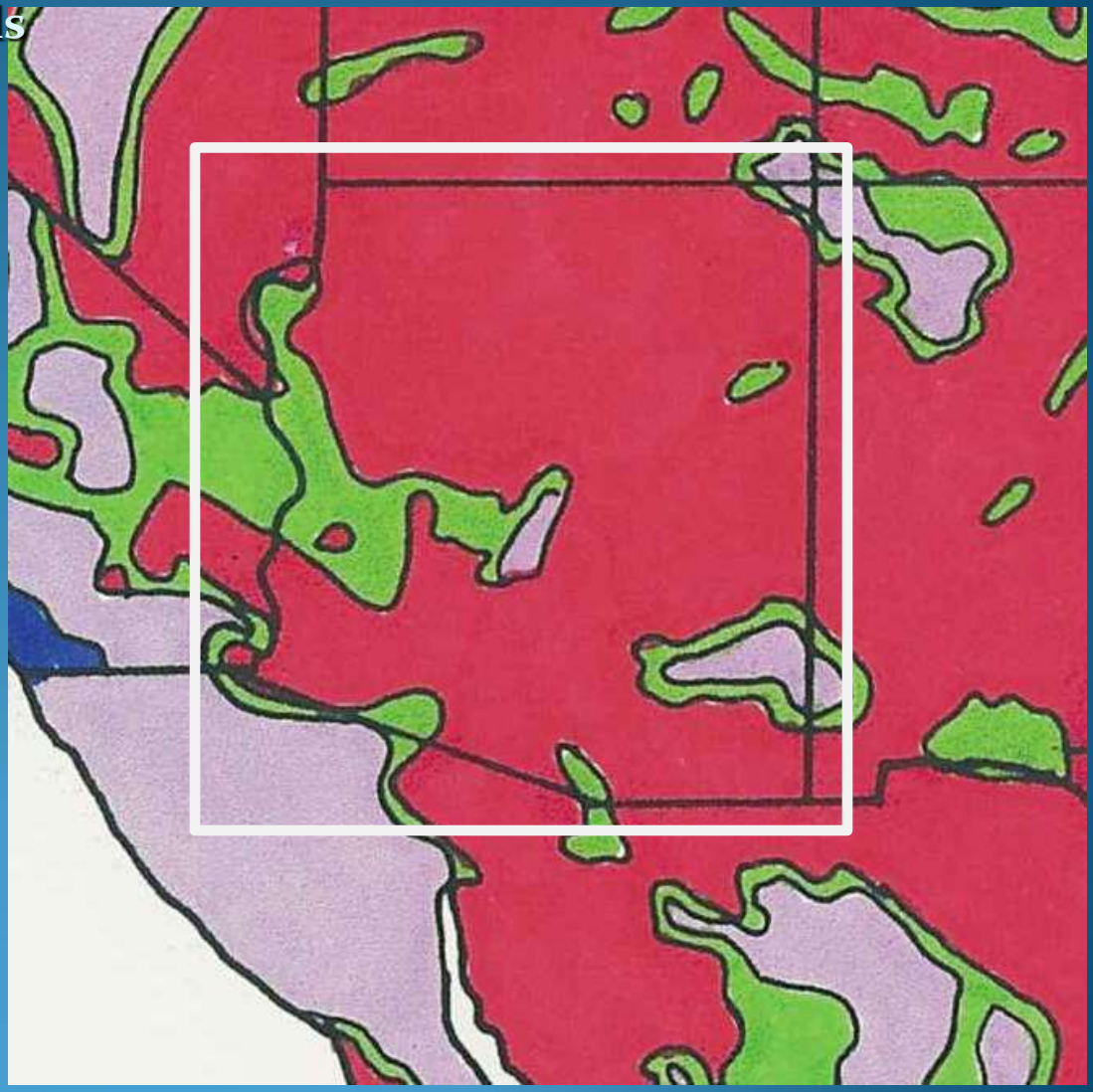
Arizona has oxidized crust

Oxidation state map of Arizona defined by oxidation states of plutons or associated mineral district models





Source: Keith, 1986



Precambrian Orogenies in Arizona

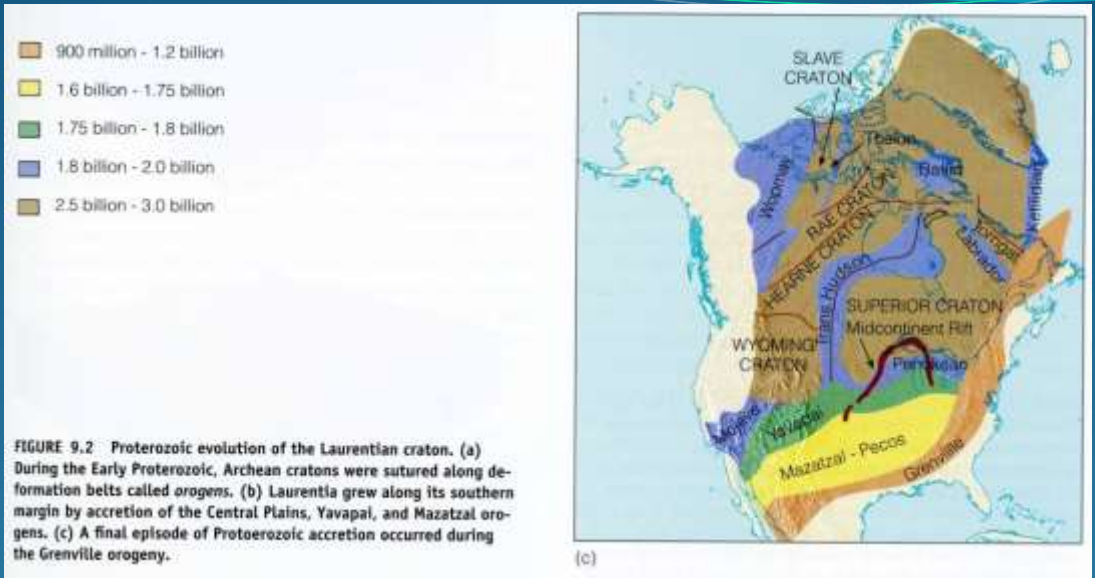


FIGURE 9.2 Proterozoic evolution of the Laurentian craton. (a) During the Early Proterozoic, Archean cratons were sutured along deformation belts called *orogens*. (b) Laurentia grew along its southern margin by accretion of the Central Plains, Yavapai, and Mazatzal orogens. (c) A final episode of Protoerozoic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

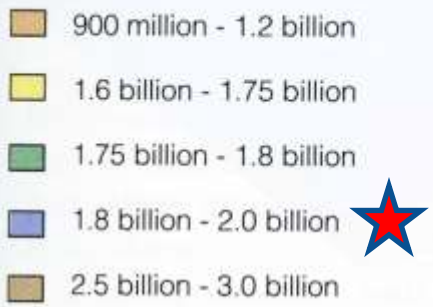
Source: Wicander, Historical Geology

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Grenville		1200-900	MQA	Serpentine asbestos, U, (Cu)	Sierra Ancha U, Chrysotile (Salt R. Canyon)
"Oracle/Ruin"		1440-1335	PCA; PAC	Be, Li, Ta-Nb, U & W	White Picacho, Tungstona, Four Peaks
Mazatzal		1750-1600	MC	Hg, Au, Sn	Mazatzal Mts., Phoenix Mts., Green Valley
Yavapai		1800-1775	MC	Zn-Cu-Au VMS, Zn-Cu-Ag VMS, BIF	Big Bug (Iron King), Verde (Jerome), Old Dick (Bruce), Pikes Peak Fe
Penokean/ Hudsonian		2000-1800	MC	gneisses	western Grand Canyon

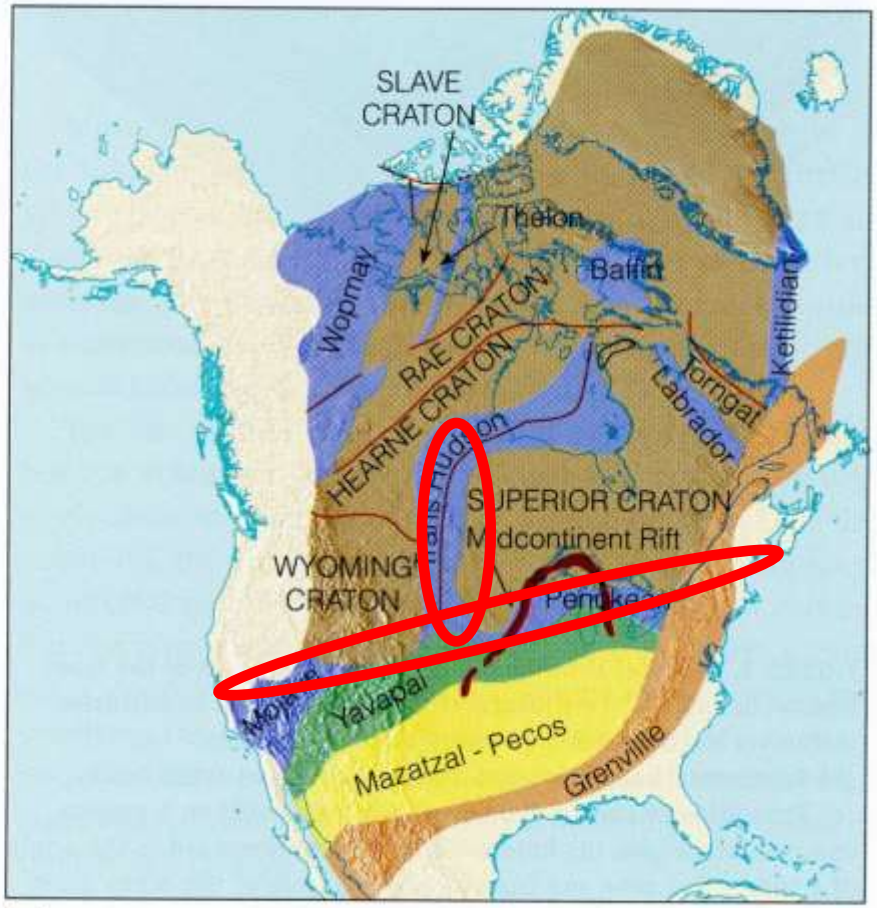
Hudsonian/Mohave Orogeny (2 – 1.8 Ga)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Penokean/ Hudsonian		2000-1800	MC	gneisses	western Grand Canyon

Possible Hudsonian ages in the westernmost Grand Canyon



Source: Wicander, Historical Geology



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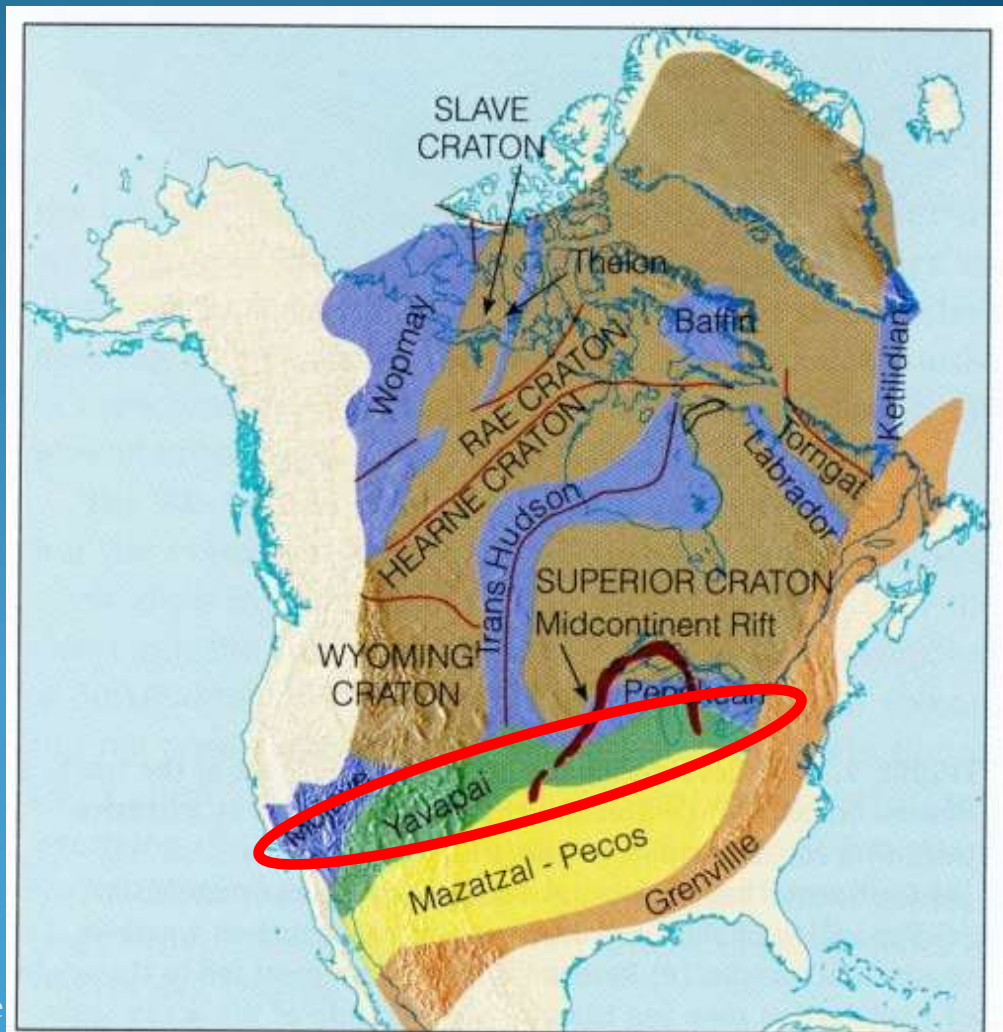
Yavapai - Jerome VMS (1.8 – 1.775 Ga)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Yavapai		1800-1775	MC	Zn-Cu-Au VMS, Zn-Cu-Ag VMS, BIF	Big Bug (Iron King), Verde (Jerome), Old Dick (Bruce), Pikes Peak Fe



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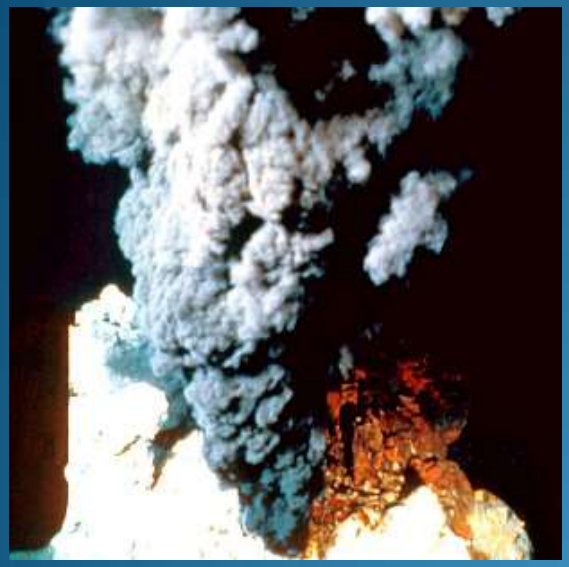
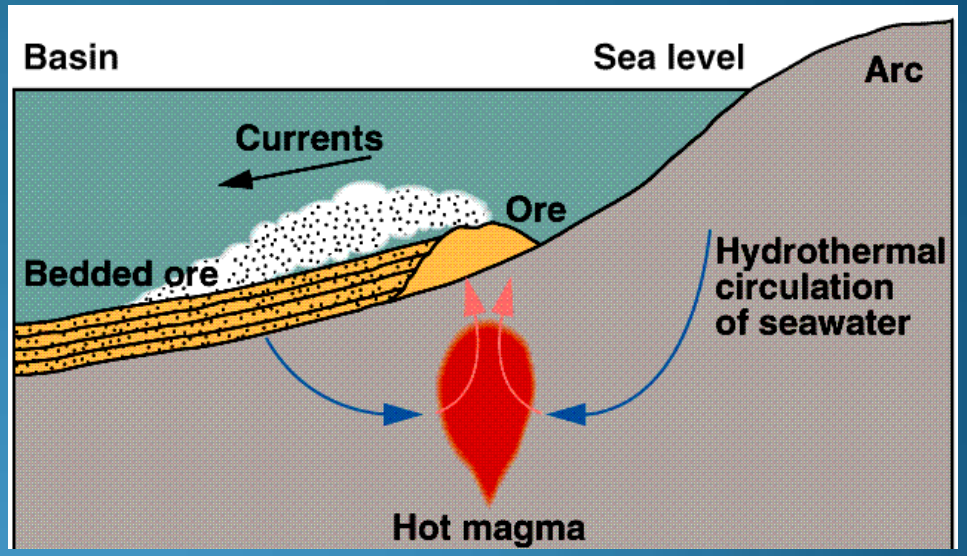


Modern Black Smoker



Verde dist. Prod. = 3,625,000,000 lb Cu
693,000 lb Pb
97,352,000 lb Zn
poss. 5,000,000,000 lb Zn reserves
1,579,000 oz Au
57,313,000 oz Ag

Volcanogenic Massive Sulfide

This is a Zinc deposit – Clarkdale smelter not set up for Zn

Source: Keith et al, 1983

Yavapai - Big Bug m.d. – Iron King VMS

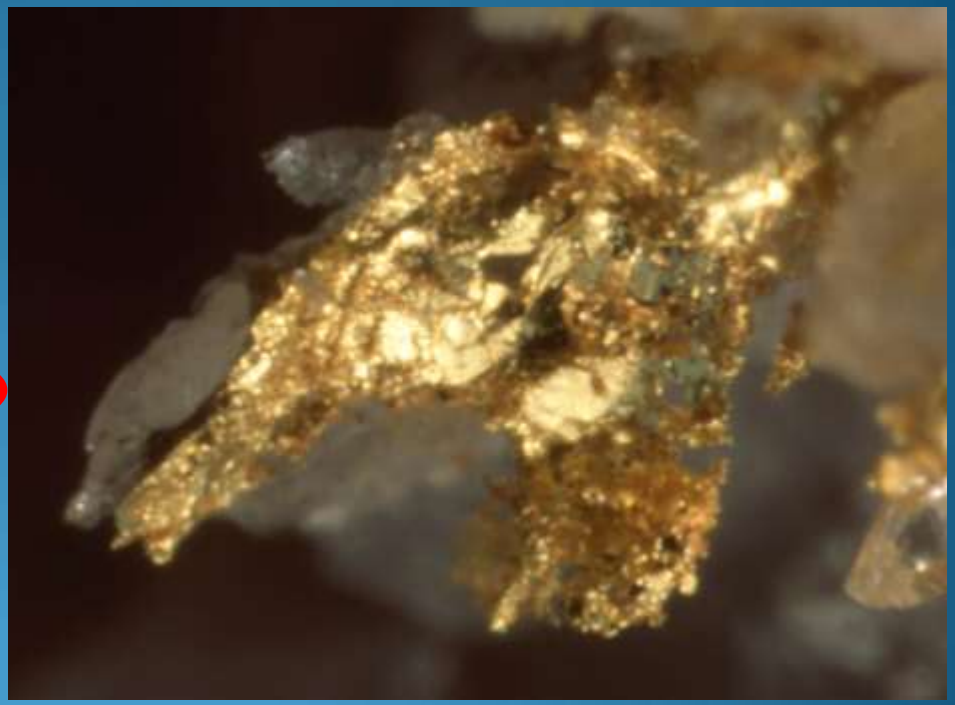
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Yavapai		1800-1775	MC	Zn-Cu-Au VMS, Zn-Cu-Ag VMS, BIF	Big Bug (Iron King), Verde (Jerome), Old Dick (Bruce), Pikes Peak Fe

Big Bug dist. prod (1902-1969) =

6,200,000 lb Cu
14,300,000 lb Pb
233,000,000 lb Zn
462,000 oz Au
16,771,000 oz Ag

Source: Keith et al., 1983, AZGS Bull 194

Laramide Ticonderoga veins intruded same crust as Iron King, but do not have the Zn signature.



Gold from Big Bug mine – micromount

Sugar White photo, Ed Huskinson sample

Yavapai Orogeny (1.75-1.6 Ga)

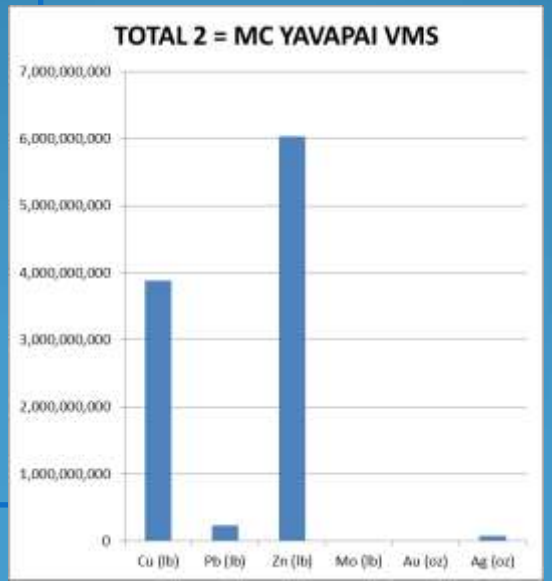
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Yavapai		1800-1775	MC	Zn-Cu-Au VMS, Zn-Cu-Ag VMS, BIF	Big Bug (Iron King), Verde (Jerome), Old Dick (Bruce), Pikes Peak Fe

Laramide Bagdad porphyry copper intruded same crust as Old Dick (within the alteration zone), but does not have the Zn signature.

Old Dick district prod. (1917-1977) =
106,396,000 lb Cu
3,041,000 lb Pb
306,584,000 lb Zn
3,500 oz Au
652,000 oz. Ag

The Bruce mine in the Old Dick mining district is a

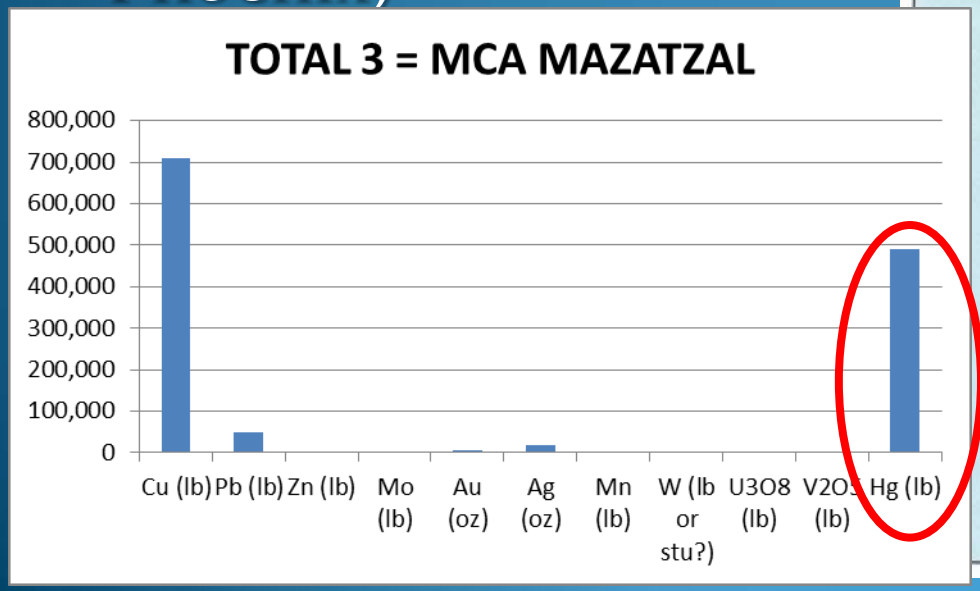
- volcanogenic massive sulfide deposit,
- Cu:Zn ratio = 1:3

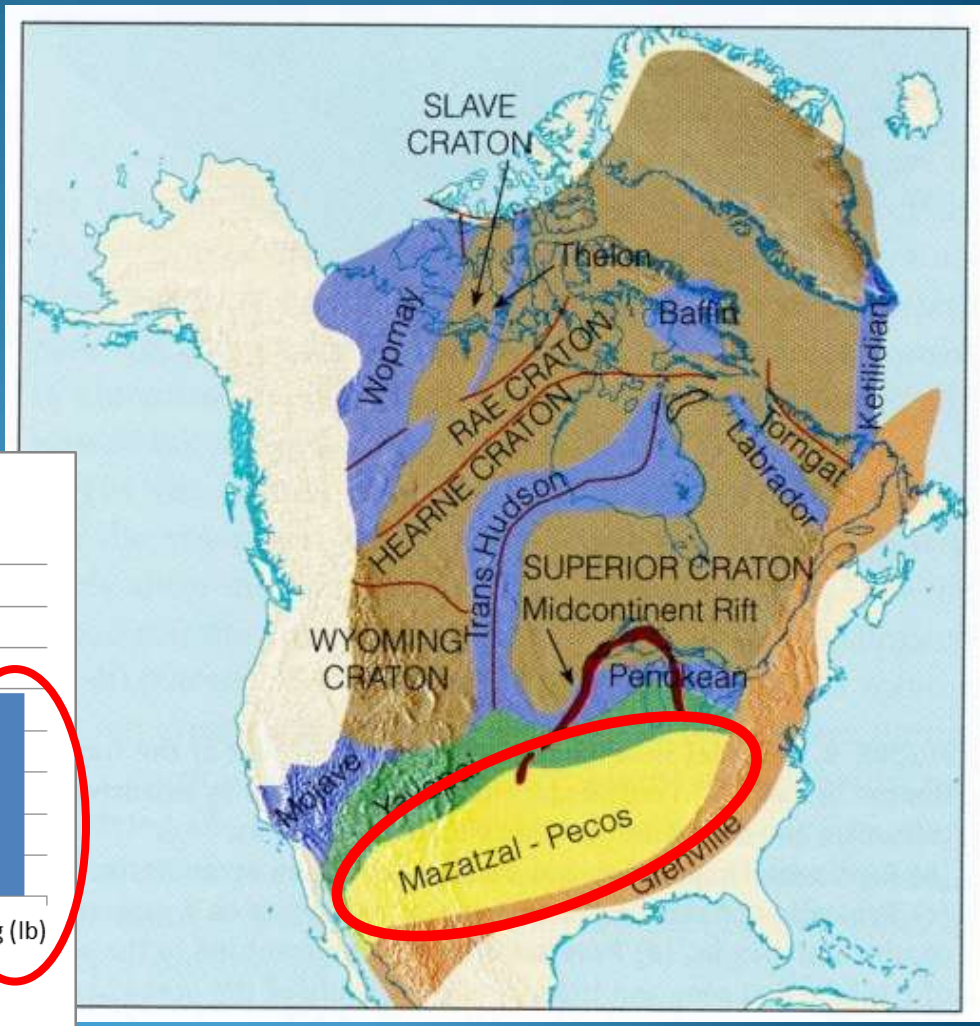


Mazatzal Orogeny (1.75-1.6 Ga)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Mazatzal		1750-1600	MC	Hg, Au, Sn	Mazatzal Mts., Phoenix Mts., Green Valley

- Hg in Mazatzal Mtns.
- Hg production from Phoenix Mtns. dist. (Dreamy Draw, Phoenix)

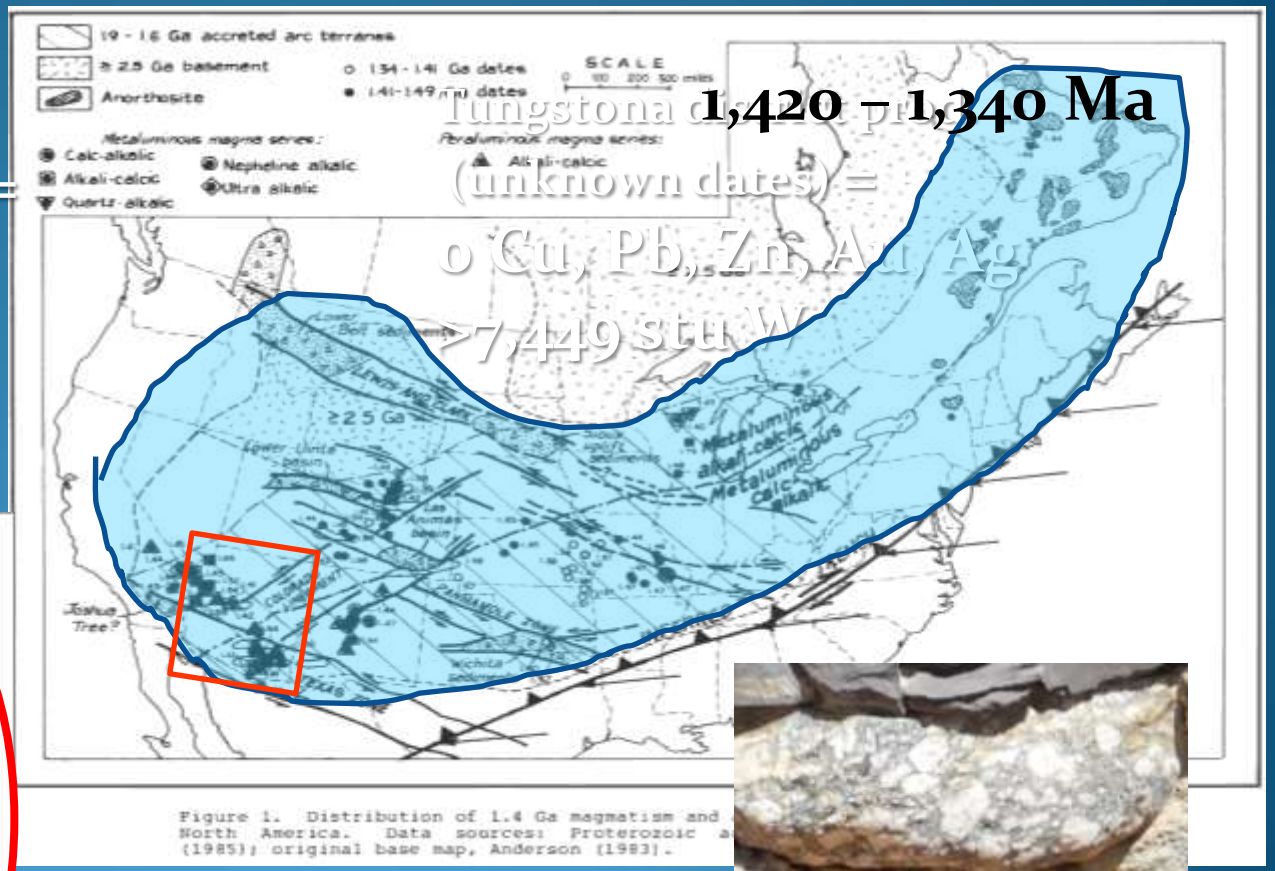


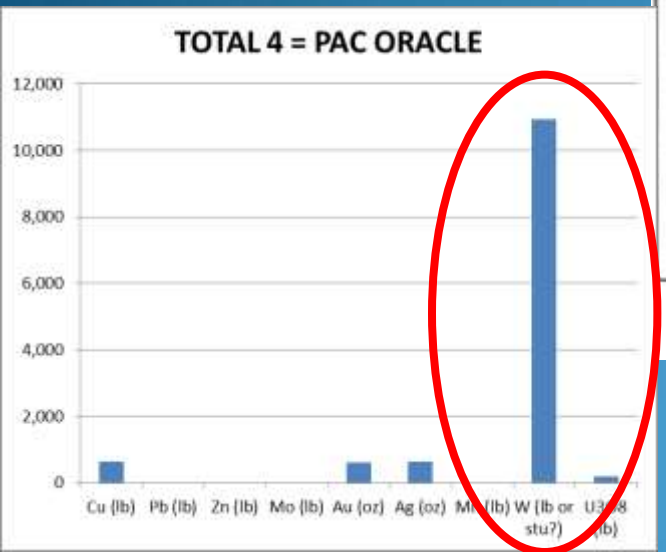


Oracle Orogeny (1.44-1.335 Ga)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
"Oracle/Ruin"		1440-1335	PCA; PAC	Be, Li, Ta-Nb, U & W	White Picacho, Tungstona, Four Peaks

Tungstona district prod.
(unknown dates) =
o lb Cu, Pb, Zn
o oz Au, Ag
>7,449 stu W





Oracle Granite, Santa Catalina Mts.

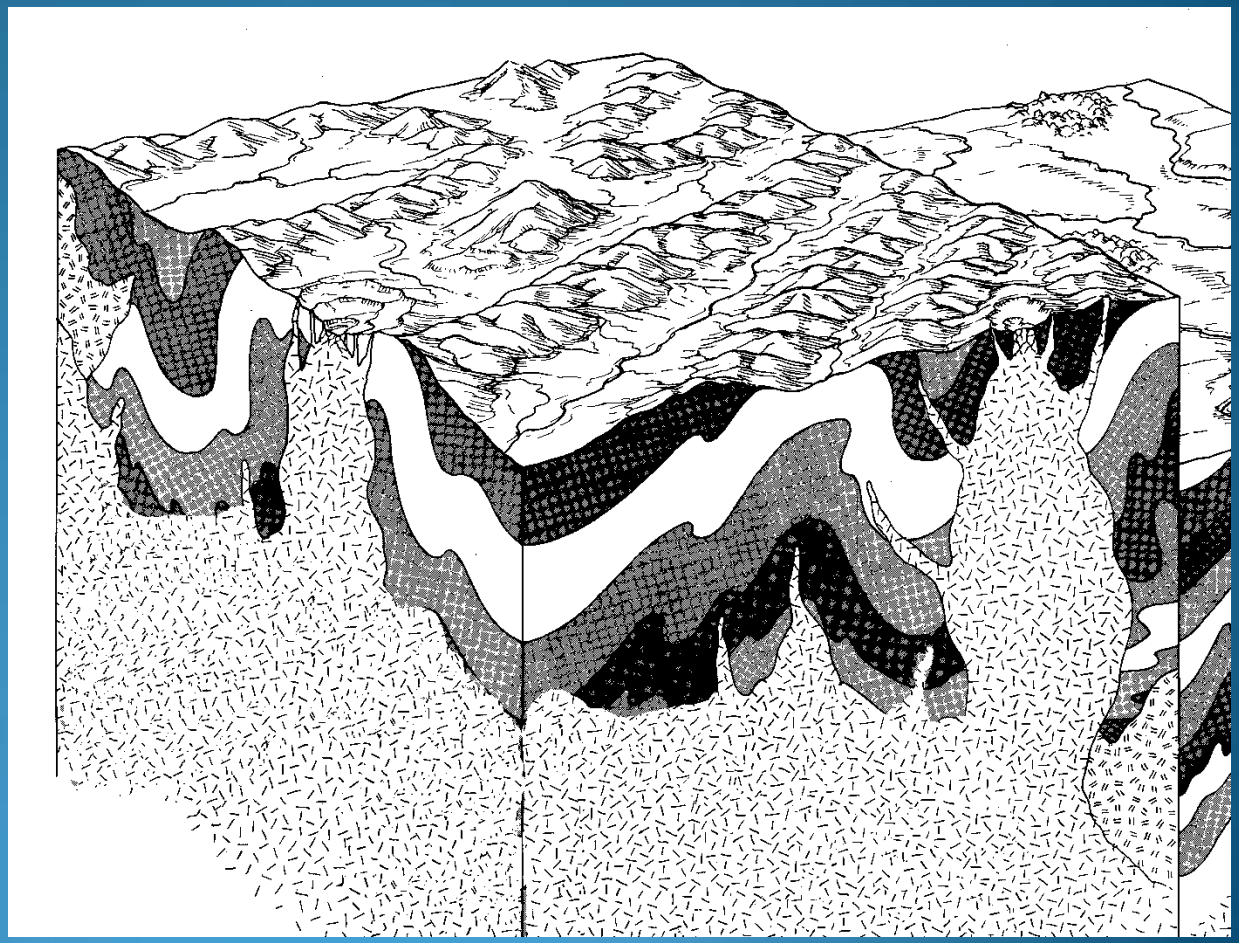
Flattest subduction (PCA, PAC) and crustal melting

Oracle Orogeny (1.44-1.335 Ga)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
"Oracle/Ruin"		1440-1335	PCA; PAC	Be, Li, Ta-Nb, U & W	White Picacho, Tungstona, Four Peaks

Large amounts of the crustal basement in Arizona is Oracle or Ruin granite.

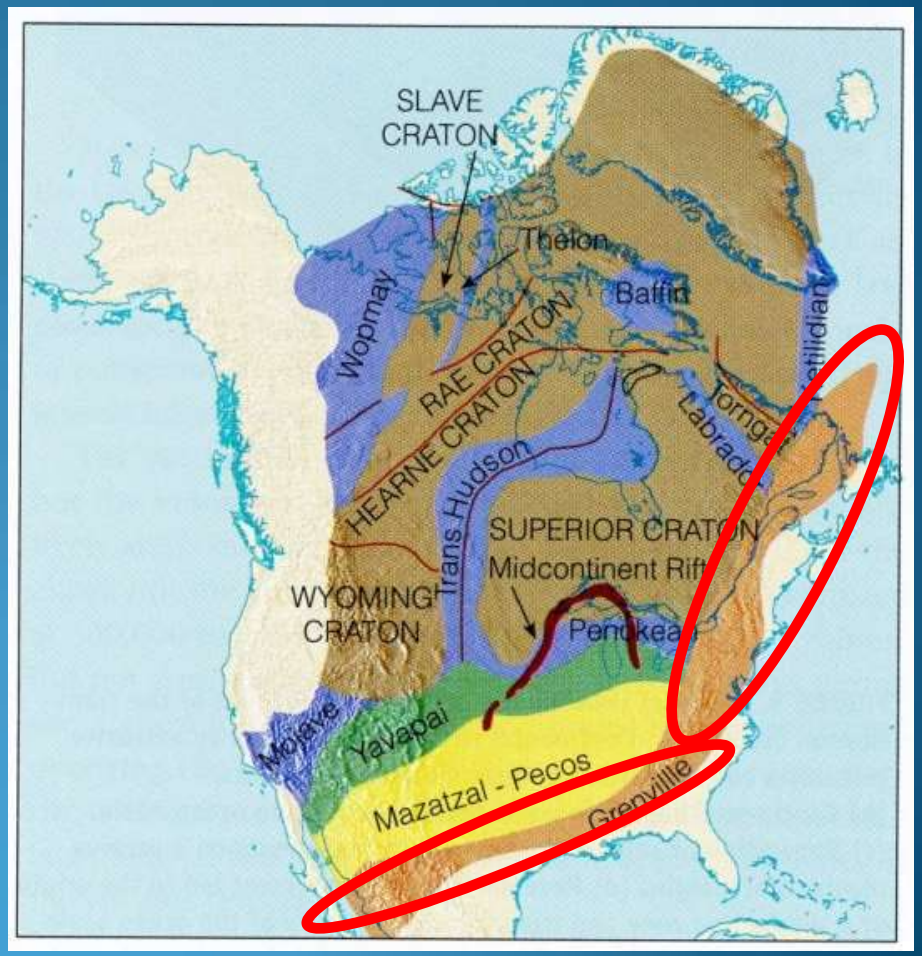
Amethyst, Four Peaks mine, Mazatzal Mts., Maricopa Co.



Grenville Orogeny (1200-900 Ma)

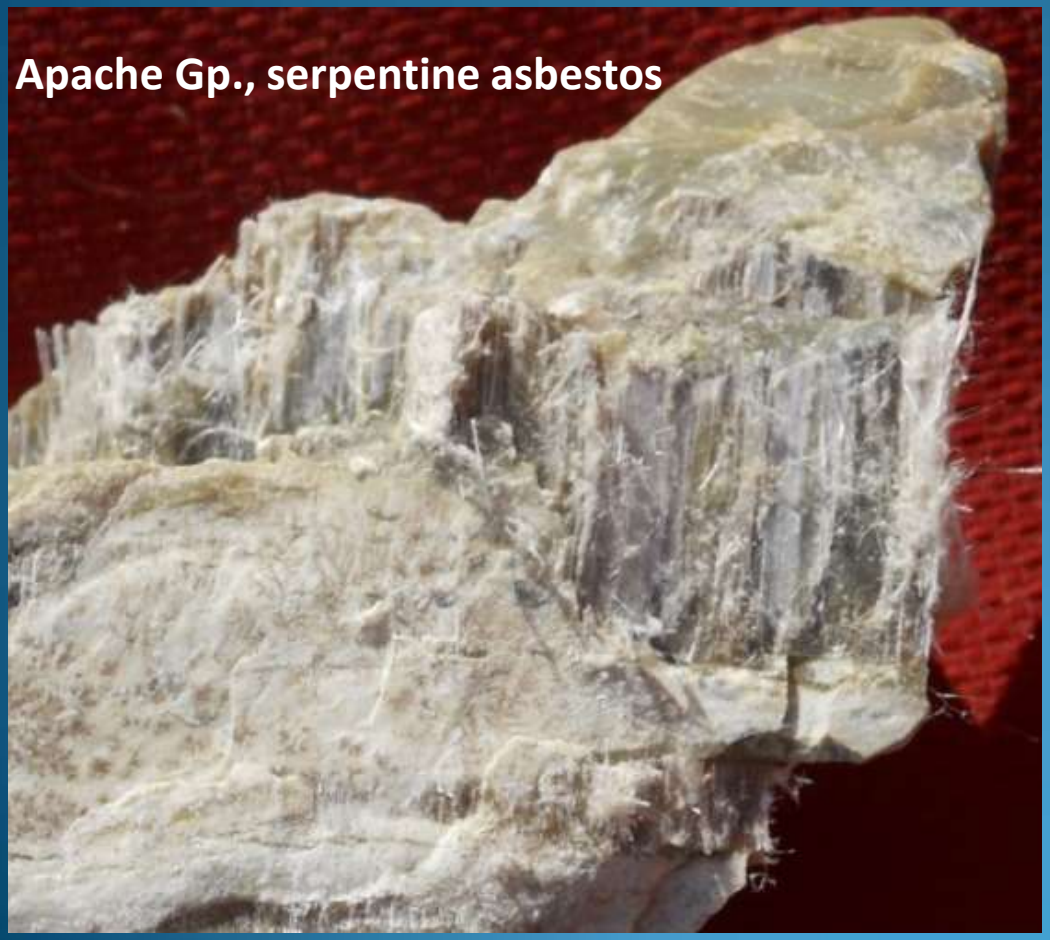
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Grenville		1200-900	MQA	Serpentine asbestos, U, (Cu)	Sierra Ancha U, Chrysotile (Salt R. Canyon)

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



Grenville Orogeny (1200-900 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Grenville		1200-900	MQA	Serpentine asbestos, U, (Cu)	Sierra Ancha U, Chrysotile (Salt R. Canyon)

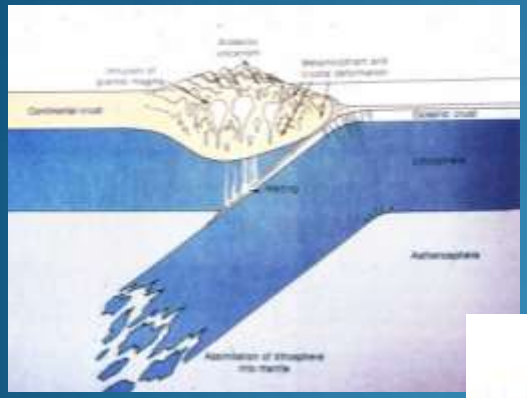


Diabase in Apache Gp., Tohono Chul Park, Tucson

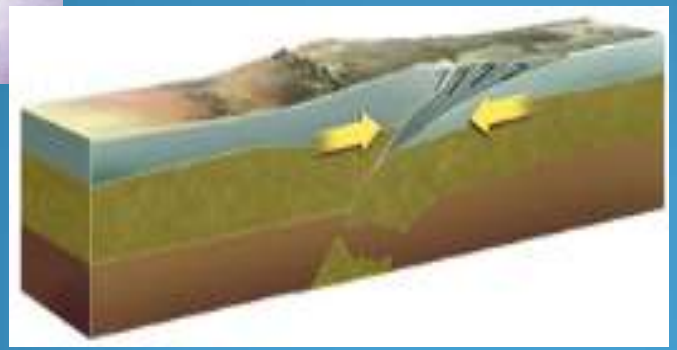
Diabase in contact with Mescal Limestone made marble and serpentine asbestos

Paleozoic Orogenies in eastern U.S.

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Alleghenian (Ouachita)		325-252	-	U, NaCl, K_2CO_3	Payson uranium, Holbrook salt, potash
Lull between Acadian & Alleghenian		355-330		Limestone	Redwall Ls., Escabrosa Ls.
Acadian/ Caledonian/ Antler (NV)		410-370	-	UltraDeep Hydrocarbon?	Percha black shale
Taconic.		460-430	-		Hosts for later replacement

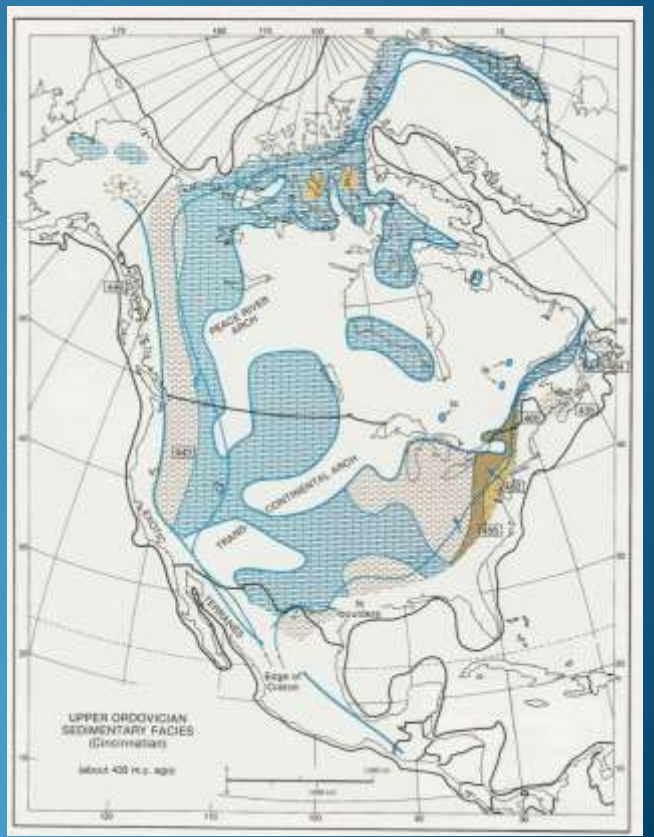


Arizona was on the western, trailing edge of North America



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

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

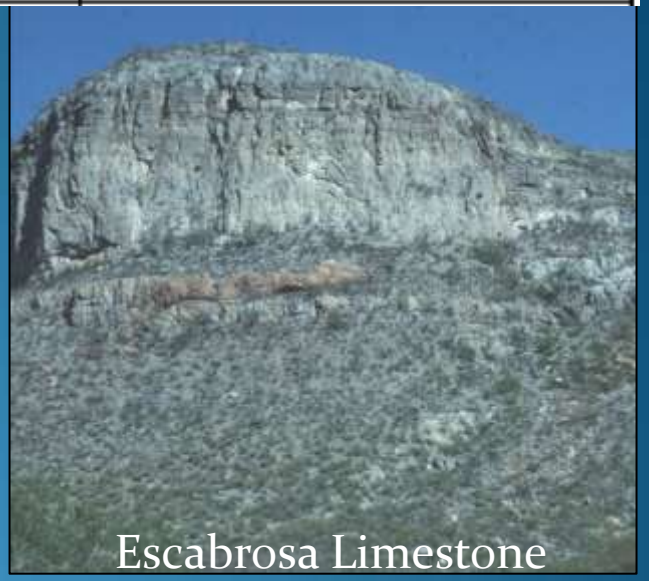


Lull - Mississippian Limestones in Arizona

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

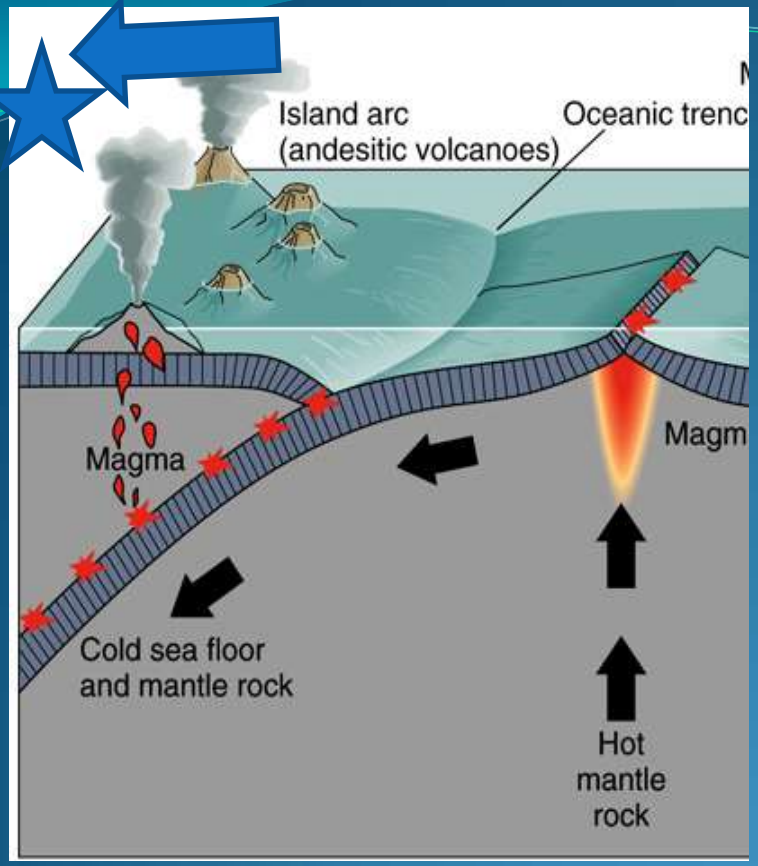


Escabrosa Limestone

Clarkdale Cement plant

Sahuarita Marble

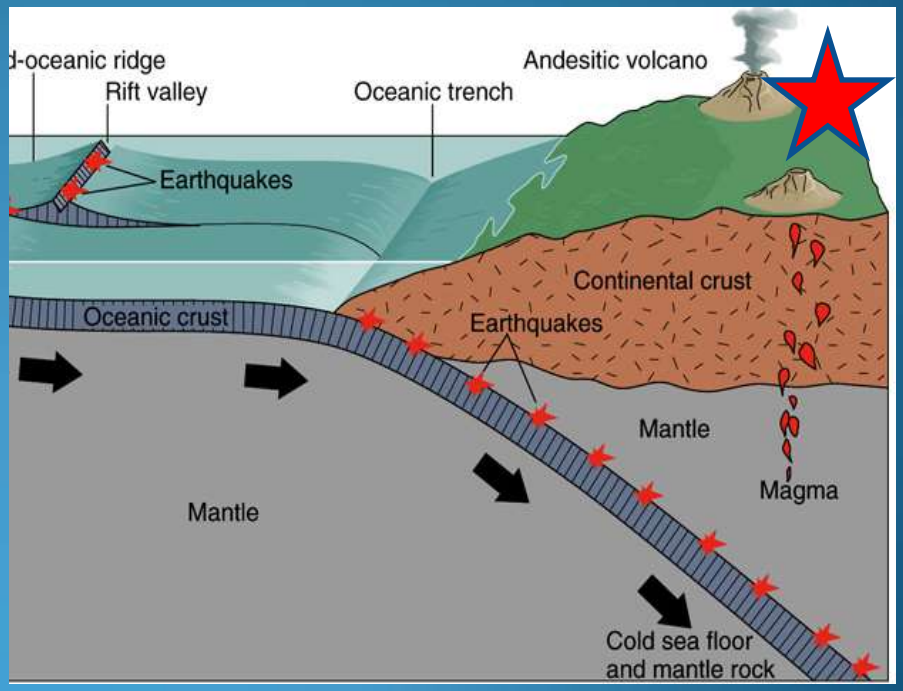
Arizona's position switched with respect to plate tectonics after Paleozoic



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

Big changes at 252 Ma

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



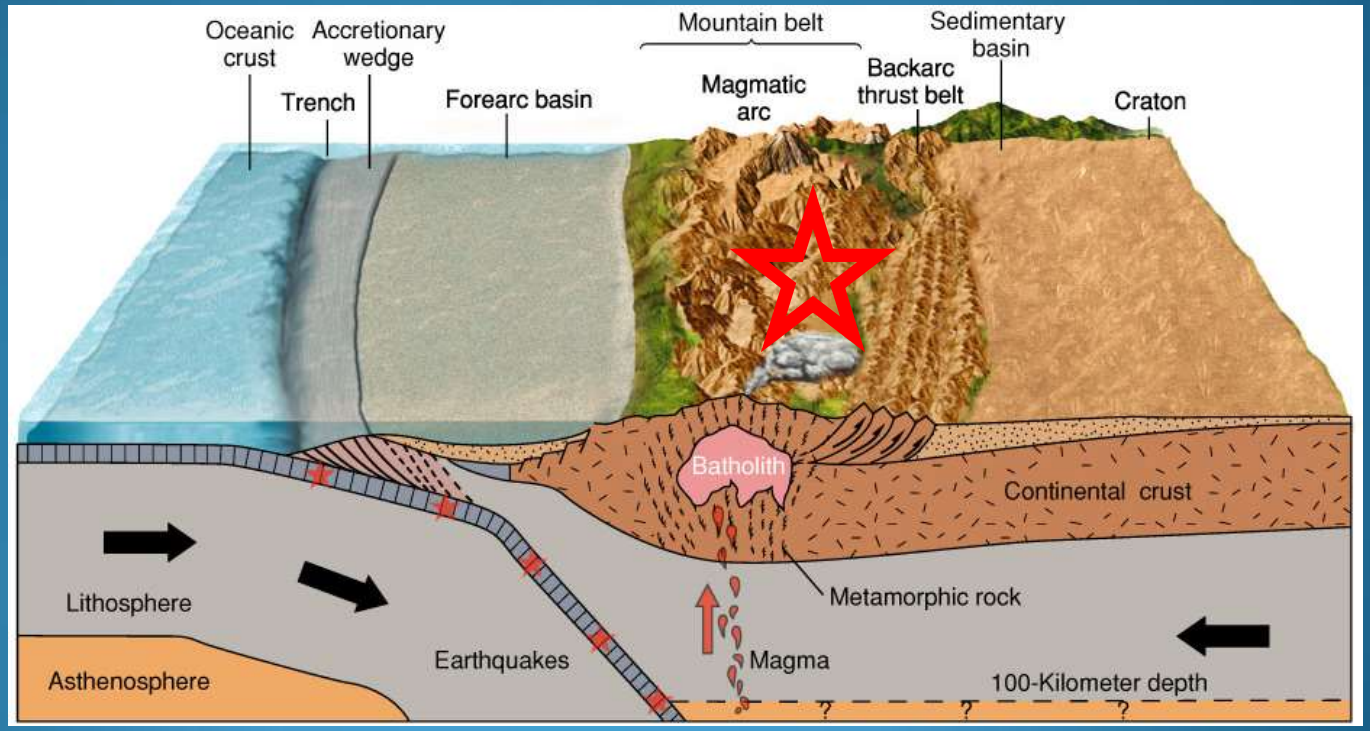
Cordilleran magmatism & resources

Cordilleran Orogeny (200 – 15 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Galiuro	Late (Whipple)	18-13	MQA	Au-Ag (Cu) F, U, Mn	Oatman, Mammoth, Rowley, Tiger
	Middle (Datil)	28-18	MAC	Pb-Zn-Ag F	Silver (Red Cloud), Castle Dome, Stanley, Aravaipa
	Early (South Mountain	30-22	MCA	Au +/- (Cu, W)	Little Harquahala, Kofa
	Earliest (Mineta)	38-28	-	U, clay, exotic Cu	Ajo Cornelia, Copper Butte (from Ray)
Laramide	Late (Wilderness)	55-43	PC; PCA	Au, W (Be)	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin
	Middle (Morenci)	65-55	MCA	porphyry Cu-Mo-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior
	Early (Tomb-stone)	85-65	MAC	Pb-Zn-Ag	Tombstone, Tyndall (Glove), Washington Camp, Salero
	Earliest (Hillsboro)	89-85	MQA	Cu-Au-Ag (Pb, Zn)	Hillsboro, NM
Sevier		145-89	-	Bisbee Group sedimentary rocks (113-100 Ma)	Limestone (Paul Spur near Bisbee)
	Latest	155-145	MCA	Not yet recognized in AZ	Yerington, NV
Nevadan	Late	170-155	MAC	Pb-Zn-Ag	Turquoise (Gleeson)
	Middle	205-180	MQA	porphyry Cu-Au	Warren (Bisbee mine), Turquoise (Courtland), Yuma King
	Early	230-205	MQA	U, V, Cu	Orphan, Grandview, Monument Valley

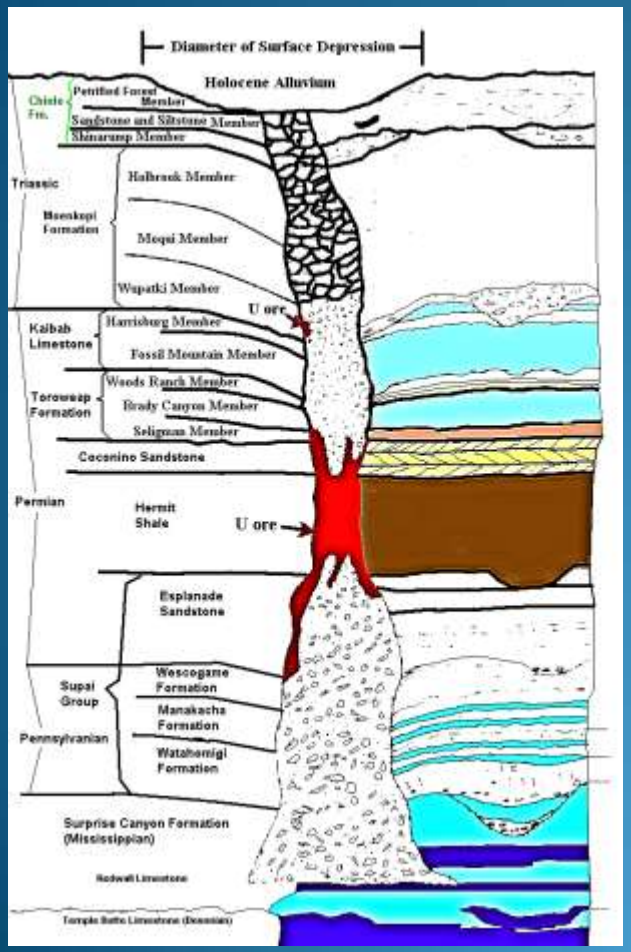
Nevadan Orogeny (230-145 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Latest	155-145	MCA	Not yet recognized in AZ	Yerington, NV
Nevadan	Late	170-155	MAC	Pb-Zn-Ag	Turquoise (Gleeson)
	Middle	205-180	MQA	porphyry Cu-Au	Warren (Bisbee mine), Turquoise (Courtland), Yuma King
	Early	230-205	MQA	U, V, Cu	Orphan, Grandview, Monument Valley



Early Nevadan (Triassic - 250-200 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Early	230-205	MQA	U, V, Cu	Orphan, Grandview, Monument Valley



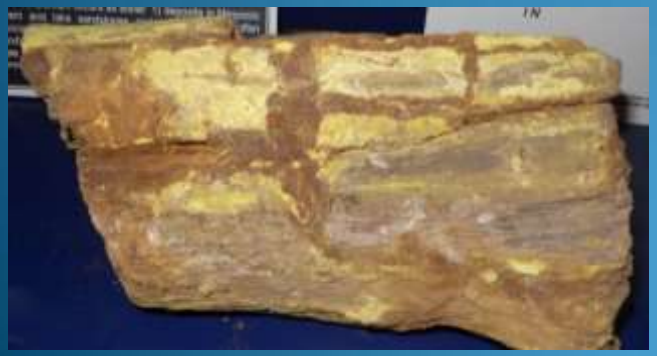
Source: K. Wenrich

Breccia pipe in Grand Canyon

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

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Early	230-205	MQA	U, V, Cu	Orphan, Grandview, Monument Valley

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



Carnotite in petrified wood, Coconino Co.
AzMMM specimen

Orphan district prod. (1951-1961) =
4,534,000 lb Cu
7,000 lb Pb
600 lb Zn
<10 oz Au
80,000 oz. Ag
4,360,000 lb U

Middle Nevadan - Warren m.d. (Bisbee)

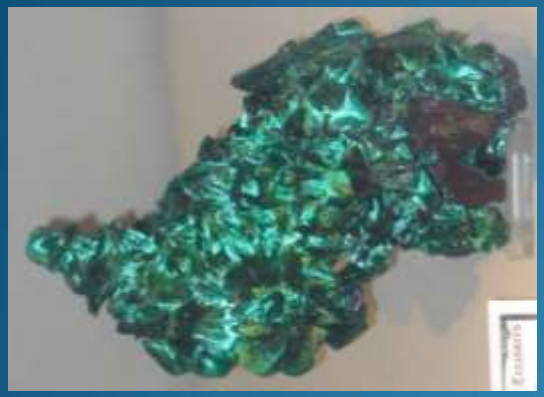
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Nevadan	Middle	205-180	MQA	porphyry Cu-Au	Warren (Bisbee mine), Turquoise (Courtland), Yuma King

Campbell shaft

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

Warren district (Bisbee) azurite

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Nevadan	Middle	205-180	MQA	porphyry Cu-Au	Warren (Bisbee mine), Turquoise (Courtland), Yuma King



Bisbee azurite, malachite, turquoise, chalcocite, cuprite

Warren district production (1880-1981) =

7,865,827,000 lb Cu

324,255,000 lb Pb

355,048,000 lb Zn

2,792,000 oz Au

102,215,000 oz. Ag

28,000,000 lb Mn

Source: Keith, et al., 1983

cuprite

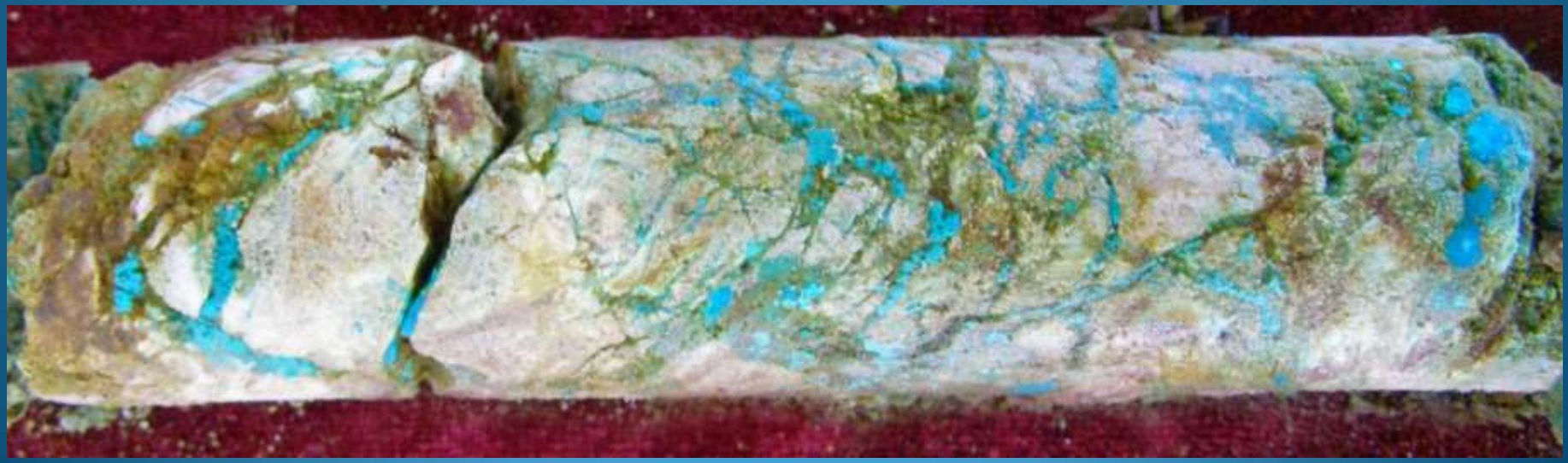
Jurassic mineralization - Western Arizona

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Nevadan	Middle	205-180	MQA	porphyry Cu-Au	Warren (Bisbee mine), Turquoise (Courtland), Yuma King

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

Quartz Monzonite - Re-Os on molybdenite – 190 Ma (date from Anglo-American - Keith pers. comm.)

Yuma King



Spiderweb Turquoise

Turquoise district – Courtland-Gleeson

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Nevadan	Late	170-155	MAC	Pb-Zn-Ag	Turquoise (Gleeson)
	Middle	205-180	MQA	porphyry Cu-Au	Warren (Bisbee mine), Turquoise (Courtland), Yuma King

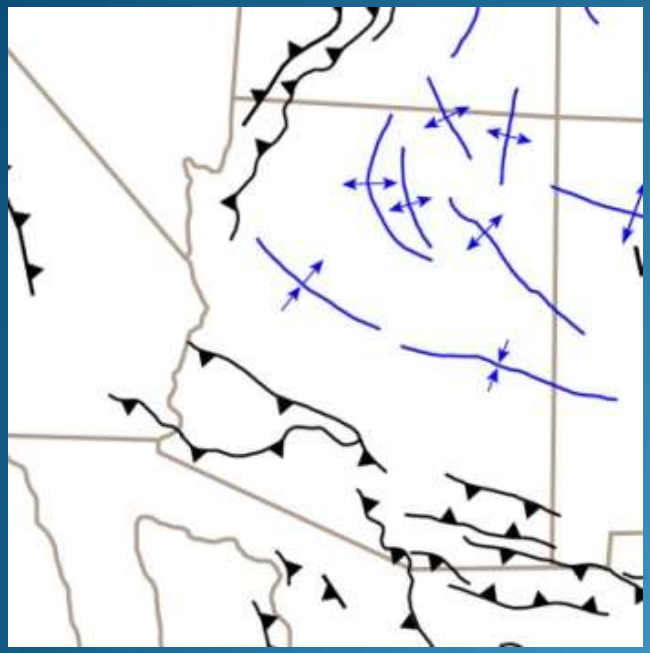
Silver Bill mine, wulfenite

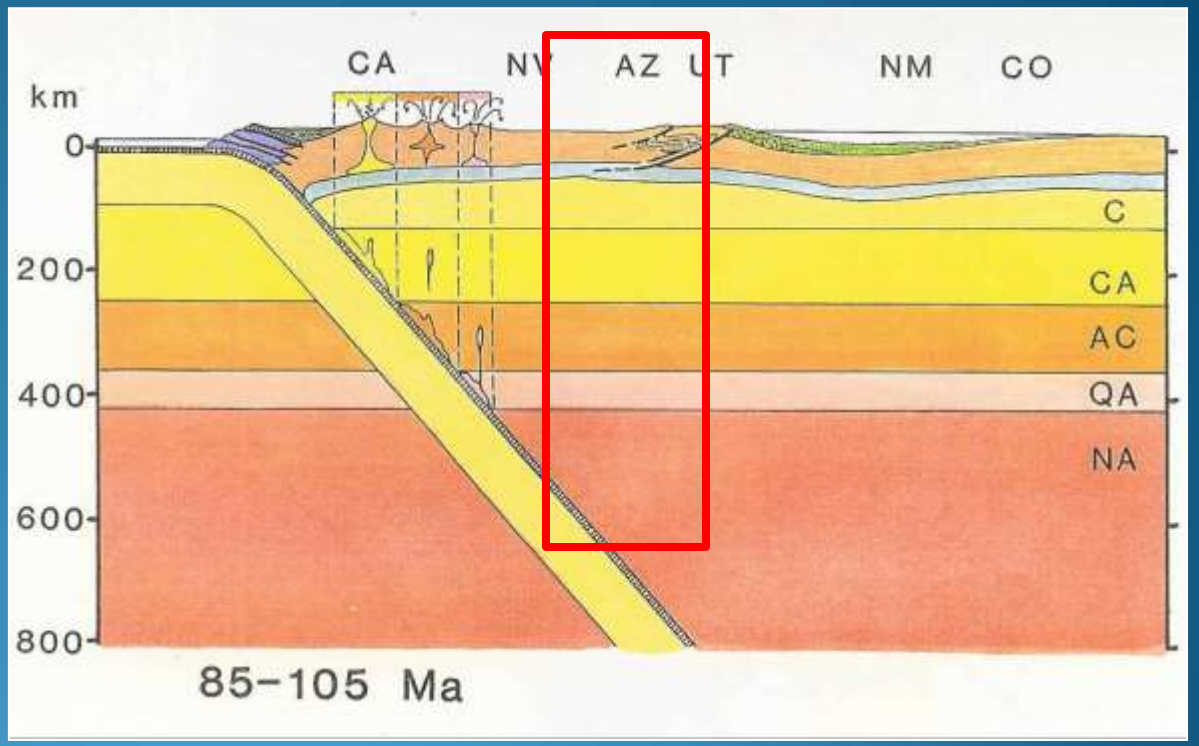
Defiance mine, wulfenite, Donor: Les Presmyk

Courtland area = 180-190 Ma - possible Quartz alkalic;
Gleeson Qtz Monz. Ridge = 165-170 Ma - probable Alkali-calcic

Sevier orogeny - alkalinity zones - 105-85 Ma

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Sevier		145-89	-	Bisbee Group sedimentary rocks (113-100 Ma)	Limestone (Paul Spur near Bisbee)





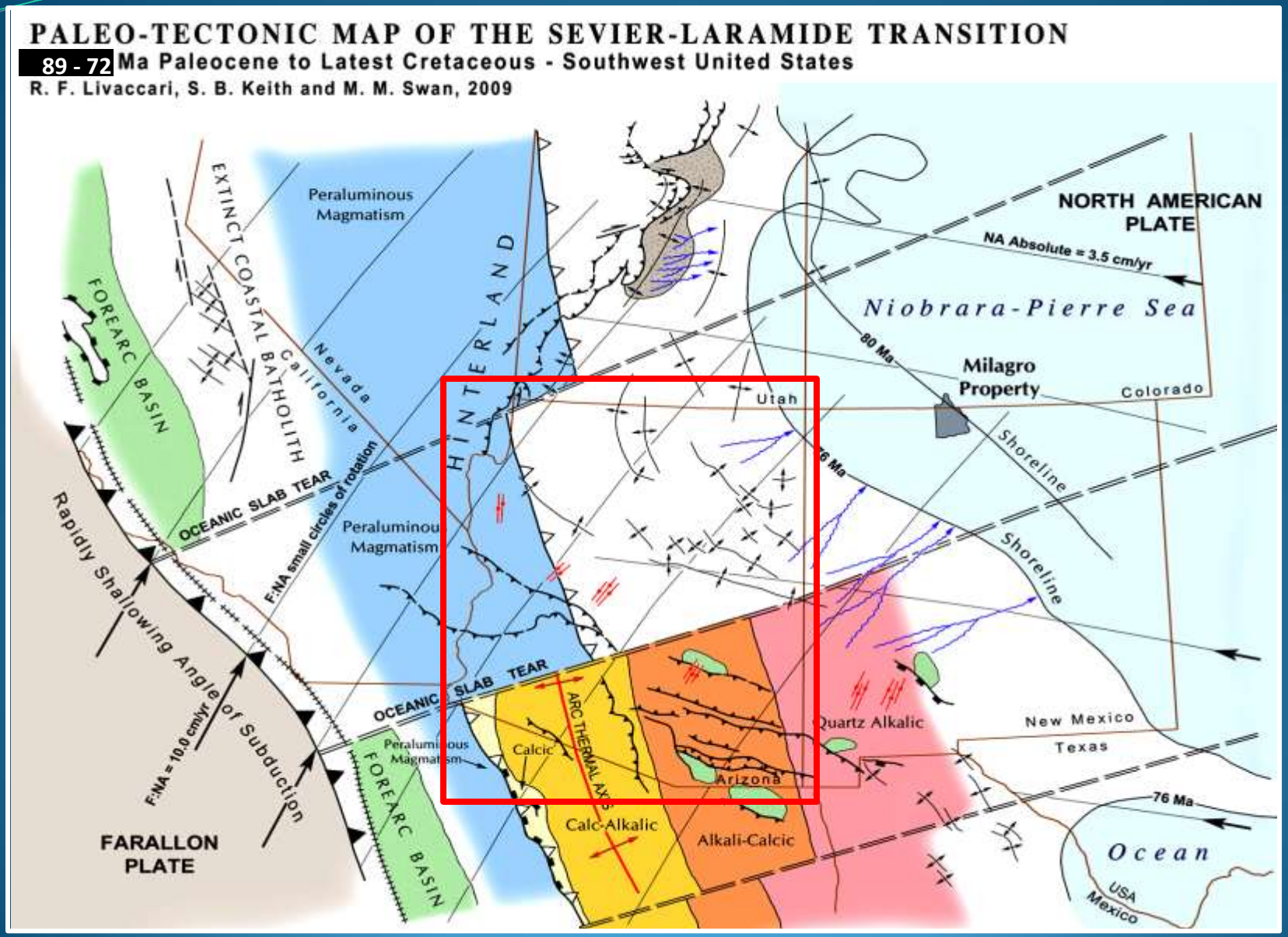
Sevier orogeny = constant dip subduction; most magmatic activity was in California.
Arizona was undergoing erosion, folding and thrust faulting.

Sevier sedimentation, faults (145-89 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Sevier		145-89	-	Bisbee Group sedimentary rocks (113-100 Ma)	Limestone (Paul Spur near Bisbee)

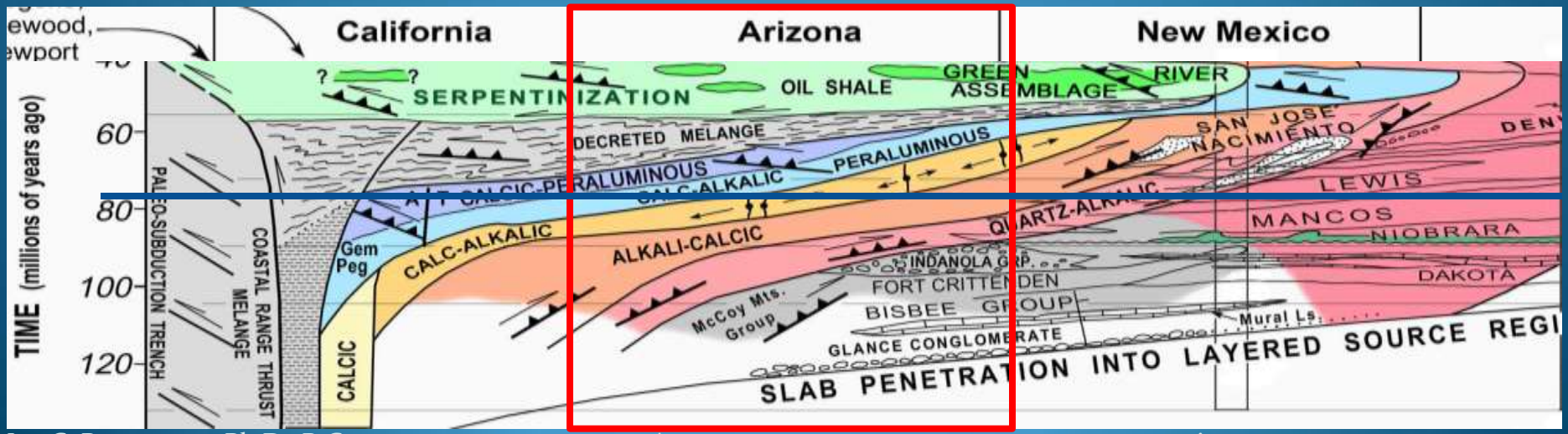
Mural Ls. (Bisbee Group) E. of Bisbee mined at Paul Spur near Douglas

Laramide Orogeny (89-35 Ma)



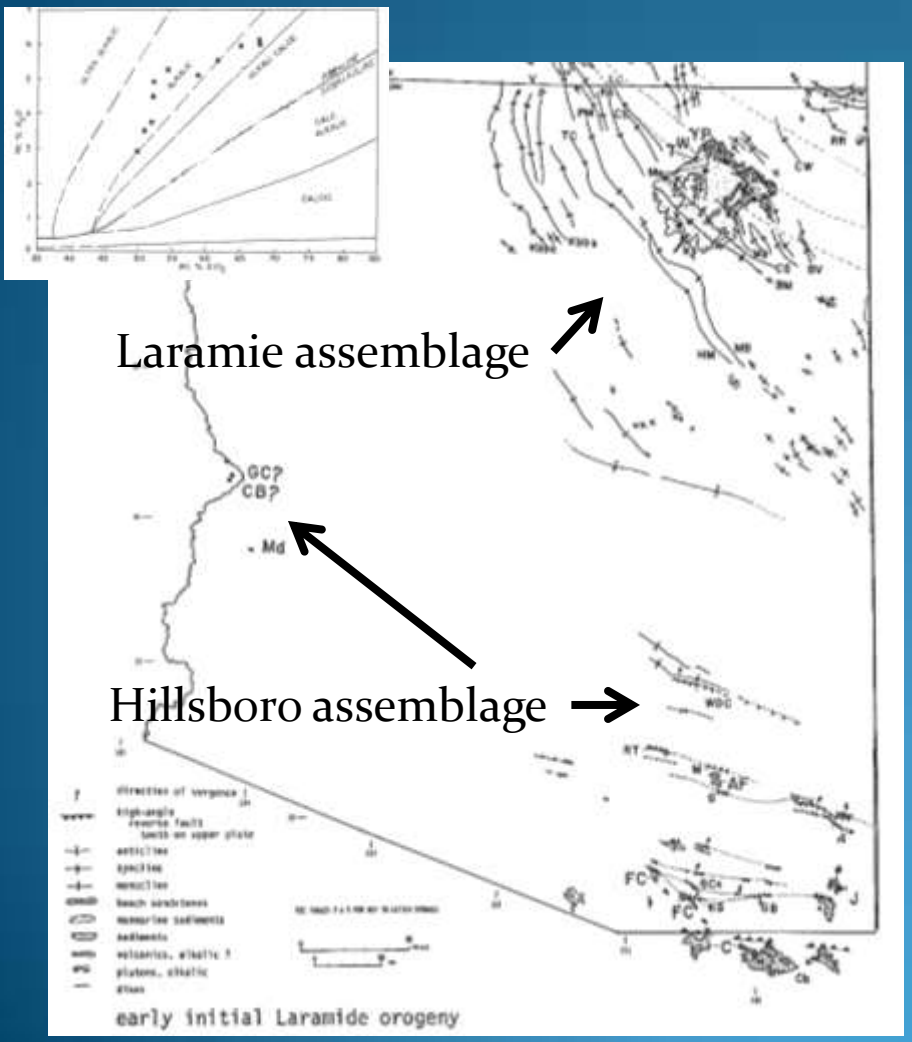
Laramide Orogeny (89-35 Ma)

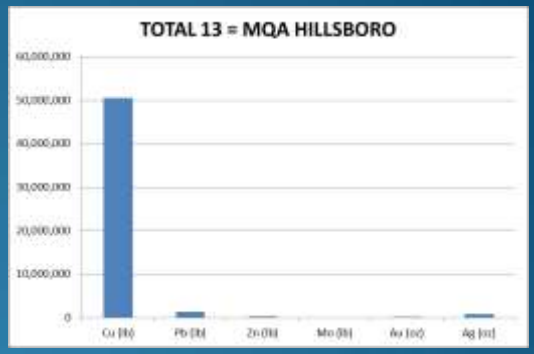
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Laramide	Late (Wilderness)	55-43	PC; PCA	Au, W (Be)	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin
	Middle (Morenci)	65-55	MCA	porphyry Cu-Mo-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior
	Early (Tomb-stone)	85-65	MAC	Pb-Zn-Ag	Tombstone, Tyndall (Glove), Washington Camp, Salero
	Earliest (Hillsboro)	89-85	MQA	Cu-Au-Ag (Pb, Zn)	Hillsboro, NM



Earliest Laramide -Laramie (89-85 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Earliest (Hillsboro)	89-85	MQA	Cu-Au-Ag (Pb, Zn)	Hillsboro, NM





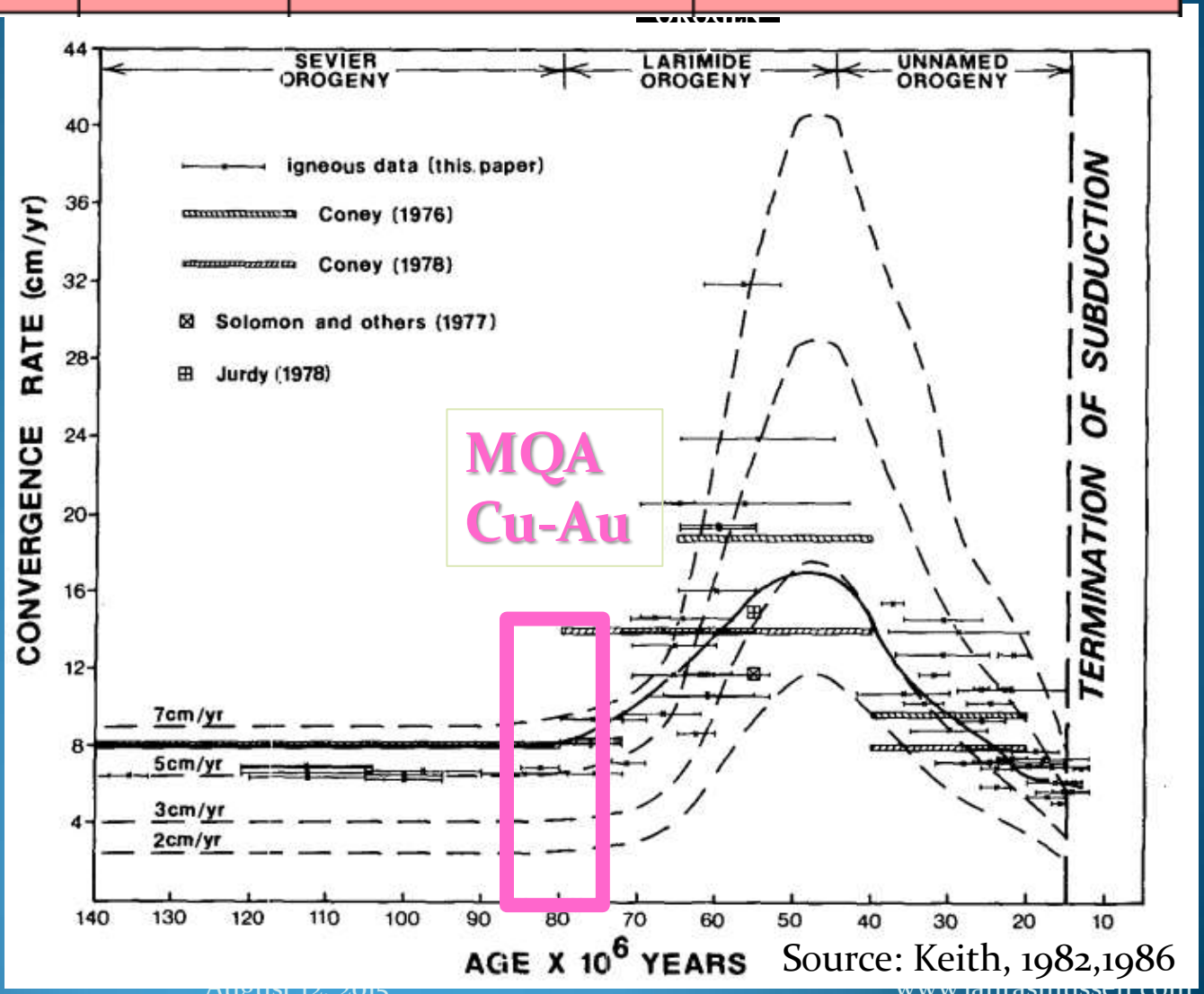
N Arizona – coal in Wepo Fm. at Black Mesa

Photo from Peabody Coal (Freeport-McMoRan)

Earliest Laramide -Hillsboro (89-80 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Earliest (Hillsboro)	89-85	MQA	Cu-Au-Ag (Pb, Zn)	Hillsboro, NM

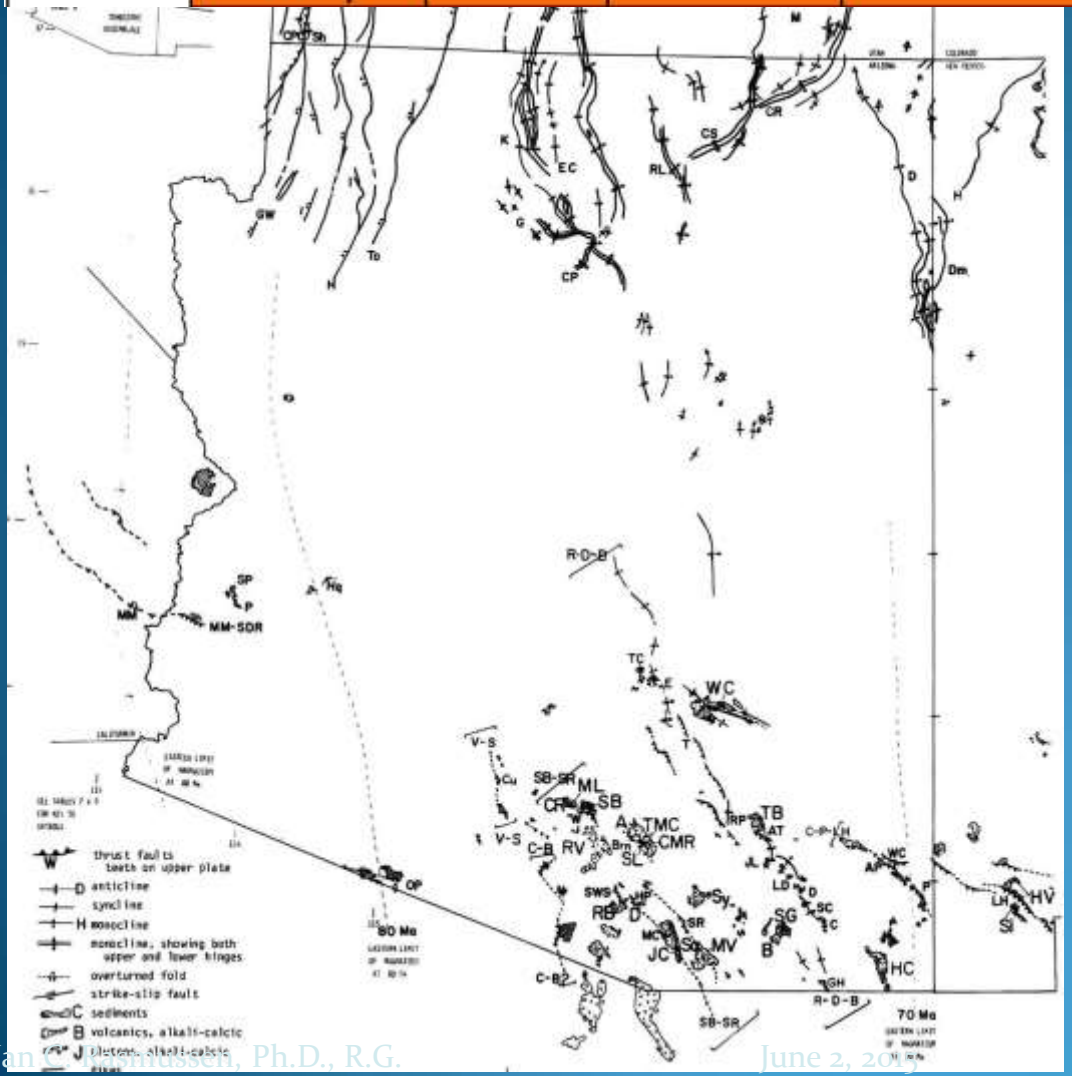
Moderate volumes of metaluminous quartz alkalic monzonitic intrusions (earliest Laramide) are associated with slower convergence rates. initial flattening subduction, local volcanism, and minor copper-silver production

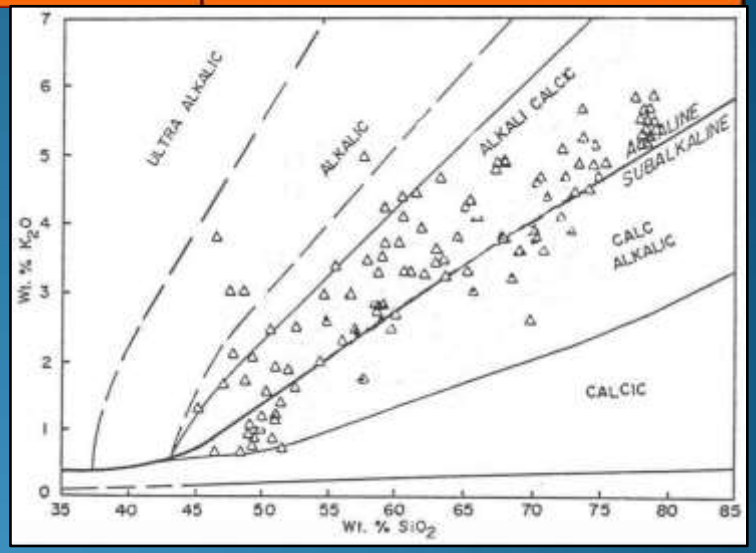


Source: Keith, 1982,1986

Early Laramide (Tombstone) (85-65 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Early (Tomb-stone)	85-65	MAC	Pb-Zn-Ag	Tombstone, Tyndall (Glove), Washington Camp, Salero





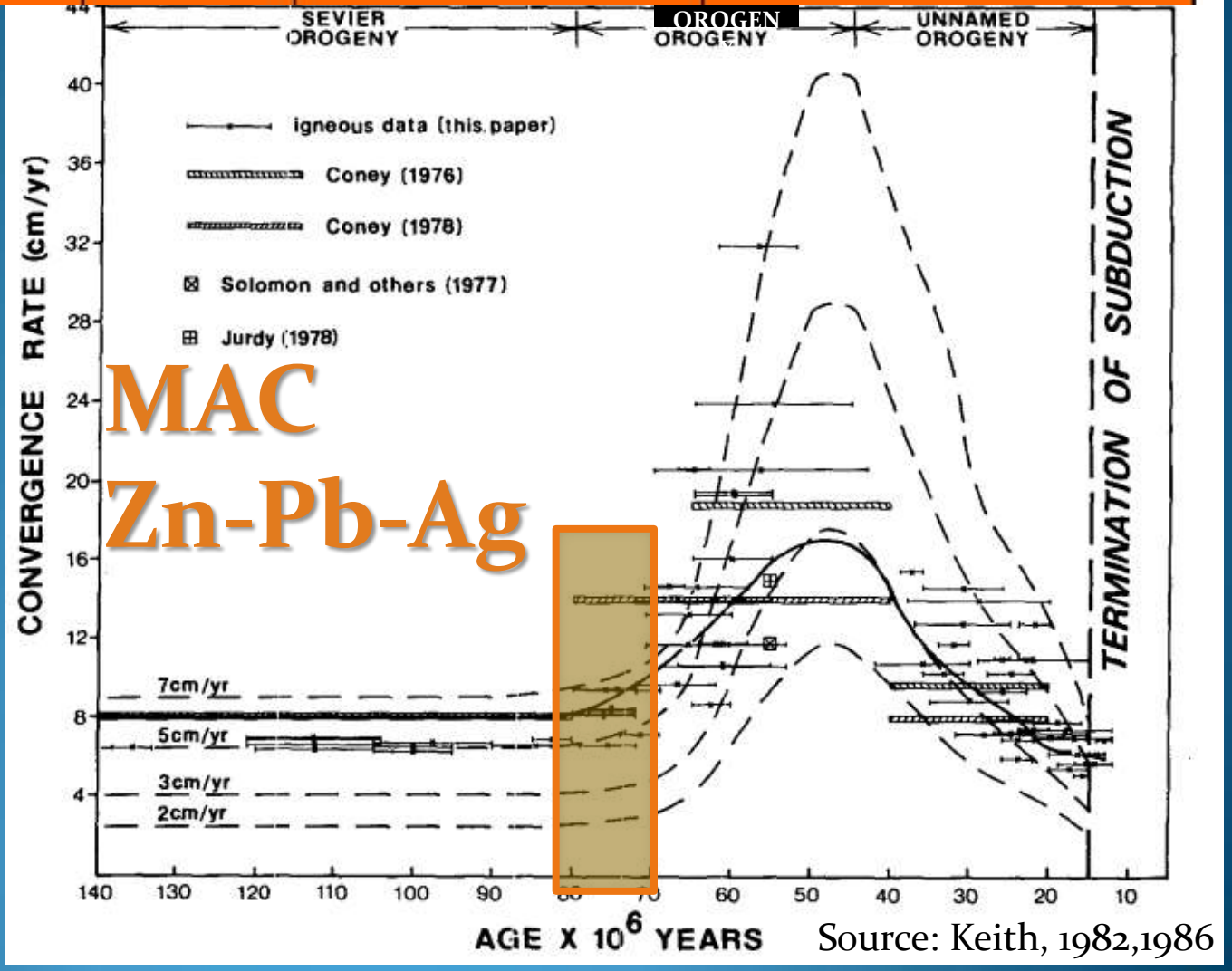
Tombstone assemblage = MAC

- Preceded porphyry Cu by ~10 Ma in each mountain range
- Pb-Zn-Ag mines
- "Barren" 'porphyry Cu' deposits

Early Laramide (Tombstone) (85-65 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Early (Tomb-stone)	85-65	MAC	Pb-Zn-Ag	Tombstone, Tyndall (Glove), Washington Camp, Salero

Moderate volumes of metaluminous alkali-calcic quartz monzonitic intrusions (early Laramide) are associated with slower convergence rates. initial flattening subduction, significant volcanism, and significant zinc-lead silver production



Source: Keith, 1982,1986

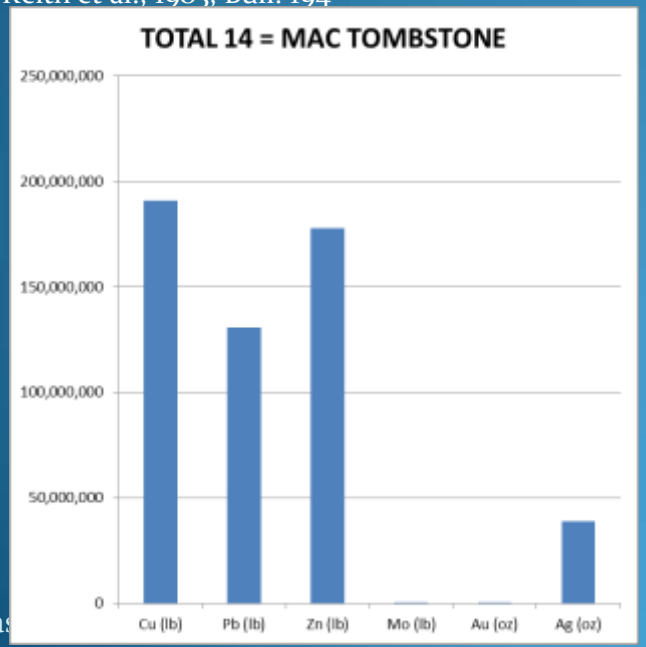
Early Laramide (Tombstone) (85-65 Ma)

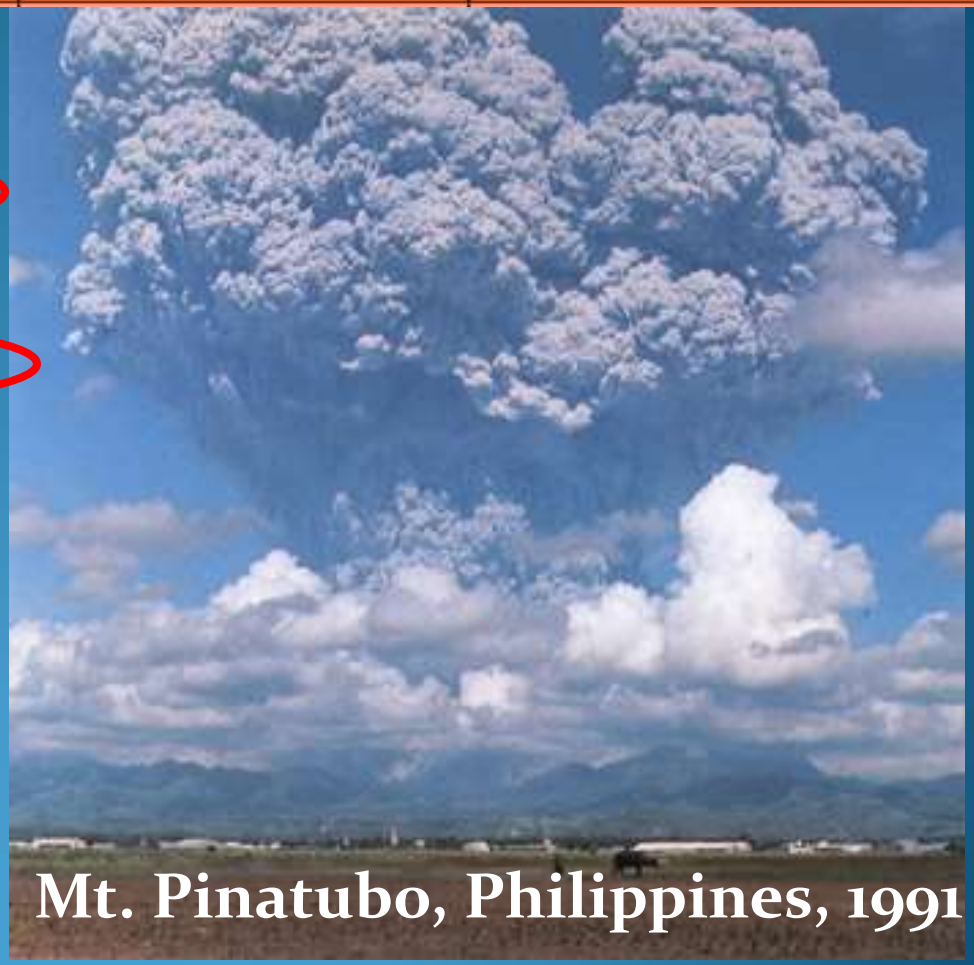
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Early (Tomb-stone)	85-65	MAC	Pb-Zn-Ag	Tombstone, Tyndall (Glove), Washington Camp, Salero

Tombstone dist. prod. (thru 1981) =

7,765,000 lb Cu
48,122,000 lb Pb
652,000 lb Zn
141,600 oz Au
32,083,000 oz Ag

Source: Keith et al., 1983, Bull. 194





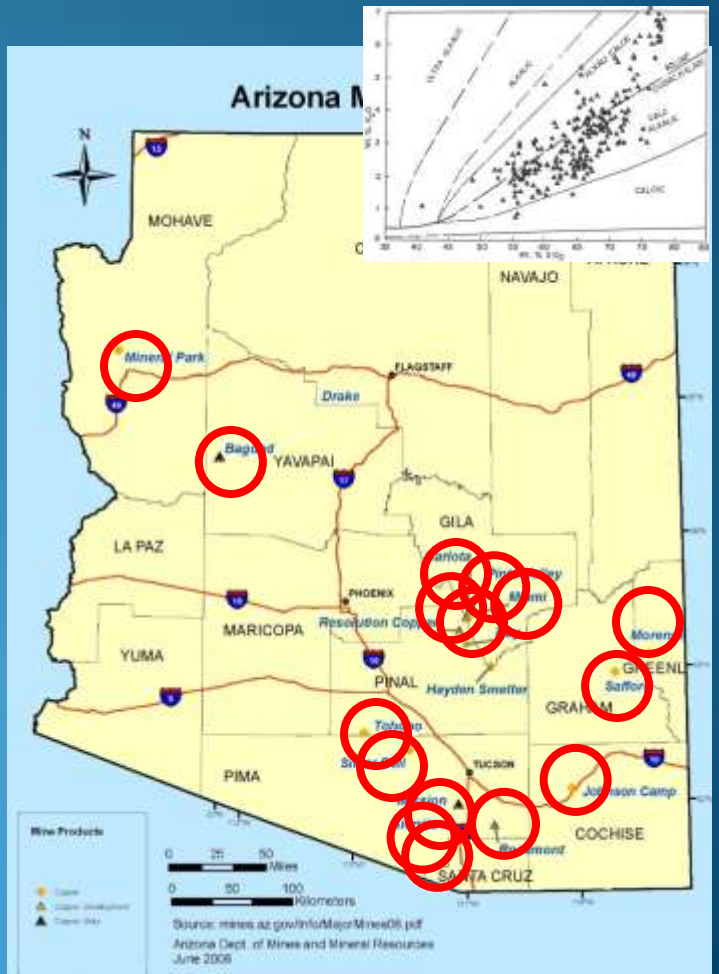
Mt. Pinatubo, Philippines, 1991

MAC = thick ignimbrite (ash) flows

Middle Laramide - Morenci (65-55 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Laramide	Middle (Morenci)	65-55	MCA	porphyry Cu-Mo-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior

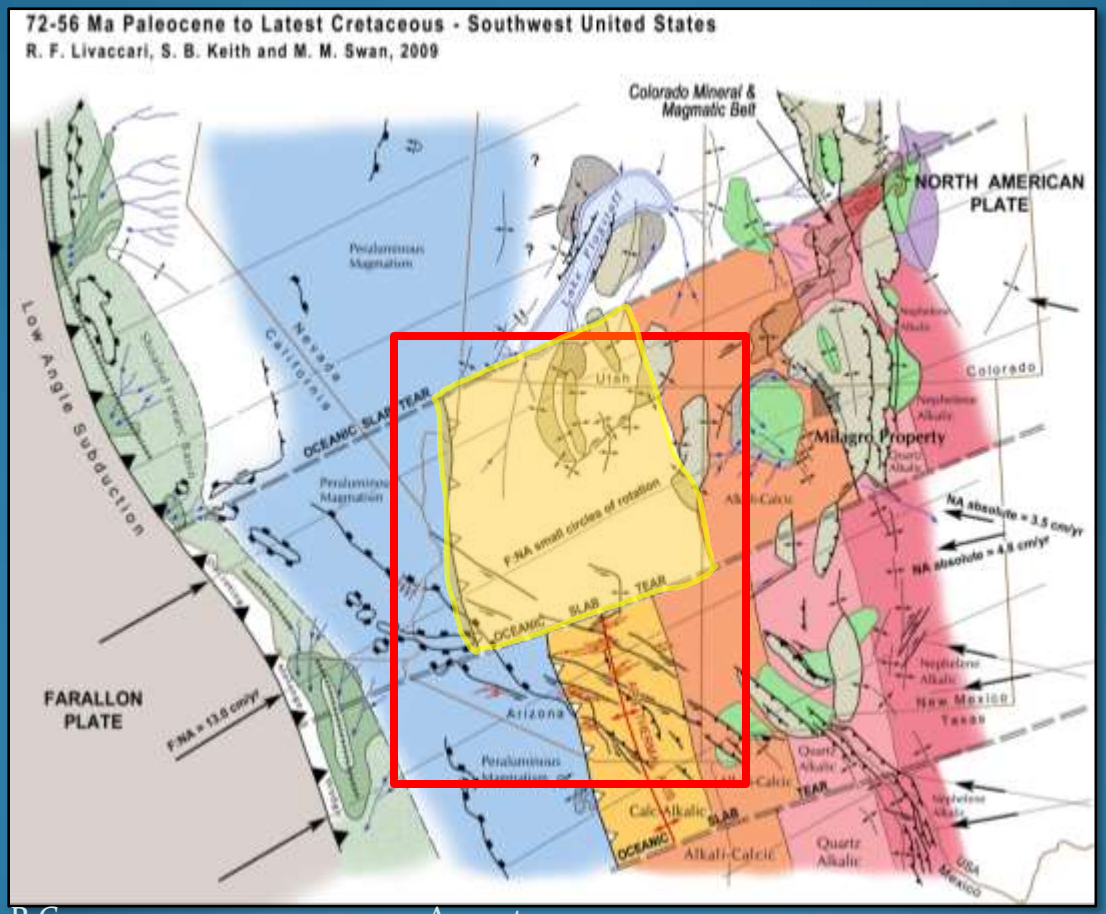
Photo courtesy of ASARCO (Grupo)



Middle Laramide - Morenci (65-55 Ma)

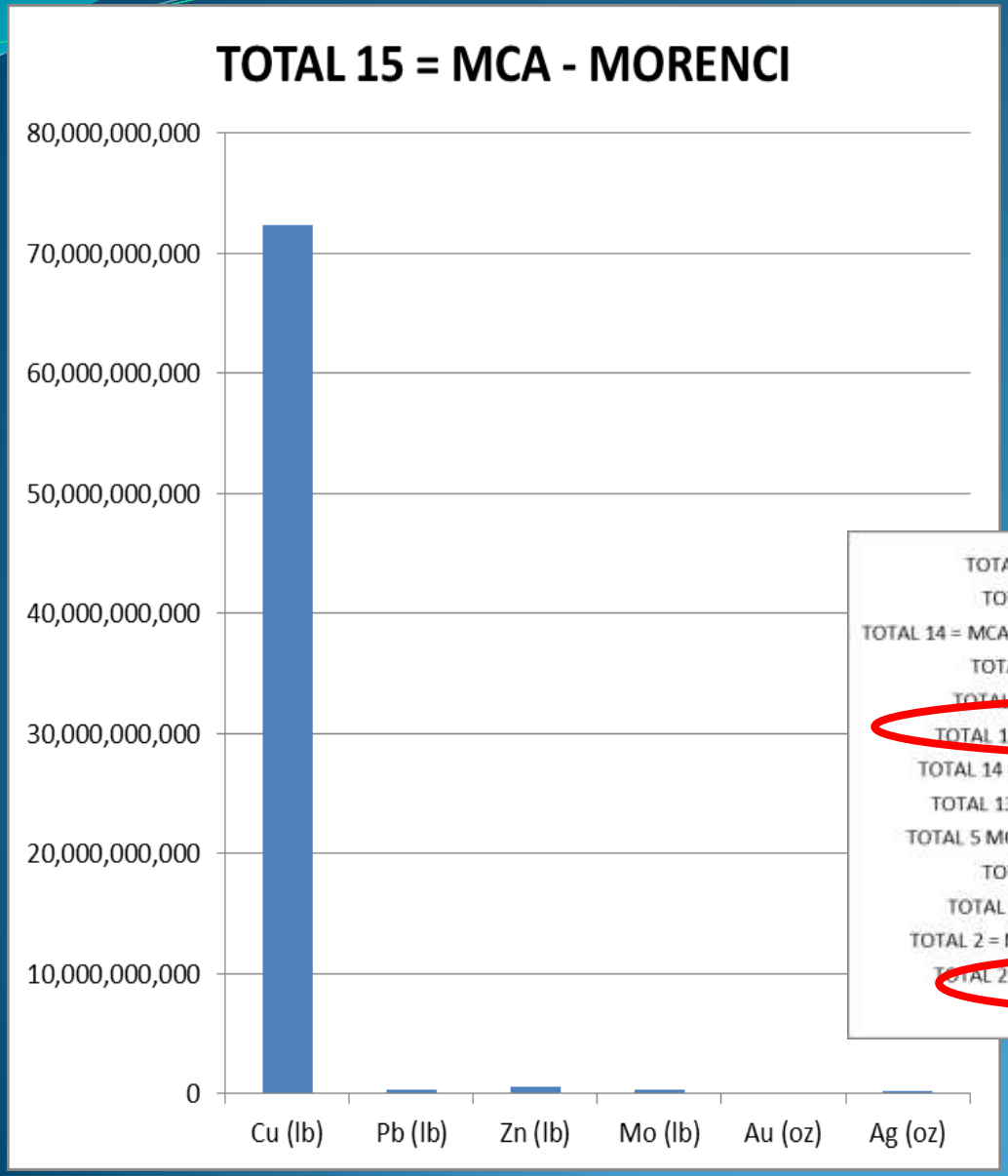
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Laramide	Middle (Morenci)	65-55	MCA	porphyry Cu-Mo-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior

Metaluminous Calc-Alkalic = yellow



72-56 Ma

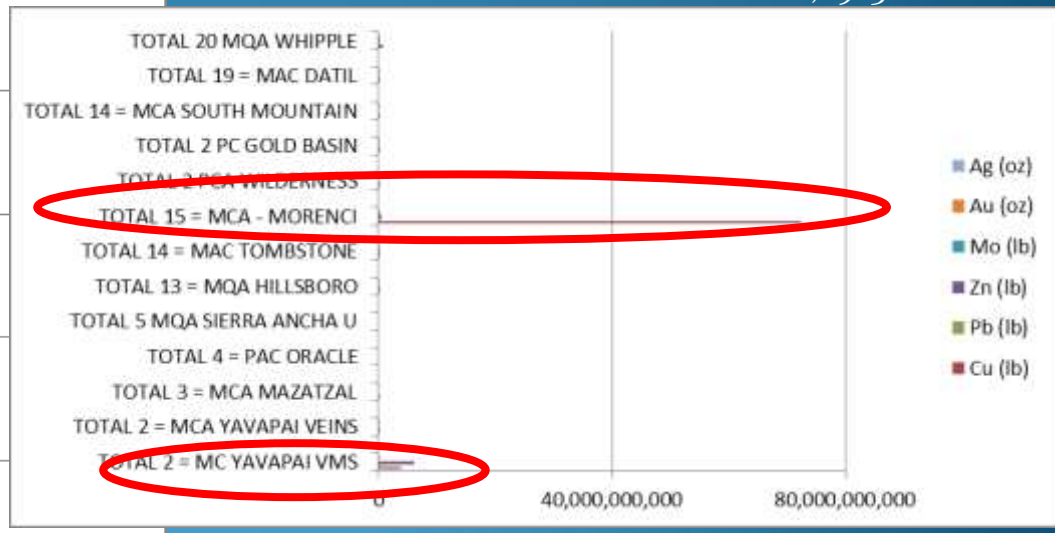
Middle Laramide - Pima district porphyry Cu



Pima dist. prod. (1880 - 1981)
+ much additional ore since Bull. 194 published =

8,359,754,000 lb Cu
75,795,000 lb Pb
132,964,000 lb Zn
26,100 oz Au
56,336,000 oz Ag
290,796 lb Mo

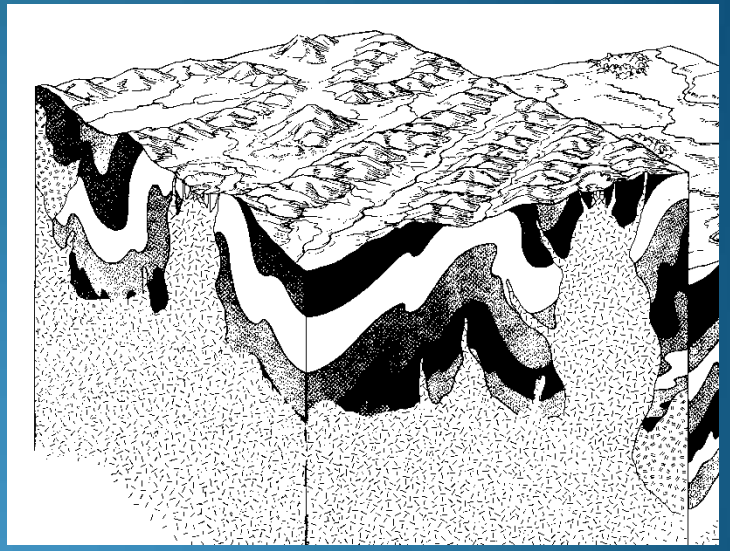
Source: Keith et al, 1983



Middle Laramide – Morenci (65-55 Ma)

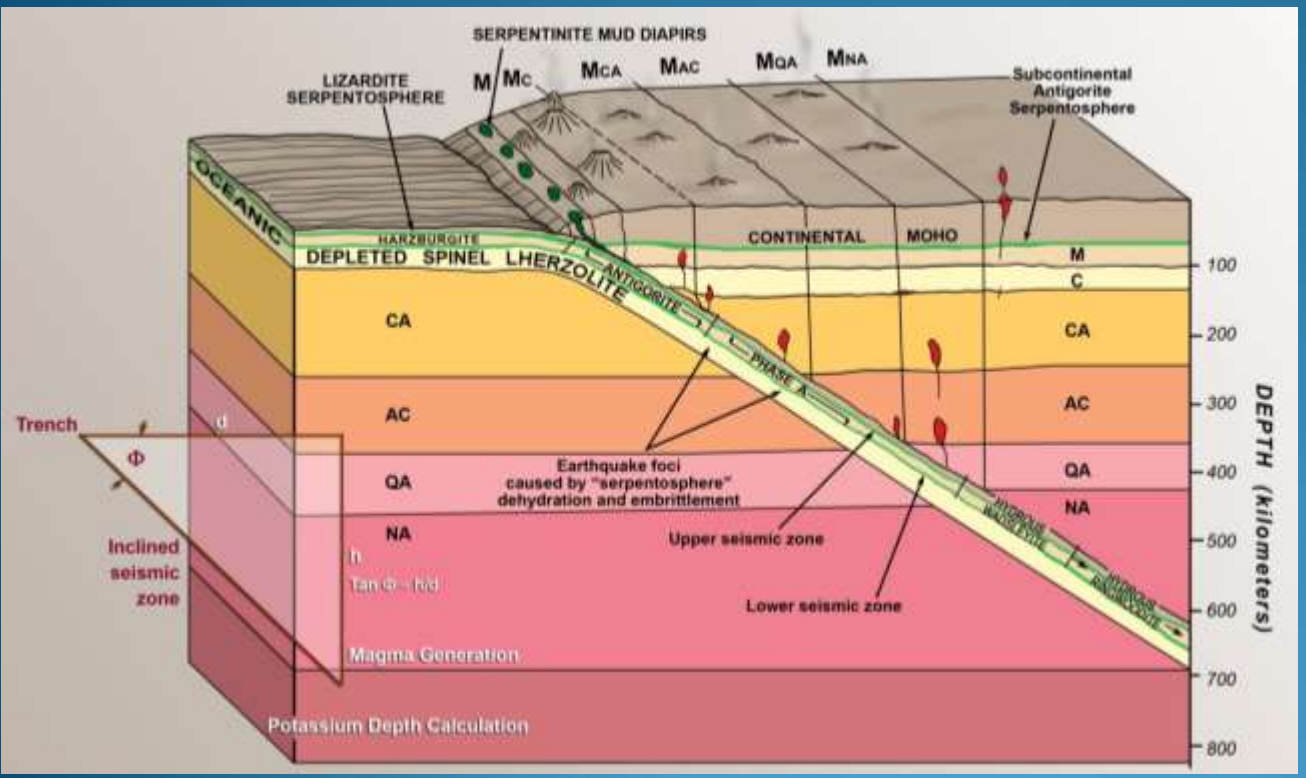
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Laramide	Middle (Morenci)	65-55	MCA	porphyry Cu-Mo-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior

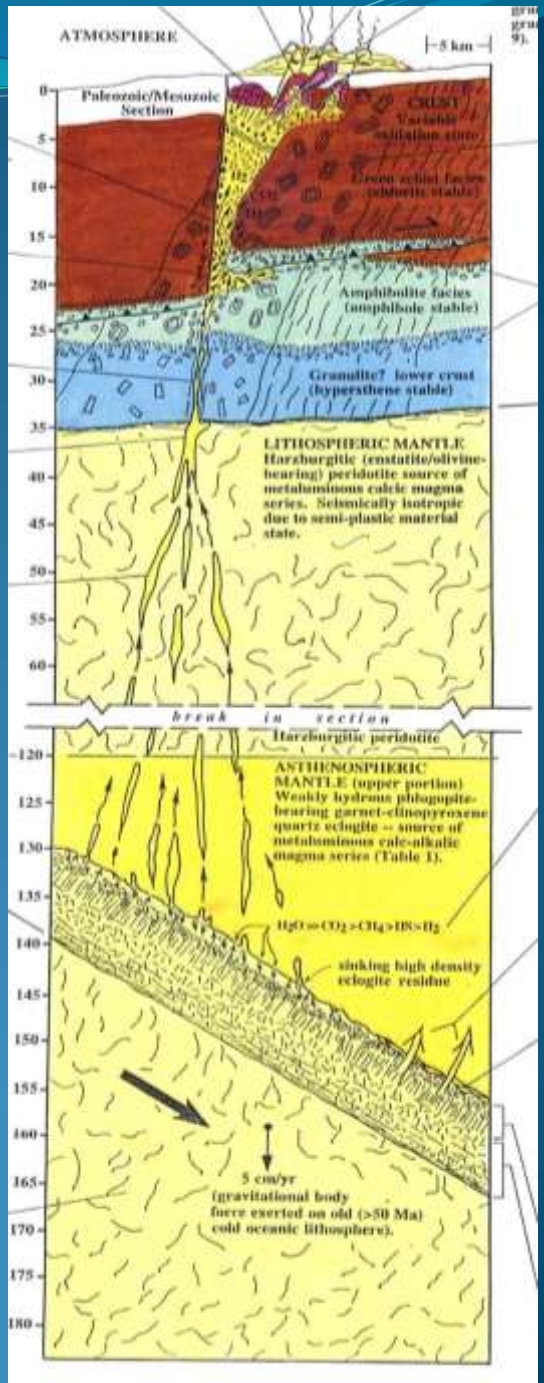
Large volumes of Oracle Granite probably occupy most of the deeper crust in the Tucson region.
The Oracle Granite has a metal signature of W and Be.



The Laramide porphyry copper deposits do not have the same W and Be characteristics as the Oracle.
It is difficult to get Cu by flushing or melting Oracle Granite.

A more favored explanation is a mantle source for the copper.

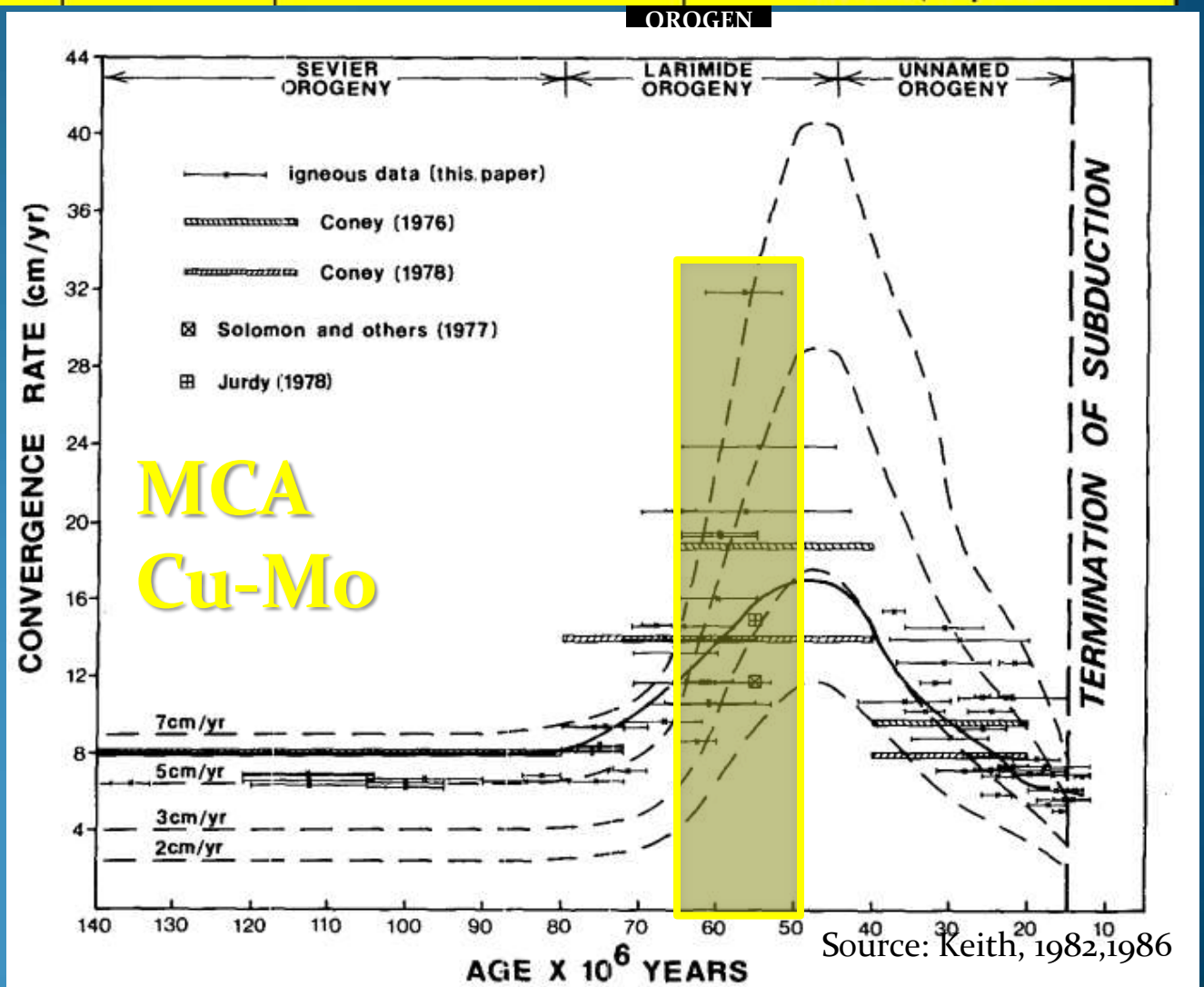




Middle Laramide – Morenci (65-55 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Laramide	Middle (Morenci)	65-55	MCA	porphyry Cu-Mo-Ag	Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe-Miami, Morenci, Superior

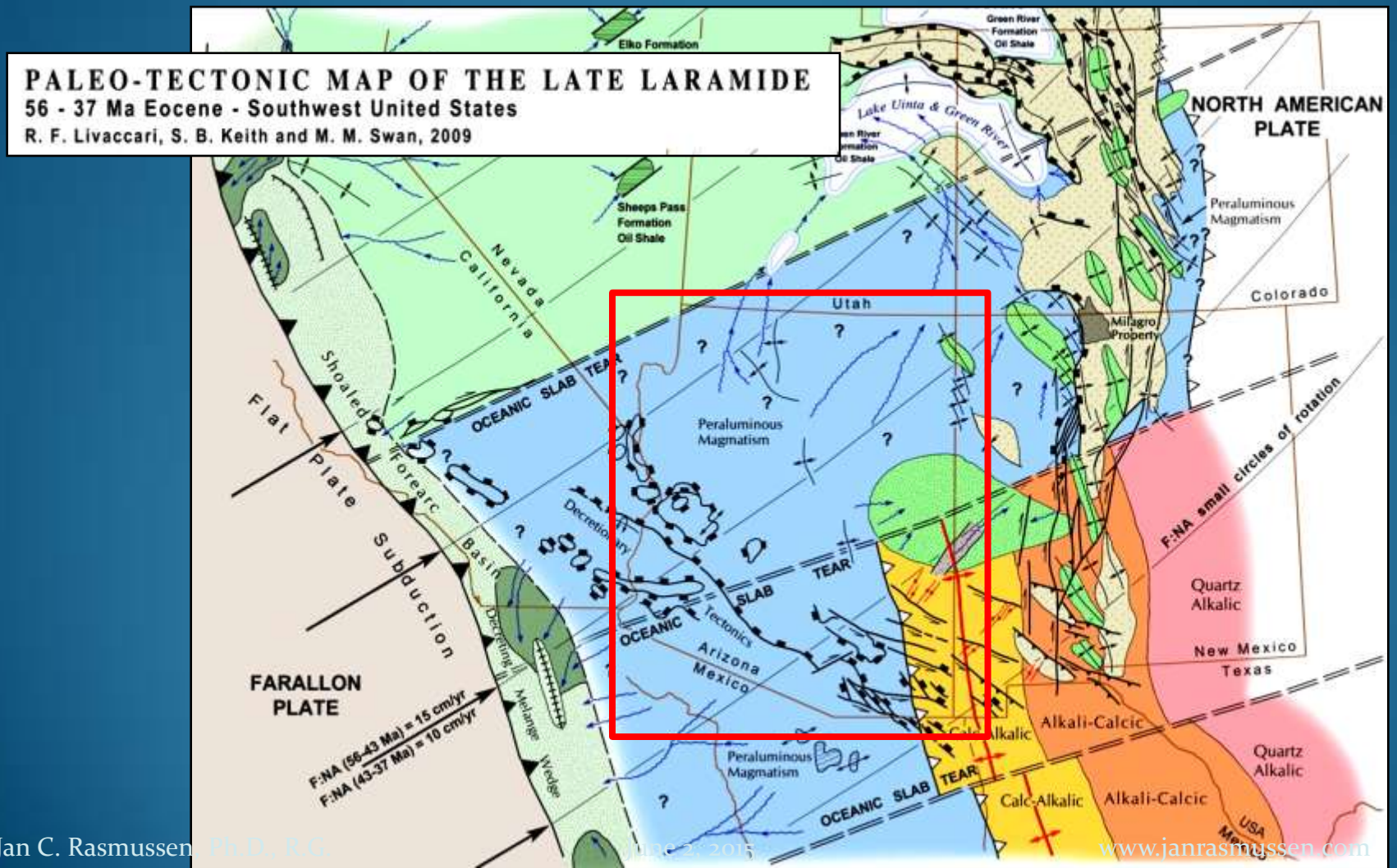
Large volumes of metaluminous calc-alkalic granodioritic intrusions (middle Laramide) are associated with faster convergence rates and flattening subduction, a general lack of volcanism; and by major copper-molybdenum production



Source: Keith, 1982,1986

Latest Laramide – Wilderness (55-43 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Late (Wilderness)	55-43	PC; PCA	Au, W (Be)	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin

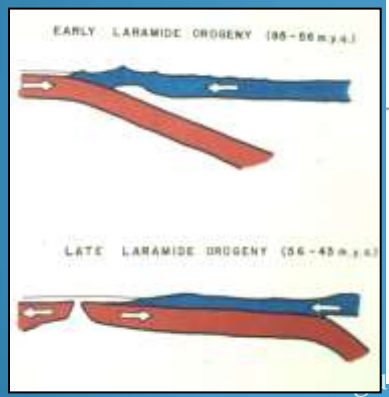


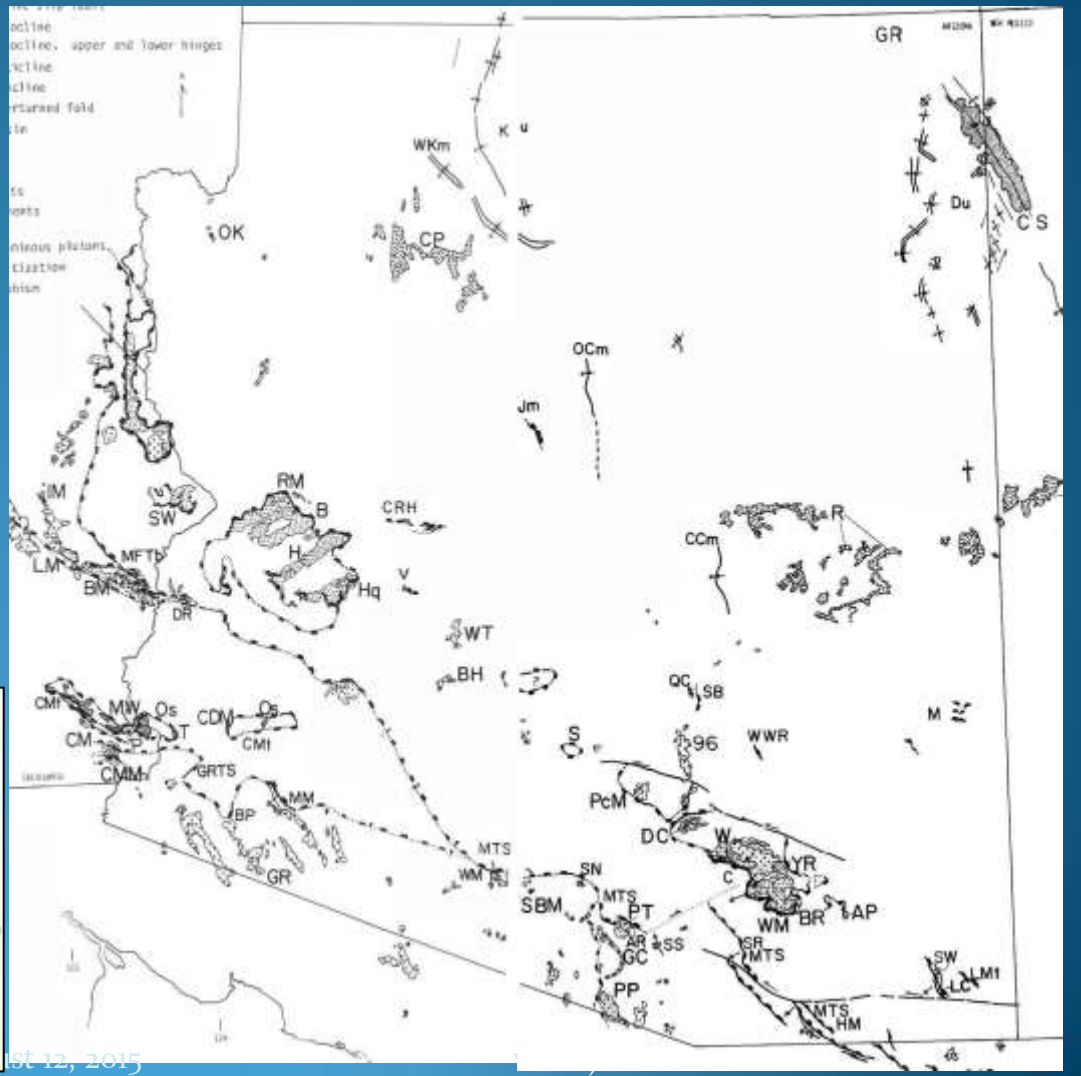
Latest Laramide – Wilderness (55-43 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Late (Wilderness)	55-43	PC; PCA	Au, W (Be)	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin

W. Santa Catalina Mts. from El Conquistador

Windy Point, Catalinas





Latest Laramide (Wilderness) mining districts

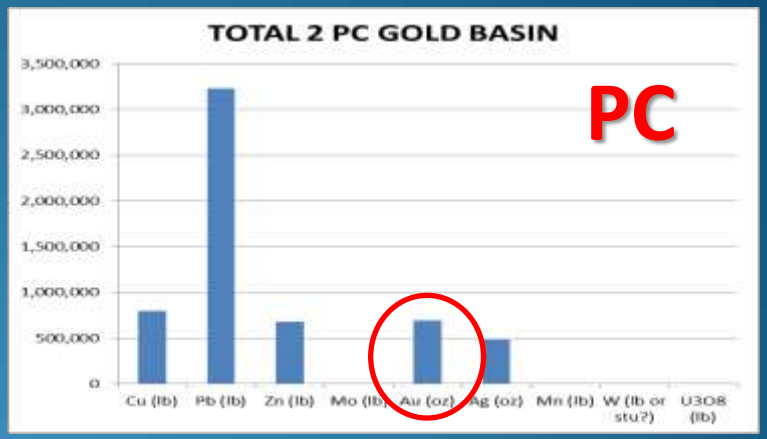
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Late (Wilderness)	55-43	PC; PCA	Au, W (Be)	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin

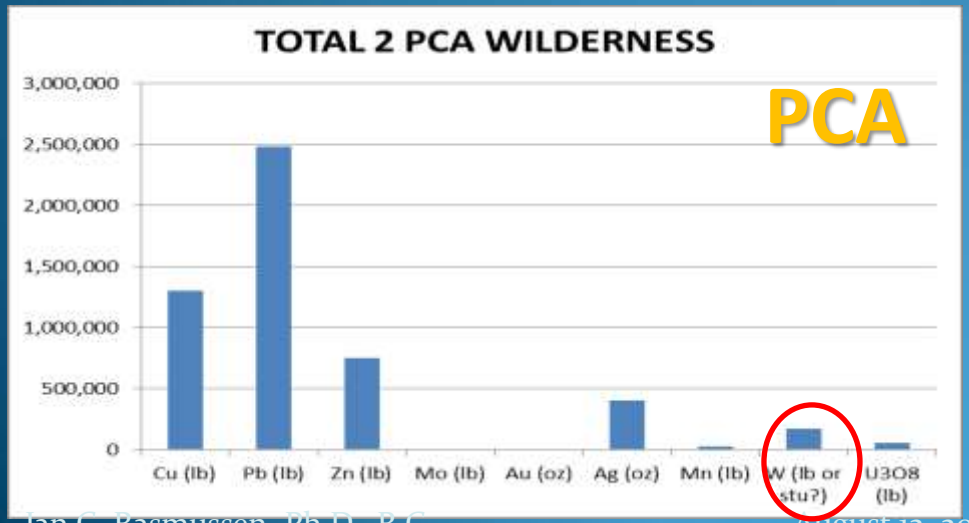
Gold Basin dist. prod. (188-1942)

587 lb Cu
34,132 lb Pb
0 lb Zn
9,352 oz Au
2,903 oz Ag

Peraluminous
Calcic

Source: Keith 2002 Grade/ton database





Boriana dist. prod. (1919-1964)

Peraluminous
Calc-alkalic

408,000 lb Cu
0 lb Pb
0 lb Zn
<100 oz Au
12,500 oz Ag
121,324 stu W

Source: Keith et al. 1983

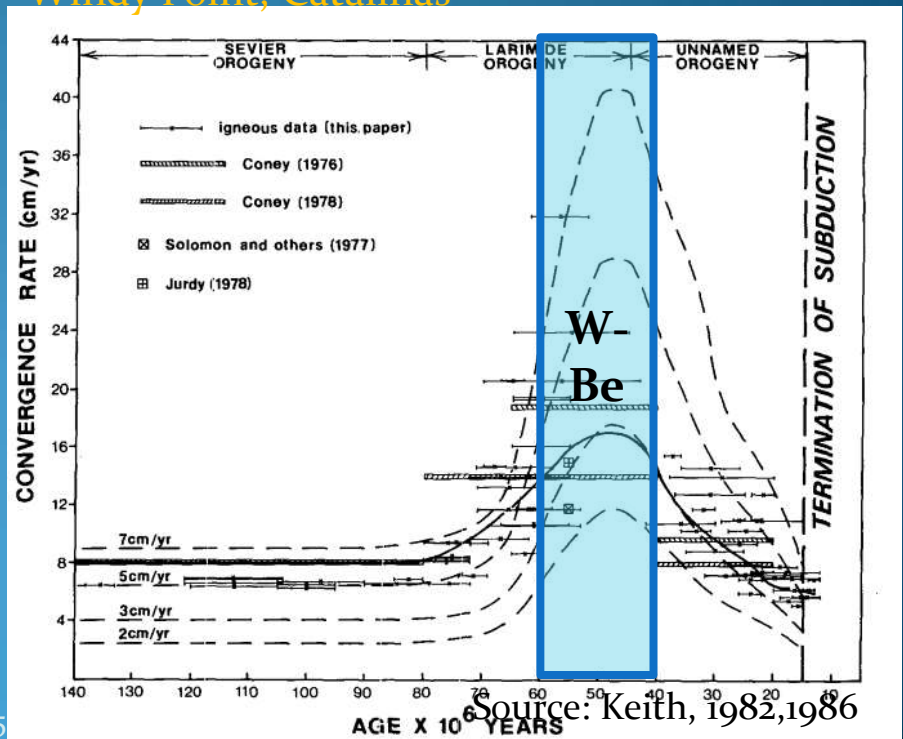
Latest Laramide (Wilderness)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Late (Wilderness)	55-43	PC; PCA	Au, W (Be)	Oracle (Wilderness granite), Boriana, Las Guijas, Gold Basin

- Largest volume of peraluminous calc-alkalic granitic intrusions (Latest Laramide) is associated with fastest convergence rates, flattest subduction, and significant W or Au production.
- This is the main Laramide igneous and tectonic event.
- ex. W=Reef, Boriana, Las Guijas, Bluebird, Wilderness; Au= Gold Basin
- Zero volcanism – crystallized too deep.
- W and Be are inherited from melted crust - Oracle Granite

Windy Point, Catalinas

Peraluminous Calc-Alkalic



Source: Keith, 1982,1986

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

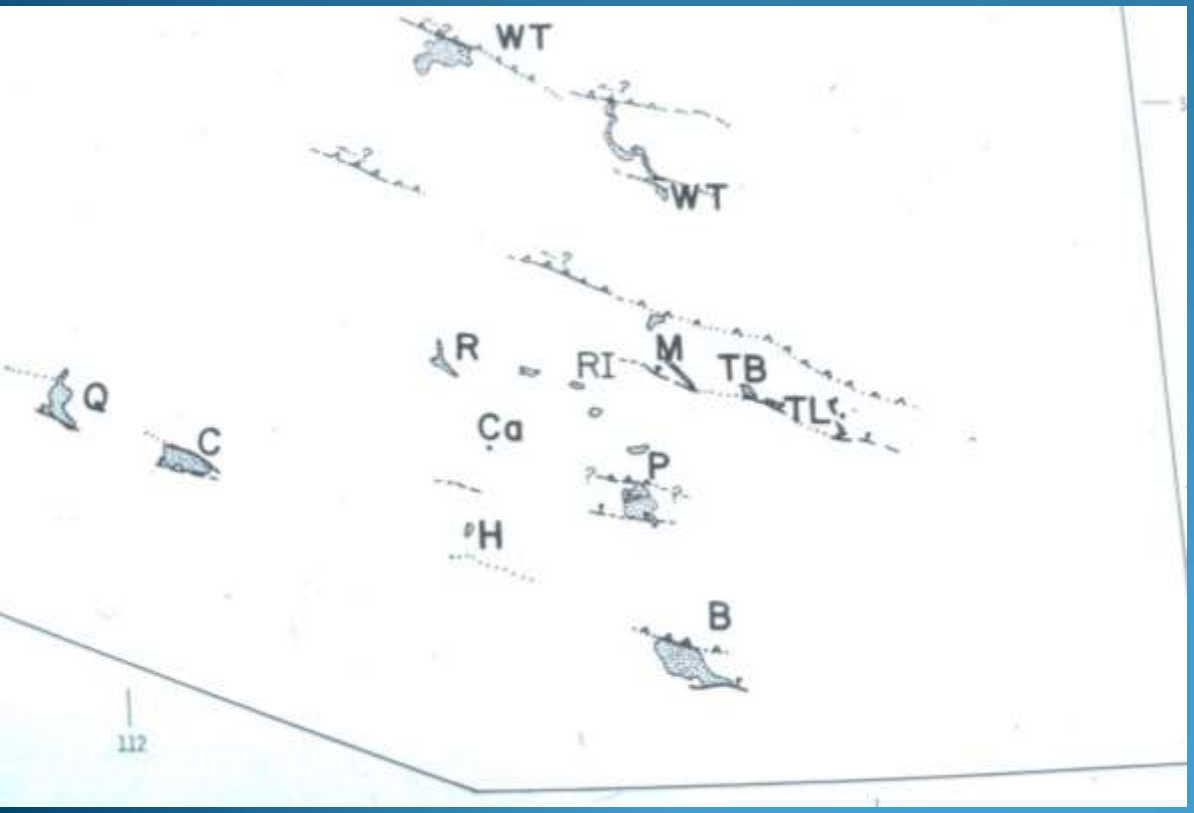
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Galiuro	Late (Whipple)	18-13	MQA	Au-Ag (Cu) F, U, Mn	Oatman, Mammoth, Rowley, Tiger
	Middle (Datil)	28-18	MAC	Pb-Zn-Ag F	Silver (Red Cloud), Castle Dome, Stanley, Aravaipa
	Early (South Mountain	30-22	MCA	Au +/- (Cu, W)	Little Harquahala, Kofa
	Earliest (Mineta)	38-28	-	U, clay, exotic Cu	Ajo Cornelia, Copper Butte (from Ray)

Chiricahua Mts. Ash flow tuffs

N. Tucson Mts.

Early Galiuro – Mineta (38-28 Ma)

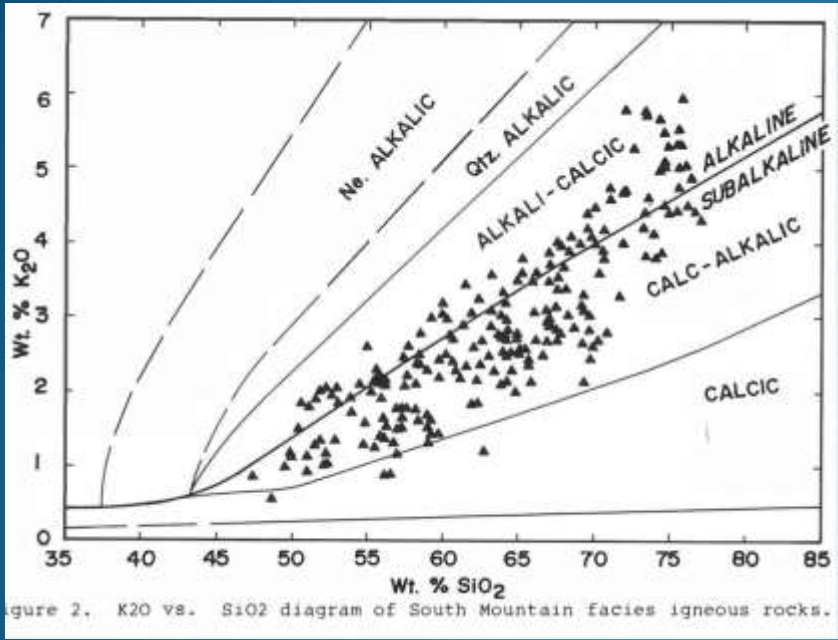
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Earliest (Mineta)	38-28	-	U, clay, exotic Cu	Ajo Cornelia, Copper Butte (from Ray)



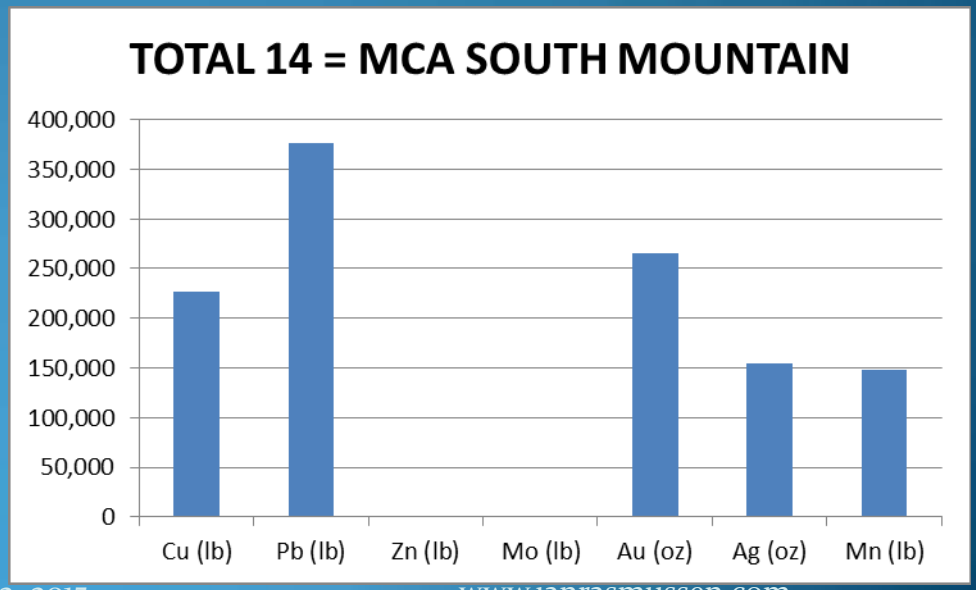
Pantano Clay, East Tucson - 1987

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

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Galiuro	Early (South Mountain	30-22	MCA	Au +/- (Cu, W)	Little Harquahala, Kofa



igure 2. K2O vs. SiO2 diagram of South Mountain facies igneous rocks.



Middle Galiuro – Datil (28-18 Ma)

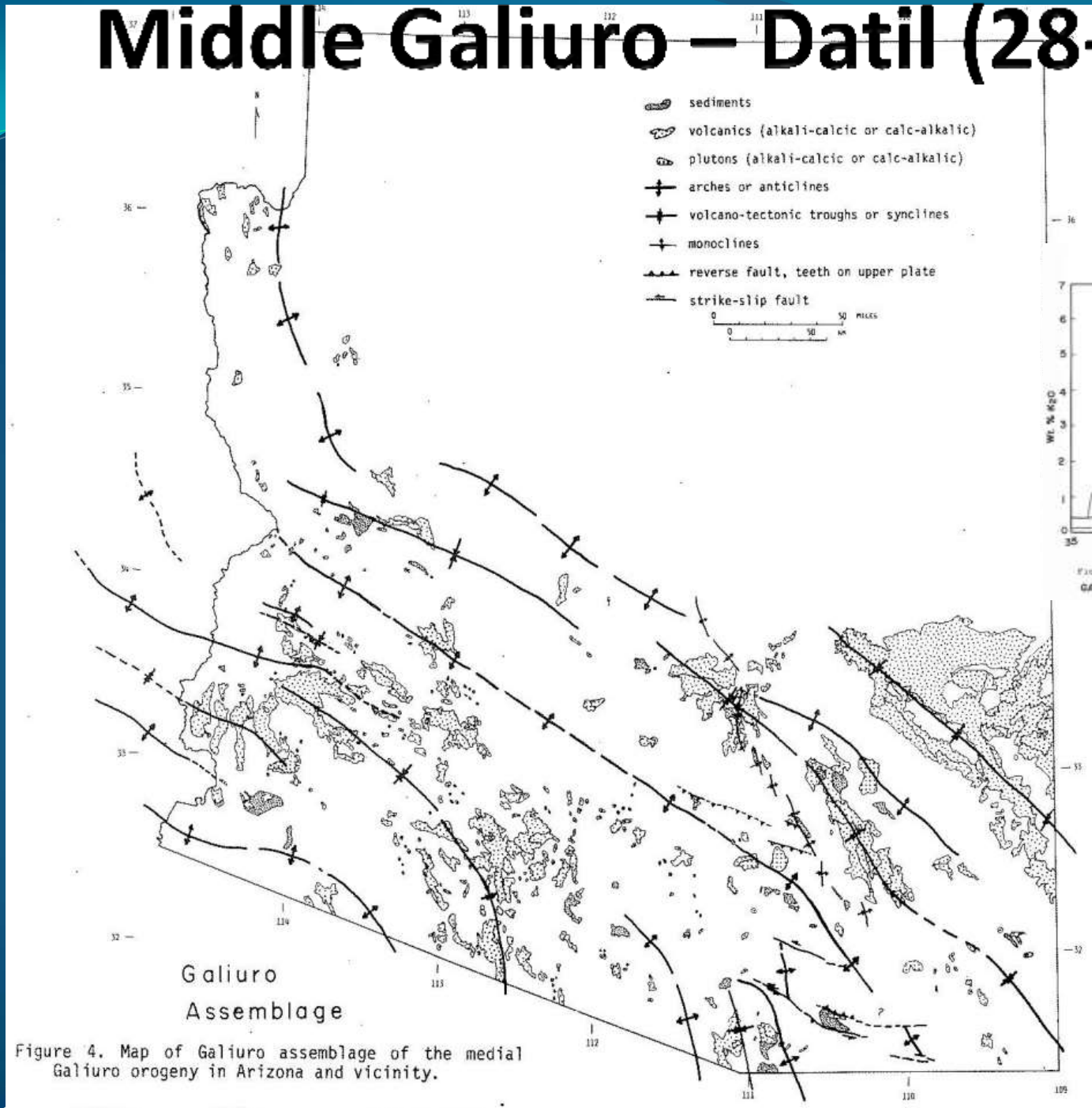


Figure 4. Map of Galiuro assemblage of the medial Galiuro orogeny in Arizona and vicinity.

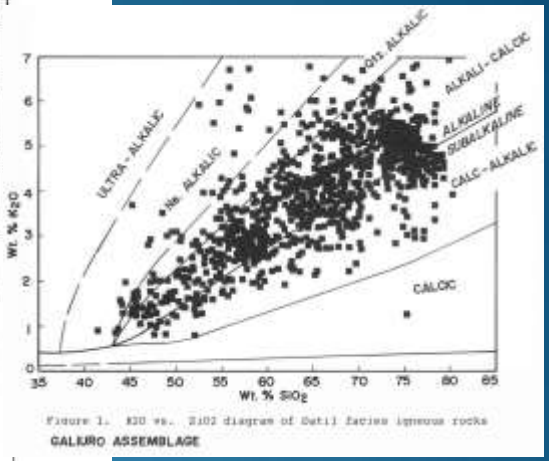


Figure 1. K2O vs. SiO2 diagram of Datil facies igneous rocks
GALIURO ASSEMBLAGE

Broad NW-trending folds, NW- and NE-trending dikes

=

Compression, not extension

Middle Galiuro – Datil (28-18 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Galiuro	Middle (Datil)	28-18	MAC	Pb-Zn-Ag F	Silver (Red Cloud), Castle Dome, Stanley, Aravaipa

Galiuro Volcanics

Aravaipa dist. prod. (1901-1971)

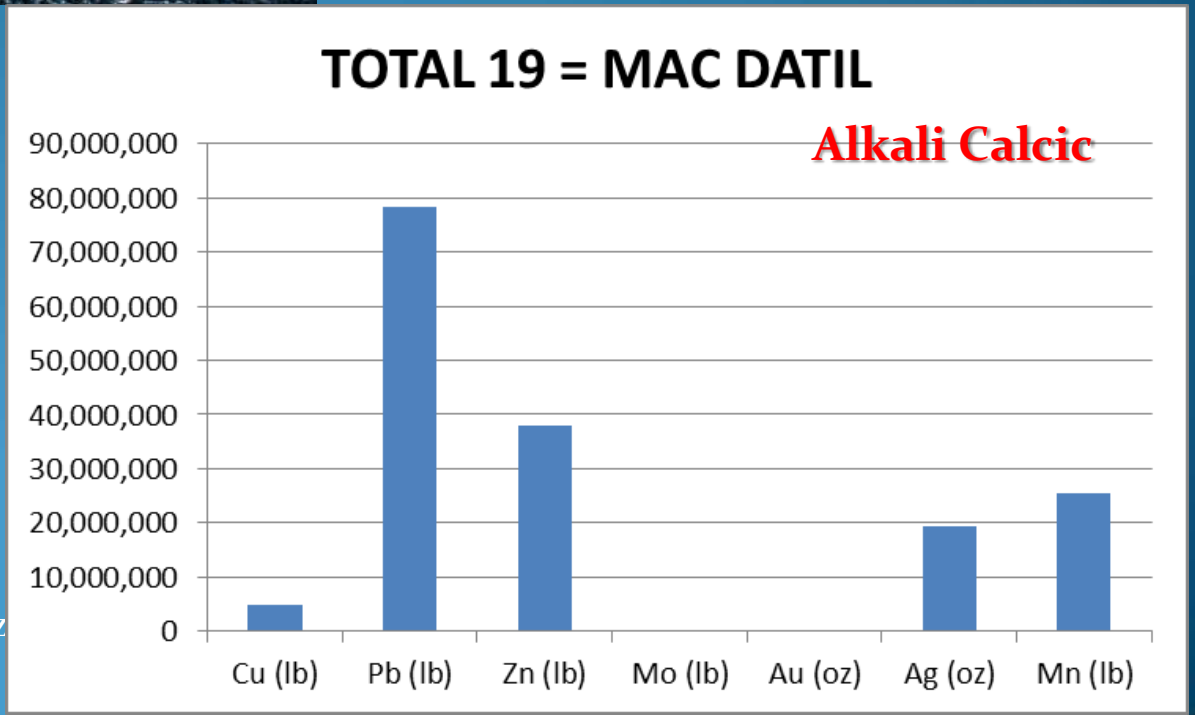
282,000 lb Cu
34,492,000 lb Pb
27,863,000 lb Zn
4,400 oz Au
363,000 oz Ag

Source: Keith et al. 1983

Silver dist. prod. (1880-1951)

2,000 lb Cu
2,456,000 lb Pb
0 lb Zn
<100 oz Au
1,311,000 oz Ag

Red Cloud Mine is in Silver district, La Paz

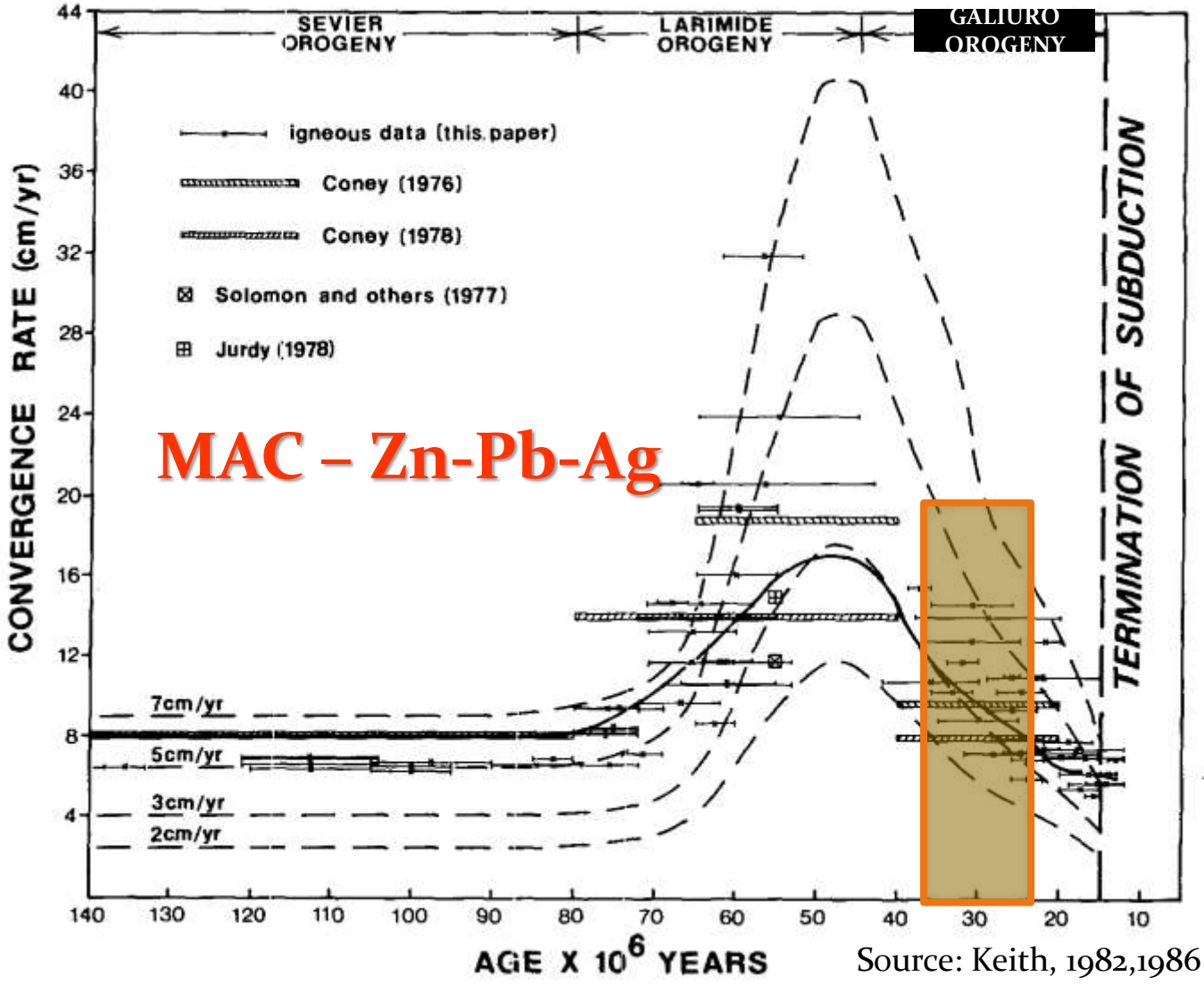


Jan C. Rasmussen, Ph.D., R.G.

Middle Galiuro – Datil (28-18 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Middle (Datil)	28-18	MAC	Pb-Zn-Ag F	Silver (Red Cloud), Castle Dome, Stanley, Aravaipa

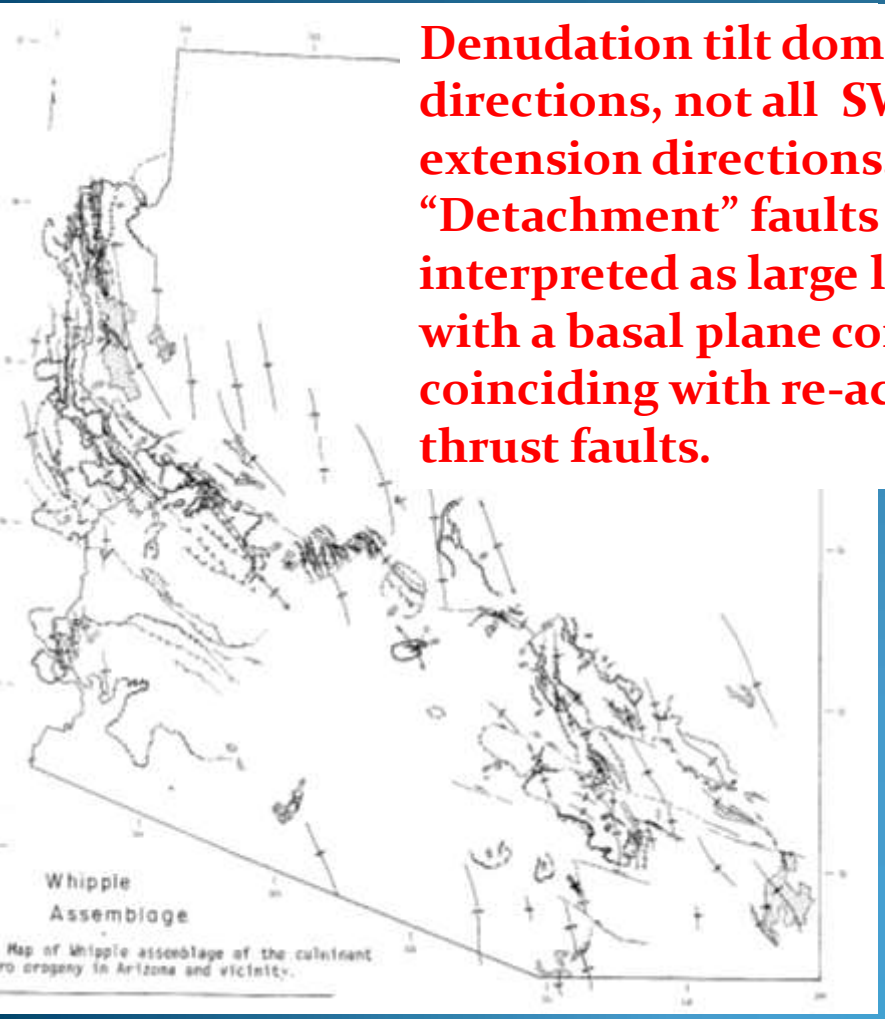
Moderate volumes of metaluminous alkali calcic quartz monzoniic intrusions (early Laramide) are associated with slower convergence rates, steepened subduction, significant volcanism, and significant zinc-lead silver production (eg. Aravaipa, Middlemarch,CA, Castle Dome, Silver)



Source: Keith, 1982,1986

Late Galiuro – Whipple (18-13 Ma)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Late (Whipple)	18-13	MQA	Au-Ag (Cu) F, U, Mn	Oatman, Mammoth, Rowley, Tiger



Map of Whipple assemblage of the culminant ro orogeny in Arizona and vicinity.

Denudation tilt domains are in many directions, not all SW-NE presumed extension directions.
"Detachment" faults are alternatively interpreted as large landslide blocks with a basal plane commonly coinciding with re-activated former thrust faults.


Fluorite, Oatman


Papago Park, Phoenix

Oatman dist. (1870-1980)

60,000 lb Cu
0 lb Pb
0 lb Zn
1,966,000 oz Au
1,147,000 oz Ag

Source: Keith et al. 1983

Late Galiuro - Mammoth-St. Anthony mine (Tiger)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Late (Whipple)	18-13	MQA	Au-Ag (Cu) F, U, Mn	Oatman, Mammoth, Rowley, Tiger

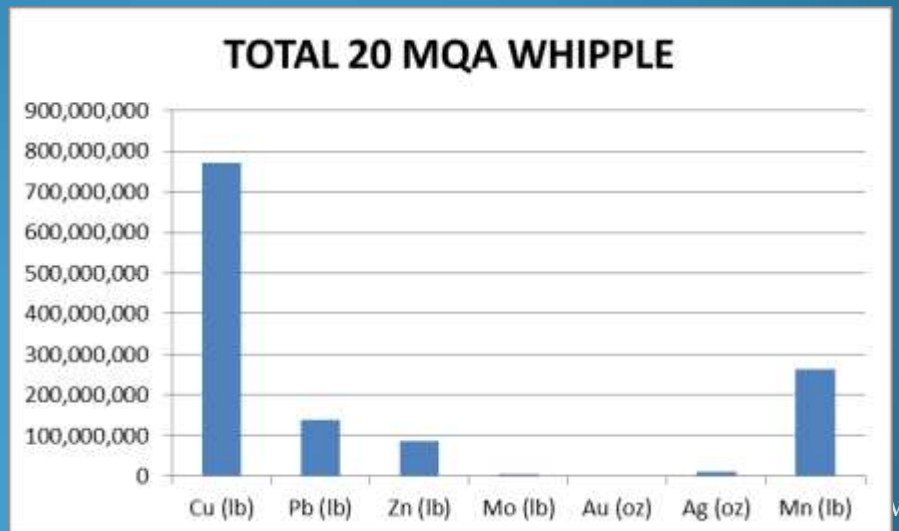
Wulfenite

Photo ~ 2005 courtesy of BHP Billiton, Mammoth St. Anthony mine

Mammoth dist. prod. (1886-1981)

10,445,000 lb Cu
132,680,000 lb Pb
87,312,000 lb Zn
349,000 oz Au
1,660,000 oz Ag

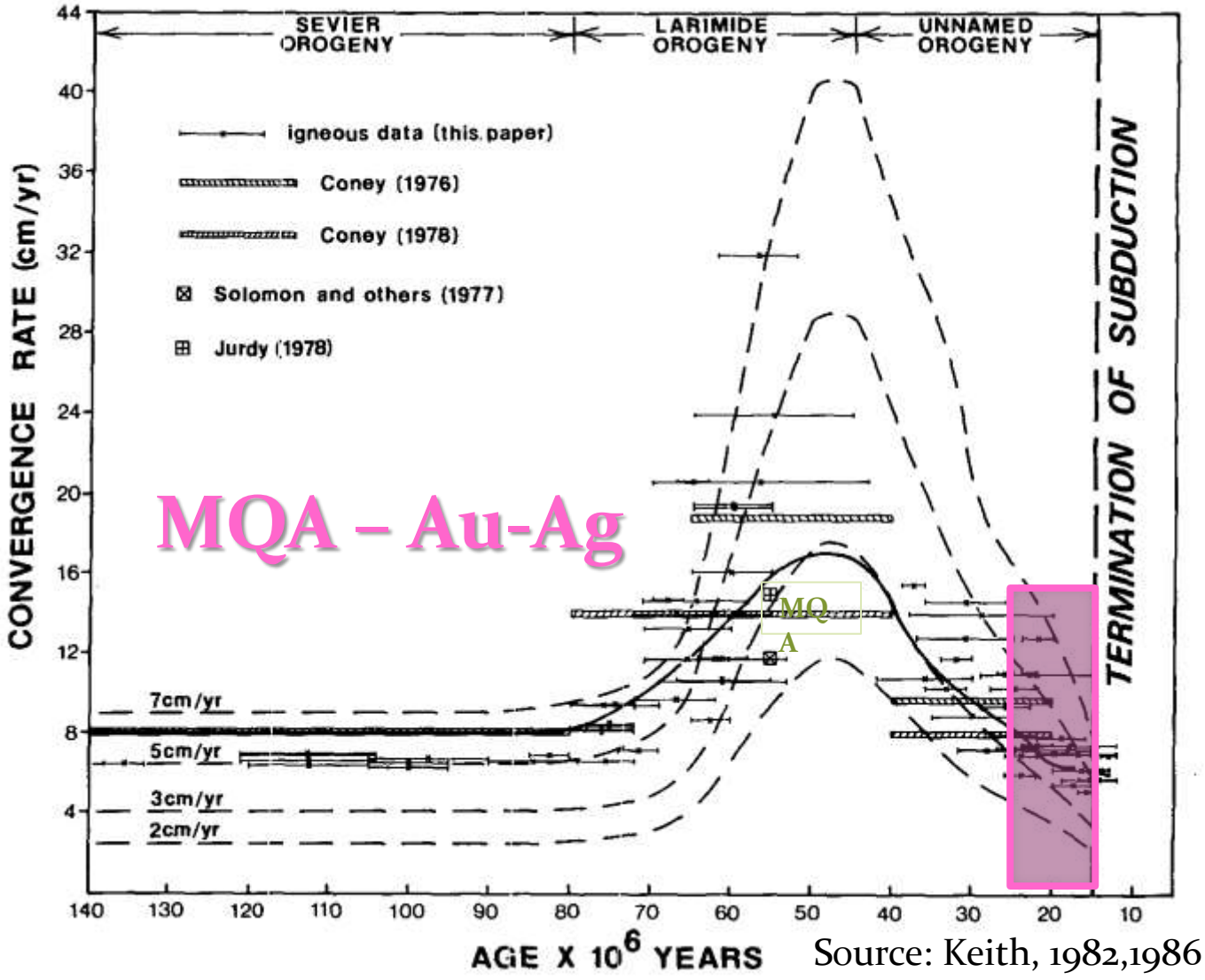
Source: Keith et al. 1983



Late Galiuro – Whipple (18-13 Ma)

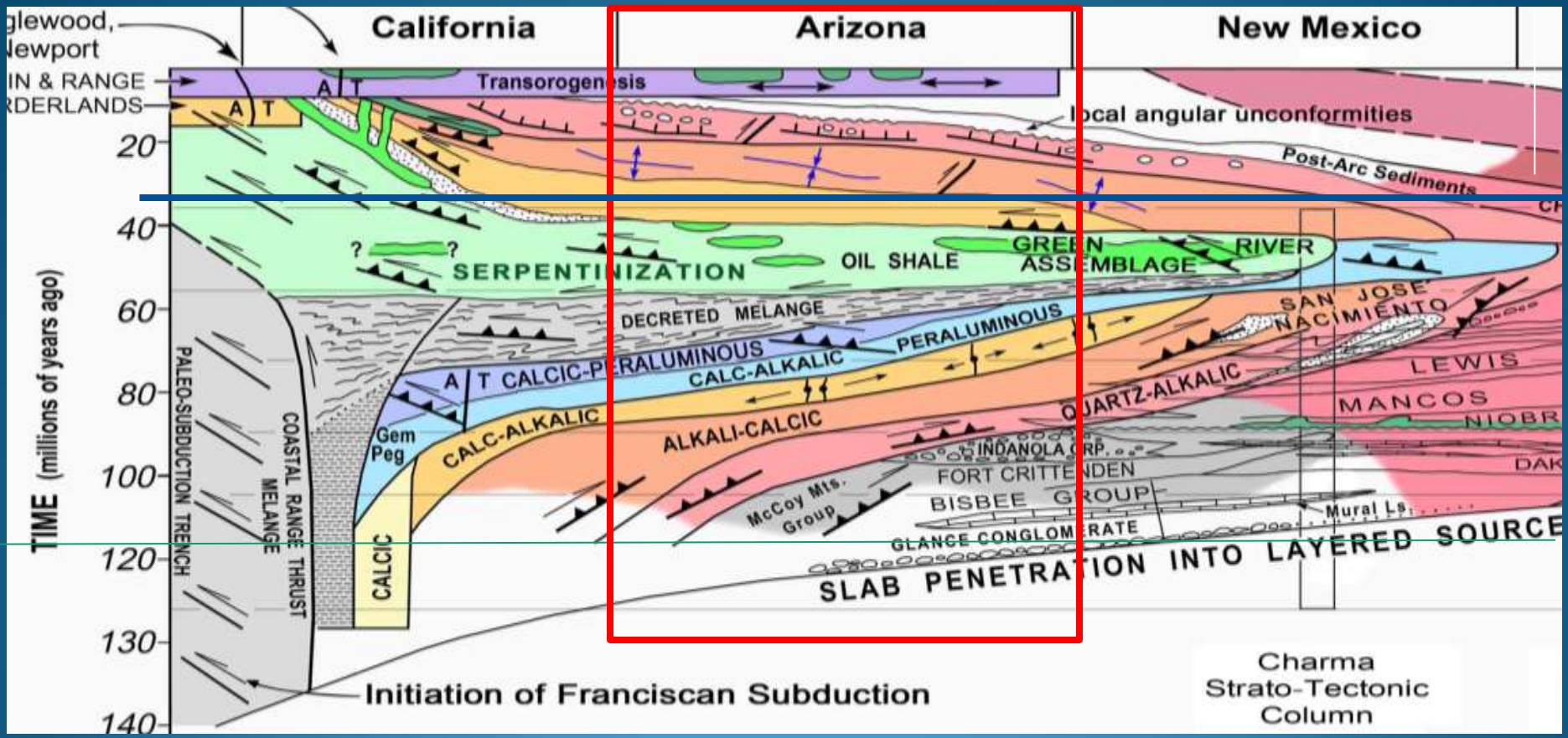
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Late (Whipple)	18-13	MQA	Au-Ag (Cu) F, U, Mn	Oatman, Mammoth, Rowley, Tiger

Moderate volumes of metaluminous quartz alkalic intrusions (Miocene) are associated with slowed convergence rates, very steepened subduction, high K rhyolite volcanism, and epithermal gold (base-metal) production (ex. Tiger, Oatman, Alice Camp)



Source: Keith, 1982,1986

Cretaceous and Cenozoic time distance



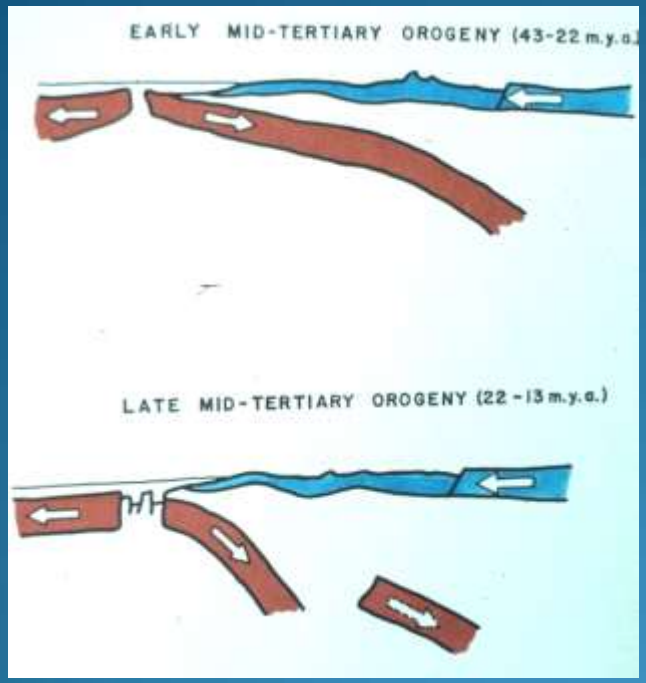
Slab flattening = Laramide eastward sweep
Flat subduction = Peraluminous, end of Laramide
Slab steepening = Cenozoic westward sweep of magmatism
San Andreas cuts off slab = Basin & Range extension & basalt volcanism

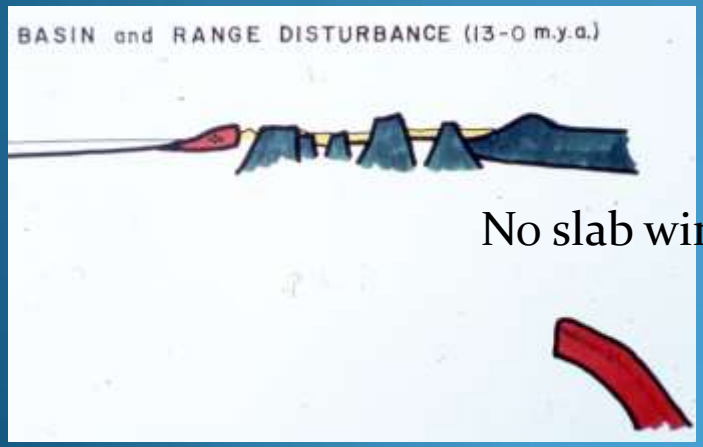
Assemblage	No. districts	Ore (tons)	Cu (lb)	Pb (lb)	Zn (lb)	Mo (lb)	Au (oz)	Ag (oz)
TOTAL 2 = MC YAVAPAI VMS	11	51,578,338	3,888,322,588	238,326,788	6029573316	0	2,107,819	76,757,861
TOTAL 2 = MCA YAVAPAI VEINS	18	363,800	5,937,984	5,645,115	1,225,436	0	100,916	1,757,127
TOTAL 3 = MCA MAZATZAL	7	21,582	708,982	50,734	0	0	4,781	17,831
TOTAL 4 = PAC ORACLE	18	71,163	650	0	0	0	614	651
TOTAL 5 = MQA SIERRA ANCHA U	5	352	6,198	560	0	0	2	2,666
TOTAL 10 = MQA NEVADAN	57	175,789,900	7,937,882,568	324,901,497	355,157,204	0	3,125,475	102,432,112
TOTAL 13 = MQA HILLSBORO	7	1,391,983	50,534,664	1,314,442	224,120	0	72,804	844,920
TOTAL 14 = MAC TOMBSTONE	28	16,861,025	190,897,047	130,736,089	177,967,773	50,000	189,259	39,086,392
TOTAL 15 = MCA - MORENCI	28	4,709,585,031	72,327,643,245	310,813,714	609,866,579	350,907,170	5,378,005	260,773,325
TOTAL 2 = PCA WILDERNESS	22	297,530	1,303,048	2,482,308	748,340	0	7,008	401,836
TOTAL 2 = PC GOLD BASIN	14	1,967,772	800,520	3,233,180	677,554	0	695,800	485,240
TOTAL 14 = MCA SOUTH MOUNTAIN	26	687,438	226,598	375,864	1,475	0	265,548	155,142
TOTAL 19 = MAC DATIL	46	3,581,969	4,905,748	78,153,739	38,014,655	1,260	133,579	19,331,091
TOTAL 20 = MQA WHIPPLE	74	15,875,583	770,823,917	139,980,327	87,838,354	3,943,046	3,398,773	10,789,148

Assemblage	Ore (Mn, etc.)	Mn (lb)	W (lb or stu?)	U3O8 (lb)	V2O5 (lb)	Hg (lb)
TOTAL 2 = MC YAVAPAI VMS	68	37,500	0	0	0	0
TOTAL 2 = MCA YAVAPAI VEINS	0	0	8	0	0	0
TOTAL 3 = MCA MAZATZAL	0	0	0	0	0	489,000
TOTAL 4 = PAC ORACLE	62	0	10,943	184	2	0
TOTAL 5 = MQA SIERRA ANCHA U	25,476	0	0	114,690	0	0
TOTAL 10 = MQA NEVADAN	68,889,976	18,478,558	0	18,395,555	0	0
TOTAL 13 = MQA HILLSBORO	214	168,700	0	0	0	0
TOTAL 14 = MAC TOMBSTONE	1031	337,315	0	2808	14	0
TOTAL 15 = MCA - MORENCI	90,856	43,917,291	332	116	122,773	0
TOTAL 2 = PCA WILDERNESS	21,822	28,500	173,590	57,623	98,000	0
TOTAL 2 = PC GOLD BASIN	0	0	0	0	0	0
TOTAL 14 = MCA SOUTH MOUNTAIN	247	148,000	313	14	0	0
TOTAL 19 = MAC DATIL	43,136	25,478,356	3,327	70,400	721,800	0
TOTAL 20 = MQA WHIPPLE	663,406	263,733,167	21,187,378	33,762	2,552,657	0

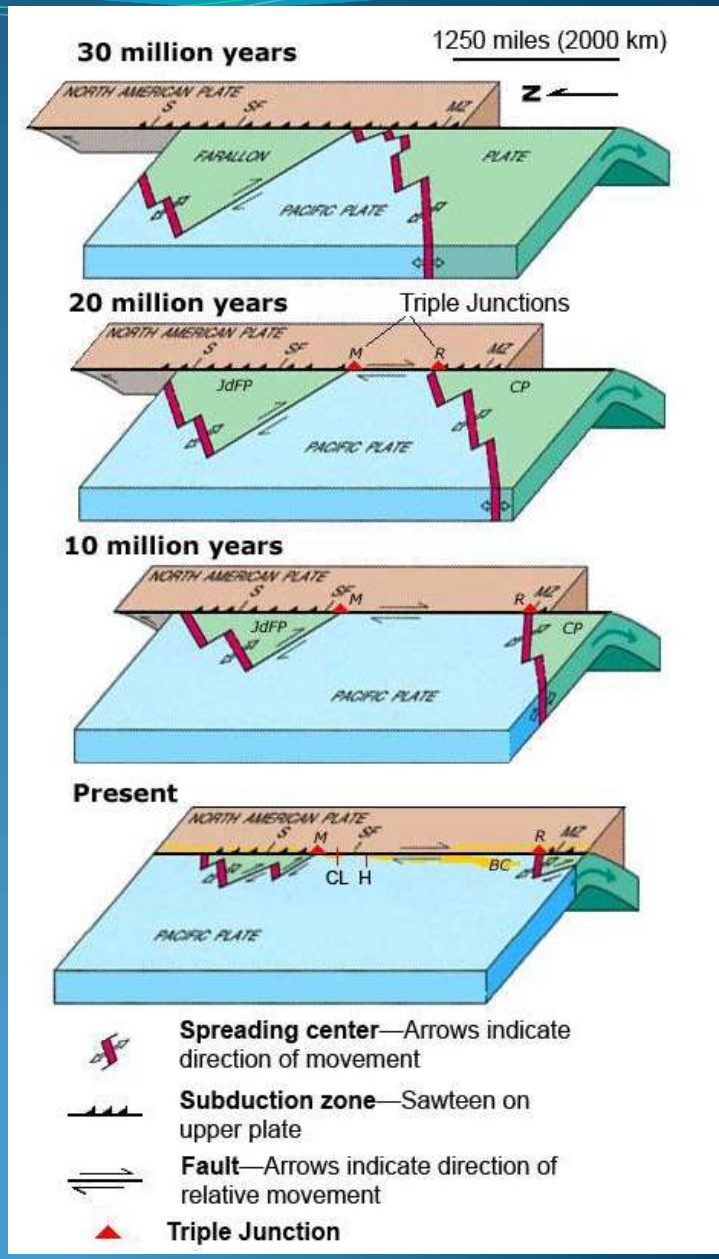
Arizona production through 1981 (Keith et al., 1983

San Andreas fault cuts off eastward-subducting slab





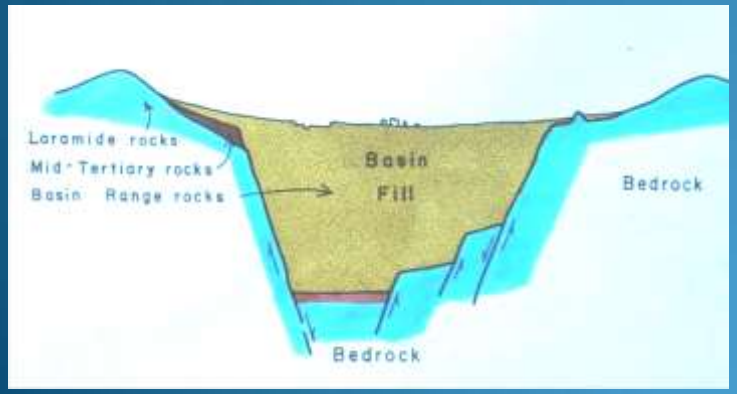
No slab window



San Andreas – Basin & Range (13-0 Ma)

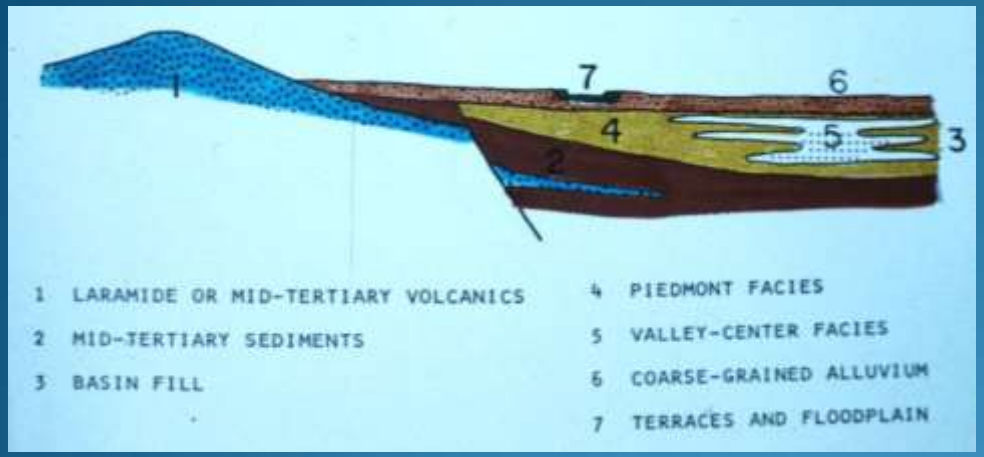
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
San Andreas	Basin & Range	13-0	MQA	Sand, gravel, salt, zeolites, gypsum	San Francisco volcanic field, San Carlos olivine, Emerald Isle exotic Cu

Basin and Range valleys are filled with sand, gravel, clay, gypsum, & salt - True extension



San Andreas (13-0 Ma) rifting - basins

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
San Andreas	Basin & Range	13-0	MQA	Sand, gravel, salt, zeolites, gypsum	San Francisco volcanic field, San Carlos olivine, Emerald Isle exotic Cu




Rillito II - ~ 21 Ma

Willcox Playa

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

Industrial minerals from basins

Sand & gravel

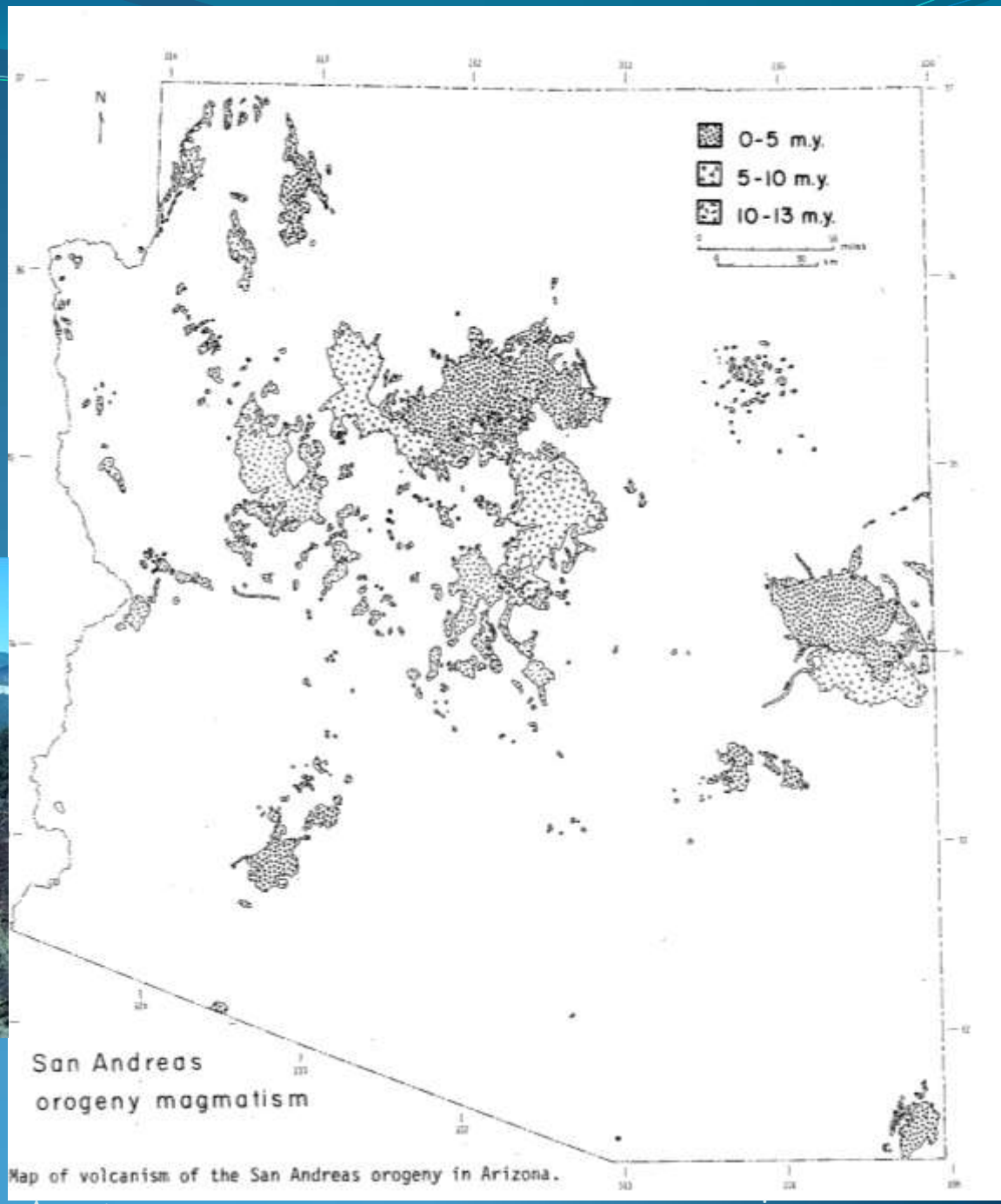
Kalamazoo Clay - 1987

Gypsum rose – St. David

Salt - Picacho Basin – UnoCal photo

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

San Francisco Peaks, Flagstaff



Map of volcanism of the San Andreas orogeny in Arizona.

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

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
San Andreas	Basin & Range	13-0	MQA	Sand, gravel, salt, zeolites, gypsum	San Francisco volcanic field, San Carlos olivine, Emerald Isle exotic Cu

Olivine in basalt, San Carlos

No metals

cinders

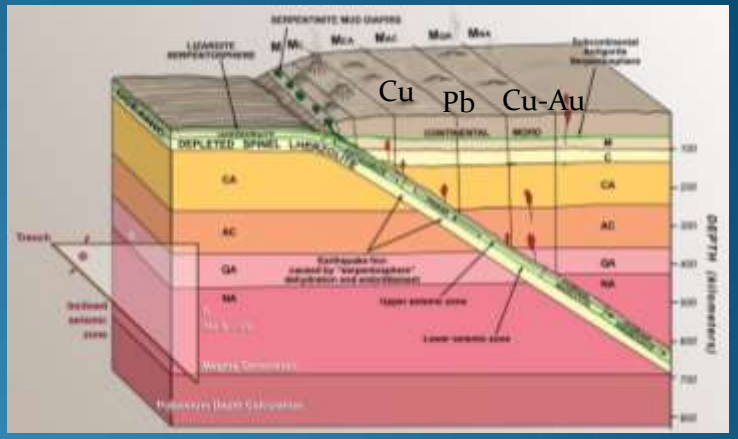
Significant Points

- Copper deposits formed in only 2 time periods – Jurassic & Laramide.
- Other 16 times were Zn, Pb-Ag, Au, W, U.
- The crust is not the source of copper deposits.
- Cannot get different metals by flushing the same crust.

Age (Ma)	Alkalinity	Resources
13-0	anhydrous	Industrial Minerals
18-13	MQA	Au-Ag (Cu) F, U, Mn
28-18	MAC	Pb-Zn-Ag F
30-22	MCA	Au +/- (Cu, W)
38-28	-	U, clay, exotic Cu
55-43	PC; PCA	Au; W (Be)
65-55	MCA	porphyry Cu-Mo-Ag
85-65	MAC	Pb-Zn-Ag
89-85	MQA	Cu-Au-Ag (Pb, Zn)
113-100	-	Limestone
150-140	PC, PCA	Au (Mo)
160-150	MCA	Not yet recognized
180-160	MAC	Zn-Pb-Cu-Ag
205-180	MQA	porphyry Cu-Au
230-205	MQA	U, V, Cu
325-252	-	U, salt, potash
355-330	-	Limestone
410-370	-	UltraDeep Hydrocarbon?
460-430	-	Hosts for later replacement
1200-900	MQA	Asbestos, U (Cu)
1440-1335	PCA	W, Be, Li, Ta-Nb, U
1750-1600	MAC	Hg, Sn, Au
1800-1775	MC	Zn-Cu-Ag-Au VMS, BIF
2000-1800	MC	?

Significant Points

- Metal associations are correlated with alkalinity, related to sources in various mantle layers.

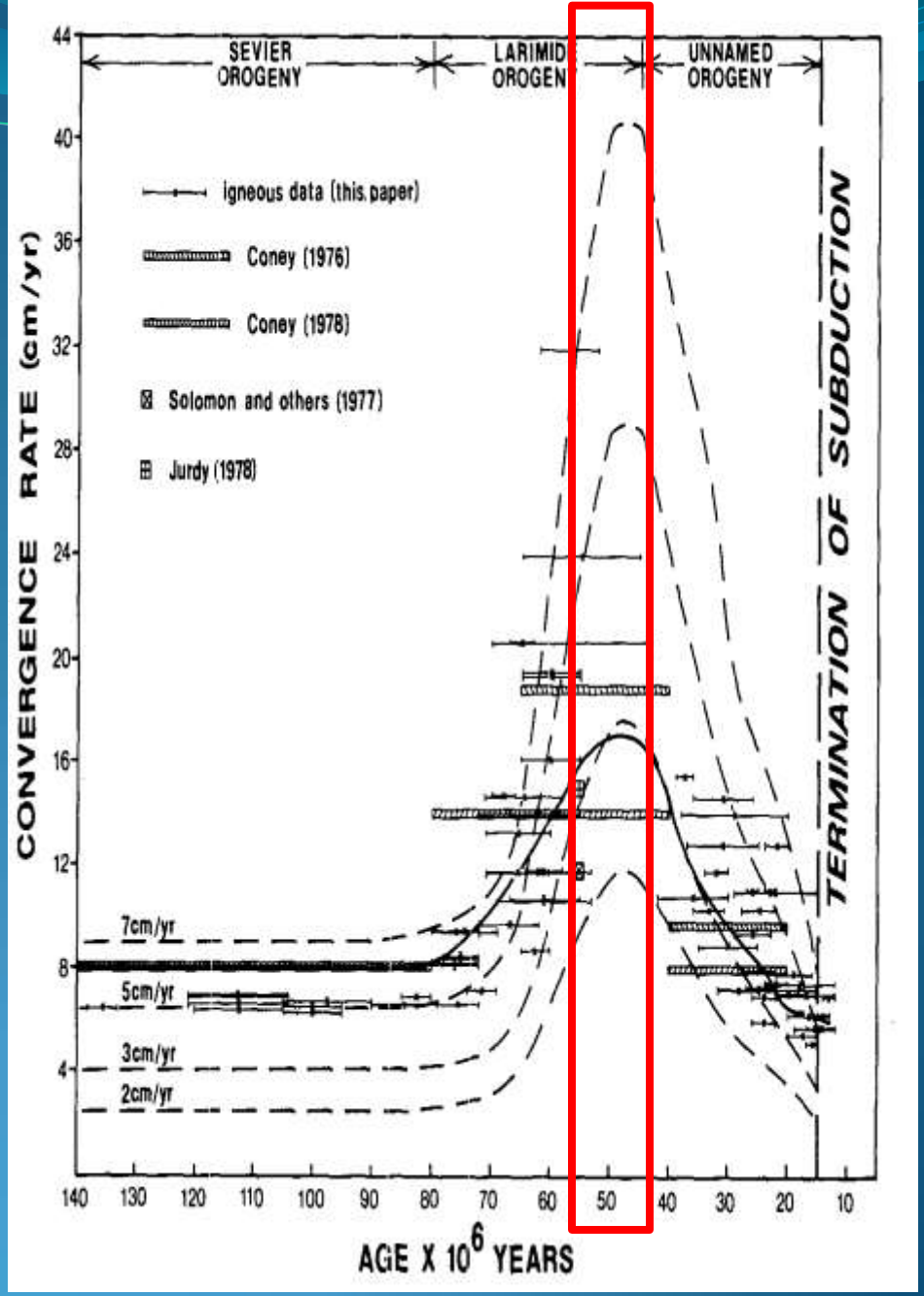


- As subducting slab became flatter through time, metal associations changed depending on the source layer in the mantle.

Significant Points

High volume of copper in middle Laramide is associated with fast spreading rates and flatter subduction.

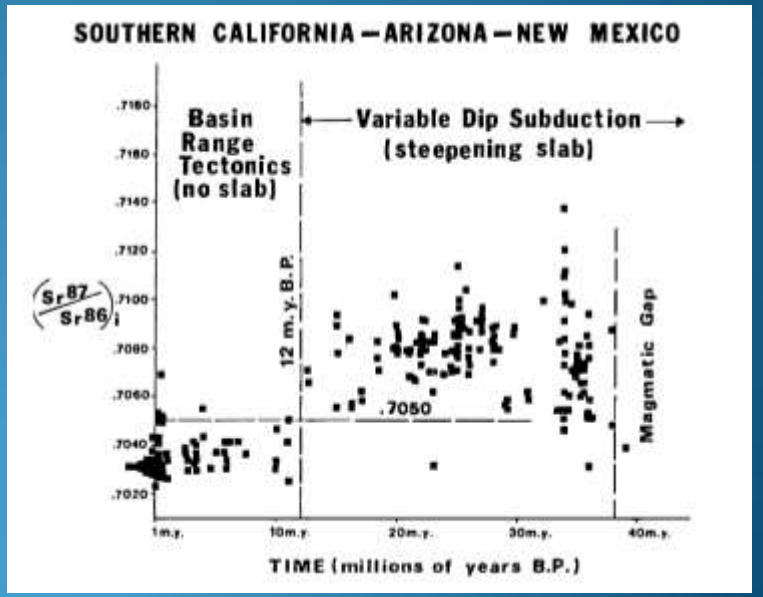
Largest volumes of intrusions are associated with flattest subduction.



Source: Keith, 1982

Significant Points

- Mid-Tertiary extension is minor.
- Compression and ore deposits associated with subduction continued from the Laramide into the mid-Tertiary.
- True extension began about 12-10 Ma when the Sr initial ratios changed and basalt volcanism began with no associated metals.



Source: Annis & Keith, 1986

Arizona Mineralization through Geologic Time

- **Copper deposits are rare through geologic time in Arizona.**
- **Presence of other metal deposit types in the same crust through geologic time indicates the crust is not the source of copper.**

Age (Ma)	Alkalinity	Resources
13-0	anhydrous	Industrial Minerals
18-13	MQA	Au-Ag (Cu) F, U, Mn
28-18	MAC	Pb-Zn-Ag F
30-22	MCA	Au +/- (Cu, W)
38-28	-	U, clay, exotic Cu
55-43	PC; PCA	Au; W (Be)
65-55	MCA	porphyry Cu-Mo-Ag
85-65	MAC	Pb-Zn-Ag
89-85	MQA	Cu-Au-Ag (Pb, Zn)
113-100	-	Limestone
150-140	PC, PCA	Au (Mo)
160-150	MCA	Not yet recognized
180-160	MAC	Zn-Pb-Cu-Ag
205-180	MQA	porphyry Cu-Au
230-205	MQA	U, V, Cu
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1200-900	MQA	Asbestos, U (Cu)
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1800-1775	MC	Zn-Cu-Ag-Au VMS, BIF
2000-1800	MC	?