Arizona Mineralization through Geologic Time

Copper , Bisbee

Silver, Lucky Cuss m.

Gold, Gold Basin, Mohave Co., AZ

by Jan C. Rasmussen

Consulting Geologist

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Acknowledgements

Stanley Keith –
data, figures, 40 years of collaboration

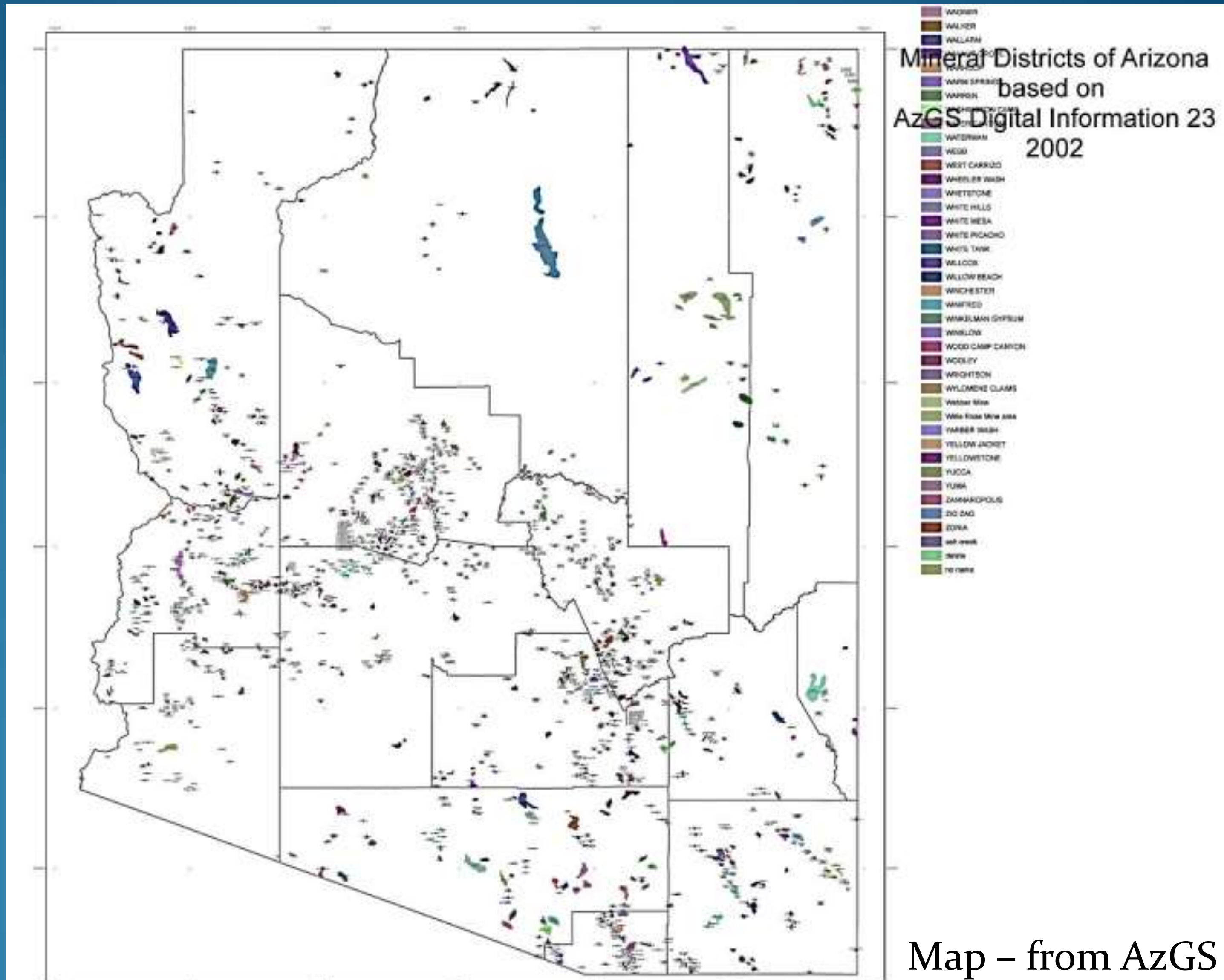
srk consulting

Arizona Mining and Mineral Museum – www.MiningMineralMuseum.com

Arizona Mining Districts

>800 districts/ subdistricts

Copper deposits were made only 2 times in AZ geologic history – early Jurassic, and middle Laramide

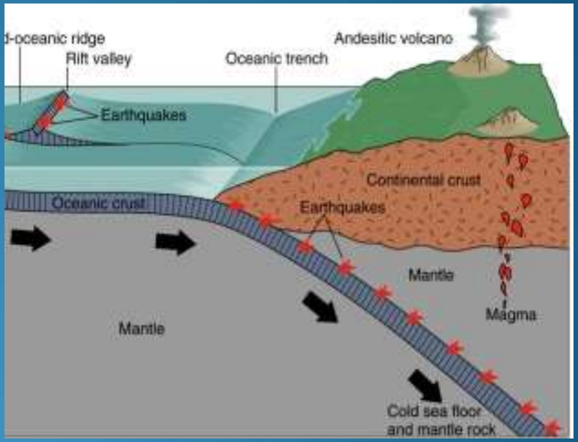


Map – from AzGS

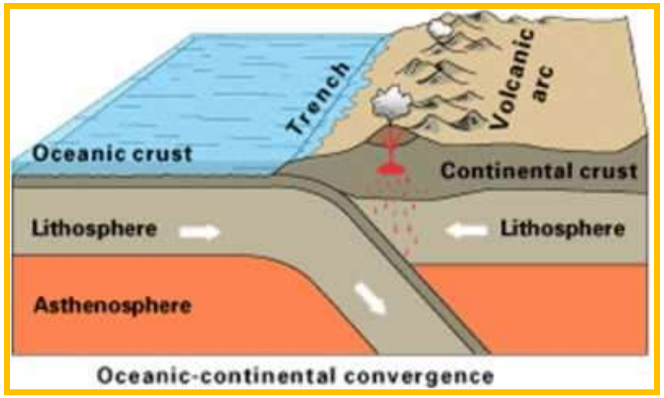
Arizona Mineralization through Geologic Time

Mineralization is related to mountain building episodes

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



Orogenies in Arizona



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 [illegible]
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
[illegible]		[illegible]		[illegible]	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
[illegible]		[illegible]			[illegible]
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

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

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Significant Points

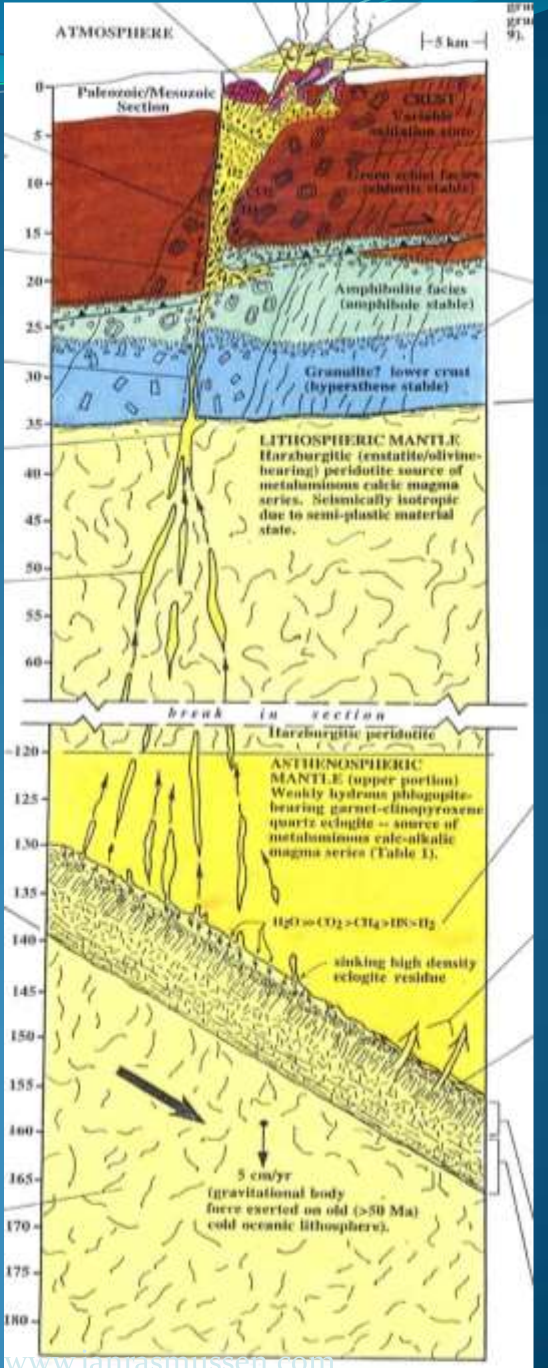
- Copper deposits formed in only 2 time periods; other 16 times were characterized by other metals (Pb-Zn-Ag, W, Au, U, Mn, Zn-Cu VMS).
- The crust is not the source of copper deposits - cannot get different metals by flushing the same crust.
- Metal associations are correlated with alkalinity and are related to sources in various mantle layers, especially Cu with MCA.

Significant Points

- High volume of copper in middle Laramide is associated with fast spreading rates and flatter subduction, hydrous MCA.
- Largest volumes of intrusions are associated with flattest subduction, fastest convergence – strongly hydrous, peraluminous – crustal melting.
- Mid-Tertiary extension is minor.
- Compression and ore deposits associated with subduction continued from the Laramide through the mid-Tertiary (Galiuro orogeny).
- True extension began about 12-10 Ma when the Sr initial ratios changed and anhydrous basalt volcanism began with no associated metal deposits.

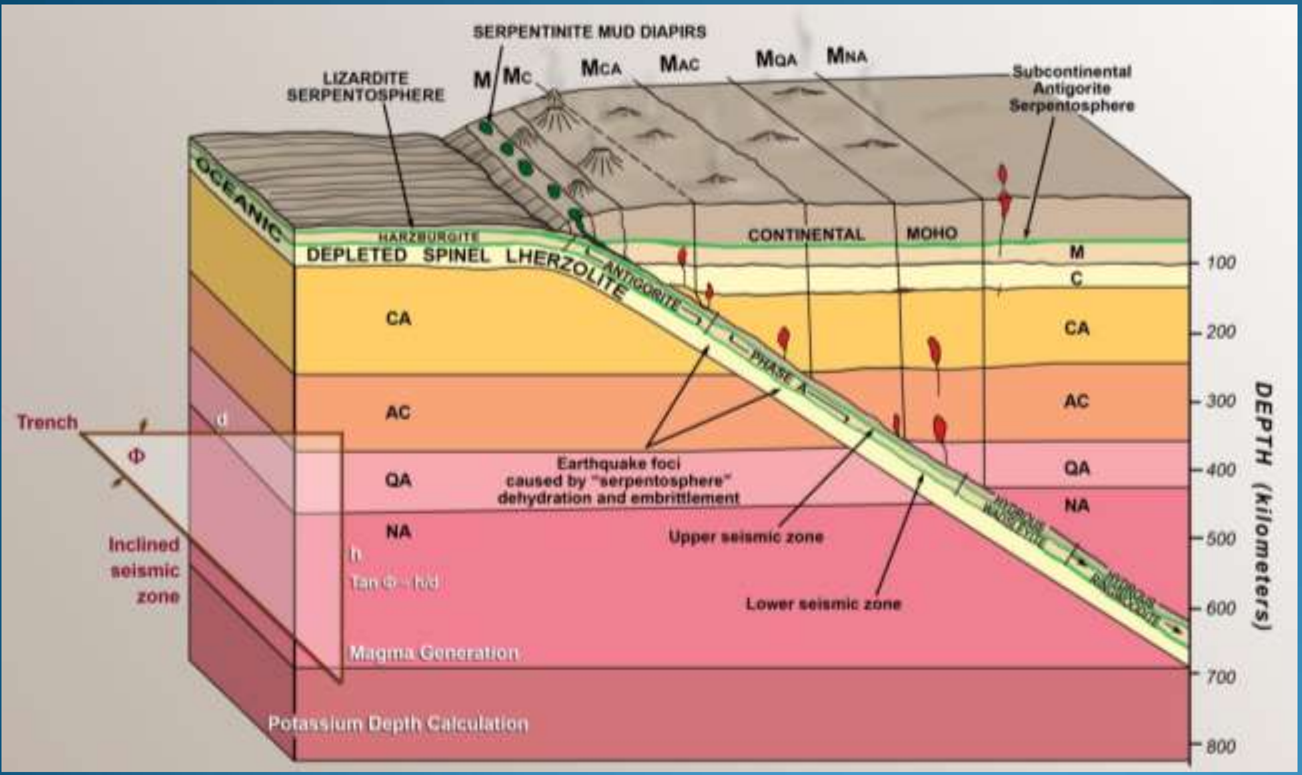
Extraction of Metal from the Layered Mantle Source Regions

- **Porphyry metal-related magmatism is extracted by volatile (mainly water)- induced melting of material from the layered mantle source in the hanging wall of a given subduction zone.**
- **While in the crust, subduction-related plutons assimilate supercritical water resident in the crust, which allow inheritance of 1) crustal oxidation state, 2) crustal isotopic signature, and 3) achieve hornblende stability.**

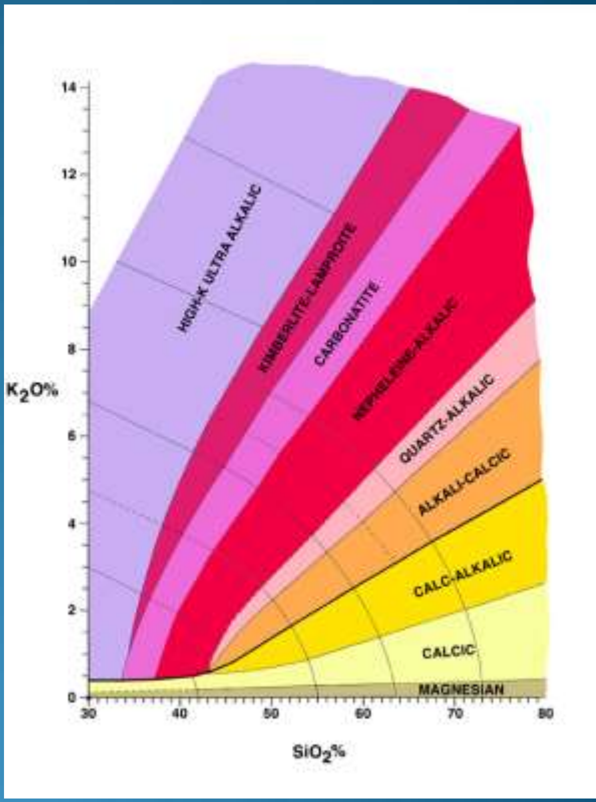


Source: Keith and Swan, 1996

Alkalinity and Potassium-Depth Ratios



Source: Keith, 1978



K2O vs SiO2 variation diagram with alkalinity fields

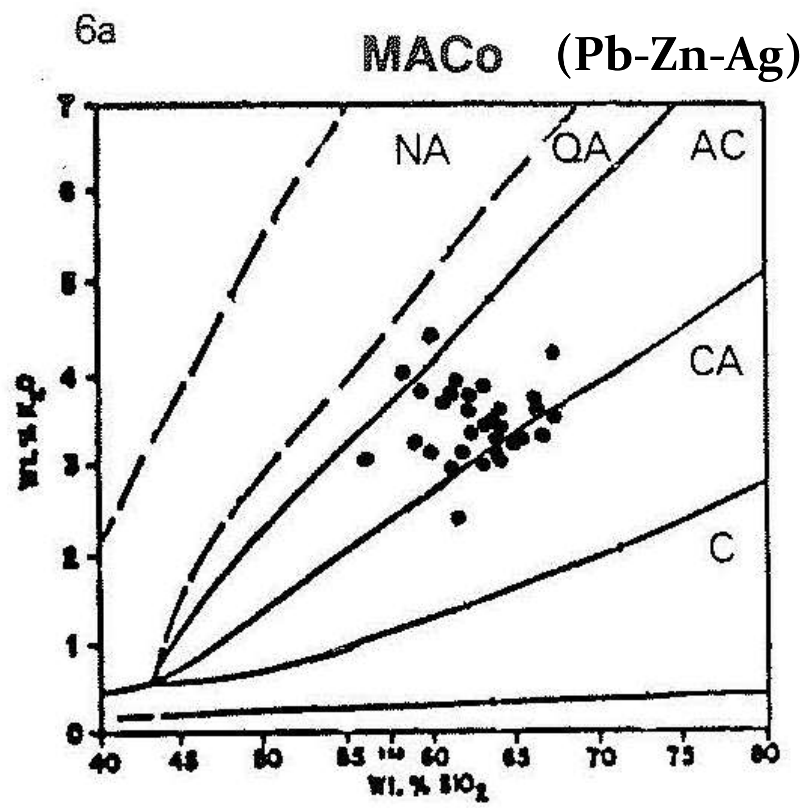
QA = Quartz alkalic = pink
AC = Alkali-calcic = orange
CA = Calc-alkalic = yellow
C = Calcic = pale yellow

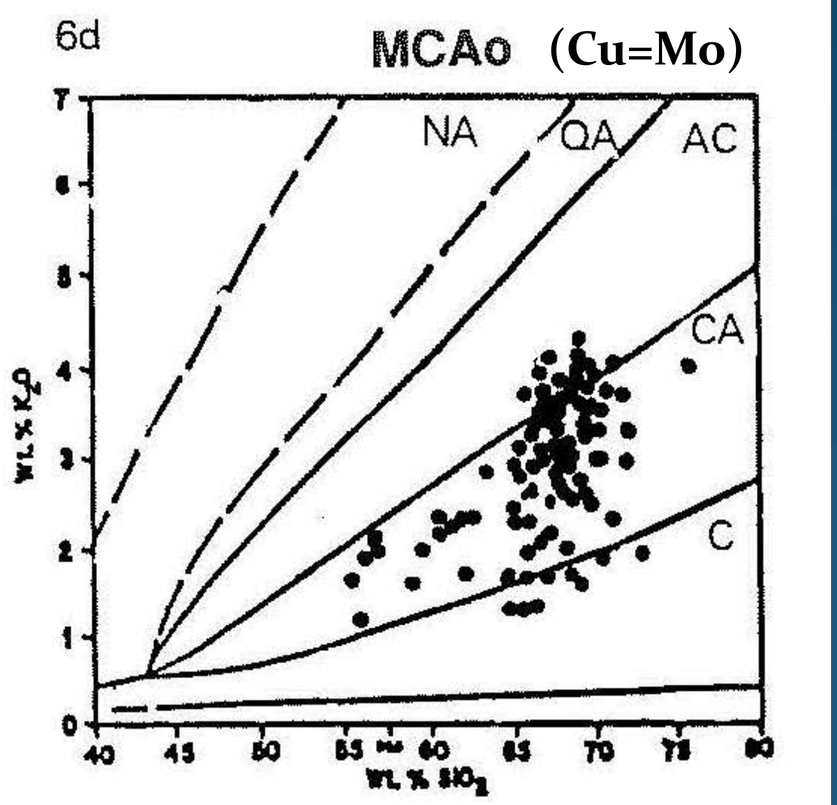
Alkalinity in mantle layers

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



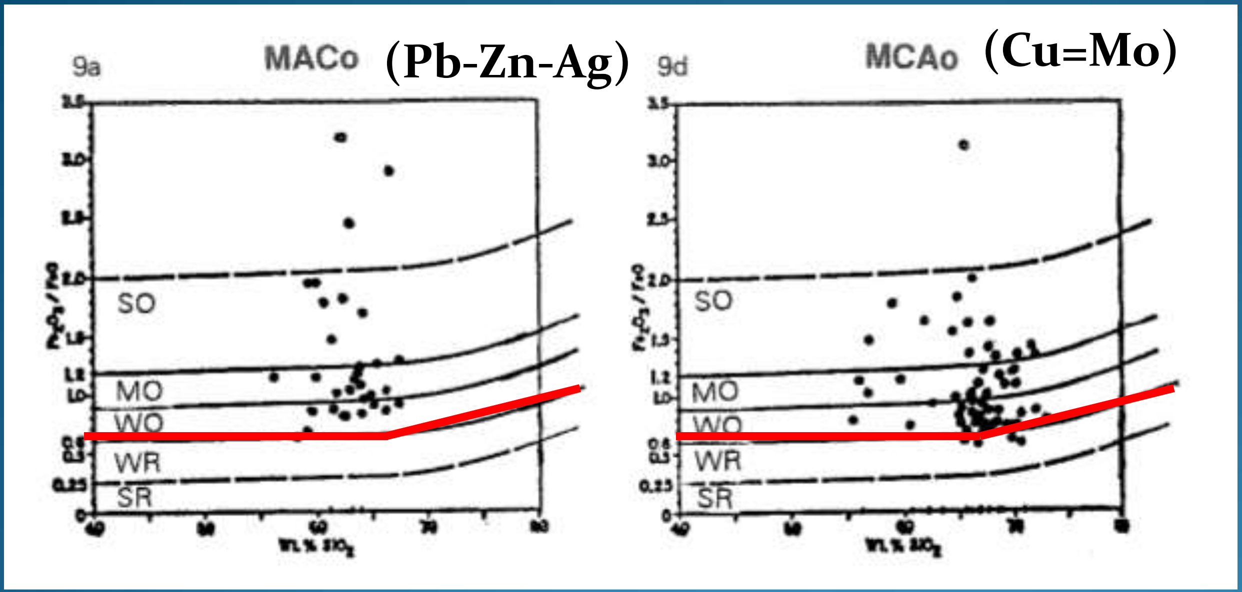


MAC = Metaluminous Alkali-calcic

MCA = Metaluminous Calc-alkalic

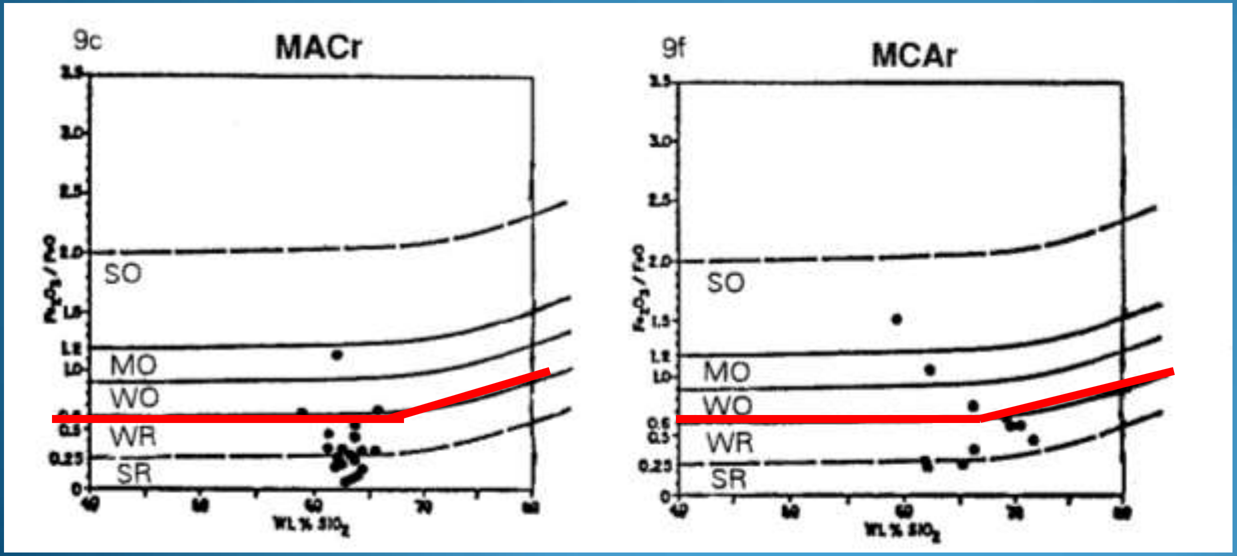
Whole rock chemistry of unaltered igneous rocks

Oxidized and Reduced plots



Oxidized = base metals ex. = AZ

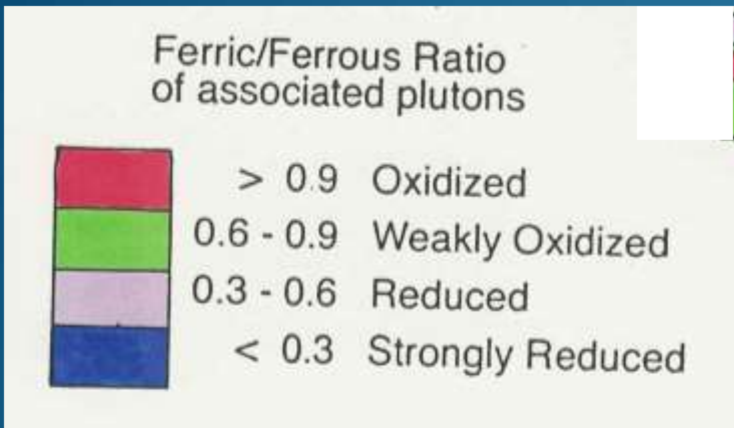
Y axis = wt% Fe2O3/FeO versus X-axis = wt% SiO2
Above ~0.5 = oxidized

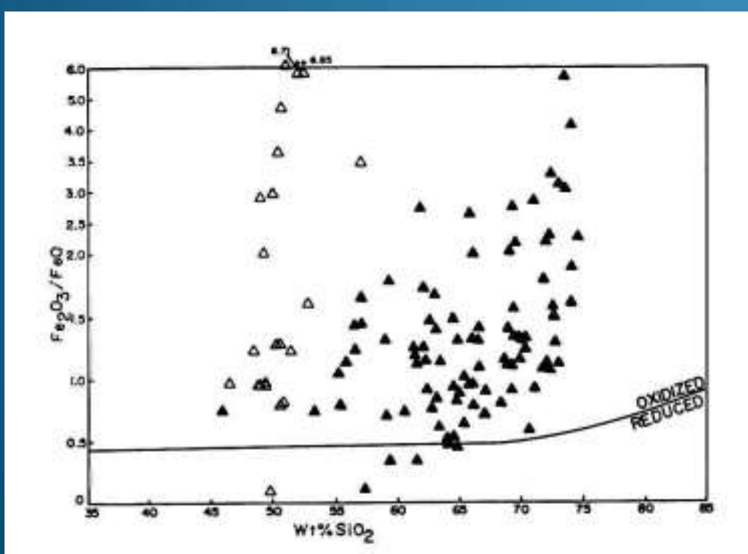


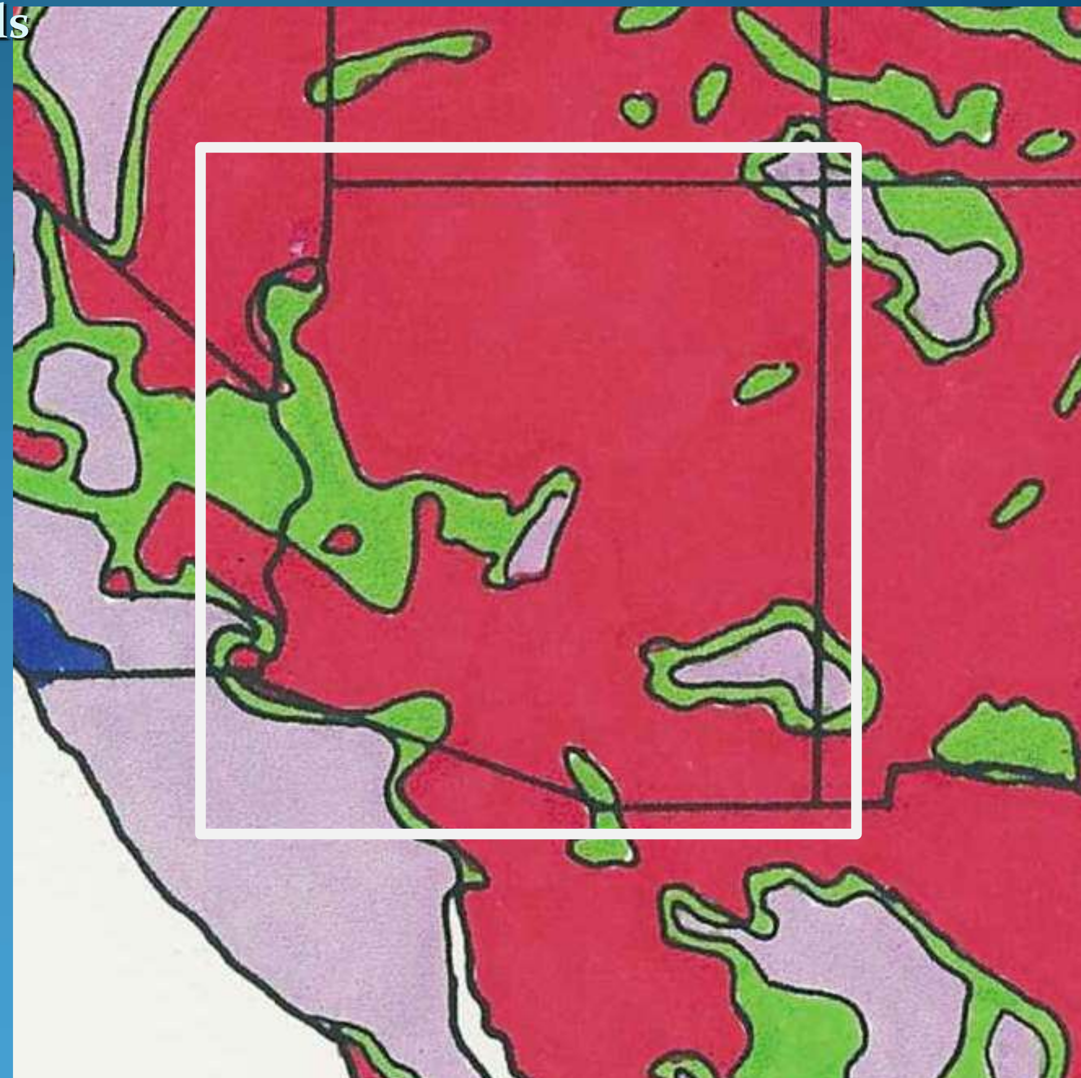
Reduced = precious metals ex. = NV

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.

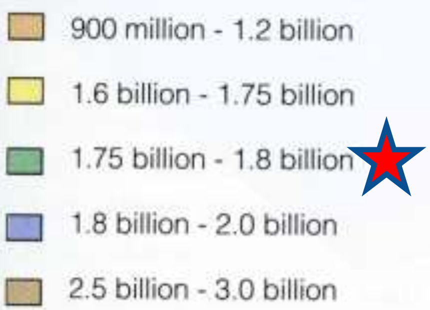
Source: Wicander, Historical Geology

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

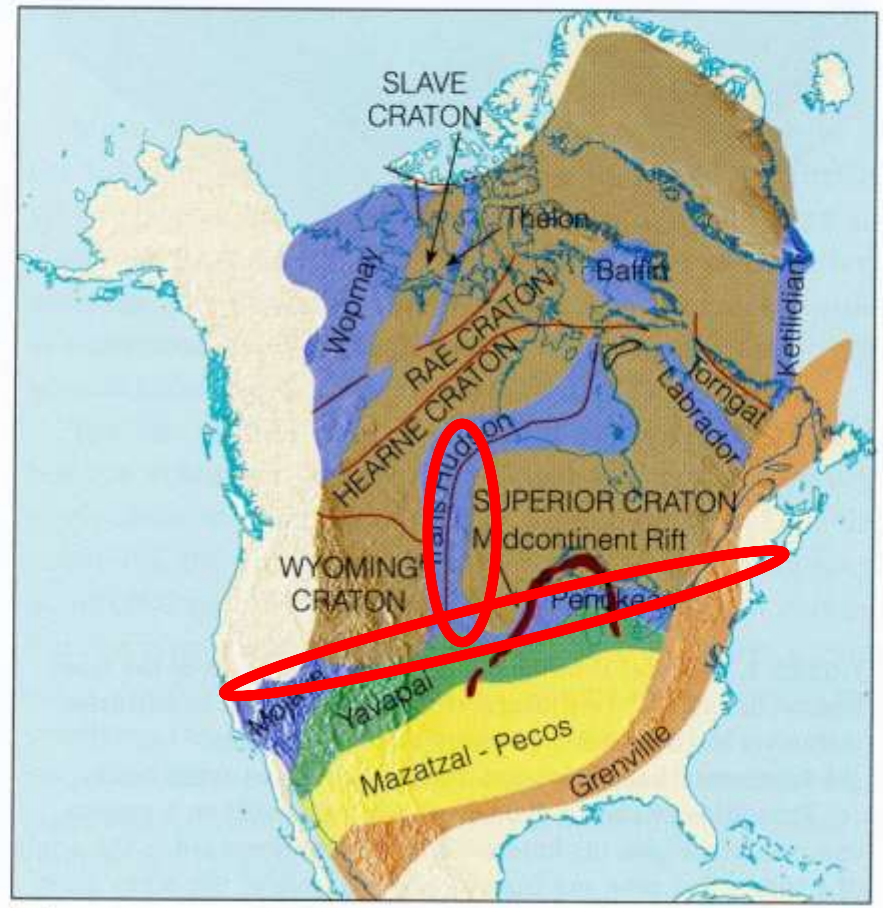
Hudsonian/Mohave Orogeny (2 – 1.8 Ga)

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



(c)

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Yavapai Orogeny – Pikes Peak BIF Banded Iron Formation

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

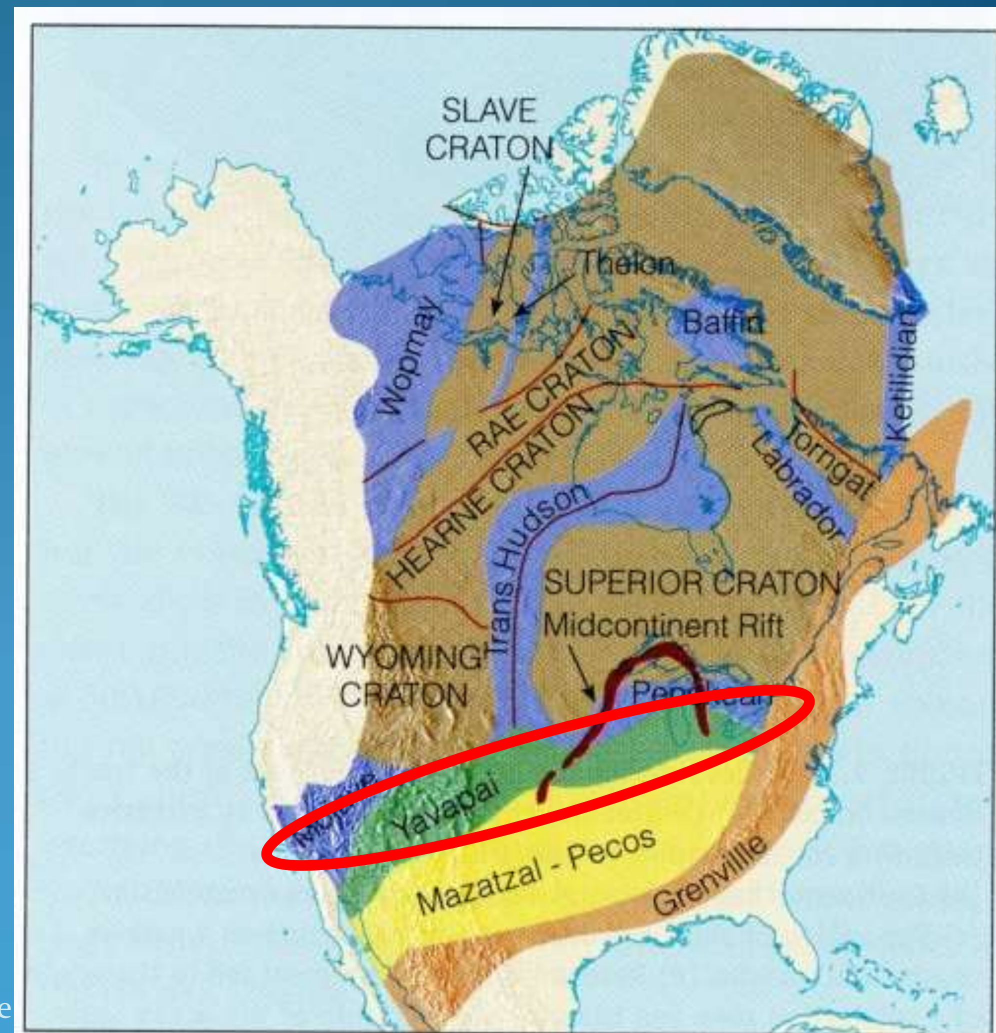
FIGURE 22. - Taconite-Like Hematite-Magnetite Iron Formation, Hieroglyphic Mountains, T 6 N, Rs 1 and 2 W, Maricopa County, Ariz. Note banded, laminated structure.

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

BIF Mingus Mountain (Jerome Historical museum) Paul Lindberg sample

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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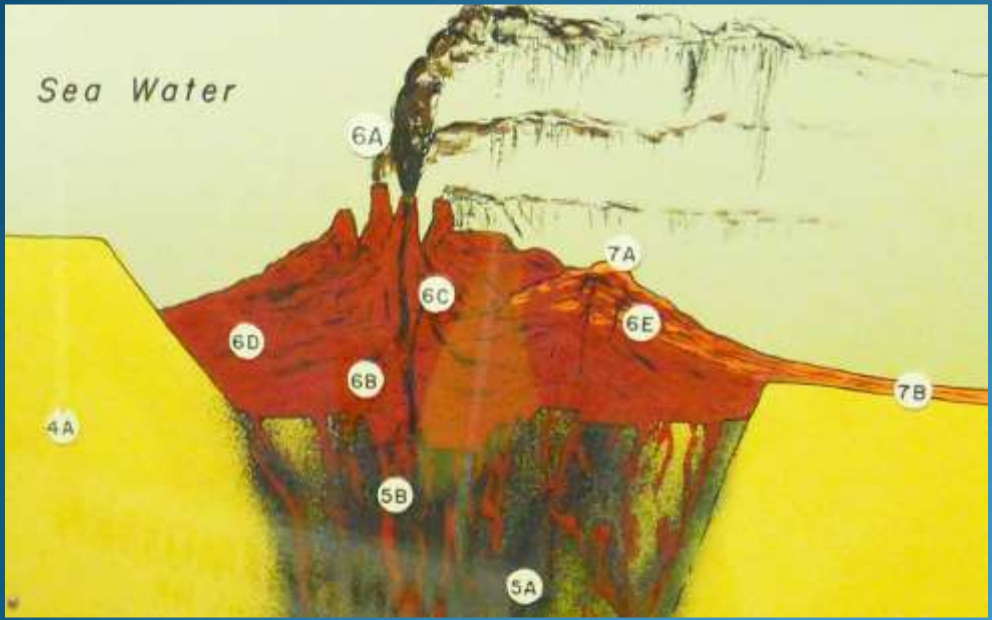


Jerome Volcanogenic Massive Sulfide

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

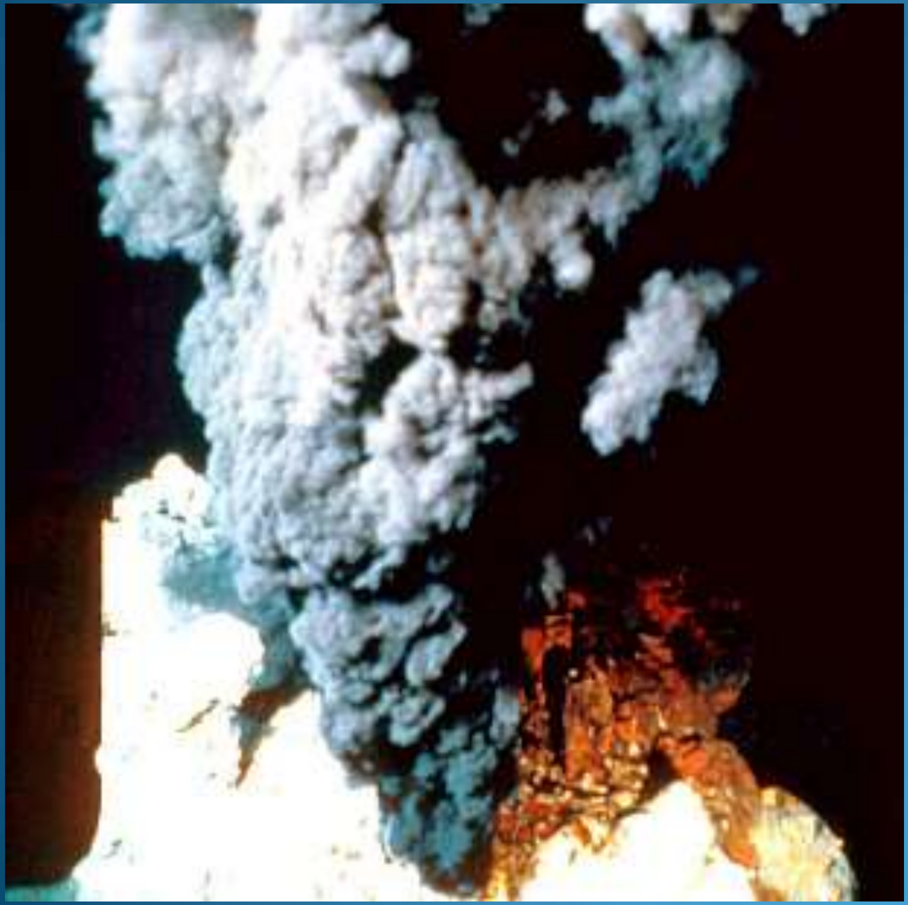
Verde dist. Prod. = 3,625,000,000 lb Cu
693,000 lb Pb
97,352,000 lb Zn
poss. 5,000,000,000 lb Zn reserves
1,579,000 oz Au
57,313,000 oz Ag

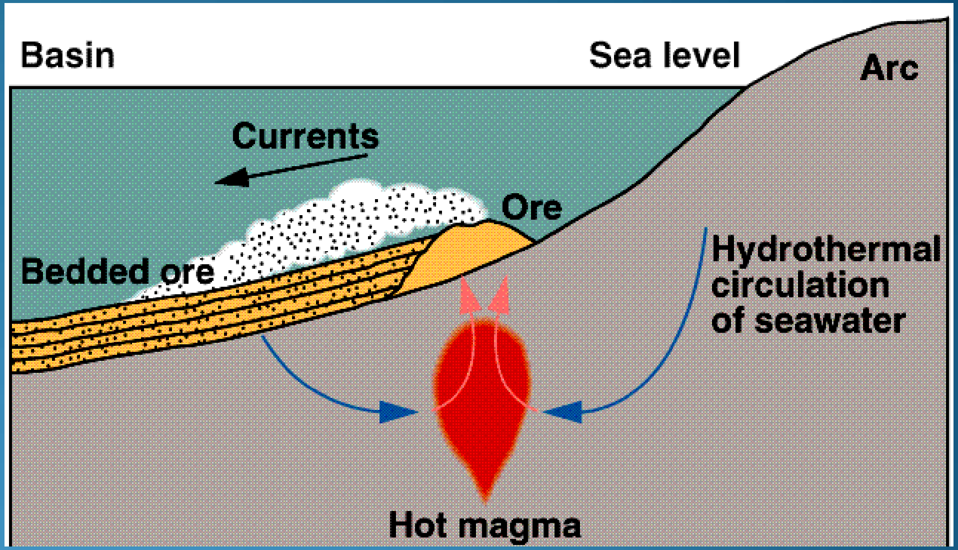
Volcanogenic Massive Sulfide

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

Yavapai - Jerome VMS (1800 – 1775 Ma)

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





Deposition of Volcanogenic Massive Sulfide ore

Black smoker, modern seafloor

Yavapai - Jerome (Verde m.d.) (1800 – 1775 Ma)

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

Chalcopyrite, United Verde mine, Jerome, AZ, AzMMM specimen

Tennantite, chalcopyrite - United Verde mine, Jerome, AZ, AzMMM sample

Bornite, chalcopyrite United Verde mine, Jerome, AZ AzMMM sample

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

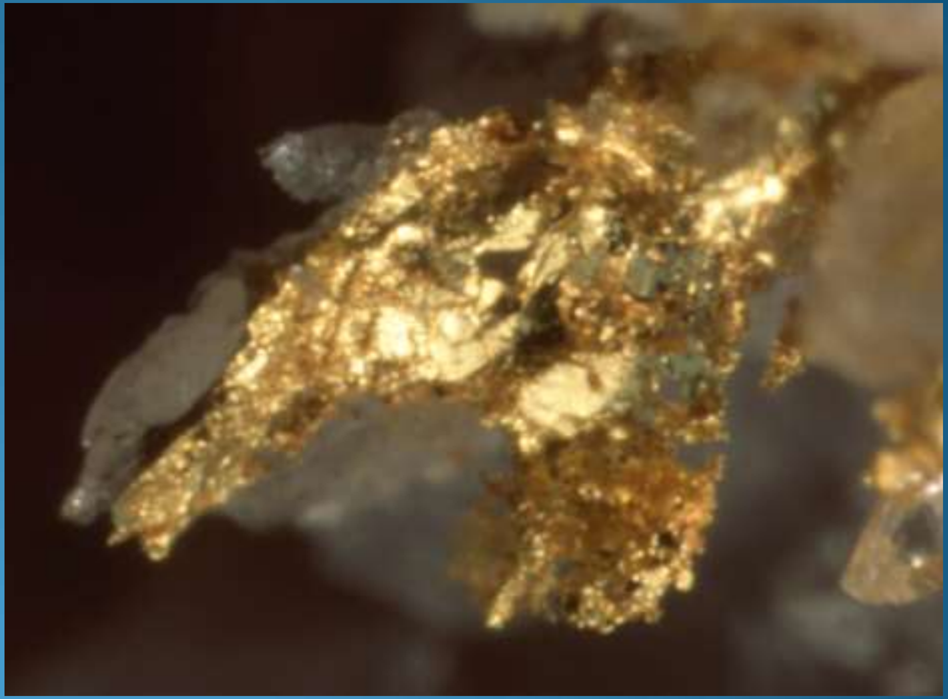
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Yavapai		1800-1775	MC	Zn-Cu-Au VMS, Zn-Cu-Ag VMS, BIF	Big Bug (Iron King), Verde (Jerome), Old Dick (Bruce), Pikes Peak Fe

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

The Bruce mine in the Old Dick mining district is a

- former underground Zn-Cu-Ag-Au-Pb-As-Co-Cd mine,
- volcanogenic massive sulfide deposit,
- Cu:Zn ratio = 1:3
- Sphalerite, galena, chalcopyrite

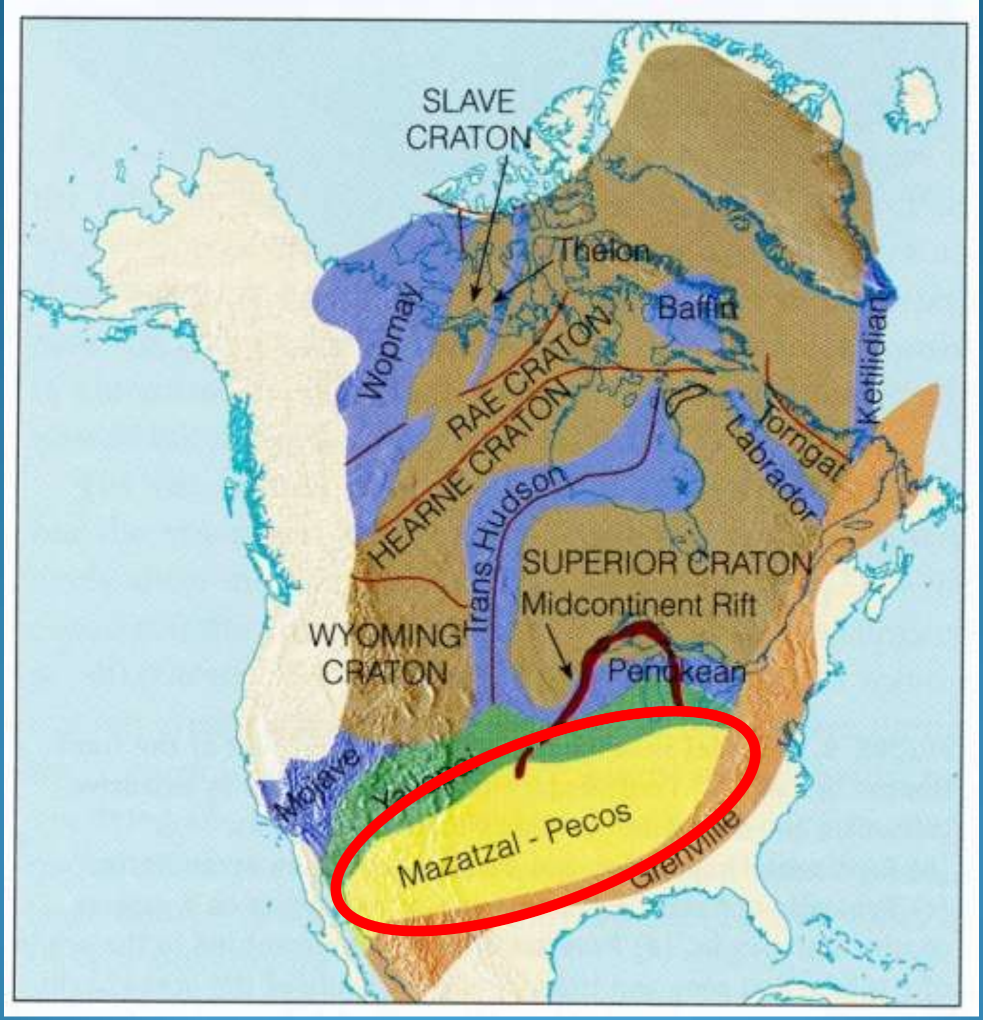
Calcite, Bruce mine, MinDat.org photo

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

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

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



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

- Tin (Sn) anomaly west of Young;
- Hg in Mazatzal Mtns.
- Hg production from Phoenix Mtns. Dist. (Dreamy Draw in Phoenix) – MACr vapor phase Hg hot spring deposits)
- Green Valley dist. (Gila Co.) 93,000 lb Cu
- 1,400 oz Au
- 5,300 oz Ag


Cinnabar (mercury sulfide) Sunflower dist, Maricopa Co

Early Oracle "anorogenic" 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

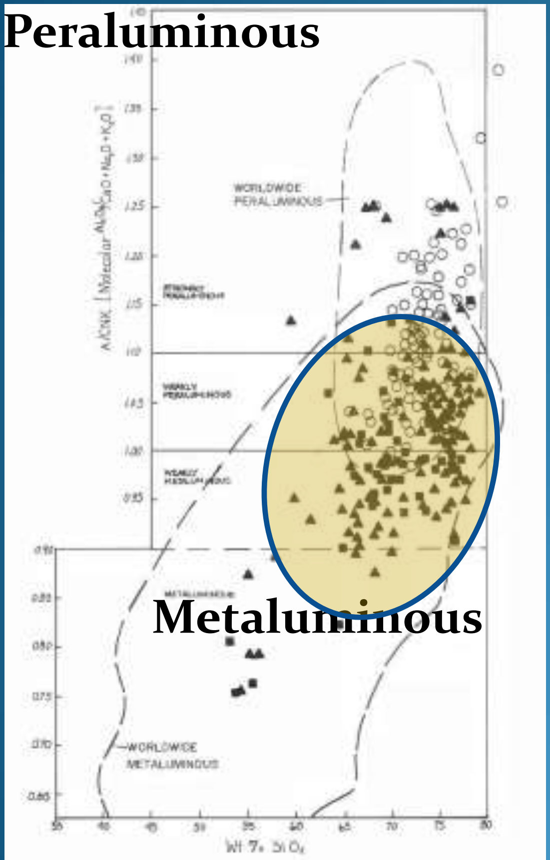


Figure 2. A/CNK versus weight percent silica variation diagram for peraluminous and metaluminous megaseries. For symbol key, see Figure 5. Data sources: Anderson (1983); Anderson (in press).

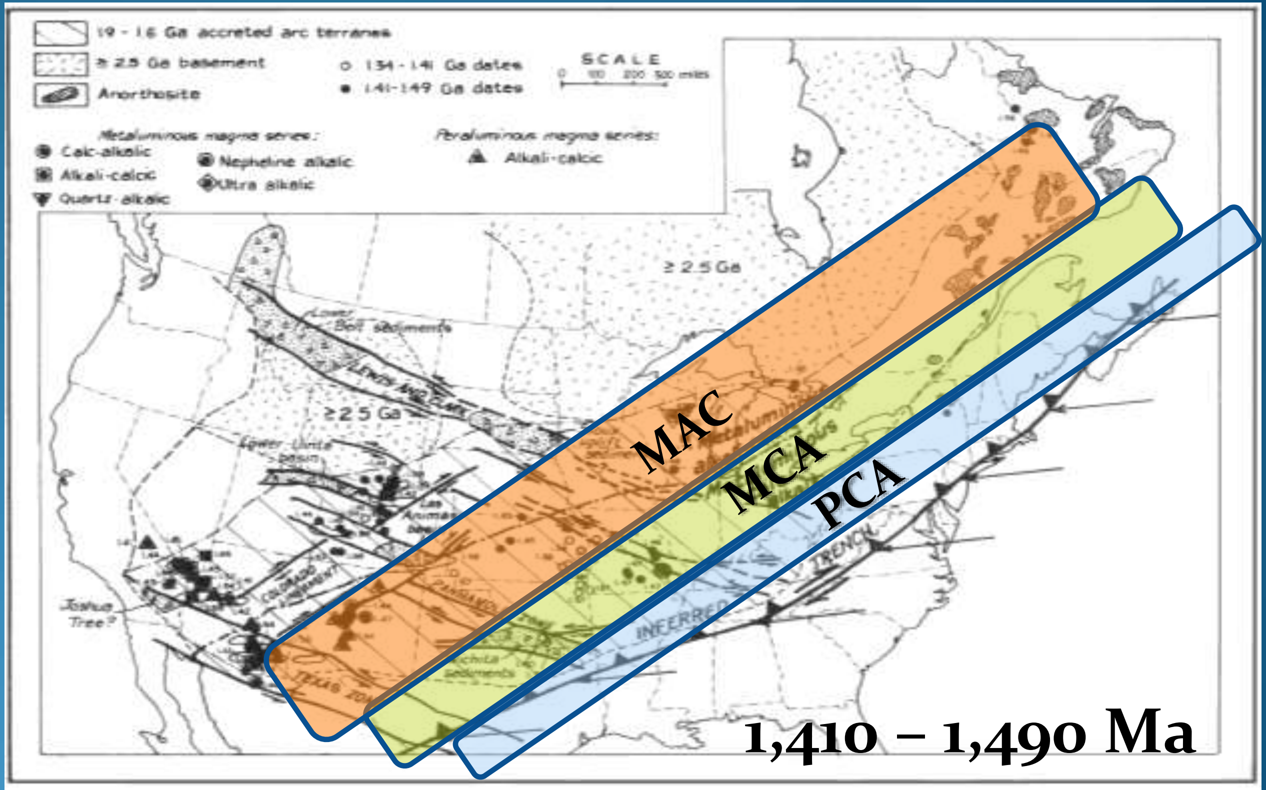


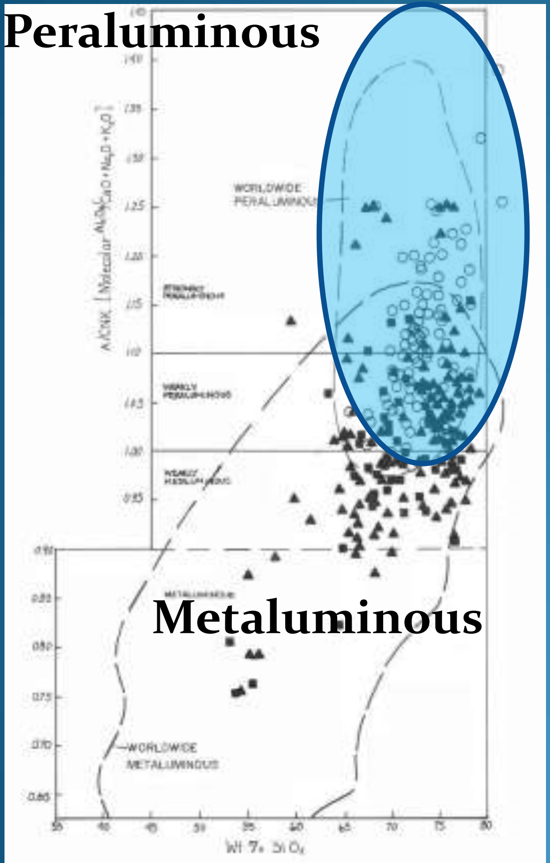
Figure 1. Distribution of 1.4 Ga magmatism and associated tectonic phenomena in North America. Data sources: Proterozoic age province, Nelson and Depaolo (1985); original base map, Anderson (1983).

Flattening subduction (MAC to MCA) to flat subduction (PCA) and crustal melting

Source: Swan & Keith, 1986

Oracle "anorogenic" 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



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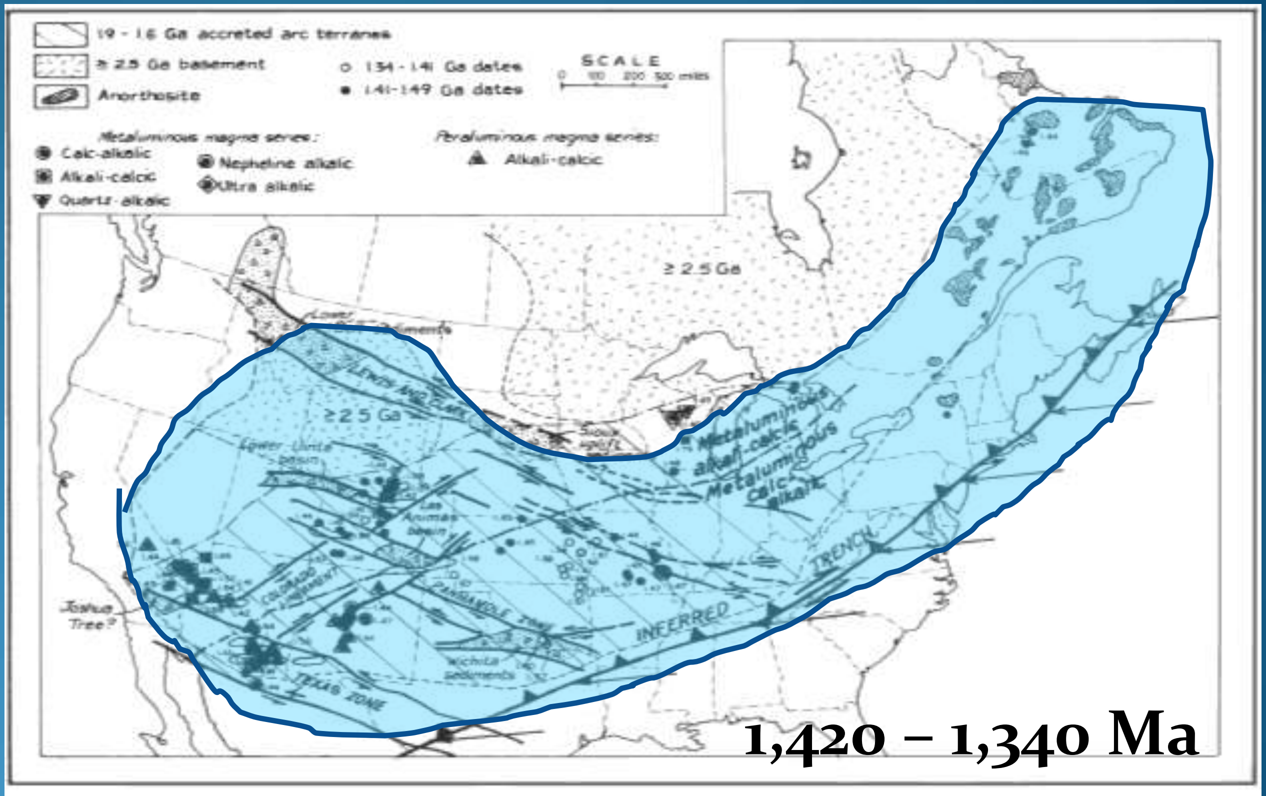

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Flattest subduction (PCA, PAC) and crustal melting

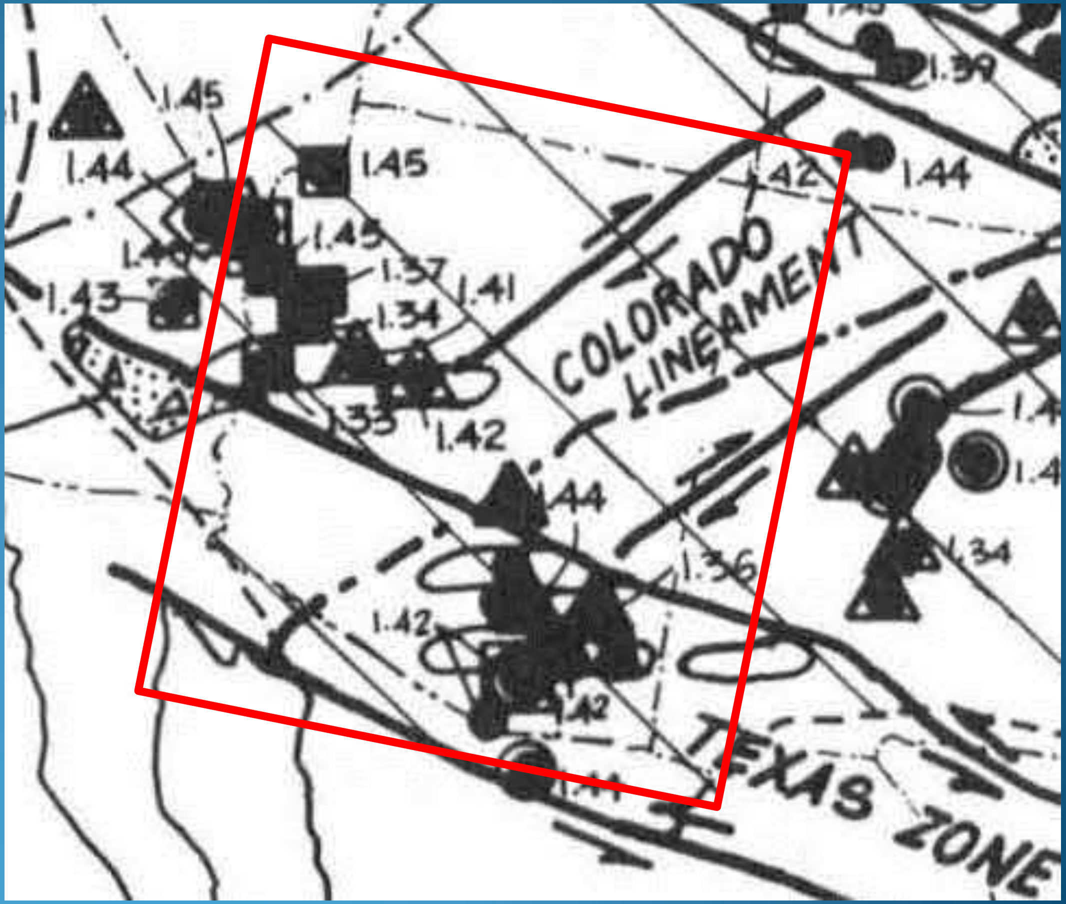
Source: Swan & Keith, 1986

Oracle "anorogenic" 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

Precambrian structures are important zones of weakness for later intrusions.

Whenever later stress regimes opened these cracks, metal-rich hydrothermal solutions rose upward and deposited ore.



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Oracle Granite, Santa Catalina Mts.

Tungstona district prod. (unknown dates) =

0 lb Cu
0 lb Pb
0 lb Zn
0 oz Au
0 oz. Ag
>7,449 stu W

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

Oracle Orogeny (1.44-1.335 Ga)

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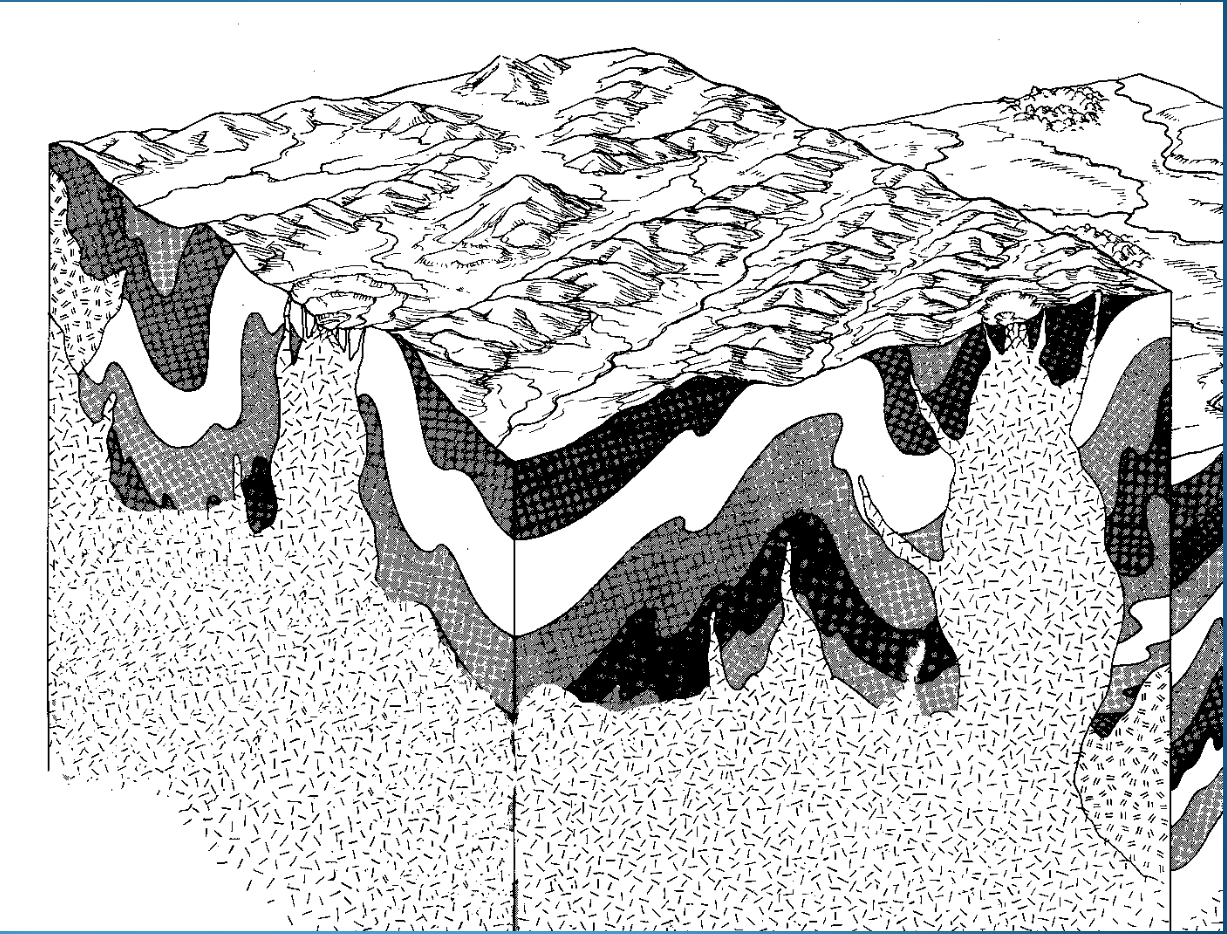
"Oracle/Ruin"		1440-1335	PCA; PAC	Be, Li, Ta-Nb, U & W	White Picacho, Tungstona, Four Peaks

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

This oxidized crust influenced later intrusions towards base metals when implosion of crustal fluids (water and soluble isotopes) established their oxidized nature.



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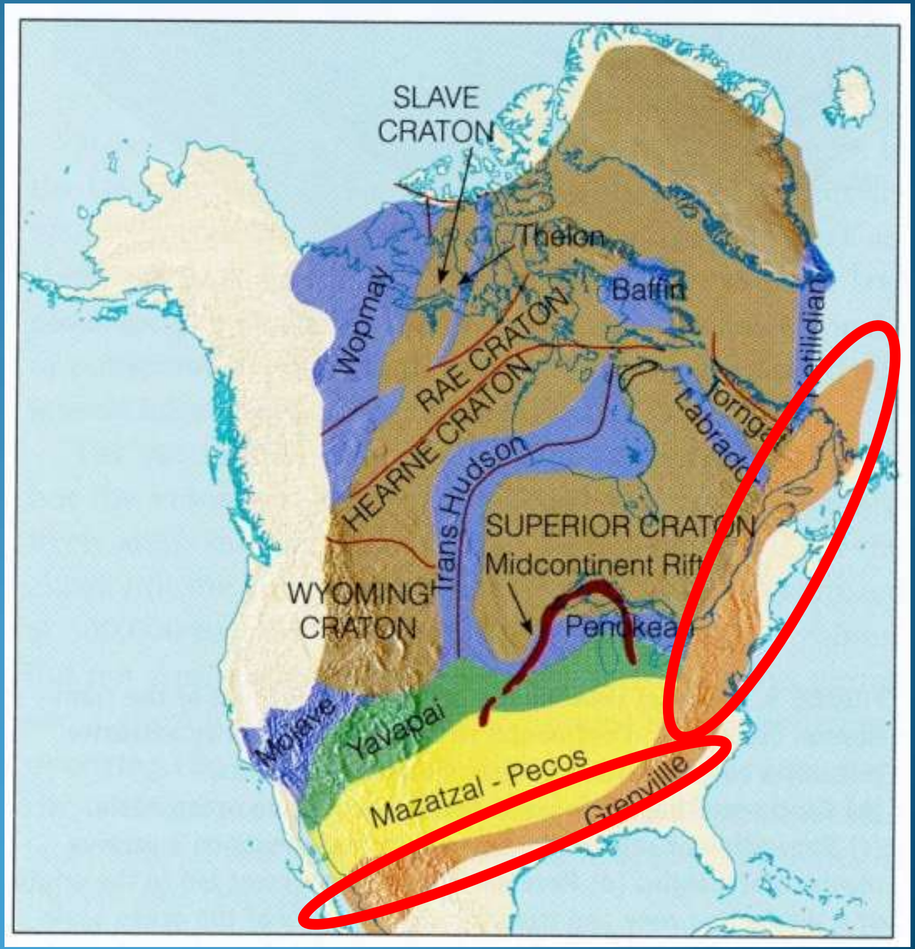
Amethyst, Four Peaks mine, Mazatzal Mts., Maricopa Co.

Amethyst, Four Peaks mine, photo by John Betts, mindat.org

Grenville Orogeny (1200-900 Ma)

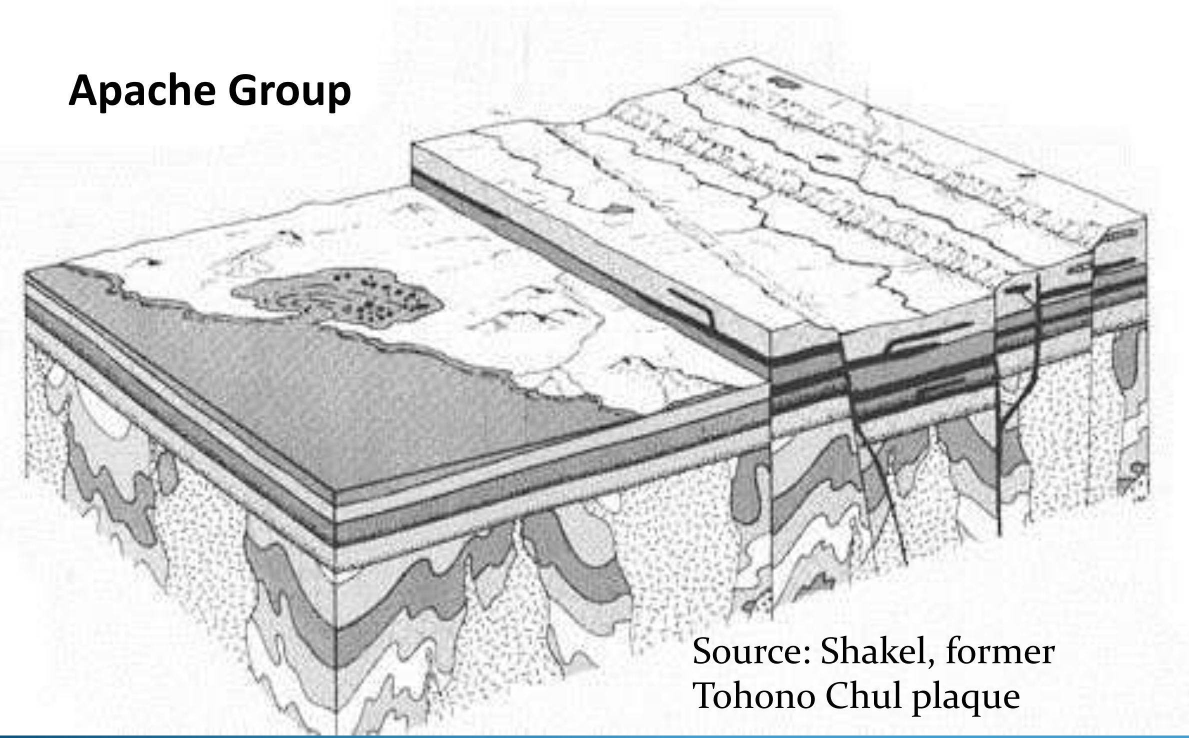
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Grenville		1200-900	MQA	Serpentine asbestos, U, (Cu)	Sierra Ancha U, Chrysotile (Salt R. Canyon)



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)



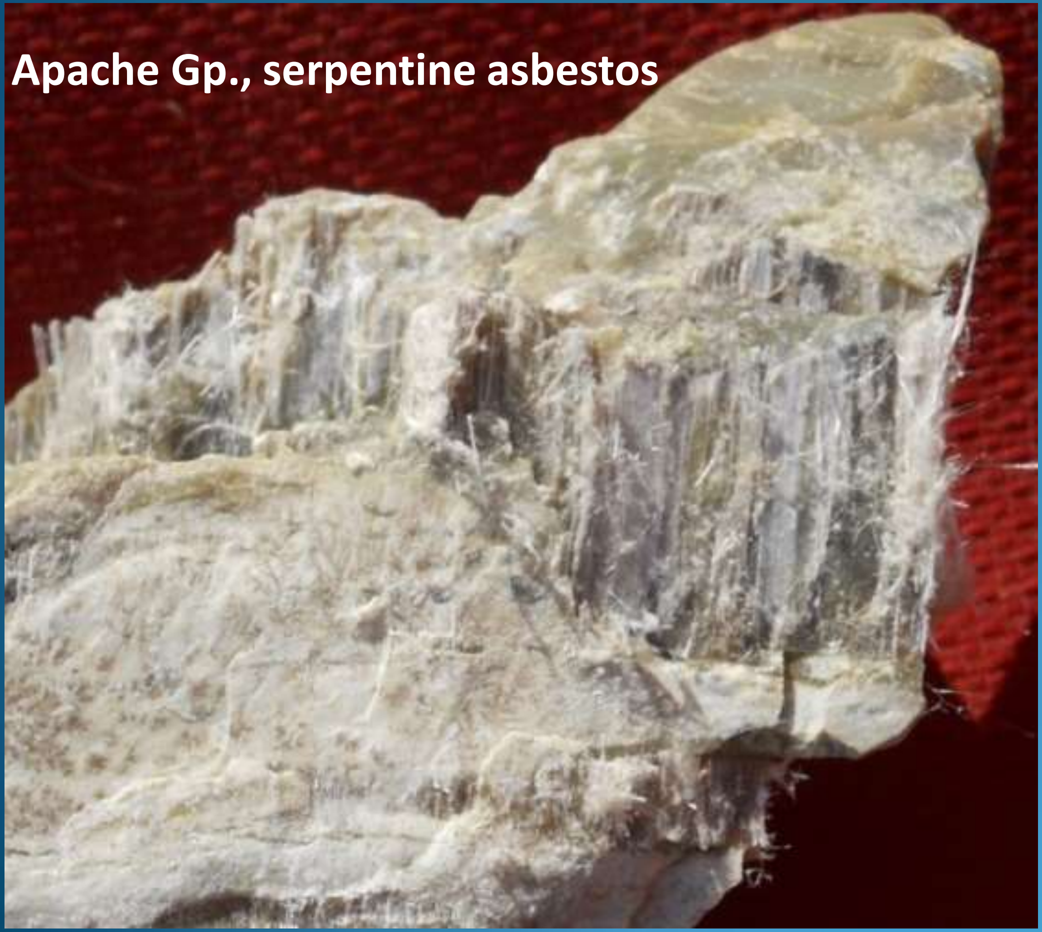
Source: Shakel, former Tohono Chul plaque

Apache Gp. ,Tohono Chul Park, Tucson

Rifting of continent – breakup of Rhodinia

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)

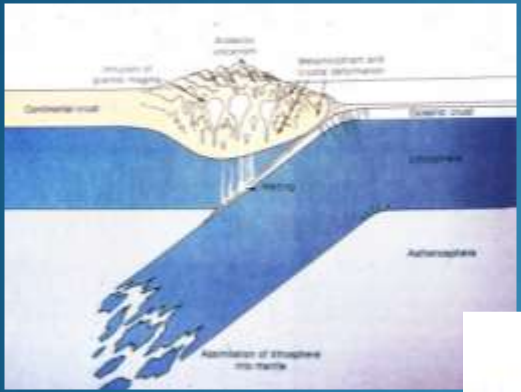


Diabase in Apache Gp. ,Tohono Chul Park, Tucson

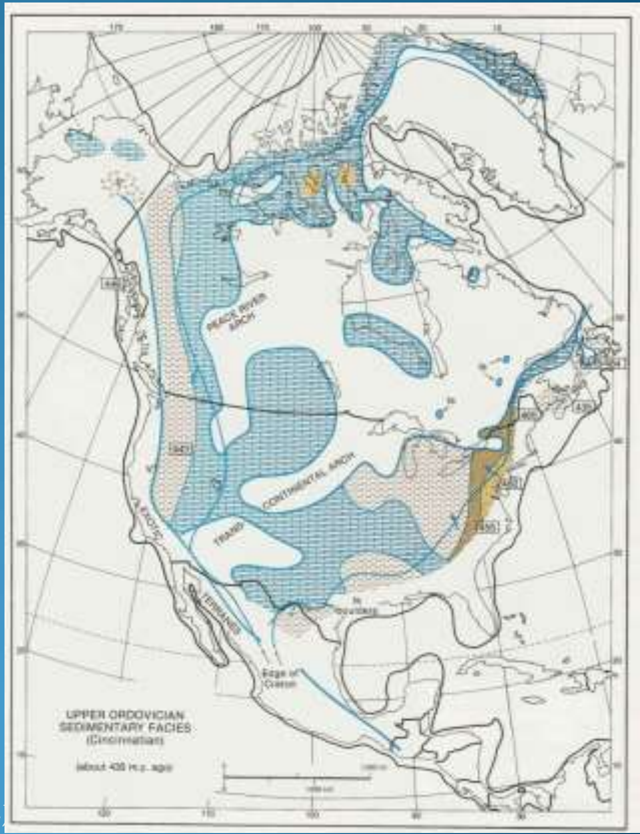
Diabase in contact with Mescal Limestone made marble and serpentine asbestos

Paleozoic Orogenies in eastern U.S.

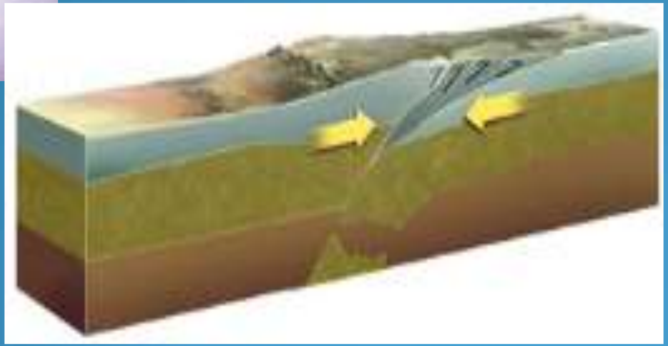
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Alleghenian (Ouachita)		325-252	-	U, NaCl, K_2CO_3	Payson uranium, Holbrook salt, potash
Lull between Acadian & Alleghenian		355-330		Limestone	Redwall Ls., Escabrosa Ls.
Acadian/ Caledonian/ Antler (NV)		410-370	-	UltraDeep 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).

Cambrian sedimentation in Arizona

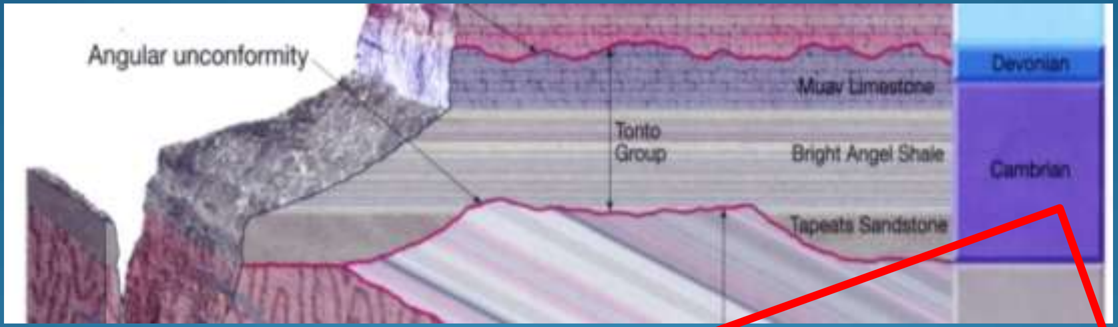
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Taconic.		460-430	-		Hosts for later replacement

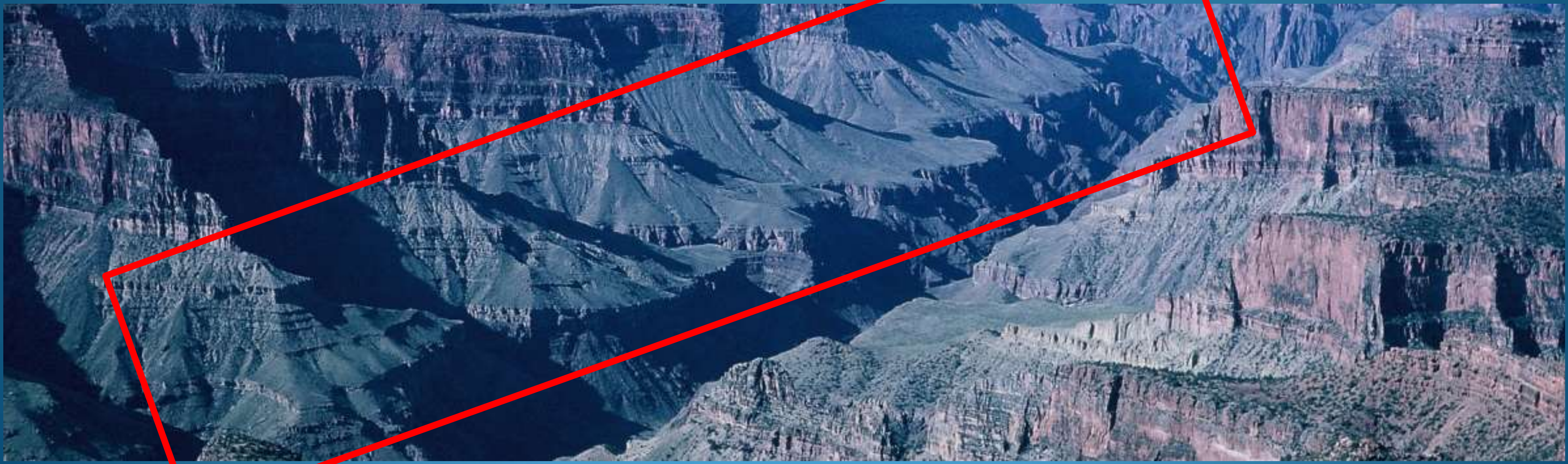
Cambrian and Devonian limestones are important hosts for base metal during later Laramide intrusions.

All paleo-geographic reconstructions from Blakey and Ranney

Cambrian sedimentation in Arizona

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Taconic.		460-430	-		Hosts for later replacement





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

Cambrian sedimentation in Arizona

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Taconic.		460-430	-		Hosts for later replacement

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

Acadian/Caledonian sedimentation in Arizona

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Acadian/ Caledonian/ Antler (NV)		410-370	-	UltraDeep Hydrocarbon?	Percha black shale

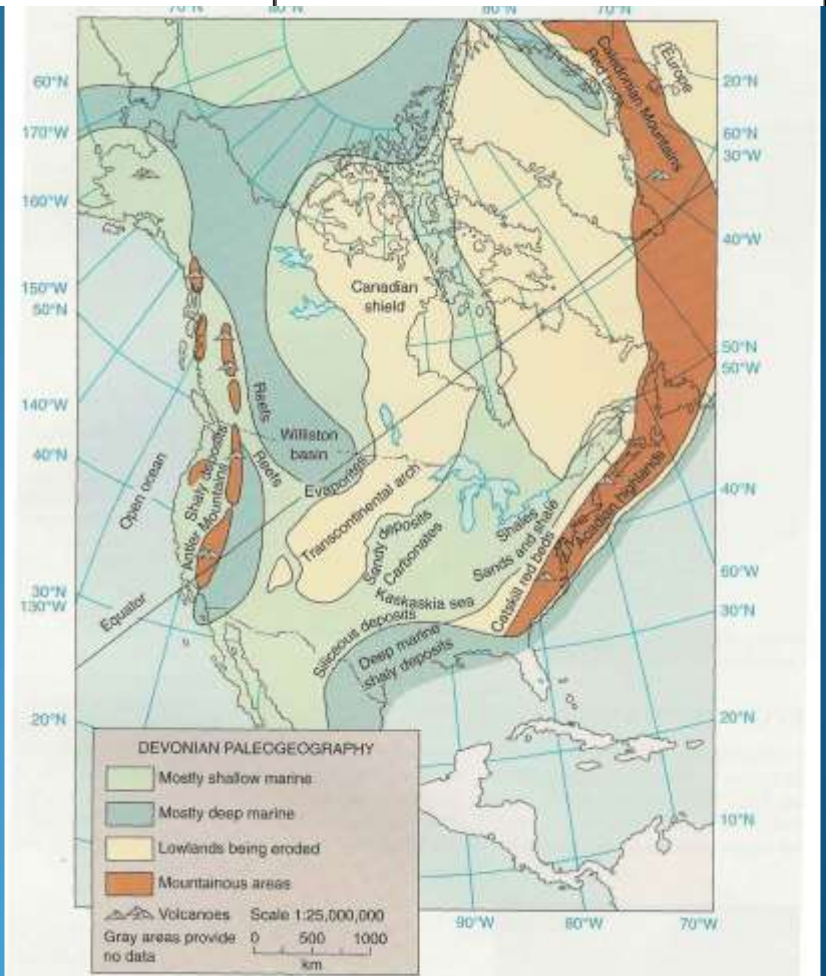


FIGURE 9-4 Paleography of North America during the Devonian Period.

All paleogeographic paintings from Blakey & Ranney

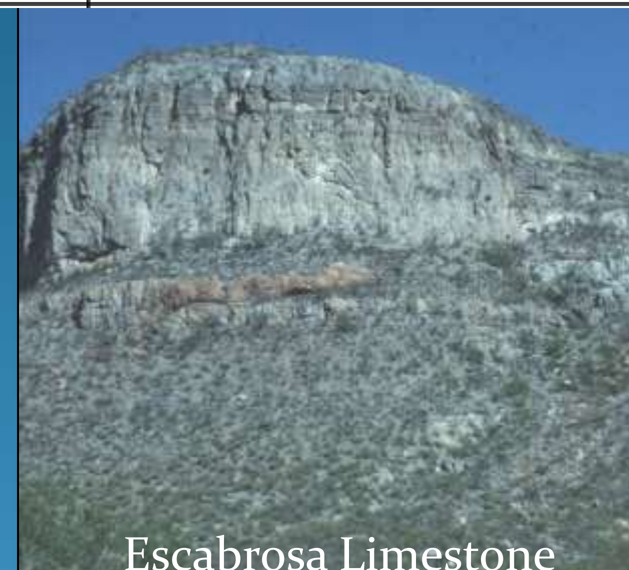
Antler orogeny in Nevada – AZ - Percha Fm. time – possible UltraDeepHydrocarbon system black shale – Payson 'diamond' quartz

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

Late Paleozoic sedimentation in Arizona

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Alleghenian (Ouachita)		325-252	-	U, NaCl, K_2CO_3	Payson uranium, Holbrook salt, potash

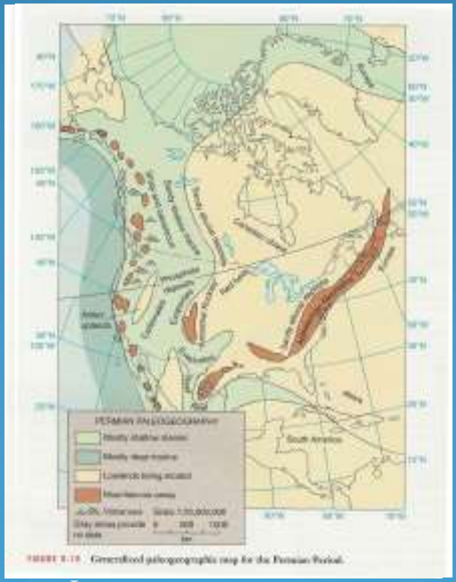
Salt – potash – Holbrook basin

Grand Canyon

Mid-Permian assembly/ice age

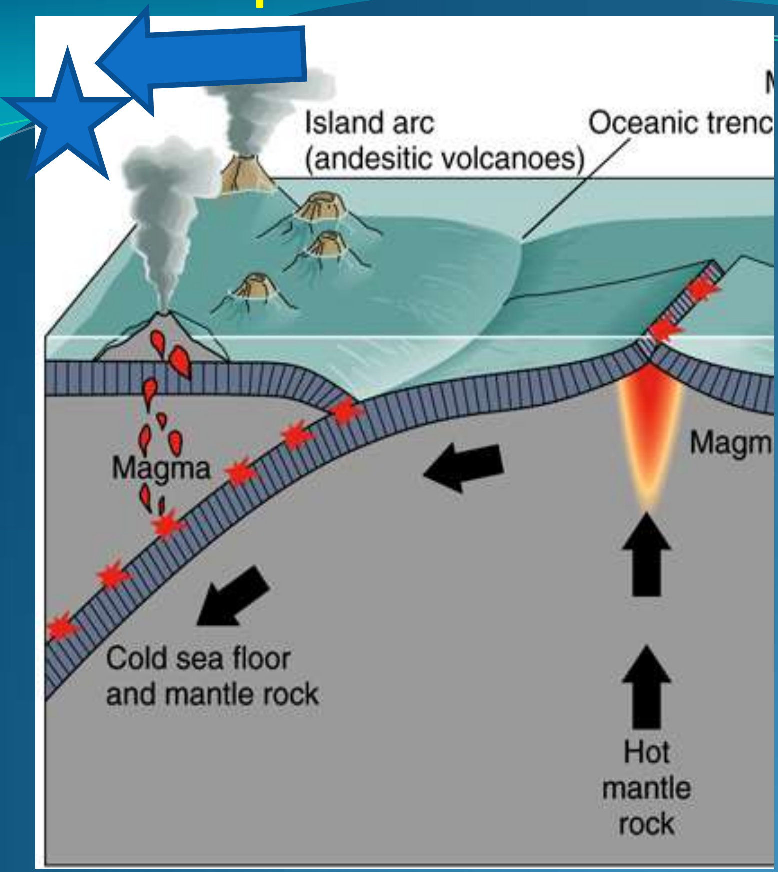
Sedona – Supai Group

Naco gp., Government Butte, S. of Tombstone



Goosenecks of the San Juan R., Hermosa Fm.

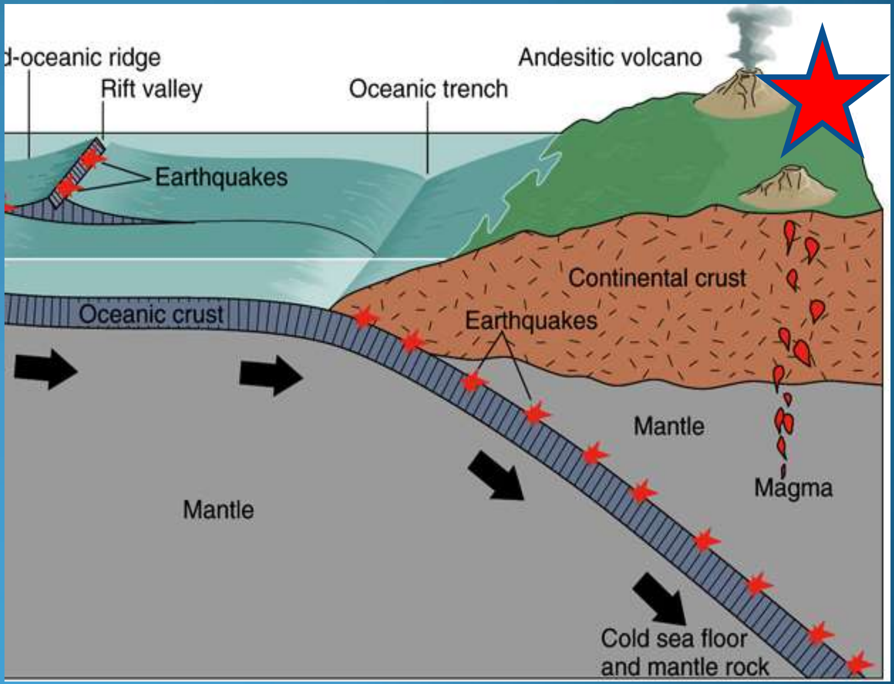
Arizona's position switched with respect to plate tectonics after Paleozoic



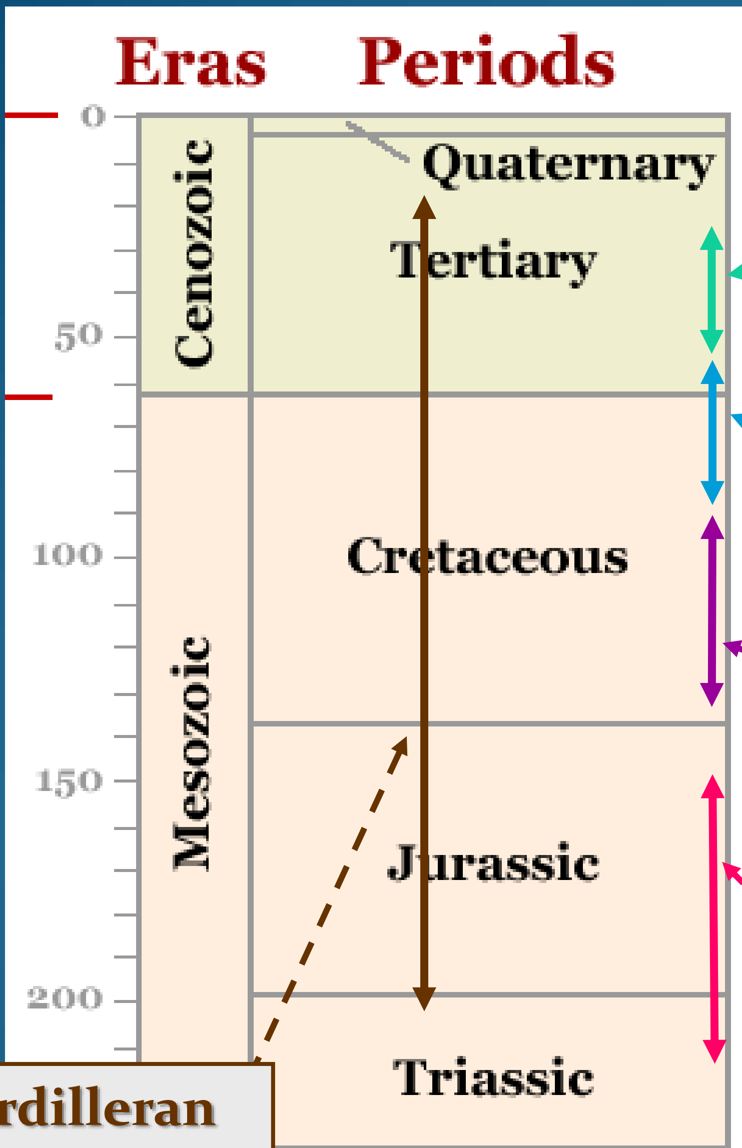
Paleozoic – Arizona was on trailing edge of N. American continent = calm seaways = no metals

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 orogenic styles



Subduction styles

Galiuro Orogeny (38 – 15 Ma)
sinking slab minor metallogeny

Laramide Orogeny (89 – 40 Ma)
basement-involved compression, slab flattening, magmatism, major metallogeny

Sevier Orogeny (~130 – 89 Ma)
continent margin magmatism, thin-skinned thrust faulting, constant dip subduction

Nevadan Orogeny (~230 – 145 Ma) arc collision, magmatism, thrust faulting, slab flattening

Cordilleran Orogeny (230 – 15 Ma)

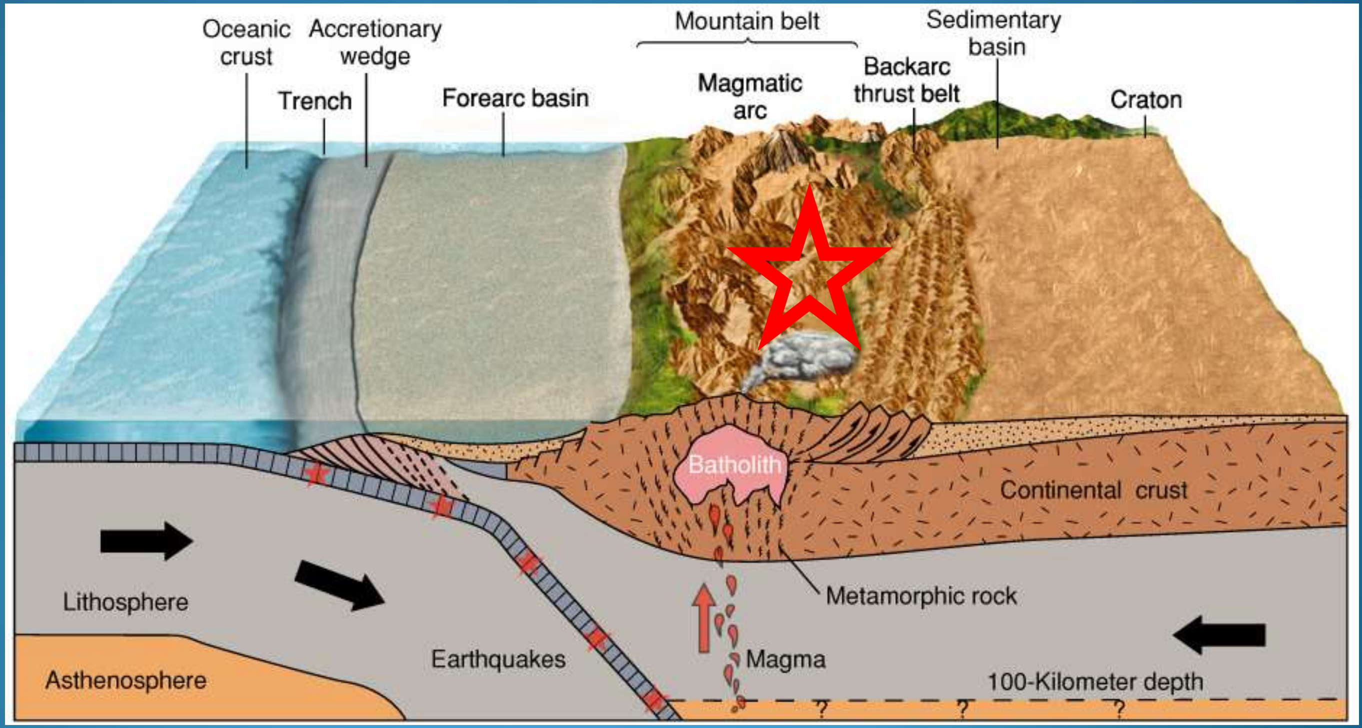
Cordilleran magmatism & resources

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)
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

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



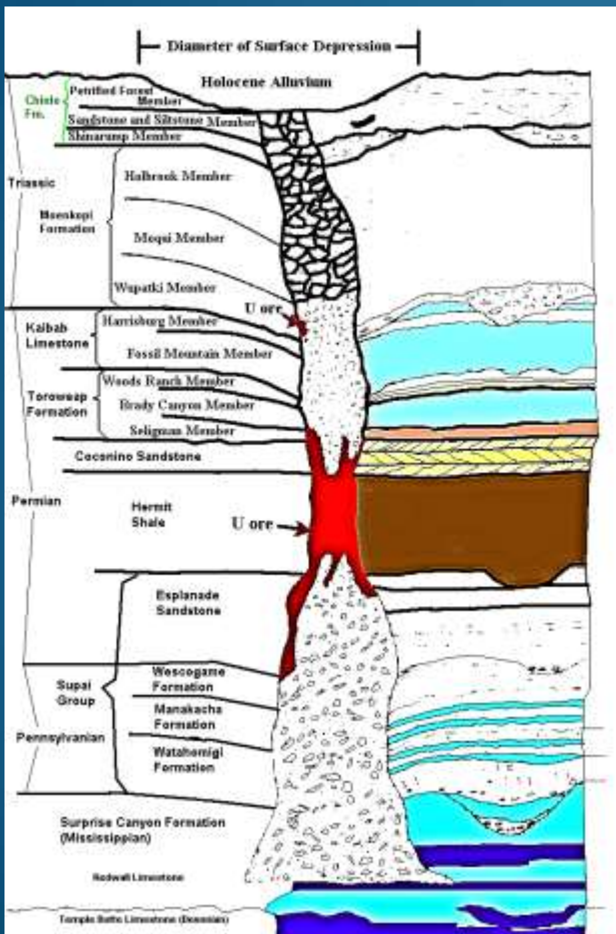
Early Nevadan Orogeny (230-205 Ma)

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

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



Source: K. Wenrich

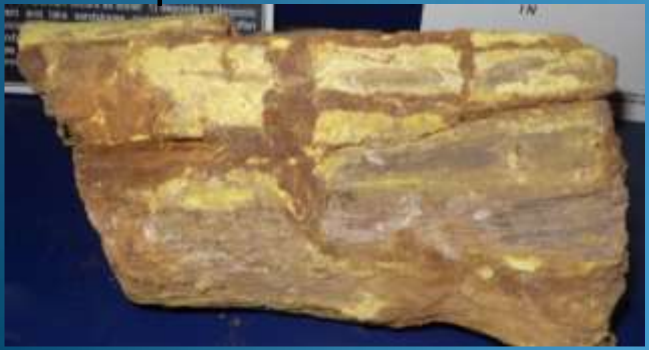
Breccia pipe in Grand Canyon

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

Ridenour mine; tyuyamunite, $Ca(UO_2)_2(V_2O_8)\cdot 5\text{-}8H_2O$
Wenrich photo

Grandview mine; cyanotrichite on antlerite
AzMMM specimen



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
(1961-1965) -
4,360,000 lb U

Middle Jurassic arc magmatism

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
	Early	230-205	MQA	U, V, Cu	Orphan, Grandview, Monument Valley

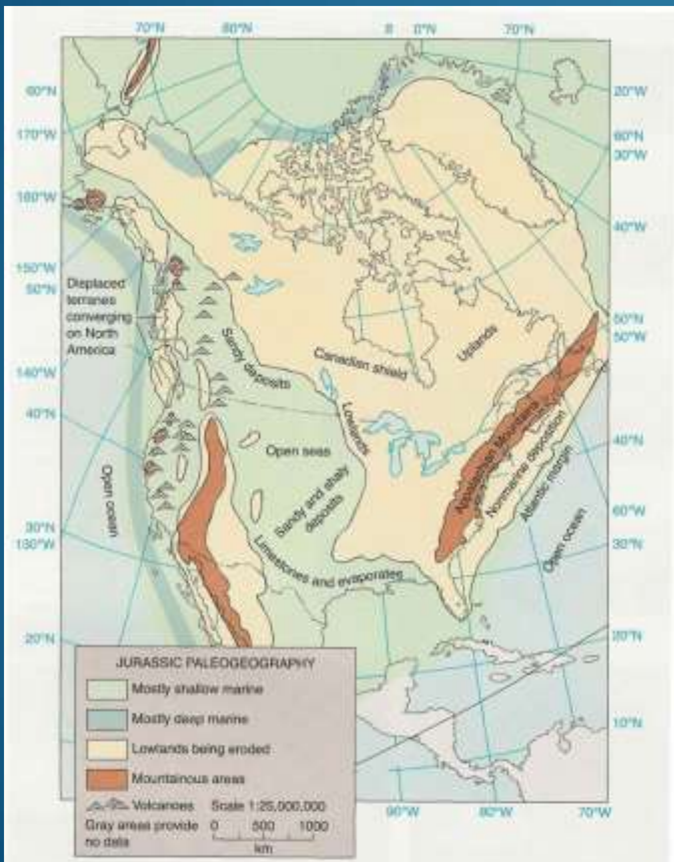


FIGURE 11-7 Generalized paleogeographic map for the Jurassic of North America.

All paleogeographic paintings from Blakey & Ranney

Jurassic arc magmatism

Orogeny	Orogenic Phase	Age (Ma)	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

Santa Rita Mts., Mt. Wrightson

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

Middle Nevadan - Warren m.d. (Bisbee)

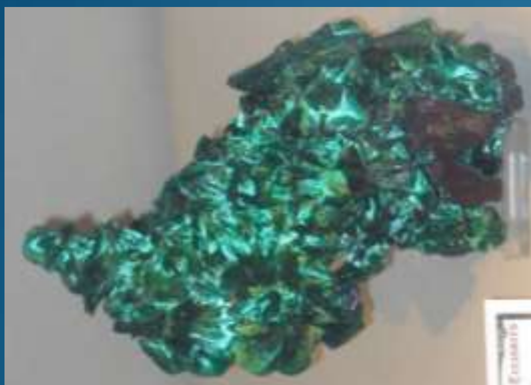
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Nevadan	Middle	205-180	MQA	porphyry Cu-Au	Warren (Bisbee mine), Turquoise (Courtland), Yuma King

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 prod. (1880-1981) =
7,865,827,000 lb Cu
324,255,000 lb Pb
copper
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

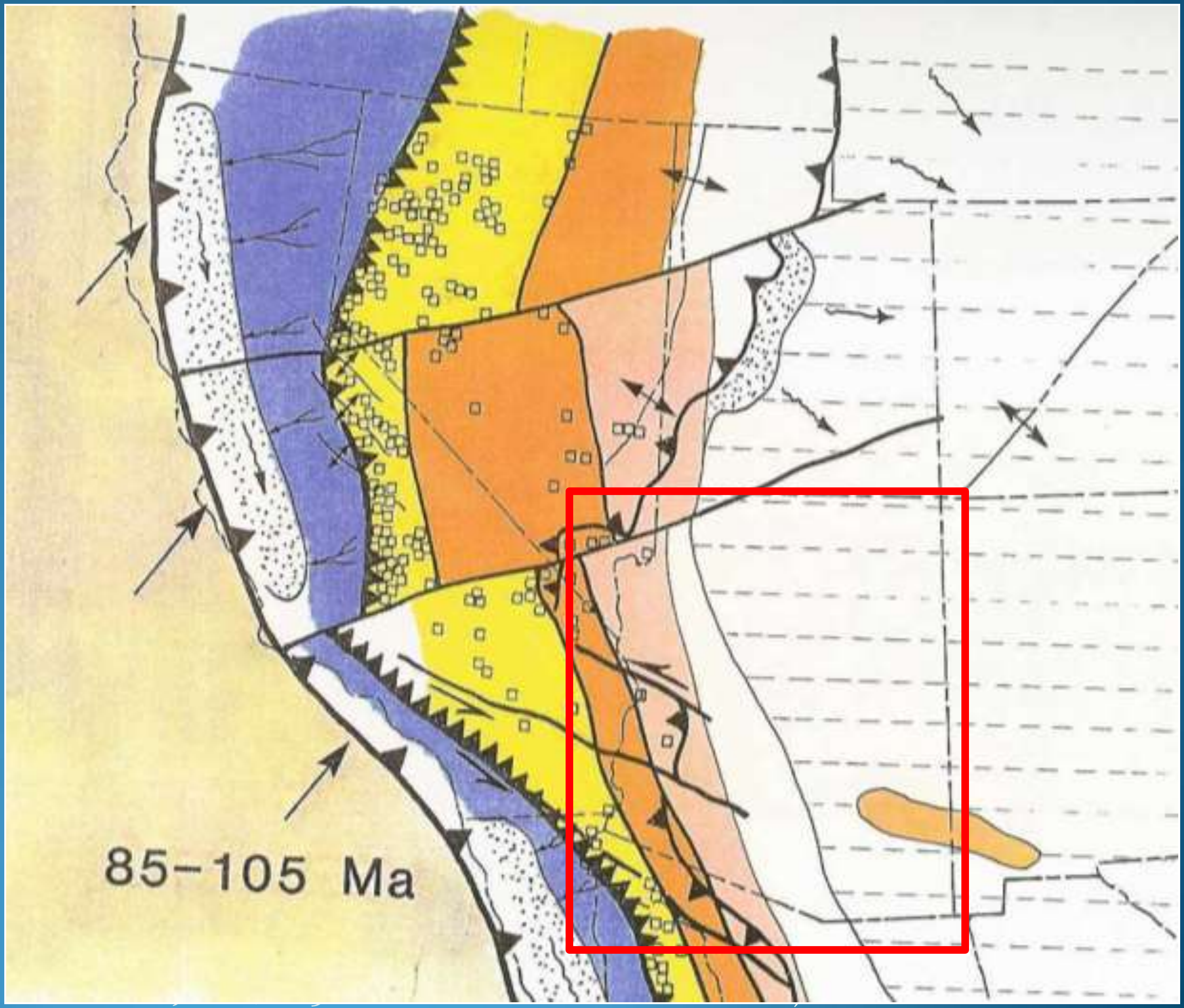
Defiance mine, wulfenite, Donor: Les Presmyk

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)

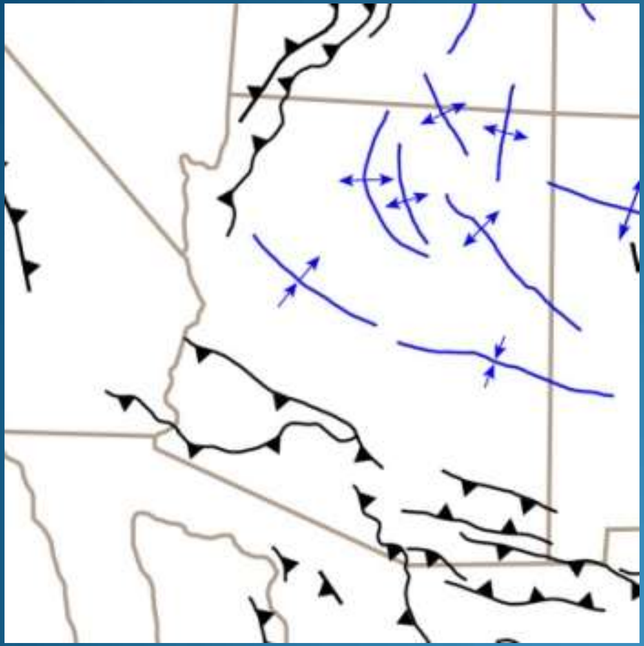
Pink = MQA
Orange = MAC
Yellow = MCA
Blue = PC

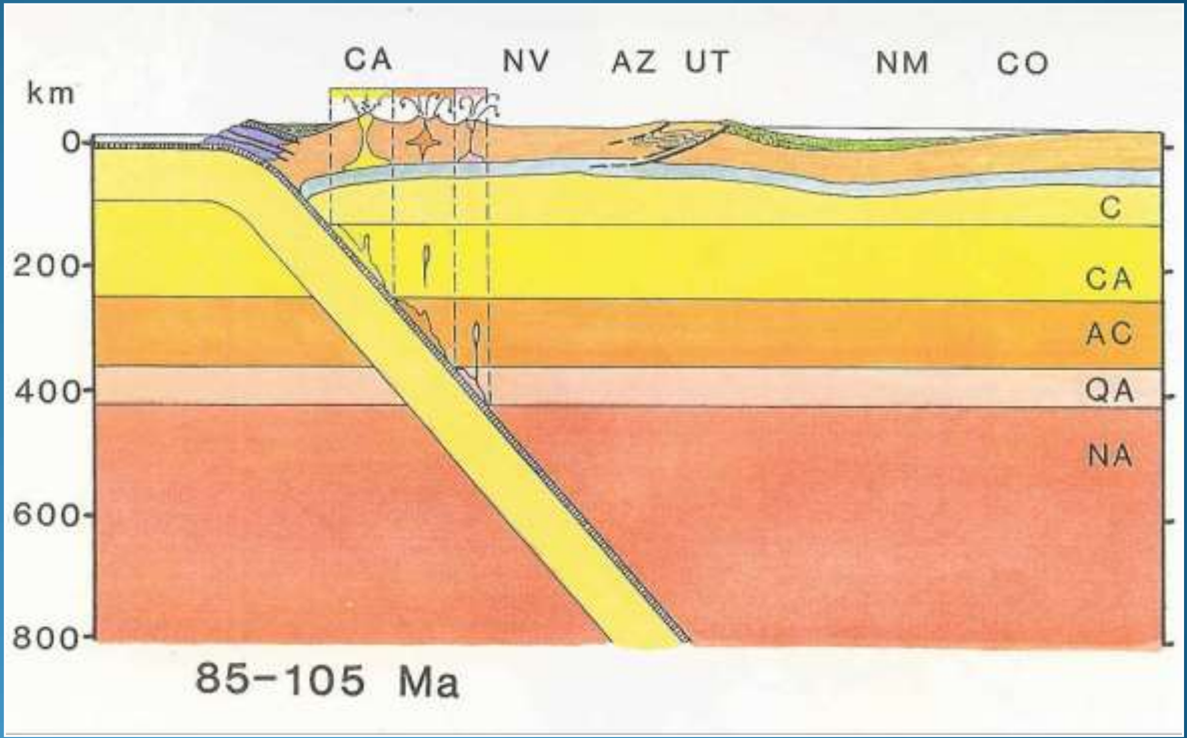


Source: Livaccari and Keith, 1990

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)



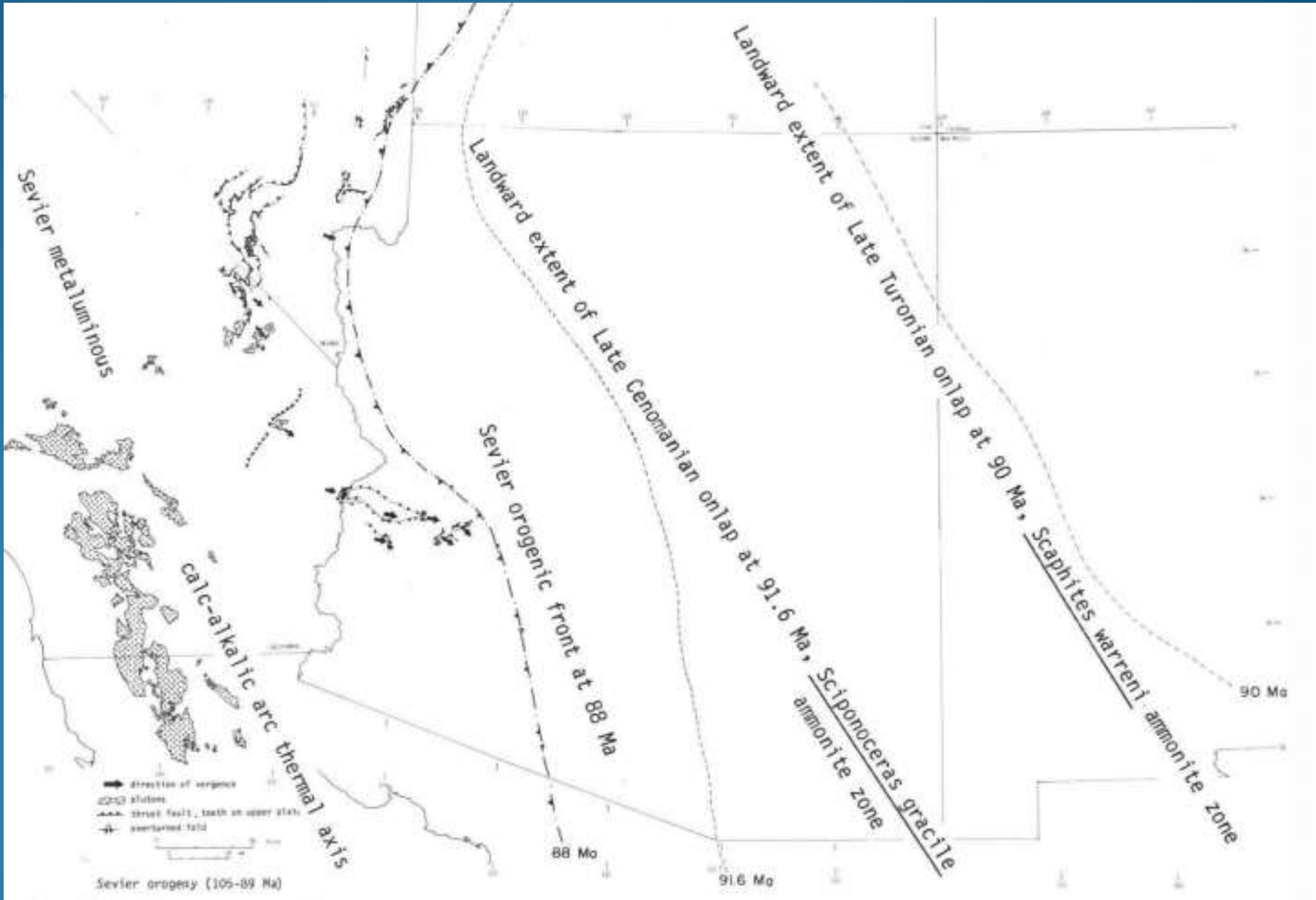


Sevier orogeny = constant dip subduction; most magmatic activity was in California.
Arizona was undergoing erosion, folding and thrust faulting.

Sevier Orogeny (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)

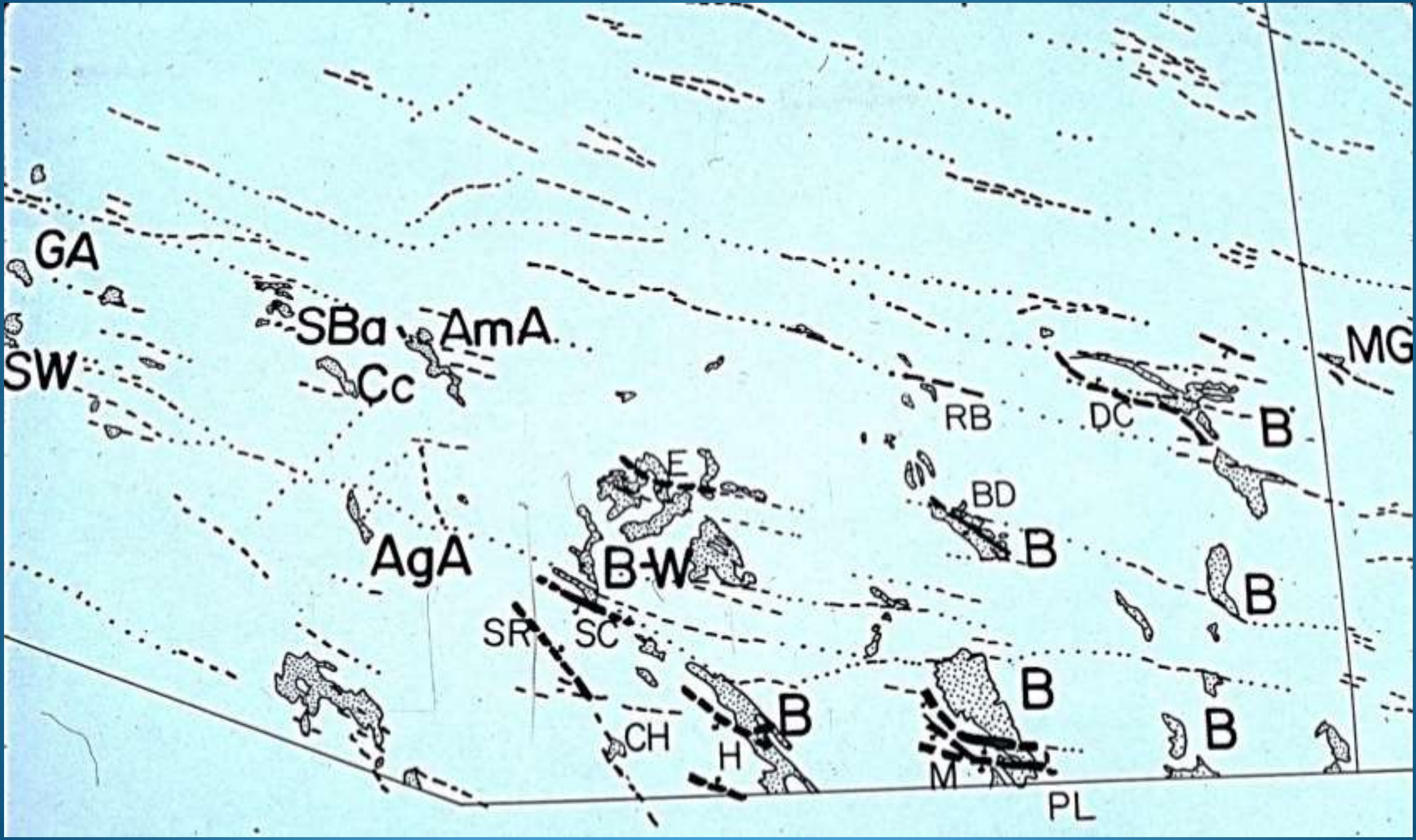
- **Magmatic arc is in California.**
- **Thrust faults in western Arizona**
- **Cretaceous interior seaway retreats to NW.**



Source: Keith & Wilt, 1986

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)



Sevier Orogeny (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)

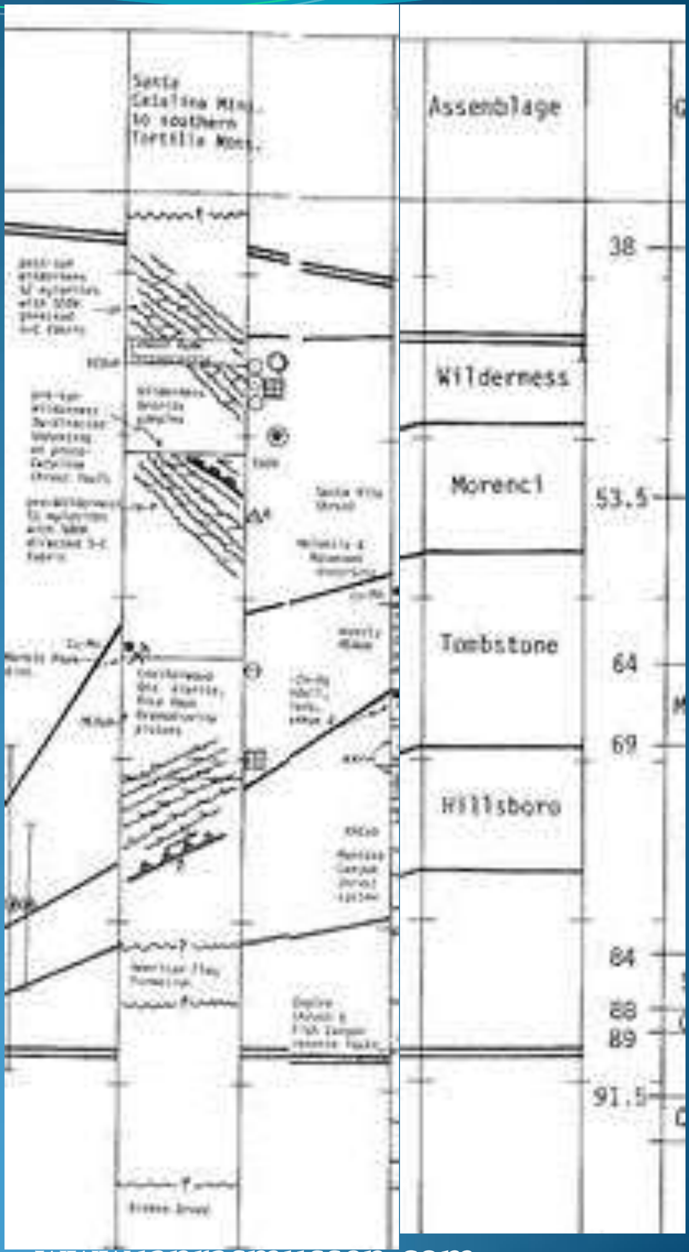
Mural Ls. (Bisbee Group) E. of Bisbee

Limestone mined at
Paul Spur, near Douglas

Stratotectonic Analysis – Time Columns

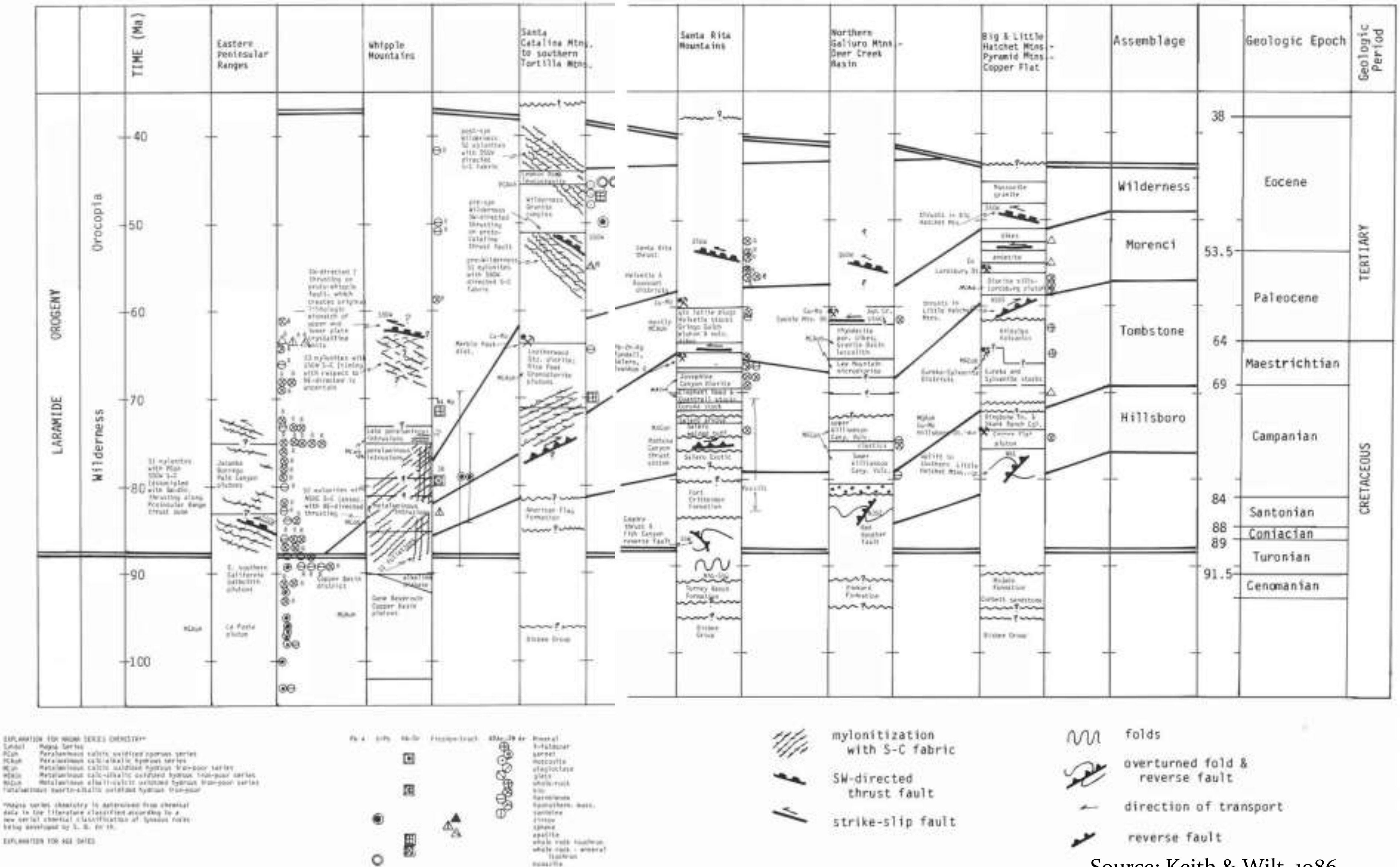
Consists of these data:

- Stratigraphy (formations, rock types)
- Structure (folding, faulting, stress regimes)
- Magmatism (rock types, magma chemistry)
- Metal Deposits (MagmaChem call – aluminum content, alkalinity, oxidized/reduced)
- Metamorphism
- Isotopic age dates
- Geochemistry (metal ratios, assemblages)
- Unconformities



Keith & Wilt, 1986

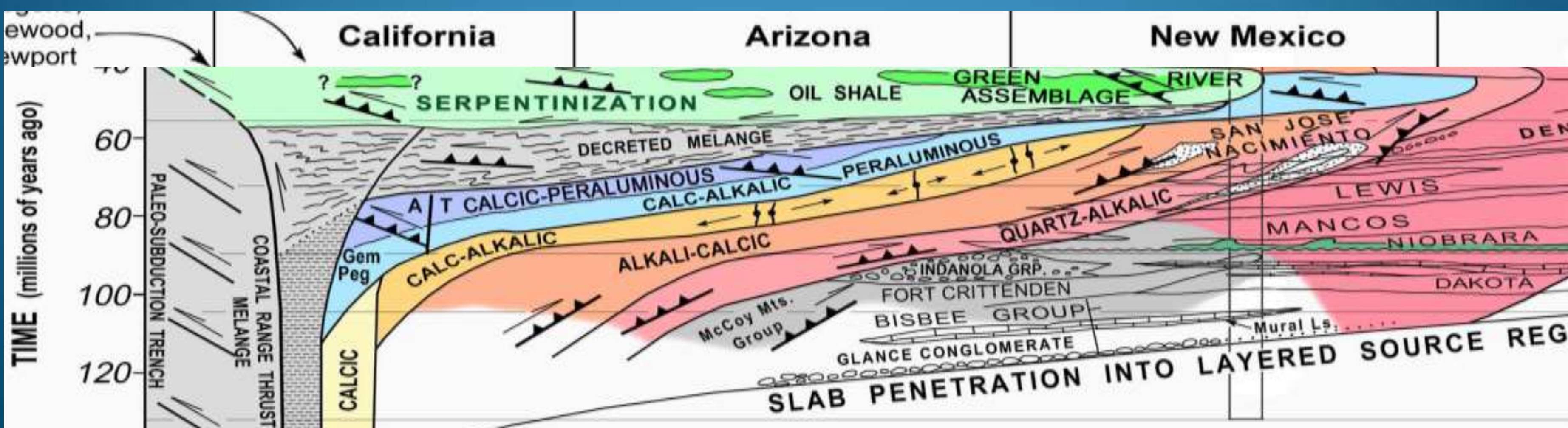
Strato-tectonic Chart for Laramide (6 of 110 columns)



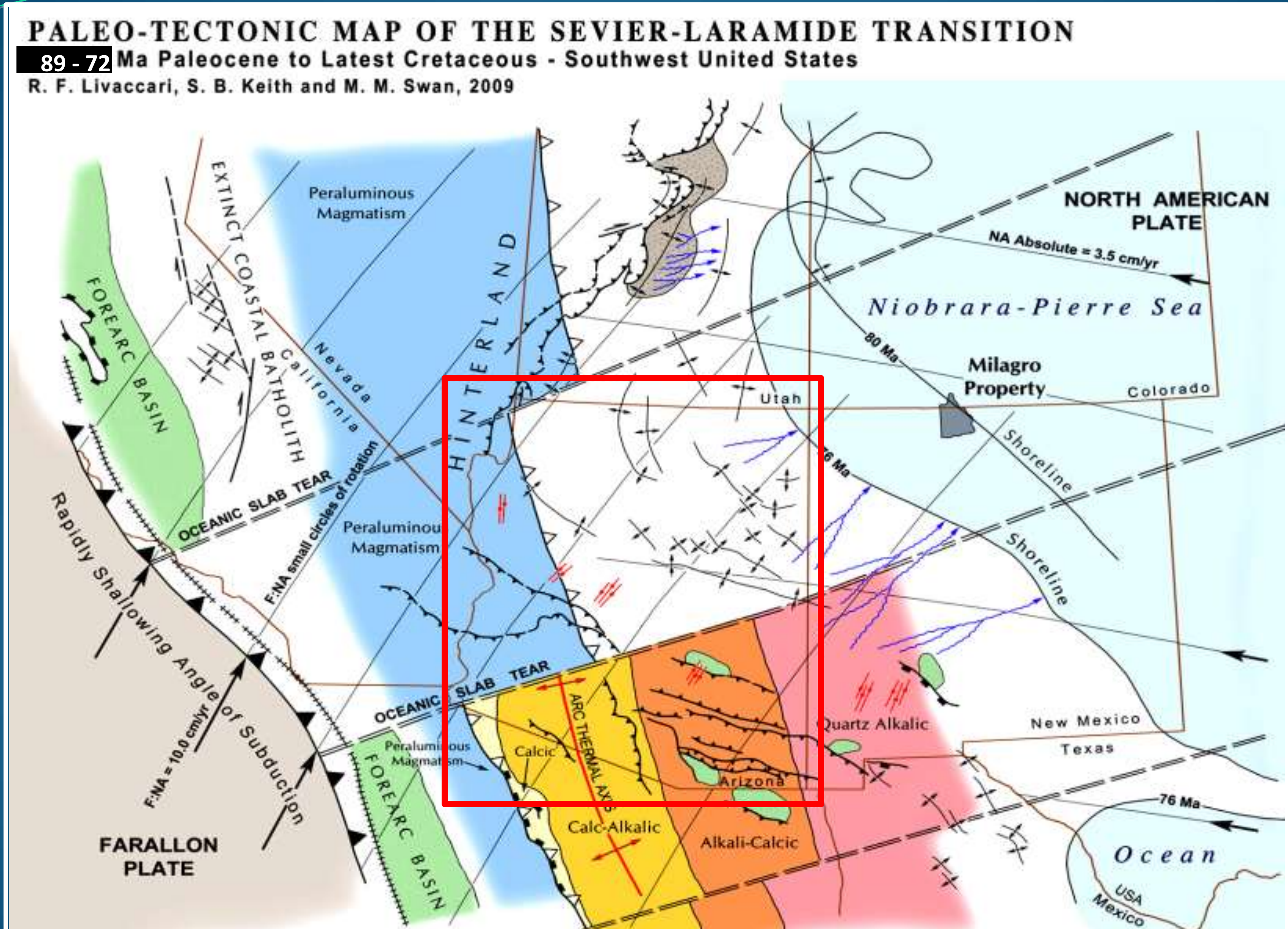
Source: Keith & Wilt, 1986

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

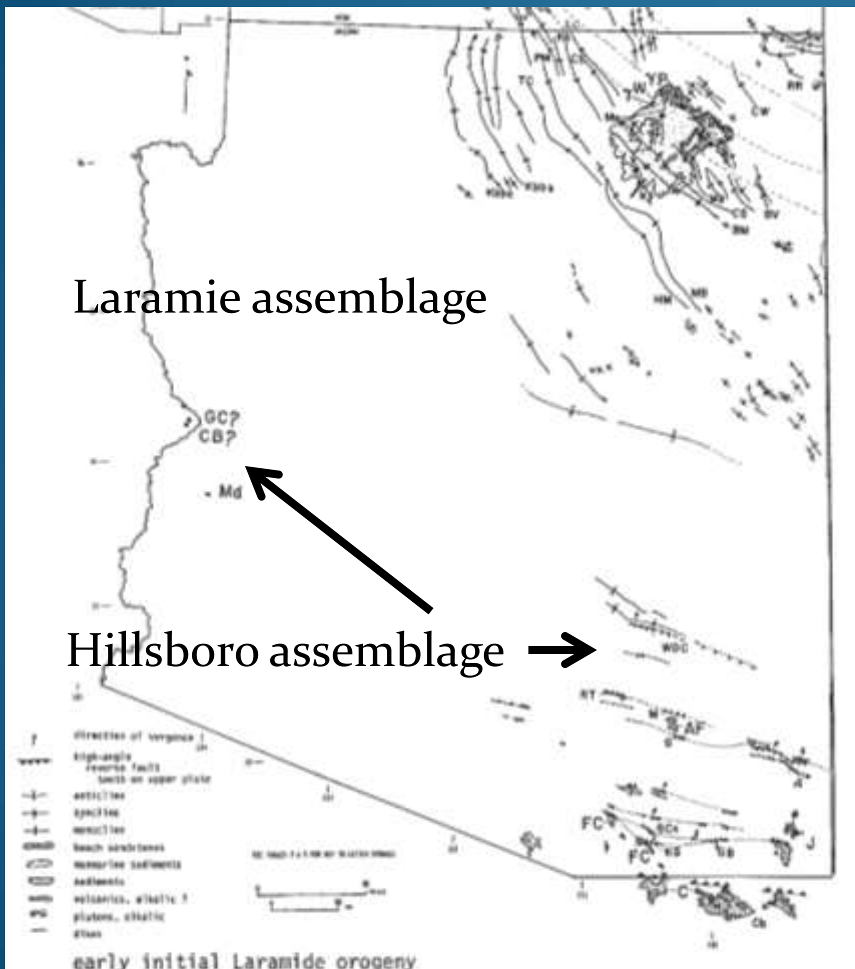


Laramide Orogeny (89-35 Ma)



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



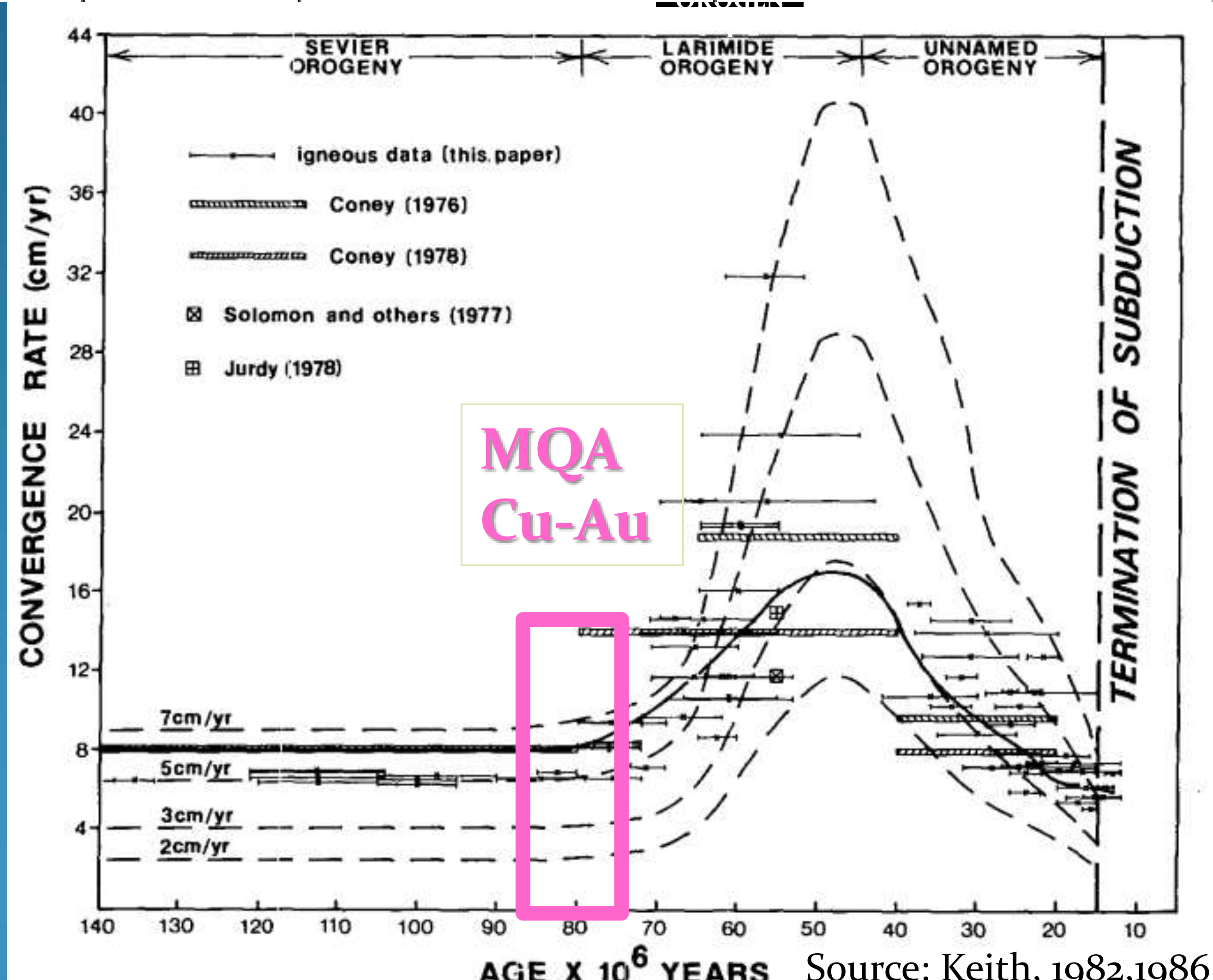
N Arizona – coal in Wepo Fm. at Black Mesa

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

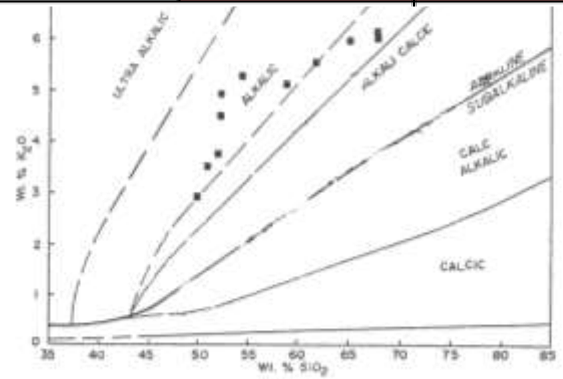
Moderate volumes of metaluminous quartz alkalic hydrous oxidized monzonitic intrusions (early Laramide) are associated with slower convergence rates. initial flattening subduction, local shoshonitic volcanism, and minor copper-silver production (eg. Cerro Colorado)



Source: Keith, 1982,1986

Earliest **Laramide** -Hillsboro (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



MQA

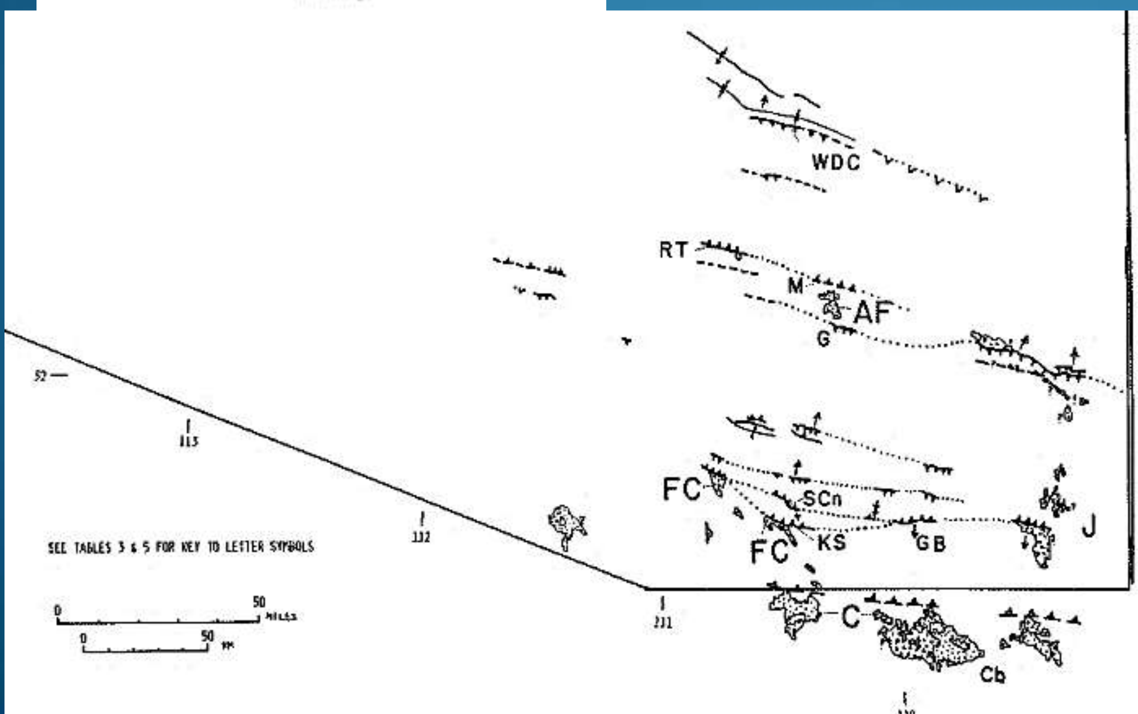
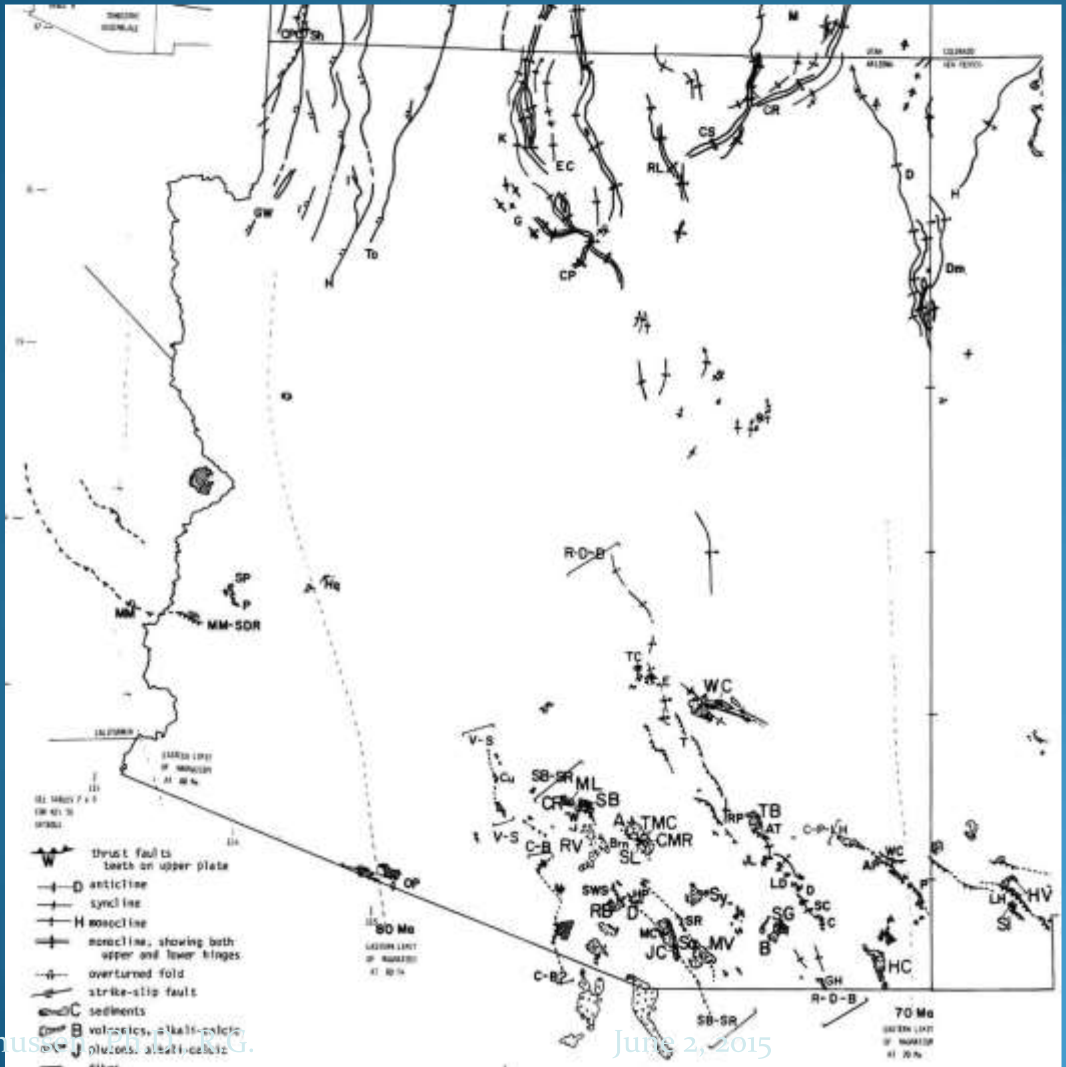


Table 5. Examples of Hillsboro Assemblage of the early initial Laramide orogeny

	SYMBOL	EXAMPLES	REFERENCES
SEDIMENTS	AF	American Flag Fm.	Creasey, 1967; Hayes, 1970
	C	Cabullona Gp.	Taliaferro, 1933
	FC	Ft. Crittenden Fm.	Drewes, 1971c; Hayes, 1970
	J	Javelina Fm.	Zeller, 1970
	R	Ringbone Fm.	Zeller, 1970
MAGMATISM	AB	Andesite breccia	Callaghan, 1953
	CB	Copper Basin	
	CF	Copper Flat stock	Thorman&Drewes,1981;Hedlund,1977
	GC	Gene Canyon	
	Md	Mudersbach pluton	Scarborough & Meader, 1983
	OG	Oro Grande stock	Beane and others, 1975
STRUCTURES	Cb	Cabullona basin	Taliaferro, 1933
	G	Geesman flt	Creasey, 1967
	GB	Government Butte	Hayes, 1970
	KF	Kino Springs Flt	Hayes & Raup, 1968
	LH	L. Hatchet Mts.	Zeller, 1970
	M	Mogul flt	Creasey, 1967
	RT	Ragged Top flt	Banks & Dockter, 1976
	SCn	Sawmill Canyon flt	Drewes, 1972b
	WDC	Winkelman-Deer Creek	Simons, 1964
RESOURCES	CF	Hillsboro	Dunn, 1983; Fowler, 1982
		Golden Rule mine	Keith, 1973
		Easter Sunday mine	Keith & others, 1983
		Plomosa Pass	Keith, 1978

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



- Preceded porphyry Cu by ~10 Ma in each mountain range
- Pb-Zn-Ag mines
- “barren” porphyry Cu deposits

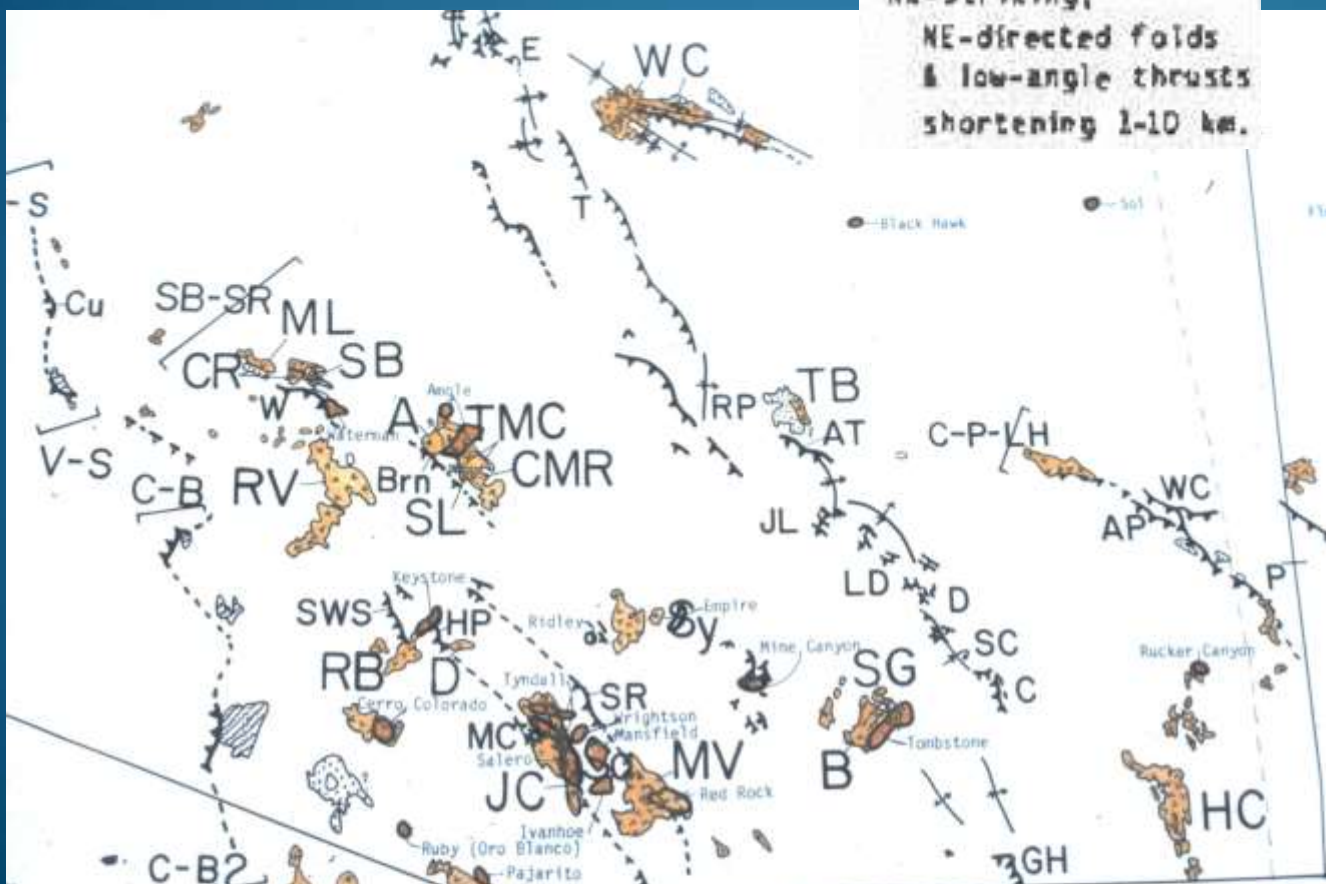
Early Laramide (Tombstone) (85-65 Ma)

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

MAC

STRUCTURES

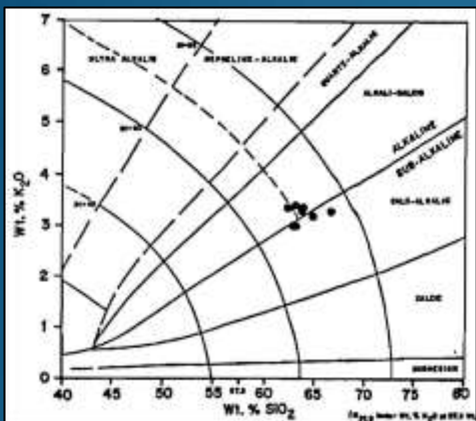
NW-striking, NE-directed folds & low-angle thrusts shortening 1-10 km.



CR	Claflin Ranch Fm.
Sa	low. Salero Fm.
TB	Teran Basin
WC	low. Williamson Canyon volc.
TMC	Tucson Mtn. Chaos
A	Amole stock
B	Bronco Volc.
CMR	Cat Mtn. Rhyolite
D	Demetrie Volc.
HC	Hunt Canyon and.
HV	Hidalgo Volc.
JC	Josephine Cany. Dior.
ML	Mt. Lord Volc.
MV	Meadow Valley
RB	Red Boy Rhyolite
RV	Roskruge Volcanics
SB	Silver Bell Fm.
SG	Schiefflin Grndior.
SL	Silver Lily dikes
Sa	Salero Fm.
Si	Silvanite stock
Sy	Sycamore stock
TH	Tres Hermanas pluton
WC	Williamson Can. Volc.

Early Laramide (Tombstone) (85-65 Ma)

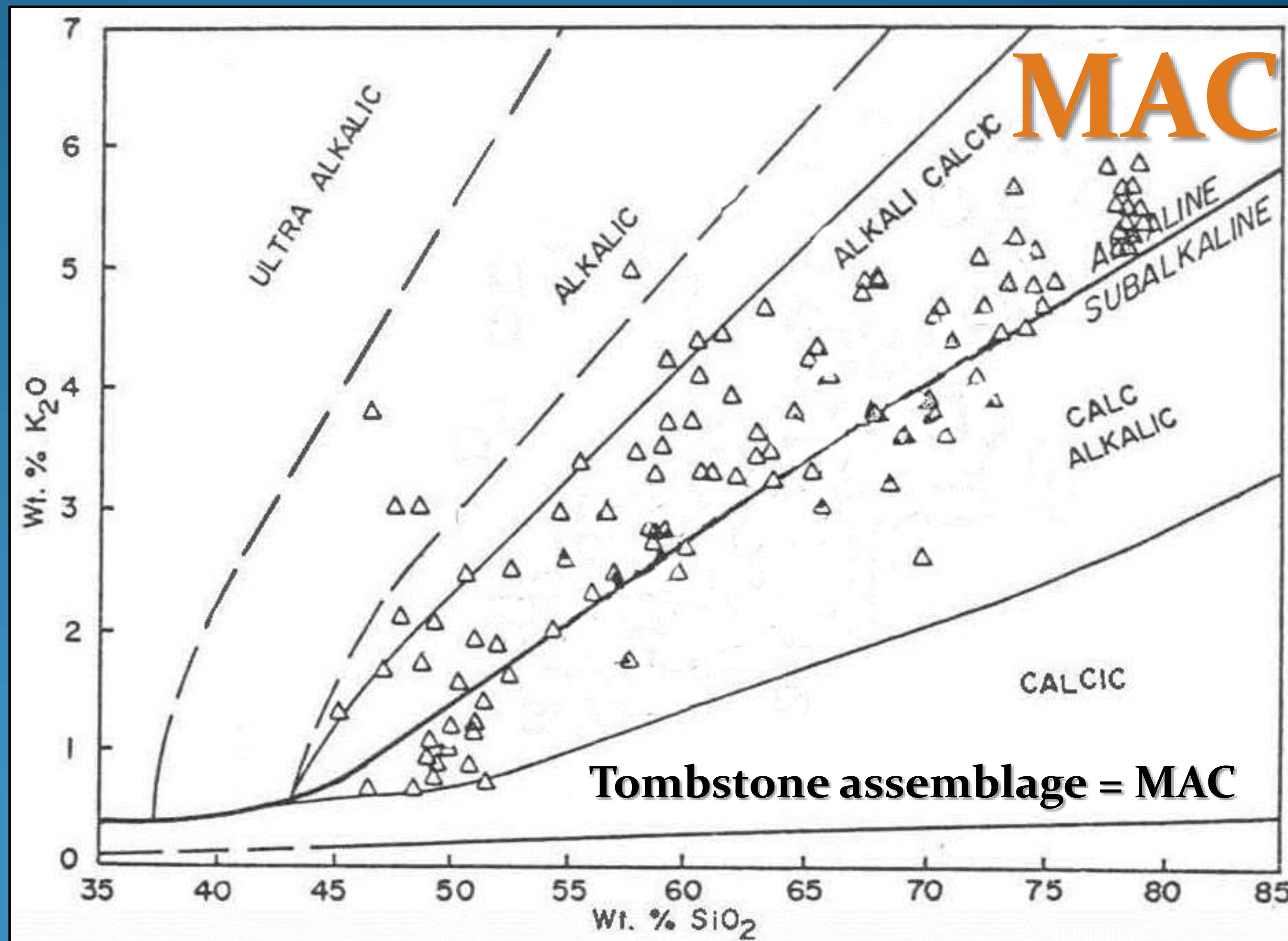
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
	Early (Tomb-stone)	85-65	MAC	Pb-Zn-Ag	Tombstone, Tyndall (Glove), Washington Camp, Salero



Tombstone

MAGMATISM

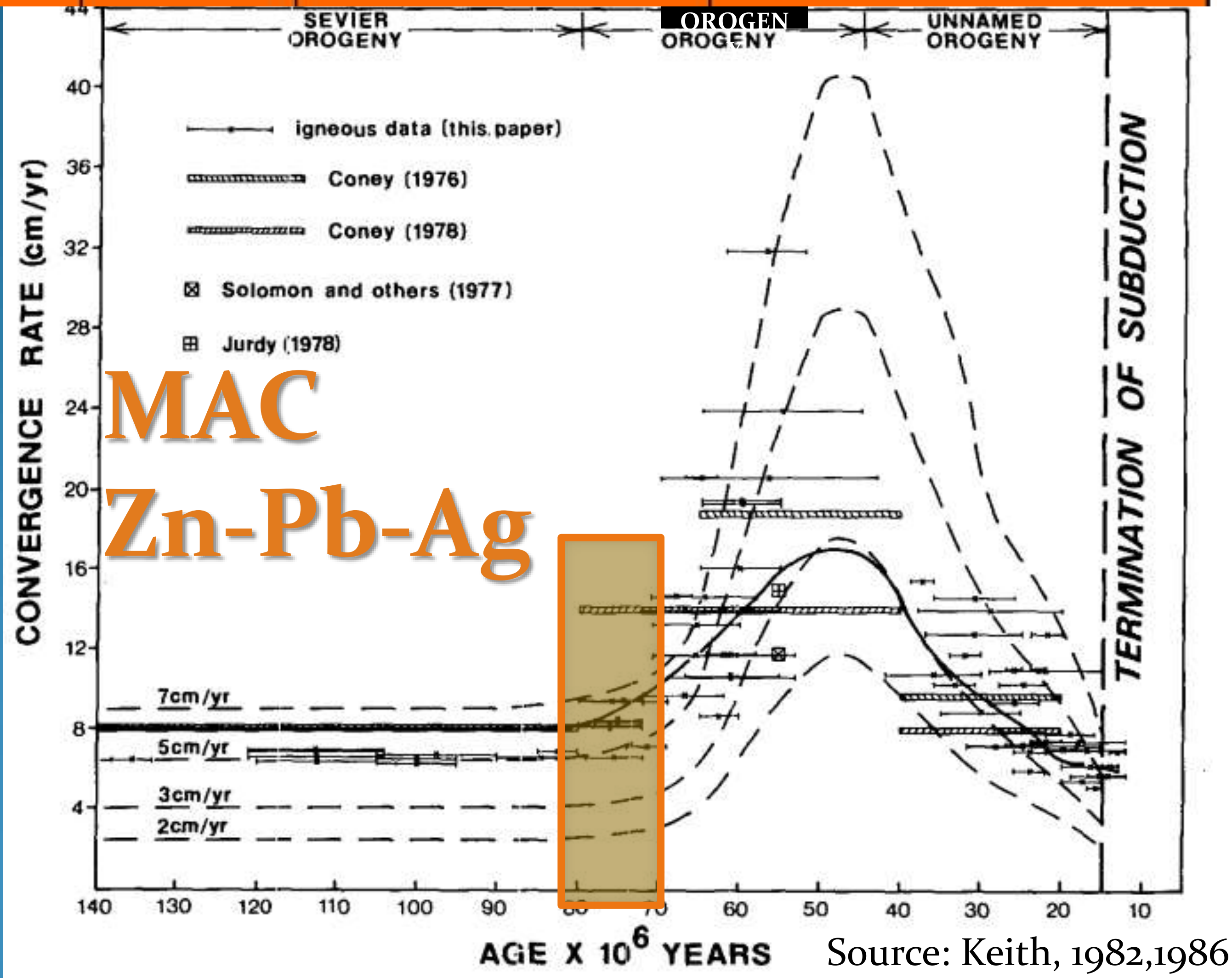
abundant pyroclastics
some epizonal qtz. monz. porphyritic stocks
low- and.-dac. breccia
up- dac.-rhy. ignimbrite flows & ash flows
metaluminous, subalkaline, alkali-calcic
gen. Fe-poor, hydrous, oxidized



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 hydrous oxidized 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

MAC = thick ignimbrite (ash) flows

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

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 Hills – Uncle Sam Tuff

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

Early Laramide - Tombstone - silver mines

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

Alabandite MnS

Emmonsite, Empire m.

Silver, Lucky Cuss m.

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

Early Laramide (Tombstone assemblage) Glove Mine

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

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

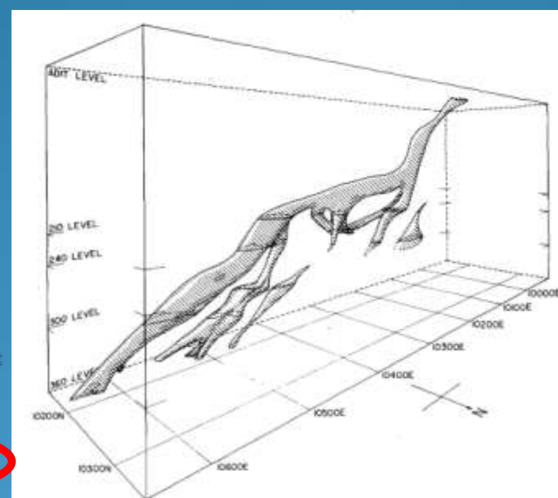


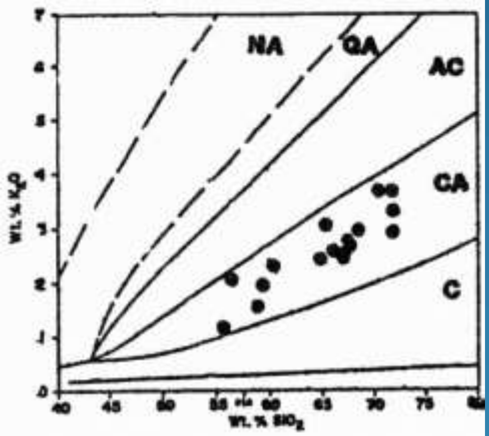
Fig. 5. Generalized view of the Glove ore body.

Tyndall dist. prod. (1908-1976) =
161,000 lb Cu
14,754,000 lb Pb
652,000 lb Zn
200 oz Au
238,000 oz Ag

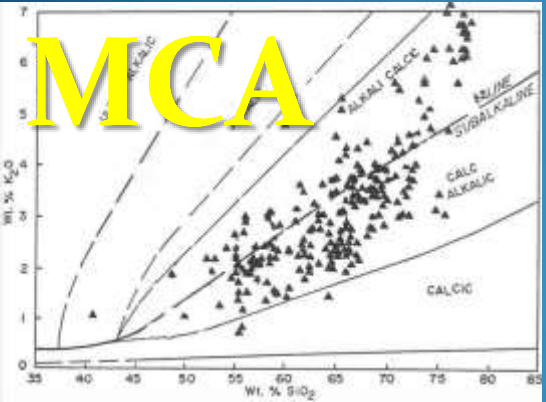
Source: Keith et al., 1983, Bull. 194

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

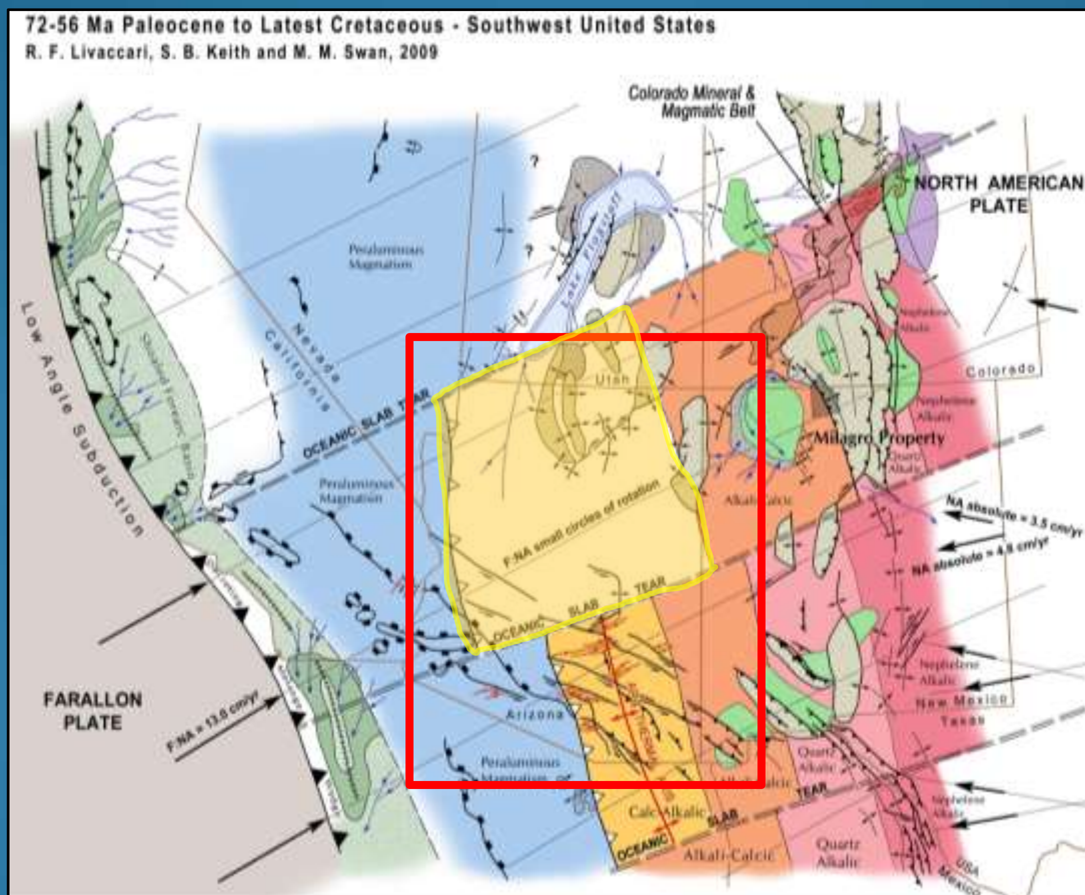


Ray



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



72-56 Ma

MCA = yellow

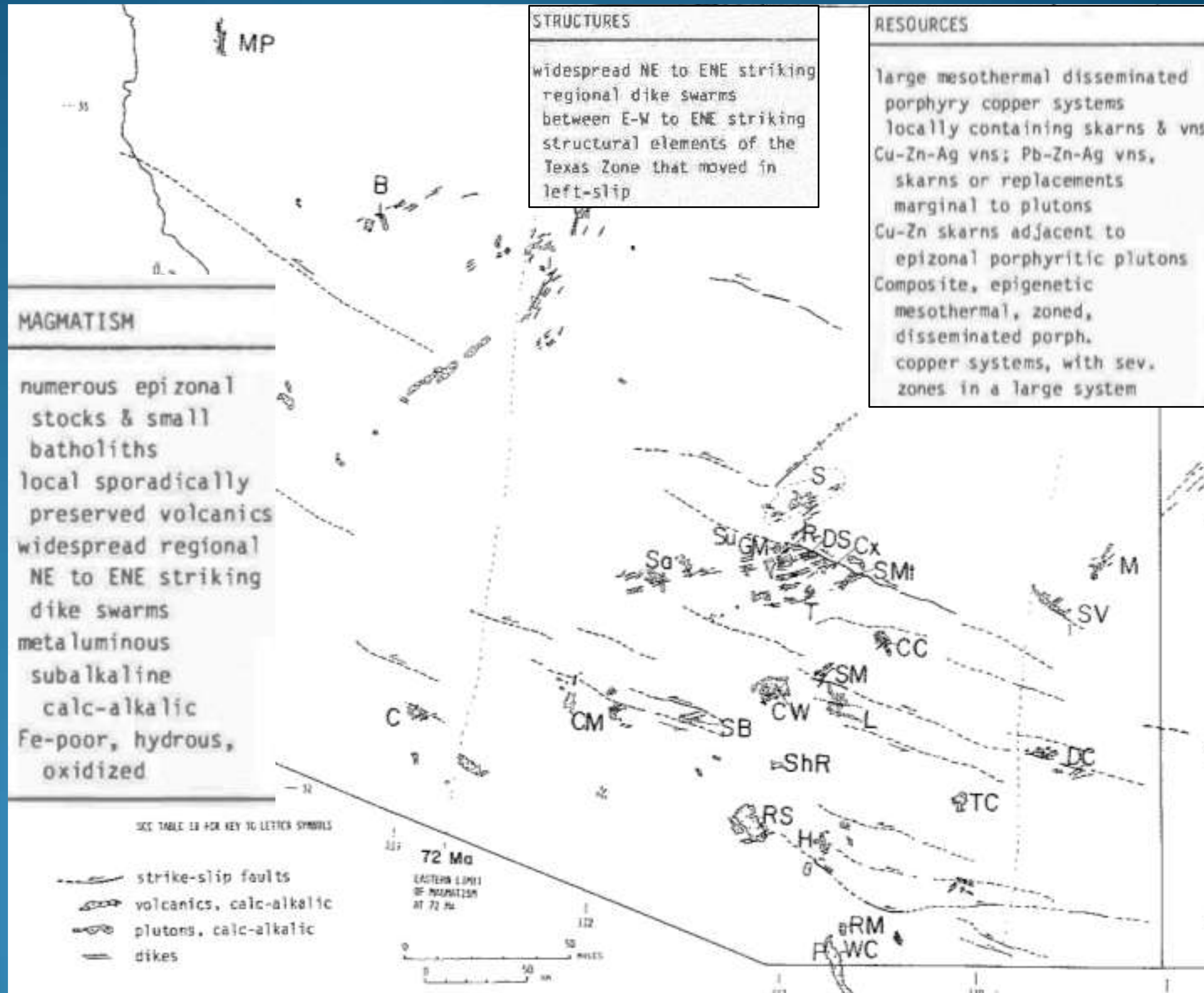
Middle Laramide - Morenci (65-55 Ma)

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

Middle Laramide - Morenci (65-55 Ma)

Table 11. Examples of Morenci

	SYMBOL	EXAMPLES
MAGMATISM	C	Cornelia Qtz. Monz.
	CC	Copper Creek grndr.
	CM	Cimarron Mtns. pluton
	CM ?	Carrizo Mtns. lac.
	CW	Chirreon Wash grndr.
	Cx	Christmas stock
	DC	Dos Cabezas
	GM	Granite Mtn. por. Ray
	L	Leatherwood qtz. dior.
	Lo	Lordsburg
	MP	Mineral Park pluton
	P	Patagonia batholith
	RM	Red Mountain
	RS	Ruby Star Qtz. Monz.
	S	Schultze Granite
	SV	Safford Volcanics
	Sa	Sacaton
	ShR	Shorts Ranch and.
	TC	Texas Canyon
	UM ?	Ute Mtn laccolith
STRUCTURES	B	Bagdad
	DS	Dripping Spring Mtns.
	SB	Silver Bell
	T	Tortilla Mtns dikes
RESOURCES	C	Ajo
	Cx	Christmas, AZ
	GH	Globe Hills, AZ
	H	Helvetia, Rosemont
	M	Morenci, AZ
	MP	Mineral Park
	MP	Wallapai
	R	Ray, AZ
	RS	Twin Buttes, AZ
	RS	Esperanza
	RS	Pima
	SB	Silver Bell
	SMt	Saddle Mountain
	SM	San Manuel
	SR	Santa Rita, NM
	Su	Superior, AZ
	Ty	Tyrone, NM
	WC	Washington Camp



Middle Laramide - Pima district (Mission m.) porphyry Cu

Bornite – peacock copper – copper iron sulfide

Chalcopyrite – copper fools gold Copper-iron-sulfide

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

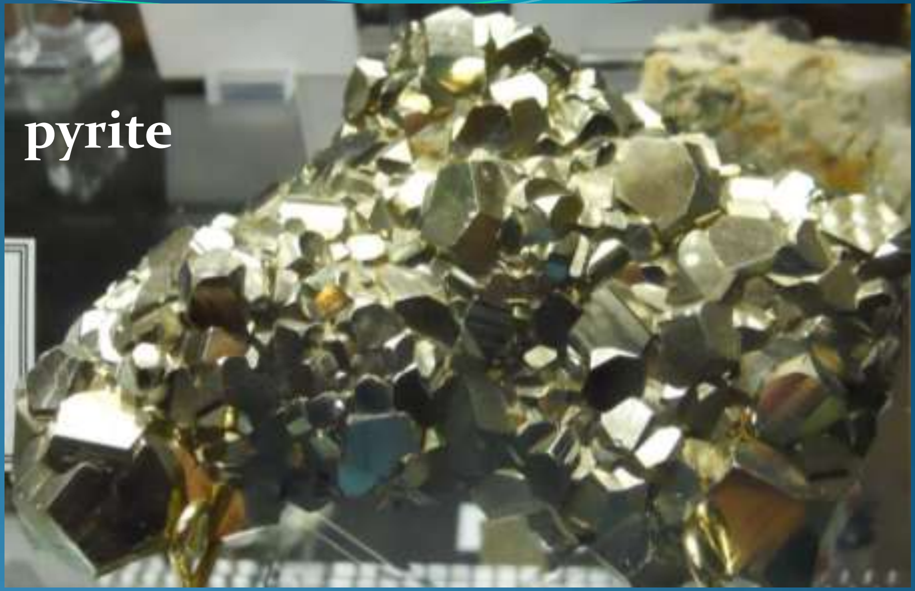
8,359,754,000 lb Cu
75,795,000 lb Pb
132,964,000 lb Zn
26,100 oz Au
56,336,000 oz Ag
290,796 lb Mo

Source: Keith et al, 1983

Middle Laramide - Superior – Magma mine

stromeyerite

pyrite



hematite

tennantite

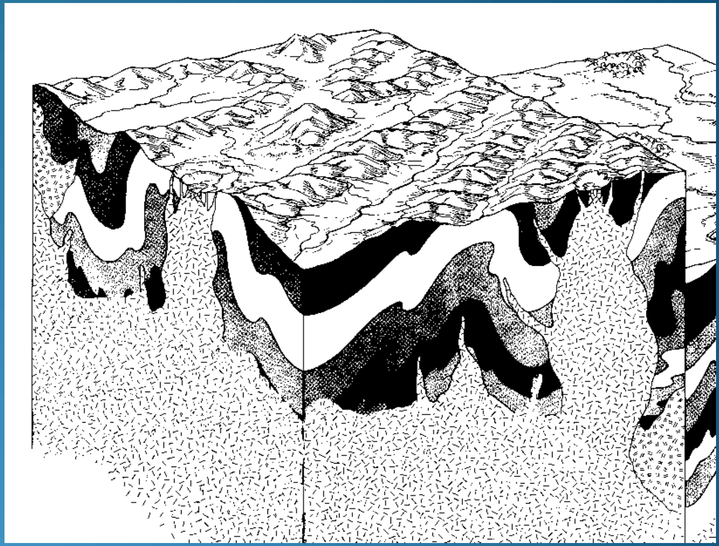
bornite

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 (Fornash et al., 2013).

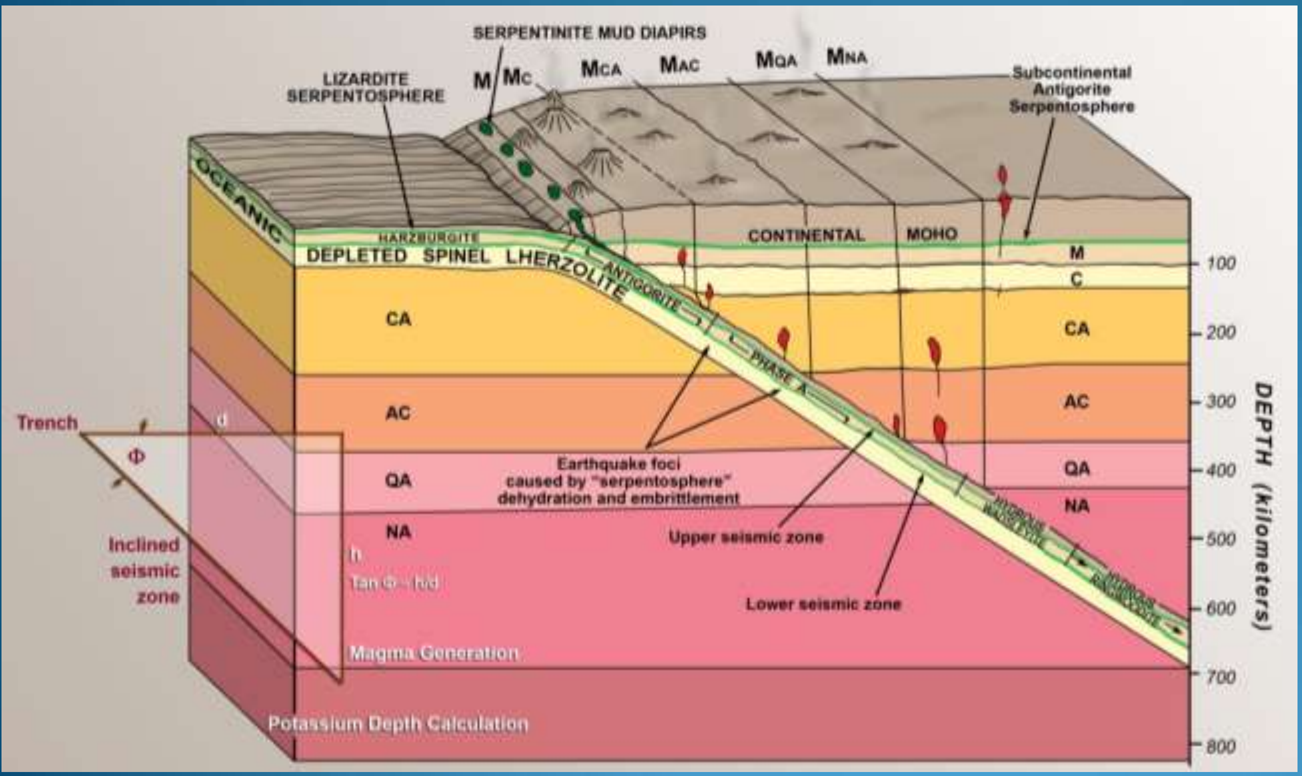
The Oracle Granite has a metal signature of W and Be.

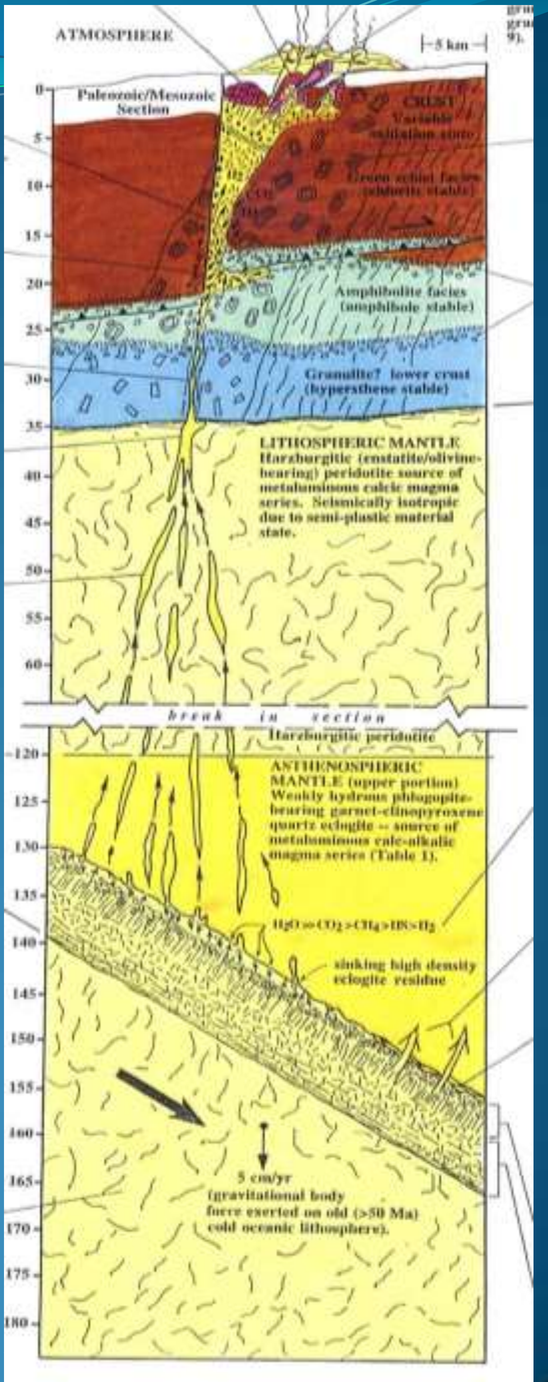


The Laramide porphyry copper deposits do not have the same W and Be characteristics.

It is difficult to get Cu out of melting the Oracle Granite.

A more favored explanation is a mantle source.





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

Why such large volumes of metal in the middle Laramide?

chalcopyrite

copper

Ray mine – 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

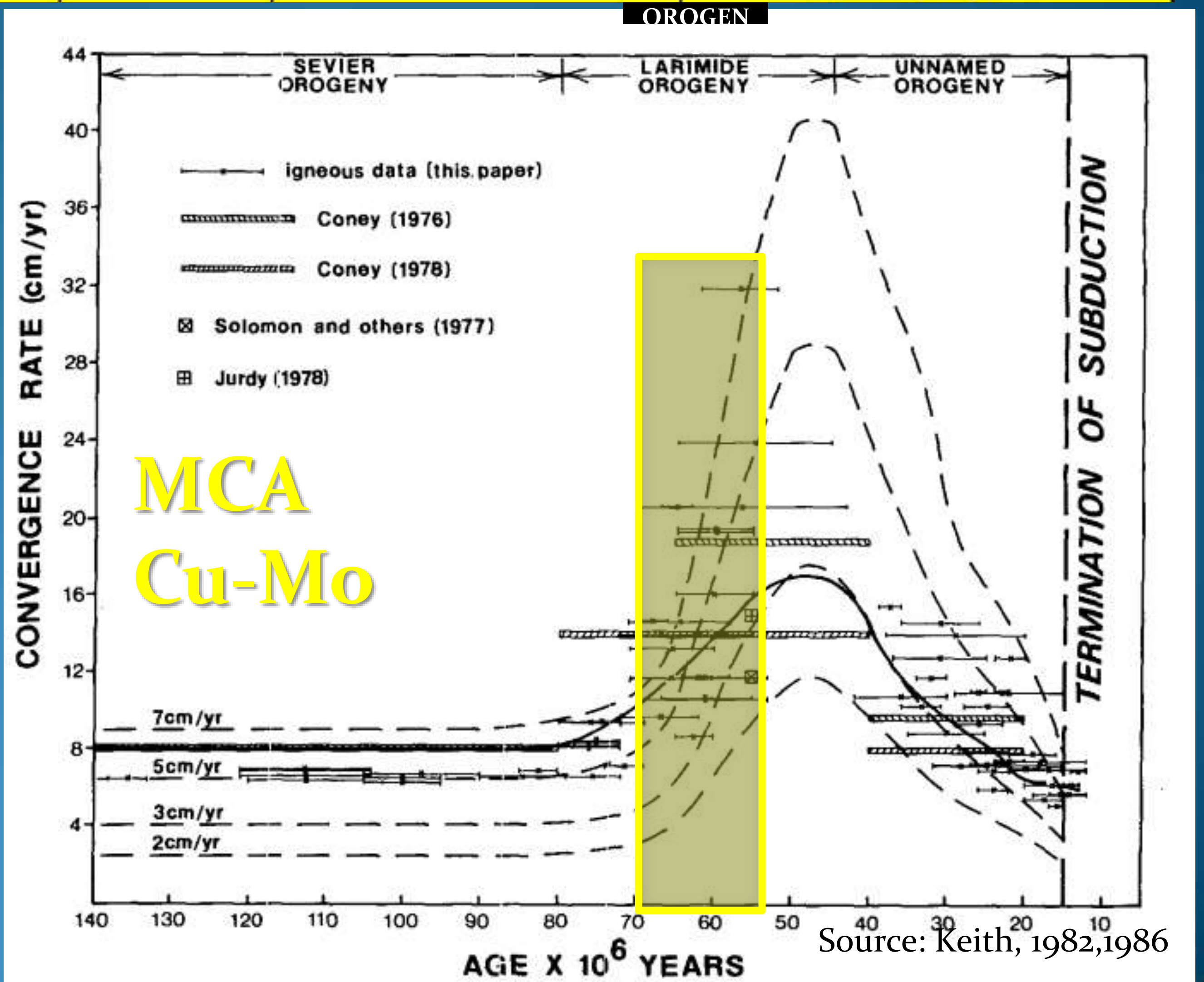
Age	mid-Tertiary	Middle Laramide	Late Cretaceous
Age (Ma)	30-20	70-50	80-70
Magmatic Chemniustry (K57.5)	2.5-4.0	0.7 to 2.5	2.6 to 4.4
Copper (kg)	7,556,000	22,253,000,000	7,655,000
Pb	85,550,000	273,800,000	48,690,000
Zn	61,160,000	1,292,000,000	17,130,000
Au	28,100	125,600	12,400
Ag	1,045,000	5,960,000	1,197,000
Zn:Pb	1:1.4	5:1	1:3
Cu:(Pb+Zn)	1:20	14:1	1:9
Cu:Au	290:1	180,000:1	620:1
Ag:Au	40:1	47:1	96:1

Why such large volumes of metal in the middle Laramide? Keith, 1979

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 strongly hydrous oxidized granodioritic intrusions (middle Laramide) are associated with faster convergence rates and flattening subduction, a general lack of volcanism and major copper-molybdenum production



Source: Keith, 1982,1986

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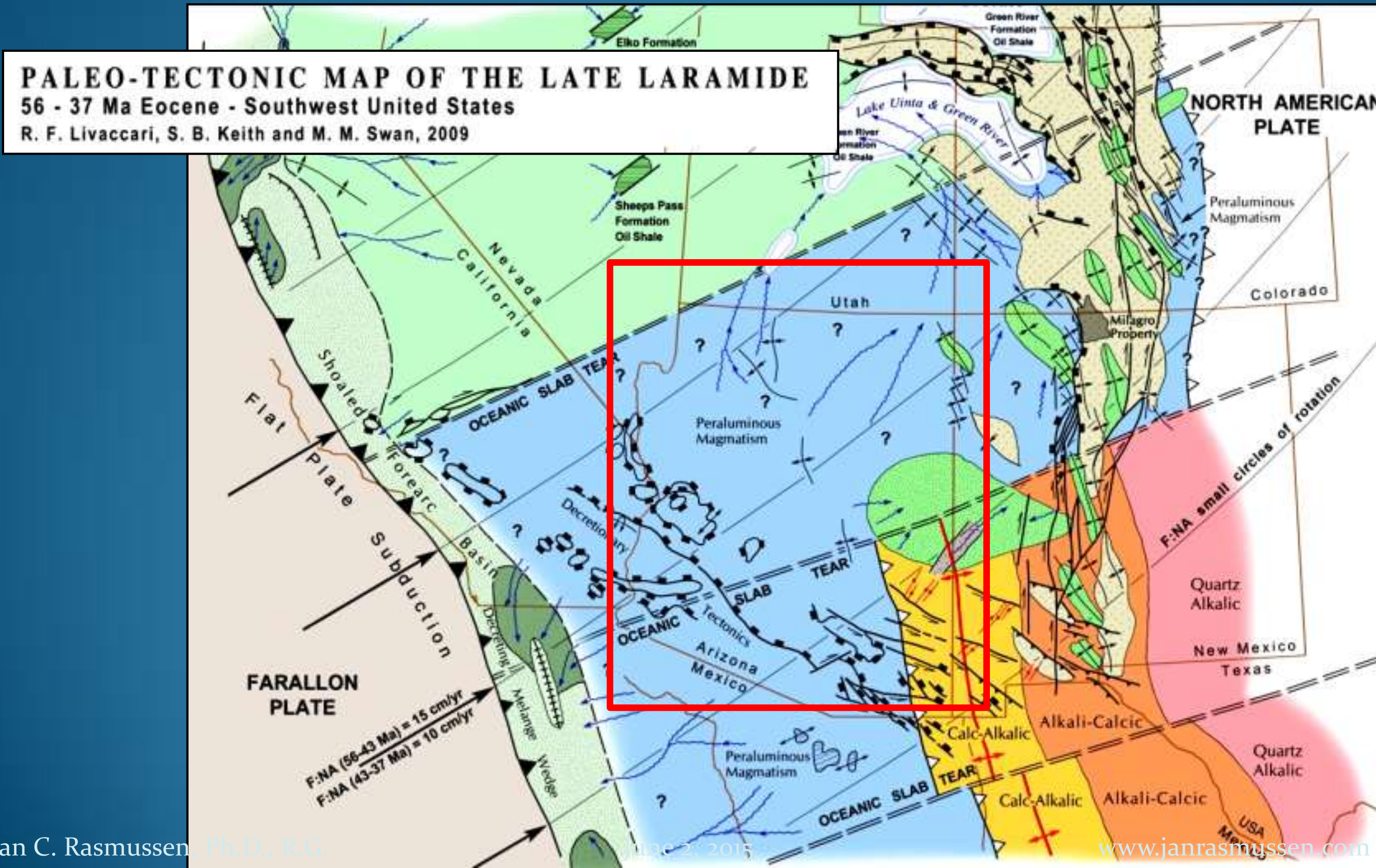
Latest Laramide – Wilderness (55-43 Ma)

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



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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

MAGMATISM

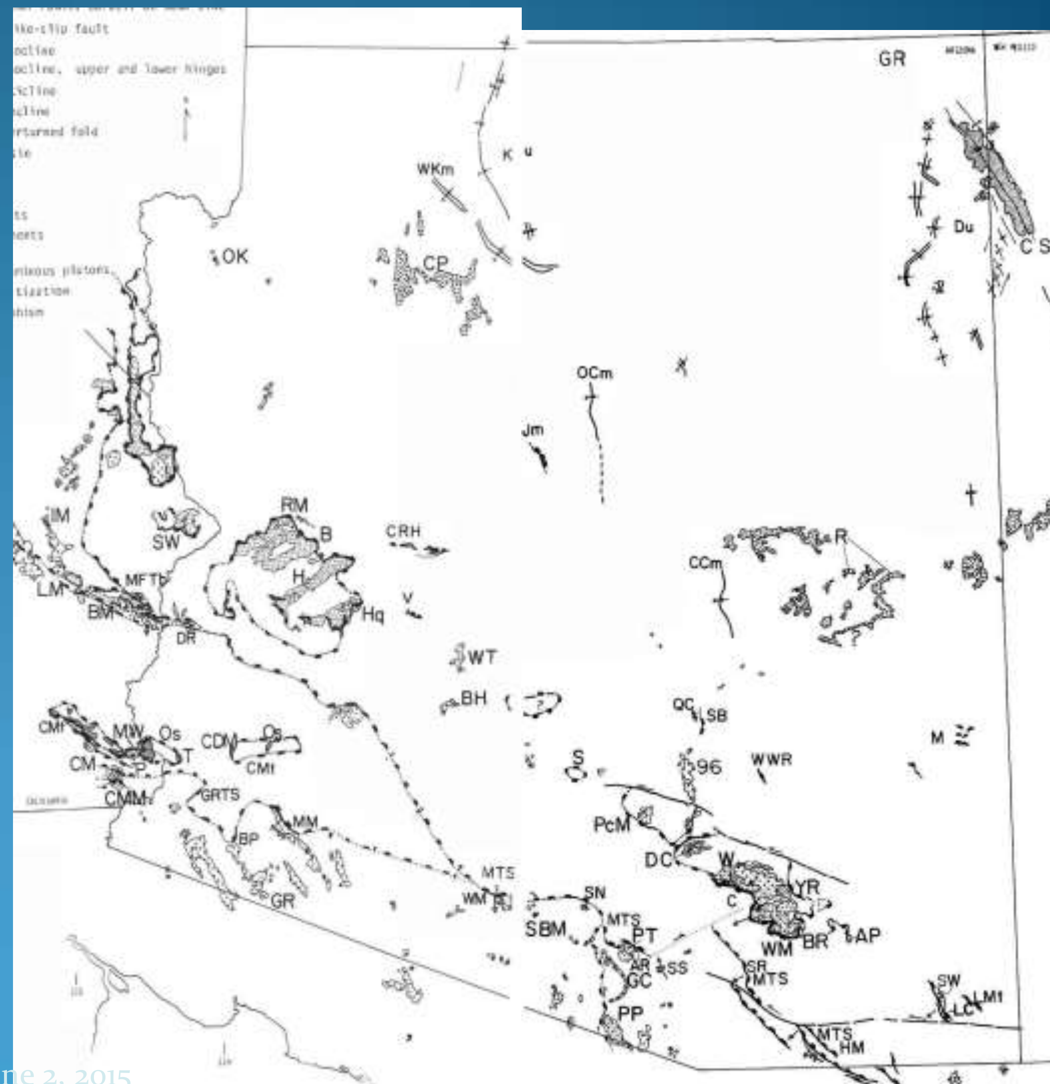
SYMBOL	EXAMPLES
96	96 Hills pluton
AP	Adams Peak leucogranite
AP	E. edge Texas Canyon
B	Buckskin Mtns.
BH	Buckeye Hills
BM	Big Maria Mts., CA
BR	Barney Ranch pluton
C	Coxcomb range
CMM	Cargo Muchacho Mtns.
CV	Cadiz Valley batholith
DC	Tortolita Mts.
DC	Derrio Canyon granite
EPR	E. Peninsular Range
GC	Gu Chuapo granite
GR	Gunnery Range batholith
Ha	E. end Harquahala Mts.
IM	Iron Mountain
J	Jacumba pluton
MW	Marcus Wash pluton
OK	Gold Basin
OK	O K pluton
PM	Picacho Mountains, AZ
PP	Presumidio Peak
PT	Pan Tak granite
PT	Coyote Mtns.
RM	Rawhide Mtns.
RP	Redington Pass
SBM	Sierra Blanca Mts.
SW	Sweetwater, Whipples
W	Wilderness pluton
WT	White Tank Mts.
WTa	White Tank adamellite
YR	Youtcy Ranch pluton

STRUCTURES

AR	Ajo Road fault
BM	Big Maria Mtns.
BP	Baker Peak
BR	east Rincon Mtns.
C	Catalina flt.
CRH	Congress, Rich Hill
DR	Dome Rock Mountains
EPR	E. Peninsular Range
EPRsz	E. Penin. Rg. shear zone
GRTS	Gunnery Range thr. sys.
HM	E. Huachuca Mts. thst
Hq	Harquahala Mtns.
Jm	Jerome area
LC	Lyle Canyon thrust
LM	Little Maria Mtns.
LMt	Limestone Mtn thrust
M	Morenci area
MFTb	Maria fold thrust belt
MM	Mohawk Mountains
MTS	Maricopa thrust system
QC	Queen Creek fold
S	lower plate, Sacaton
SB	Sleeping Beauty
SN	Sil Nakya Hills
SR	Box Canyon, Santa Rita
SS	SW Sierrita Mts. fold
SW	Swisshelm Mts.
SdC	Sierra de Cabullona
V	Vulture Mountains
WM	Wrong Mountain pluton
WMW	Window Mountain Well
WWR	Whittaker Wash Ranch flt.

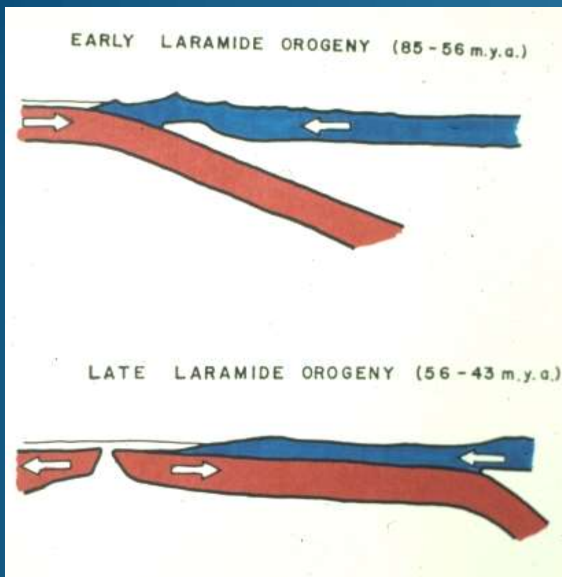
RESOURCES

	Boriana
	Reef, Las Guijas
	Cobabi
	Mesquite
OK	Gold Basin
CMM	Cargo Muchachos
P	Picacho, CA



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



MAGMATISM

widespread, (2-mica)
garnet-muscovite,
granitoid stocks,
batholithic sills,
aplo-pegmatite dikes
peraluminous,
calc-alkalic & calcic

STRUCTURES

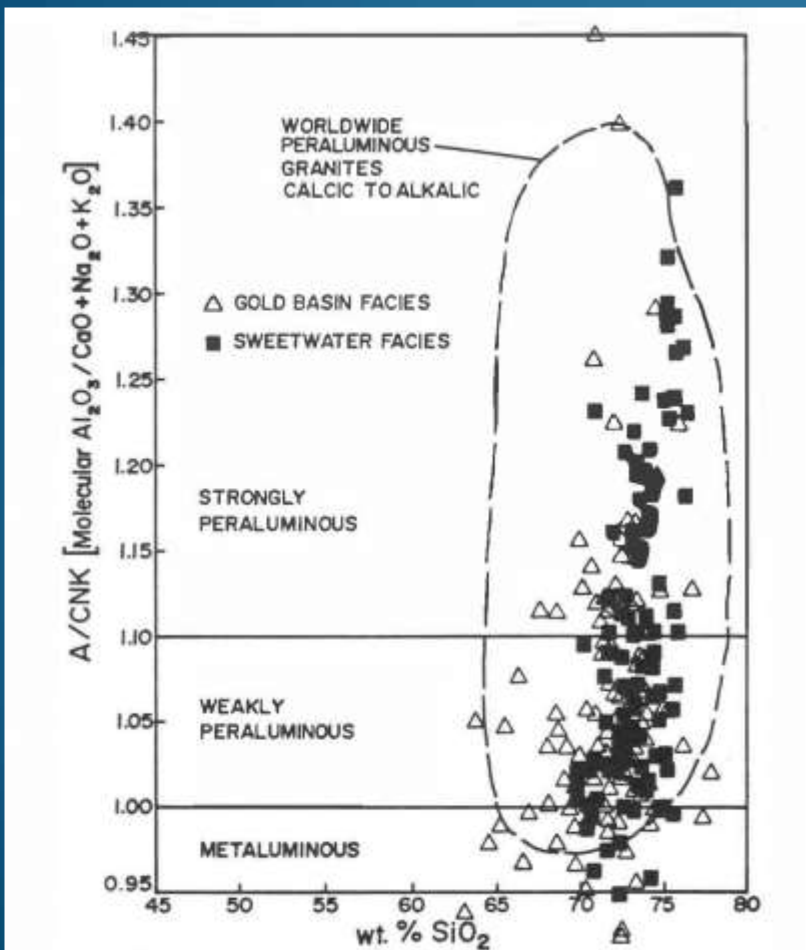
SW-directed,
low-angle thrusts
widespread,
shallowly dipping
mylonitic zones
general SW shear

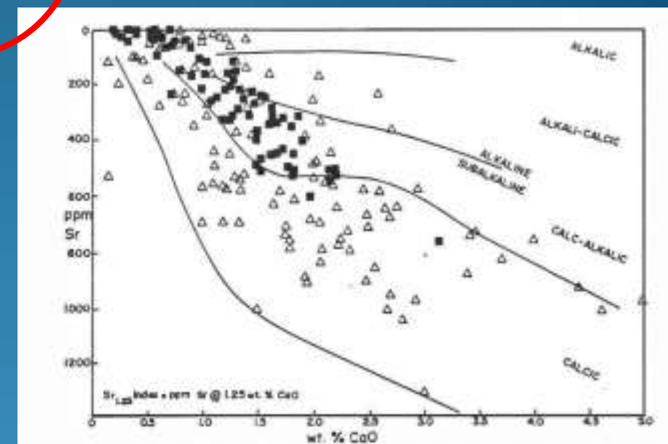
Flat subduction

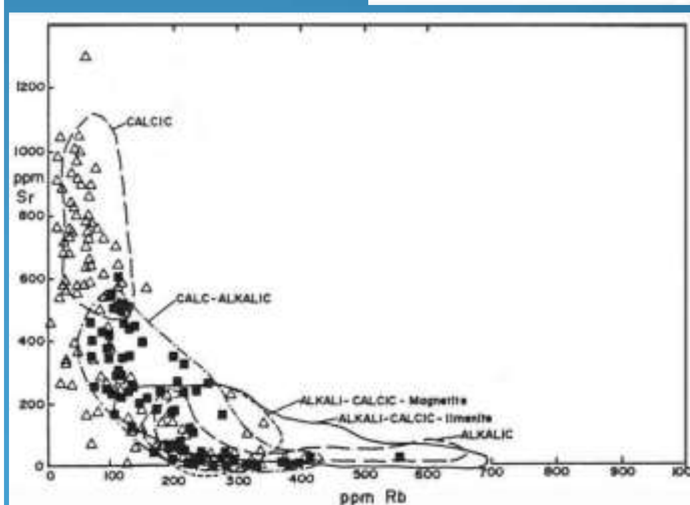

W. Santa Catalina Mts. from El Conquistador

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) 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)

PC

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

Source: Keith 2002 Grade/ton database

Gold, Gold Basin, Mohave Co., AZ

Peraluminous Calcic

Tungstite, wolframite, Boriana mine, Yavapai Co. AZ MM-1019

scheelite

Boriana dist. prod. (1919-1964)

Peraluminous Calc-alkalic

PCA

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

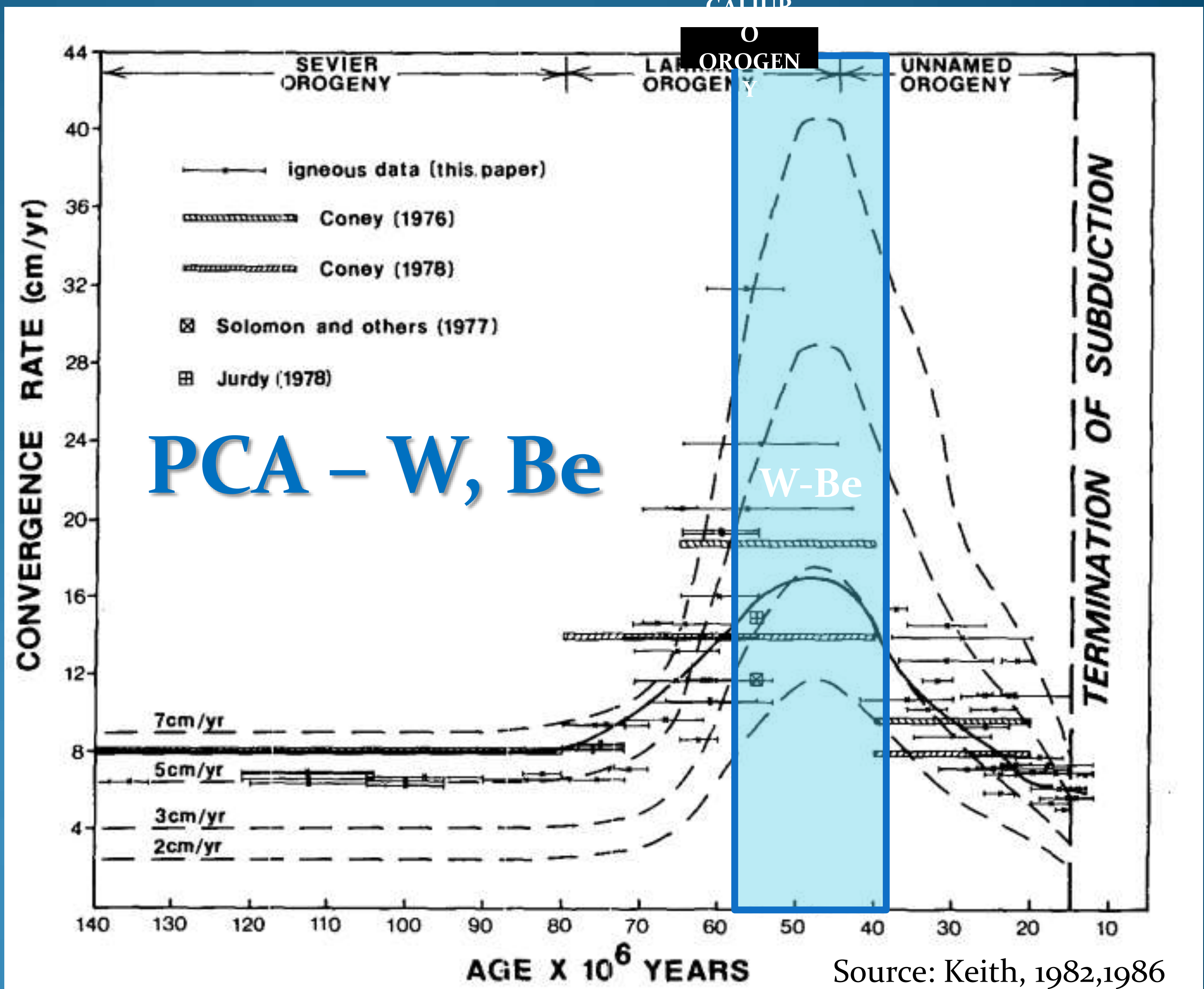
Production for Laramide assemblages (as of 1986)

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

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

Largest volume of peraluminous calc-alkalic very strongly hydrous oxidized granitic intrusions (culminant Laramide) is associated with fastest convergence rates, flattest subduction, no volcanism and significant tungsten production, and trench directed mylonitization, thrusting and underplating of Orocopia schist and associated serpentinites (This is the main Laramide [and core complex forming] Tectonic Event). (egs. Reef, Boriana, Las Guijas, Bluebird, Wilderness sill complex)



Source: Keith, 1982,1986

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

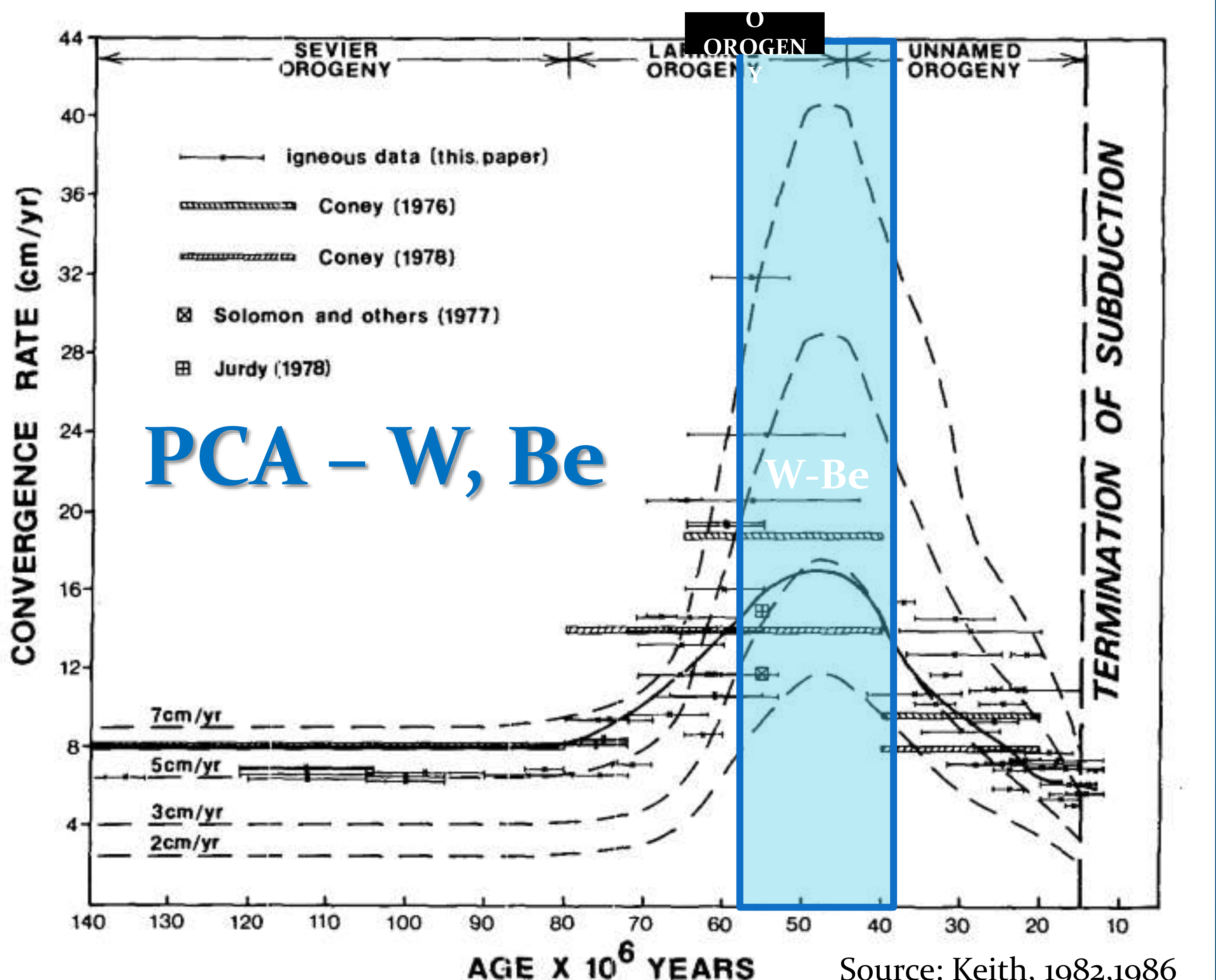
Zero volcanism – crystallized too deep.

Thickened crust and tectonically bury slab.

Less volume of metals because is recycled Oracle.

W and Be is inherited from melted crust (Oracle Granite)

Most hydrous - Muscovite stability = 10 wt% water



Source: Keith, 1982,1986

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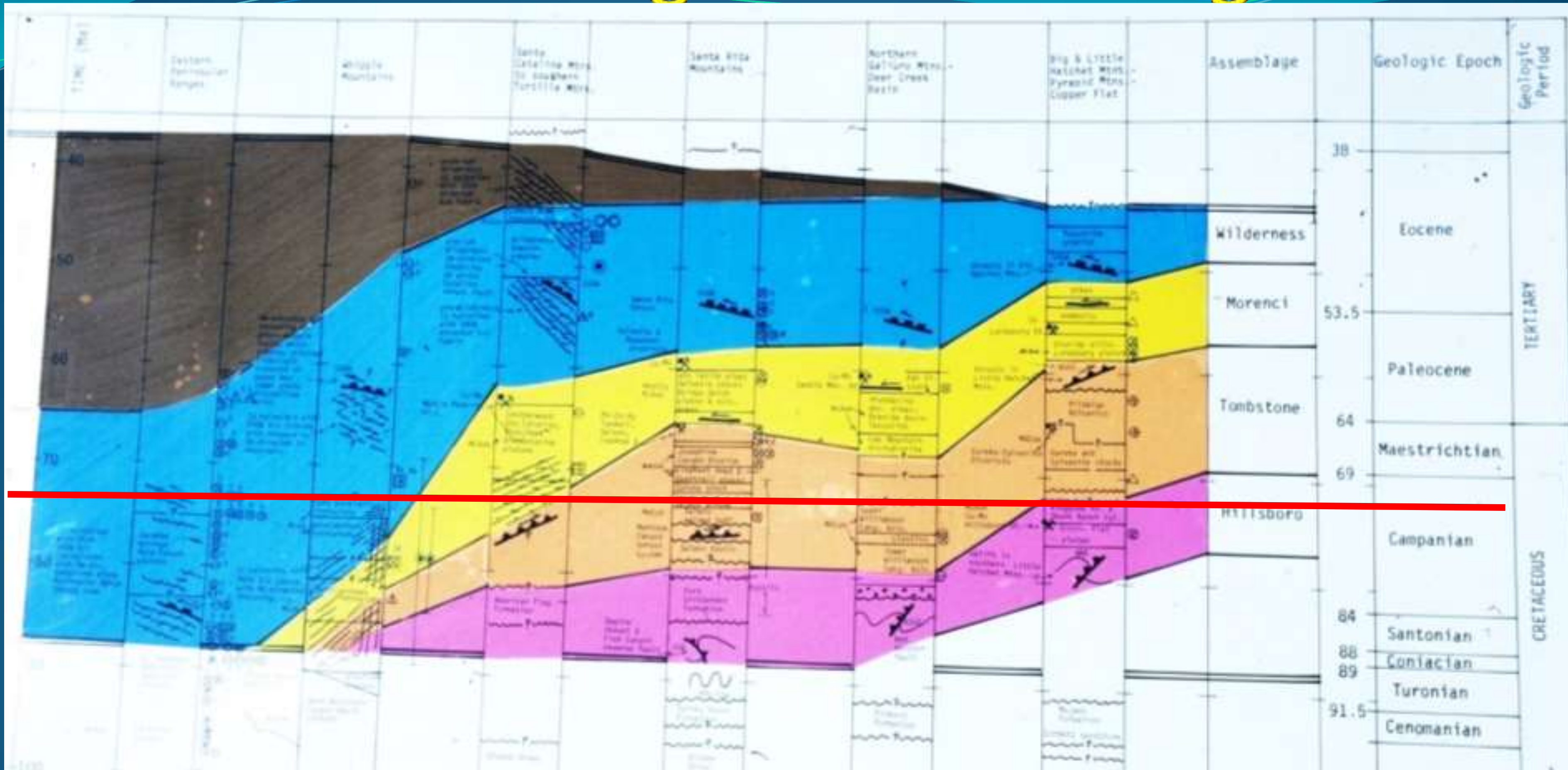
Laramide 'transgression' of magmatism



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

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

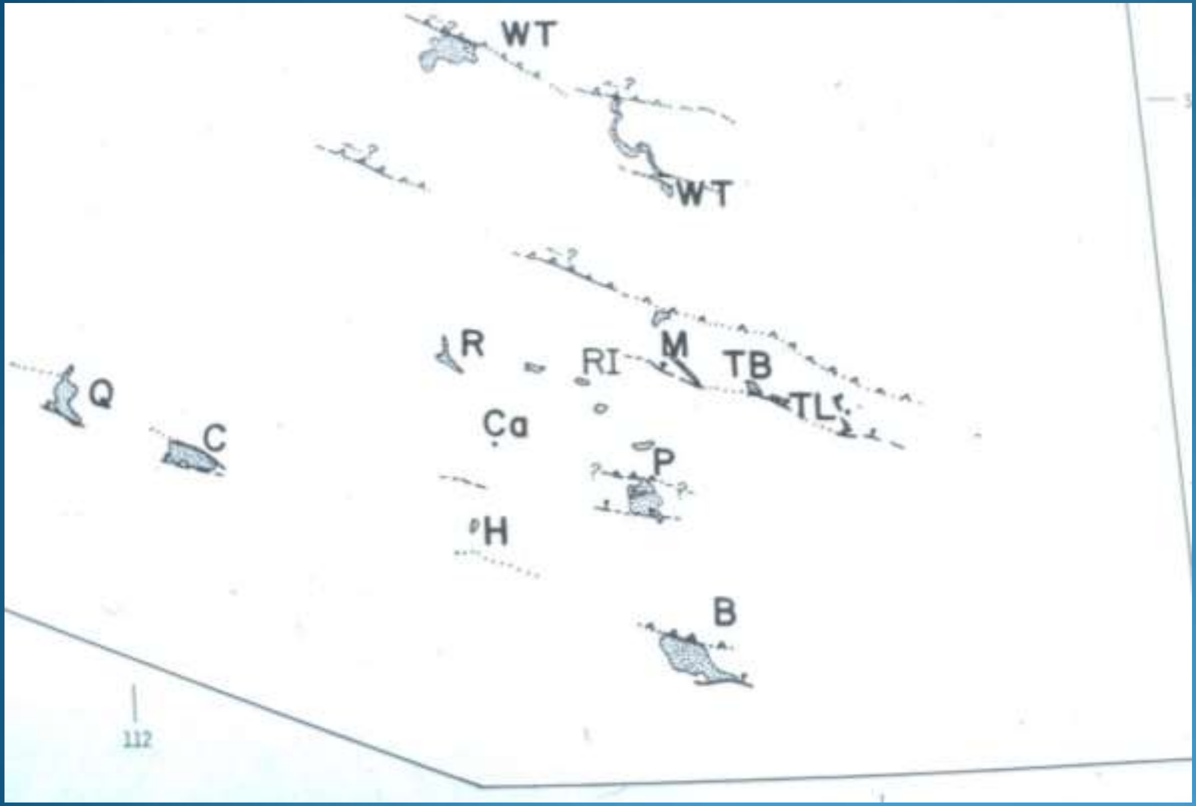
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Galiuro	Late (Whipple)	18-13	MQA	Au-Ag (Cu) F, U, Mn	Oatman, Mammoth, Rowley, Tiger
	Middle (Datil)	28-18	MAC	Pb-Zn-Ag F	Silver (Red Cloud), Castle Dome, Stanley, Aravaipa
	Early (South Mountain	30-22	MCA	Au +/- (Cu, W)	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)

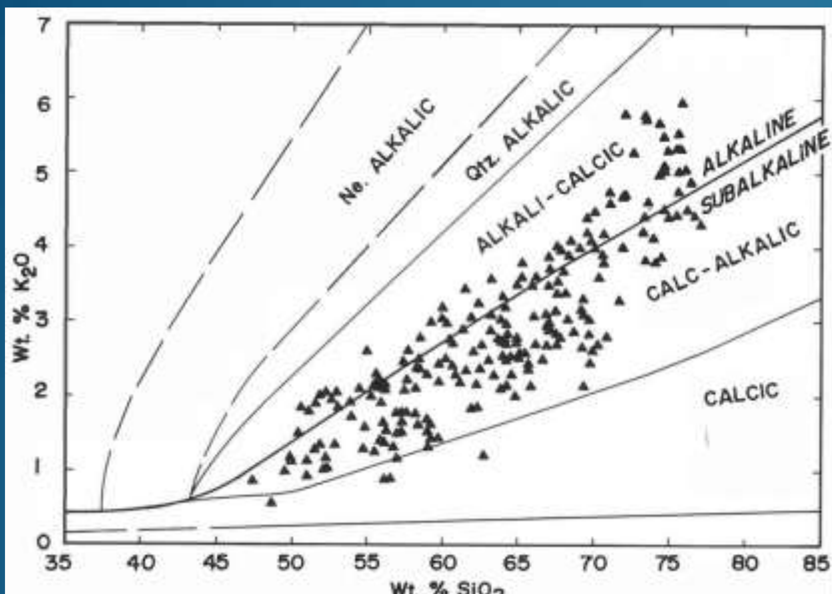


Pantano Clay, East Tucson - 1987

OROGENIC PHASE	ASSEMBLAGE	SEDIMENTATION	MAGMATISM	STRUCTURAL FEATURES	MINERAL RESOURCES	AGE (Ma)
Initial GALIURO	Mineta	coarse & fine clastics & evaporites in lacustrine environ.	rare volcanics mostly within 'volcanic gap'	local broad basins poss. WNW trend. reverse faults	uranium clay exotic copper	38-28

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

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



igure 2. K20 vs. SiO2 diagram of South Mountain facies igneous rocks.

OROGENIC PHASE	ASSEMBLAGE	SEDIMENTATION	MAGMATISM	STRUCTURAL FEATURES	MINERAL RESOURCES	AGE (Ma)
	South Mountain Facies	clastics interfinger with volcanics	calc-alkalic hydrous volcanics and epizonal plutons (metaluminous)	broad NW trend folds NW trend dikes minor NE trend dikes	Au +/- Cu-W veins & disseminated deposits	30-22 AZ 31-14 CA

Middle Galiuro – Datil (28-18 Ma)

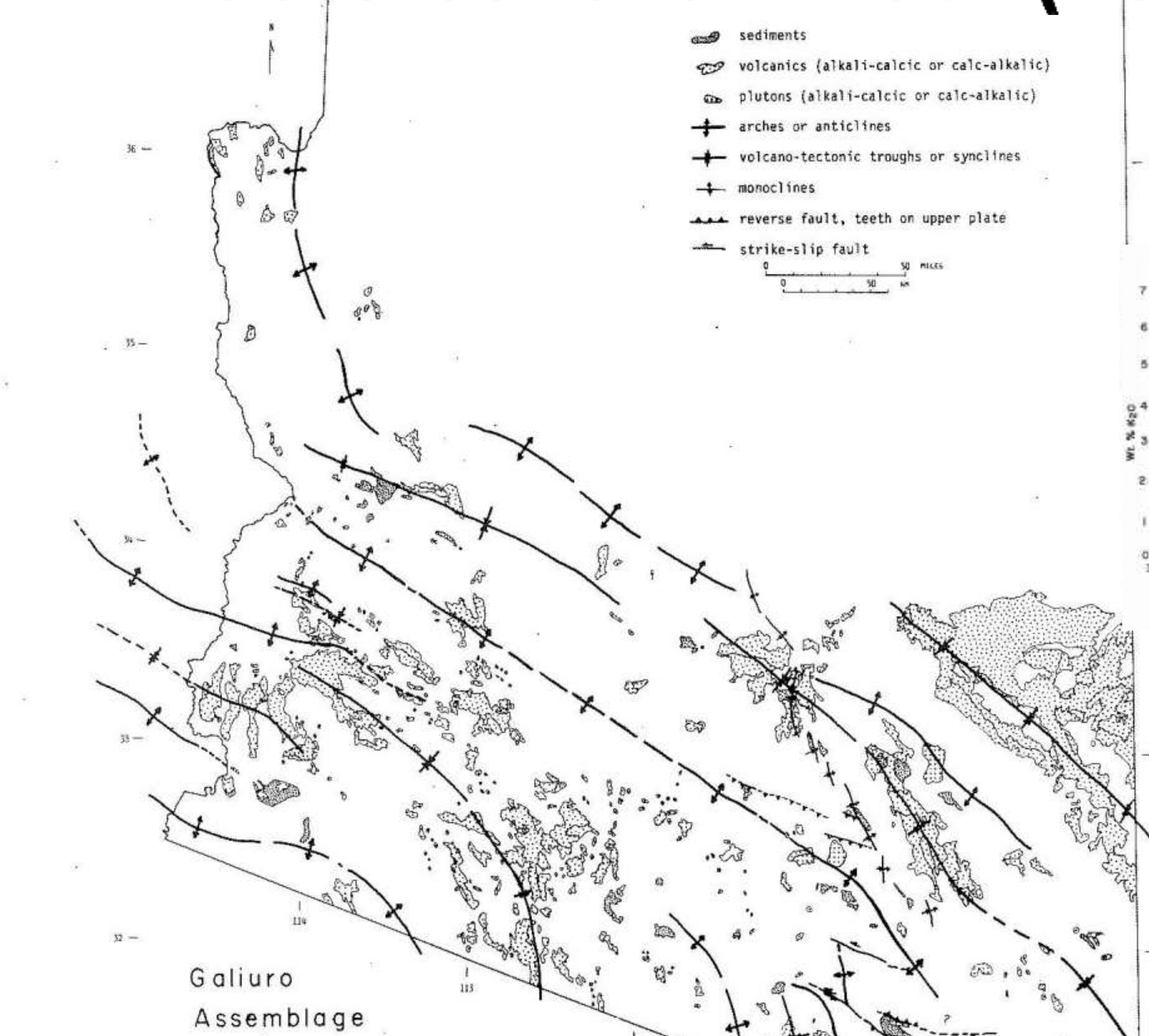


Figure 4. Map of Galiuro assemblage of the medial Galiuro orogeny in Arizona and vicinity.

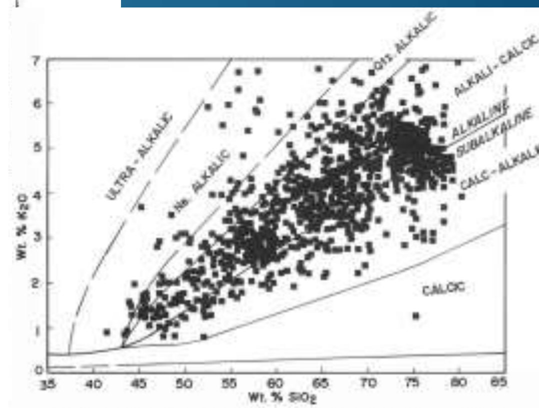


Figure 1. K2O vs. SiO2 diagram of Datil facies igneous rocks

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

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

Red Cloud Mine is in Silver district, La Paz Co.

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

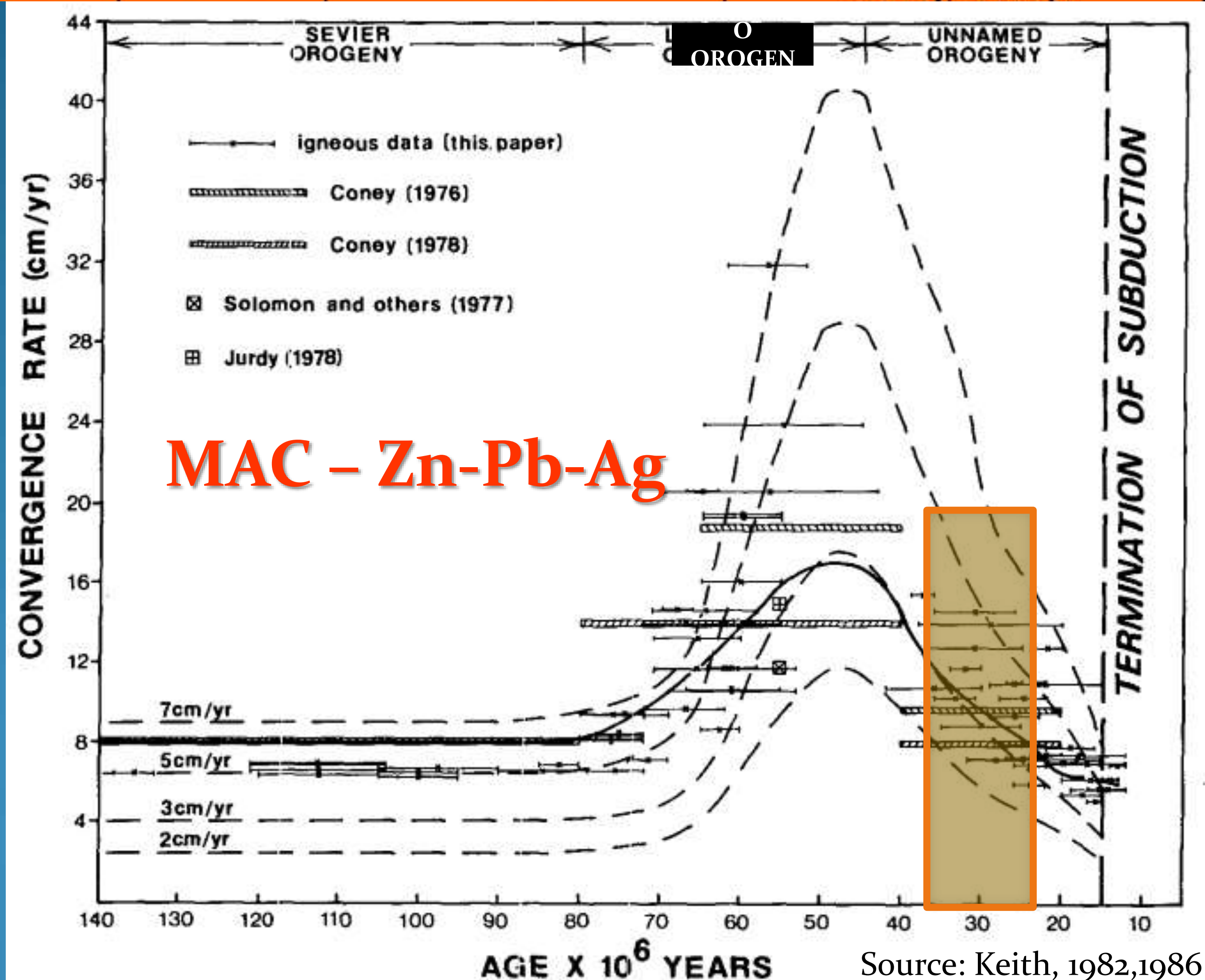
Wulfenite

OROGENIC PHASE	ASSEMBLAGE	SEDIMENTATION	MAGMATISM	STRUCTURAL FEATURES	MINERAL RESOURCES	AGE (Ma)
Medial GALIURO	Galiuro Datil Facies	local clastics interfinger with volcanics	alkali-calcic hydrous ignimbritic volcanics & epizonal plutons (metaluminous)	broad NW-trend folds NW and NE-trending dikes	Pb-Zn-Ag [illegible] & replacements epithermal Ag hotspring Mn	[illegible] 28-18 AZ 22-18 CA

Middle Galiuro – Datil (28-18 Ma)

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

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



Source: Keith, 1982,1986

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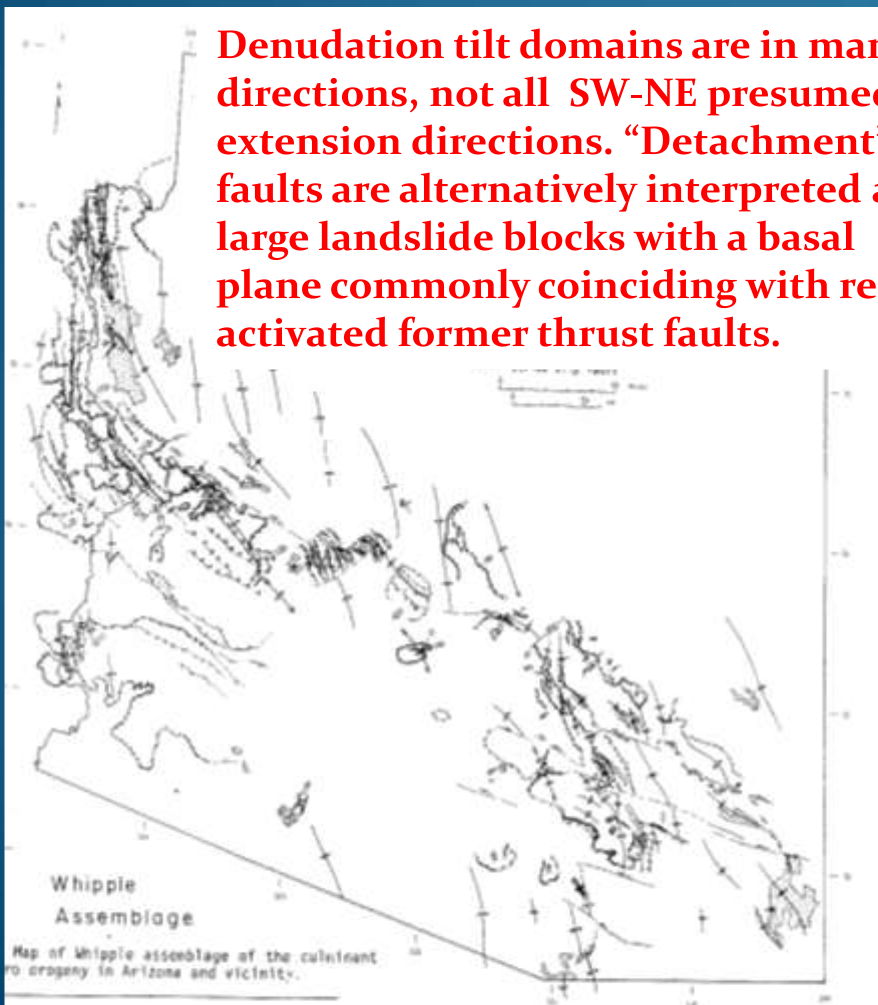
Late Galiuro – Whipple (18-13 Ma)

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



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

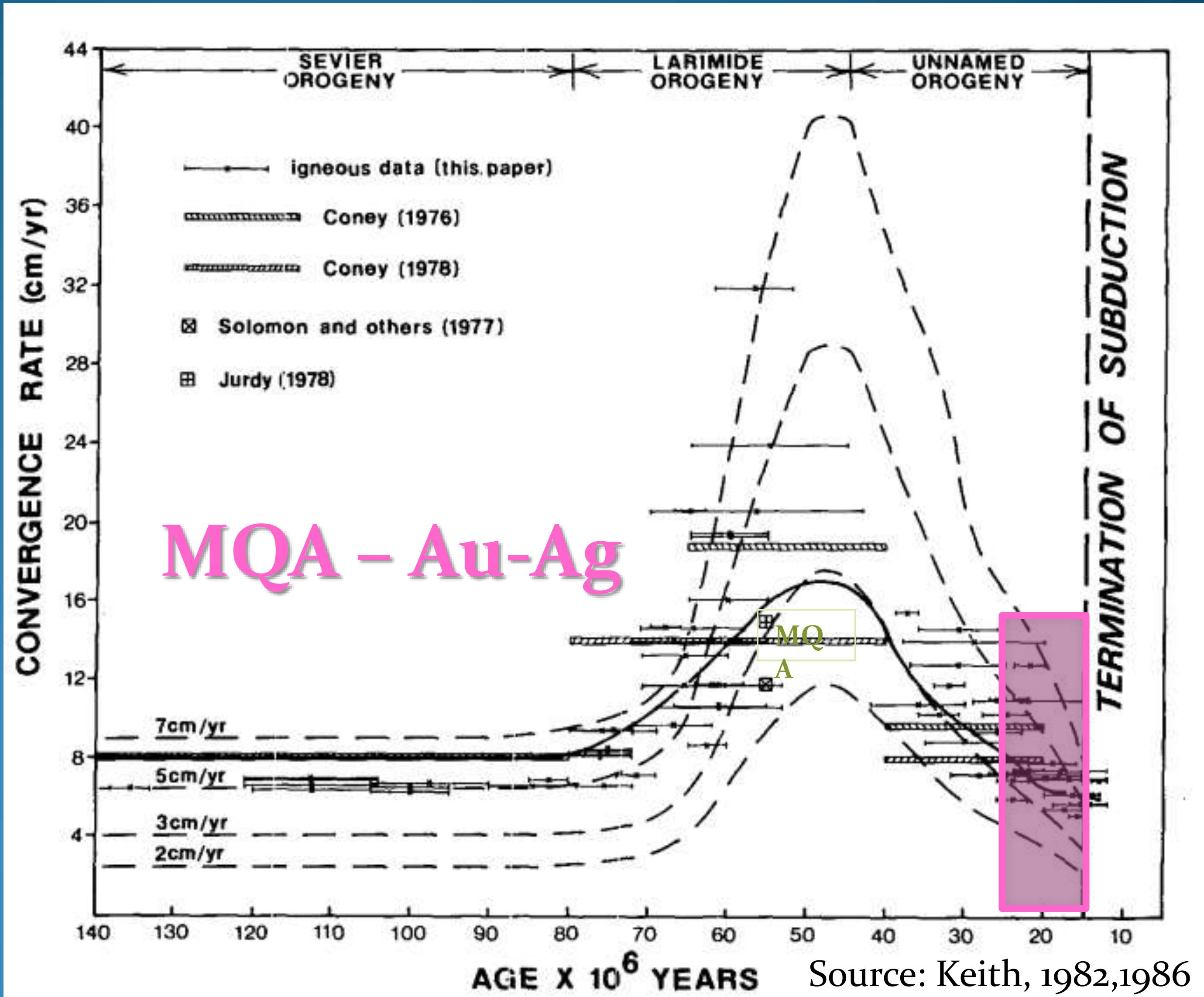
Oatman dist. prod. (1870-1980)
60,000 lb Cu
0 lb Pb
0 lb Zn
1,966,000 oz Au
1,147,000 oz Ag

Source: Keith et al. 1983

Late Galiuro – 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 hydrous oxidized high K shoshonite-rhyolite hypabyssal intrusions (Miocene) are associated with slowed convergence rates, very steepened subduction, local shoshonitic-high K rhyolite volcanism, and epithermal gold (base-metal) production (eg. Tiger, Oatman, Alice Camp)



Source: Keith, 1982,1986

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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, mimetite

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

OROGENIC PHASE	ASSEMBLAGE	SEDIMENTATION	MAGMATISM	STRUCTURAL FEATURES	MINERAL RESOURCES	AGE (Ma)
Culminant GALIURO	Whipple	coarse & fine clastics megabreccia blocks	alkalic hydrous volcanics & local epizonal stocks (metaluminous)	low-angle normal detachment faults SSE-NNW-trending folds NW-SE striking thrusts & reverse faults	Cu-Au-Ag in vns, replacement lenses & in detach. faults epithermal Au-Ag vns hotspring Mn & U	18-11 ? CA 34-13 AZ 28-18 ? NM

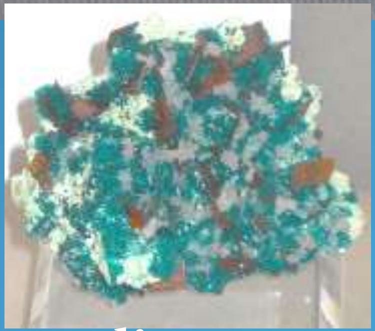
Late Galiuro – Mammoth-St. Anthony mine (Tiger townsite)

diaboleite

vanadinite

cerussite

boleite

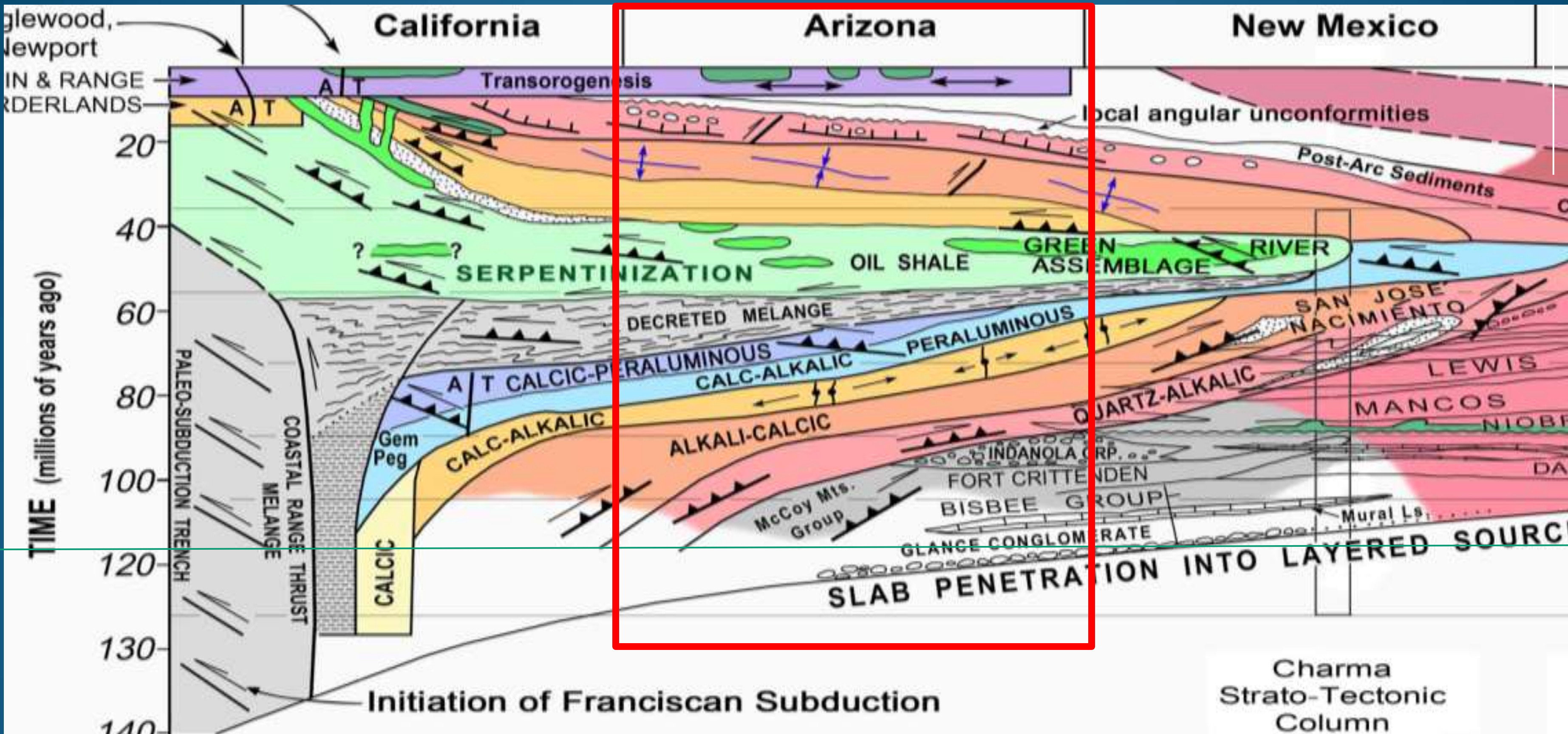


dioptase

hemimorphite

caledonite

Cretaceous and Cenozoic time distance

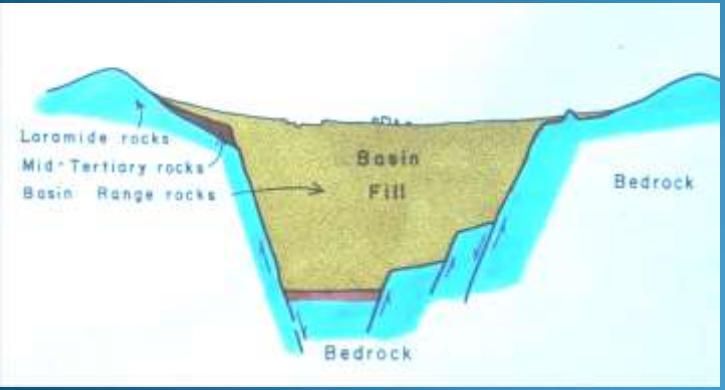


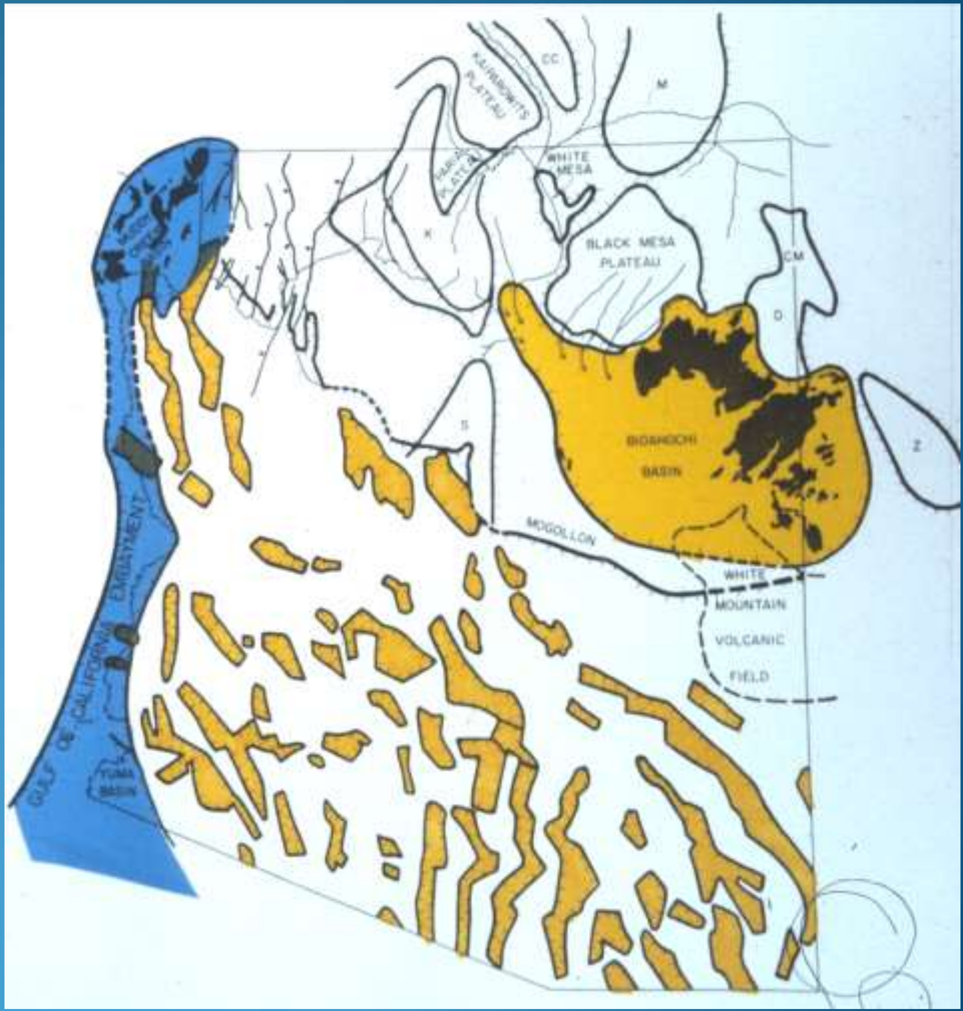
Slab flattening = Laramide eastward sweep
Flat subduction = Peraluminous, end of Laramide
Slab steepening = Cenozoic westward sweep of magmatism
San Andreas cuts off slab = Basin & Range extension & basalt volcanism

San Andreas – Basin & Range (13-0 Ma)

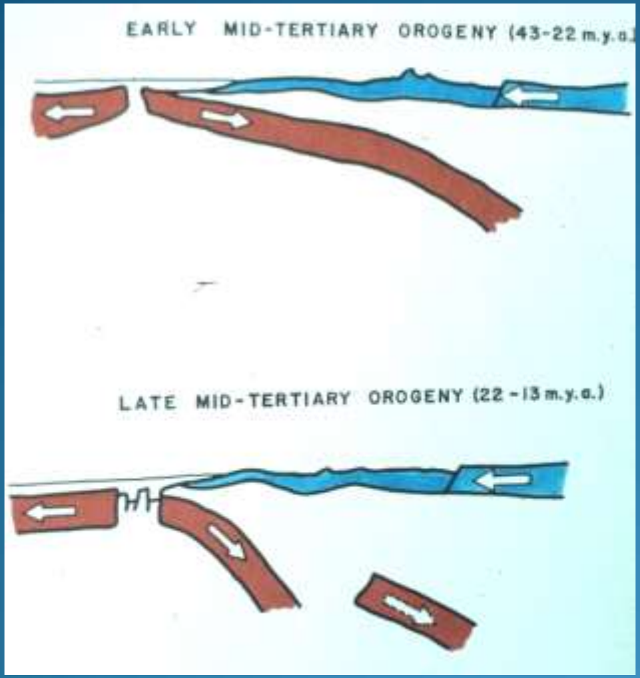
Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
San Andreas	Basin & Range	13-0	MQA	Sand, gravel, salt, zeolites, gypsum	San Francisco volcanic field, San Carlos olivine, Emerald Isle exotic Cu

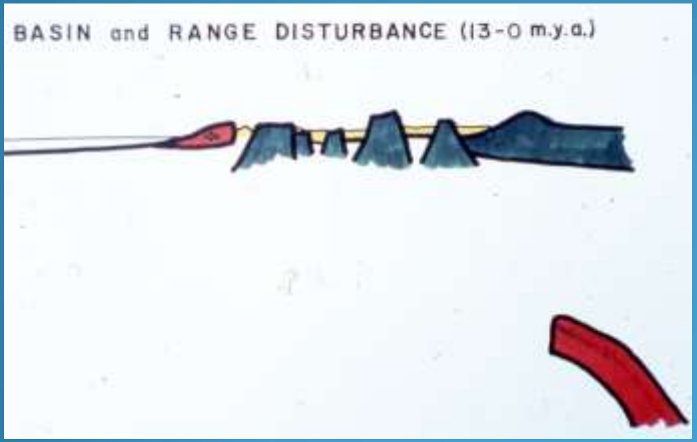
Basin and Range Valleys filled with sand, gravel, clay, gypsum, & salt - True extension

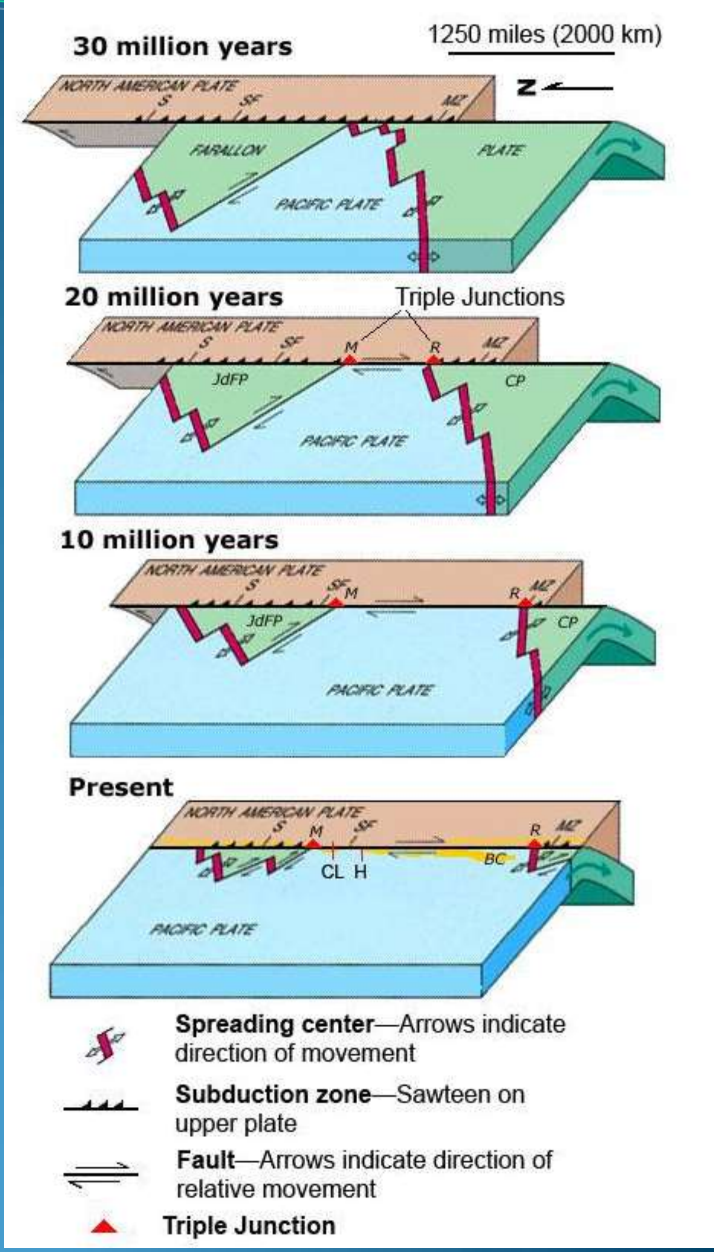




San Andreas fault cuts off eastward-subducting slab

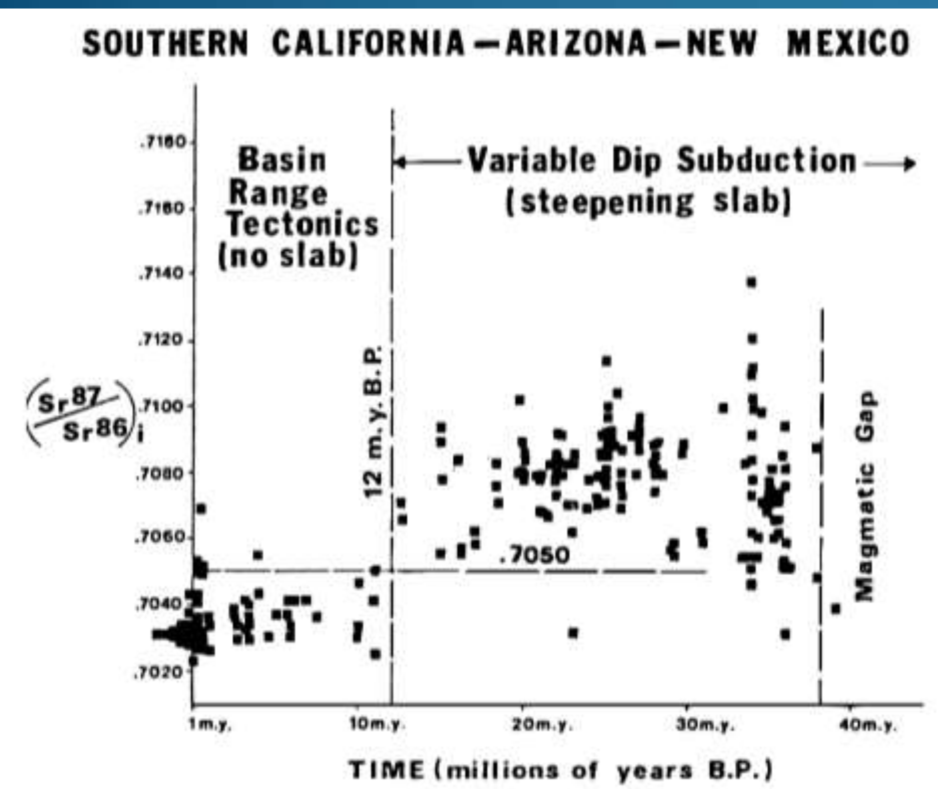




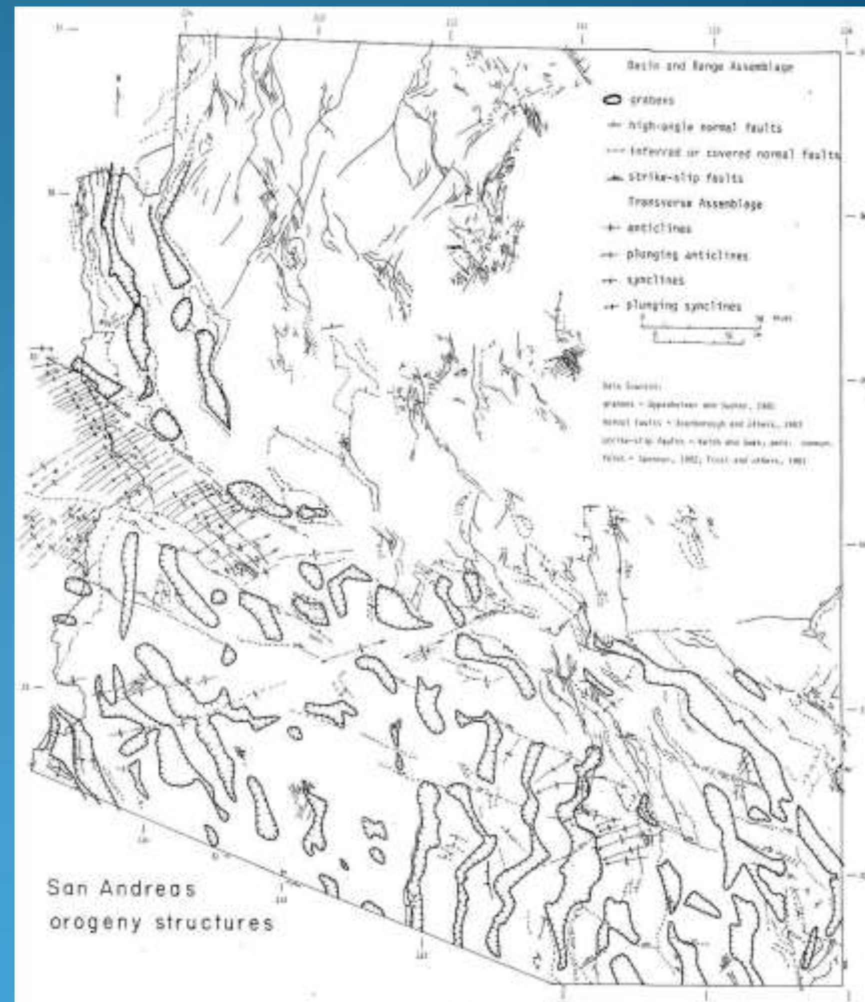


San Andreas – Basins (13-0 Ma)

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

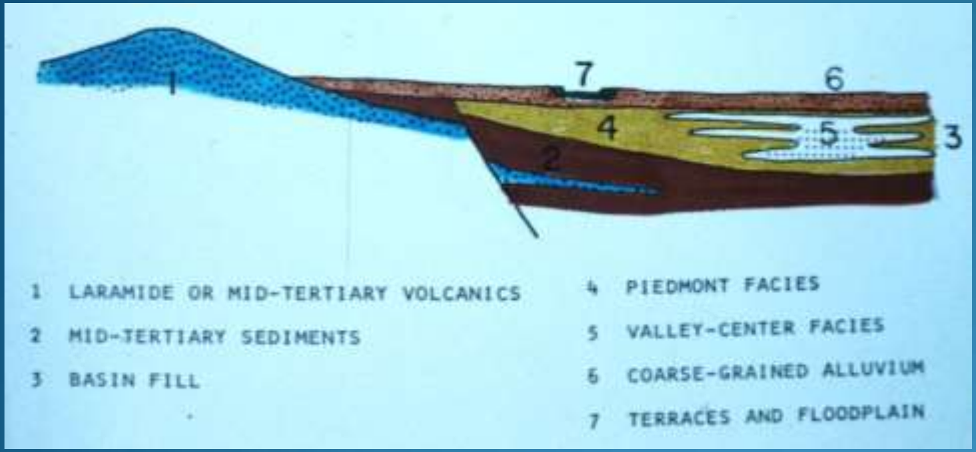


Annis & Keith, 1986



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

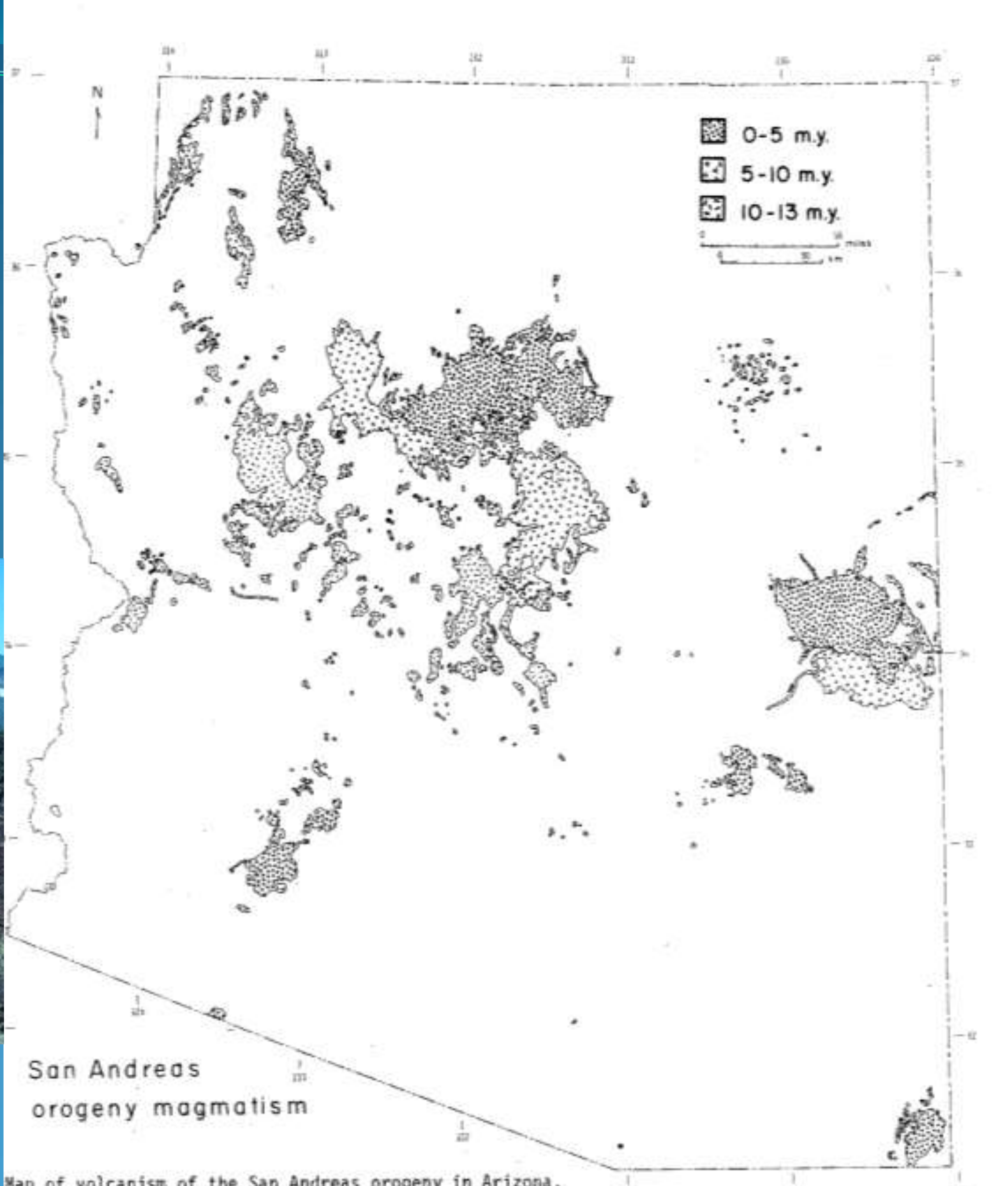


Willcox Playa

Rillito II - ~ 21 Ma

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

San Francisco Peaks, Flagstaff



Map of volcanism of the San Andreas orogeny in Arizona.

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

Olivine in basalt, San Carlos

cinders

No metals

San Andreas – Basin & Range (13-0 Ma)

Industrial minerals from basins

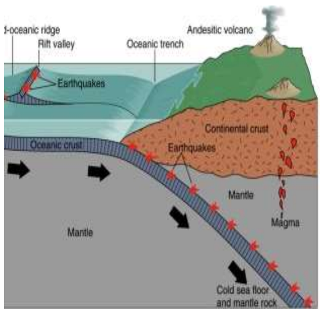
Sand & gravel

Kalamazoo Clay - 1987

Gypsum rose – St. David

Salt - Picacho Basin – UnoCal photo

Resources and Alkalinity



Orogeny	Orogenic Phase	Age (Ma)	Alkalinity	Resources
San Andreas	Basin & Range	13-0	anhydrous	Industrial Minerals
Galiuro	Late (Whipple)	18-13	MQA	Cu-Au-Ag
	Middle (Datil)	28-18	MAC	Pb-Zn-Ag F
	Early (South Mountain	30-22	MCA	Au +/- Cu-W
	Earliest (Mineta)	38-28	-	U, clay, exotic Cu
Laramide	Late (Wilderness)	55-43	PC, PCA	Au; W, Be
	Middle (Morenci)	65-55	MCA	porphyry Cu
	Early (Tombstone)	85-65	MAC	Pb-Zn-Ag
	Earliest (Hillsboro)	89-85	MQA	Cu-Au
Sevier		140-89		Limestone
Nevadan	Late	150-140	PC, PCA	W
	Late	160-150	MCA	Cu-Zn
	Middle	180-160	MAC	Zn-Pb-Cu-Ag
	Middle	205-180	MQA	porphyry Cu-Au
	Early	230-205	MQA	U, V, Cu
Alleghenian (Ouachita)		325-220	-	U
Acadian/ Caledonian		410-380	-	Limestone
Taconic.		490-445	-	
Grenville		1200-900	MQA	Asbestos, Cu
"Oracle/Ruin"		1440-1335	PCA	Be, Li, Ta-Nb, U & W
Mazatzal		1750-1600	MC	Zn-Cu-Ag-Au VMS
Yavapai		1800-1775	MC	Zn-Cu-Ag-Au VMS
Penokean/ Hudsonian		2000-1800	MC	BIF

Significant Points

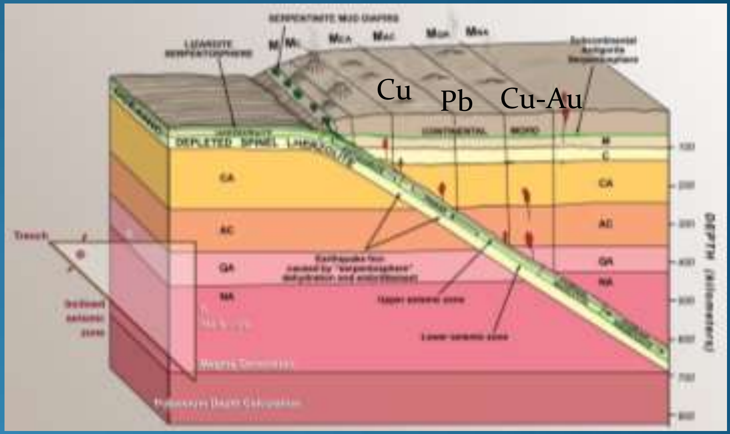
- Copper deposits formed in only 2 time periods – Jurassic & middle Laramide.
- Other 16 times were other metals (Zn, Pb, Au, W, U).

- The crust is not the source of copper deposits.
- Cannot get different metals when 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.**

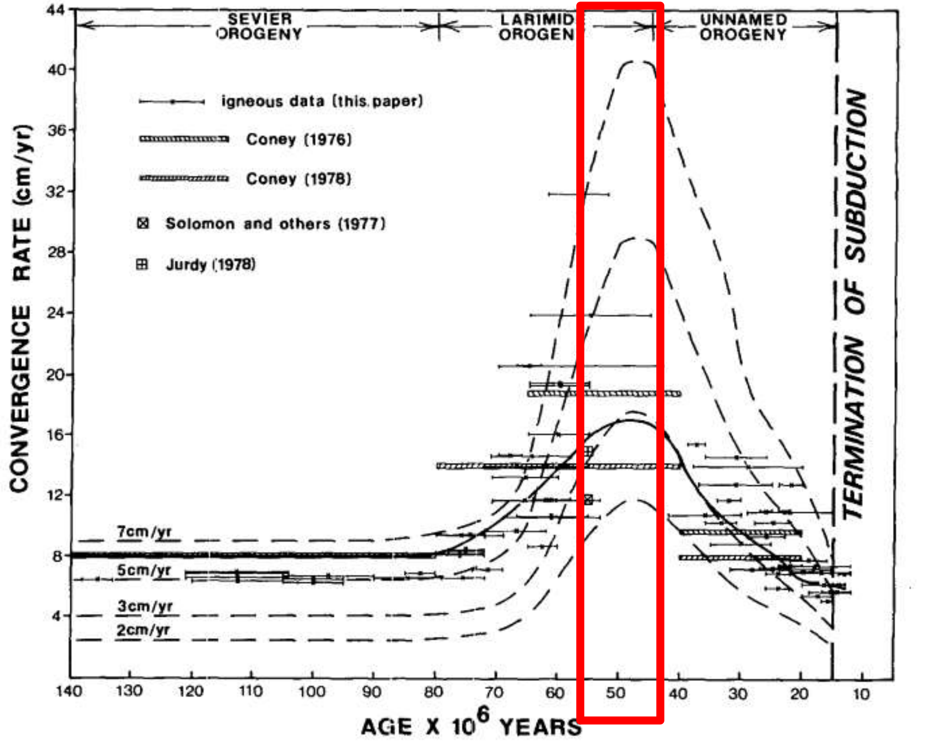


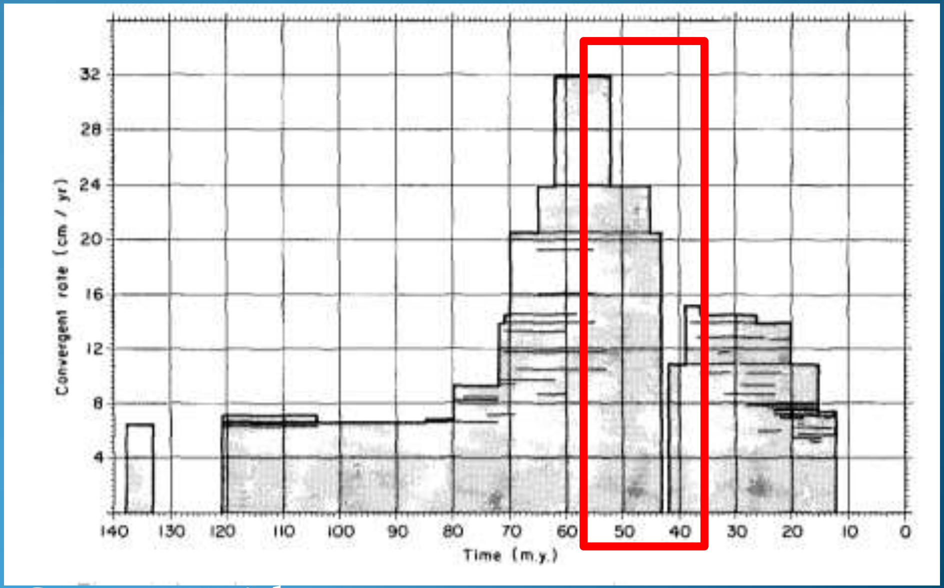
- **As subducting slab became flatter through time, metal associations changed depending on the source layer in the mantle.**

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.

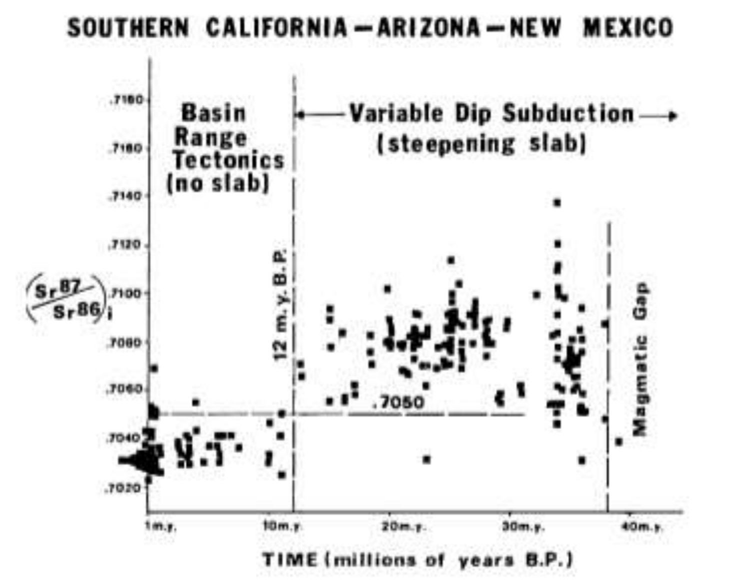




Source: Keith, 1982

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
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	?

References Cited

Annis, D.R. and Keith, S.B., 1986, Petrochemical variation in post-Laramide igneous rocks in Arizona and adjacent regions; geotectonic and metallogenic implications: Arizona Geological Society Digest v. 16, p. 502-554.

Keith, S.B., 1978, Paleosubduction geometries inferred from Cretaceous and Tertiary magmatic patterns in southwestern North America: Geology, v. 6, p. 516-521.

Keith, S.B., 1979, Spatial, temporal, chemical, and structural evolution of the southeast Arizona-southwest New Mexico porphyry copper cluster: Society of Economic Geologists Field Conference on Tucson area porphyry copper deposits, April 1979 Guidebook, 10 p.

Keith, S.B., Reynolds, S.J., Damon, P.E., Shafiqullah, M., Livingston, D.E., and Pushkar, P.D., 1980, Evidence for multiple intrusion and deformation within the Santa Catalina-Rincon-Tortolita crystalline complex, southeastern Arizona: Geological Society of America Memoir 153, p. 217-267.

Keith, S.B., 1982, Paleoconvergence rates determined from K20/Si02 ratios in magmatic rocks and their application to Cretaceous and Tertiary tectonic patterns in southwestern North America: Geological Society of America Bulletin, v. 93, p. 524-532.

Keith, S.B., Gest, D.E., DeWitt, E., Toll, N.W., and Everson, B.A., 1983, Metallic mineral districts and production in Arizona: Arizona Bureau of Geology and Mineral Technology, Geological Survey Branch Bulletin 194, 58 p.

Keith, S. B., and Wilt, J.C., 1985, Late Cretaceous and Cenozoic orogenesis of Arizona and adjacent regions: a strato-tectonic approach, *in* Flores, R.M., and Kaplan, S.S., editors, Cenozoic paleogeography of west-central United States: Rocky Mountain Section - Society of Economic Paleontologists and Mineralogists, Symposium 3, p. 403-437.

Keith, S.B., and Wilt, J.C., 1986, Laramide orogeny in Arizona and adjacent regions: a strato-tectonic synthesis, *in* Beatty, B., and Wilkinson, P.A.K., editors, Frontiers in geology and ore deposits of Arizona and the Southwest: Arizona Geological Society Digest, v. 16, p. 502-554.

Keith, S.B., and Swan, M.M., 1995, Tectonic setting, petrology, and genesis of the Laramide porphyry copper cluster of Arizona, Sonora, and New Mexico: Arizona Geological Society Digest 20, p. 339-346.

Keith, S.B., and Swan, M.M., 1991, The great Laramide porphyry copper cluster of Arizona, Sonora, and New Mexico: the tectonic setting, petrology, and genesis of a world class porphyry metal cluster, *in* Coyner, A.R., and Fahey, P.L., eds., Geology and ore deposits of the American Cordillera: Geological Society of Nevada Symposium Proceedings, Reno/Sparks, Nevada, April 1995, Proceedings volume III, p. 1667-1747.

Livaccari, R.F., and Keith, S.B., 1985, Tectonic analysis of the Sevier and Laramide orogenies in western North America: MagmaChem unpublished report, 220 p.

Swan, M.M., and Keith, S.B., I 986, Orogenic model for "anorogenic" granitoids in North America; product of oblique subduction at 1.4 Ga: Arizona Geological Society Digest 16, p. 489-498.

Wicander, R., and Monroe, J.S., 2000, Historical geology: evolution of Earth and life through time: Brooks/Cole Thomson Learning, p.217/

Wilt, Jan C., 1995, Correspondence of alkalinity and ferric/ferrous ratios of igneous rocks associated with various types of porphyry copper deposits, *in* Pierce, F. W., and Bolm, J. G., editors, Porphyry copper deposits of the American Cordillera: Arizona Geological Society Digest, v. 20, p. 180-200.

Wilt, Jan C., 1993, Geochemical patterns of hydrothermal mineral deposits associated with calc-alkalic and alkali-calcic igneous rocks as evaluated with neural networks: Tucson, AZ, University of Arizona, Ph. D. dissertation, 721 p.