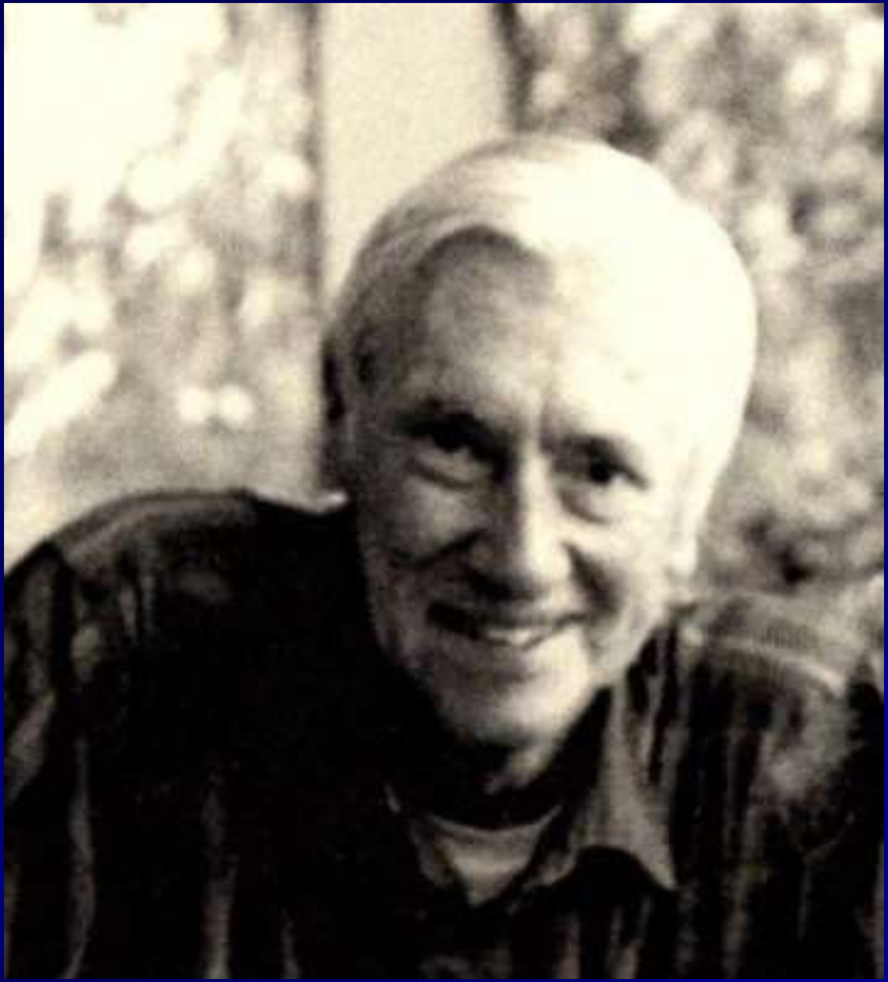
Future Exploration for Arizona Porphyry Copper Deposits: Do's and Don'ts

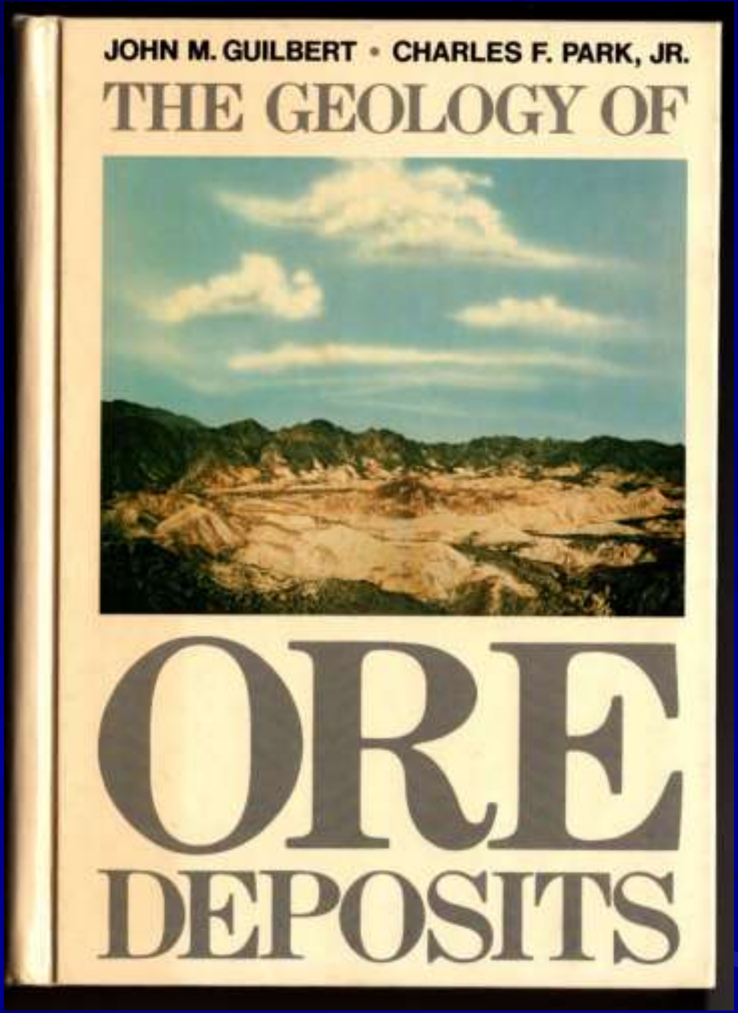
Sierrita

Jan C. Rasmussen & Stanley B. Keith

SME Tucson, May 9, 2018

Tribute to Dr. John M. Guilbert





JOHN M. GUILBERT • CHARLES F. PARK, JR.

THE GEOLOGY OF

ORE

DEPOSITS

May 12, 1931 - October 17, 2017

Mining Hall of Fame, Leadville, Sept. 29, 2018

Lowell and Guilbert, 1970 – Alteration
Guilbert and Lowell, Variations in Zoning

ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS

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Lateral and Vertical Alteration-Mineralization Zoning in Porphyry Ore Deposits

J. David Lowell and John M. Guilbert

Abstract

The geologic history of the San Manuel–Kalamazoo deposit has provided an opportunity for the examination of vertical and horizontal zoning relationships in a porphyry copper system. Precambrian Oracle "granite," a Laramide monzonite porphyry, and a Laramide dacite porphyry are hosts to zones of potassic, phyllic, argillic, and propylitic assemblages shown to be coaxially arranged outward from a potassic core through phyllic, argillic, and propylitic zones. Alteration zones at depth comprise an outer chlorite-sericite-epidote-magnetite assemblage yielding to an inner zone of quartz–K-feldspar–sericite–chlorite. Mineralization zones are conformable to the alteration zones, the ore zone (with a 0.5% Cu cutoff) overlapping the potassic and phyllic zones. Occurrence of sulfides changes upward and outward from dissemination at the low-grade core of the deposit through microveinlet to veinlet and finally vein occurrence indicating the progressively increasing effect of structural control.

Several aspects of San Manuel–Kalamazoo geology suggest that it is exemplary of the porphyry copper deposit group. To test that idea and to evolve three-dimensional aspects of these deposits, a table of geologic characteristics of 27 major porphyry deposits is presented. Consideration of the table indicates that the "typical" porphyry copper deposit is emplaced in late Cretaceous sediments and metasediments and is associated with a Laramide (65 m.y.) quartz monzonite stock. Its host intrusive rock is elongate-irregular, 4,000 × 6,000 feet in outcrop, and is progressively differentiated from quartz diorite to quartz monzonite in composition. The host is more like a stock than a dike and is controlled by regional-scale faulting. The orebody is oval to pipelike, with dimensions of 3,500 × 6,000 feet and gradational boundaries. Seventy percent of the 140 million tons of ore occurs in the igneous host rocks, 30 percent in preore rocks. Metal values include 0.45% hypogene Cu with 0.35% supergene Cu, and 0.015% Mo. Alteration is zoned from potassic at the core (and earliest) outward through phyllic (quartz-sericite-pyrite), argillic (quartz-kaolin-montmorillonite), and propylitic (epidote-calcite-chlorite), the propylitic zone extending 2,300 feet beyond the copper ore zone. Over the same interval, sulfide species vary from chalcopyrite-molybdenite-pyrite through successive assemblages to an assemblage of galena-sphalerite with minor gold and silver values in solid solution, as metals, and as sulfosalts. Occurrence characteristics shift from disseminations through respective zones of microveinlets (crackle fillings), veinlets, veins, and finally to individual structures on the periphery which may contain high-grade mineralization. Breccia pipes with attendant crackle zones are common.

Expression of zoning is affected by exposure, structural and compositional homogeneity, and postore faulting or intrusive activity. Vertical dimensions can reach 10,000 feet, with the upper reaches of the porphyry environment perhaps only at subvolcanic depths of a few thousand feet. The vertical and lateral zoning described is repeated with sufficient constancy that depths of exposure at many deposits can be cited against the model of San Manuel–Kalamazoo.

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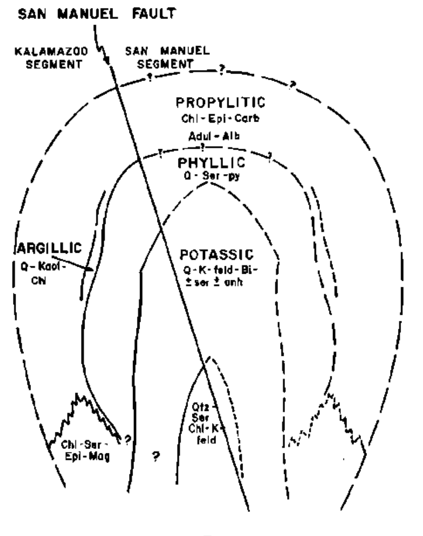

'Light bulb' model

Variations in Zoning Patterns In Porphyry Ore Deposits

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J. David Lowell, Consulting Geologist, Tucson, Arizona

Abstract

Models of alteration and mineralization of porphyry copper deposits have been useful in both scientific investigation of the deposits and in exploration activities, but many uncertainties remain. It is commonly difficult geologically to interpret and economically to evaluate individual occurrences and assemblages that depart from the norm.

In this paper, departures from the "typical" porphyry copper zoning pattern and assemblages are described, and the functions of several variable conditions in the porphyry copper environment are discussed. Depth of exposure, composition of pre-mineral wall rocks, pre-ore structural controls on intrusion, variations in composition of both igneous host rock and mineralizing fluids, size of the mineralizing system, variations in development of contemporaneous controls on mineralization (veinlets, veins and brecciation), and the breadth of stability fields of important silicate alteration minerals such as sericite and K-feldspar all affect the size, shape, mineralogy, symmetry, intensiveness and extensiveness of porphyry copper alteration-mineralization. Study of these variables can help in predicting the three-dimensional geologic-geometric characteristics of individual deposits.

Examples described to demonstrate the effects of these variables include the Valley Copper, JA and Bethlehem orebodies in British Columbia, Marcopper and Atlas in the Philippines, and the Ajo orebody in Arizona.

Introduction

SEVERAL RECENT PUBLICATIONS (Lowell & Guilbert, 1970; Rose, 1970; James, 1971; De Geoffroy & Wignall, 1972) have developed the concept that there are unifying geologic characteristics which are displayed to varying degrees by porphyry copper and molybdenum deposits. The first-named of these papers involved a tabulation of published data on the geologic features of 27 of the best-known deposits. It elicited from them, by comparison with the San Manuel - Kalamazoo model, a definition of porphyry copper-molybdenum deposits, a description of a "typical" deposit and a summary of the "normal" characteristics of porphyry ore deposits. Nineteen of those deposits are in southwestern North America, the remaining 8 being chiefly South American and Canadian deposits. It was the intent of that paper to isolate unifying geologic characteristics and to demonstrate that porphyry coppers have an interpretable lateral and vertical zoning. It was not proposed, however, that all deposits are identical. This paper will consider the nature of departures from idealized zoning patterns, reasons for those departures, and examples of variant assemblages at Bethlehem, Valley Copper and the JA orebody, B.C., Marinduque (Marcopper) and Atlas in the Philippine Islands, and Ajo, Arizona.

We are deeply indebted to the Bethlehem Copper Corporation, Ltd. for access to specimens, thin sections and deposits, and to our colleagues in Canada and Arizona — notably H. G. Ewanchuk and S. R. Titley — for stimulating discussion and critical comment. Portions of this paper have been published in Spanish (Guilbert & Lowell, 1971).

Before considering departures, the norm must be established. The "typical" southwestern North American porphyry copper deposit is emplaced in late Cretaceous sediments and metasediments and is associated with a Laramide (65 m.y.) quartz monzonite porphyry stock. Its host intrusive rock is elongate-irregular, 4,000 by 6,000 ft in outcrop, and is progressively differentiated from quartz diorite to quartz monzonite in composition. The host is more like a stock than a dyke and is controlled by regional-scale faulting. The orebody is oval to pipelike, with dimensions of 3,500 by 6,000 ft and gradational boundaries. Seventy per cent of the 140 million tons of ore occurs in the igneous host rocks, thirty per cent in pre-ore rocks. Metal values include 0.45% hypogene Cu, 0.015% Mo and 0.35% supergene Cu. Alteration (Fig. 1) is zoned from potassic (earliest and at the core) outward through phyllic (quartz-sericite-pyrite), argillic (quartz-kaolin-montmorillonite) and propylitic (epidote-calcite-chlorite) zones, with visible alteration commonly extending 2,300 feet beyond the copper ore zone. Over the same interval, sulphide species (Fig. 2) vary from chalcopyrite-molybdenite-pyrite through successive assemblages to an assemblage of galena and sphalerite with minor gold and silver in solid solution in sulphides, as metals, and as sulphosalts. Sulphide occurrence characteristics (Fig. 3) shift from disseminations through respective zones of microveinlets (crackle fillings), veinlets and veins, and finally to discrete peripheral structures that may contain high-grade mineralization. Breccia pipes with attendant crackle zones are common.

De Geoffroy and Wignall (1972) more than doubled Lowell and Guilbert's control group to 58 deposits, chiefly by the addition of 28 British Columbia occurrences, for a computerized statistical study of porphyry base-metal deposits. Their results, summarized in their Tables 4 and 5, permit their description (Table 6, p. 666) of a "composite geological model of the most typical ore-bearing porphyry intrusive complex", which is in very close agreement with the Lowell-Guilbert conclusions. The addition of a large number of examples from British Columbia has not

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Manuscript Submitted: on April 26, 1973; revised manuscript received November 16, 1973.

Keywords: Porphyry copper deposits, Zoning patterns, Alteration, Mineralization, Valley Copper deposit, JA deposit, Bethlehem Copper deposits, Marcopper deposit, Atlas deposit, Ajo deposit.

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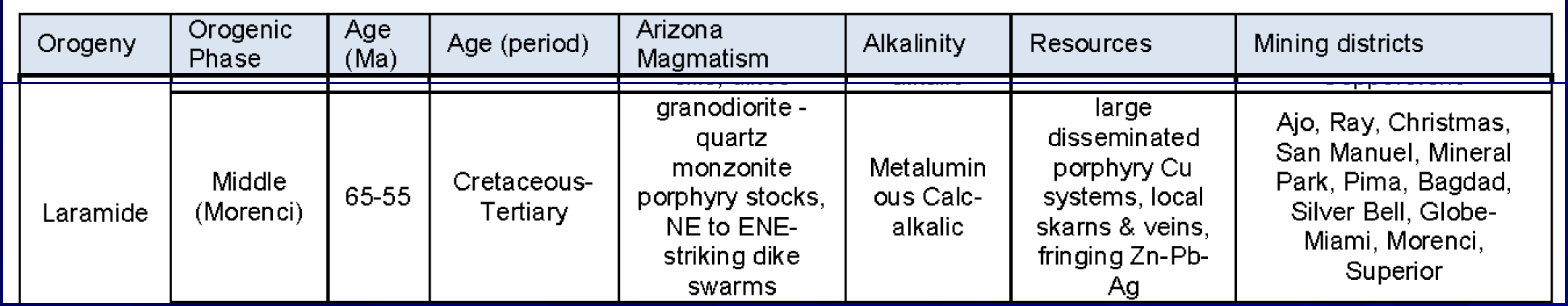
Significant papers with major impacts on exploration

Laramide porphyry copper (69-55 Ma)



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

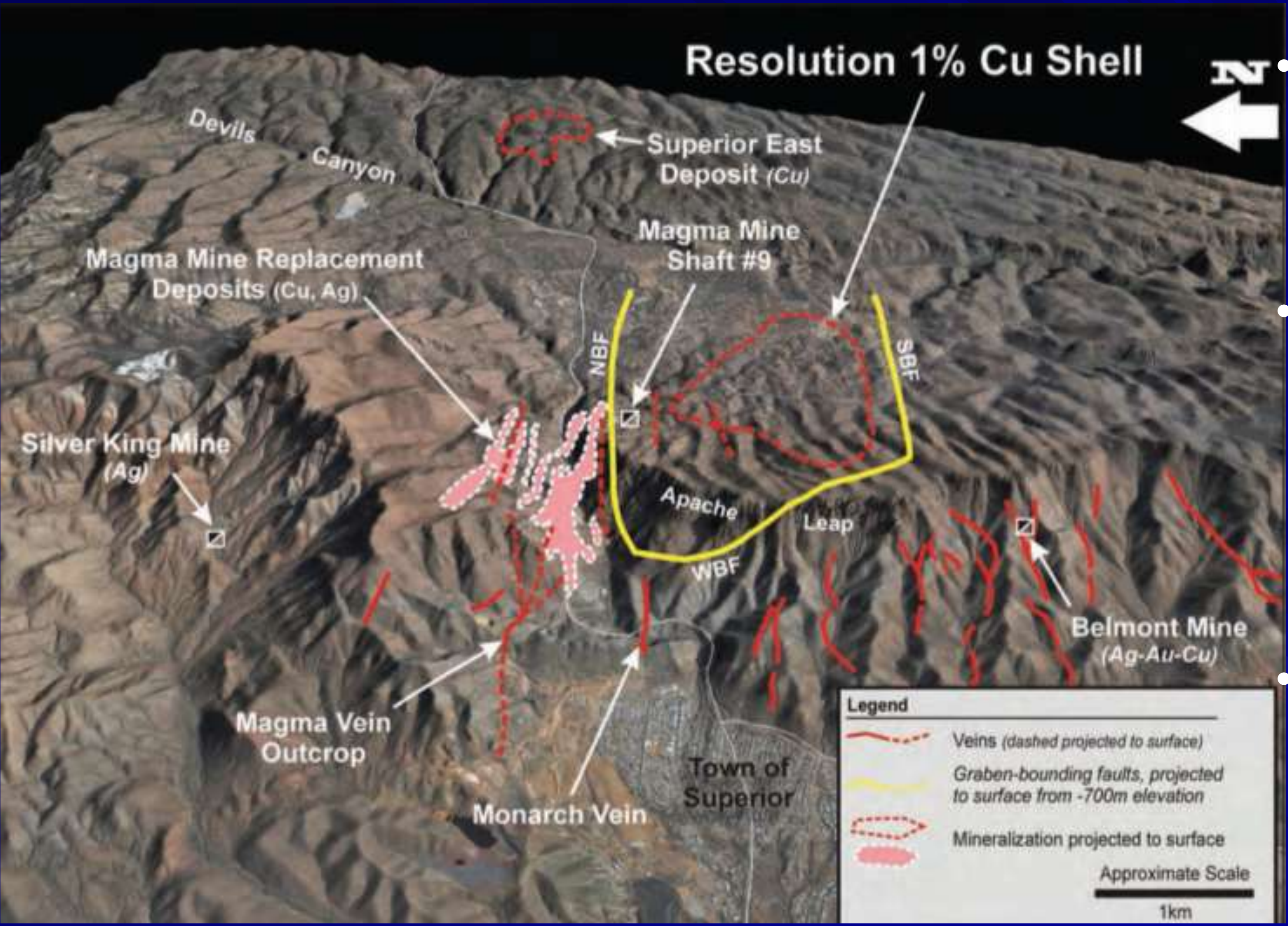
Ray mine

Ray shovel, haul truck
Dave Briggs photos

Wealth generators: Our jobs depend on them

Ray mine, looking S

Resolution Copper

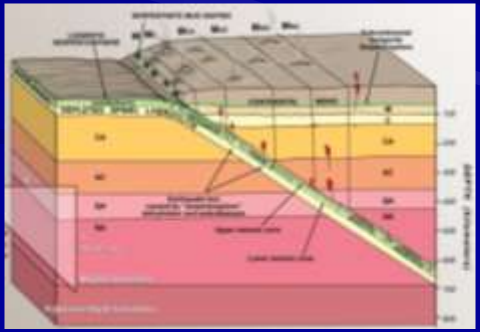


Hehnke et al., 2014

- Initial discovery 1994;
- Confirmed 1998 DH 1.75% Cu, 0.029% Mo;
- Resources (2017): 1,787,000,000 Metric Tons @ 1.54% Cu, 0.035%Mo;
- Encouraged renewed copper exploration in Arizona

Magma-Metal Series Classification

- **Empirically based** correlation of **magma chemistry and metal/ mineral associations** linked in time and space
- **Repeatable, Specific, Source-based**
- **Cause and effect predictive** relationship between magmatic source and hydrothermal products

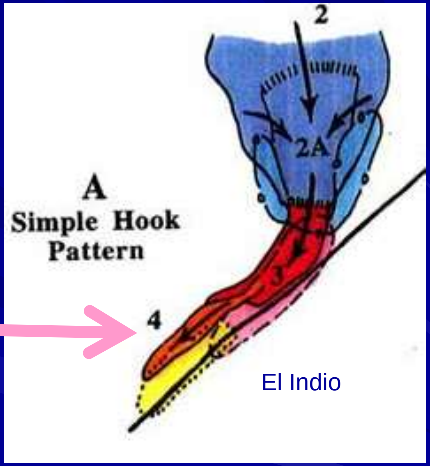


Magma-Metal Series Classification

- ❑ **Reduce exploration risk** in a sequenced regional-to-drillhole scale methodology

- ❑ Goal: **identify specific, low-risk drill targets** in economically favorable systems

- ❑ Tools:
  - ❑ **Pluton Vectoring**
  - ❑ **Element Dispersion Analysis**
  - ❑ **Kinematic Structural Analysis**
  - ❑ **Detailed Geologic Mapping**



Using the Magma-Metal Series Approach

Local mineral system to drillhole scale

- Identifies the **economically favorable** portion of the system
- Characterized by **specific** mineral and element assemblages
- Specific **low-pressure structural site** within the pluton-mineral system

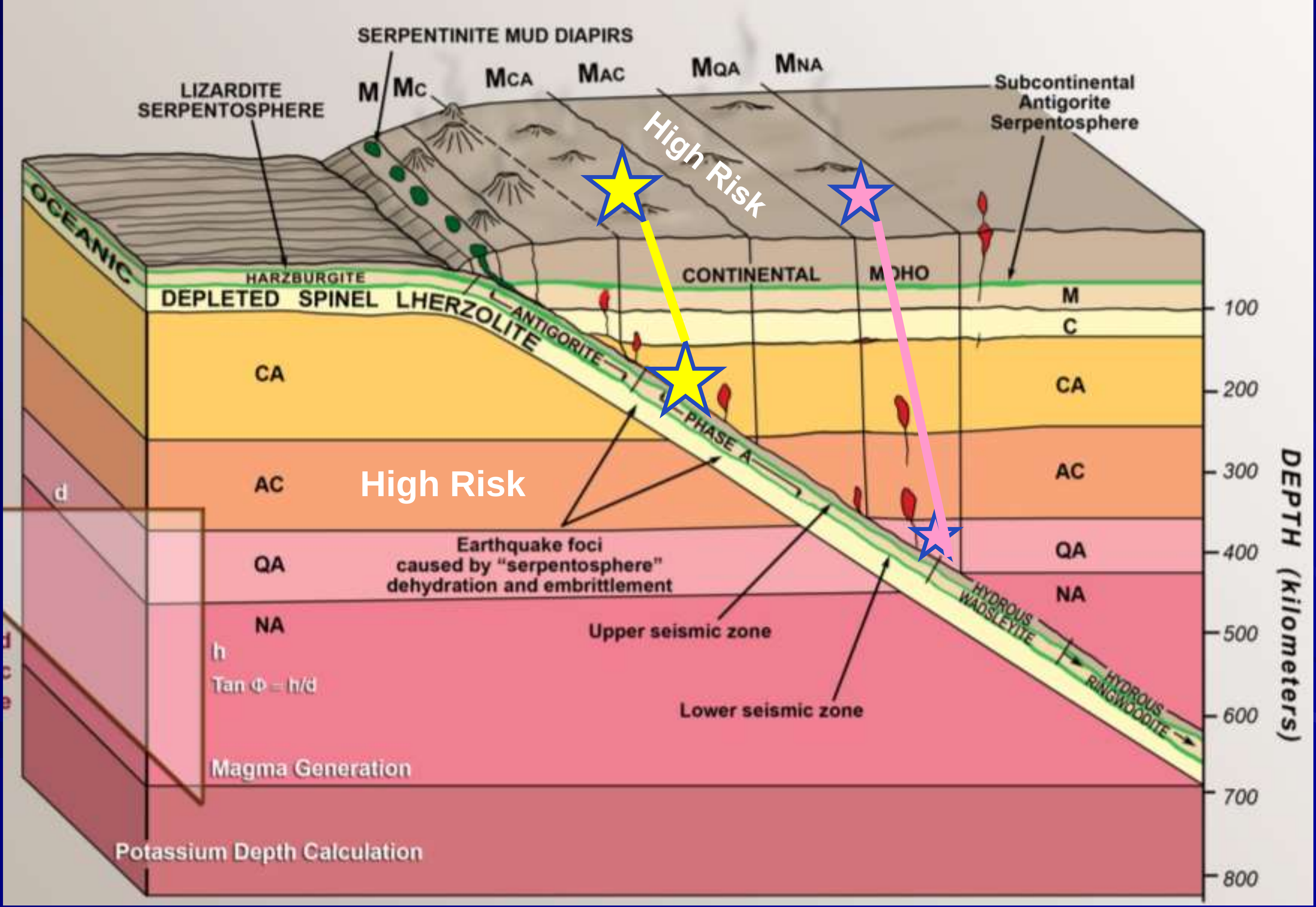
New Cornelia pit, Ajo, showing differentiation vectors for intrusive complex and Stage 4 target in and SE of the pit

Mountain Building Episodes in Arizona

Only 2 periods with porphyry copper deposits

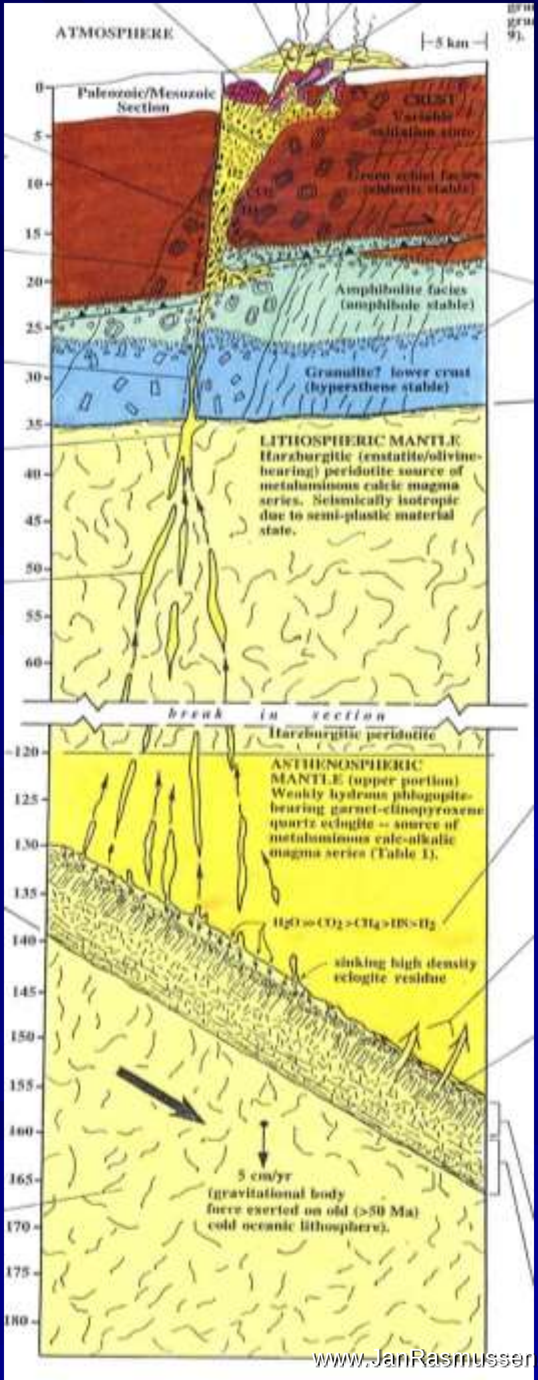
Orogeny	Orogenic Phase	Age (Ma)	Age (period)	Arizona Magmatism	Alkalinity	Tucson Mts. formations	Age dates
San Andreas	Basin and Range	13-0	Latest Tertiary	Anhydrous basaltic volcanism		Tertiary-Quaternary alluvium; Recortado Tuff in Roskruge Mts.	12.9 Ma
Galiuro	Late	18-13	Late Tertiary	Quartz alkalic volcanics; detachment faulting	MQA	None in Tucson Mts.	
	Middle	28-18	Mid-Tertiary	Alkali-calcic ignimbritic volcanics & plutons	MAC	Safford Dacite & associated tuffs, Volcanics & tuffs of Tumamoc Hill	25.1 Ma Safford Peak dacite, 25.9 Ma Safford Tuff, 39.5 Ma basal Tsf1; 28.6-26.4 Ma Tumamoc basalts
	Earliest	39-28	Mid-Tertiary	Lake beds and possible erosion & secondary enrichment of Cu		Uranium sedimentary beds at Cardinal Avenue & Mission Rd.; Pantano Fm.	39.5 Ma basal Safford volcanic flow
Laramide	Late	55-40	Early Tertiary	Peraluminous 2-mica granites at great depths	PAC	None; Eocene erosion surface/unconformity below Safford Peak volcanics	43 Ma Wilderness Granite in Santa Catalina Mts.
	Middle	65-55	Cretaceous-Tertiary	Porphyritic granodiorite stocks, dacites, andesites, tuffs	MCA	Tuff of Beehive Peak, porphyritic granodiorite of Sedimentary Hills & Saginaw Hill, S. Tucson Mts.	58.3 Ma Twin Hills dacite
	Early	80-65	Late Cretaceous	Granite & granodiorite stocks; rhyolite ash flows, dikes	MAC	Cat Mountain Tuff rhyolite; Amole Granite-granodiorite; Silver Lily dikes	73.1 Ma welded tuff Kcw, 72.3 Ma Silver Lily dikes; 73 Ma Amole Granite
	Earliest	85-75	Late Cretaceous	High K shoshonite, latite, and rhyolite lavas	MQA	Yuma Mine volcanics in N. Tucson Mts.; Ft. Crittenden ss. equivalent	Large hadrosaur dinosaur bones in sandstone
Sevier		145-89	mid-Cretaceous	None	-	Amole Arkose (Albian-Cenomanian)	100 Ma
evad	Late	160-145	Late Jurassic	Volcanics		Andesite porphyry of Brown Mountain	159 Ma
	Middle	205-160	Late & Middle Jurassic	Volcanic and plutonic rocks		Recreation Redbeds	190 Ma?
Alleghenian		290-260	Permian	None	-	Naco Group (Concha & Rain Valley at Snyder Hill; Scherrer at Sus P.A.	
Ancestral Rocky Mts./ Ouachita		315-307	Middle Penn.	None	-	Horquilla at Sus P.A. and Twin Peaks	
Acadian (E coast) Antler (NV)		410-380	Devonian	None	-	Martin, Escabrosa at Twin Peaks, Rillito Cement mine; Sus PA	
Taconic (E coast)		470-440	Ordovician	None	-	Cambrian Bolsa, Abrigo at Twin Peaks	
Picuris		1440-1335	Meso-proterozoic	K-feldspar megacrystic or porphyritic granites	PCA, PAC, some M	Porphyritic Oracle Granite – Twin Peaks South side	~1440 Ma
Mazatzal		1750-1800	Paleo-proterozoic		MC	Pinal Schist – Twin Peaks West side	~1650 Ma

Alkalinity and Depth Source - AZ



Extraction of Metal from the Layered Mantle Source Regions

Petrotectonic
model
For Arizona-
Sonora-
New Mexico
Porphyry copper
Cluster.
(From Keith
and Swan, 1996)



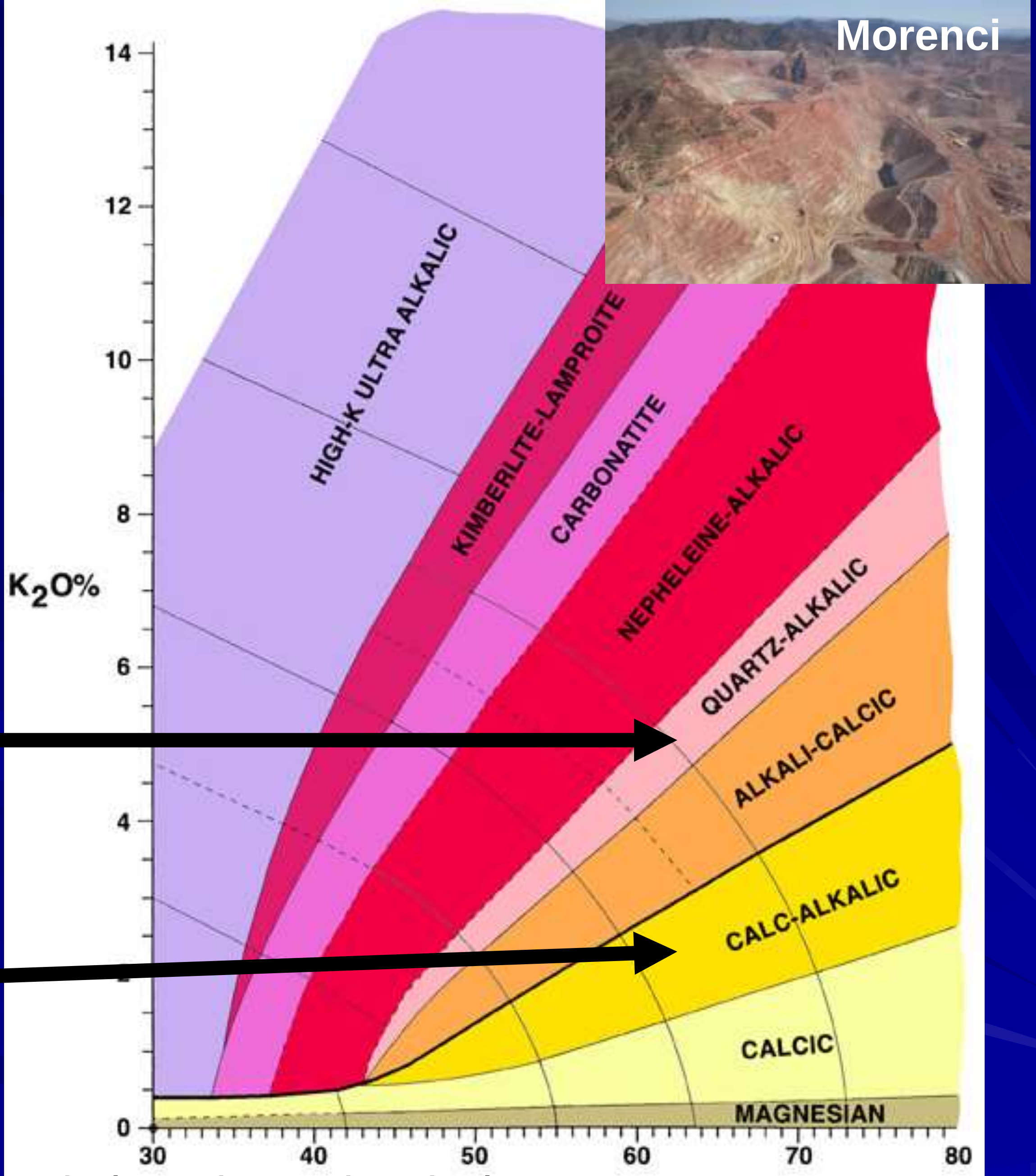
- Extraction is by volatile (mainly water)-induced melting of material from the layered mantle source in the hanging wall of the Farallon subduction zone.

Keith and Swan, 1996

Alkalinity of metaluminous magmas associated with weakly oxidized to oxidized magma sources of Arizona porphyry copper deposits

Bisbee Type
Quartz alkalic
Cu-Ag-Au

Morenci type
Calc-alkalic
Cu-Mo-Ag

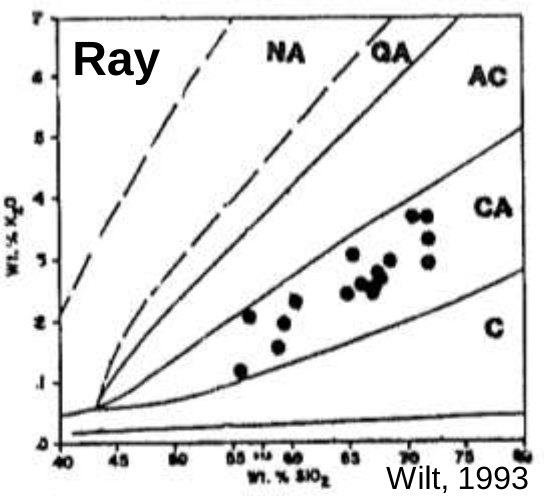


Whole rock geochemical analyses

Keith and others, 1991

Arizona Porphyry Copper Mines

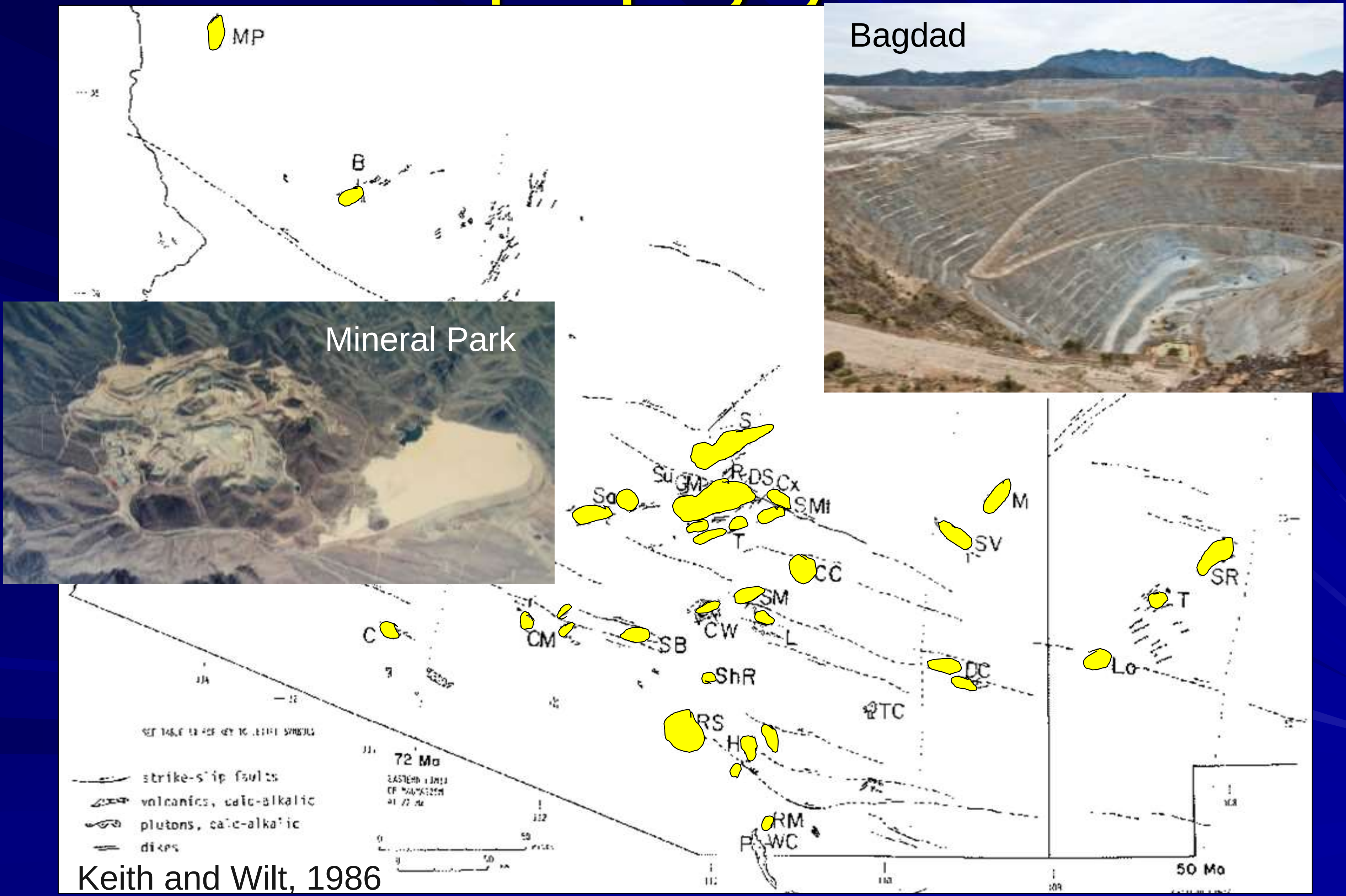
Middle Laramide – 74-52 Ma (million years ago)



Wilt, 1993

Source: mines.az.gov/Info/MajorMines08.pdf
Arizona Dept. of Mines and Mineral Resources
June 2008

Laramide porphyry Cu - MCA

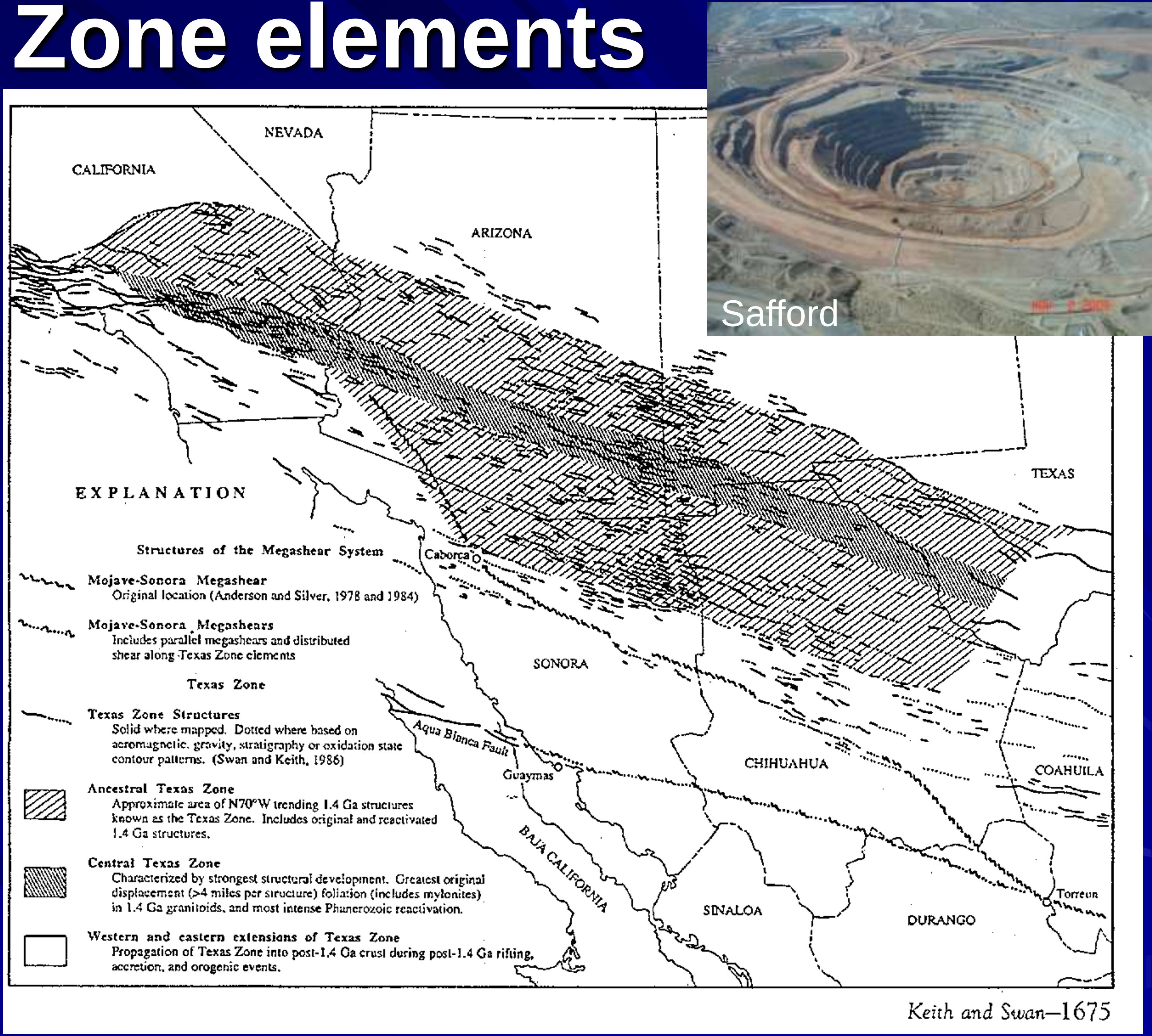


Keith and Wilt, 1986

Texas Zone elements

West-northwest shears – deep-seated Precambrian structures (~1440 Ma)

When stress directions opened these cracks, they were a path for Cu-rich intrusions



EXPLANATION

Structures of the Megashear System

Mojave-Sonora Megashear
Original location (Anderson and Silver, 1978 and 1984)

Mojave-Sonora Megashears
Includes parallel megashears and distributed shear along Texas Zone elements

Texas Zone

Texas Zone Structures
Solid where mapped. Dotted where based on aeromagnetic, gravity, stratigraphy or oxidation state contour patterns. (Swan and Keith, 1986)

▨ **Ancestral Texas Zone**
Approximate area of N70°W trending 1.4 Ga structures known as the Texas Zone. Includes original and reactivated 1.4 Ga structures.

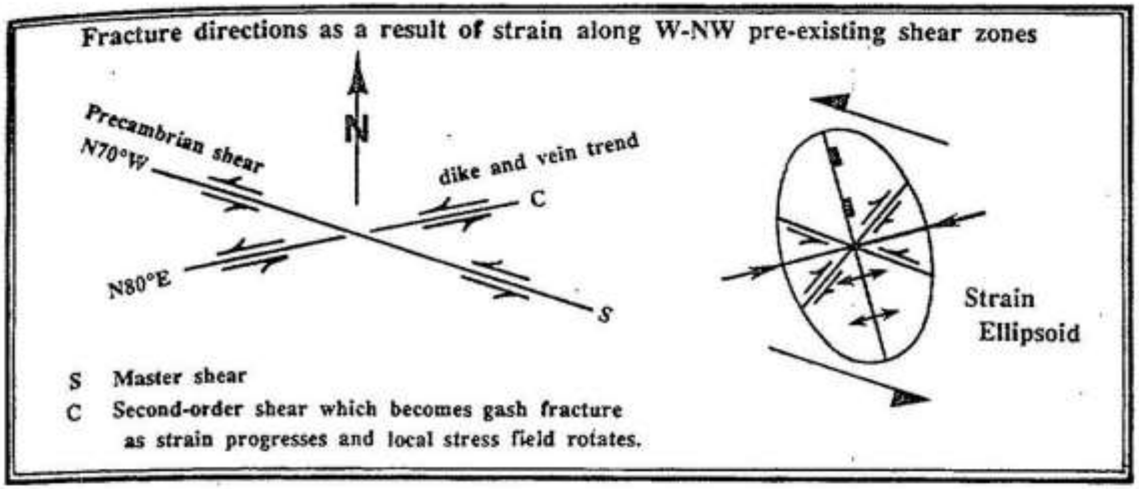
▨ **Central Texas Zone**
Characterized by strongest structural development. Greatest original displacement (>4 miles per structure) foliation (includes mylonites) in 1.4 Ga granitoids, and most intense Phanerozoic reactivation.

☐ **Western and eastern extensions of Texas Zone**
Propagation of Texas Zone into post-1.4 Ga crust during post-1.4 Ga rifting, accretion, and orogenic events.

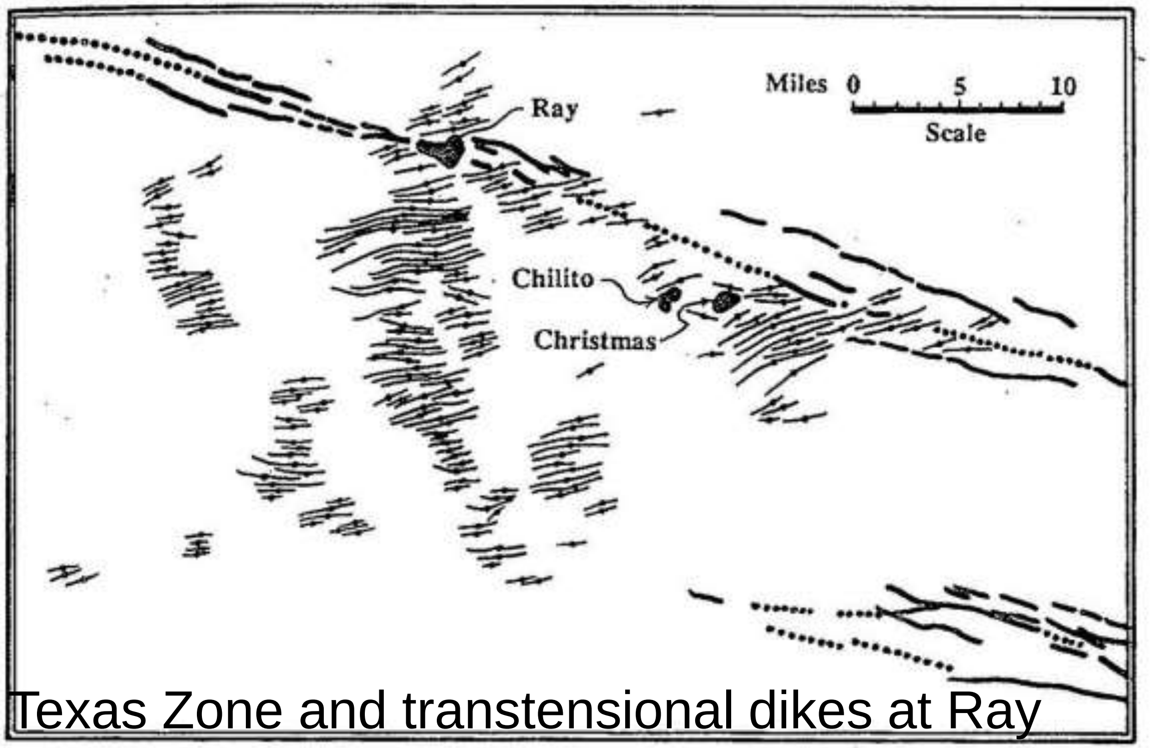
Keith and Swan—1675

Importance of structure

Laramide porphyry copper deposits exploited transtensional zones related to deep-seated Texas Zone faults operating in left slip between 72 and 52 Ma

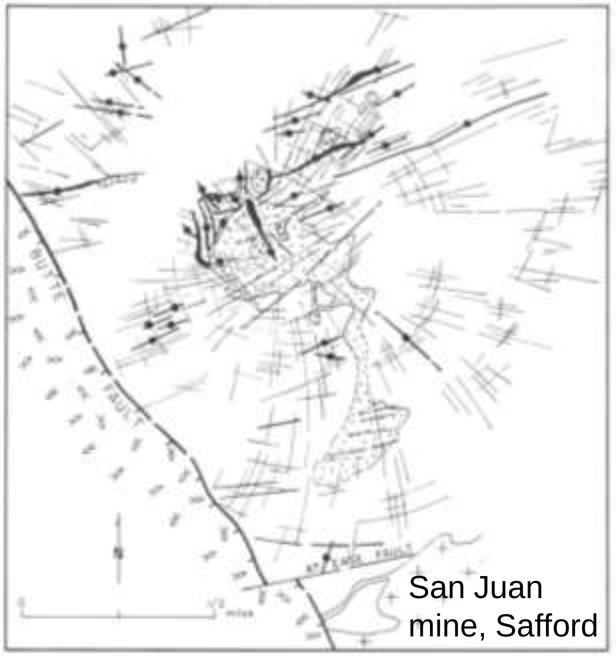


Keith and Swan, 1996



Texas Zone and transtensional dikes at Ray region

Figure 34—Laramide-age calc-alkalic dikes of the Porphyry Copper Cluster and their relationship to Texas Zone structures.



San Juan mine, Safford

Heidrick & Titley, 1982

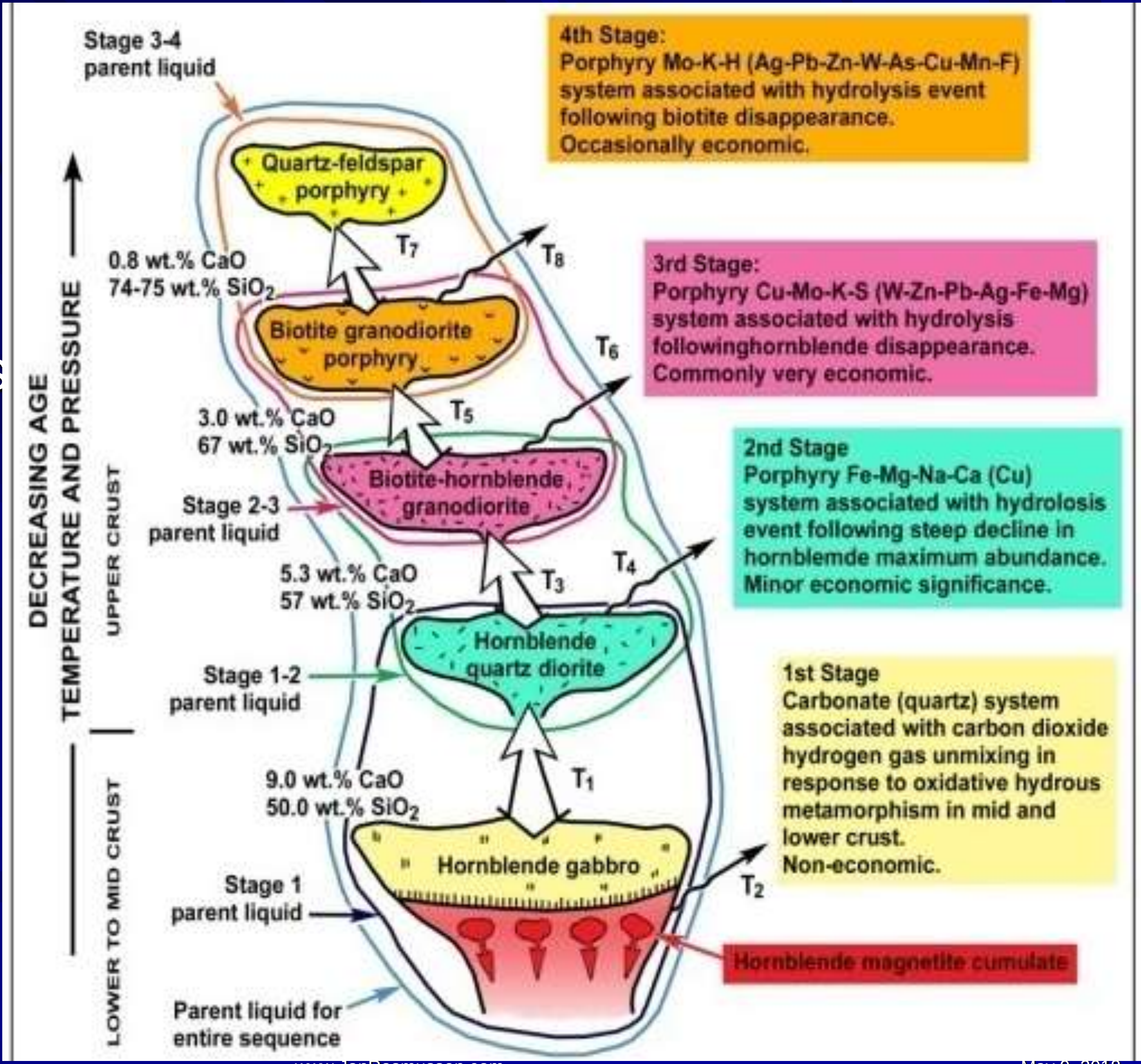
Middle Nevadan - Warren m.d. (Bisbee)

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

200 Ma
Quartz
Alkalic

Stages

As pluton system fractionates it emits hydro-thermal fluids



4th Stage:
Porphyry Mo-K-H (Ag-Pb-Zn-W-As-Cu-Mn-F) system associated with hydrolysis event following biotite disappearance. Occasionally economic.

3rd Stage:
Porphyry Cu-Mo-K-S (W-Zn-Pb-Ag-Fe-Mg) system associated with hydrolysis followinghornblende disappearance. Commonly very economic.

2nd Stage
Porphyry Fe-Mg-Na-Ca (Cu) system associated with hydrolosis event following steep decline in hornblemde maximum abundance. Minor economic significance.

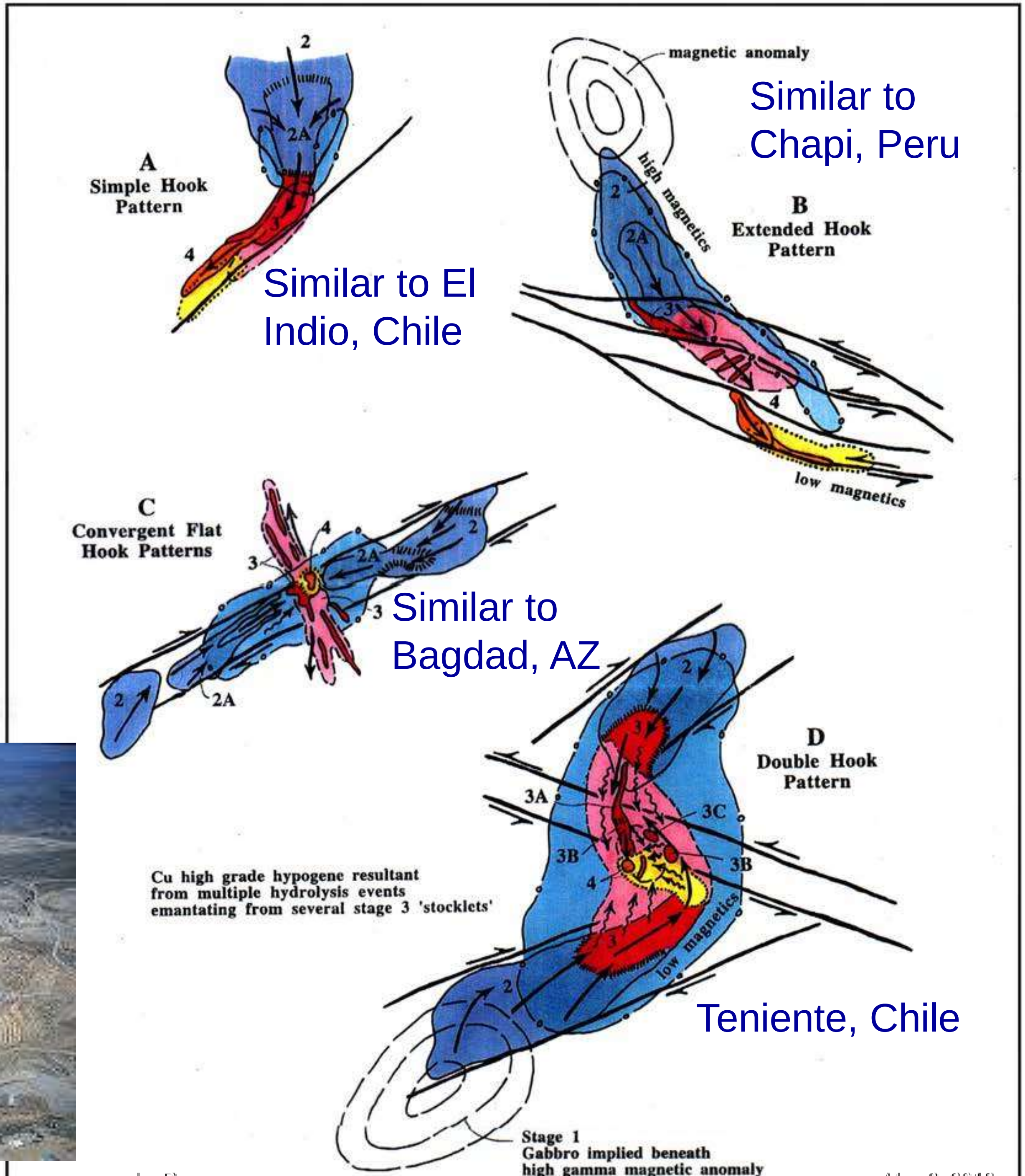
1st Stage
Carbonate (quartz) system associated with carbon dioxide hydrogen gas unmixing in response to oxidative hydrous metamorphism in mid and lower crust.
Non-economic.

Pluton Vectoring

- Porphyry metal deposits typically represent the economic portions of a sequence of **separate fluid releases that accompany a sequence of intrusives.**
- Maps of these fractional differentiation sequences reveal a laterality that allows specific and predictive map delineation of drill targets. To some extent, map views of the sequence constitute cross-sectional views of the entire differentiation process. Consequently, many porphyry metal systems have yielded **new exploration targets by considering the laterality of the process.**
- The lateral nature of the process implies an **association with lateral structural features, especially strike-slip faults.**

Pluton Vectoring – Map Views of different case histories

Twin Buttes



Similar to El Indio, Chile

Similar to Chapi, Peru

Similar to Bagdad, AZ

Teniente, Chile

IT'S THE WATER – Faster convergence rates = Wetter plutons = bigger hydrothermal systems (hornblende-stable = in wet window)

Volcanism

MAC = much (lower H_2O)

MCA = rare (high H_2O)

PCA = none (very high H_2O)

PC = none (very high H_2O)

Convergence Rates

MAC = 7-10 cm/yr (low water)

MCA = 9-25 (32) cm/yr

PCA = 14-42? cm/yr (very high water)

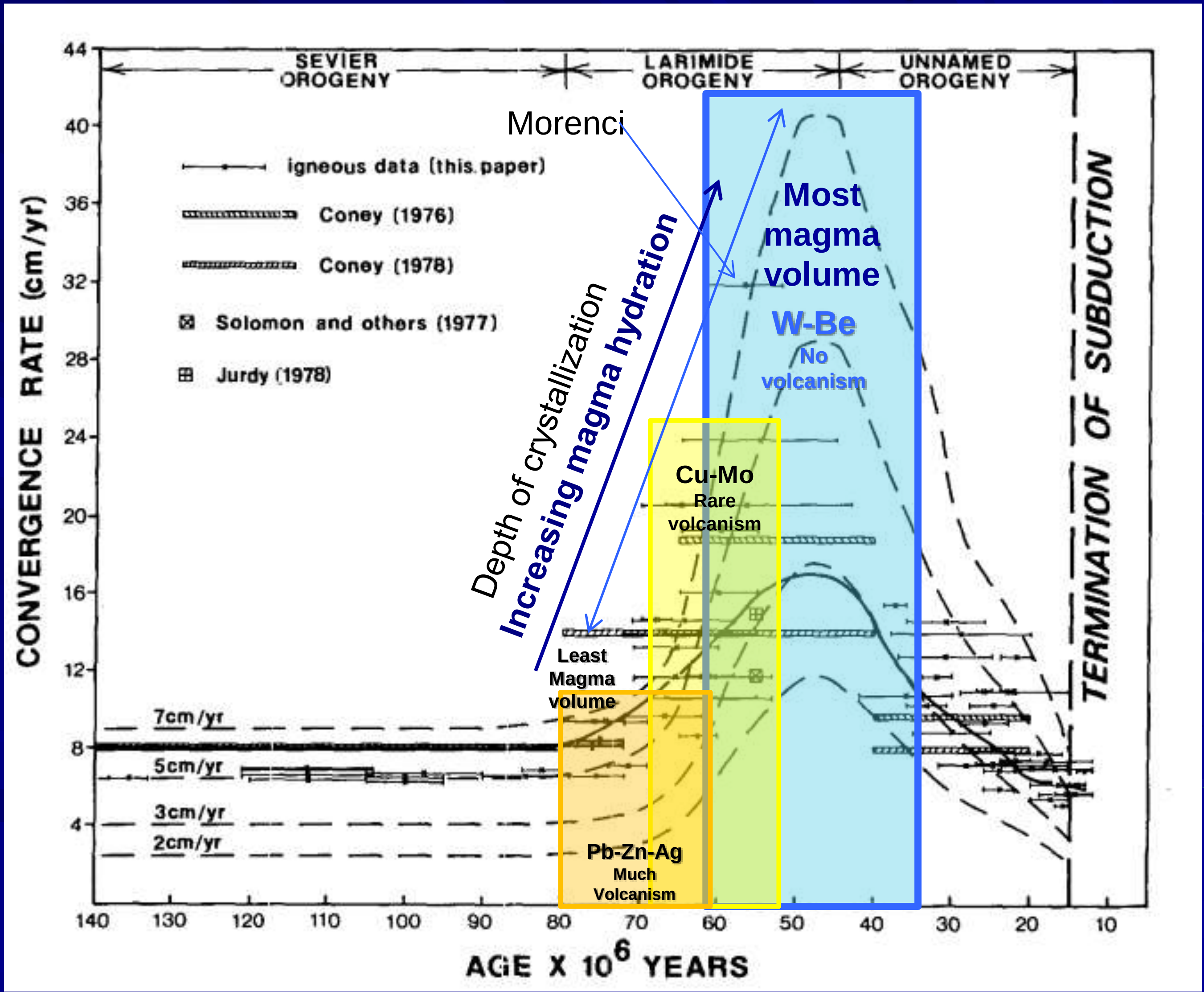
Depth of Emplacement

MAC = 3-0 km (low water)

MCA = 5-2 km

PCA = 8-12 km

PC = 10-15 km (very high water)



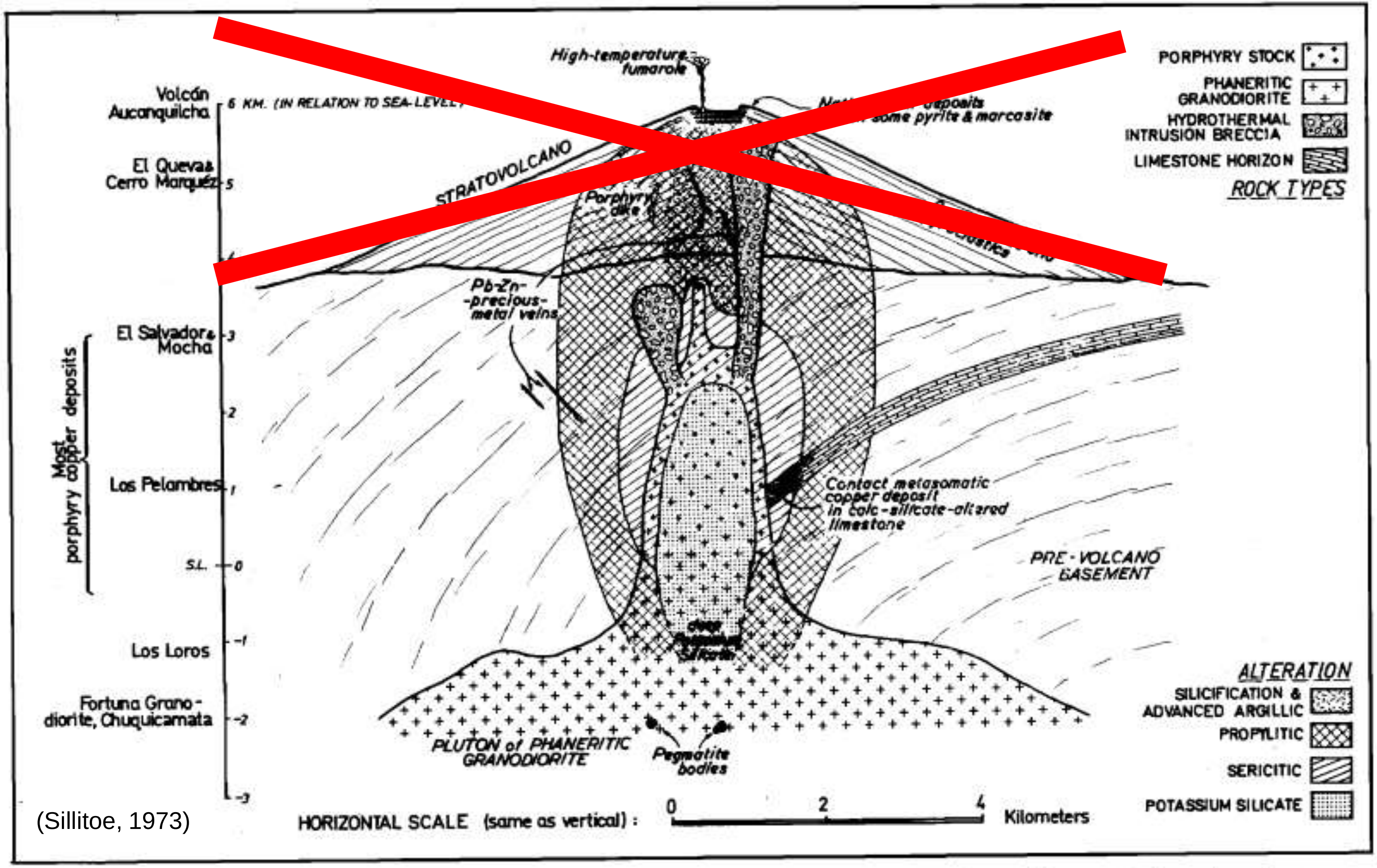
John Guilbert was instrumental In the beginning of Stan Keith's career ~ 1970

79 Mine Geologic map sponsored by John Guilbert

Mistaken Concepts

1. Volcanics are not usually associated with porphyry Copper deposits on timeline; they are not lithocaps.
2. Calderas are not related to porphyry copper deposits
3. Pb-Zn-Ag is **not** a zoning fringe of Stage 3 porphyry copper plutons
4. (However, Pb-Zn-Ag may be fringe to arsenical (tennantite) Stage 4 copper veins. Ex. Magma vein, Old Dominion vein)
5. Qtz-sericite-pyrite QSP is not exclusively associated with porphyry Copper. It is common to many deposit types.
6. Propylitic alteration (mainly Na feldspar, epidote, chlorite, magnetite, actinolite) is not a fringe time-equivalent halo of porphyry copper; it predates the porphyry coppers.

No Stratovolcano above Porphyry Copper



(Sillitoe, 1973)

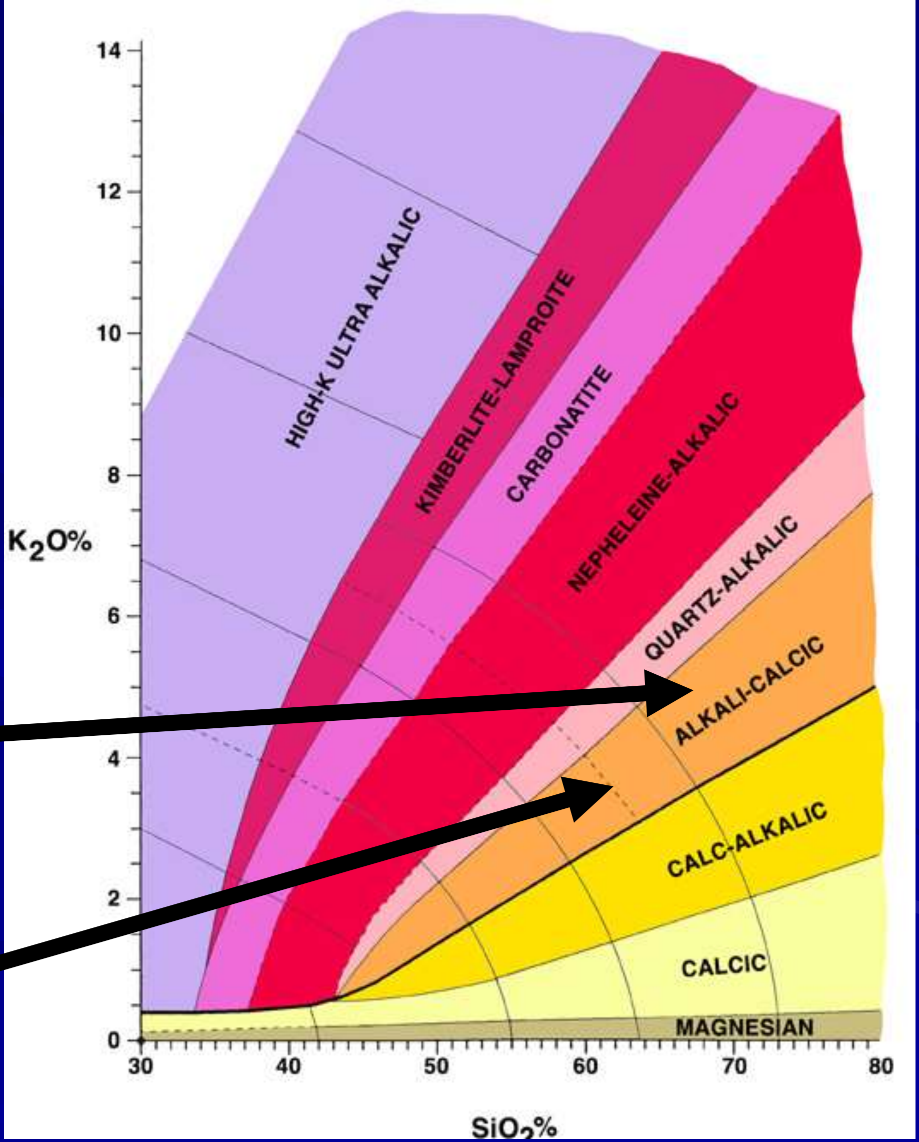
FIG. 1. Idealized cross section of a typical, simple porphyry copper deposit showing its position at the boundary between plutonic and volcanic environments. Vertical and horizontal dimensions are meant to be only approximate.

Stay away from Alkali-Calcic = Cu-Barren

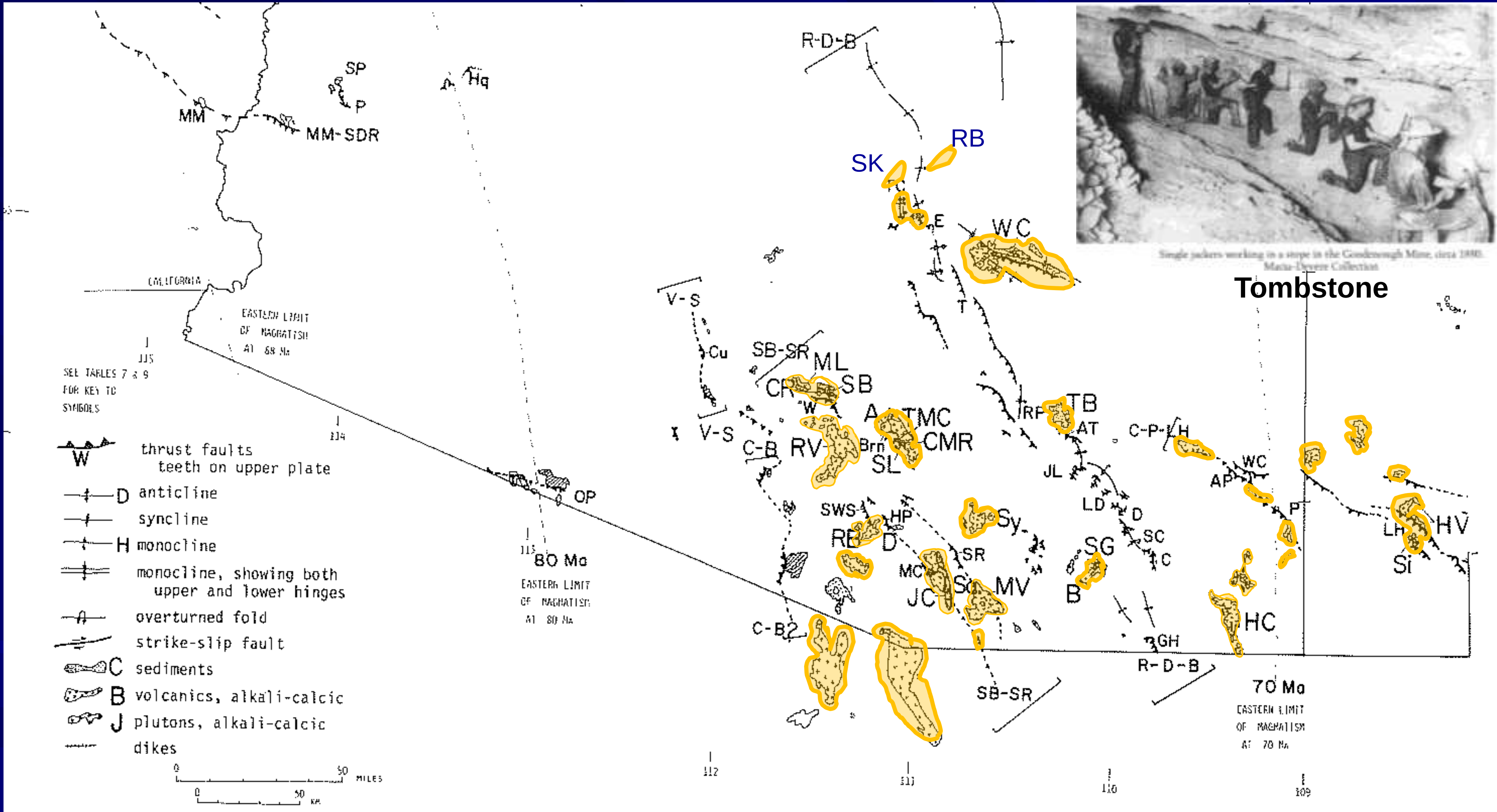
Alkali-calcic metaluminous magmas associated with weakly oxidized to oxidized magma sources mesothermal lead-zinc-silver vein/replacement deposits

MAPIMI (skarn, veins) TYPE alkali-calcic Pb-Zn-Ag-As(Cu-Mn-F-Mo)

TINTIC TYPE alkali-calcic Pb-Zn-Ag(Cu-As-Mn-Te-Bi)



Stay Away from Alkali-Calcic



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

Keith and Wilt, 1986

late initial Laramide orogeny

Figure 4. Map of Denver and Tombstone Assemblages of the late initial Laramide orogeny in Arizona and vicinity.

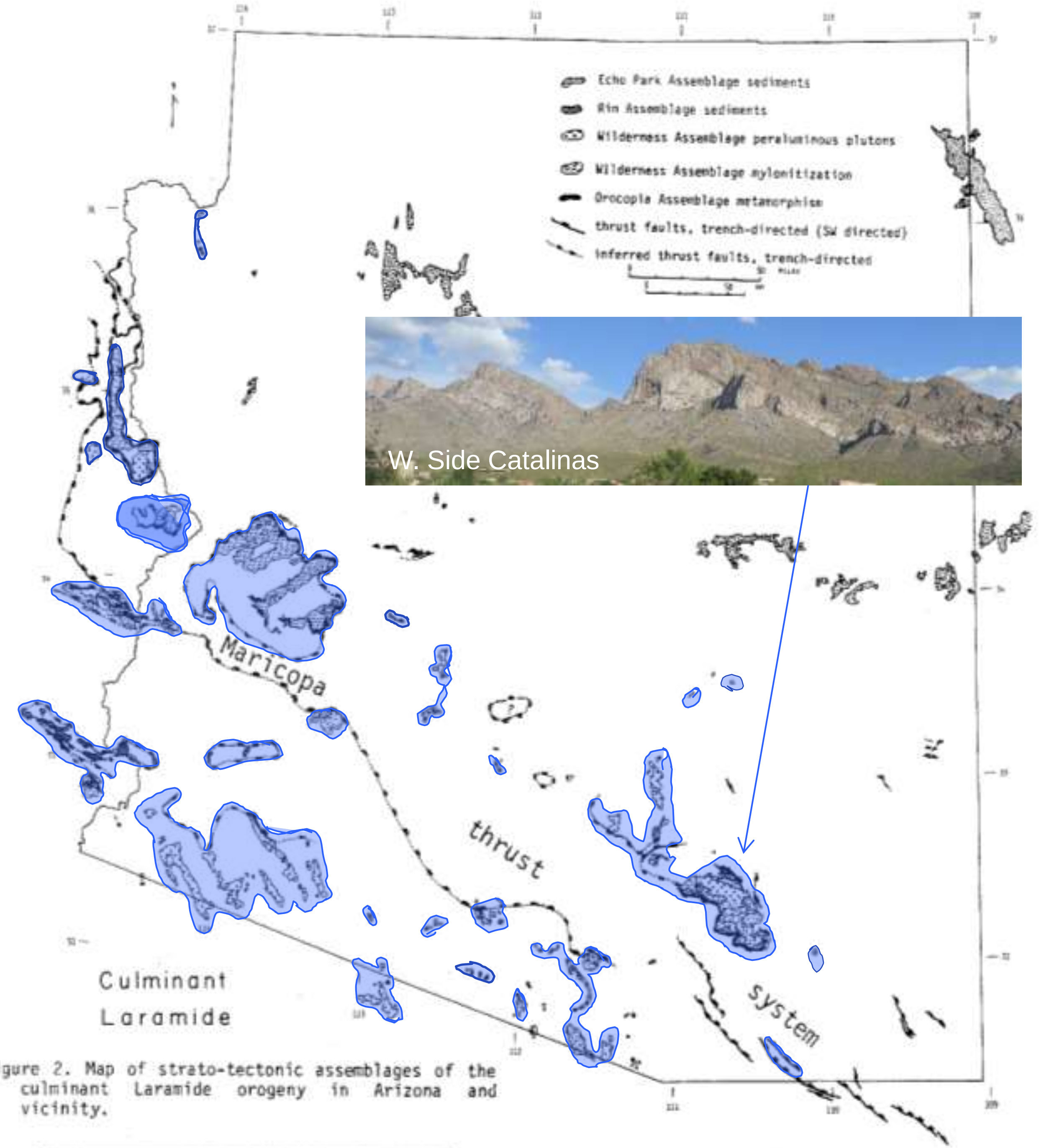
AZ Porphyry Copper Exploration: **Don'ts**

1. Don't chase <u>strong</u> IP anomalies (indicated pyrite). (Moderate is OK for Stage 3 porphyry Cu)
2. Don't chase epidote- or magnetite-stable sulfide anomalies associated with propylitic alteration associated with Stage 2 hornblende diorite fluid releases (e.g. chlorite-epidote-pyrite alt. in diabase)
3. Stay away from Metaluminous Alkali-Calcic Systems (Johnson Camp, Cerro Colorado, Robber's Roost breccia pipes at Tombstone and Tombstone, Washington Camp)
4. Stay away from caldera models and volcanics – They are not lithocaps to underlying porphyry Cu. – In AZ, Laramide volcanics are typically 10 Ma older
5. Do Not Chase Laramide Peraluminous Plutons

Don’t Chase Laramide Peraluminous Plutons

Two-mica granites with biotite & muscovite, are younger than Laramide porphyry copper systems.

Are W- or Au-rich



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

Keith and Wilt, 1986

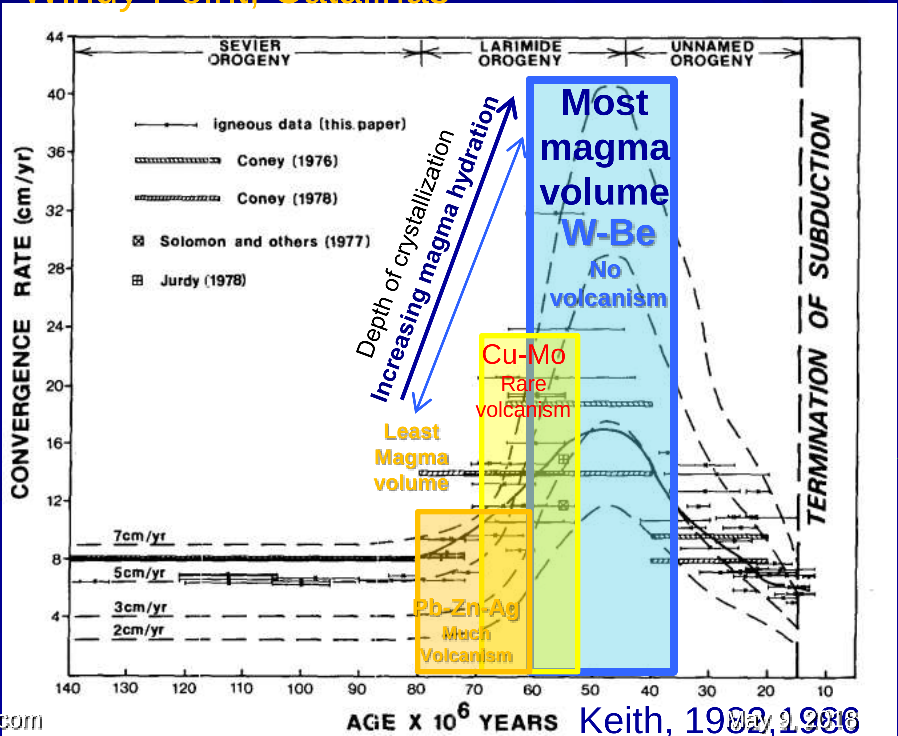
Latest Laramide (Wilderness)

Orogeny	Orogenic Phase	Age (Ma)	Aluminum & Alkalinity	Resources	Mining districts
Laramide	Late (Wilderness)	55-43	PC; PCA	Au, W (Be)	**W Blue Bird, Reef, Quinlan** **Au Gold Basin, Vulture**

- **Largest volume of peraluminous calc-alkalic granitic intrusions (Latest Laramide) is associated with fastest convergence rates, flattest subduction, maximum dewatering, and significant W or Au production.**
- **This is the main Laramide igneous and tectonic event.**
- **ex. W(Be)=Reef, Quinlan, Canoa Ranch, Bluebird, Wilderness; Au= Gold Basin, Vulture**
- **Zero volcanism – crystallized too deep when water exsolved and froze the granites.**
- **W and Be are inherited from melted crust - Picuris age peraluminous granite**

Peraluminous Calc-Alkalic

Windy Point, Catalinas



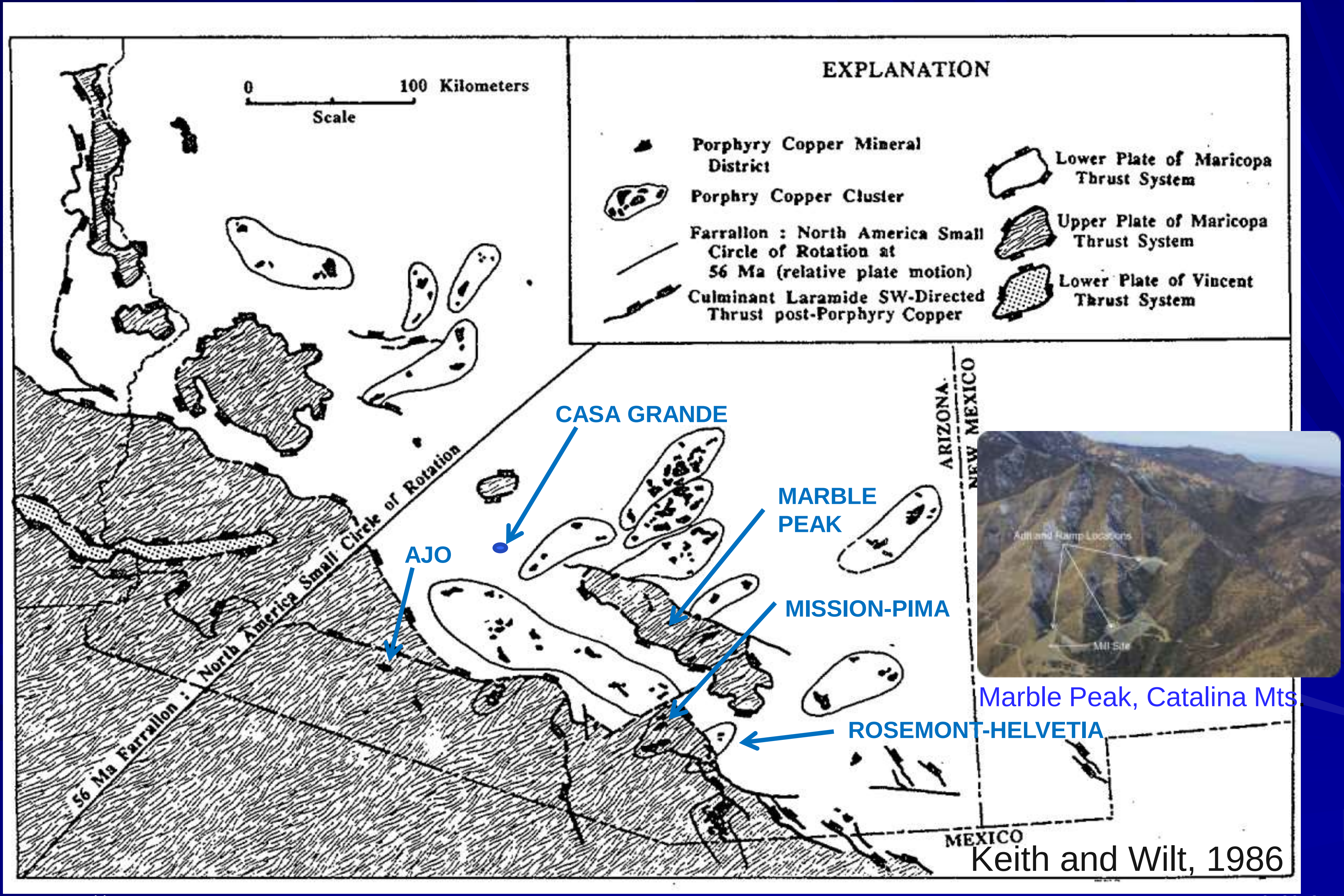
Keith, 1982,1986

Sucker Plays (Break Your Pick)

1. Tortilla Mountains propylitic alteration
2. Little Gold Gulch Stage 2 magnetite alteration
3. Williamson Canyon epidote-rich propylitic alteration
4. I-10-Johnson Camp ZINC-minor Cu
5. Wooley pipe western Tortilla Mountains
6. Mammoth magnetite pipes west of Bagdad
7. Magnetite-chlorite-epidote-pyrite-stable alteration in diabase (Dripping Spring Wash, Troy West)
8. Alkali-calcic 'Death Trap' copper occurrences = Pb Zn Ag (Tombstone, Cerro Colorado, Johnson Camp, I-10, Black Diamond, Middlemarch Canyon)

Source: mines.az.gov/Info/MajorMines08.pdf
Arizona Dept. of Mines and Mineral Resources June 2008

Post-Porphyry Copper Thrust Faults

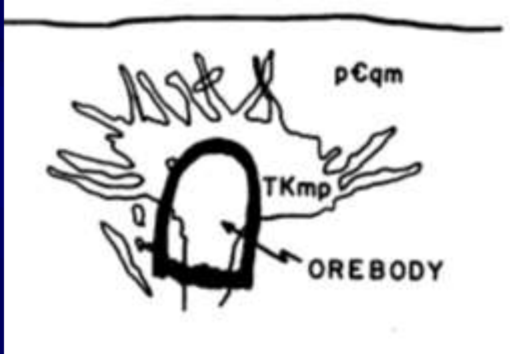


Marble Peak, Catalina Mts.

Keith and Wilt, 1986

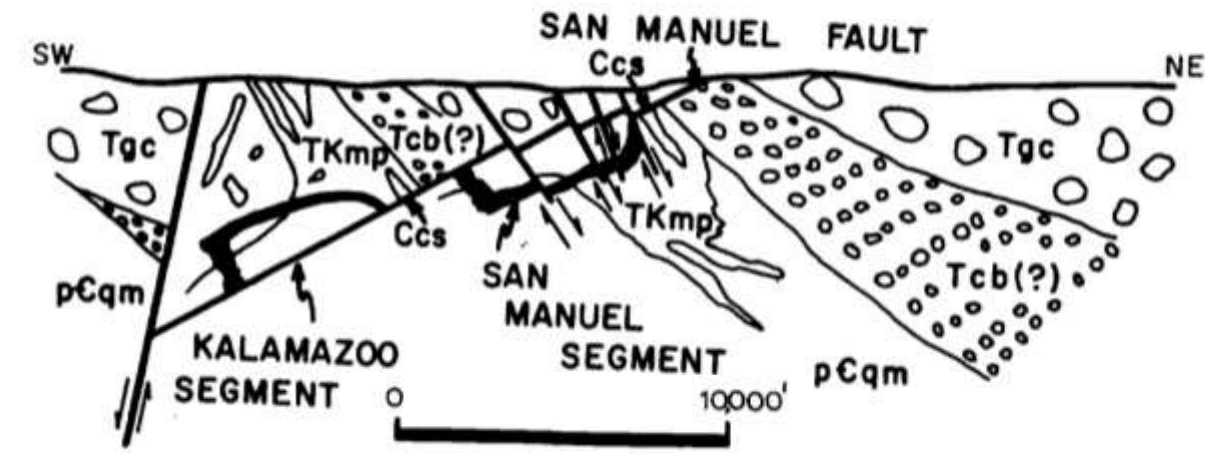
Post-porphyry copper normal faulting – San Manuel (Lowell and Guilbert, 1970)

San Manuel tilted and faulted – discovery of Kalamazoo via offset copper shells



Original orientation

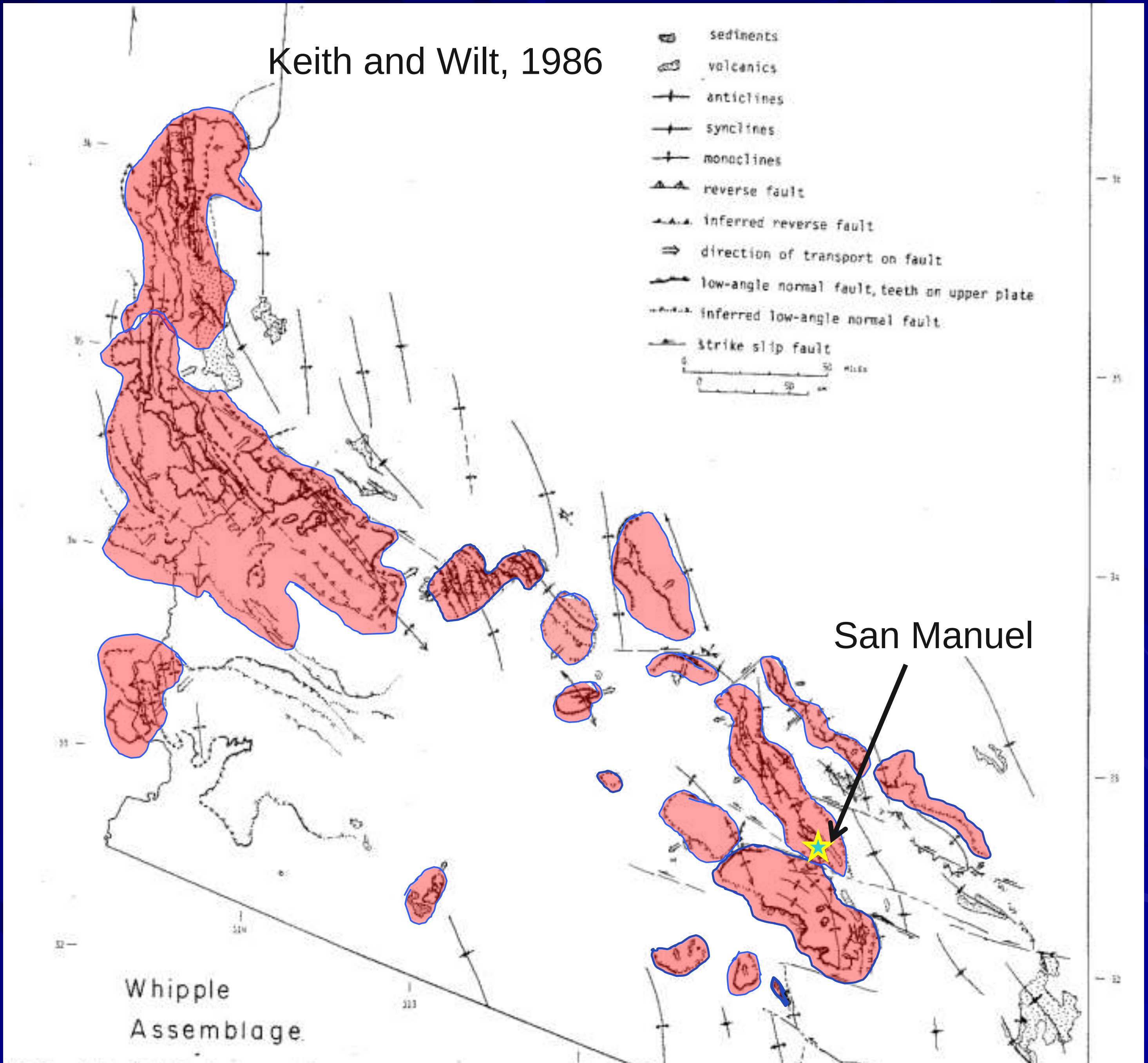
Orientation after tilting and faulting



- Led to numerous attempts to find similar offsets – without success
- Was the first successful porphyry discovery by deep drilling (which led to other successful deep discoveries)

Post-porphyry slide domains

Only the San Manuel porphyry copper has been successfully reconstructed using the slide block (detachment) model

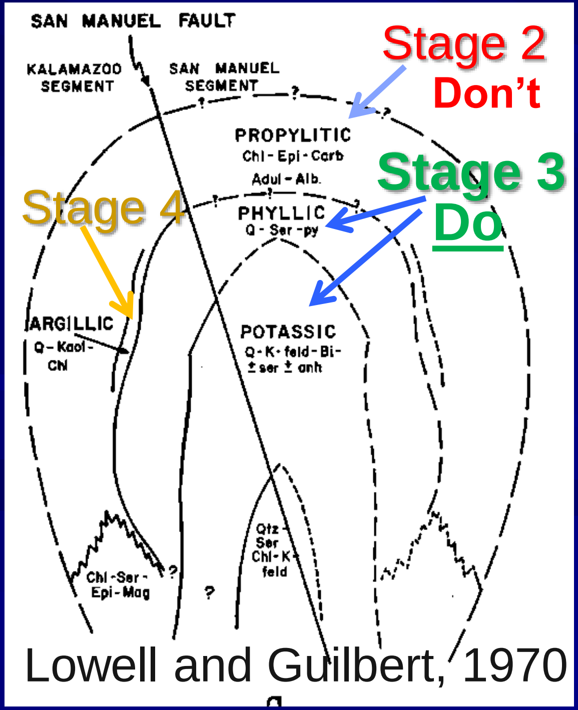

Keith and Wilt, 1986

San Manuel

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

Modifications to the 'Light Bulb'

- Propylitic alteration is not related to the 'light bulb'; rather it is related to prior propylitic alteration released from Stage 2 hornblende diorites.
- The copper shells are deposited at the change from potassic to phyllic alteration, as part of the alteration zoning of the Stage 3 fluid release accompanying the biotite hornblende granodiorite.
- The changeover reflects a pH shift to oxidative proton metasomatism (phyllic).
- Argillic alteration is typically not part of the 'light bulb' and is associated with low pH, stage 4 fluid releases from biotite granodiorite and is associated with late quartz feldspar porphyries.



Lowell and Guilbert, 1970

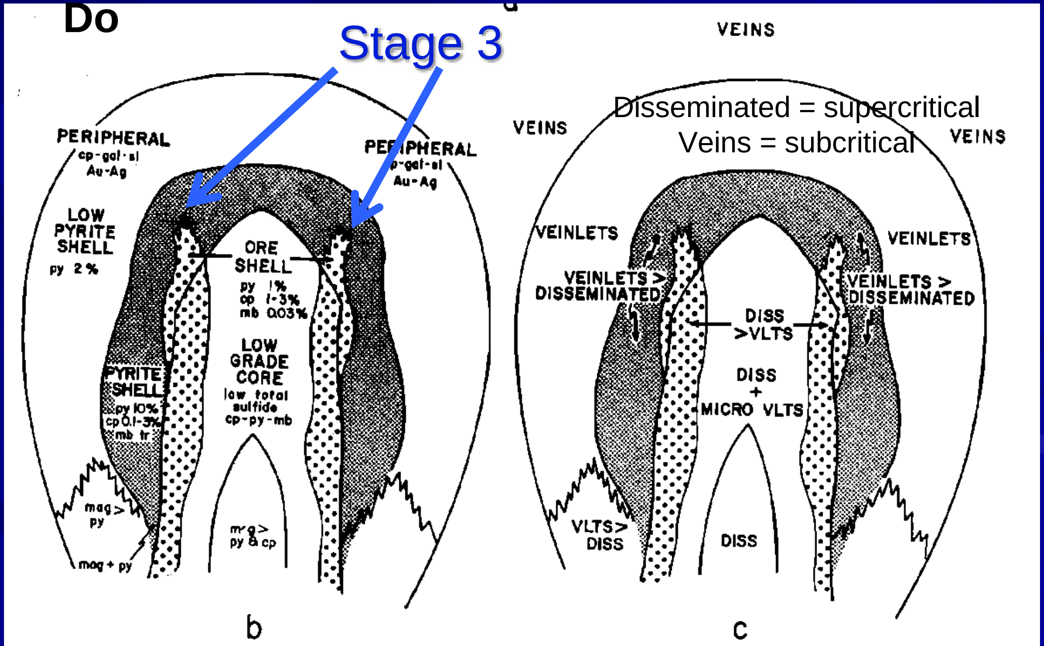


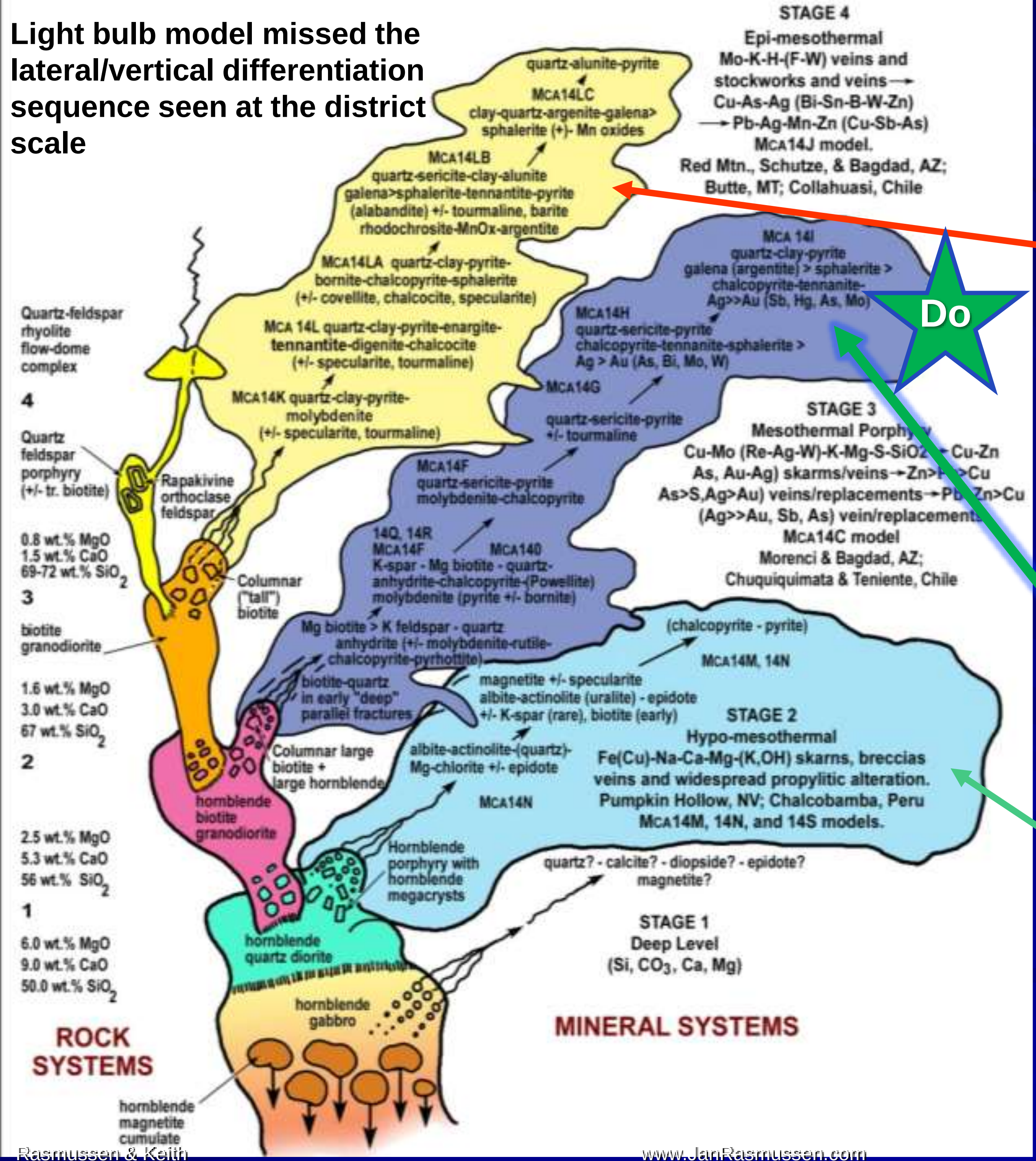
FIG. 3. Concentric alteration-mineralization zones at San Manuel–Kalamazoo. (a) schematic drawing of alteration zones. Broken lines on Kalamazoo side indicate uncertain continuity or location and on San Manuel side extrapolation from Kalamazoo. (b) schematic drawing of mineralization zones. (c) schematic drawing of the occurrence of sulfides.

Porphyry Copper Exploration in AZ: Do's

1. Chase Cu-related alteration associated with **Stage 3 biotite granodiorites of Metaluminous Calc-alkalic, hydrous, oxidized, magma-metal series**
2. **Think lateral as well as vertical, especially at the district scale (i.e., use pluton vectoring)**
3. **Look for Stage 3, Cu-rich fluid releases in favorable host rocks (especially biotitic and rutilated diabase)**
4. Look for **transitions between potassic and phyllic** alteraton types (Guilbert showed in San Manuel diagram) – pH shift from basic phlogopite-orthoclase stable ("A" & "B" veins) to quartz sericite pyrite; to more acid, low-pH; Cu drops at pH shift = proton metasomatism = "D" veins of Gustafson and Hunt (1975)

PLUTON - HYDROTHERMAL VECTORING

Light bulb model missed the lateral/vertical differentiation sequence seen at the district scale



Stage 4 Quartz-sericite-pyrite with local digenite/ chalcocite/ polymetallic sulfosalts that crosscut Stage 4 aplites and quartz feldspar porphyry dikes (TR-3) as well as all older plutonic phases in the intrusive sequence.

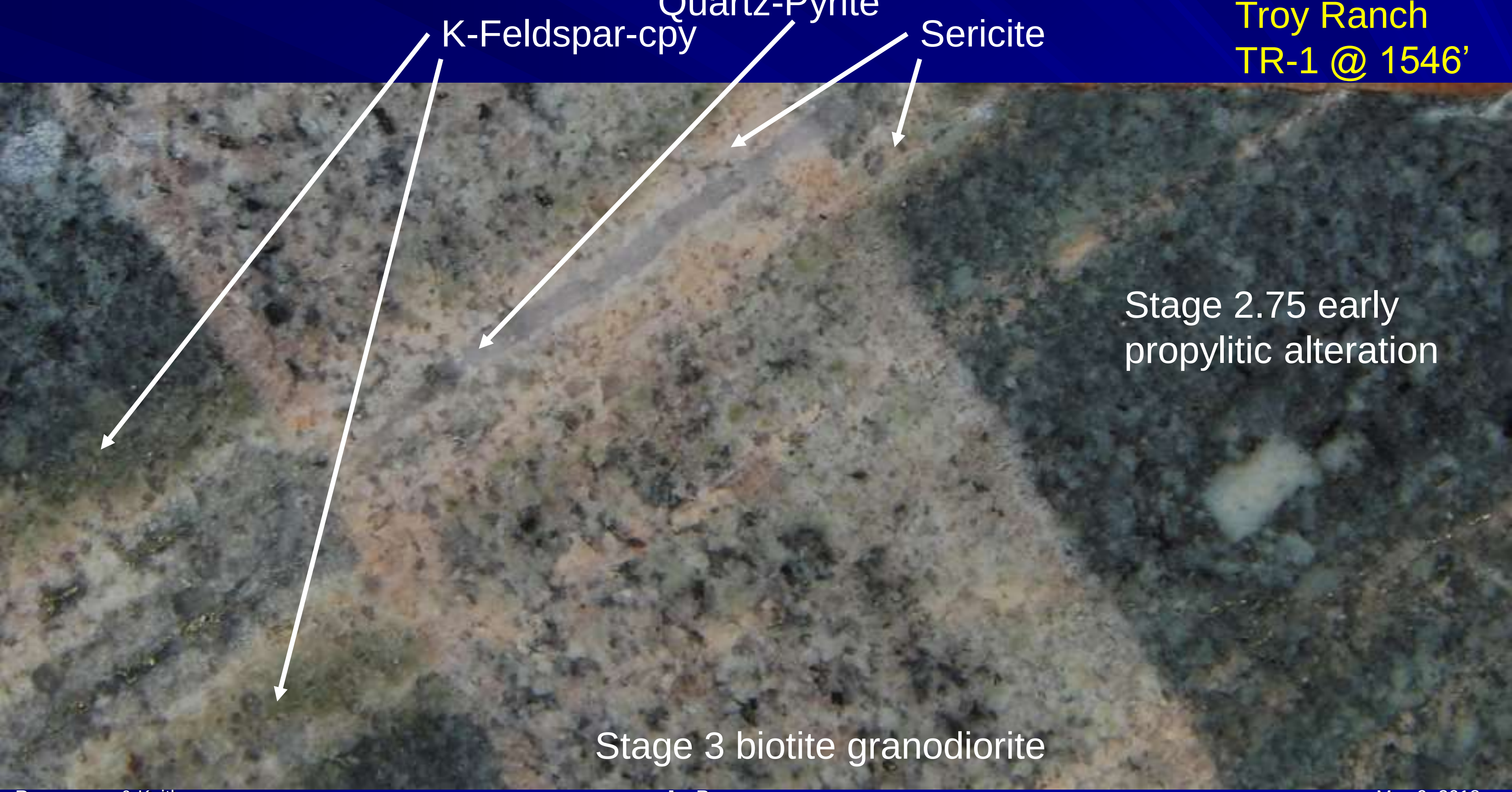
Stage 3 Potassicly altered pyrite-chalcopyrite (molybdenite-anhydrite) veins and disseminations in Stage 2.75 biotite (hornblende) and Stage 3 biotite granodiorite

Stage 2 Epidote chlorite veins and chloritic alteration in south and east part of pluton complex and in Pre-Cambrian diabase (also with magnetite)

Stage 2.75 biotite (hornblende) granodiorite cut by Stage 3.0 biotite granodiorite cut by Stage 3 quartz-pyrite-sericite-vein which cuts/re-enters

early stage 3 K-feldspar-chalcopyrite vein

Troy Ranch
TR-1 @ 1546’



Do: Precambrian Diabase Host Rock

Source: mines.az.gov/Info/MajorMines08.pdf
Arizona Dept. of Mines and Mineral Resources
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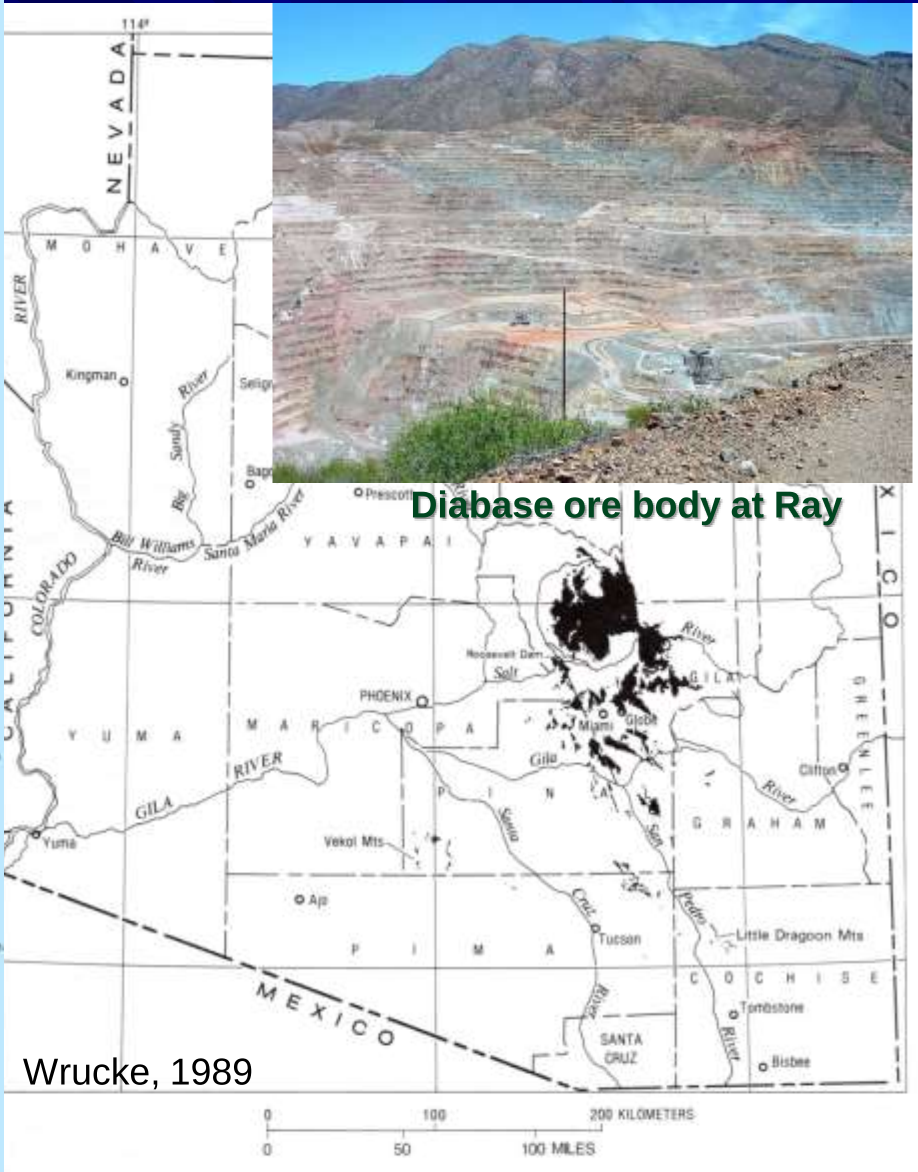


Diabase ore body at Ray

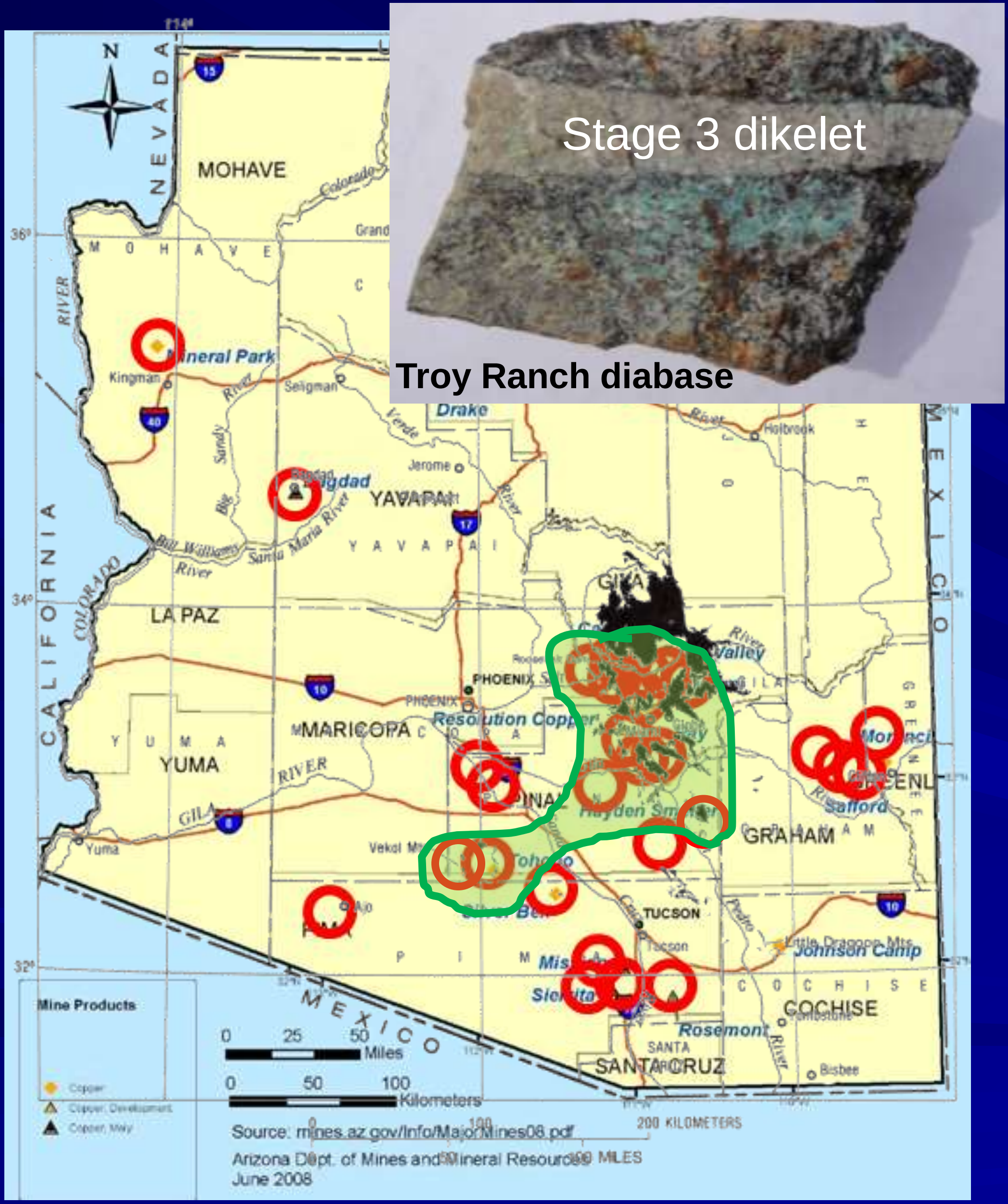
Wrucke, 1989

Known Diabase Resources

- Resolution Cu-Mo-Ag deposit (1.787 billion tons @ 1.54 wt.% Cu, .035 wt% Mo ([3 ppm Ag, and 50 ppb Au from Ballantyne et al. 2014; latest Cu Mo resources 2017).
- Ray sulfide ore (mainly hosted in diabase) (1.524 billion tons @ .75 Cu) reserves as of 1995 reported in Long (1995)

High grade copper ore as chalcopyrite-quartz-phlogopite veins hosted in biotized diabase In core from ResolutIon Cu-Mo-Ag deposit. Photo by S. Keith early June, 2010.

Coincidence of Diabase and Stage 3 porphyry Cu
The Big ‘Do’



Source: mines.az.gov/Info/MajorMines08.pdf
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Known large diabase-hosted Cu resources

1. Resolution
2. Ray diabase ore body
3. Magma & Old Dominion veins, (portions of the large veins),

   Miami, Carlota, Lakeshore, etc.

Possible Expandable diabase-hosted Cu resources

1) Chilito diabase
2) Christmas diabase
3) Lakeshore
4) Troy Ranch prospect

KEY POINT: All of the above copper deposits exhibit a strong spatial association between Stage 3 biotite granodiorite intrusions and diabase

Brownfields

porphyry copper plays

1. North Resolution*
2. Deep Resolution*
3. Chilito Southeast*
4. Christmas West*
5. Lakeshore (Tohono)*
6. Garfield (north Morenci)?
7. Red Hills (north of Ray)
8. Ajo East

*Includes diabase

Kinoite, Christmas, MinDat.org

Source: mines.az.gov/Info/MajorMines08.pdf
Arizona Dept. of Mines and Mineral Resources
June 2008

Greenfields

MCA por. Cu plays

1. Troy Ranch*
2. 79 Mine Southeast*
3. Sunnyside South
4. Saddle Mountain
5. Resolution North*
6. Claypool North (Old Dominion-Copper Cities)*
7. Vekol *
8. New Year's Deep*
9. Santa Monica Camp Deep
10. Greaterville?
11. Santa Rosa
12. San Juan (south of Durham-Suizo)
13. Copper Creek (Bunker Hill)*
14. Knox (South of Ajo)

*Known or possible diabase play

Source: mines.az.gov/Info/MajorMines08.pdf
Arizona Dept. of Mines and Mineral Resources
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Greenfields

possible MCA por. Cu plays (exotic oxide copper deposits with unknown sources)

1. Zonia
2. Carlota
3. Cactus
4. Durham-Suizo
5. Little Hills
6. North Star
7. Red Hills east of Florence
8. Azurite
9. Monitor

Chrysocolla, Live Oak pit, Miami, source: MinDat.org

Source: mines.az.gov/Info/MajorMines08.pdf
Arizona Dept. of Mines and Mineral Resources
June 2008

Greenfields

MQA Jurassic por Cu-Au-Ag-Mo plays

1. Yuma King (recently dated @ 191 Ma)
2. Planet
3. Cienega
4. Clara
5. Cobralla?
6. Pride?
7. Swansea?
8. Courtland?
9. North Trigo?
10. Cinnabar?

Malachite, Planet mine

Source: mines.az.gov/Info/MajorMines08.pdf
Arizona Dept. of Mines and Mineral Resources
June 2008

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