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

Jan C. Rasmussen & Stanley B. Keith

SME Tucson, May 9, 2018
Tribute to Dr. John M. Guilbert

May 12, 1931 - October 17, 2017

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

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Lowell and Guilbert, 1970

Guilbert and Lowell, Variations in Zoning

‘Light bulb’ model

Significant papers with major impacts on exploration
# Laramide porphyry copper (69-55 Ma)

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<tr>
<th>Orogeny</th>
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<th>Arizona Magmatism</th>
<th>Alkalinity</th>
<th>Resources</th>
<th>Mining districts</th>
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<tr>
<td>Laramide</td>
<td>Middle (Morenci)</td>
<td>65-55</td>
<td>Cretaceous- Tertiary</td>
<td>granodiorite - quartz monzonite porphyry stocks, NE to ENE-striking dike swarms</td>
<td>Metaluminous Calc-alkalic</td>
<td>large disseminated porphyry Cu systems, local skarns &amp; veins, fringing Zn-Pb-Ag</td>
<td>Ajo, Ray, Christmas, San Manuel, Mineral Park, Pima, Bagdad, Silver Bell, Globe- Miami, Morenci, Superior</td>
</tr>
</tbody>
</table>

Wealth generators: Our jobs depend on them

Ray mine, looking S

Ray shovel, haul truck
Dave Briggs photos
Resolution Copper

- 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

Hehnke et al., 2014
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

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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.
Only 2 periods with porphyry copper deposits

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<th>Arizona Magmatism</th>
<th>Alkali-ness</th>
<th>Tucson Mts. formations</th>
<th>Age dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Andreas</td>
<td>Basin and Range</td>
<td>15-0</td>
<td>Latest Tertiary</td>
<td>Anhydrous basaltal volcanism</td>
<td>None</td>
<td>Tertiary-Quaternary alluvium; Recordaro Tuff in Roskrug Mts.</td>
<td>12.9 Ma</td>
</tr>
<tr>
<td>Galuro</td>
<td></td>
<td>16-13</td>
<td>Late Tertiary</td>
<td>Quartz alkaline volcanics, detachment faulting</td>
<td>MQA</td>
<td>None in Tucson Mts.</td>
<td>25.1 Ma Safford Peak dacite; 25.9 Ma Safford Tuff; 39.5 Ma basal Tuff; 28.6-28.4 Ma Turamoc basalt</td>
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<tr>
<td>Laramide</td>
<td></td>
<td>26-18</td>
<td>Mid-Tertiary</td>
<td>Alkaline-calcic ignimbritic volcanics &amp; plutons</td>
<td>MAC</td>
<td>Safford Dacite &amp; associated tuffs, Volcanics &amp; tuffs of Turamoc Hill</td>
<td>38.5 Ma basal Safford volcanic flow</td>
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<tr>
<td>Earliest</td>
<td></td>
<td>39-28</td>
<td>Mid-Tertiary</td>
<td>Lake beds and possible erosion &amp; secondary enrichment of Cu</td>
<td>None</td>
<td>Uranium sedimentary beds at Cardinal Avenue &amp; Mission Rd., Pantano Fm.</td>
<td>73.1 Ma welded tuff Kcw; 72.3 Ma Silver Lily dikes; 73 Ma Amole Granite</td>
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<tr>
<td>Laramide</td>
<td></td>
<td>55-40</td>
<td>Early Tertiary</td>
<td>Porphyrous 2-mica granites at great depths</td>
<td>PAC</td>
<td>None; Eocene erosion surface/unconformity below Safford Peak volcanics.</td>
<td>43 Ma Wilderness Granite in Santa Catalina Mts.</td>
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<tr>
<td>Laramide</td>
<td></td>
<td>65-55</td>
<td>Cretaceous-Tertiary</td>
<td>Porphyritic granodiorite stocks, dacites, anodesites, tuffs</td>
<td>MCA</td>
<td>Tuff of Beavert Peak, porphyric granodiorite of Sedimentary Hills &amp; Siganaw Hill, S. Tucson Mts.</td>
<td>58.3 Ma Twin Hills dacite</td>
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<tr>
<td>Early</td>
<td></td>
<td>80-85</td>
<td>Late Cretaceous</td>
<td>Grenite &amp; granodiorite stocks; rhyolite ash flows, dikes</td>
<td>MAC</td>
<td>Cat Mountain Tuff rhyolite, Amole Granite- granodiorite; Silver Lily dikes</td>
<td>169 Ma</td>
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<tr>
<td>Earliest</td>
<td></td>
<td>85-75</td>
<td>Late Cretaceous</td>
<td>High K shoshonite, latite, and myolite lavas</td>
<td>MQA</td>
<td>Yuma Mine volcanics in N. Tucson Mts.; Pt. Crittenden ss. equivalent</td>
<td>Large hadrosaur dinosaur bones in sandstone</td>
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<tr>
<td>Sevier</td>
<td></td>
<td>145-89</td>
<td>Mid-Cretaceous</td>
<td>None</td>
<td>-</td>
<td>Amole andaro (Albian-Cenomanian)</td>
<td>100 Ma</td>
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<tr>
<td>Sevier</td>
<td></td>
<td>160-145</td>
<td>Late Jurassic</td>
<td>Volcanics</td>
<td>None</td>
<td>Amole porphyry of Brown Mountain</td>
<td>169 Ma</td>
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<tr>
<td>Alleghenian</td>
<td></td>
<td>200-260</td>
<td>Late &amp; Middle Jurassic</td>
<td>Volcanic and plutonic rocks</td>
<td>None</td>
<td>Recreation Redbeds</td>
<td>190 Ma?</td>
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<tr>
<td>Ancestral Rocky Mts./ Ouachita</td>
<td></td>
<td>315-307</td>
<td>Permian</td>
<td>None</td>
<td>None</td>
<td>- Horquilla at Sus P.A. and Twin Peaks</td>
<td>169 Ma</td>
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<tr>
<td>Acadian (E coast)</td>
<td></td>
<td>410-390</td>
<td>Devonian</td>
<td>None</td>
<td>None</td>
<td>- Martin, Escabroa at Twin Peaks, Rillito Cement mine; Sus PA</td>
<td>169 Ma</td>
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<tr>
<td>Taconic (E coast)</td>
<td></td>
<td>470-440</td>
<td>Ordovician</td>
<td>None</td>
<td>None</td>
<td>- Cambrian Bolsa, Abrigo at Twin Peaks</td>
<td>169 Ma</td>
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<tr>
<td>Picuris</td>
<td></td>
<td>1440</td>
<td>Mesoproterozoic</td>
<td>K-feldspar megacrystic or porphyritic granites</td>
<td>PCA, PAC, some M</td>
<td>Porphyric Oracle Granite – Twin Peaks South side</td>
<td>~1440 Ma</td>
</tr>
<tr>
<td>Mazatzal</td>
<td></td>
<td>1750</td>
<td>Paleoproterozoic</td>
<td>None</td>
<td>MC</td>
<td>Pinal Schist – Twin Peaks West side</td>
<td>~1650 Ma</td>
</tr>
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Alkalinity and Depth Source - AZ

High Risk

Earthquake foci caused by “serpentosphere” dehydration and embrittlemennt

Upper seismic zone

Lower seismic zone

Magma Generation

Potassium Depth Calculation
Extraction of Metal from the Layered Mantle Source Regions

- 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
Laramide porphyry Cu - MCA

Keith and Wilt, 1986

Keith and Wilt, 1986

Bagdad

Mineral Park

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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
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

heidrick & titley, 1982

san juan mine, safford

keith and swan, 1996

figure 34—laramide-age calc-alkalic dikes of the porphyry copper cluster and their relationship to texas zone structures.
Middle Nevadan - Warren m.d. (Bisbee)

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<tbody>
<tr>
<td>Nevadan</td>
<td>Middle</td>
<td>205-160</td>
<td>Late &amp; Middle Jurassic</td>
<td>Canelo Hills volcanics; plutonic rocks</td>
<td>Metalum. Alkalic</td>
<td>porphyry Cu-Au at Bisbee, Gleeson</td>
<td>Warren (Bisbee mine), Turquoise (Courtland-Gleeson)</td>
</tr>
</tbody>
</table>

Lavender Pit

200 Ma Quartz Alkalic
Stages
As pluton system fractionates it emits hydrothermal fluids.
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

Similar to Bagdad, AZ

Similar to El Indio, Chile

Similar to Chapi, Peru

Twin Buttes

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

Volcanism
MAC = much (lower H₂O)
MCA = rare (high H₂O)
PCA = none (very high H₂O)
PC = none (very high H₂O)

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

Sergei Diakov

Stan Keith
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

late initial Laramide orogeny

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

Keith and Wilt, 1986
AZ Porphyry Copper Exploration: Don’ts

1. Don’t chase strong 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

Keith and Wilt, 1986
• 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.

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<td>Laramide</td>
<td>Late (Wilderness)</td>
<td>55-43</td>
<td>PC; PCA</td>
<td>Au, W (Be)</td>
<td>W Blue Bird, Reef, Quinlan Au Gold Basin, Vulture</td>
</tr>
</tbody>
</table>

Windy Point, Catalinas
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)
Post-Porphyry Copper Thrust Faults

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

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

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.

Light bulb model missed the lateral/vertical differentiation sequence seen at the district scale.
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.
Do: Precambrian Diabase Host Rock

Diabase ore body at Ray

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

Wrucke, 1989
Known Diabase Resources

- Resolution Cu-Mo-Ag deposit (1.787 billion tons @ 1.54 wt.% Cu, 0.035 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’

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
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
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
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?
References Cited


