CHARACTERIZATION AND RECONSTRUCTION OF THE TEA CUP PORPHYRY SYSTEM, PINAL COUNTY, ARIZONA

by

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APPROVAL BY RESEARCH COMMITTEE

As members of the Research Committee, we recommend that this prepublication manuscript be accepted as fulfilling the research requirement for the degree of Master of Science.

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ABSTRACT

Currently many deposits in the Laramide province are reasonably well described at the scale of the individual ore bodies; however, alteration products formed on the distal flanks and roots of the systems have only recently been identified. A system-scale understanding of their evolution remains to be developed. This study takes advantage of a cross-sectional view of the Laramide arc produced by Tertiary extension to help better understand the system scale evolution of porphyry systems. Building upon earlier work, we synthesize results of mapping rock type, structure, and alteration and U-Pb dating of zircons in the Tea Cup porphyry system of the northern Tortilla Mountains in central Arizona, to provide a preliminary system-wide understanding of the evolution of the Tea Cup porphyry system.

Results show that at least two, and possibly three, hydrothermal systems containing potassic, sericitic, greisen, sodic-calic, and propylitic can be mapped in the study area. These systems display both porphyry copper and porphyry molybdenum mineralization. Distal from the most intense potassic alteration in two of the systems, locally intense iron oxide copper gold alteration and mineralization is present. Subsequently, Tertiary normal faults rotated the Tea Cup porphyry system ~90° to the east, and extended it over 200%, along five sets of normal faults that initiated at high angles (~60°-70°).

Palinspastic reconstruction of a 30 km cross section reveals a composite pluton intruding the eastern margin of a basement-cored uplift. The intrusion geometry is not influenced by Laramide reverse faults and displays three stacked phases of the pluton, each creating its own porphyry system. In each system the highest grade mineralization is located structurally above the cupola of the respective phase of the pluton. Potassic alteration dominates the core of the systems, with sericitic alteration at higher levels, sodic-calcic alteration 2-4 km distal on the flanks of the systems, greisen alteration several kilometers beneath potassic alteration, and propylitic alteration surrounding the other alteration types.

Extension in the study area behaved similarly to other areas in the Basin and Range where normal faults broke at high angles, rotated to low angles, and were subsequently cut and rotated by later generations of normal faults. However, more generations of normal faults were superimposed in the study area, producing greater amounts of tilting and extension than has normally been documented by the superimposed half-graben style of extension.

A previous study using apatite and zircon fission track analyses calculated the pre-extension geothermal gradient of the study area to be 17 ± 5°C km^{-1}, nearly half the current geothermal gradient in the basin and range. By projecting these data into the new restorable palinspastic reconstruction a new estimate of the pre-extension geothermal gradient is made at 24°C km^{-1}. These results show that rigorous palinspastic reconstruction of tilt blocks prior to estimations of geothermal gradients can help refine these estimates and further elucidate the role of heat flow in highly extended areas.

INTRODUCTION

Porphyry deposits in the Laramide province of southwestern North America have received considerable attention at the scale of the individual ore bodies (Titley, 1966, 1982); however, alteration products formed on the distal flanks and roots of the systems have only recently been identified, so a system-scale understanding of their evolution remains to be developed. One complexity that has hindered a system-scale understanding is the complex normal faulting that dismembered most Laramide porphyry systems after their emplacement. This often separates once adjacent parts of porphyry systems by kilometers and juxtaposes systemically unrelated rocks. Thus, detailed attention to the structural geology in and surrounding porphyry systems is required in order to palinspastically reconstruct the systems and reveal their pre-extension manifestation.

Once extension is removed, however, the pieces of the porphyry systems are can be put in context. The increased exposure across many different paleodepths created by normal faulting becomes an asset in understanding system-scale processes. For example, root zones beneath mineralization, which would most likely never be drilled in an upright system, can be brought to the surface to be examined in footwall blocks of normal faults (Seedorff et al., 2008). Rotation along normal faults also increases the vertical exposure of the porphyry systems, allowing for examination of fluid pathways in outcrop. An understanding of these pathways can help determine the sources of fluids in the system and any mixing that may occur between fluids of different sources (i.e. magmatic fluids with basinal brines). The increased vertical exposure of porphyry systems in the Basin and Range province benefits the exploration geologist because tilting of systems can reveal multiple vectors towards mineralization which only need be palinspastically reconstructed to be utilized.

The structural complexities revealed in highly extended areas of the Basin and Range province have been studied in detail (Crittenden et al., 1980; Dickinson, 1991; Davis et al., 2004) and have produced long-standing controversies that center on the geometry, timing, and magnitude of normal faults (Wernicke, 1981; Lister and Davis, 1989; Gans, 1991; Maher, 2008). Economic geologists working in highly extended porphyry systems provided some of the first insights into these debates (Lowell, 1969; Proffett, 1977), and continue to refine the understanding of this issue (Dilles, 1995; Wilkens and Heidrick, 1995; Stavast et al., 2008).

This study describes the rock types, hydrothermal alteration, and critically examines a new palinspastic reconstruction of the Tea Cup porphyry system in the Northern Tortilla Mountains, Pinal County, Arizona. The results are based on new field work combined with earlier mapping by Schmidt (1971), Cornwall and Krieger (1975), Bradfish (1978), Spencer and Reynolds (1997), and Barton et al. (2005). The new mapping for this study and the work of Barton et al. (2005) both paid particular attention to characterizing hydrothermal alteration, internal variations in the igneous rocks, and the structural geology in the area. In addition to mapping and structural restorations, U-Pb geochronology was done to better constrain the timing of the igneous and hydrothermal systems. These features, in combination with the general geologic patterns reported in earlier work, are critical to interpreting the structural evolution of the study area, and thereby reconstructing the Laramide magmatic and related hydrothermal systems.

GEOLOGIC SETTING

Located in the heart of the porphyry copper belt of southwestern North America, the Tea Cup porphyry system is one of many porphyry copper systems of the Northern Tortilla Mountains in central Arizona that have been the focus of long-standing investigation (e.g. Ransome, 1903; Cornwall, 1978; Maher, 2008; Maher et al., this issue). Major deposits located in the district include Ray, Globe-Miami, Superior, and Christmas (Fig. 1). Exploration for porphyry copper deposits in the region has ebbed and flowed in close tandem with copper prices with times of widespread exploration in the 1950's, 1960's, 1970's and the first decade of the 2000's. Recently, the discovery of the Resolution deposit near Superior has renewed the interested of both junior and major companies in the region.

The Middle Proterozoic Pinal Schist and Madera Diorite compose the metamorphosed basement of the Northern Tortilla Mountains. These rocks were intruded by the 1.4 Ga anorogenic Ruin Granite (Fig. 2.). Subsequently, the rocks were beveled and unconformably overlain by approximately one km of dominantly siliciclastic sedimentary rocks of the Apache Group and Troy Quartzite. Near the time of deposition of the Troy Quartzite, the Proterozoic sequence and underlying crystalline rocks were intruded by diabase sheets and sills, dated at ~1.1 Ga (Shride, 1967; Wrucke, 1989). The diabase sheets intruded up feeder dikes exposed in some areas, and are focused in the upper kilometer of the Ruin Granite and Apache Group sediments (Howard, 1991). The consistent orientation and depth of emplacement of the sheets and sills across much of Arizona and parts of California allows the features to be used as structural markes in the crystalline rock (Howard, 1991; Spencer and Reynolds, 1996; Barton et al., 2005). Approximately 1-1.5 km of Paleozoic, mainly carbonate rocks, disconformably overlie strata of the Troy Quartzite and Apache Group.

In Laramide times the rocks of the rocks in the Northern Tortilla Mountains were first compressed to form basement cored uplifts similar to those of the Central Rocky Mountains (Davis, 1979), and then intruded as part of a large volcanic arc on the western margin of the North American plate (Drewes, 1976; Seedorff, in press). The arc produced numerous intrusions and at least ten porphyry systems in the Northern Tortilla Mountains (Maher, this issue). Dikes of many generations protrude from any given pluton and usually had a northeast oriented strike, parallel to the axis of least principal stress during subduction at the time (Titley, 1982). U-Pb dates of the intrusions from the Northern Tortilla Mountains span from 73-62 Ma (Seedorff et al., 2008). Late Cretaceous volcanic and volcaniclastic rocks of the Williamson Canyon Volcanics and broadly correlative units were deposited at this time.

A period of tectonic quiescence and erosion took hold after Laramide time until ~25 Ma, when extension began to dismember the Laramide porphyry systems and surrounding rocks (Howard and Foster, 1996). Locally, areas in the Northern Tortilla Mountains were extended <400% (Maher, 2008). In the study area 90° rotation occurred along multiple generations of normal faults. The Whitetail Conglomerate is the oldest post-Laramide formation in the study area and records as much as 100° of rotation in Hackberry Wash (Maher, 2008). Younger sedimentary and igneous volcanic rocks associated with a rhyolite dome field appear to overlie the Whitetail conglomerate in an angular unconformity and dip as much as 10-40˚ (Richard and Spencer, 1997). Post-extension, newly formed basins were filled with Tertiary gravels to form vast pediment surfaces that rest unconformabley on older rocks. Today, the landscape is undergoing exhumation as the pediment surfaces are exhumed (Richard and Spencer, 1997).

GEOLOGIC UNITS

Proterozoic

Ruin Granite

The Ruin granite is comprised of several distinct phases: one being porphyritic, one equigranular, and one fine grained. The most abundant phase is the porphyritic biotite granite, comprised of 25-30% 2-5 mm diameter plagioclase, 20-35% 2-10mm anhedral quartz grains, 15-35% 1-5 cm diameter K-feldspar in rounded to blocky phenocrysts, and 5-10% biotite in 1-5mm diameter flakes or interconnected clots (Richard and Spencer, 1997). The equigranular biotite granite phase contains biotite clots up to 1 cm in diameter. K-feldspar grains are smaller in this phase, usually 1-2 cm. The fine-grained biotite granite phase is equigranular, with crystals ranging from 1-2mm in size and only sparse biotite (Richard and Spencer, 1997). The Ruin is also cut by numerous felsic aplite and pegmatite dikes comprised of quartz, plagioclase, and K-feldspar.

The Late Proterozoic

Rocks in the study area from the late Proterozoic include the Troy Quartzite and the Apache Group. The Troy Quartzite is comprised of quartzite and sandstone. Total thickness of the formation in the study area ranges from 100-500 feet (Cornwall and Krieger, 1975b).

Resting above the Troy Quartzite the Apache Group is comprised of the Pioneer Formation, Dripping Spring Quartzite, Mescal Limestone, and basalt. It is described in detail by (Cornwall and Krieger, 1975b). The Pioneer formation is comprised of a basal conglomerate and a tuffaceous siltstone, arkosic sandstone member. Total thickness ranges from 120-220 feet. The Dripping Springs Quartzite is comprised of a basal conglomerate, arkose, and siltstone member, with a total thickness of 600-700 feet. The Mescal Limestone has a total thickness of 150-320 feet and also includes some dolomitic and cherty layers.

The basalt in the Apache Group consists of one or more flows up to 60 feet thick. It is porphyritic in nature with a dark groundmass comprised of placioclase, pyroxene, olivine, and magnetite-ilmenite, and plagioclase phenocrysts 2-8mm long.

Diabase Sheets

Diabase sheets and sills intrude older Proterozoic rocks, as flat sheets and feeder dikes. The sheets intruded parallel to the surface when they formed (Howard, 1991). They display an often strong sub-ophitic, diabase texture. Mineralogically the diabase sheets consist of 35-45% 1-3mm plagioclase laths in a black groundmass of pyroxene and magnetite. In the study area these sheets dip vertically, and served as reactive hosts for hydrothermal alteration and some mineralization (Force, 1998)

Paleozoic

Approximately 1-1.5 km of Paleozoic, mainly carbonate rocks, disconformably overlie strata of the late Proterozoic. The Paleozoic sequence is restricted to the eastern third of the study area and is comprised of the Bolsa Quartzite, Abrigo Formation, Martin Limestone, Escabrosa Limestone, and Naco Limestone (Cornwall and Krieger, 1975b).

Laramide igneous rocks

Williamson Canyon Volcanics

This unit outcrops west of the Gila River in the southeast portion of the study area. It consists of porphyritic andesitic volcanic breccias with abundant xenoliths of Troy Quartzite and unidentified rock fragments. The andesite is comprised of plagioclase crystals <1 mm in diameter, pyroxene crystals <1mm in diameter, and magnetite, in a groundmass of plagioclase, mafic minerals, and magnetite (Cornwall and Krieger, 1975b). These deposits represent eruptions from Laramide intrusions that vented to the surface (reference, xxxx ?).

Tea Cup Pluton

The principal exposures of the pluton zone crudely inward and westward from the outermost hornblende-biotite quartz monzodiorite to main phases of biotite-hornblende granodiorite, biotite granite, and the westernmost biotite-muscovite±garnet granite (Barton et al., 2005).

The quartz monzodiorite lies on the southwest edge of the pluton and is the oldest of the intrusive phases. The hornblende-biotite granodiorite occupies the eastern portion of the Tea Cup pluton and forms the prominent cupola of the pluton.

The biotite phase of the Tea Cup pluton occupies the central portion of the pluton and outcrops again southwest of the main pluton. The unit is comprised of equigranular, medium-grained leucocratic granitoids with 40% 3-10 mm-diameter anhedral quartz, 25% pink subhedral 3-4 mm-diameter K-feldspar inter-grown with 30-40% subhedral white plagioclase in 2-4mm diameter grains, and 2-3% 1 mm diameter biotite. (Richard and Spencer, 1997)

The biotite-muscovite±garnet granite phase of the Tea Cup pluton is a equigranular, medium- to medium-fine-grained aplitic granitorid. It consists of 30% quartz in 2-4 mm diameter anhedral grains, 60-70% feldspar, mostly plagioclase, in 2-6 mm-diameter, anhedral grains, and 5-7% mica, with a highly variable muscovite to biotite ratio. (Richard and Spencer, 1997)

Porphyry Dikes

Porphyry dikes in the study are concentrated in two swarms: one east of the Tea Cup pluton and another centered on Box-O Wash. Cornwall (1982) characterized the petrography of dikes in and east of the Tea Cup pluton, and Richard and Spencer (1997) described porphyry dikes in and around Box-O Wash (Table 1.). Several dike types are found in both dike swarms. The dikes have a preferred orientation striking 070° and dipping vertical, and were critical structural markers used in field mapping. The distinctive Muscovite-Bearing Quartz Latite porphyry dike observed in the Tea Cup dike swarm and the Box-O Wash dike swarm was critical in constraining fault offsets and may be a singular feature.

Geochronology of Laramide rocks

U-Pb geochronology of zircons from Laramide rocks in east-central Arizona has been conducted by Seedorff et al. (in press). New ages of plutons in the study range from 75 to 61 Ma and are typically 1-5 million years older than K-Ar dates. The age range of magmatism and mineralization in a cluster of deposits north of the study area near the Schultze Granite, including the Globe-Miami, Pinto Valley, and Resolution deposits, is from ~69 to 61 Ma. To the south in the Tortilla and Dripping Spring Mountains, the porphyry systems range from ~74 Ma in the Tea

Cup Pluton to ~69 Ma at Ray and ~65 Ma at Christmas. At the three localities where geologic constraints exist, mineralizing plutons were emplaced following Laramide contractional deformation. New U-Pb dates of zircons from this study determined the age of the Red Hills Porphyry Dikes, Granite Porphyry Dike, and the Muscovite-Bearing Quartz Latite (Table 2).

Other nearby Laramide Intrusive Rocks

Nearby Laramide igneous rocks include the Tortilla Quartz Diorite, the Rattler Granodiorite, the Granite Mountian Porphyry, and the Tea Pot Mountain Porphyry, which are described by Cornwall (1982) (Fig. 1). The most similar of these to the Tea Cup pluton is the Granite Mountain porphyry. It lies 3 km north of the Tea Cup pluton and is the source of the Ray deposit (Phillips et al., 1974; Cornwall, 1982). The pluton is mostly granodiorite, but also is comprised of quartz monzonite.

Tertiary

Whitetail Conglomerate

The Whitetail Conglomerate is a dark reddish brown, poorly sorted to massive conglomerate that probably correlates with the Hackberry Member of the Cloudburst Formation (Dickinson, 1991; Maher, 2008). Cobbles and rare boulders are comprised of granitoids, schist, and less abundant felsic volcanic or hypabyssal rocks.

Rock Avalanche Breccia

This unit located in and near Donnelley Wash is comprised of a monolithologic breccia consisting of unsorted angular clasts of mostly Ruin Granite. Also contained in the breccia are Laramide rhyolite dikes which can be traced for several tens of meters as lenses of breccia. (Richard and Spencer, 1996). Similar smaller deposits have been mapped in the eastern portion of the study area by Krieger (1977). In Donnelly Wash, Richard and Spencer (1997) considered these rocks to be younger than the Whitetail Conglomerate, however Maher (2008) found evidence that similar deposits to the east represented the base of the Whitetail Conglomerate.

Volcanic Units

This unit contains the many volcanic units in the western third of the study area, including several varieties of tuff and basalt, all Miocene and younger in age.

Conglomerate

The conglomerate is the youngest Tertiary unit and consists of massive, crudely to moderately well bedded, cobble to boulder conglomerate, and poorly sorted gravels. It also contains local volcanic deposits which formed during the conglomerate deposition. (Richard and Spencer, 1997).

Quaternary

Undifferentiated Deposits

This unit is comprised of conglomerates, landslide deposits, river gravels, alluvium, and other surficial deposits.

HYDROTHERMAL FEATURES

At least two, and possibly three, hydrothermal systems containing potassic, sericitic, greisen, sodic, sodic-calic, and propylitic can be mapped in the study area (Figs. 3, 4). These systems display both porphyry copper and porphyry molybdenum mineralization. Distal from the most intense potassic alteration in two of the systems, locally intense iron oxide copper gold alteration and mineralization is present (Table 3).

Potassic Alteration

The most intense potassic alteration in the study area is found near the cupola of the biotite-hornblende granodiorite grades where sulfide-poor veins of quartz-K-feldspar, biotite, quartz, and magnetite-quartz are abundant (Fig. 4A) This grades into more sulfide-rich sericitic alteration in hosted by the Ruin Granite to the east. Moderate potassic alteration in the form of quartz-K-feldspar-muscovite±biotite±sulfide veins is also found just east of Mount Grayback near the cupola of the biotite-muscovite±garnet granite (Fig. 4B). Weak to moderate potassic alteration is found in the Red Hills prospect where shredy biotite and quartz±K-feldspar±pyrite±chalcopyrite veins (Fig. 4C) are bound on the east by a low angle normal fault with several kilometers of offset.

Sericitic Alteration

Much of the sericitic alteration in the study area is centered just to the east of the Tea Cup pluton, where sericitic alteration with high pyrite contents is associated with sparse porphyry dikes. Exposures near the towns of Kelvin and Riverside contain zones of sericitic alteration, including breccia pipes that were cemented with pyrite, quartz and chalcopyrite. East of, and overlapping with, potassic alteration near Mount Grayback, sericitic alteration takes the form of quartz-muscovite-chalcopyrite-molybdenite-pyrite veins. East of the Red Hills prospect locally intense quartz-sericite-pyrite alteration can be found in ~20 m steeply dipping east-west striking zones in the Ruin Granite (Fig. 4D)

Both overlapping with and spatially distinct from sulfide-rich sericitic alteration near the eastern margin of the Tea Cup pluton, and in the area in and east of the Red Hills prospect, locally intense sulfide-poor Iron Oxide Copper Gold style sericitic alteration is developed in the Ruin Granite. Veins of specular hematite-chlorite-quartz±magnetite±pyrite (Figs. 4E, 4F) are pervasive, and locally areas of quartz+specularite hematite completely destroy preexisting texture. Surrounding the most intense areas of alteration are zones of chlorite±quartz alteration.

Sodic and Sodic-Calcic Alteration

To the north and, particularly, to the south of the zone of most intense potassic alteration near the cupola of the biotite-hornblende granodiorite, sodic and sodic-calcic assemblages, including endoskarn, are widespread. Sodic assemblages contain quartz, albite, chlorite, and epidote, whereas actinolite-oligoclase epidote and local garnet and quartz leaching comprise sodic-calcic assemblages (Fig. 4G) (Maher, 2008).

Griesen Alteration

Greisen muscovite±pyrite±quartz is developed weakly west of Mount Grayback (Fig. 4H) Greisen occurs in some cases as narrow muscovite-rich veinlets, while other zones have widths of tens of centimeters. The character of the greisen occurrences varies along strike from solely

muscovite-rich alteration envelopes to quartz-sulfide–rich cores encased in muscovite rich envelopes; locally, both have outer envelopes of K-feldspar (Seedorff et al. 2008)

Low Temperature Alteration

Propylitic alteration is widespread across the entire study area, but only locally intense. Carbonate veins were found immediately west of Donnelly Wash cutting quartz veins in the Ruin Granite. No base metal veins have been observed in the system.

Mineralization

Porphyry Cu mineralization occurs in several fault slices east of the main exposures of the Tea Cup pluton, the largest of which is the Kelvin prospect. (Schmidt, 1971a; Zelinski, 1973; Corn and Ahern, 1994; Wilkins and Heidrick, 1995). A weak zone of porphyry Mo-Cu mineralization is present surrounding Mount Grayback, but has never been investigated as an exploration target. Mineralization associated with the Red Hills prospect is both porphyry copper and iron oxide copper gold style; however, the majority of the mineralization at the Red Hills prospect is associated porphyry copper style alteration. Several fault slices to the east of the Red Hills contain exploration pits and shafts showing oxidized copper at the surface.

STRUCTURES

Laramide

At least one Laramide reverse fault outcrops in the study area characterized by exposed cataclastic zones that strike roughly north south and have a steep eastward dip. Across this zone the diabase sheets are repeated. The cataclastic zone is cut by the cupola of the hornblend-biotite phase of the Tea Cup pluton, providing a minimum age for the fault of ~73 Ma. Maher et al (2008) hypothesized that this fault may be equivalent to the Walnut Canyon thrust fault exposed several kilometers north of the study area. Breccia pipes exposed in the Ruin Granite east of Ripsey Wash locally contain sedimentary rocks demonstrating the presence of overlying or overthrust supracrustal rocks at the time of mineralization (Barton et al., 2005)

Veins and dikes in the study area have a strong preferred orientation in outcrop striking east-northeast and dipping steeply (Fig. 5). Titley (1982) noted this preferred orientation over much of Southeastern and Central Arizona and suggested that the dikes were intruding along the axis of least principal stress as the Farallon plate collided with the North America plate during Laramide times. This interpretation assumes that the veins are in their original Laramide orientation which is not the case in the study area. However, after rotating the veins 90° about an axis of 355° (perpendicular to the extension direction, see below) the veins and dikes show the same preferred orientation parallel to the Laramide axis of least principal stress.

Tertiary

After Laramide time, Tertiary normal faults extended and dismembered the Tea Cup porphyry system (Fig. 6). The extension was accomplished on at least five sets or generations of normal faults. Each generation of normal faults broke with similar strikes and dips and then cut and extended the porphyry system while the fault plane rotated to shallower dips. Once the fault planes rotated to angles that were kinematically unfavorable for slippage (<30°; Anderson, 1959), new faults planes formed which cut and rotated the older fault planes along with the

porphyry system. Since there is no observable evidence for high angle faults soling into low angle faults, and many cross cutting relationships display high angle faults cutting low angle faults, it is concluded that the outcropping low angle faults rotated to their current orientation after breaking at high angles between 55°-75°. This repeated sequence of events produced total rotation of ~90° about an axis of 355° as evidenced by dips of the diabase sills and the earliest generation of normal faults.

Generation 1

The oldest set of normal faults in the study area; these faults strike ~350° and have been rotated to a dip of 15° W, overturned. A younger over older relationship is maintained by these overturned faults, but their slip direction is now up-dip in their current orientation. Judging from the inclination of the faults compared to the diabase dikes, this generation of normal faults must have broken at ~75° and rotated to 45° before being cut and offset by the second generation of normal faults. Estimated offset on faults of this generation is poorly constrained but appears to be as great as 3 km. Due to their low angle to the present day surface these faults rarely outcrop. However, in the Hackberry Wash just southeast of the area spectacular exposures of a 15° W dipping normal fault display as an extensional clippé of Paleozoic limestone resting on Ruin Granite (Barton, 2005).

Generation 2

The second oldest fault set strikes at ~350° with a dip of ~15° east where measured. Slip on these faults ranges from 2-7 km and is often constrained using the diabase sills as markers. Judging from their orientation to the now-vertical diabase sheets, this generation of normal faults must have broken at ~60° and rotated to ~30° before being cut and offset by the third generation of normal faults. Displacement is greatest on this generation of faults, with the Walnut Canyon fault possibly having as much as 7 km of offset. A fault of this generation can be measured in outcrop immediately east of the Red Hills prospect. There the fault places Ruin Granite displaying intense iron oxide copper gold sericitic alteration in the hanging wall, on Ruin Granite with moderate propylitic alteration in the footwall, with a dip of 15° E (Fig. 7A).

Generation 3

This fault set strikes at ~340° and has dips of ~45° E (Fig. 7B). Slip on these faults is as great as 2 km. Near Box-O Wash a fault of this generation can be measured with a dip of 50° where it cuts and offsets a porphyry dike. At this location the slip is estimated to be ~700m based on the offset created in the Big White Dike which dips 80° N in Box-O Wash.

Generation 4

Faults of this generation have strikes of ~010° and dips of ~70° E. Slip on these faults is usually less than 1 km, with little to no rotation occurring along this fault set. A fault of this generation can be measured immediately south of the Red Hills prospect. Here the fault is extimated to have ~250m of displacement judging from the offset created in the Big White Dike which dips 80° N in Box-O Wash.

Generation 5

Faults of the youngest generation have strikes of ~350° and dips of ~70° E. Slip on these faults is usually less than 1 km, with little to no rotation occurring along this fault set. Outcrops of this fault set are well-exposed in the Tertiary volcanic units near South Butte.

PALINSPASTIC RECONSTRUCTION

Approach

A thirty kilometer palinspastic reconstruction was attempted across the study area. Displacement along the normal faults was removed in sequential order from the youngest to the oldest generation of normal faults, as determined by dip measurements and crosscutting relationships. Slip on faults was constrained using observed lateral offsets of dikes and faults, drill hole data, offsets of diabase sheets and sills, and by placing unconformities of the same age at similar structural levels, rotating Tertiary sedimentary rocks to horizontal, and matching textures in the Ruin Granite, and matching alteration assemblages. Smaller faults (slip<150m) were not used.

Due to the predominance of igneous rocks in the study area, a number of uncertainties remain unresolved in the restoration. The three dimensional shape of the igneous rocks is unconstrained and is based predominantly on symmetry with the map pattern and supposition. Also, the dip of igneous rocks across the study area is assumed to be nearly vertical based on observation of the diabase sheets; however, these sheets have irregular edges which are difficult to measure in outcrop. Observing the exposure across topography in map pattern is a more useful means of determining their dip but only loosely constrains their true dip (~ ± 10°). Furthermore, it was impossible to measure the dips of some faults in outcrop. In these cases, cross-cutting relationships were used to attempt to determine the relative age of the fault, and measured dips from faults of the same generation were used.

Results of Palinspastic Reconstruction

The reconstruction reveals a composite pluton intruding the eastern margin of a basement-cored uplift (Fig. 8.). The intrusion geometry is not influenced by Laramide reverse faults and displays three stacked phases of the pluton, each creating its own porphyry system: the biotite-hornblende granodiorite being the oldest, followed by the biotite granite, and the biotite-muscovite±garnet granite. The cupola of the biotite-hornblende granodiorite is shown to lie just beneath the modern surface but could lie substantially further east or west in the reconstruction.

The biotite granite is shown rising to higher levels in the crust beneath the Red Hills prospect. This hypothesis is based upon the mineralogy of the most common porphyry dikes in the Red Hills which contain only biotite as a mafic phase. The biotite-muscovite±garnet granite is shown rising only to depths of approximately seven kilometers. Its cupola and the core of its associated molybdenum mineralization may lie further east or west in the reconstruction, or out of the line of section.

In the palinspastic restoration of hydrothermal alteration three centers of porphyry alteration are shown (Fig. 9). Potassic alteration restores to areas near the cupolas of the hornblende-biotite, biotite, and two mica phases of the Tea Cup pluton. Sericitic alteration is structurally higher, and overlapping the zones of potassic alteration in all three systems. Propylitic alteration

restores to areas distal to the potassic alteration. Greisen alteration is restricted to lower levels of the Tea Cup pluton from depths of seven to ten kilometers.

The intense iron oxide copper gold-style sericitic alteration restores to areas two to four kilometers distal from the cupola of the hornblende-biotite phase of the Tea Cup pluton. This relationship is concordant with what is observed in map view, with intense iron oxide copper gold-style alteration lying mostly within the two to four kilometer range north and south of the cupola of the hornblende-biotite phase of the Tea Cup pluton. At the Red Hills prospect iron oxide copper gold style alteration is superimposed on moderate porphyry-style potassic alteration.

The Kelvin prospect restores to a position approximately 1 km above and slightly east of the cupola of the hornblende-biotite phase of the Tea Cup pluton. The Red Hills prospect restores above the cupola of the biotite phase of the Tea Cup pluton for reasons discussed above; however, the limited potassic alteration and abundant porphyry dikes found in the Red Hills does not strictly require that it lies directly above the center of a porphyry system. It may represent the distal flank of the porphyry system created by the biotite-hornblende granodiorite. This appears unlikely, however, because potassic alteration, and the abundance of porphyry dikes, diminishes to the east toward the cupola of the biotite-hornblende granodiorite. In either case, the proximity of the Red Hills prospect to the Tea Cup pluton in the reconstruction strongly suggests the porphyry dikes and alteration are sourced by a phase of the Tea Cup pluton.

DISCUSSION

Comparisons to other Laramide Porphyry Systems

Previous studies of Laramide porphyry systems have focused on the spatial distribution of igneous and hydrothermal features. Specific areas of dialogue include the distribution of igneous rocks, grade and metal ratios, veins and minerals, and the depth and level of exposure of the systems (Seedorff et al., 2005).

Similar to other porphyry systems of the northern Tortilla Mountains, the highest grade Cu mineralization (Kelvin prospect, Red Hills prospect) is located structurally above the cupola of the pluton in the Tea Cup porphyry system. The cupola restores to a position ~4km from the paleosurface within the range of 1 to 6 km in which most cupolas of porphyry systems lie (Seedorff et al., 2005) While these prospects constitute the highest grade mineralization in the system, their grades and tonnages are similar to those found in similarly sericitically altered areas located structurally above porphyry ore bodies in the Northern Tortilla Mountains (Maher et al, this volume). Additionally, the greisen style alteration observed near Mount Grayback is typical of the “root” zones of porphyry systems that lay structurally below restored ore bodies at the Miami-Inspiration, Sierrita-Esperanza, and Ray porphyry systems (Seedorff et al., 2008). Finally, base- and precious-metal veins have not been observed in the Tea Cup porphyry system similar to most Laramide systems in the Northern Tortilla Mountains (Maher et al, this volume).

As with all porphyry systems, there are many features which make the Tea Cup porphyry system distinctive. First, the zoning of the Tea Cup pluton from a hornblende-biotite quartzmonzodiorite, to main phases of biotite-hornblende granodiorite, biotite granite, and biotite-muscovite±garnet granite distinguishes the system from others in the Northern Tortilla Mountains, but similar zoning has been observed by John (1988) in the Laramide(?) felsic

Chemehuevi Mountains plutonic suite of southeastern California. The superposition of the Mo-Cu mineralization produced from the biotite-muscovite±garnet granite on top of the copper mineralization produced from the biotite-hornblende granodiorite is also uncommon but may be analogous to mineralization at Sierrita-Esperanza (Stavast et al, 2008).

Combining results of this study with observations from Sierrita-Esperanza by Stavast et al. (2008) it appears that sodic-calcic alteration maybe widespread in the Laramide province, and not restricted to Jurrasic aged systems such as the Yerington district. Furthermore, the presence of widespread iron oxide copper gold style alteration and mineralization indicates that deposits such as Pumpkin Hollow of the Yerington district could exist in Laramide systems.

Exploration Targets

The reconstruction reveals at least two potential exploration targets (Fig. 2); one associated with the biotite-hornblende granodiorite phase and another with the biotite granite phase of the Tea Cup pluton. First, rocks lying under the Tertiary and Quaternary filled basin west of Mount Grayback restore to similar structural levels and distances from the cupola of the hornblende-biotite phase of the Tea Cup pluton to the Kelvin prospect. Exposures of the Ruin Granite west of Donnelly Wash which restore beneath the west-Grayback basin target are dominantly propylitic altered, but do contain an approximately one hundred square meter area with quartz veining abundance of ten volume percent. One shaft nearby of approximately ten meters depth revealed locally significant copper mineralization. Other small pits immediately west of Donnelly Wash contained mineralization associated with late-stage carbonate veins.

Another potential exploration target lies west of the Red Hills beneath Quaternary cover. As discussed above, the Red Hills may represent the upper levels of a porphyry system centered on the biotite granite phase of the Tea Cup pluton. Lower levels of this system may lie west of the Red Hills depending on the nature of covered normal faults that undoubtedly underlie the Quaternary cover.

Style of Extension

The manner in which the lithosphere responds to extensional strain continues to be a topic of great debate. Most controversies center on the geometry, timing, and magnitude of normal faults in extended terrains (Maher, 2008).

The amount of curvature on fault planes has dramatic consequences on the path of fault blocks during extension, and thus controls the locations of pieces of dismembered porphyry systems after extension. Strongly listric faults which flatten at depth produce differences in the amount of tilt in the hanging and footwall blocks of the fault. Tilt produced by nearly planar faults creates little difference in tilt between hangingwall and footwall blocks and requires fault planes to be rotated along with the hangingwall and footwall blocks (Gans and Miller, 1983).

Proffett (1977) recognized that normal faults of similar low angle dips were cut and offset by younger high angle faults with similar dips. This led to the idea that normal faults occurred in generations. Wernicke (1981) proposed that areas of major extension were underlain by a low angle detachment fault that truncated higher angle faults. While the detachment fault remained active throughout extension, higher angle faults formed, rotated, and died out repeatedly. Alternatively, in a mingling of the previous two models, Buck (1988) proposed a flexural rotation model where high angle faults were rotated to low angles and became underlying detachment fault. In metamorphic core complexes estimated displacement on detachment faults

is often in the tens of kilometers (e.g. Lister and Davis, 1989). However, faults that are known to initiate at high angles have much smaller offsets rarely exceeding 4 km (reference, xxxx ?).

While the amount of extension in the study area is as great or greater than is estimated at some metamorphic core complexes (Howard and John, 1987) results of this study show that in the study area all higher angle normal faults cut normal faults of lower angles, and that fault geometries were curviplanar, occurred in generations, and had maximum displacements less than tens of kilometers.

A comparison of the study area to areas that have extended in a similar manner is made in Table 4. In the study area five generations of normal faults were superimposed on each other, which produced greater amounts of tilt and extension than is observed in most of the other localities. Offset along the Walnut Canyon fault at 7 km is greater than any of the other faults examined. However, west of the Walnut Canyon fault a distance of several miles is covered by quaternary fill. Normal faults which would reduce the estimated amount of extension in the reconstruction undoubtedly lie under the Quaternary cover but are not incorporated into the reconstruction.

Geothermal Gradient

Debate over geothermal gradients in areas of high extension has played a central role in the controversy surrounding extensional styles in the basin and range (Foster and others, 1990; Gans, 1991; John, 1993). In the Colorado River extensional corridor Howard and John (1987) concluded that because high-grade metamorphic rocks are not exposed in the footwalls of detachment faults with continuous down-dip exposure over tens of kilometers, then the low-angle faults must have initiated at low angle. This conclusion requires that the geothermal gradient was not abnormally low during extension, and that the footwall is not significantly extended. In the Sierra Mazatán core complex, Sonora, Mexico, Wong and Gans (2008) argue for a geothermal gradient ~20°-25°C km^{-1} prior to extension based on $^{40}Ar/^{39}Ar$ thermochronology and geologic observations that indicate both the hangingwall and footwall of the detachment fault rotated 50°-60° during extension, and that the footwall block avoided extension.

Howard and Foster (1996) conducted a thermochronologic investigation into the thermal and unroofing history of the study area. They used fission-track thermochronology of apatite and zircon samples to conclude the geothermal gradient was 17 ± 5°C km^{-1} at the onset of extension ~25 Ma, nearly 50% of the current geothermal gradient in the Basin and Range province (Table 5.). Implicit in this calculation was that the study area was tilted eastward 90 ±15°, and that the area from Ripsey Wash east to the Walnut Canyon fault was an intact fault block. Two calculations were made to determine the geothermal gradient. The first was made using the difference in paleodepths divided by the difference in closure temperature between the apatite and zircon fission-track samples interpreted to record the onset of extension. The second measurement was made using the difference between the same apatite fission-track age and the Proterozoic-Tertiary unconformity in Ripsey Wash, assuming that the unconformity was within 1.5 km of the surface and at a temperature of 15° ± 10° C. The calculations derived geothermal gradients of 17.1 ± 5.3 km^{-1} and 16.7 ± 4.9°C km^{-1} respectively, which were averaged and simplified to produce their final estimate.

While neither the focus of this paper, nor the impetus for this study, projecting the fission track ages of Howard and Foster (1996) into our more detailed restorable cross section produces

informative results. By removing the assumption that the area from Ripsey Wash east to the Cochran fault was an intact fault block, and instead viewing it as an area cut by numerous normal faults of five different generations that repeat section, paleodepths estimates become more shallow, and the derived geothermal gradient rises (Table 6) (Fig. 9).

While our calculated geothermal gradient of 24°C km^{-1} is lower by several degrees than the current geothermal gradient of the Basin and Range province, it is significantly higher than was interpreted by Howard and Foster (1996). It is important also to remember that this calculation estimates the geothermal gradient prior to extension. For this reason it is prudent to compare the results to calculated geothermal gradients in Laramide basement-cored uplifts which may be more representative of the study area prior to extension (Davis, 1979; Dickinson, 1991). Apatite fission-track dating in the Beartooth Mountains, Montana-Wyoming, revealed a maximum Tertiary geothermal gradient of 17°C km^{-1} (Omar et al., 1994). Results from a (U-Th)/He apatite ages in the Bighorn Mountains, Wyoming, also suggest a geothermal gradient <20°C km^{-1} throughout Tertiary time. The geothermal gradient derived in this study does not closely match that of the modern Basin and Range province or unextended Laramide uplifts, but lies in between those values. One speculative explanation for this inconsistency is that the data may record the warming of the post-Laramide lithosphere prior to the onset of extension.

These results indicate that rigorous palinspastic reconstruction of tilt blocks prior to estimations of paleodepths used to calculate geothermal gradients can help refine these estimates and further elucidate the role of heat flow in highly extended areas. Furthermore, by combining rigorous palinspastic reconstructions with detailed timing of the generations of faulting and thermochronology, it may be possible to see how geothermal gradients evolve over time during extension.

SUMMARY / CONCLUSIONS

Results show that the intrusion of the composite Tea Cup pluton occurred in four phases and created at least two and possibly three hydrothermal systems. Potassic alteration dominates the core of the systems, with sericitic alteration at higher levels, sodic-calcic alteration 2-4 km distal on the flanks of the systems, and propylitic alteration surrounding the other alteration types. Also, greisen alteration is found several kilometers directly beneath potassic alteration. Tertiary normal faults have rotated the entire study area ~90° to the east, and extended it over 200%, along five sets of normal faults that initiated at high angles (~55°-75°). Rotation caused by normal faulting provides a unique cross-sectional view at the present surface of the porphyry system, from its distal flanks, to paleodepths >10 km

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FIGURE CAPTIONS

Figure 1. Location map of the Northern Tortilla Mountains in east-central Arizona, showing geographic features, major intrusive centers, and generalized hydrothermal centers. Approximate middle Tertiary extension directions are shown. Location of the study area is outlined in black (Adapted from Maher, 2008).

Fig. 2. Geologic map of the study area. See text for discussion.

Fig. 3. Plan map of alteration in the Tea Cup porphyry system. See text for discussion.

Fig. 4. Pictures of Laramide hydrothermal veins. A. K-feldspar-quartz veins in the cupola of the biotite-hornblende granodiorite. B. Quartz veins with a K-feldspar envelope just east of Mount Grayback in the biotite-granite. C. Oxidized pyrite+chalcopyrite±quartz vein with K-feldspar envelope in Ruin Granite in the Red Hills prospect. D. Intense sericitic alteration with oxidized pyrite cubes surrounded by sericite in the Ruin Granite near Box-O Wash. E. Specular hematite-quartz dike in the Ruin Granite in the Red Hills prospect. F. Specular hematite-quartz-sericite breccia in the Ruin Granite from the Red Hills prospect. G. Albite-epidote-chlorite±garnet sodi-calcic alteration in the Ruin Granite on the southeastern flank of the tea cup pluton. H. Quartz vein surrounded by coarse grain muscovite in the biotite-muscovite±garnet granite west of west of mount Grayback.

Fig. 5. Equal area plot stereonets of Laramide hydrothermal features in the study area. The top row is all strike and dip measurements of veins and porphyry dikes from the study area. The second row is data from the youngest hydrothermal system sourced from the biotite-muscovite±garnet granite near Mount Grayback. The third row is data from the middle-aged hydrothermal system sourced from biotite granite and located in and around the Red Hills prospect. The fourth row is data from the oldest hydrothermal system sourced from the biotite-hornblende granodiorite. The first two columns display unrotated data, while the last two columns display the data rotated 90° about an axis striking 355°.

Fig. 6. Map of faults across the study area, including the line of section used in the palinspastic reconstruction

Fig. 7. A. Second generation low angle normal fault which bounds the east side of the Red Hills prospect, placing intense hematite/magnetite-chlorite-quartz alteration on weak chlorite-quartz alteration. (Photo taken by George Davis) B. Third generation normal fault exposed in Donnelly Wash placing Tertiary volcanic units on Proterozoic Ruin Granite. (Photo taken by Eric Seedorff)

Figure 8. Sequential palinspastic reconstruction from A-A'. The scale for all panels is shown in panel G. There is no vertical exaggeration. A. Modern cross section. B. Removal of 5th

generation of normal faults. C. Removal of 4th generation of normal faults. D. Removal of 3rd generation of normal faults. E. Removal of the 2nd generation of normal faults. F. Removal of the 1st generation of normal faults. G. Hypothetical Laramide cross section showing the composite Tea Cup pluton intruding a basement cored uplift .

Figure 9. Reconstruction of hydrothermal alteration showing the hypothesized 73 Ma paleosurface, the pre-extension 25 Ma paleosurface, and the modern surface. No vertical exaggeration.

FIGURES

Figure 1.

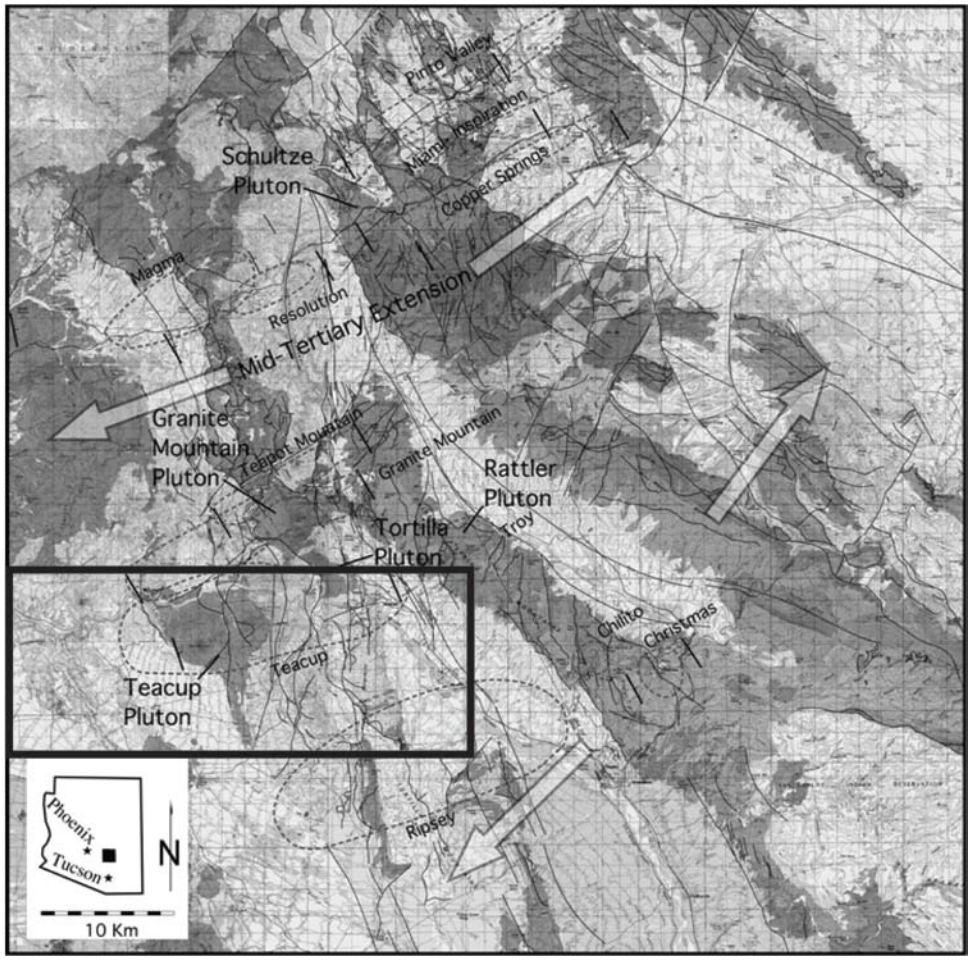


Figure 2.

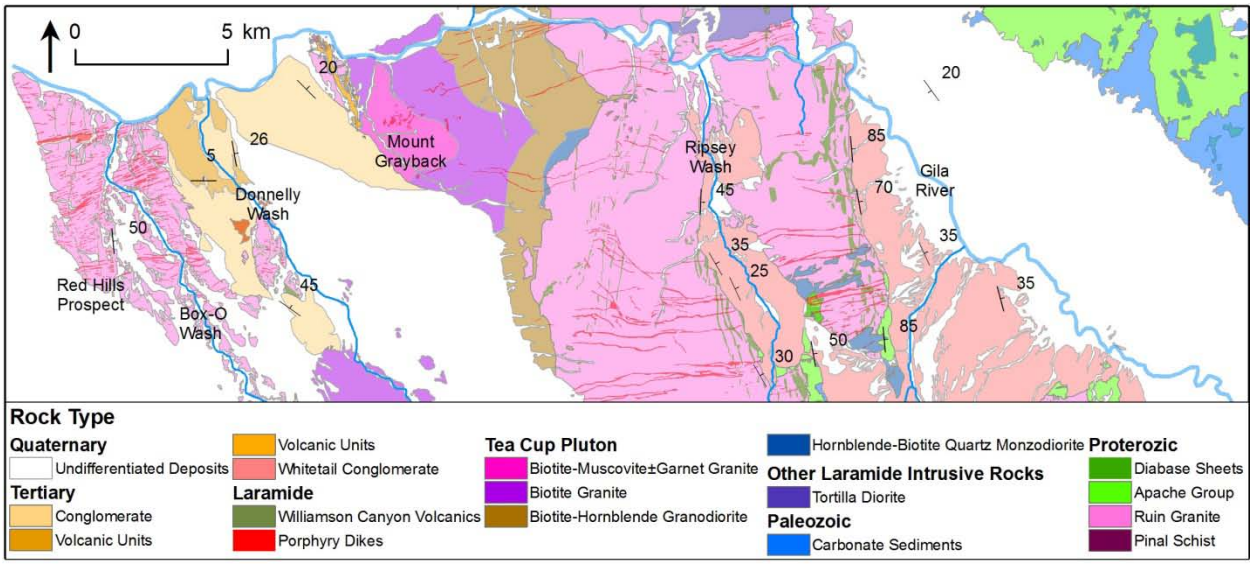

0
5 km
20
26
5
Donnelly
Wash
Mount
Grayback
50
Red Hills
Prospect
Box-O
Wash
45
Ripsey
Wash
45
35
25
30
50
85
70
Gila
River
85
20
35
35
Rock Type
Quaternary
Undifferentiated Deposits
Tertiary
Conglomerate
Volcanic Units
Volcanic Units
Whitetail Conglomerate
Laramide
Williamson Canyon Volcanics
Porphyry Dikes
Tea Cup Pluton
Biotite-Muscovite±Garnet Granite
Biotite Granite
Biotite-Hornblende Granodiorite
Hornblende-Biotite Quartz Monzodiorite
Other Laramide Intrusive Rocks
Tortilla Diorite
Paleozoic
Carbonate Sediments
Proterozic
Diabase Sheets
Apache Group
Ruin Granite
Pinal Schist

Figure 3.

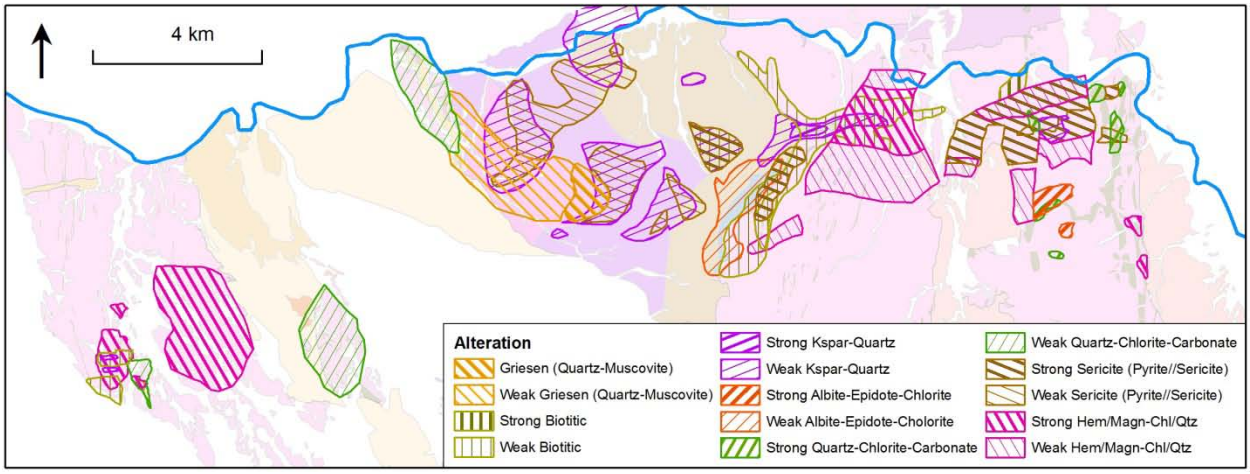

4 km
Alteration
Griesen (Quartz-Muscovite)
Weak Griesen (Quartz-Muscovite)
Strong Biotitic
Weak Biotitic
Strong Kspar-Quartz
Weak Kspar-Quartz
Strong Albite-Epidote-Chlorite
Weak Albite-Epidote-Cholorite
Strong Quartz-Chlorite-Carbonate
Weak Quartz-Chlorite-Carbonate
Strong Sericite (Pyrite//Sericite)
Weak Sericite (Pyrite//Sericite)
Strong Hem/Magn-Chl/Qtz
Weak Hem/Magn-Chl/Qtz

Figure 4.

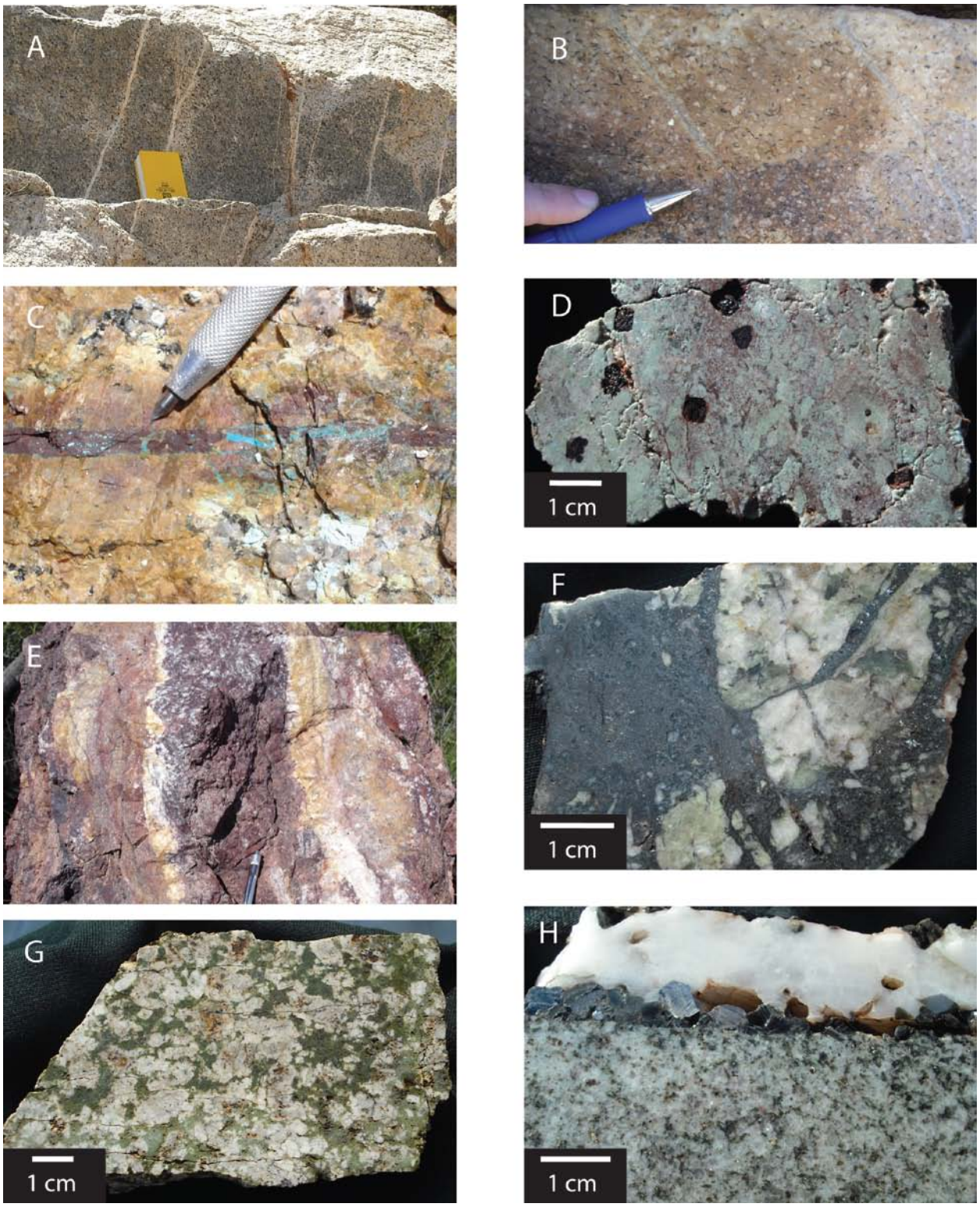


Figure 5.

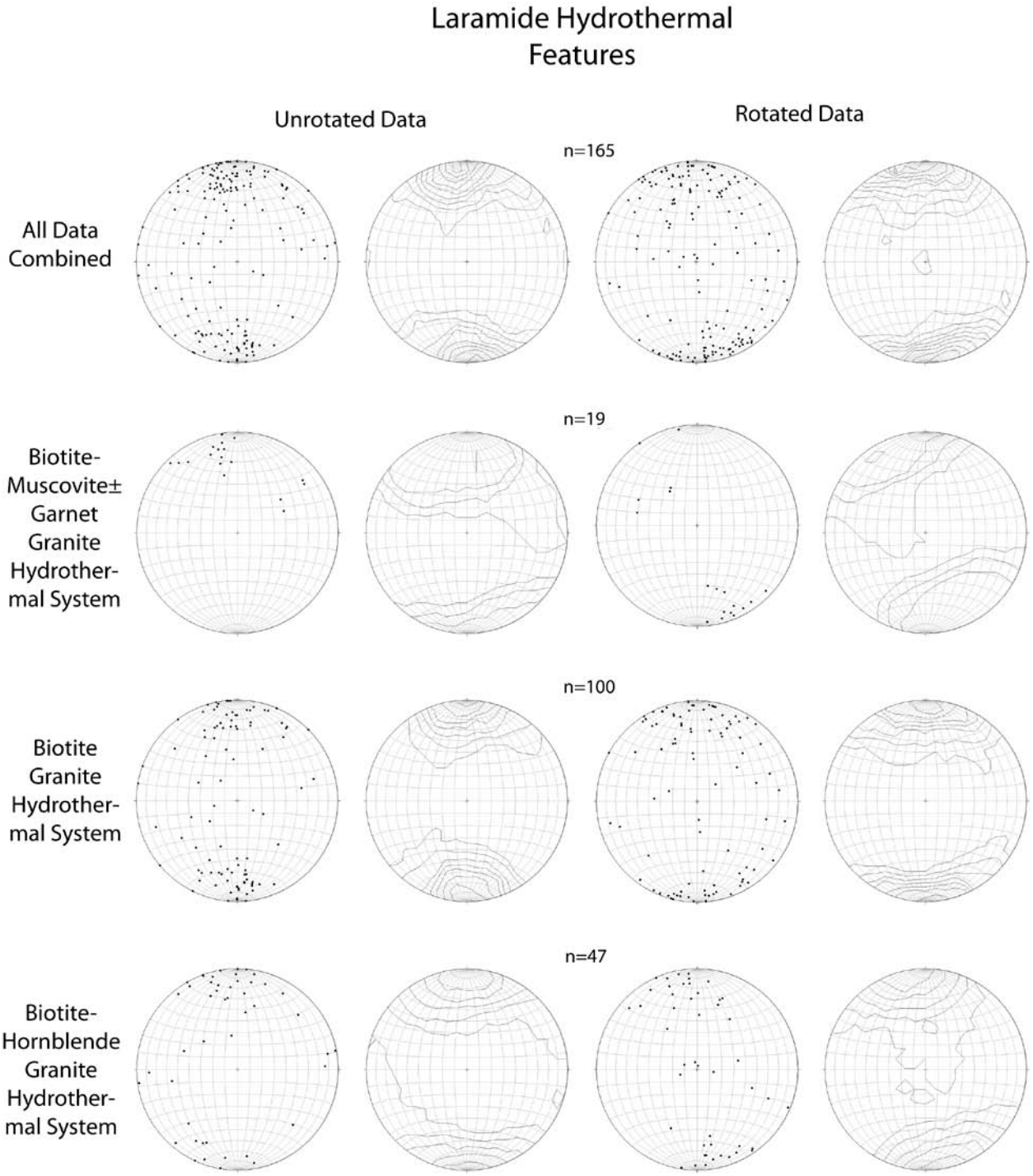

Laramide Hydrothermal Features
Unrotated Data
Rotated Data
n=165
All Data Combined
n=19
Biotite-Muscovite± Garnet Granite Hydrothermal System
n=100
Biotite Granite Hydrothermal System
n=47
Biotite-Hornblende Granite Hydrothermal System

Figure 6.

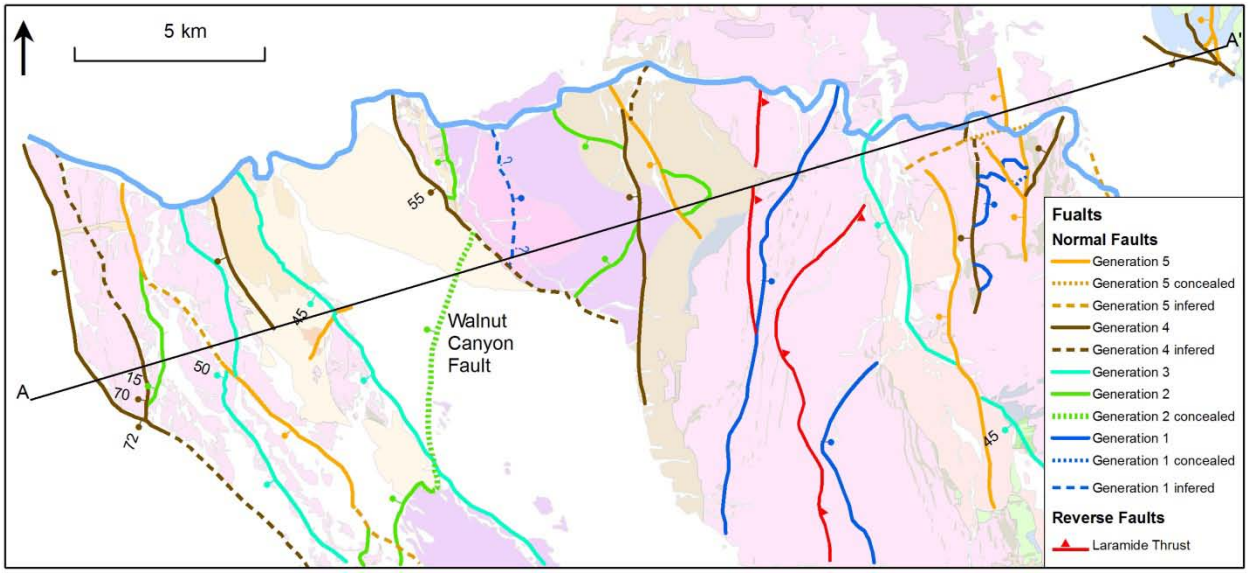

5 km
A
A'
Walnut
Canyon
Fault
55
45
50
15
70
72
45
Fualts
Normal Faults
Generation 5
Generation 5 concealed
Generation 5 infered
Generation 4
Generation 4 infered
Generation 3
Generation 2
Generation 2 concealed
Generation 1
Generation 1 concealed
Generation 1 infered
Reverse Faults
Laramide Thrust

Figure 7.


A


B

Figure 8.

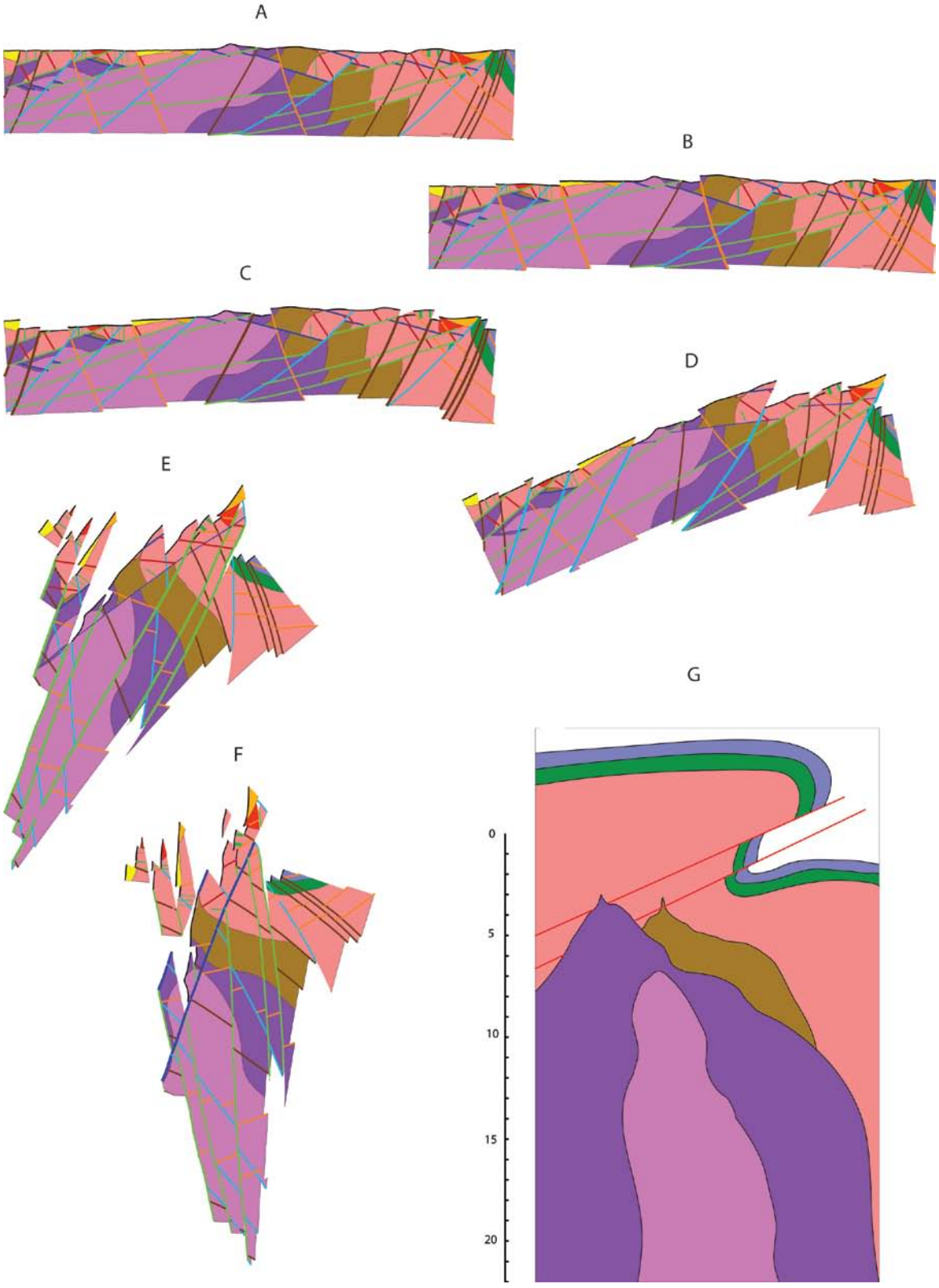
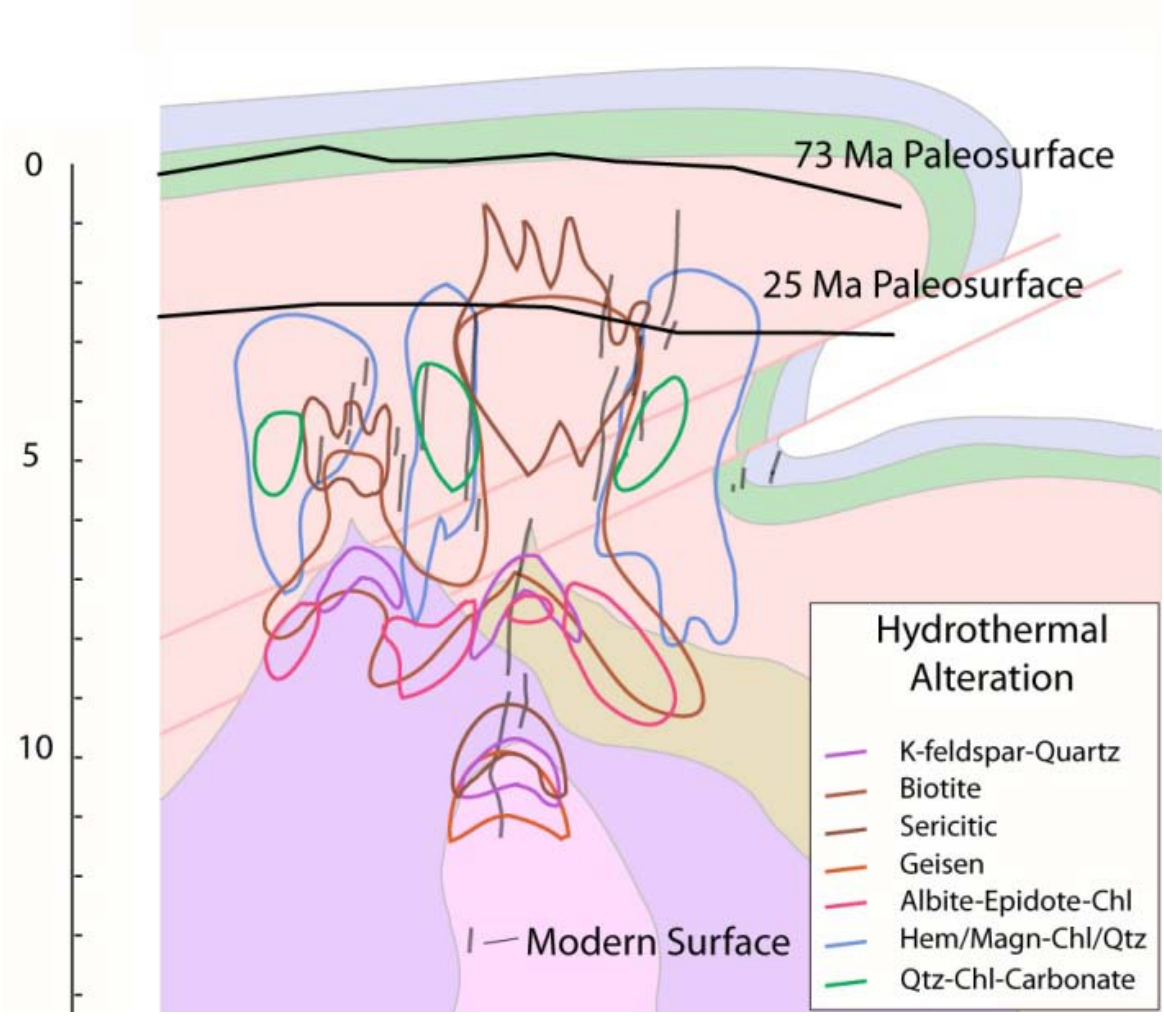


Figure 9.


0
5
10
73 Ma Paleosurface
25 Ma Paleosurface
Modern Surface
Hydrothermal Alteration
K-feldspar-Quartz
Biotite
Sericitic
Geisen
Albite-Epidote-Chl
Hem/Magn-Chl/Qtz
Qtz-Chl-Carbonate

TABLES

Table 1. Laramide Dikes located in the study area

Name	Description	Relative Age (1= Oldest, 7=Youngest)	Location	Reference
Hornblende Rhyodacite Porphyry	1-4 mm phenocrysts include andesine, hornblende, and sparse quartz and makeup 1-30% of the rock. Groundmass is fine grained , locally trachytic and consists of plagioclase, hornblende, magnetite, K-feldspar, quartz, sphene, and apatite.	1	South and East of the Tea Cup pluton, and throughout the Box-O Wash dike swarm.	Cornwall and Krieger, 1975
Rhyodacite Porphyry	Phenocrysts 1-4 mm long make up 10-30% of the rock and consists of andesine, biotite, hornblende, magnetite, and sparse quartz. Groundmass is minerals are the same as the phenocryst minerals	2	East of the Tea Cup pluton	Cornwall and Krieger, 1975
Large Quartz Rhyodacite Porphyry	Dikes have distinctive prominent quartz phenocrysts as well as plagioclase, biotite, and hornblende phenocrysts. Groundmass is anhedral-granular and consists of K-feldspar, all phenocryst minerals, and accessory apatite, allanite, zircon, and sphene.	3	Wide spread in the east of the Tea Cup pluton, and to the north Sonora and Kearny quadrangles. Less abundant to the West in the Box-O Wash dike swarm.	Cornwall and Krieger, 1975
Red Hills Dikes	Phenocrysts of 2-12 mm quartz (3-8%), plagioclase (15-25%), up to 3 cm K-Feldspar(2-5%), and 1-3 mm biotite (1-2%). Dikes grade from those with prominent quartz to those with prominent plagioclase.	4	Most highly concentrated near the Red Hills prospect and continue to the east in the Box-O Wash dike swarm	Richard and Spencer, 1997
Intermediate Composition Dikes	Compositionally variable dikes ranging from crystal poor light gray felsite with 1-3% 1-2 mm plagioclase crystals to crystal rich dikes that contain 5-25%, 1-6 mm plagioclase and generally sparse 2-4 mm quartz phenocrysts. Mafic crystals are 1-2 mm of biotite and hornblende. Also includes equigranular, microcrystalline to fine grained diorite to granodiorite dikes.	5	Located mostly north of the Red Hills prospect in the Box-O Wash dike Swarm	Richard and Spencer, 1997
Muscovite-Bearing	Phenocrysts .3-4mm in diameter of quartz, plagioclase, sanidine,	6	Outcrops across the Box-O Wash	Cornwall and Krieger, 1975

Quartz Latite Porphyry	biotite, magnetite and sparse muscovite make up 10 to 40% of the rock. The groundmass is anhedral-granular to aphanitic and is comprised of intergrown K-feldspar, quartz, plagioclase, magneitite, apatie and sericite.		dike swarm and the through the Tea Cup pluton. In both instances there appears to be only one dike of this generation.	
Granite Porphyry	Very fine grained to aphanitic groundmass with 10-15% 4-10 mm-diameter quartz crystals, 10% K-feldspar crystals up to 4 cm long, 40% 2-4 mm-diameter plagioclase crystals, and 2-3% biotite crystals.	7	A single large dike north of the Red Hills prospect and west of Box-O Wash.	Richard and Spencer, 1997

Table 2. Results of new U-Pb dating of porphyry dikes

Sample #	Unit	U-Pb Age	Latitude	Longitude
SP 102	Granite Porphyry	68.5±1.6	N 33°04'42.8"	W 111°14'26.9"
SP 101	Muscovite-Bearing Quartz Latite Porphyry	70.53±0.70	N 33°02'35.8"	W 111°12'51.3"
SP 103	Muscovite-Bearing Quartz Latite Porphyry	70.75±0.88	N 33°05'31.0"	W 111°04'11.9"
SP 100	Red Hills Dikes	70.92±0.69	N 33°02'33.6"	W 111°13'07.5"

Table 3. Description and location of alteration types, assemblages, and veins

Deposit Type	Alteration Type	Mineral Assemblages	Veins	Location
Porphyry	Potassic	K-spar, qtz, bt +/- cpy, mol	Kspar-qtz, bt, qtz, mt-qtz	Cupolas of Hb-Bt and Two Mica phases of Tea Cup Pluton, Red Hills Prospect
	Sericitic	ser, pyr, qtz, +/- cpy	qtz,-pyr +/- ser, qtz, ser	East of Tea Cup Pluton, Red Hills
	Greisen	qtz, musc	qtz-musc	Grayback Mountain
	Propylitic	chl, ept, qtz, carb	chl, ept, qtz, carb	Widespread
IOCG	Sodic, Sodic-Calcic	alb, epi, chl,	epi, chl	Radio Tower
	Sericitic	hem, chl, qtz +/- mag	hem-chl-qtz, qtz-chl, hem, mag, chl,	Red Hills-Box-O Wash, Zelleweger Wash, Ripsey Wash,

Table 4. Comparison of extended porphyry copper and related areas in Arizona and Nevada.

Location	Tilt of Bedding	Generations of Faults	Dip of Oldest Generation Faults	Maximum Displacement of Faults	Curvature of Fault Planes	Total Extension
Yerington						

District, Nevada	60°	3	10°	4km	3-7°/km	137%
Royston District, Nevada	50°	2	10°	3.5km		130%
Caetano Caldera, Nevada	40-50°	3	5-20°	6km		110%
Robinson District, Nevada	35-65°	7	5°			
GMSRC* Region, Arizona				~4km	1-3°/km	20-400%
Teacup-Red Hills, Arizona	90°	5	15° overturned	7 km	1°/km	225%

Table 5. Howard and Foster (1996) calculation of the geothermal gradient prior to extention. Sample H90 To-11 was not projected into the cross section because of its great distance south of the line of section. Instead a paleodepth estimate was made restoring the sample to the Tertiary-Proterozoic unconformity on a line of section further south and parallel to that of the palinspastic reconstruction.

Sample Number	Mineral	Latitude	Longitude	Previous Paleodepth* km	Recalculated Paleodepth km	Temperature °C
H90 To-11	apatite	N 33°03´03´´	W 111°03´54´´	5.9 ± .3	4.2	110 ± 10
H90 To-15	zircon	N 32°59´15´´	W 111°06´44´´	12.1 ± 1.0	9.0	220 ± 30
Surface				<1.5	0	15 ± 10

Table 6. Recalculation of the geothermal gradient using new palinspastic reconstruction.

Calculation	Δ °C	Δ Paleodepth Previous	Previous Geothermal Gradient °C km^{-1}	Δ Paleodepth Recalculated	Recalculated Geothermal Gradient °C km^{-1}
1	110	6.2	17.1 ± 5.3	4.8	22.9
2	95	5.9	16.7 ± 4.9	4.2	25.0
Final Estimate			17 ± 5		24

APPENDIX 1

U-Pb dating of zircons from porphyry dikes was conducted to better constrain the timing of the intrusive and hydrothermal history of the Tea Cup porphyry system (Figs. 1-4). Standard methods of sample preparation were employed, using crushing, pulverizing, mineral separation, and cathodoluminescence (CL) imaging (Seedorff, in press. The multiple-collector laser-ablation inductively coupled plasma-mass spectrometry (MC-LA-ICP-MS) method was used for U-Pb geochronology of zircons at the Arizona LaserChron Center at the University of Arizona (Gehrels et al., 2006; Gehrels and Ruiz, in review). The method involves spot analyses of single grains and simultaneous measurement of U, Th, and Pb isotopes.

Fig. 1 Graph of zircon sample ages from sample SP 100

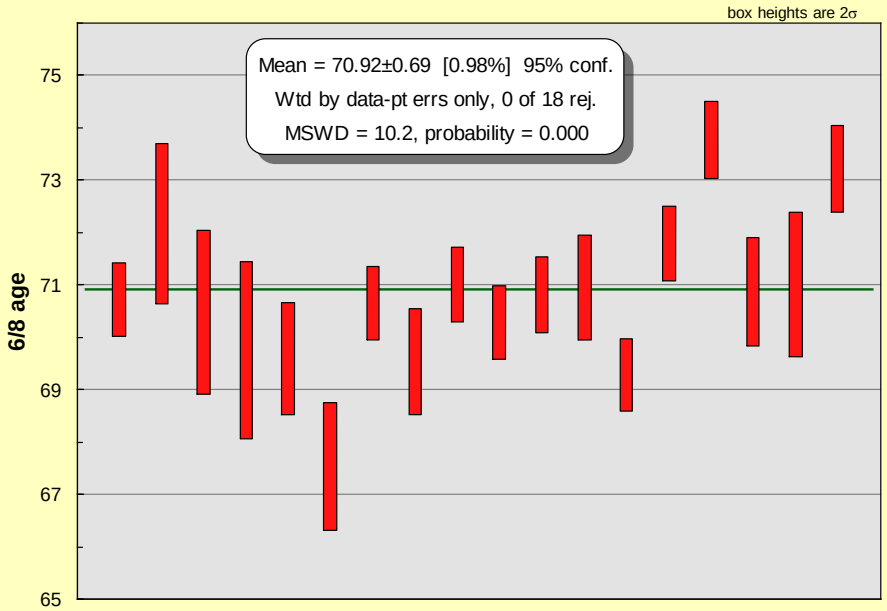


Fig. 2 Graph of zircon sample ages from sample SP 101

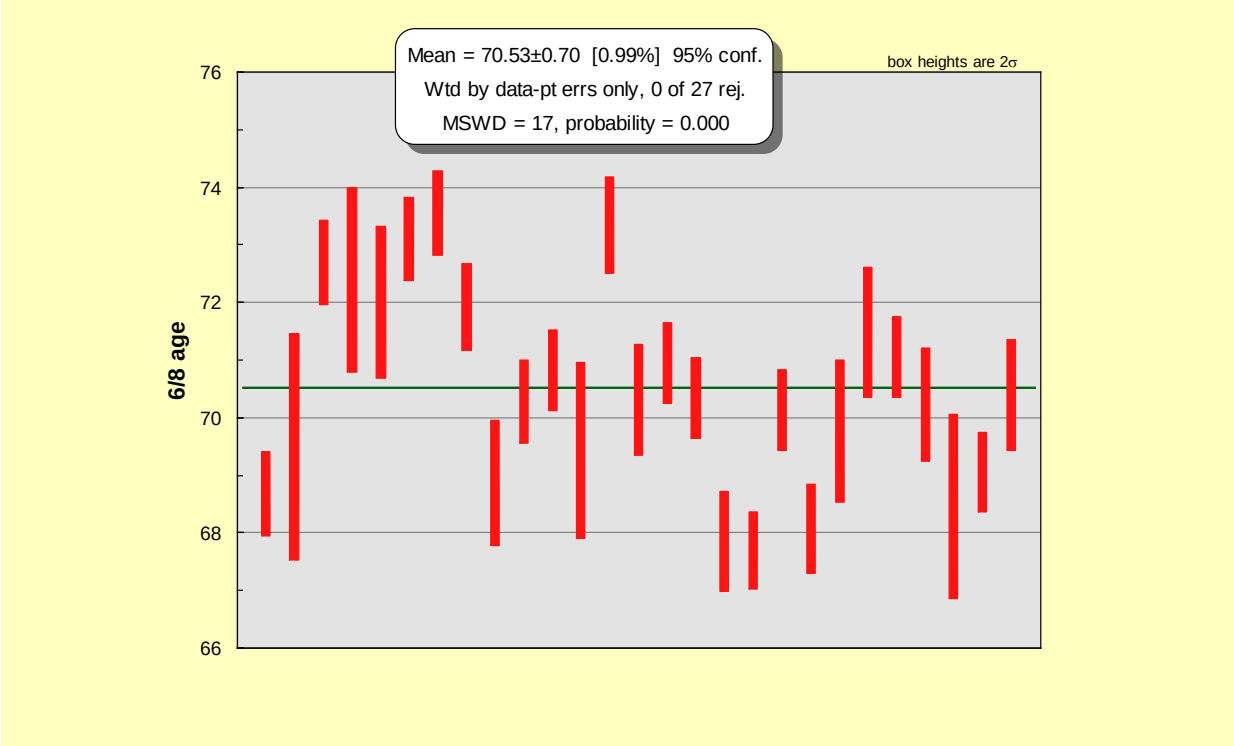


Fig. 3 Graph of zircon sample ages from sample SP 103

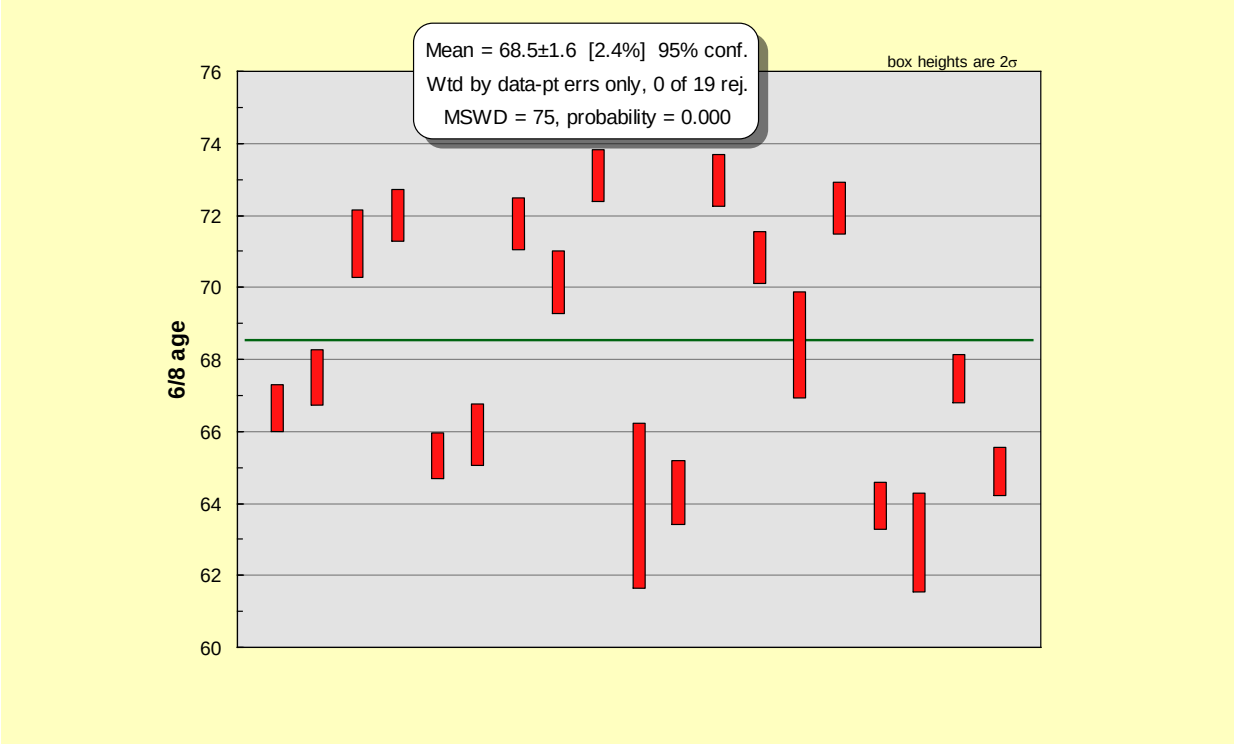
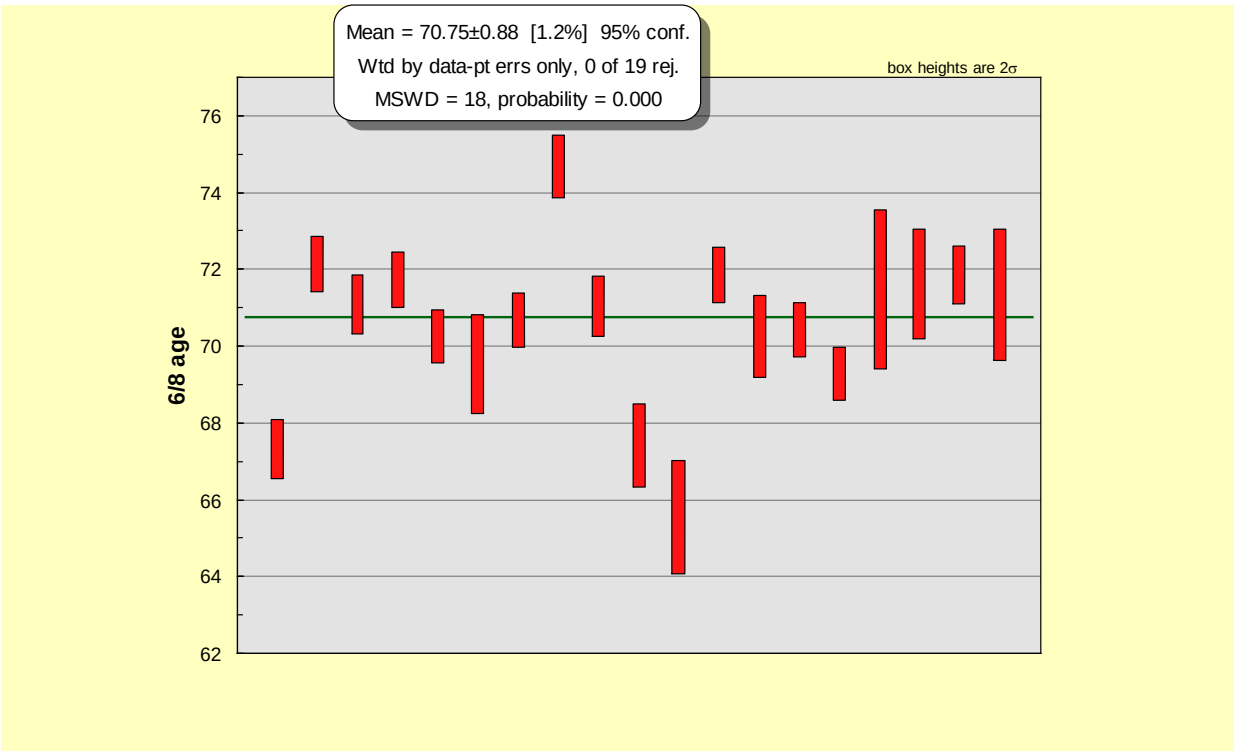


Fig. 4 Graph of zircon sample ages from sample SP 103



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Gehrels, G.E., Valencia, V.A., and Pullen, A., 2006, Detrital zircon geochronology by Laser-Ablation Multicollector ICPMS at the Arizona LaserChron Center, *in* Loszewski, T., and Huff, W., eds., Geochronology: Emerging Opportunities, Paleontology Society Short Course: Paleontology Society Papers, v. 11, 10 p.

Gehrels, G.E., and Ruiz, J., in review, U-Th-Pb geochronology by Laser Ablation Multicollector ICP Mass Spectrometry at the Arizona LaserChron Center: Journal of Analytical Atomic Spectrometry.