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Final Technical Report

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Project title: Dismembered Laramide porphyry deposits in southern Arizona

Purpose

This document serves to document the key results and products developed during this project, and serves as the formal final report for the project. The project resulted in a model of the roots of porphyry copper systems based on dismembered systems in areas of major post-ore crustal extension, and it is pointing toward a new model of how the crust extends by superimposed sets of normal faults.

The document summarizes the oral presentations that have been given to disseminate some of the results, the major paper and thesis that have resulted to date from the project, and the status of other aspects of the study that we expect to publish subsequently. The principal results are a paper in *Economic Geology*, in which the PI is the lead author, and an M. S. thesis by a graduate student.

Oral presentations

We have disseminated results at four talks. I presented a new model for the origin of Cordilleran metamorphic core complexes at the annual meeting of the Geological Society of America in Philadelphia, Pennsylvania, Sunday 22 Oct 2006, in a well-attended theme session on “Unraveling tectonics: The power behind balanced cross sections and kinematic reconstructions” (Seedorff, 2006).

I presented a preliminary interpretation of the origin of the Catalina core complex, including stepwise structural reconstructions and new findings regarding the distribution of alteration-mineralization in the area, to a large, lively audience of industry, government, and academic geologists at the 1 May 2007 meeting of the Arizona Geological Society (Seedorff, 2007a).

I gave a similar talk at the international symposium on "Ores and Orogenesis: Circum-Pacific Tectonics, Geologic Evolution, and Ore Deposits" in late September 2007 in Tucson (Seedorff, 2007b). The symposium, which honored the career of Bill Dickinson, was sponsored by the Arizona Geological Society and co-sponsored by the U. S.

Geological Survey, the Society of Economic Geologists (SEG), the Geological Society of Nevada (GSN), and the Society for Mining, Metallurgy, and Exploration (SME). This meeting was attended by many of our customers for this project, who are government policy makers, land managers, economic geologists and structural geologists in government, academia, and industry. The talk was given to a packed room and sparked lively discussion afterward.

Alex Strugatskiy, the graduate student who completed an MS thesis in the Happy Valley area on the southeastern side of the Catalina core complex , presented the preliminary results of his thesis work as an oral presentation in April 2008 with abstract (Strugatskiy, 2008a) at the GeoDaze Geoscience Symposium, a student research symposium at University of Arizona that is attended by students, faculty, alumni, and other members of the southern Arizona geological community. Alex made a solid presentation that clearly engaged the audience, which judges rated as the best talk of his session and garnered him a cash award.

Manuscripts and Thesis

Major paper: A principal product of the project was the full-length paper "Root zones of porphyry systems—Extending the porphyry model to depth" was published in *Economic Geology* in 2008 (Seedorff et al. 2008). This publication was based on work in this project and on our other recent work in the region and was anticipated to be a deliverable for this project in the proposal. The paper draws information from six porphyry deposits in Arizona and Nevada that are exceptionally well exposed over a great vertical depth because of post-ore extensional faulting and associated tilting. This work provides an update on the porphyry copper model, focusing on alteration and mineralization features that are present at deep levels beneath the orebody (Fig. 1), from where many of the ore components must have originated. In particular, we highlight the importance of greisen muscovite alteration and sodic-calcic alteration and their possible significance.

All six systems occur in areas with unusually large exposures in both the lateral and vertical paleodirections (locally to paleodepths of >10 km). No two systems are alike, but many share the presence of the following hydrothermal characteristics (Fig. 1): quartz veins and potassic alteration, sodic-calcic and sodic alteration, calcic alteration, and relatively coarse grained muscovite-quartz (greisen). Quartz veins and potassic alteration are focused centrally, directly above related cupolas; sodic-calcic and sodic alteration, calcic alteration, and evidence for leaching of silica are observed on the deep flanks of certain systems; and greisen occurs directly beneath ore within and beneath coeval cupolas in many systems. Certain systems exhibit evidence of multiple cycles of release of magmatic fluid followed by incursion of saline ground waters, which are analogous to the biological cycle of exhale-inhale, respectively.

In many respects, the study resulted in more new questions than answers, but the characteristics of the root zones do provide important constraints on the exsolution and transport of the magmatic aqueous phase that leads to ore formation, the variable incursion of external fluids into the hydrothermal system marked by sodic-calcic alteration, and the degassing of magmatic volatiles that may not be related directly to porphyry ore formation as marked by formation of muscovite greisen. The results offer implications for mineral assessment studies and provide ways in which the characteristics of the root zones can be used to vector toward exploration targets in higher levels of the system.

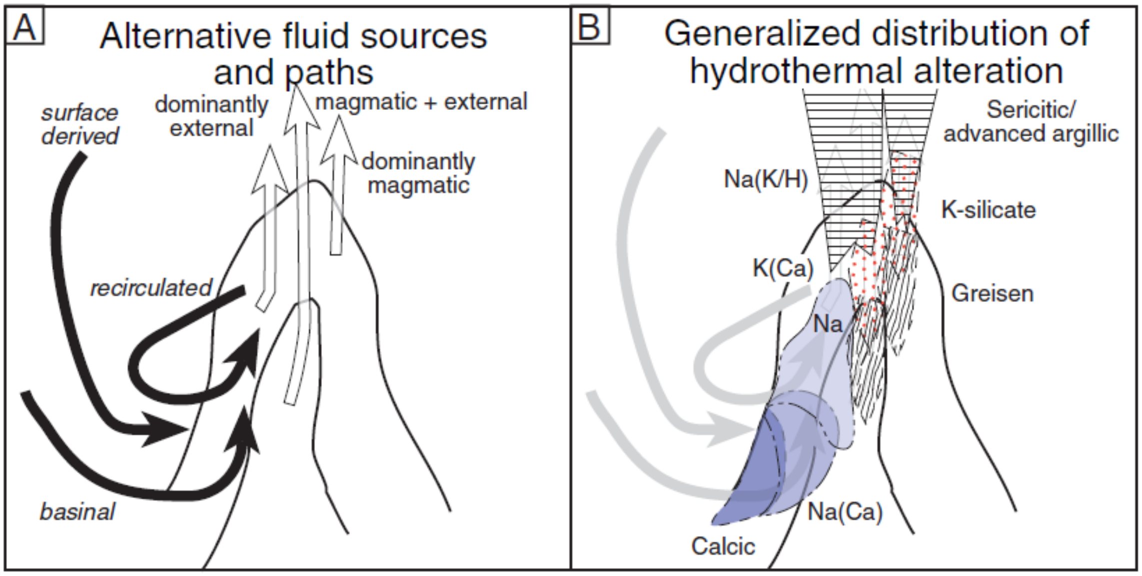

Figure 1. Model of fluid circulation and alteration in the root zone of a porphyry system (from Seedorff et al., 2008).

The paper lays the groundwork for interpreting features observed in the Chirreon Wash pluton in the Tortolita Mountains, which we have speculated may be the roots of the San Manuel-Kalamazoo system. We made reconnaissance investigations in the Chirreon Wash pluton and sampled it during this study, and this area is part of our continuing work in the area, which will be appropriately acknowledged in future publications.

M. S. thesis: Another principal product of the project was the completion of the Master's thesis project by Alex Strugatskiy, "Structural reconstruction and reinterpretation of the area near Happy Valley, Little Rincon Mountains, southeastern Arizona." Strugatskiy joined the project as an intern prior to his beginning course work, when he Alex assisted me in scanning existing geologic maps and constructing cross sections. We jointly made geologic traverses in many parts of the area, during which we collected samples for geobarometry (see below), which led to the selection of his thesis project.

Alex presented the results as an oral presentation with abstract in April 2008 (Strugatskiy, 2008a) and then completed the thesis in December 2008 (Strugatskiy, 2008b). His work was supported by a Research Assistantship funded by this project. Strugatskiy spent two months mapping, making an original map at a scale of 1:12,000 of a 15-km^2 area immediately northeast of Happy Valley (Fig. 2). In addition, he mapped several smaller areas within a broader region that extends from the Little Rincon Mountains, across the

San Pedro Valley, and into the Galiuro Mountains and Johnny Lyon Hills, as part of developing a regional structural synthesis of a larger area (~100 km^2), resulting in a map at a scale of 1:24,000 (Fig. 3). He then made three regional-scale cross sections through the area and then made a stepwise restoration of the Tertiary normal faults for each of the three cross sections.

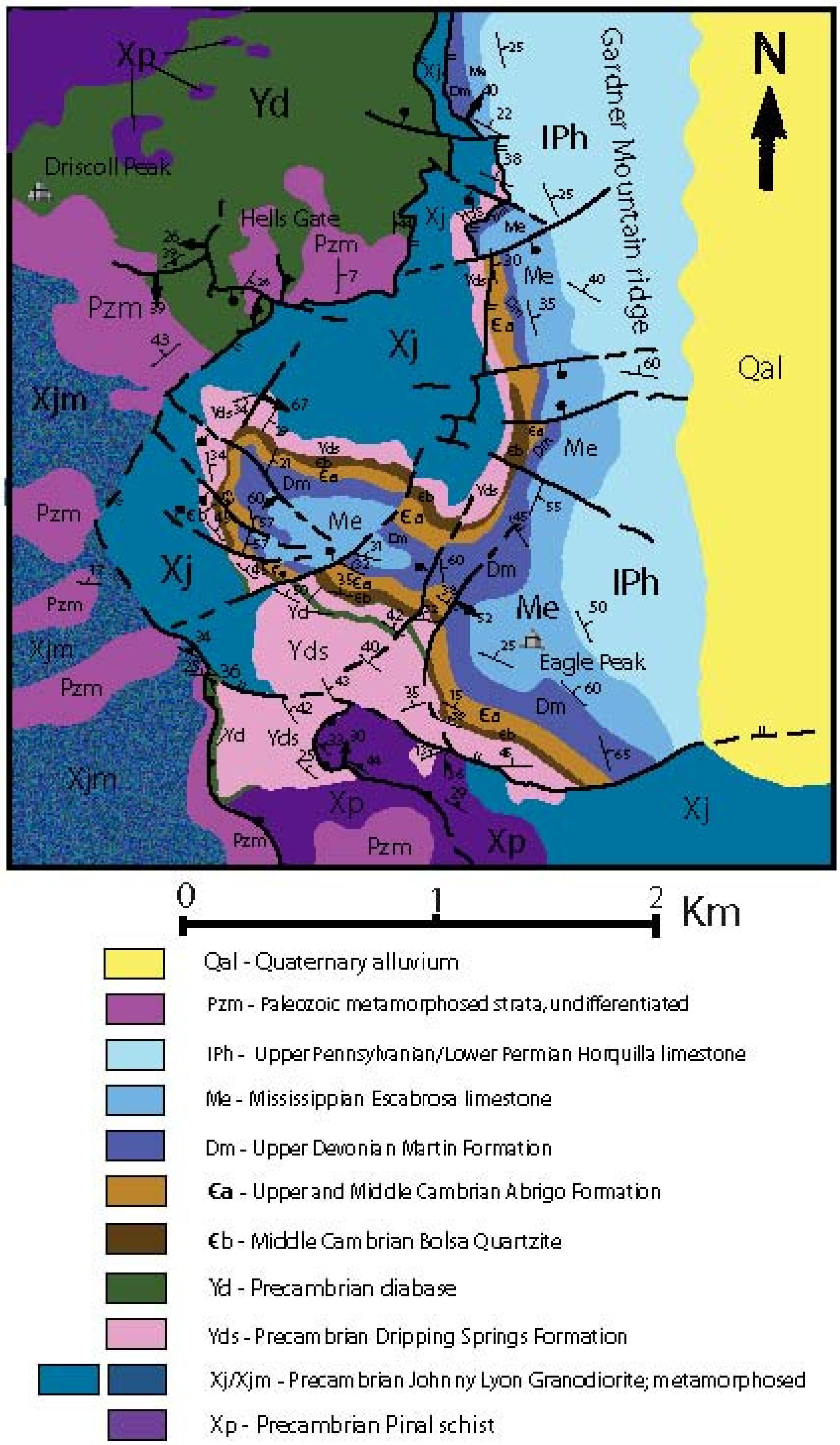

Figure 2. Detailed geologic map of an area near Happy Valley (from Strugatskiy, 2008b).

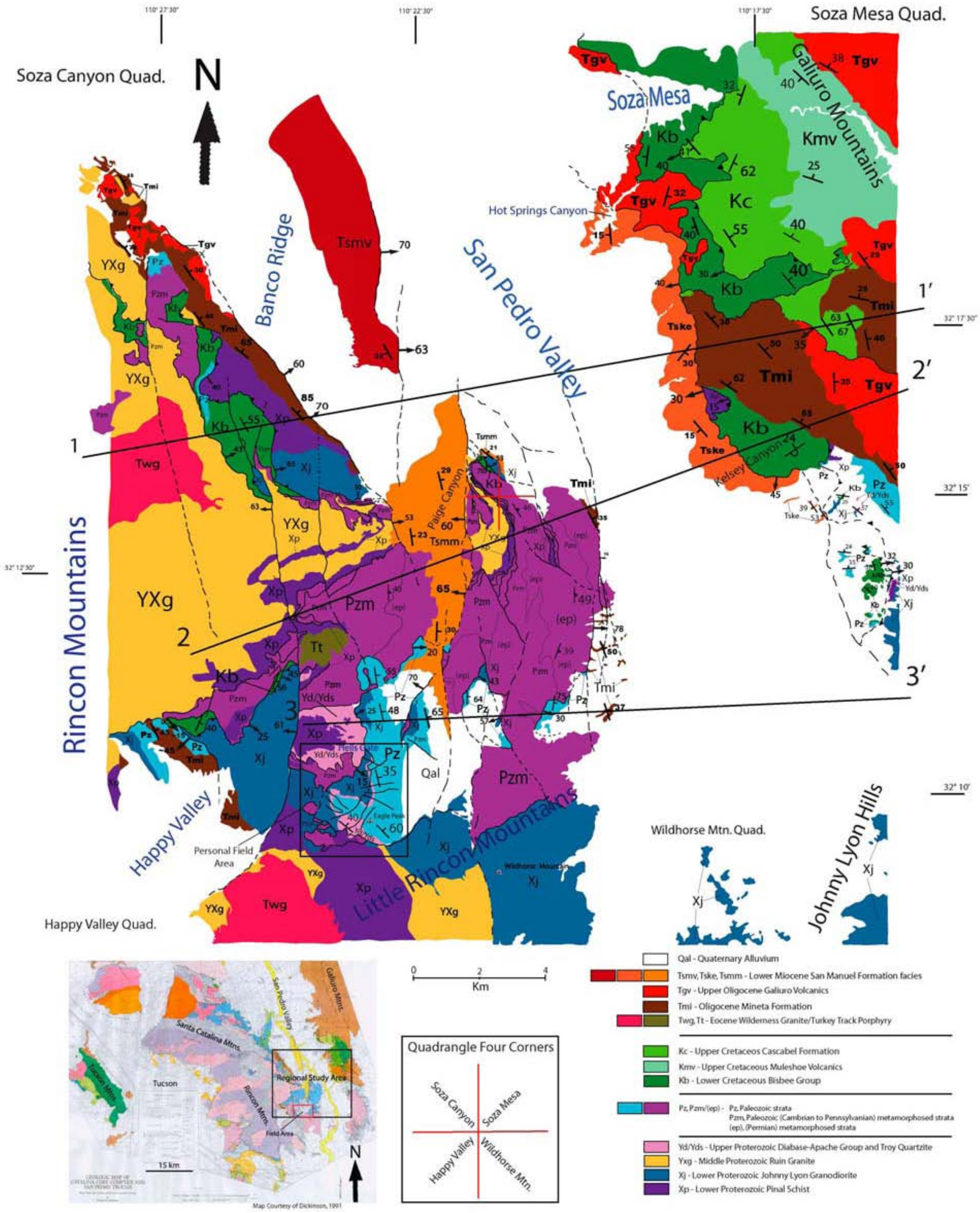

Figure 3. Geologic map of the greater study area with locations of three regional cross sections (from Strugatskiy, 2008b).

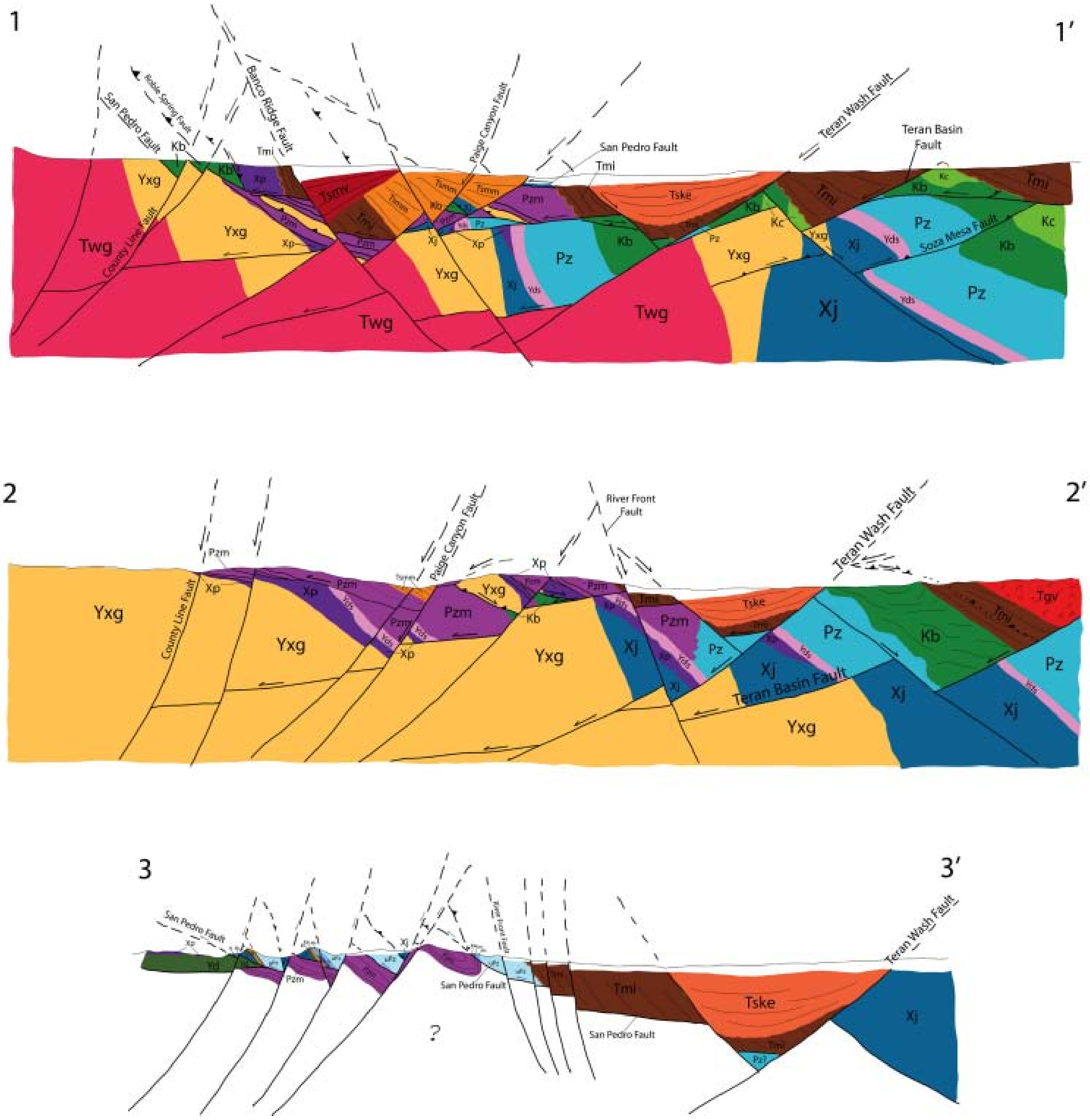

Figure 4. Three geologic cross sections, with locations shown in previous figure (from Strugatskiy, 2008b).

Strugatskiy (2008b) documented that the broader area contains at least five generations of approximately north-south striking normal faults, with both easterly and westerly dips, in which the biggest fault has ~3 km of slip. These faults make for an exceptionally complicated geologic map. These faults are responsible for 50% of extension east of the San Pedro Valley and as much as 190% in parts of the western side of the region. Together, the faults have exposed the entire stratigraphic section from Precambrian granite on the west near the Rincon Mountains to Tertiary sedimentary rocks east of the San Pedro Valley. The mid-Tertiary Mineta Formation presently dips 50-90° to the east, which is a measure of the net tilting of the area. Reconstructions show that an early generation of normal faults crops out as low-angle, east-dipping, overturned normal faults, which previously have been mapped as the San Pedro detachment faults. By reconstructing the Mineta Formation to horizontal, this generation of normal faults upon inception would have originally dipped 50-60° to the west. The Laramide reverse faults on the western side of the San Pedro Valley, which presently dip eastward, restore to westward dips of 20-50°. These attitudes are consistent with the vergence of Laramide faults and presence of Laramide foreland clastic rocks in the eastern side of the study region.

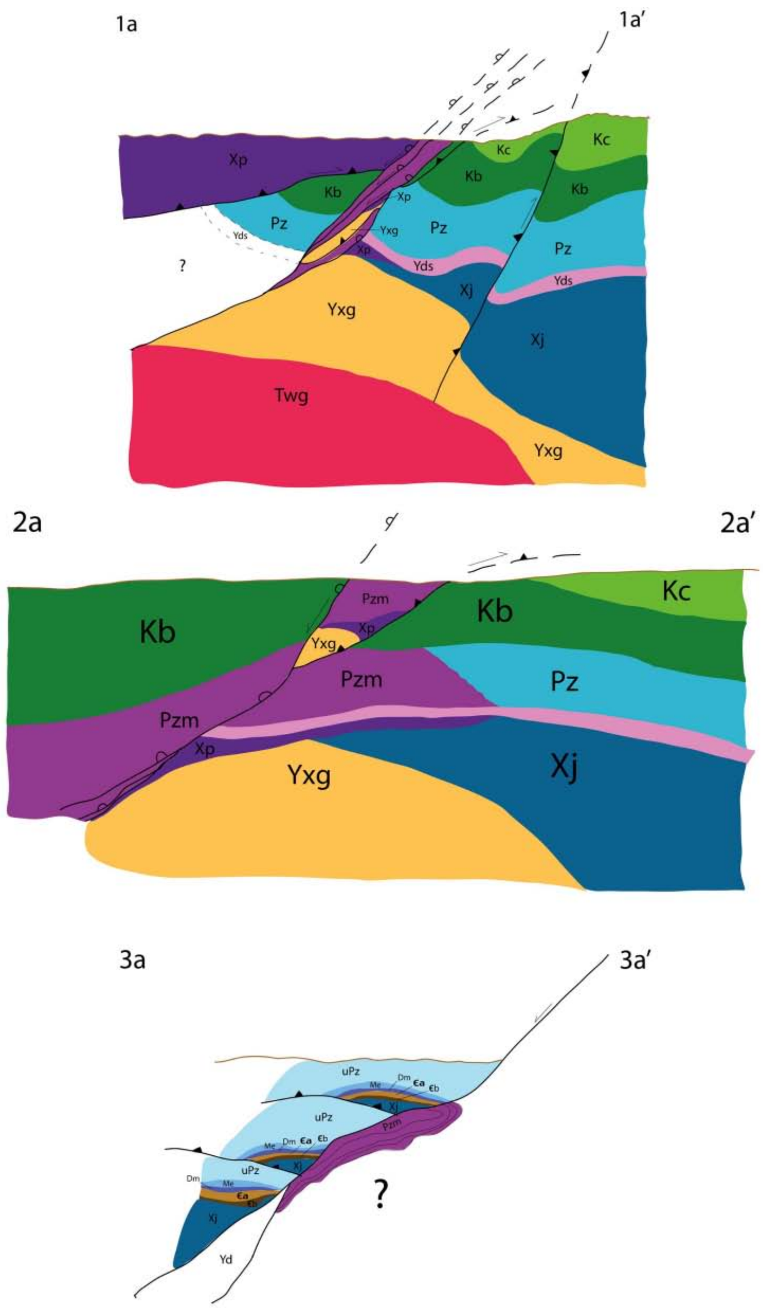

Figure 5. Palinspastically restored versions of the cross sections shown in the previous figure (from Strugatskiy, 2008b).

The balanced reconstruction of this area begs reevaluation of the detachment model as it has been applied to the area near Happy Valley and provides new insights into post-Laramide geology at the time of development of the mid-Tertiary erosion surface. Although Strugatskiy (2008b) was written as a prepublication manuscript, we decided that the manuscript is not suitable for a stand-alone publication as-is, and we intend to incorporate the results in a paper that addresses the larger issue of a structural reconstruction of the Catalina core complex, in turn leading to a new model for structural extension and the origin of metamorphic core complexes..

I have part of a draft of a manuscript regarding the new model for core complexes for crustal extension in a journal of wide distribution, such as *Geology* or *Science*. It became clear to me, however, that it was important to marshal additional evidence from other areas to use in this manuscript—specifically from my work in the Robinson district in east-central Nevada, another area of devilishly complicated normal faulting. I made a concerted effort to solve the geologic problems at Robinson last spring and am close to having something that can be used in this paper. This manuscript remains a major goal of mine, and funding from this project will be acknowledged

Regional geologic map and cross sections

We are compiling a new geologic map of a region that encompasses the Catalina Cordilleran metamorphic core complex and surrounding areas in the greater Tucson area of southern Arizona. The study area includes the classic, albeit structurally controversial, porphyry copper locality at San Manuel-Kalamazoo and a number of other prospects and newly recognized altered areas. We have scanned the existing geologic maps and have draft compilation maps over most of the area in a mix of mylar overlays and electronic versions at 1:24,000 scale, showing rock types and structure. We have incorporated the results of our reconnaissance mapping at 1:24,000 in selected areas and geologic traverses in a number of areas, from the Oracle area in the northeast, to the Tortolita Mountains in the northwest, Rincon Valley in the south, and Johnny Lyon Hills in the southeast. We also have gathered information regarding alteration characteristics and sources of data.

The final compiled map will be presented at a scale of 1:48,000. We had planned to have the map completed and released by this time, but this part of the project is not complete. We are still committed to publishing an electronic map of the area. This project will be recognized as the principal funding source for that map.

Building on the regional compilation effort, we have drawn 11 cross sections and 3 long sections at scales ranging from 1:24,000 (same as topographic and certain geologic quadrangles) to 1:125,000 (same as map of Dickinson, 1991), although the final scale of all cross sections will be 1:48,000. In part as a result of this work, I have developed a new model for the origin of Cordilleran metamorphic core complexes (Seedorff, 2006).

In the northern part of the area, there are numerous sets of normal faults with both down-to-the-east and down-to-the-west sense of displacement. We have drawn six cross sections that are roughly parallel to the direction of structural transport at a scale of 1:24,000 (sections A, B, C, X, Y, Z) through the Tortolita Mountains, the northern tip of the Santa Catalina Mountains, the Black Hills, the San Pedro Valley, and the Galiuro Mountains. The cross sections are intersected nearly at right angles by three “long” sections (sections U, V, W) at the same scale (the “long” sections are actually shorter than the cross sections).

We have attempted several structural reconstructions, but we are still refining many of the sections further. We still maintain that the Chirreon Wash granodioritic pluton in the Tortolita Mountains, the porphyry copper prospect in Little Hill mine area in the northwestern corner of the Santa Catalina Mountains, and the Kalamazoo and San Manuel porphyry copper deposits in the Black Hills may be dismembered products of the same magmatic-hydrothermal system. In other words, the Chirreon Wash pluton may be the roots of both the Little Hill prospect and the San Manuel-Kalamazoo deposits, which is consistent with the existing U-Pb geochronology (Seedorff, 2007a).

Further to the south, we have drawn five cross sections at a scale of 1:125,000 from the Santa Catalina, Rincon, and Little Rincon Mountains on the west to the Galiuro Mountains and Johnny Lyon Hills on the east: sections CFR (for Catalina Fore Range), Kb (linking a series of exposures of Cretaceous Bisbee Group), Xj (linking a series of exposures of Proterozoic Johnny Lyon Granodiorite), Italian Trap, and Rincon Valley. In our interpretations, the Italian Trap and Rincon Valley cross sections both have seven sets (or generations) of normal faults, each of which initiated at high angles (~60°). We have made a series of stepwise restorations of the latest six generations of normal faults for both sections, which represent ~240% total extension (Seedorff, 2007a, b).

Hornblende barometry

In our original proposal, we planned to develop controls on paleodepth in the crystalline rocks that yield no stratigraphic constraints using hornblende barometry, which would aid structural reconstructions and potentially reveal cryptic faults in areas of homogeneous rock type or poor exposure. As we noted in the interim project report near the end of the first year of work, this proved to be largely unproductive because of the absence of sufficiently fresh samples of the target rocks, i.e., the degree of hydrothermal alteration, even at deep structural levels, is far greater that previously reported.

As we discussed earlier, we made geologic traverses through the following areas collecting samples (with principal associated hornblende-bearing intrusive rock type) for hornblende barometry: (1) Samaniego Ridge, Santa Catalina Mountains (Catalina Granite); (2) Rincon Valley (Johnny Lyon Granodiorite); (3) Johnny Lyon Hills (Johnny Lyon Granodiorite); (4) Tortolita Mountains (Chirreon Wash Granodiorite); and (5) The Narrows area of the western San Pedro Valley (Johnny Lyon Granodiorite). Part of this work led to the selection of the area mapped by Strugatskiy (2008b). We collected about 40 samples from these sites, and we examined polished thin sections returned from three of the five areas, with the goal of doing electron microprobe analyses of hornblende and feldspars for the purpose of determining the depths of emplacement of the various rocks.

The hornblende barometry method is applicable only to fresh hornblende-bearing rocks of the appropriate igneous mineral assemblage (Anderson and Smith, 1995), so only those samples that have fresh igneous grains in thin section should be analyzed. The plutonic rocks, however, are intensely hydrothermally altered in many of the areas we examined (in many cases there was no point in sampling for barometry). The alteration observed includes intense biotitic alteration with trace copper occurrences, as well as intense chlorite- and epidote-bearing alteration with relative few sulfide or oxide minerals. Although these are clues to potential new mineral occurrences, they inhibit our ability to do geobarometry. We initially postponed the inception of microprobe analysis to continue searching for fresh rocks, but proved unrealistic.

Funding expended

The budget for the project was $25,173 in Year 1 and $58,988 for Year 2, for a total of $84,160. The spending for the project was essentially on budget, with total expenditures of $84,160.95. The main expenses were wages for the graduate student (RA and summer support), supplemental pay for the PI, and related expenses of $56,158.23 (vs. a budget of $54,235). Indirect charges totaled $26, 926.33 (virtually on budget). Other categories were all budgeted for $3000 or less each.

We utilized other funding sources to pay for some travel, polished thin sections, and other supplies.

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