FINAL REPORT FOR SCEC PROJECT # 12093

Pat Williams

Resolving a 14ka slip-rate, Coachella Valley segment, San Andreas fault

Coachella San Andreas Projects supported by SCEC 12093 funds:

1. *SCEC collaboration for testing and development of structure-from-motion techniques for fault mapping by low altitude aerial photography with K.* Johnson, E. Nissen, S. Saripalli, R. Arrowsmith, P. McGarey, K. Scharer, and K. Blisniuk.
2. *SCEC collaboration for evaluation of Slip Rate with K. Blisniuk, and K. Scharer.*
3. *SCEC Collaboration for evaluation of vertical deformation within the Indio Hills, San Andreas Fault, California with K. Scharer, K. Blisniuk, W. Sharp, and K. Johnson.*
4. *Mapping recent geomorphic offsets to evaluate slip per event, San Andreas Fault, Coachella Valley, Contribution to UCERF3, P. Williams.*
5. *Evaluation of fault structure and interaction across the Indio Hills, San Andreas and Banning faults, P. Williams.*

Abstract:

This project began as the evaluation of an alluvial fan offset by the San Andreas in the southern Indio Hills of Coachella Valley (see proposal 12093). In subsequent discussions, colleagues expressed doubt on the context of the site, and the primary project was put on hold. After discussion with SCEC leadership, the focus of the project was redirected to support ongoing fault study efforts in the Coachella Valley. Three of these supported projects are continuation of my own work: slip-per-event interpretations from geomorphic evidence, structural interpretation of the San Andreas –Banning fault connections through the Indio Hills, and detailed work to evaluation an apparent very long term displacement record just north of Thousand Palms Canyon in the Indio Hills. SCEC collaborations during the period of this project included assisting Katherine Scharer and Kim Blisniuk with field work to support total deformation evaluations for the southern San Andreas fault, and guiding a demonstration of Structure-from-Motion data collection at two study sites: southern Mecca Hills and north of Thousand Palms Oasis. Summaries of these projects reference meeting abstracts (project 1, 2 and 3), a manuscript in preparation (project 4), a meeting abstract (project 5), and manuscript materials (project 6).

Project 1. Rapid mapping of ultrafine fault zone topography with structure from motion

Johnson, K., **Nissen, E.,** Saripalli, S., Arrowsmith, J. R., McGarey, P, Scharer, K., Williams, P., and Blisniuk, K., (Paper abstract from *Geosphere, 2014*)

Structure from Motion (SfM) generates high-resolution topography and co-registered texture (color) from an unstructured set of overlapping photographs taken from varying viewpoints, overcoming many of the cost, time, and logistical limitations of Light Detection and Ranging (LiDAR) and other topographic surveying methods. This paper provides the first investigation of SfM as a tool for mapping fault zone topography in areas of sparse or low-lying vegetation. First, we present a simple, affordable SfM workflow, based on an unmanned helium balloon or motorized glider, an inexpensive camera, and semi-automated software. Second, we illustrate the system at two sites on southern California faults covered by existing airborne or terrestrial LiDAR, enabling a comparative assessment of SfM topography resolution and precision. At the first site, an ~0.1 km^2 alluvial fan on the San Andreas fault, a colored point cloud of density mostly >700 points/m^2 and a 3 cm digital elevation model (DEM) and orthophoto were produced from 233 photos collected ~50 m above ground level. When a few global positioning system ground control points are incorporated, closest point vertical distances to the much sparser (~4 points/m^2) airborne LiDAR point cloud are mostly <3 cm. The second site spans an ~1 km section of the 1992 Landers earthquake scarp. A colored point cloud of density mostly >530 points/m^2 and a 2 cm DEM and orthophoto were produced from 450 photos taken from ~60 m above ground level. Closest point vertical distances to existing terrestrial LiDAR data of comparable density are mostly <6 cm. Each SfM survey took ~2 h to complete and several hours to generate the scene topography and texture. SfM greatly facilitates the imaging of subtle geomorphic offsets related to past earthquakes as well as rapid response mapping or long-term monitoring of faulted landscapes.

Project 2 Vertical deformation along the Indio Hills, San Andreas Fault, California *with K. Scharer, K. Blisniuk, W. Sharp, K. Johnson* (meeting poster AGU 2014 and SCEC 2014)

Halfway between the Salton Sea and San Gorgonio Pass, the southernmost San Andreas Fault (SAF) bifurcates into the Mission Creek and Banning strands. These strands bound the Indio Hills (IH), and mark the first of a series of left-stepping branches that define the transpressional, southern Big Bend of the SAF. Between the fault strands, the Quaternary Ocotillo Formation is deformed with fold axis orientations consistent with dextral shear; structurally the IH are synclinal in the east, transitioning to a complex antiform with increased uplift suggested by exhumation of Tertiary units in the west. We report new long- and short- term erosion rates across the IH and uplift rates on the Banning strand, and we evaluate these measurements in terms of slip rates across the fault system and structural deformation within the IH. Two methods of catchment-averaged erosion rates provide minimum rates yield similar results, (0.08 to 0.34 mm/yr) across 6 catchments. The long-term rates are calculated from eroded volumes estimated from a 10-m DEM surface enveloping the Indio Hills and assume that all folding and uplift initiated ca. 500ka (the 750 ka Bishop ash is uplifted and warped within the IH). The short-term rates, determined from 10Be concentrations of fluvial sand, increase gradually to the northwest. Similarity of the rates suggests steady state uplift over the history of the fold; ongoing structural analysis and dating needed to constrain the maximum rates will test this possibility. The new uplift rate for the Banning strand at the east end of the IH is determined from a 60 pts/m^2 DEM produced by structure from motion photogrammetry and U-series ages and cosmogenic dates that provide an age range of 18-76ka for a fan vertically offset by ~2.5 m. The resulting uplift rate on the fault (0.03-0.13 mm/yr) overlaps with the short- term catchment-averaged erosion rate for this location (0.08 mm/yr). Consequently, we interpret that vertical strain is partitioned onto both the Banning fault and in uplift and folding of the IH. The uplift rates increase westward along the IH, possibly indicating increased activity on the Banning strand to the west. This pattern will be considered in the context of paleoseismic and horizontal slip rate studies in the region, and implications for rupture directivity on this hazardous fault system.

Project 3. *New geologic slip rate estimate for the Mission Creek fault zone.*
AGU, Fall Meeting 2013, abstract #T42A-01. With K. Blisniuk, K. Scharer, W. Sharp, R. Bürgmann, R., M. Rymer.

The potential for a large-magnitude earthquake (Mw ≥ 6.7) on the southern San Andreas fault zone (SAFZ) is generally considered high (Working Group on California Earthquake Probabilities, 2007). However, the proportion of slip accommodated by each of its three major fault strands (Mission Creek, Banning, and Garnet Hill, from north to south) in the Indio Hills is poorly constrained. Each of these strands cut through San Gorgonio Pass west to the Los Angeles metropolitan region. To better assess the relative importance of these faults and their potential for a major earthquake, we dated offsets at two sites on the Mission Creek fault in the central Indio Hills, an offset channel at Pushawalla Canyon and an offset debris cone at a small unnamed canyon located ~1.5 km farther southeast. Previous work on this strand at Biskra Palms, in the southern Indio Hills, demonstrated a slip rate between 12 and 22 mm/yr, with a preferred rate of 14-17 mm/yr (Behr et al., GSAB, 2010). It is generally assumed that the slip rate on the Mission Creek fault decreases northwestwards from Biskra Palms (e.g. Fumal et al., BSSA, 2002) towards these two sites in the central Indio Hills. However, our initial results from uranium-series dating of pedogenic carbonate and 10Be cosmogenic exposure dating of surface clasts from deposits offset 1.3-1.6 km since ~70 ka and 44-50 m since ~2.5 ka indicate that during the late Pleistocene and Holocene slip on the Mission Creek fault in the central Indio Hills has occurred at a relatively constant and unexpectedly high rate of ~20 mm/yr. Combined with published paleoseismic studies for the Mission Creek fault, which show an average earthquake recurrence interval of 225 years for the past 5 events since 900 AD (Fumal et al., 2002), these data imply an average slip-per-event of ~4.5 m. The last earthquake to rupture this section of the Mission Creek fault occurred over 300 years ago (ca. 1690), which indicates that ca. 5.0 to 7.5 m of strain may have accumulated since the last surface-rupturing event. While additional work is needed to better understand how slip along the SAFZ is partitioned in the northwestern Indio Hills, the new data underscore the seismic hazard posed by the Mission Creek fault in this region.

Project 4. *Mapping recent geomorphic offsets to evaluate slip per event, San Andreas Fault, Coachella Valley*, P. Williams

During the period of this project field work was completed for slip-per-event characterization along the southern 100 km of the San Andreas fault between Durmid Hill and Cottonwood Canyon. The SSAF is deemed the most likely fault in California to generate a large or great earthquake during the next 30 years. The high geologic and geodetic slip rate (ca. 20mm/a), quiescence of ~330 years and average recurrence interval of ~200 years, provide circumstantial evidence that the Coachella Valley segment (CVS) of the southern San Andreas fault has the largest characterized potential of any onshore fault in the United States to rupture in a large or great earthquake.

To better understand modern rupture potential, this work focuses on the displacement history of the Coachella Valley portion of the southern San Andreas fault (SSAF). Small-scale offsets of streams and stream margins have been examined. Slip curves derived from the geomorphic displacement record may be applied to modeling and forecasting of future rupture parameters and can disclose spatial and temporal variability in past behavior. The evidence can also be applied to the correlation of events between distant sites along a given fault and applied to testing of regional rupture scenarios. Prehistoric displacement parameters provide primary input for evaluation of fault energy release and strain rate.

Measured increments of geomorphic and stratigraphic offset are the sole means to recover objective displacement parameters for ancient fault ruptures (i.e. before the historic period). In a local example, stratigraphic displacement in the latest two CVS events was found indistinguishable at the Indio and Salt Creek sites, separated by 50 kilometers. The stratigraphic findings are consistent with geomorphic offsets in the surrounding areas, providing an important test and constraint for the geomorphic interpretation (Sieh, 1986; Williams, 1989; Sieh and Williams, 1990; this study). Stratigraphic offset evidence is preferable in that it can often be associated with radiometric event ages, however the stratigraphic method is challenged by a rarity of suitable sites. Unfortunately, young geomorphic offsets cannot be dated with sufficient resolution to associate them with individual earthquakes.[1] To make use of the geomorphic record we presume that a well-recorded set of local geomorphic offsets can be correlated with a complete set paleoseismic event ages. It is fortunate that the CVS has become relatively rich in event age studies. These studies indicate that five offsets occurred during the interval AD 800 to 1700. These age evaluations are being refined, but the consistency between well separated sites is relatively strong and provides a rich environment for developing long spatial - temporal models.

Consistent landform evaluation improves data quality and objectivity of results. A check list for field description is summarized in Table 1 and was used throughout the study:

GPS location
Site appearance - slope aspect, inherited landscape,
Fault location and complexity
Channel aspect to fault---angle of intersection: (high 65-90°) (moderate: 45-65°) (low 25-45°) (grazing <25°)
Fault location: A_F: Multiple, clear, local field evidence of fault location[2]. Fault trace interpreted to be simple and narrow. B_F: Field evidence strongly indicates location of fault, but exact location of active trace is interpreted from multiple permissive evidence. Fault may be branching, bending or wide.

C_F: Location permissive but not clear ("C_F" sites are not used in compiling slip curve).
Geomorphic fault offset: A_G: Consistent with well known fault location, good, uniform preservation; multiple consistent measurements, smaller reported uncertainties. B_G: Clearly offset by fault, projection of piercing lines to fault are longer, Interpreted across multiple traces; preservation moderate or non-uniform; preferred but non-unique interpretations are reported, reported uncertainties are larger. C_G: Offset may be apparent or biased by stream deflection against uphill-facing scarp, side-slope, or stream processes ("C_G" sites are not used in compiling the slip curve)
Stream incision (shallow 0.1 -0.5m) (shallow to moderate 0.5-1.0m) (moderate 1.0-1.5m) (significant >1.5m)

Prior surveys of CVS stream offsets focused on the latest 2-3 offsets and were conducted during 1978-1980 by Kerry Sieh (unpublished data), and continued during 1985-1987 by Williams (1989). The current mapping of fault offsets extended to larger offsets and benefited from a new set of low-altitude very-large-scale aerial photographs acquired for the project in 2005. All of the offset features were documented in the field.

Distinguishing fault creep in evaluation of offset features is an issue for all paleoseismic investigation in the Coachella Valley. Sieh and Williams (1990) presented evidence from several sites during historic and multiple post-seismic intervals for creep at rates of 2 to 4 mm/yr. It is not clear whether creep is a significant issue with respect to CVS moment release, WGCEP (2007) assigned an aseismic slip factor of 0.1 (10% aseismic) to the CVS. It is clear, however, that surface creep at rates of 4 or 5mm/yr over 330 years should be expected cause significant displacement, and presumably produce commonly observed offsets of 1 to 1.5m. Results of the study were contributed to the WGCEP UCERF3 evaluation of California fault rupture hazard analysis.

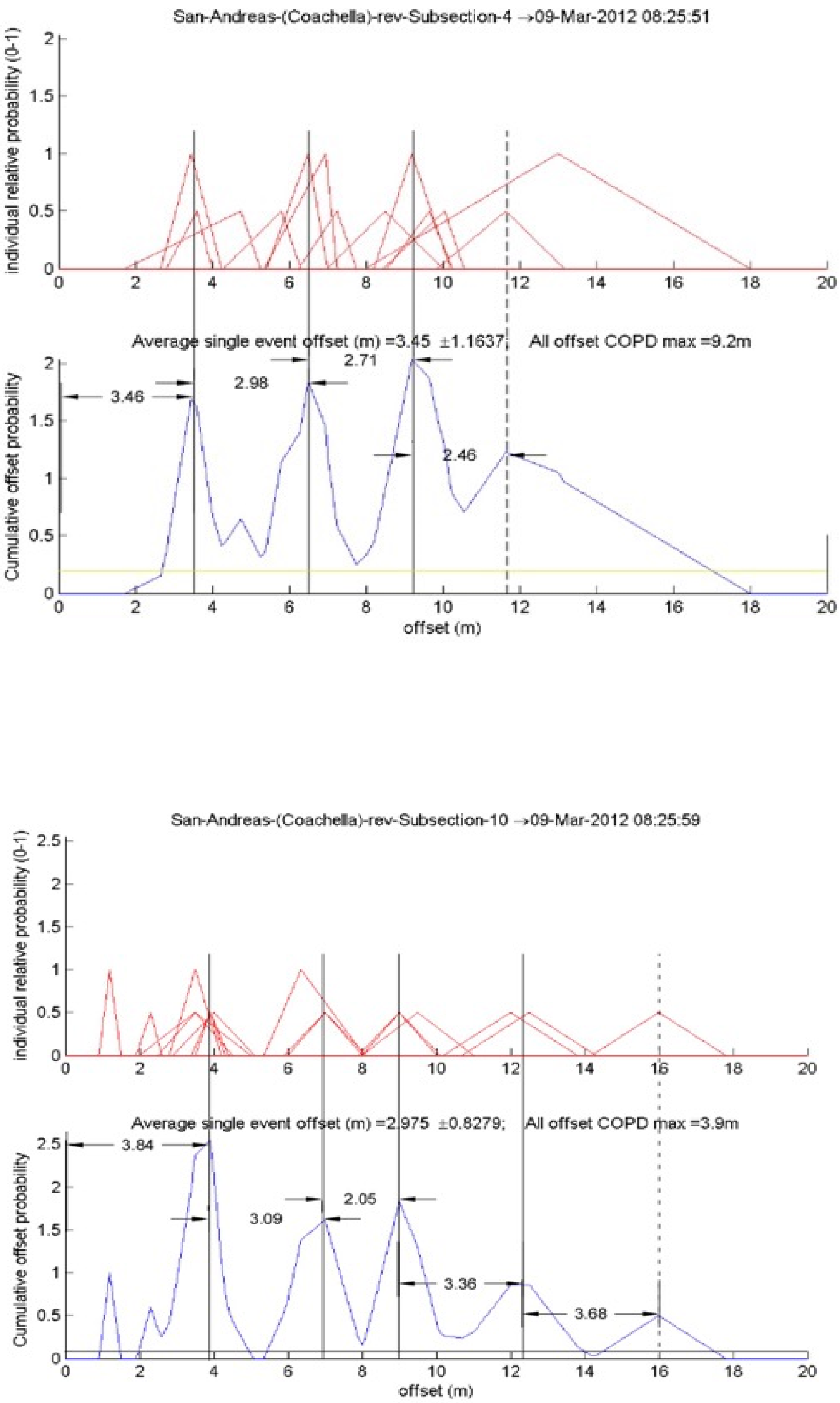

Figure 1. UCERF3 compilation of offset channel data indicates offsets of 3 to 4m in the past four fault ruptures. (Field, E.H., and 2014 Working Group on California Earthquake Probabilities, 2015, UCERF3: A new earthquake forecast for California's complex fault system: U.S. Geological Survey 2015–3009, 6 p., http://dx.doi.org/10.3133/fs20153009.

Project 5. *Evaluation of fault structure and interaction across the Indio Hills, San Andreas and Banning faults, P. Williams.*

The Banning and Mission Creek strands of the southern San Andreas fault zone (SSAFZ) bound the northern Indio Hills for a distance of ~23km in Coachella Valley. During the period of this grant mapping was carried out along each of the bounding faults to complete a survey of stream offsets and to attempt to evaluate the spatial pattern of interaction between these two fault strands in the northern Indio Hills. The new mapping helps clarify the context of other fault studies in this area particularly for the *Biskra fan* slip-rate site and the *Thousand Palms* paleoseismic site, and identifies the locus of transfer structures that are likely to participate in ruptures of the SSAFZ in Coachella Valley.

The Banning fault (BF) bounds the western margin of the northern Indio hills, striking 5–20 degrees more westerly than the Mission Creek fault (MCF - Figure 2). The faults diverge from their (projected) intersection near Biskra fan in the southern Indio Hills and continue northwestward towards the north end of Coachella Valley. Geomorphology and seismology clearly illustrate that an active BF crosses the valley north of the Indio Hills. The modern MCF, in contrast, is probably inactive north of the hills. Within the Indio Hills, this pattern appears to be reversed. That is, the MCF expresses distinctive evidence of ongoing surface slip across most of the hills, while the BF appears to be inactive or much less active south of Edom Hill (Figure 3).

Stream-offset mapping constrains a zone of northward-decreasing slip on the MCF, extending from Thousand Palms Oasis to Happy Valley. Similarly, slip decreases southward along the BF across the width Edom Hill (Figure 3). Geological mapping and structural reconnaissance locate and infer areas of folding, thrust faulting and transfer faulting between the MCF and BF (Figure 3). Oblique folds express greater shortening northward towards the center of the step-over (Figure 4). Activity of these structures is indicated by accumulation of stream offset across sinistral faults within the step-over. Synthesis of the displacement and structural evidence locates a zone of transpressional strain extending for ≥15 km across the northern Indio Hills (Figure 3). The transfer zone crosses from old geomorphic surfaces through areas of partial to profound dissection, presenting an outstanding opportunity for mapping and quantitative evaluation the step-over in cross section and plan view (Figure 4).

During the period of this project reconnaissance mapping was conducted across the area accommodating slip transfer between the two major faults. A set of active cross faults consistent with the kinematic evidence has located described in reconnaissance fashion. Fewer cross faults were found than expected, but the features that have been identified have clear and prominent evidence of fault displacement and probable ongoing activity.

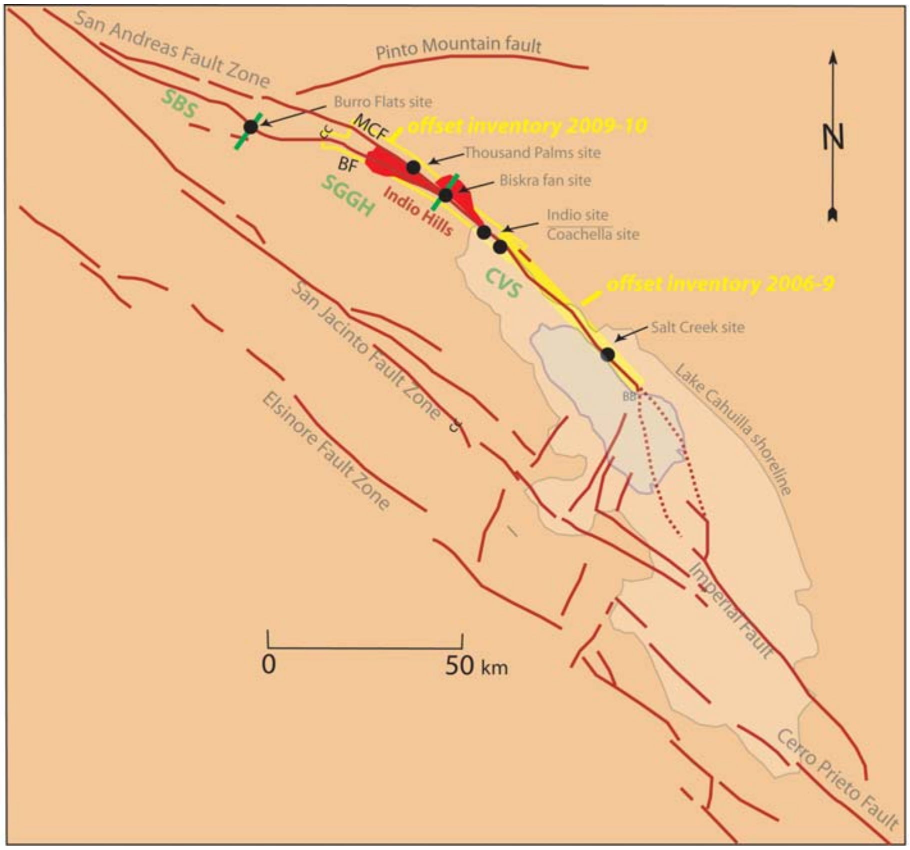

Figure 2. Location map for Banning fault (BF) and Mission Creek fault (MCF) with WGCEP (2007) fault segments: SBS = San Bernardino South section; SGGH = San Gorgonio-Garnet Hill Section; CVS = Coachella Valley Section extending from the Salton Sea (outlined in blue) to the Mission/Banning fault junction at Biskra Fan;. Yellow patterns indicate two phases of stream offset inventory. From Bombay Beach (BB) to the Indio Hills (solid); and continuing to Cottonwood Canyon (CC) The Indio Hills are shaded red. Cross faults between two San Andreas fault traces are contained in the area between the Thousand Palms site and the north end of the

Figure 3. Area of stepover in northern Indio Hills. MCF and BF are narrow white lines. Pattern of folding, thrust faulting and transfer faulting interpreted from reconnaissance, DEM imagery, air photos and mapping is shown by wide shaded lines. Transfer appears to be concentrated in the labled area, but may extend even farther than shown. Note locations of Biskra Fan Thousand Palms and Edom Hill.

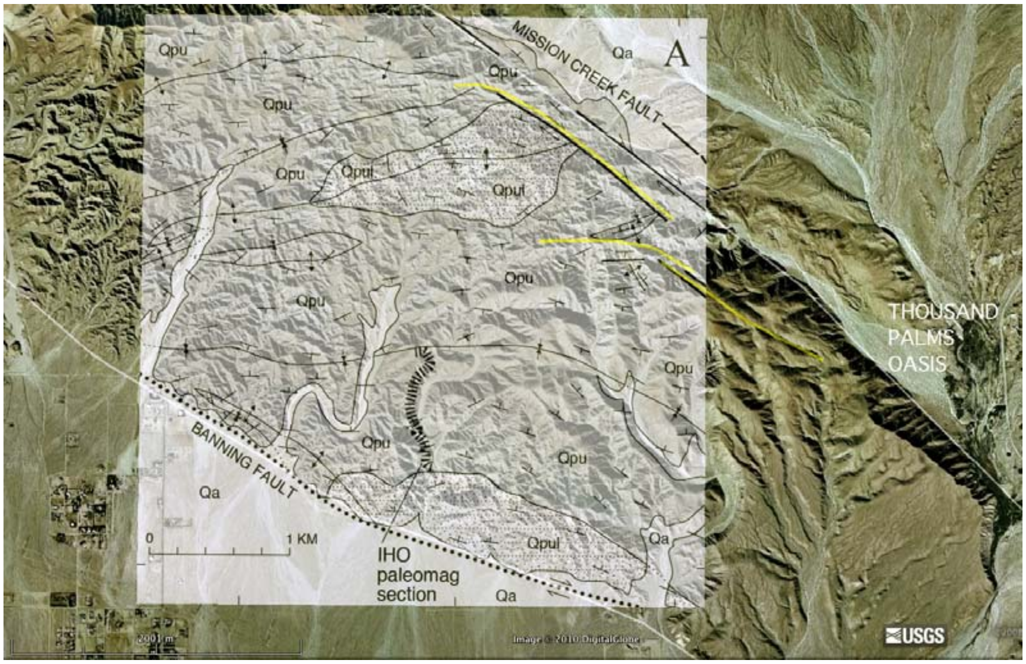

Figure 4. Previously published portion of of Rymer's Indio Hills map (simplified) superimposed on Google Earth photography. Note that fold limbs become progressively shorter and turn to a more oblique geometry northward. This supports an interpretation that shortening increases to the north with progressive strain transfer.