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Recent slip-per-event history, Coachella Valley Segment San Andreas fault

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Terrestrial and airborne LiDAR data, low altitude aerial photography and published maps have been utilized in conjunction with field work to systematically identify and map single and multiple-offset geomorphic sites along all strands of the San Andreas fault in the Coachella Valley. Central goals of the work are characterizing the full range of offsets associated with the fault's prehistoric surface ruptures, evaluating patterns of along-fault displacement, and disclosing of the mechanics and extent of the prominent Banning-Mission Creek fault junction. Fieldwork or this project is complete (one exception is discussed in below) for an inventory of small geomorphic offsets preserved along 55km of the San Andreas fault (SAF) between Indio and Cottonwood Canyon, Coachella Valley (CV), California (Figure 1). The study area includes a 45 km length of the Banning fault (B-SAF) from its origin near Biskra Palms (Indio Hills) to Cottonwood Canyon in eastern San Gorgonio Pass (SGP). An inventory of the Mission Creek fault (MC-SAF) extends 30 km north from "Terra Lago" golf course in Indio, California to the northern Indio Hills. While the primary goal of this project, presentation of a high quality, graphical slip-per-event profile for all branches of the SAF in CV remains in preparation, preliminary findings can be discussed here.

I. Evidence of "characteristic" rupture behavior has been investigated. The clearest findings of the study indicate a recent history of 3 to 4m offsets, thus essentially characteristic displacement behavior in recent time, but with indications of a bimodal history, as suggested by preliminary evidence of a few older, substantially larger offsets.

II. Evidence of large, probable "multi-segment" ruptures remain suggestive, but is expected to develop and become more robust as field evidence is compiled. Because multi-segment ruptures are expected to exhibit larger displacements within interior (middle) portions of the rupture profile (e.g. Wesnowsky 2008), paleo-slip evidence may also indicate that some CV ruptures extended north from CV to San Bernardino, perhaps farther. In preliminary inspection, the several most recent offsets do not appear to express simple "growth ramps" to the north. This may result, in part, from paucity of evidence to the north (between the Indio Hills and SGP). Because of the importance of this issue, efforts have continued beyond the period of this grant to resolve access for a 2km length of the fault near the Devers Southern California Edison substation between Hwy 62 and North Palm Springs. It is hoped that sufficient evidence can be extracted from the few good locales between the northernmost Indio Hills and Cottonwood Canyon to constrain slip profiles in the northern CV.

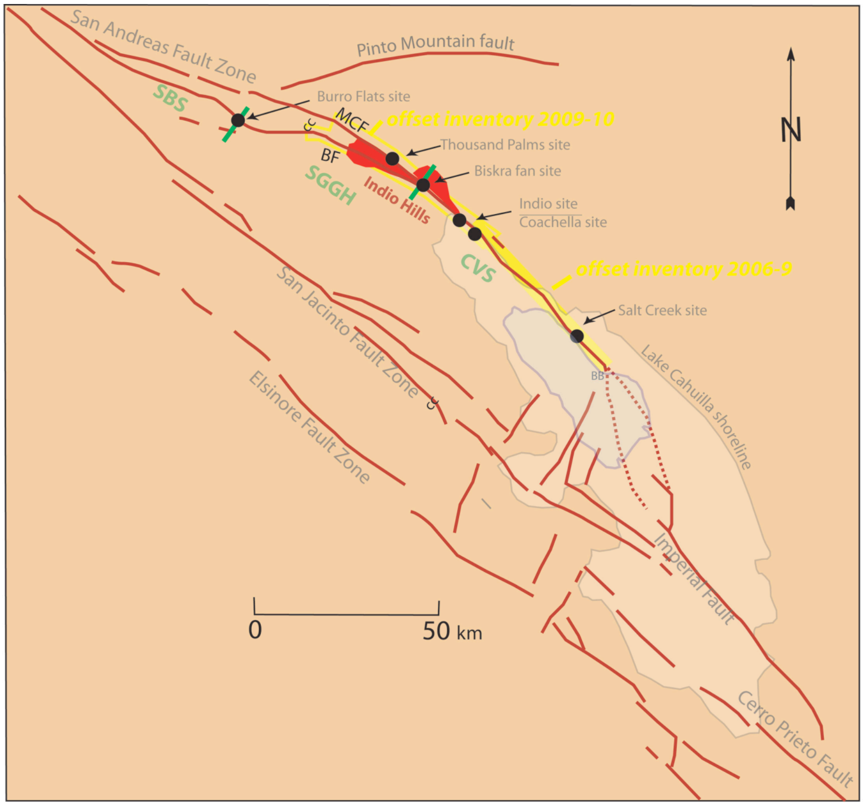

Figure 1. Location map for Banning fault (BF) and Mission Creek fault (MCF) with WGCEP (2007) fault segments: SBS = San Bernardino South section; SGGH = San Gorgonio-Garnet Hill Section; CVS = Coachella Valley Section extending from the Salton Sea (outlined in blue) to the Mission/Banning fault junction 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 Hills.

III. A relevant but unanticipated result of this study is discovery of a pair of subtle very long-term slip-per-event sites (~10 and ~14 events respectively) along the Mission Creek fault in the central Indio Hills.

IV. Indirect results from this project indicate that the parameters of fault interaction across the Indio Hills can be derived from the distribution and magnitude of paleo-event offsets along the primary B-SAF and MC-SAF bounding faults. Displacements narrowly define the positions and kinematics of an area of distributed penetrative and discrete “inter-fault” deformation between the B-SAF and MC-SAF. The zone is expressed by local patterns of folding, thrust faulting, and synthetic strike-slip faulting. Inputs to this deformation are derived from the mapped areas and magnitudes of displacement along the principal faults.

V. A second indirect result of fieldwork for this project is the identification of small number of sites that can produce “intermediate term” slip rates, i.e. 1-15ka. A single osl date from a ~15ka site in the southern Indio Hills provides a promising preliminary slip rate. Two consistent osl dates from a site in the northern Mecca Hills produce an ~8ka slip rate. Multiple-event stream offset sites within the study area can be interpreted in conjunction with paleoseismic event ages to derive ~1ka slip rates of >15mm/a. Early indications are for generally consistent (15-20mm/a) rates within these time ranges.

Methods

Site analyses involve description landscape features, measurements of offset reference lines, and detailed characterization of the uncertainties associated with the measured offsets. Preservation of offset features is found to be associated with landscape conditions including: (1) well-confined and relatively widely spaced source streams up-slope of the fault; (2) persistent geomorphic surfaces below the fault; (3) slope directions oriented approximately perpendicular to the fault. Small (<1m-wide) low gradient streams are found to have a greater tendency to accumulate discrete multiple offsets in fine grain deposits; multiple offsets identified in medium grain deposits are more commonly associated with moderate-sized streams (i.e. 1-to-2m-wide) with low to moderate gradient; and multiple-offset records located within coarse deposits are associated with more energetic larger streams (>2m-wide). These associations may result in part from the carrying capacity of streams, but stream energy and size is independent of local substrate in many places. Notably, a pair of multiple-event offset sites have been recognized in coarse fan deposits below the Mission Creek fault near 1000 Palms oasis. Each of these sites is associated with a single source drainage oriented approximately perpendicular to the fault, and preserves a record of individual fault displacements affecting the southern portion of the Mission Creek branch of the San Andreas fault. The two sites individually record long (>10 event) slip-per-event histories.

The map base for field mapping and description of small geomorphic offsets combines full resolution images aerial images aquired from *Google Earth Pro* (resolution ~3m); *B4* Lidar imagery (CV resolution ~1m); and low altitude aerial photographs acquired during the course of this study (resolution10-30cm). These materials were compiled, studied in the office, printed and utilized in a systematic field inventory of geomorphic offset evidence.

In order to provide displacement parameters for recent earthquakes, stream offsets are mapped in the field to recover individual event offsets and changes of offset behavior with time at single sites, and with distance along the fault with the sum of multiple sites. The quality of offset evidence judged for each offset described in this study, and only those deemed well or very well preserved across well-located and narrowly defined faulting were incorporated in this study.

Age dating. Current methods for direct dating of alluvium typically cannot be used gto date young geomorphic offsets with sufficient resolution to be associated with specific dated earthquakes. Despite this shortcoming, the best-represented increments of geomorphic offset can be correlated to locally determined earthquake ages with some confidence. The CVS has become relatively rich in paleoseismic event studies extending through the past ~1000 years (e.g. Fumal et al., 2002; Williams and Seitz, 2007; Philibosian et al., 2007). This investigation relies on the premise that a complete geomorphic record of offset events can correlated with a complete set of age dated paleoseismic events within the a given fault segment. Thus individual paleoseismic events can be more fully characterized, and paleoseismic dating be applied to evaluation of millennial slip rate.

Field methods. Large format digital aerial photography are used as a cost-effective means to collect imagery for detailed description of geomorphic offsets. This is found to be an effective way to identify and describe the abundant but often very subtle offset features that will continue to be systematically inventoried and evaluated in this investigation in the current project and working independently approximately 10,000 geo-located large format air photos have been acquired semi-continuously along the SSAFZ faults in Coachella Valley. We are investigating means to catalog and release this photoset to the community.

Complex processes associated with formation and preservation of geomorphic fault displacements necessitates incorporating a means for critical evaluation of field evidence. Repeat site evaluation (and measurement) was discovered to be an important means to test the stability of site measurement, for minimizing the influence of observational bias and for increasing analytical statistics. Criteria for stream offset site-selection enable the better-preserved offsets sites to control interpretation of local displacement.

Site visits at individual geomorphic offset features entailed fault description and mapping of fault location and features directly on air photos. The bases for determination of fault location and fault width are described, along with evidence of fault complexity such as multiple branches, step-overs or bends. The association of the mapped fault to offset geomorphic features was subsequently characterized, in particular tendencies for local slope, stream processes, or scarp geometry to mimic, minimize, or exaggerate fault offset.

A consistent system of quality rankings for geomorphic evaluation were developed and carried through the course of the study --- criteria are summarize in a field checklist (Table 1).

Table 1. Stream offset field checklist

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[1]. 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)

Fault location was graded "A" if it is clear and simple with multiple consistent evidence. A- was given if evidence of location was good and consistent but required longer projections from areas of better expression. B+ and lower grades were assigned with increase of fault width or complexity. Lower grades were also attributed if fault location was found to be ambiguous. Sites with fault location lower than B+ were rarely used in the study. WAAS-corrected gps (*Wide Angle Augmentation System gps*) points were measured at each site, typically at the projection of the source channel and the fault. Ultimately the best-preserved and contextually simple stream offsets were chosen to control the interpretation of slip history. More detailed descriptions of feature formation, evolution, and preservation were recorded as needed for evaluation of more complex sites.

Offsets of stream banks were measured separately where upstream and downstream margins were present. Independent minima and maxima were evaluated for all fault-piercing offsets and offset projections. In many cases a single stream evaluation produced 8 objective offset uncertainties. For example NW(bank) Upstream (+/-); NW Downstream (+/-); SE Upstream (+/-); SE Downstream (+/-). Maxima and minima have been combined separately for each offset feature (in this case NW and SE banks) using the method of *"square root of the sum of squares"* positive and negative respectively, for each offset feature. Asymmetric uncertainties were often recorded for individual piercing features in the field, in these cases asymmetry is are carried through to the reported uncertainties. Recorded uncertainties were intended to be "2 sigma," i.e. they are conservative, and are meant to capture uncertainty in determination of the original offset of the piercing feature 99% of the time. At the best-preserved sites with good fault characteristics (i.e. the fault is interpreted to be narrow and well located), the data are asserted to be *well-conditioned* and sufficient for examination in a 1-sigma framework. In a few cases a *preferred offset* was recorded in the field. This information is reported as in the summary site descriptions, with substantiating descriptions, and is shown with point symbols in Figures.

Summary

The investigations conducted in this project were designed to quantify the spatial distribution of recent surface activity. Field mapping of geomorphic offsets along the Coachella Valley branches of the San Andreas fault, and evaluation of the resulting data set are showing excellent promise to broadly elucidate spatial and temporal patterns of activity of the Banning and Mission Creek faults in Coachella Valley. Mapping indicates a prevalence of moderate ruptures and a small number of large offsets. This is consistent with evidence developed in systematic mapping of individual and multiple event stream offsets in the area extending south to the Salton Sea. Continuing work seeks to more fully populate the dataset of larger offsets, evaluate means to objectively date the larger offsets, and characterize past and future rupture behavior of the San Andreas fault in the Coachella Valley.

Presentations

Salisbury, J.B. and P. Williams, *Field and LiDAR measurements of offsets along the Clark fault and the southernmost San Andreas,* 2010 SCEC Annual Meeting: Southern San Andreas Fault Evaluation (SoSAFE) Workshop, 12 September 2010.

Williams, P., D. Phillips, E. Bowles-Martinez, E. Masana, P. Stepancikova, *Identification of geomorphic conditions favoring preservation of long time series of individual fault offsets across transform faults.* EOS, AGU annual meeting 2010.