Solid Earth Discussions

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Comment on se-2022-9

Jonathan Matti (Referee)

Referee comment on "Tectonic evolution of the Indio Hills segment of the San Andreas fault in southern California, southwestern USA" by Jean-Baptiste P. Koehl et al., Solid Earth Discuss., https://doi.org/10.5194/se-2022-9-RC2, 2022

Manuscript se-2022-9 consists of three parts:

- a detailed structural analysis of macro- and micro-folds and associated faults that deform a sequence of Pliocene-lower Pleistocene sedimentary rocks exposed in the tectonically uplifted Indio Hills;
- a comparison of the Indio Hills structural geology with that of two similar uplifted and inverted late Cenozoic basin fills occurring farther SE within the San Andreas Fault zone (SAFZ);
- integration of the structural data into a synthesis that interprets coeval uplift of the various inverted basins in the context of Quaternary dextral-oblique transpressive tectonics within the southern San Andreas Fault system writ large.

The manuscript explores these three themes with mixed success:

- The discussion of fold and fault structures in the Indio Hills is robust and comprehensive, including appropriate analytical data and exceptional aerial and outcrop photographs that nicely illustrate structural features and relationships. One concern I have is that the structural terminology and technical language used in the manuscript are pitched toward the structural specialist—not toward general geologists like myself. I address this point below.
- The manuscript’s comparison of the Indio Hills structural setting with that farther to the southeast within the SAFZ is moderately successful. The report depends heavily on results of other published investigations, and provides only cursory discussion of structural correlations and comparisons among the three inverted basins. The report would benefit from expanded discussion of these correlations, including one or more new map-type figures that better summarize geologic structures SE of the Indio Hills (otherwise, the reader has to chase the other publications down in order to evaluate manuscript se-2022-9’s proposed structural comparisons and correlations).

- By comparison with the preceding two themes, the manuscript's regional synthesis in my opinion is the weakest link in the three themes. In my review I raise some technical questions and issues that I believe need to be addressed more completely—and in some cases explained or corrected. These are not deal-breakers, but should be addressed by the authors.

I do not know whether Copernicus Publications provides an extensive review by a science editor, but I think that manuscript se-2022-9 needs a heavy editorial hand—either by Copernicus staff or by the authors themselves based on peer-review feedback. In part, problems with the narrative structure may stem from the fact that English may not be the first language of two of the three authors. But in addition, I sense that the narrative is too cursory and includes logic jumps that need to be explained more fully. My marginal comments on the manuscript identify many specific instances where I think the narrative can be improved both content-wise and in terms of organization.

All of this said, I enjoyed reading the manuscript. *First*, it adds to the body of detailed structural analysis so critical to documenting and understanding the geologic history of the southern San Andreas Fault zone and associated depositional basins; and *second*, it provides a testable regional synthesis for dextral and contractional events within the SAFZ writ large—including possible interactions with the Eastern California Shear Zone and the sequential development of discrete SAFZ strands in the Salton Trough.

My recommendation: The manuscript needs work, but it should be published by Copernicus Solid Earth.

My review consists of two parts:

- General comments contained in this memo
- Detailed comments, questions, and suggested edits integrated into the .pdf version of Manuscript se-2022-9.

NOTE: For my review I separated the manuscript into four discrete documents: (1) the text without references, (2) references alone, (3) figures alone, and (4) supplemental material.

General comment #1: Who is your audience?—In my opinion it is not clear who manuscript se-2022-9 is trying to reach: the specialist in structural geology? Or the regional geologist who primarily is interested in reconstructing the tectonic history of the SAFZ and related faults over the last 6 ma?

I assert this because the structural analysis of fold and faults in the Indio Hills and their kinematic interpretation (theme 1, above) is laden with specialized structural terms with which the average geologist will not be familiar. This easily can be solved by the author's sensitivity to those geologists that are interested in the paper but become irritated when the technical language stands in the way of understanding local and regional structures.

This easily can be addressed—not by dumbing down and diluting the structural contributions—but rather by using techniques like the following example:

Instead of "Farther southeast along strike, the Indio Hills and Banning faults merged along a dextral freeway junction (Platt and Passchier, 2016) that may have enhanced…." (manuscript lines 610-611), consider the following:

"Farther southeast along strike, the Indio Hills and Banning faults presumably merge along a dextral freeway junction—a type of fault intersection where the faults have similar shear sense in all three branches (see Platt and Passchier, 2016; Passchier and Platt, 2017). This configuration may have enhanced…….". (BTW, you may want to add the Passchier and Platt [2017] citation to your list of references).

I recommend you use this type of narrative format to speak both to the structural geologist (probably familiar with the term already) and to the regional geologist like me (inquiring minds want to know).

Specialized structural terms are scattered throughout the manuscript. Here are a few that could be explained:

fore-limb (of folds)

back-limb (of folds)

ladder structure

shear-folding (as opposed to other fold drivers)

General comment #2: Discussion of faults in the greater Coachella Valley region—Manuscript se-2022-9 discusses faults of the greater San Andreas system (writ large) in three separate segments of the report: lines 39-47, lines 116-124, and lines 320-336. Not only are these lines scattered throughout various parts of the report (thus making it hard for the reader to keep track of which faults are doing what and when), but the scattered text contain assertions and interpretations that the reader has to remember and appreciate from isolated sections, and then relate within a total picture of tectonic history stretching over 6-7 million years.

This is difficult to do without a well-organized and complete section at the front of the manuscript that summarizes regionally-important faults *throughout* the greater Coachella Valley region. Absent this introductory summary, the reader reaches no sense of structural complexity within the SAFZ in southern California—both in terms of discrete faults strands throughout the region and how they evolved through time and space.

Why is a coherent introductory regional statement needed?

The manuscript ostensibly focuses on structural relations from the latitude of the southern Indio Hills south. However, the report integrates certain regional faults, concepts, and nomenclature not only into its concluding tectonic synthesis but also into its use of fault names locally. This especially is apparent with how the authors use the name "Banning Fault" (*General Comment 3 below*) and with how they integrate late Quaternary strain history in the Indio Hills with modern strain patterns in the Eastern California Shear Zone (*General Comment 5 below*).

Absent a coherent introductory summary of regional fault relations, the reader can't help but believe that the manuscript's findings in the southern Indio Hills (and similar domains to the southeast) resolve all issues related to strain distribution in the southern SAFZ throughout the last 6-7 Ma.

Recommendation:

To address this, I recommend that all discussion of regional faults be moved into a single section under "Geologic Setting", following an outline like this (or something like it):

Geologic Setting

Regional faults (including what is known about fault ages; see figure 2 in Kendrick and others, 2015)

Regional stratigraphy (already discussed in the manuscript)

Regional Tectonic Culminations (already discussed in the manuscript)

This new section hopefully will incorporate (and resolve) issues and questions identified in General Comments 3, 4, and 5 (below).

General comment #3: Use of the term "Banning Fault"—The manuscript applies this fault name from the San Gorgonio Pass region southeast beyond the southern Indio Hills (see figures 1 and [especially] 2, and lines 39-42, 633-634). This runs counter to the way most workers interpret faults and fault names.

The problem: Because the manuscript lacks a coherent discussion of fault nomenclature, distribution, and movement history in the greater Coachella Valley region, the reader reaches no sense of structural complexity within the southern California SAFZ—both in terms of discrete faults strands throughout the Coachella Valley region, how they evolved through time and space, and how they interacted together. Although the manuscript ostensibly focuses on structural relations from the latitude of the southern Indio Hills south, it nevertheless brings certain concepts (and attendant nomenclature) southward from the northern Coachella Valley where structural relations are more complex than implied in the manuscript. The reader can't help but believe that the findings in manuscript se-2022-9 resolve all remaining issues related to strain distribution in the southern SAFZ throughout the last 6-7 Ma.

Manuscript se-2022-9's use of the term "Banning Fault" inadvertently (but unfortunately) contributes to this problem

Recommendation:

If manuscript se-2022-9 retains its current nomenclatural approach regarding the Banning Fault, at a minimum the report needs to address how its usage differs from that of other workers (discussed below). It would be better if the authors evaluated regional tectonic implications of extending the name "Banning Fault" as far south as they do—especially because northwest of their study area the fault has been shown to have a very limited time during which if functioned as a discrete strand of the SAFZ, and this time frame is incompatible with that the authors propose for the "Banning Fault" in the southern Indio Hills.

In short: Manuscript se-2022-9 needs to acknowledge that the timing they propose for movement on the "Banning Fault"—and the important structural role it plays in their analysis of how the tectonic culmination evolved—is not compatible with what is known about slip on the Banning strand of the SAF in the northern Coachella Valley.

Nomenclatural and fault-reconstruction precedents:

Matti and others (1992; Matti and Morton, 1993) have addressed nomenclature problems for strands of the SAFZ in the Coachella Valley region. They applied the name "Banning Fault" southward from eastern San Gorgonio Pass to the fault's junction with the Mission Creek Fault midway along the Indio Hills. In addition, they alluded to "Coachella Valley segments" of the various faults, anticipating future nomenclatural refinements that have emerged over the last decade or so.

Recent investigators follow this precedent regarding the spatial extent of the "Banning Fault". Behr and others (2010), Fuis and others (2012, 2017), Fattaruso and others (2014, 2016), Gold and others (2015), Kendrick and others (2015), Beyer and others (2018), and most other workers do not apply the term "Banning Fault" southeast of its junction with the Mission Creek strand. Beyond that juncture, some workers apply the name "Indio strand" to the SAF (Behr and others, 2010; Gold and others, 2015; see fig. 1 of both reports). Other workers apply the name "Coachella Valley segment of the SAF" to the fault southeast of the juncture (see Fattaruso and others, 2014, 2016).

You are not obliged to use the more common usage of "Banning Fault". However, it is incumbent on you to address the nomenclature issue.

If you choose to revise your nomenclatural approach, then you need to come up with a name that you can apply to the "San Andreas Fault" strand southeast of the Banning/Mission Creek junction. Given that—in the Indio Hills region—the Mission Creek Fault was the major SAF strand during the period 4 Ma to Holocene (the critical period during which you require a bounding dextral fault on the SW side of the Indio Hills culmination), I personally would apply the name "Mission Creek Fault" in place of your universal application of the name "Banning Fault" to this structure.

Finally, almost all workers agree that the Banning strand of the SAF between San Gorgonio Pass and its juncture with the Mission Creek strand evolved during the late Quaternary time (last 200 ka???) as the result of a left step from the Mission Creek to a newly evolving strand to the west (i.e., the Banning Fault) (Matti and others, 1985; 1992; Matti and Morton, 1993) (especially see the important paper by Gold and others, 2015, that explores exhumation and uplift rates in the northwestern Indio Hills—a story that sounds a bit like your own, only younger?).

General comment #4: Indio Hills Fault—Manuscript se-2022-9 proposes that the Indio Hills Fault plays a significant structural role in both (1) evolution of the local tectonic culmination and (2) the evolution of the SAFZ. The authors identify three phases of movement history for the Indio Fault:

- An initial role as a southwest-dipping normal fault (late Miocene);
- An intermediate role as a dextral strike-slip fault;
- A penultimate and current role as an active transpressive dextral-oblique thrust fault.

I found it difficult to understand its polyphase role (normal fault followed by dextral-slip fault followed by oblique reverse-thrust fault)—especially the timing of activity during each tectonic phase. Comments and observations and interpretations about this structure are scattered throughout the manuscript, so it was hard for me to keep these three phases in mind and to appreciate when each was active.

New to my awareness is the manuscript's proposal that the Indio Hills Fault initially was a late Miocene normal-slip fault (1, above). This assertion needs to be supported with evidence. The authors at some places in the report point to previous workers who propose a southwest-dipping "basin-and-range" type of structure that had to exist early in the evolution of the San Andreas Fault system in the Salton Trough, but I am not aware that the Indio Hills structure was part of that "basin-and-range"-type system. Please explain and elaborate, including where this regional "basin-and-range"-type system can be recognized NW of the Indio Hills

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General comment #5: Landers-Mojave Line connection with Indio Hills Fault—I have problems with how the manuscript projects the Indio Hills Fault into a seismic trend that Nur and others (1993a, b) identified as the "Landers-Mojave Line". That "concept" was defined to represent a seismicity belt that was observed following the 1992 Landers earthquake in the Mojave Desert (note that a recent paper by Spotila and Garvue (2021) challenge some of the assertions by Nur and others, 1993a, b). Manuscript se-2022-9 asserts that the Indio Hills Fault can be connected structurally with the Landers-Mojave Line via faults in the Little San Bernardino Mountains (LSBM).

My concerns include:

- The manuscript (fig. 1) connects the Indio Hills Fault northwestward to a presumed fault at the south edge of the LSBM. Although this fault is depicted in some publications, its distribution, structural role, and age have not been documented. Therefore any reference to this fault in manuscript se-2022-9 needs to acknowledge this reality.

I recommend that you cite the recent digital geologic-map database of Joshua Tree National Park by Powell and others (2015) for a more recent and detailed rendering of geologic units and faults. The report can be viewed only in a GIS (ArcMap, for example), but once loaded into a GIS platform the files reveal much more about JTNP geology than was known previously.

- The unnamed fault is depicted by Rymer (2000, fig. 1) who plots it east of his West Deception Canyon Fault. Although Rymer (his figs. 1 and 2) shows the epicenter of the 1992 Joshua Tree earthquake located a few km north of the unnamed fault, he did not report any ground rupture on it. Instead, Rymer documented ground rupture on the West Wide Canyon Fault (see his figure 2). This structure is well to the NW of where manuscript se-2022-9 speculates that the "active" Indio Hills Fault would intersect the LSBM and connect with the "Landers-Mojave Line".
- In lines 600-603 the authors reference Dokka and Travis (1993a, b) in support of the hypothesis that the Indio Hills Fault [strand of the San Andreas Fault] "connects" with the Eastern California Shear zone (ECSZ) and the "Landers-Mojave Line of Nur and others (1993). Reference to Dokka and Travis as supportive evidence for this hypothesis is not appropriate because those authors (1990a, b) do not show the ECSZ extending south of the left-lateral Pinto Mountain Fault (see figs. 2, 14, 15, and 18 of Dokka and Travis, 1990a, and figs. 2 and 3 of Dokka and Travis, 1990b). In fact, Dokka and Travis, 1990b, p. 1325 clearly explore the notion that connection between the ECSZ and the San Andreas Fault (in this case, the Indio Hills strand) is based on slip budgets for the North American plate margin—the physical and kinematic basis for this connection is not obvious.
- Occurrence of (a) ground rupture triggered by the 1992 Joshua Tree earthquake and (b) ground rupture on the Eureka Peak fault *south* of the Pinto Mountain Fault during the 1992 Landers earthquake (Treiman, 1992a, b) is tempting evidence that strain *probably* is transferred kinematically between the southern San Andreas Fault and the ECSZ. Note, however, that ground rupture associated with the Joshua Tree event was not coextensive with the Eureka Peak Fault. Thus, it is unlikely that transfer of strain between the ECSZ and the SAFZ occurs along a single fault trace (the authors don't claim that it does, but their figure 1 implies as much. Better to clarify).
- The California Geological Survey classifies the Indio Hills Fault as a late Pleistocene and older feature, with no evidence for Holocene displacement. For current interpretation of fault activity, see California's interactive geologic-hazards map at

https://maps.conservation.ca.gov/geologichazards/DataViewer/index.html and also the Quaternary Fault and Fold Database at https://www.usgs.gov/programs/earthquake-hazards/faults). These data call into question the notion that the Indio Hills Fault is a Holocene extension of the Holocene and Recent ECSZ and Nur's Landers-Mojave Line.

The authors probably will protest that the scope and purpose of manuscript se-2022-9 is much broader and regional in scope to address details of the kind that I provide here in General Comment 5. I agree. I provide my analysis mainly to remind the authors that any model that incorporates latest Quaternary activity on the NE-bounding structure of their Indio Hills tectonic culmination (in this case, the Indio Hills Fault) needs to be compatible with what is known about the distribution and geologic history of fault elements that might (or might not) connect their tectonic model for the SAFZ with the ECSZ—or with SAFZ structures northwest of the Indio Hills culmination.

General comment #6: Ages for fault activity—In general, I found it quite difficult to determine the sequencing and ages for faults the manuscript discusses and integrates into their concluding time-space model. This is very frustrating because the timing of fault movements (1) relative to overall history of SAF history in the greater Coachella Valley region and (2) relative to when and how the Indio Hills tectonic culmination evolved is a critical part of the author's tectonic model.

Recommendations:

- Develop a new section called "Summary of fault ages", and consolidate all the disparate observations about age of faulting currently scattered throughout the report.
- I recommend developing a new diagram like figure 2 of Kendrick and others (2015).
- Make certain that the manuscript's use of "Pliocene", Pleistocene", and "Holocene" conform to current international standards (see Pillans and Gibbard, 2012; Cohen and others, 2013; Gibbard and others, 2013; Walker and others, 2019; and other references on this subject). The boundary between Pliocene and Pleistocene now is ~ 2.6 Ma.

General comment #7: "Possibly", "or", and "may have"—The manuscript frequently has sentences like the following:

"Structural feature X formed by process Y, *and (or) it [possibly, may have] formed by process Z*".

As a reader, I asked myself "are the authors *not committing themselves to structural feature X formed by process Y*—their first choice"? Adding caveats like "or may have" makes sentences containing this kind of grammatical structure [presentation] sound like the authors are not sure about their assertions, and are covering themselves.

Recommendation:

- Examine the narrative, find those kind of grammatical instances, and design a more appropriate way of expressing the level of confidence the authors have in conclusions X and Y—in other words, include [discuss] the error bars that prevent complete confidence.

In short: the authors need to choose more definitively among the suite of interpretive possibilities, and not just cover their hypotheses with "or alternatively it could be a different way"! As Gozer challenged the *Ghostbusters*: "Choose the form of the Destructor".

General comment #8: Identity, position, and age of "SW master bounding fault"—It may just be me, but I had trouble understanding *what* the SW-bounding master fault was throughout the evolution of the Indio Hills uplift, *where* was it positioned throughout this evolution, *when* did the uplift start, *how long* did it last, and is it *still active*? Comments here not only are relevant to the narrative but also to figures—especially figure 7.

Regarding the *what*: In general comment #3 I questioned your application of the name "Banning Fault" to the SAF strand on the SW flank of the Indio Hills uplift. My comment there pointed out that (according to current understanding) the Banning strand of the SAF in the northwestern Coachella Valley became active only in the last few hundred thousand years (late Pleistocene and slightly older). That "fact" calls into question whether the "Banning Fault" could have been the SW-bounding "master fault" during (say) 500 ka? 1.0 Ma? 1.5 Ma? 2.0 Ma? So, together with my concerns in Comment #3 I question whether you should use the term "Banning Fault" for whatever SAF strand may have formed the "master fault" bounding the SW side of the long-evolving Indio Hills uplift.

But if current thinking regarding the age of the Banning strand of the SAF in the northwestern Coachella Valley is correct, then during the last few hundred thousand years that strand was feeding slip SE along the Pacific margin of the Indio Hills uplift, so at that time application of the name "Banning" to that SW-bounding master fault may have been appropriate (as implied in fig. 7c) (but only during that slip episode).

Bottom line: Multiple SAF strands northwest of the Indio Hills have been active throughout the last 6-8 Ma, those strands have evolved sequentially (Kendrick and others, 2015, fig. 2), each of those strands has a different name, and each of those strands sequentially has fed dextral slip southeast toward the Indio Hills uplift. So the SAF bounding the SW margin of the Indio Hills has had a "changing name" throughout the total 6-8 Ma of southern SAF evolution in the Coachella Valley.

This is why application by Behr and others (2010) and Gold and others (2015) of the term "Indio strand" or "segment" to the SAF southeast of the junction between the Mission Creek and Banning Faults is so appealing: throughout time, all the messy SAF strands NW of the Indio Hills have sequentially evolved northwestward of the Indio strand—presumably NW of the current junction between the Mission Creek and Banning strands of the SAF.

Regarding the *where*: Your figures 7a and 7b position a queried "Banning Fault" west of the trace of the "Banning" shown in fig. 7c. Why do you do this? What is the basis for the location difference?

Regarding the *when* and for *how long*: In my General Comment #6 I recommended a new section that consolidates all fault-age information currently scattered throughout the report—or not addressed clearly. I also recommended a new figure like figure 2 of Kendrick and others (2015). Such a figure easily could add a "range-bar" for the Indio Hills tectonic culmination, thereby resolving my questions about the *when* and *how long*.

Regarding the *still active?*: In my General Comment #5 I questioned your correlation of the Indio Hills Fault with the "Landers-Mojave Line" of Nur and others (1993a, b). Depending on how you address my comments there, the Indio Hills fault may (or may not) still be active—and the tectonic culmination may (or may not) still be actively growing.

Relevant to the question of "is it still growing"—I can't remember whether your manuscript discusses the evidence for reverse-dextral slip on the SW-bounding SAF strand (whatever its name). Do you have fault-plane evidence or other evidence that the SW-bounding fault has generated up-on-the-NE displacement (other than the fact that the landscape is higher to the NE than the SW)? Is it possible that the Indio Hills uplift tilted SW away from a high landscape adjacent to the Indio Hills Fault toward a low landscape to the SW? In other words: has uplift on both NE- and SW-bounding master faults been equal? I think this is an important question to address.

Recommendation:

- The manuscript needs to expand and clarify questions about the what, where, and when aspects of tectonic culmination of the Indio Hills. I recommend a new section, or at least addressing these questions in a single part of the narrative.

General comment #9: Character of folds as they approach the Banning Fault—In lines 336 and 508 (and elsewhere) you discuss the geometry of folds as they "approach" the Banning Fault. But these folds presumably are older than a few hundred thousand years, and their axes never reach the position of the "Banning Fault" as you depict it in figures 7a and 7b (and folds closest to the "modern" Banning Fault" in figure 7c area fault-parallel and are not relevant to folds that are oblique to the master faults. Therefore, for the latter, how can you comment on the structural style, morphology, and configuration of the fold sets depicted in figs 7a and 7b? They do not reach the queried and discontinuous "Banning Fault" trace that you shoe more valleyward in figures 7a and 7b. Please clarify.

General comment #10: Update references—Lines 140-150 need to cite Gold and others (2015), and do a more thorough job of describing what Keller and others (1982). At the end of this memo I include many references that you should at least consider for inclusion and evaluation for your report.

I enjoyed reviewing this manuscript, although I have questions and comments that may (or may not) improve the paper. I trust that the authors will receive my comments and critique in the spirit with which they are offered: to refine and clarify an important contribution our understanding of the tectonic evolution of the southern San Andreas Fault system.

Good luck with forward progress of the manuscript.

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Please also note the supplement to this comment:
https://se.copernicus.org/preprints/se-2022-9/se-2022-9-RC2-supplement.zip