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U.S. Nuclear Regulatory Commission
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Subject: Comment on Cenozoic Tectonics in the Central Basin and Range: Magnitude, Rate, and Distribution of Upper Crustal Strain

Dear Dr. Justus:

The attached manuscript is comment on an article, by the same title, recently published in vol. 300, pp. 659–719 of the American Journal Science by Drs. Snow and Wernicke. Snow and Wernicke develop a model to reconstruct the extensional belt in southern Nevada and eastern California, a part of which is in disagreement with the results developed in Stamatakos, et al. (Paleomagnetic constraints on the tectonic evolution of Bare Mountain, Nevada, GSA Bulletin, 1998) specifically with regards to Bare Mountain, Nevada.

If you have any questions please contact Dr. John Stamatakos at (210) 522-5247 or me at (210) 522-5252.

Sincerely,

Budhi Sagar
Technical Director

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Attachment

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COMMENT ON CENOZOIC TECTONISM IN THE CENTRAL BASIN AND RANGE: MAGNITUDE, RATE, AND DISTRIBUTION OF UPPER CRUSTAL STRAIN

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In their recent paper, Snow and Wernicke (2000) reconstruct the Death Valley extensional belt to its pre-extensional state 36 million years ago. Akin to a jigsaw puzzle, the proposed reconstruction fits together exposed fragments of a once continuous Sevier-age fold and thrust belt dismembered by Tertiary extension of the Basin and Range. Key components in the reconstruction are palinspastic markers such as stratigraphic pinchouts and fault cutoffs, paleoflow directions, and paleomagnetic data. Bare Mountain, Nevada, which exposes two pre-Tertiary thrust faults within a thick section of Neoproterozic to late Paleozoic strata, has important features that bear on the validity of Snow and Wernicke's (2000) hypothesis. Although we do not take issue with the entire Snow and Wernicke (2000) reconstruction, we disagree strongly with their interpretations of vertical and horizontal-axis rotations of Bare Mountain.

Covariance of Thrust Faults and Paleoflow Data

Snow and Wernicke (2000) conclude that Bare Mountain rotated clockwise about a vertical axis nearly 90° between ca.16 and 10 Ma (figure 7, pp. 668–670 of Snow and Wernicke, 2000). They cite the apparent covariance in orientations of thrust faults and paleoflow directions as evidence for the large vertical-axis rotation.

Thrust Faults

Snow and Wernicke interpret two pre-Tertiary thrust faults, the Panama thrust in southern Bare Mountain and the Meiklejohn Peak thrust in northeastern Bare Mountain, as part of their reconstructed fold and thrust belt. They draw the two pre-Tertiary thrust faults with east-west strikes (figure 3 of Snow and Wernicke, 2000, p. 662) compared with their inferred north-south trending and linear pre-extensional fold and thrust belt. According to the map of Monsen and others (1992) however, the Panama thrust actually strikes northeast-southwest and the Meiklejohn Peak thrust strike varies from northwest to east-northeast.

Paleoflow Data

Mean paleoflow directions from trough cross-beds in Neoproterozoic to Cambrian quartzites at Bare Mountain were interpreted to trend north compared to west trends of mean paleoflow directions in the same rock units exposed on nearby "unrotated" ranges (Snow and Prave, 1994). Nevertheless, paleoflow data for Bare Mountain exhibit a wide range of flow directions. As shown on figure 3 of Snow and Prave (1994, p. 171), azimuths of paleoflow directions from Bare Mountain are nearly evenly distributed between azimuth 330° and azimuth 120°. This type of broad and possibly bi-modal distribution is common in shallow marine and tidal depositional systems. As discussed in Potter and Pettijohn (1977), shallow marine sandstones may have paleoflow directions that are oriented offshore, oblique, and parallel to the paleoshoreline and paleoslope. In addition to questions about possible original variations in the orientation of sediment transport directions over such large distances, we conclude that such a broad distribution of directions does not provide a compelling basis for any interpretations of vertical-axis rotations.

Paleomagnetic Data

Permian-Triassic and Miocene magnetizations from Bare Mountain do not indicate any statistically significant vertical-axis rotations (Stamatakos, Ferrill, and Spivey, 1998). Specifically, we observed three distinct magnetizations at Bare Mountain, all without significant vertical-axis rotations. These are: (1) a dual-polarity Miocene primary or secondary magnetization in the 14 to 15 Ma porphyry dikes (ages based on conventional $^{40}Ar/^{39}Ar$ dates from Weiss, 1996) carried by magnetite with relatively high unblocking temperatures (~560 to 580 °C); (2) a dual-polarity Miocene or younger secondary magnetization (**H**-component magnetization) in the Ordovician carbonate rocks carried by hematite; and (3) a dual-polarity Permian to Triassic secondary magnetization (**M**-component magnetization) carried by magnetite with relatively moderate unblocking temperatures (~420 to 480 °C) and intermediate coercivities (10 to 40 mT).

Snow and Wernicke (2000) dismiss these paleomagnetic results in favor of the paleoflow and fault-strike argument. They claim that our analysis of the paleomagnetism was flawed, arguing that we incorrectly interpreted the age and significance of the **M**-component magnetization. Instead of our interpreted Permian-Triassic age, they conclude that the **M**-component magnetization was acquired in the late Miocene from hydrothermal alterations associated with movement along the nearby Fluorspar Canyon Detachment. Snow and Wernicke (2000) assert that the **M**-component magnetization was acquired just after significant clockwise rotation of Bare Mountain. Their assertion is based on proximity of the paleomagnetic sites to the Fluorspar Canyon Detachment, the dual polarity of the **M**-component magnetization compared to the dominant reversed polarity for Triassic-Permian magnetization elsewhere in southern Nevada, and an alternative structural plunge correction for Bare Mountain (*east-southeast* plunge instead of our *northeast* plunge) based on thermochronologic data from Hoisch, Heizler, and Zartman (1997). The alternative *east-southeast* plunge correction aligns the **M**-component magnetization with the Miocene reference direction. This reassessment of our paleomagnetic analysis is however incompatible with geological and geomagnetic evidence from Bare Mountain.

Remagnetization Related to Fluorspar Canyon Detachment

In spite of proximity to the Fluorspar Canyon Detachment, carbonate rocks that carry the **M**-component magnetization are relatively unaltered compared to all other carbonate rocks at Bare Mountain. We found no evidence of hydrothermal alterations in the carbonate rocks bearing the **M**-component magnetizations. To the contrary, the rocks in the hanging wall of the Meiklejohn Peak thrust are the least altered rocks exposed at Bare Mountain. This observation is supported by paleothermometry data from calcite-twin geothermometry (Stamatakos and Ferrill, 1996) and conodont color alteration indices (Grow, Barker, and Harris, 1994) which show that these rocks record the lowest paleotemperatures of all rocks at Bare Mountain.

In addition, the timing argument proposed by Snow and Wernicke (2000) is incompatible with the age and orientation of the 14–15 Ma porphyry dikes exposed in eastern Bare Mountain. Snow and Wernicke (2000) propose: (1) 90° clockwise vertical-axis rotation beginning at 16 Ma; (2) Fluorspar Canyon detachment faulting and acquisition of the **M**-component magnetization between 13 and 10 Ma; and (3) ~30°east-southeast tilting after remagnetization (i.e., after 13–10 Ma).

The problem with this interpretation is that the14–15 Ma porphyry dikes in eastern Bare Mountain presently strike north-south and dip vertically. This orientation is consistent with known Miocene east-west extension (e.g., Zoback, Anderson, and Thompson, 1981). Thus, we contend that rotations of Bare Mountain about vertical or horizontal axes predates intrusion of the dikes. This assertion is based on the premise that the dikes were intruded vertically, perpendicular to the regional extension direction. The Snow and Wernicke proposed *south-southeast* tilt and 90° vertical-axis rotations requires dikes with 60° dips to the north such that they were fortuitously tilted and rotated to their present north-south vertical positions by the later vertical- and horizontal-axis rotations.

Therefore, because rotation of eastern Bare Mountain occurred prior to 14–15 Ma, a Miocene secondary magnetization acquired from hydrothermal fluids associated with 10–13 Ma motion on the Fluorspar Canyon Detachment could not record this earlier horizontal-axis tilting. The assertion by Snow and Wernicke (2000) that the **M**-component is a pre-tilting Miocene magnetization associated with movement on the Fluorspar Canyon Detachment is thereby negated by the details of timing between dike intrusion, horizontal-axis rotation, and movement on the Fluorspar Canyon Detachment.

Dual Polarity Magnetization

The argument by Snow and Wernicke (2000) that Permian-Triassic secondary magnetizations should all have reversed polarities is unfounded. In fact, dual polarity Permian-Triassic remagnetization should be expected. Unlike carbonate rocks in the central Appalachians, which were remagnetized during the approximately 30 m.y. long reversed-polarity Kiamen superchron, the Permian-Triassic secondary magnetizations in the Basin and Range were acquired at a time when the field was reversing at a rate comparable to average reversal-rate for the Tertiary (e.g., ca. 30 reversals in last 20 m.y. of the Permian according to Haag and Heller, 1991). More importantly, we noted that the character of the **M**-component demagnetizations (i.e., moderate unblocking temperature and coercivity spectra) match those of other Permian-Triassic secondary magnetizations elsewhere in Nevada (e.g., Gillette and van Alstine, 1982). In addition, and in contrast to most localized hydro-chemical secondary magnetizations, the moderate unblocking temperatures are characteristic of Paleozoic orogen-scale remagnetizations of carbonate rocks worldwide (e.g., McCabe and Elmore, 1989; Stamatakos, Hirt, and Lowrie, 1996; Van der Voo, Stamatakos, and Parés, 1997).

North-northeast Versus East-Southeast Structural Plunge

The *east-southeast* tilt for Bare Mountain inferred by Snow and Wernicke (2000) is based on a comparison of thermochronologic data from samples in the Bullfrog Hills to a spatially limited distribution of samples in the northwest corner of Bare Mountain (see figure 1, p. 2816 of Hoisch, Heizler, and Zartman, 1997). The result is an interpretation of plunge from essentially a linear distribution of data. We suggest that this limited 2D survey of paleotemperatures is insufficient to adequately define the 3D structural correction for all of Bare Mountain, especially for the hanging wall anticline of the Meiklejohn Peak thrust.

Our *northeast* plunge correction, which rotates the *in-situ* M-component magnetization to a Permian-Triassic direction, was determined from Pi-diagrams based on direct measurement of bedding around the Meiklejohn Peak fold plunge. Snow and Prave (1994, p. 716) used an identical procedure (measurements of bedding around folds near the Panama Thrust) to correct the paleoflow data from southern Bare Mountain.

The *northeast* structural plunge of Bare Mountain is, however, is not limited to the hanging wall of the Meiklejohn Peak thrust. The overall map pattern of extensional structures exposed throughout most of Bare Mountain consists of north-dipping bedding and east-dipping extensional faults (see map of Monsen and others, 1992). The resulting bedding-fault cutoff lines define the *northeast* structural plunge of extensional structures throughout most of the range (Ferrill and others, 1998). Detailed measurements of extensional faults and bedding along the west flank of Bare Mountain define a structural plunge of 042/37 (Ferrill and others, 1998), and this is consistent with the 039/33 structural plunge determined from bedding measurements around contractional structures in the hanging wall of the Meiklejohn Peak thrust. This northeast structural plunge is in fact consistent with the overall pattern of younging stratigraphy from southwest to northeast across the range, and lowest burial, metamorphic, and deformation temperatures in the northeast corner of the range (Stamatakos and Ferrill 1996).

Moreover, correction for an *east-southeast* tilt, as used by Snow and Wernicke (2000), restores the Meiklejohn Peak thrust to an orientation at odds with their correlative structures in the Last Chance thrust plate and equivalents in southern Nevada. Specifically, if the *east-southeast* tilt and later 90° vertical-axis rotation of Snow and Wernicke (2000) is assumed, then the fold axis of the Meiklejohn Peak hanging wall anticline corrects to ca. 345/30. This fold-axis orientation is not parallel to the pre-extension north-south fold and thrust belt envisioned by Snow and Wernicke (2000, figure 7, pp. 668–670).

Conclusions

We reaffirm our findings that the **M**-component magnetization predates Basin and Range extension and that Bare Mountain has not been rotated clockwise 90° as suggested by the Snow and Wernicke (2000) reconstruction. As an alternative, we suggest that one underlying assumption of the reconstruction— in which the original fold and thrust belt, with a single 400 km-long backfold, was neatly linear and narrowly confined—may be overly simplistic, especially when compared to similar fold and thrusts belts around the world. A general feature of many fold thrust belts is their along-strike sinuosity. Curvature in trends of contractional structures in fold-thrust belts is produced by lateral variations in thickness or mechanical behavior of precursor basin stratigraphy, lateral variation in displacement magnitude, and regional or temporal variation in shortening directions (e.g., Macedo and Marshak, 1999; Gray and Stamatakos, 1997; Ferrill and Groshong 1993; Marshak and Wilkerson 1992). Along-strike changes in structural trend of 45°or more are common over distances of 10's to 100's of km. Thus, we propose that the reconstruction by Snow and Wernicke (2000) be modified to permit original along-strike curvatures of the thrust belt similar to those curvatures observed in the Appalachian, Idaho-Wyoming, Jura, Alpines, Carpathian, Sierra Madre Occidental, and numerous other fold thrust belts around the world. This modification would preserve the regional correlation developed by Snow and Wernicke (2000) but remove the unsupported 90° vertical-axis rotation of Bare Mountain.

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