GEOMETRY OF MIOCENE EXTENSIONAL DEFORMATION, LOWER COLORADO RIVER REGION, SOUTHEASTERN CALIFORNIA AND SOUTHWESTERN ARIZONA: EVIDENCE FOR THE PRESENCE OF A REGIONAL LOW-ANGLE NORMAL FAULT; R.M. Tosdal and D.R. Sherrod, U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025

The geometry of Miocene extensional deformation changes along a 120 km-long, northeast-trending transect from the southeastern Chocolate Mountains, southeastern California, to the Trigo and southern Dome Rock Mountains, southwestern Arizona (fig. 1). Based upon regional differences in the structural response to extension and estimated extensional strain, the transect can be divided into three northwesterly-trending structural domains. From southwest to northeast, These domains are: A) southeastern Chocolate-southernmost Trigo Mountains; B) central to northern Trigo Mountains; and C) Trigo Peaks-southern Dome Rock Mountains (Fig. 1). All structures formed during the deformation are brittle in style; fault rocks (1) are composed of gouge, cohesive gouge, and locally microbreccia. Younger high-angle dip-slip and strike-slip(?) faults are not discussed.

In each structural domain, exposed lithologic units are composed of Mesozoic crystalline rocks unconformably overlain by Oligocene to Early Miocene volcanic and minor interbedded sedimentary rocks (2-6). Breccia, conglomerate, and sandstone deposited synchronously with regional extension locally overlie the volcanic rocks. Extensional deformation largely postdated the main phase of volcanic activity, but rare rhyolitic tuff and flows interbedded with the syndeformational clastic rocks suggests that deformation began during the waning stages of volcanism. K-Ar isotopic ages indicate that deformation occurred in Miocene time, between about 22 and 13 m.y. ago (5,6).

In the southeastern Chocolate Mountains and southernmost Trigo Mountains domain (fig. 1), the Tertiary and Mesozoic rocks are broken into numerous blocks bounded by curviplanar normal faults. Movement along the faults has tilted the rocks gently to the west and southwest. Deformation and rotation of each block is typically independent of the adjacent block; for example, in one block the beds dip 10 to 20^{o}, whereas in the adjacent block the identical rocks dip as much as 40^{o}. The curviplanar normal faults consist of fault segments of contrasting attitudes and displacements. The more continuous fault segments are north to northwest-trending, moderately dipping (35-70^{o}) normal faults. These normal faults abruptly terminate in north to northeast-trending, steeply dipping (60-80^{o}) faults with inferred strike-slip to oblique-slip displacements. These steeply-dipping cross or transfer faults (7) commonly extend only short distances beyond the junction of the two fault segments. In three dimensions, the geometry of the curviplanar faults at the junctions is that of an elongate spoon or trough with its long axis parallel to the intersection of the two fault segments. This geometry suggests that the relative transport of the upper plate of the faults was parallel to the axis of the troughs, that is towards the northeast or east. Assuming a listric geometry for the faults, the angular relations between bedding in the Tertiary strata and the northwest-striking curviplanar faults (8) suggest approximately 10 to 20% extensional strain.

The trace of the curviplanar block-bounding faults as well as smaller faults within individual blocks are commonly controlled by pre-existing planar anisotropies such as lithologic and structural contacts. For example, the trace of the Gatuna fault (Fig. 1), which is the largest and most continuous of the curviplanar faults, closely follows the trace of the late Mesozoic Chocolate Mountains thrust (2) and the inferred trace of the Sortan fault (3). The curviplanar trace of the Gatuna fault may also be in part inherited from

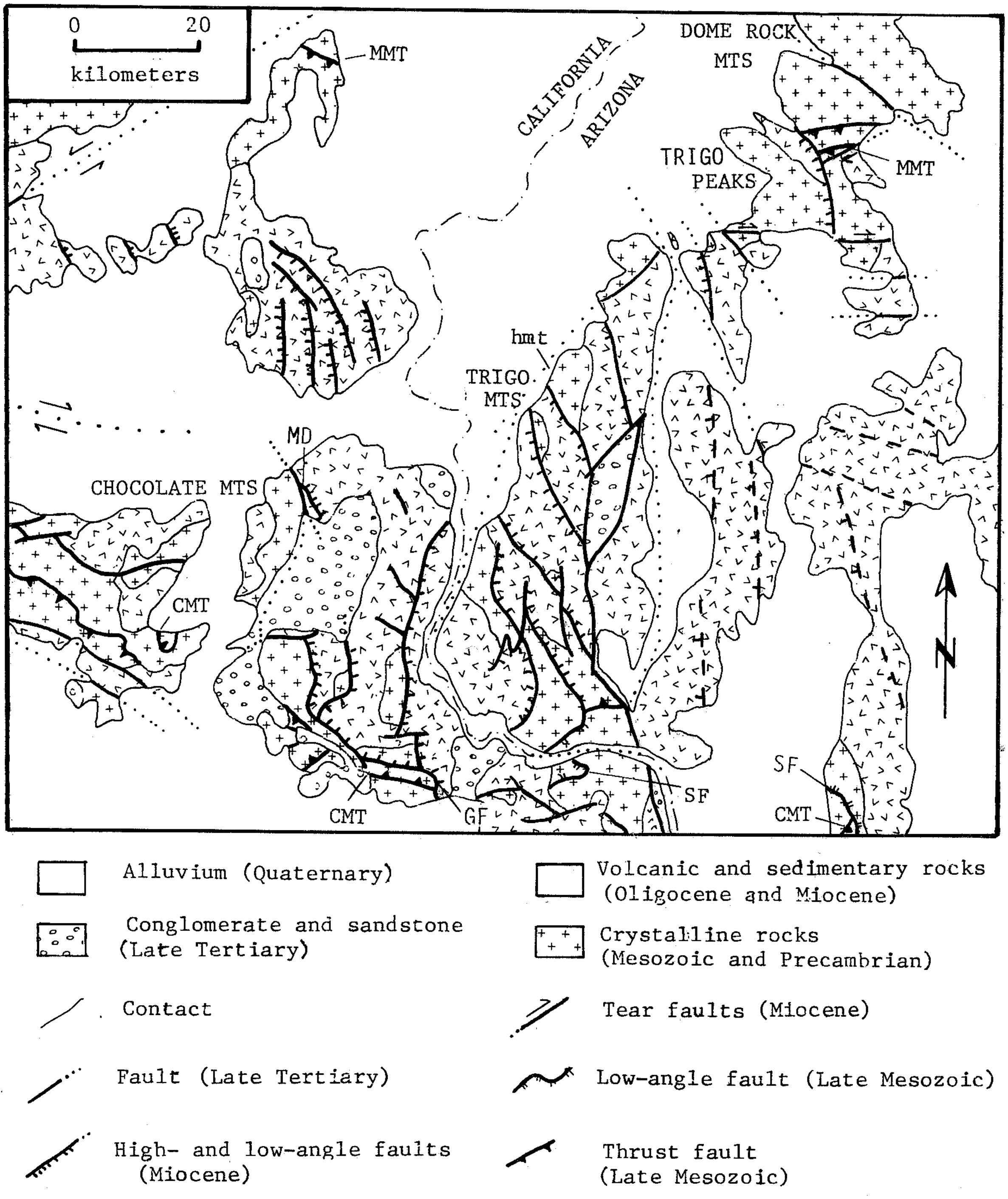

Figure 1. Generalized geologic map of the lower Colorado River region, southeastern California and southwestern Arizona. Geology shown in mountains range in the southeast part of the map is based on sir phots interpretation. CMT-Chocolate Mountains thrust, GF-Gatuna fault; MD-Midway detachment fault; MMT-Mule Mountains thrust; SF-Sortan fault; hmt-Hart Mountain mine.

open folds of the Chocolate Mountains thrust and planar fabrics of the thrust zone.

The Gatuna fault probably correlates with the Midway detachment fault (Fig. 1) (6), located some 20 km to the north. These faults together define the southwestern and western margins of the extended terranes.

The transition from the southeastern Chocolate-southern Trigo Mountains domain to the central to northern Trigo Mountains domain occurs over a zone of complex deformation about 10 km wide. Within the transition zone, faults characteristic of both domains are present. In addition, normal fault-bounded blocks, with little internal rotation and deformation of nearly flat-lying Tertiary rocks, are juxtaposed against blocks of moderately faulted and rotated rocks.

The Trigo Mountains domain (fig. 1) is composed of numerous northwest-trending structural panels ranging in width from ten's of meters to about a kikometer. The panels are bounded by shallowly-dipping normal faults that consistently dip 20 and 45^{o} to the southwestward. The Tertiary rocks and the unconformity with the underlying crystalline rocks dip 50 and 70^{o} northeastward. Listric geometry for the shallowly-dipping normal faults is suggested by the presence at higher structural levels of horsetail fault structures (7) that converge with depth to define a shallowly-dipping normal fault; this structure is best seen in the Hart Mountain mine area. Assuming a listric geometry for these faults (8), an extensional strain of approximately 30-40% is indicated.

Steeply dipping faults, which are antithetic to and bounded by the shallowly-dipping faults, break the larger panels into smaller blocks ; some of the antithetic faults cut shallowly-dipping faults. Many of the antithetic faults were initiated along oversteepened, northwest-dipping, lithologic contacts. Some of the antithetic faults have been previously interpreted as regional low-angle normal faults and cited as evidence for the presence of a very shallow, undulating regional low-angle normal or detachment fault now exposed in a series of antiformal culminations (10).

The simple pattern of northeast-tilted structural panels in the central to north Trigo Mountains domain extends northward into the Trigo Peaks-southern Dome Rock Mountains domain (fig. 1). In this domain, the northwest-trending structural panels are cut by several east striking high-angle tear faults with dextral strike-slip separation of as much as 5 km. These tear or transfer faults (7) formed in reponse to differential displacements between the apparently unrotated Dome Rock Mountains to the north and the imbricately-faulted Trigo Peaks to the south. (Because Mesozoic deformational fabrics in the Dome Rock Mountains are colinear with those in ranges to the west of the extended terrane, the range is apparently unrotated and is, therefore, a simple fault-bounded block). The transfer faults which separate the rotated from unrotated terranes closely follows and modifies segments of the Late Mesozoic Mule Mountains thrust (11). Temporal relations between the transfer faults and low-angle normal faults are obscure due to younger high-angle faults and alluvial cover; the tranfer and low-angle normal faults are inferred to be coeval and kinematically related. Estimated extensional strain is approximately 40%.

The observed variations in structural style and extensional strain from southeastern Chocolate Mountains to the Dome Rock Mountains suggest that the rocks exposed in this region constitutes the upper plate of a regional low-angle fault (fig 2a,b). This regional fault is inferred to be subparallel to other large low-angle normal or detachment faults located to the north and northeast (12) and thus probably dips gently to the northeast towards the

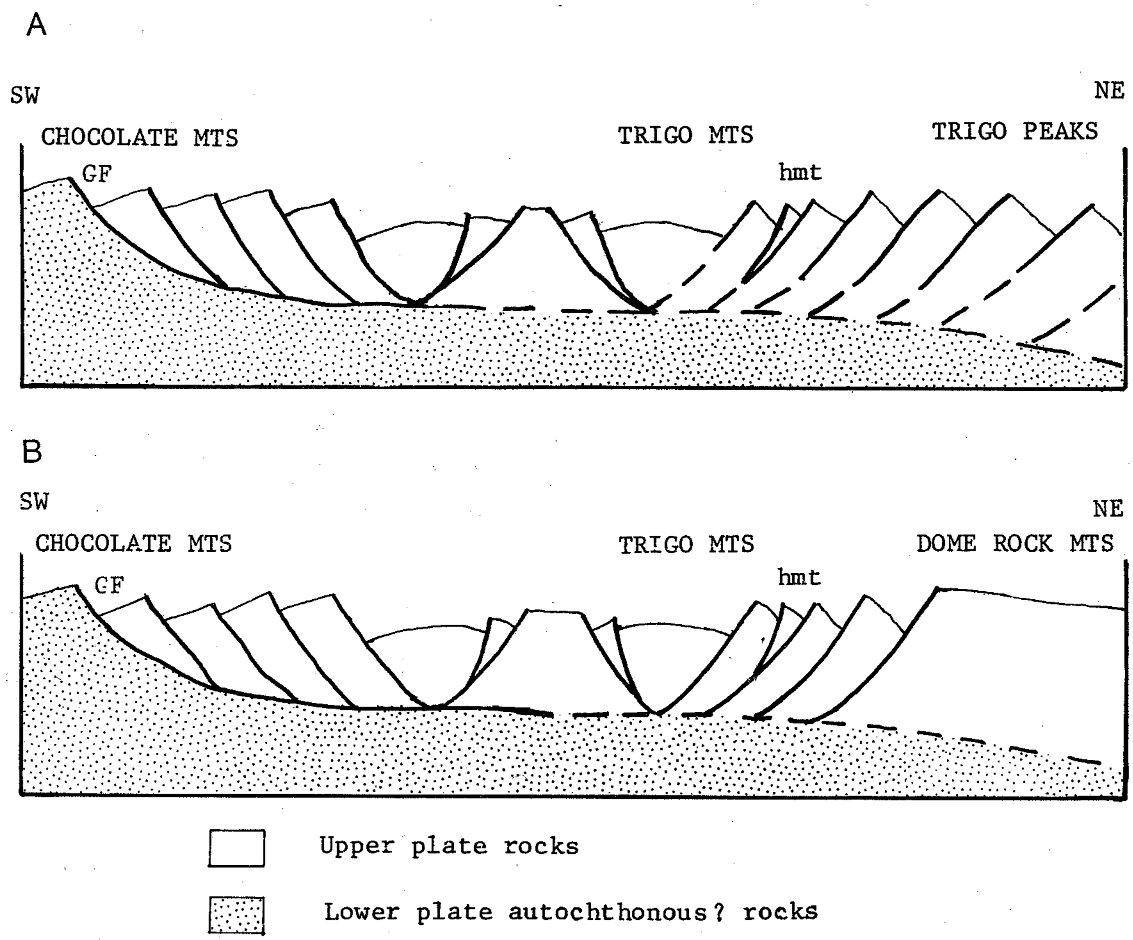

Figure 2. Schematic structural cross section along the transect between the southeastern Chocolate Mountains, California, and the Trigo Peaks and southern Dome Rock Mountains, southwestern Arizona. Syn- and post-extensional clastic rocks and younger faults are not shown on the cross section. Cross section are not drawn to scale and have a large vertical exageration. A) crossection between the southeastern Chocolate Mountains, to southwest, and the Trigo Peaks area, to the northeast; and B) cross section with the fault-bounded, unrotated Dome Rock Mountains projected into the line of the cross section. GF-Gatuna fault; hmt-Hart Mountain mine

Colorado Plateau. The headwall or breakway zone of the extensional allochthon is the Gatuna fault-Midway detachment of the southeasternmost Chocolate Mountains. In this model, the exposed southwest-dipping low-angle normal faults in the Trigo Mountains-Trigo Peaks-Dome Rock Mountains domains would be counter faults (7) and probably intersect the underlying regional sole fault at high angles. The lateral transition from the imbricately extended ranges of the Trigo Mountains-Trigo Peaks area to the apparently unrotated fault-bounded Dome Rock Mountains occurs across a complex zone of dextral transfer faults and low-angle normal faults. The Dome Rock Mountains block probably was also transported as part of the extensional allochthon.

This interpretation of the geometry of extensional deformation at depth in the lower Colorado River region differs significantly from a model which proposes a regional set of antiforms and synforms in a low-angle normal fault that formed as a result of anastomozing brittle and ductile shear zones at depth (13). The planned CALCRUST seismic reflection profile crosses part of this transect and will provide an independent test of both models.

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