Magnitude and significance of Miocene crustal extension in the central Mojave Desert, California

Allen F. Glazner Department of Geology, CB# 3315, Mitchell Hall, University of North Carolina, Chapel Hill, North Carolina 27599

John M. Bartley Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah 84112

J. Douglas Walker Department of Geology, University of Kansas, Lawrence, Kansas 66045

ABSTRACT

The newly recognized Waterman Hills detachment fault (WHDF) of the central Mojave Desert, California, is significant because it provides the first unambiguous evidence for large-scale core complex-style crustal extension in the central Mojave Desert, and because it has significantly rearranged the pre-Miocene paleogeography of the Mojave Desert. The WHDF places steeply dipping to overturned Miocene volcanic and sedimentary rocks upon mylonitic pre-Tertiary basement. The mylonites, which apparently formed during extension, are predominantly L-tectonites which manifest top-to-northeast shear. The WHDF dips to the northeast beneath domino-faulted ranges of the central Mojave Desert and detachment faults of the Colorado River trough, forming an imbricated early Miocene system of detachment faults. Extension continued in the Colorado River trough after extension had ceased in the central Mojave Desert.

Tentative correlations of Mesozoic intrusions suggest about 40 km of slip across the WHDF, which carries eugeoclinal Paleozoic rocks in its hanging wall and cratonal/miogeoclinal Paleozoic rocks in its footwall. Restoration of 40 km of slip (1) removes a prominent kink in the boundary between eugeoclinal and cratonal/miogeoclinal facies, (2) aligns cratonal/miogeoclinal strata near Victorville more closely with the late Paleozoic continental margin farther north, (3) places cratonal/miogeoclinal rocks structurally beneath eugeoclinal rocks, implying that the facies were stacked by thrusting, and (4) straightens the western margin of the Late Jurassic Independence dike swarm.

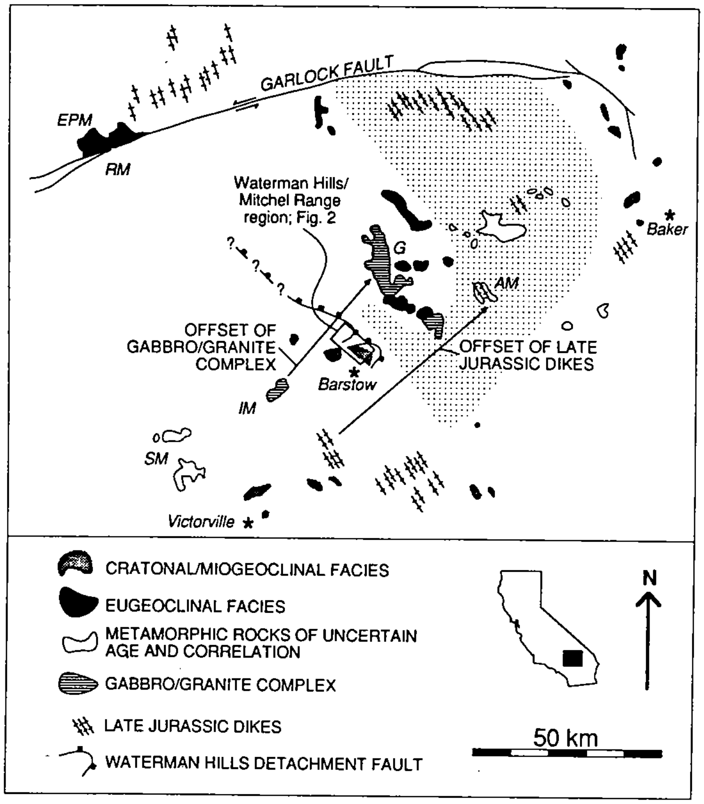


Figure 1. Paleogeographic elements of central Mojave Desert. Waterman Hills detachment fault (WHDF) may have undergone 40 km or more of low-angle displacement (arrows). Stippled area constrains location of boundary between cratonal/miogeoclinal Paleozoic rocks and eugeoclinal Paleozoic rocks; note that contact is poorly constrained everywhere except in Waterman Hills-Goldstone area. Removing slip on WHDF places cratonal/miogeoclinal rocks of Mitchel Range and Hinkley Hills structurally beneath eugeoclinal rocks of Goldstone area. Location of WHDF north and south of Waterman Hills is poorly constrained. AM = Alvord Mountains, EPM = El Paso Mountains, G = Goldstone-Lane Mountain area, IM = Iron Mountains, RM = Rand Mountains, SM = Shadow Mountains.

INTRODUCTION

Although it is well established that much of the southwestern United States was affected by significant crustal extension in the Tertiary, Cenozoic extension in the central Mojave Desert is poorly quantified. Tilted fault blocks of mid-Tertiary rocks in the central Mojave Desert (Dokka, 1986; Glazner, 1988) record at least moderate amounts of extension over a large area, but direct evidence for large-scale, metamorphic core-complex extension similar to that in the Colorado River trough has been lacking. Mylonitic rocks near Barstow were recognized long ago (Bowen, 1954; Dibblee, 1970), but no clear link was established between these tectonites and Tertiary extension.

In this paper we present evidence that structures exposed in the Waterman Hills area (Fig. 1) imply large amounts of early Miocene extension in the central Mojave Desert. These structures define the Waterman Hills detachment fault (WHDF), a newly recognized extensional detachment exposed north of Barstow, California (Fig. 2). Relations of the WHDF clearly imply large amounts (several tens of kilometres) of Tertiary extension.

WATERMAN HILLS DETACHMENT FAULT

Lithologies

Along the WHDF, steeply tilted to overturned Tertiary volcanic and sedimentary rocks lie in low-angle fault contact upon pre-Tertiary, mylonitized granodiorite and gneiss. Details of the stratigraphy and structure in the region are given in Glazner et al. (1988); only a brief summary is given here.

The footwall of the WHDF comprises two distinct units. The Waterman Gneiss is a heterogeneous assemblage of mylonitized metasedimentary and metaigneous rocks (Bowen, 1954; Dibblee, 1967). The gneiss is intruded by a granodiorite pluton of probable Jurassic or Cretaceous age. Following correlations made in surrounding areas by Stewart and Poole (1975) and Kiser (1981), we infer that metasedimentary strata in the Waterman Gneiss correlate with miogeoclinal/cratonal strata of Late Proterozoic and early Paleozoic age in the southern Great Basin. The Waterman Gneiss shows evidence for at least two distinct metamorphic events. The first event, which predated intrusion of Mesozoic granodiorite, reached conditions in the amphibolite facies; the second, of probable early Miocene age, is recorded by a chlorite-grade mylonitic fabric that is pervasively superimposed on the higher grade mineral assemblages.

The hanging wall of the WHDF in the Waterman Hills is composed of Tertiary rhyolite flows and lithic tuffs that pass upward into conglomerate and sandstone. These strata are intruded by rhyolite plugs, and all Tertiary units are truncated against the underlying WHDF. All hanging-wall rocks have undergone pervasive potassium metasomatism identical to that seen in other low-angle normal fault complexes (e.g., Chapin and Glazner, 1983; Brooks, 1986; Glazner, 1988). On the basis of lithologic similarity, we correlate these units with the nearby Pickhandle Formation, which has yielded a 19 Ma age on rhyolite (McCulloh, 1952; Dibblee, 1968; Burke et al., 1982). A minimum age for the Pickhandle Formation in the Mud Hills is given by the unconformably overlying Barstow Formation, which is approximately 18–13 Ma (Burke et al., 1982; MacFadden et al., 1988).

Structural Geology

The WHDF complex records both brittle and ductile deformation related to low-angle normal faulting. The contact between hanging-wall rhyolites and footwall granodiorite is knife-sharp where well exposed at the summit of the Waterman Hills. Rocks within several metres above and below the WHDF are finely comminuted by cataclasis. For hundreds of metres both above and below the contact, the rocks are cut by myriad small faults. In the hanging wall, these faults consistently attenuate the stratigraphic section. Within several tens of metres beneath the WHDF, footwall shattering is accompanied by chloritic alteration.

The Waterman Gneiss is variably mylonitic throughout its exposure, but it is strongly mylonitic, brecciated, and chloritized within tens of metres of the WHDF. The granodiorite is isotropic to faintly lineated away from the WHDF. However, it contains a diffuse mylonitic fabric about 2 km from the trace of the fault which becomes intense within tens of metres of the WHDF. On the basis of these field relations, we infer a Miocene age for formation of the mylonites. The mylonitic fabric is distinctive because only a lineation is apparent in many samples; it is uncommon to find that lineation developed within a coeval foliation. The mean mylonitic lineation trends N40°E, and field and microscopic features of footwall mylonites consistently indicate a top-to-northeast shear sense (Glazner et al., 1988).

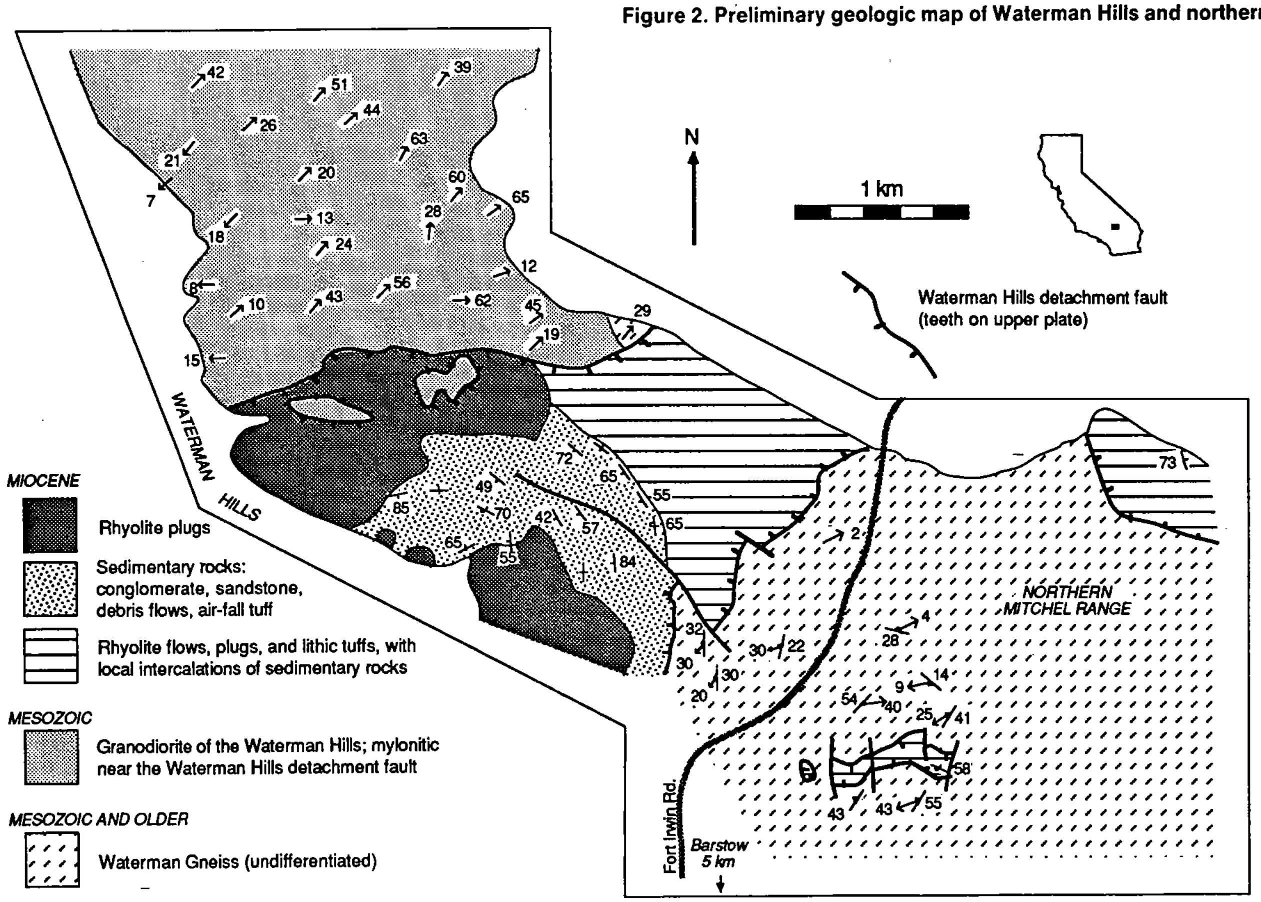
TECTONIC HISTORY

Timing of Deformation

Movement on the WHDF occurred no longer ago than the age of hanging-wall strata, which is poorly constrained at about 19 Ma. A minimum age of faulting can be inferred only indirectly. The extremely coarse nature of clastic rocks in the Pickhandle Formation indicates that they are syntectonic deposits related to displacement on the WHDF. Fine-grained fluviolacustrine strata of the Barstow Formation lie in angular unconformity upon the Pickhandle Formation in the Mud Hills (Dibblee, 1968). We interpret the 18–13 Ma Barstow Formation to record post-tectonic filling of an extensional basin formed adjacent to the Waterman Hills metamorphic core complex by displacement along the WHDF. These relations indicate that displacement on the WHDF occurred about 19–18 Ma.

This is consistent with timing of extension in surrounding ranges. For example, mapping by Dibblee (1964) indicates that tilting in the Newberry Mountains is constrained to the interval between eruption of tilted basalt, dated at 23.7 ±2.3 Ma (Nason et al., 1979; corrected to new decay constants of Dalrymple, 1979), and eruption of the flat-lying Peach Springs Tuff, which has been dated at 18.3 ±0.3 Ma (D. Lux, J. Nielson, and A. Glazner, unpub. $^{40}Ar/^{39}Ar$ age; also see Glazner et al., 1986). In the southeastern Cady Mountains, which lie 70 km east of the Waterman Hills, tilting is bracketed between eruption of 20 Ma tilted volcanic rocks and eruption of the Peach Springs Tuff (Glazner, 1988).

Figure 2. Preliminary geologic map of Waterman Hills and northern Mitchel Range.



Tectonic Model

Tentative correlations between the hanging wall and footwall indicate that the WHDF may have accumulated slip of 40–50 km or more. Distinctive gabbro complexes that are cut by dikes of muscovite-garnet granite crop out in the footwall in the Iron Mountains, 20 km southwest of the Waterman Hills (Bowen, 1954, and our reconnaissance), and in the hanging wall in the Lane Mountain area, 20 km northeast of the Waterman Hills (McCulloh, 1952; Miller and Sutter, 1982). Restoring slip on the WHDF so that these areas are aligned straightens a 50 km jog in the western edge of a Late Jurassic dike swarm (Fig. 1; Miller and Sutter, 1982). In addition, Stone and Stevens (1988) noted that miogeoclinal/cratonal strata near Victorville and in the San Bernardino Mountains crop out anomalously far to the west, relative to an inferred irregular Paleozoic continental margin; aligning the gabbro-granite complexes brings these western exposures much closer to the inferred continental margin.

Figure 3 is a series of schematic cross sections that illustrates our interpretation of relations between the HWDF, sedimentation, and pre-Tertiary basement terranes.

REGIONAL IMPLICATIONS

Recognition of the WHDF as a major extensional fault is important for several reasons. It provides the first unambiguous evidence for large-scale, core complex–like crustal extension in the central Mojave Desert. Although domino-style normal faulting was recognized in ranges east of the Waterman Hills (e.g., Newberry Mountains, Dokka, 1986; Cady Mountains, Glazner, 1988), structures in these areas are brittle and probably reflect hanging-wall deformation for the most part. The WHDF represents the first direct evidence that extension in the central Mojave Desert was of a large enough magnitude to bring ductilely extended rocks to the surface.

The WHDF lies well west of the extended terranes of the Colorado River trough and is separated from that region by an area where Tertiary rocks are nearly flat lying and little extended (Nielson and Glazner, 1986; Glazner and Bartley, 1988). Field relations of the Peach Springs Tuff indicate that extension in the central Mojave Desert ended before extension in the Whipple area ended. In the central Mojave Desert the Peach Springs Tuff is generally flat lying above tilted rocks and thus was erupted after major extension; in the Colorado River trough, significant tilting and extension occurred after eruption of the tuff (K. A. Howard, 1985, personal commun.; Davis, 1986; Nielson and Glazner, 1986). Davis and Lister (1988) proposed that the Whipple detachment system lies in the hanging wall of a slightly older, northeast-dipping detachment system and that mylonitic gneisses in the footwall of the Whipple detachment are exhumed mid- to lower crustal rocks related to the older system. Davis and Lister's (1988) conceptual model of imbricate major detachment systems is therefore supported by timing and kinematic relations between the central Mojave Desert and the Colorado River trough, after removal of Neogene slip on intervening right-lateral faults.

The possibility of large slip (tens of kilometres) on the WHDF implies that pre-Miocene structures and facies trends have been significantly modified. Stratigraphic data demonstrate that the original juxtaposition of miogeoclinal/cratonal and eugeoclinal strata in the Mojave Desert was of Permian-Triassic age (Burchfiel et al., 1980; Walker et al., 1984; Walker, 1988). However, the trace of the boundary between eugeoclinal and miogeoclinal/cratonal facies of Paleozoic rocks is sharply kinked around Barstow (Fig. 1; Burchfiel and Davis, 1981; Kiser, 1981). The coincidence of this kink with the area affected by the WHDF strongly suggests that the kink is a consequence of Tertiary extension.

Miogeoclinal/cratonal Paleozoic facies are exposed in the footwall of the WHDF, whereas eugeoclinal facies in the northern Calico Mountains

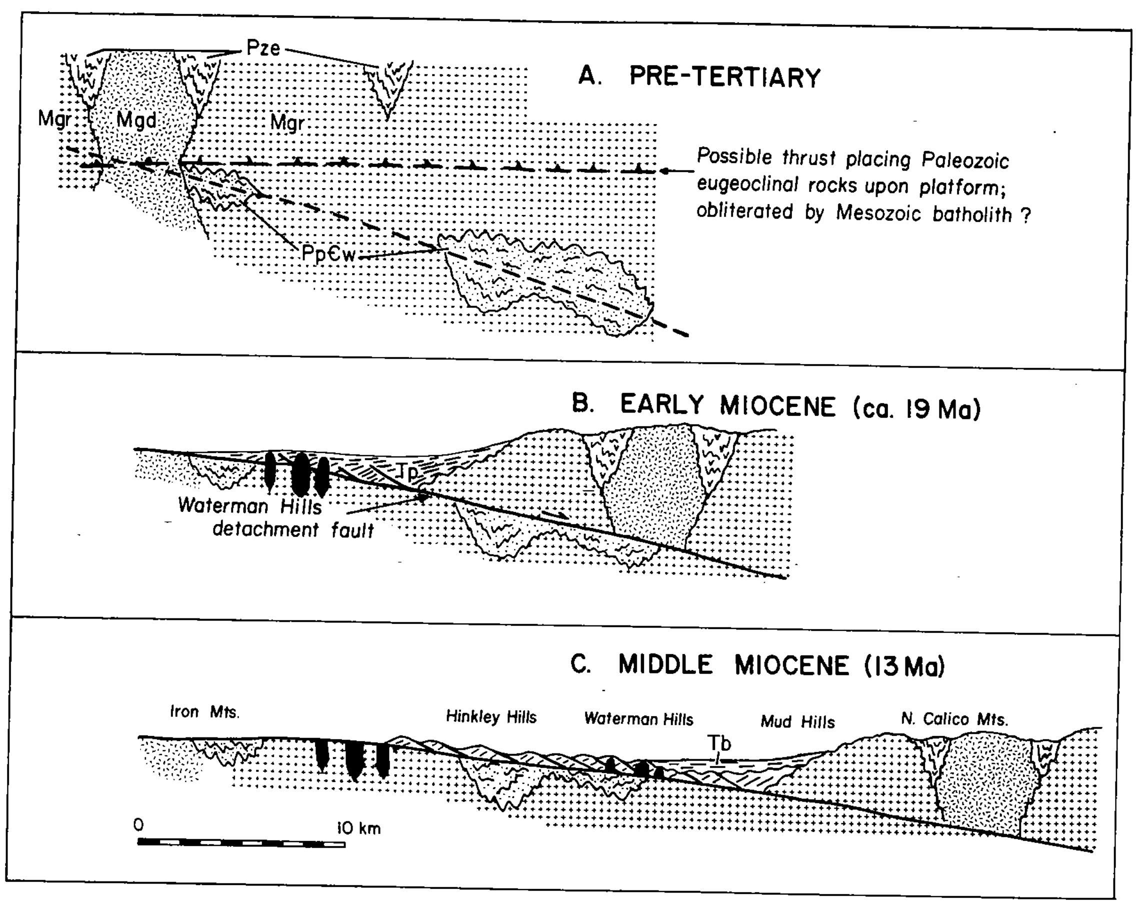


Figure 3. Conceptual model for evolution of Waterman Hills detachment fault (WHDF). Neogene folding related to right-slip Calico fault (Dibblee, 1968) has been removed. A: Geometry with 40 km of displacement on WHDF restored. Eugeoclinal Paleozoic rocks (Pze) lie structurally above miogeoclinal/cratonal Paleozoic strata in Waterman Gneiss (Pp€w). These strata are engulfed by Mesozoic batholith, including gabbro-diorite complex (Mgd) and more widespread granodioritic intrusions (Mgr). B: Geometry during displacement along WHDF. Pickhandle Formation (Tp) is deposited in extensional basin formed by displacement along WHDF and is syntectonically intruded by rhyolite plugs (black). Continued displacement truncates plugs, upper parts of which now are exposed in Waterman Hills; roots of plugs have not been located. C: By mid-Miocene time, after movement has ceased, post-tectonic Barstow Formation (Tb) accumulates unconformably upon Pickhandle Formation in topographic depression formed by extension.

are carried in the hanging wall (Figs. 1 and 3). If normal slip on the WHDF system has been about 15 km or more, then footwall miogeoclinal rocks restore to a pre-Tertiary position structurally below the eugeoclinal rocks. This restoration is consistent with the low metamorphic grade of the eugeoclinal sequence, which contrasts sharply with the amphibolite-facies metamorphism that has affected the miogeoclinal/cratonal rocks. This restoration implies that before Tertiary extension, the eugeoclinal rocks lay upon a thrust contact above the miogeoclinal rocks. Verification of this thrust geometry, the age and significance of the thrusting, and its ultimate implications for Paleozoic-Mesozoic paleogeography must await documentation of the magnitude and areal distribution of the Tertiary extensional overprint.

CONCLUSIONS

1. The Waterman Hills detachment fault is a major low-angle detachment system, and it may be the master shear zone above which hanging-wall extension of ranges to the east was accommodated. Kinematic data indicate that the hanging wall moved northeast relative to the footwall. Low-angle normal faulting occurred in the Miocene, approximately 19–18 Ma, and mylonitization of footwall rocks apparently accompanied faulting.

2. The WHDF roots to the northeast, beneath extensional systems in the Colorado River trough (after restoration of Neogene right-lateral shear), and is slightly older than detachment faults in the Whipple Mountains area. This geometry is compatible with the recent model of Davis and Lister (1988).

3. The Miocene Pickhandle and Barstow Formations were deposited during and after extension, respectively, in an extensional basin or set of basins formed by normal displacement on the Waterman Hills detachment fault.

4. Tentative correlation of gabbro-granite complexes in the hanging wall and footwall of the WHDF indicates 40 km of normal slip on the fault. Removal of this slip straightens the western boundary of a prominent Late Jurassic dike swarm.

5. Restoration of slip on the WHDF moves cratonal/miogeoclinal Paleozoic rocks in the footwall structurally beneath eugeoclinal Paleozoic rocks in the hanging wall, implying that a thrust fault juxtaposed the facies belts prior to Tertiary extension. Restoration also reduces, and perhaps even removes, a prominent bend in the facies boundary, suggesting that the bend is a Tertiary feature.

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