# Western Old Woman Mountains shear zone: Evidence for late ductile extension in the Cordilleran orogenic belt

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## ABSTRACT

**Rocks within the 1-km-thick Western Old Woman Mountains shear zone (WSZ) contain ductilely deformed quartz and ductilely and brittlely deformed feldspars, indicating greenschist to lower amphibolite facies mylonitization. Foliation measured in 73 Ma mid-crustal granitoids within the zone generally dips west-southwest, and sense-of-shear indicators demonstrate top-to-the-west sense of movement parallel to gently southwest plunging lineation. The top of the shear zone is not exposed, but 10 km to the west unmetamorphosed Late Cretaceous-age upper crust is present. The WSZ is thus most simply interpreted as a normal-sense low-angle shear zone. Timing of deformation is constrained to the interval 73 to ca. 65 Ma by the age of deformed granitoids and $^{40}$Ar/$^{39}$Ar chronology. This interval coincides with a period of rapid cooling of rocks now exposed in the Old Woman Mountains that probably resulted from 4 to 8 km of unroofing. We suggest that movement along the WSZ is responsible for at least some of this unroofing. The proposed history involves tectonic denudation along a low-angle ductile shear zone and is similar to that demonstrated for Tertiary Cordilleran metamorphic core complexes.**

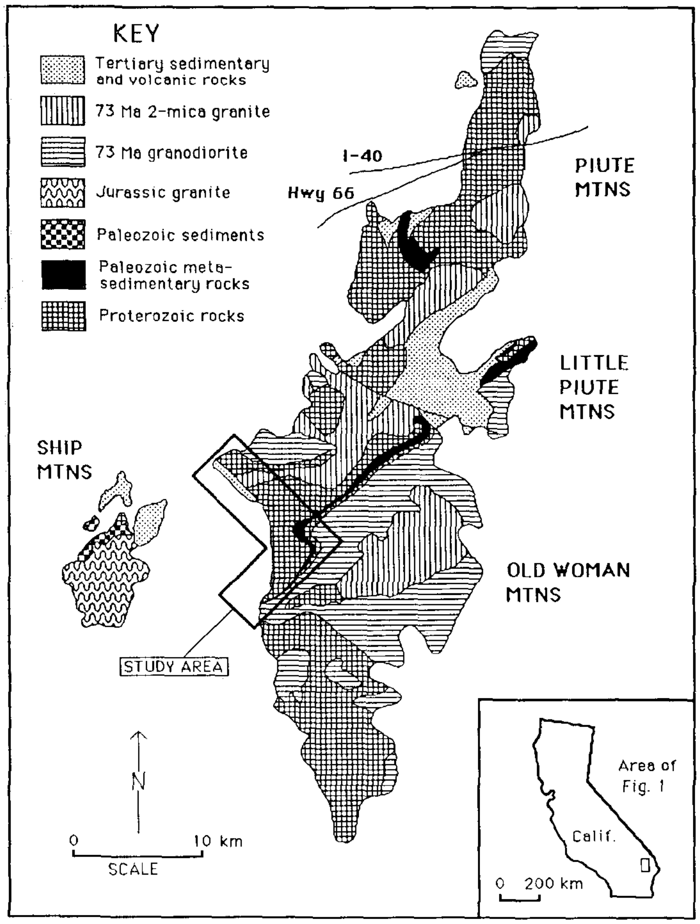

**Figure 1. Sketch geologic map of Old Woman, Piute, Little Piute, and Ship Mountains. Study area is outlined.**

## INTRODUCTION

The eastern Mojave Desert is part of an area that underwent Mesozoic crustal shortening and Cenozoic extension. Shortening is thought to have spanned much of Jurassic and Cretaceous time (e.g., Burchfiel and Davis, 1981; Hamilton, 1982; Foster et al., 1990). Ductile nappes emplaced strata as young as Triassic beneath Proterozoic basement (e.g., Howard et al., 1987; Spencer and Reynolds, 1990). Extension is generally interpreted to be limited to the latter half of Cenozoic time and is most spectacularly manifested in this region by mid-Tertiary metamorphic core complexes (e.g., Crittenden et al., 1980; Davis, 1988).

The Old Woman Mountains (Fig. 1) display a strong imprint of Mesozoic ductile deformation but were only mildly affected by the mid-Tertiary extension that intensely deformed many nearby areas to the east and west (e.g., Miller et al., 1982; Howard et al., 1987; Foster et al., 1990; Hileman et al., 1990). Previous interpretations have held that the ductile deformation here was entirely contractional and that contraction continued through the Late Cretaceous, ending at approximately the time of emplacement of the Old Woman–Piute batholith (73 Ma; Foster et al., 1989; cf. Miller et al., 1982; Howard et al., 1987). Our structural and thermochronologic studies in the western Old Woman Mountains bracket closely the timing of the terminal, postbatholithic stages of deformation, and suggest that this deformation—and conceivably some of the earlier, preplutonic to synplutonic deformation—was extensional and similar in some respects to core complex tectonism.

## WESTERN OLD WOMAN MOUNTAINS SHEAR ZONE

### Geology of the Shear Zone

Rock types of the western Old Woman Mountains are similar to those found throughout the range, including prebatholithic Early Proterozoic through Jurassic rocks that are metamorphosed to upper amphibolite facies and 73 Ma batholithic granitoids. Distinct from most of the range, however, is the penetrative imprint of postbatholithic lower temperature ductile deformation. Within a zone that is exposed for 15 km at the western edge of the range, all rocks, including the granitoids, are affected by noncoaxial penetrative deformation. This area is referred to as the Western Old Woman Mountains shear zone (WSZ).

Foliation within the WSZ generally dips 10°–30° west-southwest, although steeper dips are present locally (Fig. 2). The strike of the foliation bends westward, and dips steepen in the southern part of the shear zone. Lineations are generally downdip (240°–250°), though in the south they plunge obliquely to the northwest dip of the foliation (260°–270°, 10°–30°).

The base of the WSZ, as defined by the disappearance of retrograde tectonic fabric in the Late Cretaceous granitoids, follows the foliation, dipping generally west-southwest and bending to the northwest in the south. The exposed structural thickness is about 1 km. Intensity of deformation is highly variable but generally increases from east to west, structurally upward (Fig. 2). The batholithic granitoids best document late ductile deformation and therefore are emphasized in this study. To the east, these granitoids are virtually undeformed: they retain igneous, generally isotropic fabrics, feldspars are undeformed, and quartz exhibits only

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weak undulatory extinction. At the extreme western edge of the range, the brittle mid-Tertiary Ship Mountains fault truncates the WSZ and juxtaposes it against Tertiary conglomerates (Hileman et al., 1990). At the highest exposed structural level, granitoids are strongly mylonitized and typically record considerable grain-size reduction and modest to strong S-C fabrics. Quartz is intensely strained, forming fine-grained ribbons, and feldspars are dynamically recrystallized, brittlely fractured, and pulled apart. At intermediate levels within the WSZ, quartz is less intensely strained and feldspar is undeformed or dynamically recrystallized but not brittlely fractured. Ductile recrystallization of quartz and ductile to brittle behavior of feldspars suggest that deformation occurred under greenschist and probably lower amphibolite facies conditions (cf. Simpson, 1985), which is consistent with the minor mineralogical adjustments that accompanied deformation (partial chloritization of biotite and hornblende, sericitization of feldspars). The absence of brittle behavior in feldspar at lower levels indicates either that deformation there took place at higher temperature than that at upper levels or that strain rate (higher at upper levels?) determined the deformation mechanism.

Quantitative assessment of strain within the exposed part of the WSZ is difficult. However, angles between S and C surfaces in S-C mylonites (22°–36°) and attenuation of feldspars, quartz ribbons, and micas in the more highly deformed rocks (length/width ratios up to 10, commonly near 10, and >>10, respectively) provide constraints. Petrographic and field observations suggest that average shear strain within the exposed part of the WSZ was at least one.

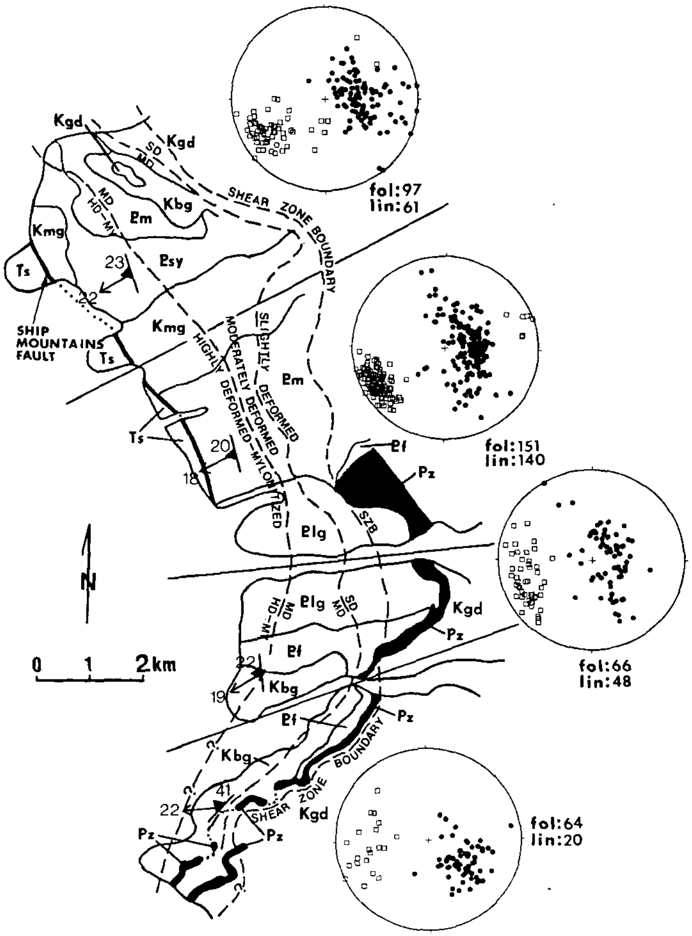

**Figure 2. Dashed lines on map indicate approximate transitions between zones of varying deformation. Foliations and lineations on map are averages for subareas; equal-area projections show all measured foliations (dots) and lineations (squares) in subareas. Numbers of data points are given beside each stereograph. SZB = shear zone boundary; SD = slightly deformed; MD = moderately deformed; HD = highly deformed; MY = mylonitized; fol = foliations; lin = lineations. Rock units: Ts = Tertiary sedimentary; Kbg, Kmg = Cretaceous biotite, muscovite granite; Kgd = Cretaceous granodiorite; Pz = Paleozoic metasedimentary; Ꝑlg = Proterozoic leucogranite gneiss; Ꝑf = Proterozoic Fenner Gneiss (1.68 Ga); Ꝑm = Proterozoic metasedimentary; Ꝑsy = Proterozoic syenite.**

Sense of shear indicators, including S-C relations; asymmetry of feldspars, mica fish, and shear bands; and displacement of fragments of feldspars were evaluated in the field and in thin section. All indicators consistently demonstrate top-to-the-west (generally downdip) shear sense.

### Kinematics and Displacement

Downdip, top-to-the-west-southwest movement within the WSZ suggests normal-sense movement. It is conceivable that subsequent deformation rotated an initially east-dipping, reverse-sense zone to its present orientation, but several lines of evidence make this interpretation unlikely. Both paleobarometry of Cretaceous plutonic and metamorphic rocks and studies of Tertiary tectonism suggest that major east-west tilting has not occurred since the plutons were emplaced (Foster, 1989; Foster et al., 1989; Hileman et al., 1990). Fission-track geochronometry indicates instead that there has been minor *eastward* tilting (Foster et al., 1991). Furthermore, the rapid latest Cretaceous cooling in the area (Foster, 1989; Foster et al., 1989) is far easier to reconcile with normal than reverse movement.

Total displacement within the exposed shear zone can be only crudely approximated because of the absence of marker units and our imprecise knowledge of shear strain. If the average shear strain parallel to the shear-zone boundary is at least one, then total displacement over the 1-km-thick zone is at least 1 km. If the shear zone has not been rotated much after movement occurred, the vertical component of the displacement was roughly one-third of total displacement (based on the present dip of about 20°). Actual displacement (total and vertical) could have been much greater, because strain increases upward and the top of the zone is not exposed. Furthermore, the initial dip of the shear zone may have been steeper (hence greater vertical displacement component), and our crude estimate of shear strain does not take into account potentially large displacements on very narrow high-strain zones (e.g., Bartley, 1985).

### Timing of Deformation

Rapid Late Cretaceous cooling of rocks exposed in the Old Woman Mountains has been documented by the $^{40}Ar/^{39}Ar$ method (Foster, 1989; Foster et al., 1989). During emplacement of the Old Woman–Piute batholith at 73 Ma, country-rock temperatures at deeper levels reached 650 °C (Hoisch et al., 1988; Foster, 1989). Within 1 m.y., the batholith and country rocks had cooled to 450–500 °C; cooling continued at ~30 °C/m.y. for the next 5 m.y., and then slowed dramatically (Foster, 1989). Five samples collected from within the WSZ document this history (Fig. 3A).

The cooling history and nature of deformation constrain the timing of ductile deformation within the WSZ (Fig. 3B). Temperatures in excess of about 450 °C are required for dynamic recrystallization of feldspar in shear zones (e.g., Tullis and Yund, 1985; Simpson and Wintsch, 1989), whereas quartz can accommodate dynamic recrystallization at temperatures above about 300 °C (e.g., Voll, 1976). Fabrics of samples from the WSZ indicate that temperatures spanned the ductile-to-brittle feldspar behavior transition. We infer that movement within the WSZ occurred between about 73 and 65 Ma, when temperatures were greater than 300 °C. Deformation involving ductile behavior of feldspar must have occurred no later than 71–72 Ma, but ductile-quartz/brittle-feldspar deformation may have continued for several million more years.

## DISCUSSION

### Latest Cretaceous Unroofing Event

The latest Cretaceous thermal history of the Old Woman Mountains is inconsistent with static conductive cooling following batholith emplacement. Initial depths and rates of cooling imply instead considerable

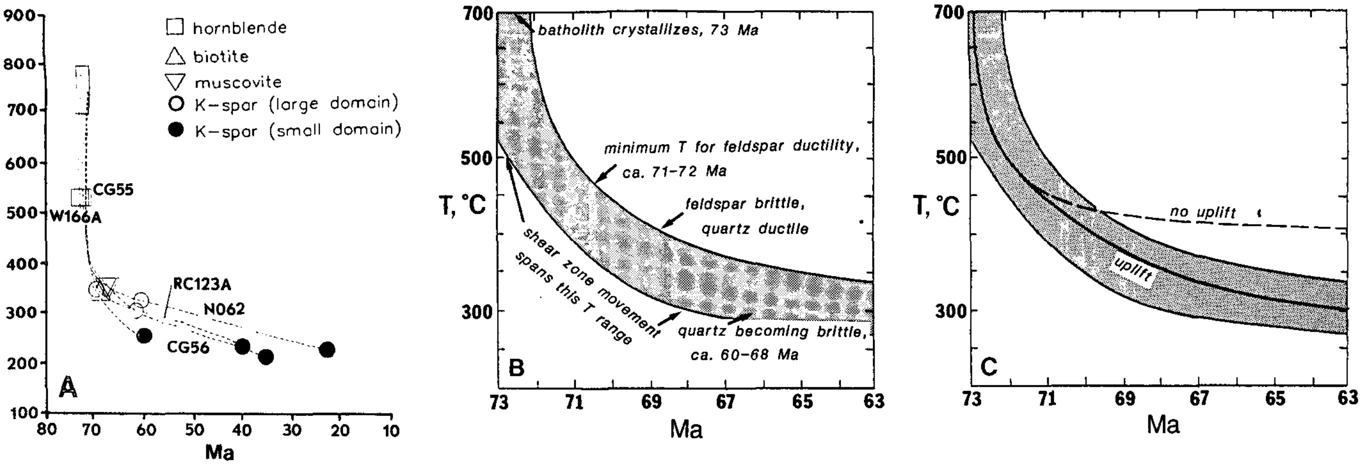

**Figure 3. A: Time-temperature history of rocks of Western Old Woman Mountains shear zone, based on $^{40}Ar/^{39}Ar$ thermochronology of deformed samples and U/Pb geochronology and zircon saturation thermometry of Cretaceous granitoids (Foster et al., 1989; Foster, 1989). B: Timing constraints on deformation in WSZ, based upon thermochronology and styles of deformation (see text). Shaded area represents thermal history of shear zone from A. C: Calculated cooling history of rock in middle of 4-km-thick pluton emplaced at 12 to 16 km depth, compared with shear-zone thermal history. Curves are shown for cooling without denudation and for cooling with denudation at rate of 1 mm/yr between 73 and 68 Ma. Initial geothermal gradient is set at 30 °C/km above pluton and 20 °C/km below it. Temperatures vary significantly with choices of input parameters, but general shapes of cooling curves after ca. 72 Ma are sensitive only to uplift history. Modeling was done using program 1DT (Haugerud, 1989).**

denudation during this time. Thermobarometry indicates that the granitoids of the Old Woman Mountains were emplaced at a depth of 15 ±3 km. Peak Mesozoic metamorphism, which coincided with pluton emplacement, occurred at pressures of 3–5 kbar (Foster, 1989; Rothstein et al., 1989). Aluminum contents of hornblende in granodiorite indicate pressures of about 4–5 kbar, based upon the experimental calibration of Johnson and Rutherford (1989) (earlier estimates of 5.5–6 kbar [Foster et al., 1989; Young and Wooden, 1988] used the empirical calibration of Hollister et al. [1987]). Garnet-plagioclase-muscovite-biotite barometry of two-mica granites is hampered by high Mn and low Ca in garnets and low Ca content of plagioclase, but it is consistent with pressures of 4–5 kbar (Foster, 1989; F. Florence, 1989, personal commun.).

It is difficult to reconcile temperatures less than 300 °C with depths greater than 12 km in an area of thickened, magmatically active orogenic crust. Indeed, thermochronological evidence indicates that prebatholithic geothermal gradients in this area were substantially greater than 25 °C/km (Foster, 1989; Foster et al., unpublished). Furthermore, although the initial very rapid cooling of the Old Woman Mountains is clearly a response primarily to conductive heat loss from the batholith, this mechanism is significant for only 1 or 2 m.y. and cannot account for the protracted 30 °C/m.y. cooling (Fig. 3C). On the other hand, even dramatic changes in heat transfer from the very deep crust or upper mantle would result in regional cooling at much slower rates than those observed in the Old Woman Mountains. Regional cooling occurred in the eastern Mojave Desert between 65 and 55 Ma (Hoisch et al., 1988; Foster et al., 1990). For example, Dumitru's (1990) model of crustal refrigeration of the Sierra Nevada explains cooling that occurred over a 10–20 m.y. interval as a consequence of cessation of magmatism and initiation of low-angle subduction, but temperatures declined only slightly during the first several million years after magmatism ended. Cooling by circulation of cold fluids is also unlikely to have been important, because hydrothermal alteration is very minor and stable isotope data for granitoids and country rocks do not support involvement of meteoric water (Miller et al., 1990; Morrison, 1991). Several million years of moderately rapid cooling is most simply explained as a response to uplift and denudation. Unroofing rates of 1–2 mm/yr over periods of 3–5 m.y. yield time-temperature paths that match the thermal history well (Fig. 3C).

## Role of the WSZ in Denudation

The WSZ was active during the time that we infer the rocks now exposed in the Old Woman Mountains were being unroofed. As a low-angle normal shear zone, the WSZ provides an appealing explanation for denudation. As currently exposed, it does not appear capable of having accommodated the roughly 5 km of denudation (vertical component of displacement) required for our interpretation of the cooling history. However, a considerable amount of displacement may have occurred in the upper part of the zone that has been eroded away. Alternatively, the WSZ may have been only one of several denudational structures that accommodated the total unroofing. Upper crustal rocks are exposed in the Ship Mountains, 10 km west of the WSZ (Fig. 1). $^{40}Ar/^{39}Ar$ data indicate that temperatures in the Ship Mountains during the Cretaceous were well below 250 °C, suggesting that the upper crustal rocks were shallower than 8 to 10 km (Foster et al., 1990), and Al content in hornblende from the Jurassic Ship Mountains pluton indicates an emplacement depth of less than 4 km (Foster et al., unpublished). The close proximity of these two contrasting crustal levels, combined with the absence of westward tilting, suggests that a major structure or structures lies between them.

## Cretaceous Metamorphic Core Complex?

Late Cretaceous geologic features of the Old Woman Mountains are in several respects similar to those of metamorphic core complexes. A mid-crustal "metamorphic core" composes most of the range. This core is bounded on the west by the ductile, low-angle, normal-sense WSZ. Another postplutonic, Late Cretaceous, greenschist grade ductile shear zone exposed at the southeastern edge of the Old Woman Mountains dips southeast (Howard et al., 1989) and has top-to-the-southeast displacement; a domal Late Cretaceous extensional structure is thus suggested.

## Relation to Earlier Deformation

Ductile structures in the Old Woman Mountains, most notably the Scanlon or Old Woman nappe, have been interpreted to be Late Cretaceous (synplutonic to slightly preplutonic) in age and contractional in nature (e.g., Howard et al., 1980, 1987; Miller et al., 1982; Rothstein et al., 1989). The time interval between the development of at least some of these ductile features and the WSZ was very brief, if there was an interval at all: supposedly contractional deformation spanned pluton emplacement (e.g., Rothstein et al., 1989), and the WSZ was active within about 1 m.y. of pluton crystallization. Part of the Scanlon nappe is within the WSZ, and kinematic indicators preserved in the two structures suggest similar shear sense (Carl, 1989; Rothstein et al., 1989). The WSZ could simply be the last manifestation of movement related to the Scanlon nappe; if so, presumably either both structures are contractional or both are extensional. If they are contractional, downdip movement in the WSZ might be explained as occurring along an irregularity in the base of a flat to east-dipping, west-directed nappe; we do not favor this interpretation. Alternatively, although crustal shortening at some time during the Mesozoic must be invoked to account for emplacement of the Paleozoic section beneath many kilometres of Proterozoic rock, intense Late Cretaceous extensional deformation could have obscured the earlier contractional imprint. This contraction could have occurred as early as the mid-Mesozoic (e.g., Foster et al., 1990, and unpublished), or there may have been an extremely rapid transition from contraction to extension, perhaps facilitated by magmatically induced heating and weakening of the crust (cf. Wernicke et al., 1987). Finally, we note that Hodges and Walker (1990a, 1990b) have suggested that, during the Cretaceous, extension *contemporaneous with contraction* may have been widespread in the Cordilleran hinterland.

## CONCLUSIONS

The western Old Woman Mountains shear zone, which was active between 73 and 65 Ma, represents the final stages of ductile deformation in this area. Movement was top-to-the-west (down-dip), and thus the WSZ is most simply interpreted as an extensional structure. The interval of movement coincided with a period of rapid cooling that is most easily explained by denudation, quite likely along the WSZ and perhaps other similar contemporaneous structures. If this interpretation is correct, the Old Woman Mountains underwent core complex–like tectonism long before the accepted advent of crustal extension and core complex development in the southwestern United States.

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