

Geologic evolution and regional implications of southern Old Dad Mountain, Mojave Desert, California

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ABSTRACT

Our remapping of a portion of Old Dad Mountain is mostly consistent with geology described by Dunne (1977). There are three major structures at Old Dad that correlate to three periods of deformation: 1) the Mid-Late Mesozoic age Powerline Canyon Shear Zone may be associated with lateral strain accommodation along an obliquely converging margin, 2) a Late Cretaceous Sevier structure, the Playground Thrust, that transports Paleozoic carbonate rocks to the southeast atop Jurassic metavolcanics; and 3) the Late Cenozoic Old Dad normal fault that is most likely associated with Miocene Basin and Range extension. Cross cutting relationships and kinematic data obtained in this study make it unlikely that a strand of the active dextral Soda-Avawatz Fault zone is present in the map area, but make obvious the similarities between the structure of Old Dad and the structure of other localities in the Eastern Mojave Desert, such as the Clark and New York mountains. Observations and kinematic data from this study may be useful in unraveling the complex development of active faults within the Mojave Desert, especially if combined with future geochronologic data from the samples taken at Old Dad.

INTRODUCTION

The Mojave Desert lies within the area being actively deformed due to transform motion along the Pacific and North American plate boundary. Only 75% of the plate motion is accommodated along the San Andreas Fault, and the rest is occurring inland along complex fault systems (Miller et al., 2001). Major faults that are part of this system are located in or around the Mojave Desert, in particular the east-west trending, left-lateral Garlock Fault, northwest trending, right-lateral Southern Death Valley Fault, and the right-lateral Soda-Avawatz fault zone that forms where the two aforementioned faults meet. The Soda-Avawatz fault zone continues southward into the Mojave National Preserve (Fig. 1). Horizontal displacement along the Garlock Fault Zone is 64 km (Andrew et al., 2015), along the Southern Death Valley Fault is most likely 55 km (Topping, 1993), and along the Soda-Avawatz fault zone a poorly constrained estimate of between 8 and 45 km (Davis, 1977; Brady 1984; McQuarrie and Wernicke, 2005). Large differences in the estimates of offset along the Soda-Avawatz Fault Zone may be due to the presence of unknown faults to the east and west of Old Dad that are involved in a multi-stranded style of deformation. Determining the offset of the Soda-Avawatz Fault Zone is important to understanding the history and mechanics of interaction between the Southern Death Valley Fault and Garlock Fault Zone. Three models have been proposed to explain the nature of interaction and displacement along these faults: 1) The Southern Death Valley Fault cuts and offsets the Garlock Fault. This would require a remnant of the Garlock Fault to be present on the eastern side of the Soda-Avawatz Fault Zone and offset on the Soda-Avawatz Fault Zone would be ~55 km, similar to the SDV fault, 2) the two faults act as an unzipping zipper through time and the offset on the Soda-Avawatz Fault Zone would be small (perhaps ~ 9 km, the difference between offset on the

Garlock and SDV faults) or 3) some combination of the two that would result in an intermediate amount of slip along the Soda-Avawatz Fault Zone.

Old Dad Mountain is located on eastern side of the Soda-Avawatz Fault Zone, ~9 km south of the Soda Mountains, ~55 km south of the Avawatz Mountains, and adjacent to the Cowhole Mountains (Fig. 2). This study focuses on the remapping of a part of Old Dad Mountain in order to gather kinematic and fault-relationship data that can be compared with similar data in the Cowhole Mountains, Soda Mountains and Avawatz Mountains to aid in understanding the offset on the Soda-Avawatz Fault Zone and even if it is present in the area along similar striking structures. Mapping was accomplished using StraboSpot mobile app, an open source mapping software, in conjunction with basic field mapping techniques.

GEOLOGIC SETTING

In the Mojave Desert region, Precambrian Basement rocks range in age from 1400 to 1700 Ma. From the Upper Precambrian to the lower Permian, the western edge of the North American craton was a passive margin where miogeosynclinal rocks were deposited atop the basement rocks. Old Dad Mountain was on the southeastern margin of the Cordilleran miogeosyncline (Walker et al., 2002; Dunne, 1977). In the late Paleozoic, the Mojave went from an inboard position to an outboard position on the plate margin, achieved by left-lateral strike slip truncation of the continental margin (Walker, 1988). By Late Permian- Early Triassic, the Mojave Desert region was part of an active east directed subduction margin (Walker et al., 2002). In the middle Jurassic, magmatic arc activity was present in the Mojave Desert region, along with associated sedimentation, which is evidenced by the Jurassic volcanic and metavolcanic units with intercalated sandstone at Old Dad Mountain. From the Triassic to present, the Mojave area

experienced multiple episodes of deformation, including the Late Jurassic Nevadan Orogeny, Late Cretaceous Sevier Orogeny and Cenozoic deformation associated Early Miocene large magnitude extension, and later Neogene transpression (Walker et al., 2002; Glazner et al., 2002). Large scale thrusting within the Old Dad area is probably associated with the Sevier Orogeny, as no large-scale compressional structures of Laramide or younger age are believed to exist in the northeastern Mojave (Dunne, 1977). It seems there was a period of relative tectonic quiescence in the Old Dad area in the early Cenozoic. The main structural features at Old Dad Mountain consist of the Powerline Canyon Shear Zone, Playground Thrust Fault, and Old Dad Normal Fault, which will be described detail in the following sections (Fig. 2 and 3).

ROCK UNITS

The rock units observed within the map area are described below in order from oldest to youngest, modified slightly from Dunne (1972, 1977), Walker (1988), Stewart (1970), and Rogers (1974).

Precambrian Basement

The basement exposed east of Old Dad Fault is composed chiefly of granitoid rocks that are locally foliated. The granitoids intrude into intermediate to felsic gneisses and minor schists (Dunne, 1977). These rocks were not studied further in the current work.

Lower Paleozoic Carbonates within Shear Zone

Pods of variably metamorphosed limestone were observed within the Powerline Canyon Shear Zone. The majority exposed south of Powerline Canyon are white and metamorphosed to locally

foliated marble. Carbonates exposed to the north of Powerline Canyon are bright red and orange and appear to be hydrothermally altered. Dunne (1972) identified these carbonates as early Paleozoic units.

Pennsylvanian-Permian Bird Spring Formation

The bulk of this unit within the map area is composed of 1-8 meter thick beds of medium-light gray limestone that is fossiliferous and cherty (Dunne, 1972). Some carbonate beds contain abundant chert nodules, and abundant crinoids were observed locally (west of W-fault, Fig. 3). Interbedded buff to pink, silty to sandy limestone and thin silty shales are present throughout the section. Its weathering profile has a cliff-bench appearance controlled by bedding and is modified by gravity induced slumping and brecciation (Dunne, 1972). The maximum exposed thickness of the unit in this area, as described by Dunne 1977, is ~ 550 m.

Jurassic Aztec Sandstone and Volcanics

Dunne (1977) mapped this unit as Triassic Volcanics (TRlv). It consists of hydrothermally altered, dark-colored subaerial flow rock, flow breccia, and minor tuff. It also contains interbedded volcanoclastic sedimentary rock and quartzite. Volcanic units appear to be basalt, andesite, and dacite, and probably have calc-alkalic chemical affinities (Rogers et al, 1974). Dunne (1972b) suggests a correlation with the Soda Mountains Formation described by Grose (1959), which is known to be of Jurassic age (Walker, unpublished data). The quartzites within the unit are then correlated with the Lower Jurassic Aztec Sandstone (Grose, 1959; Marzolf, 1983) and/or the Middle Jurassic quartzites in the Cowhole Mountains (Busby-Spera et al., 1987).

Jurassic Volcanic Rocks (*Jd*)

This unit is dark purple and porphyritic. It has a fine grained, dark purple ground mass and variably abundant white, elongate phenocrysts that appear in hand-sample to be dominantly plagioclase. In the sections observed, phenocrysts do not appear to have any obvious mineral alignment due to flow or shear. In Dunne's (1972) more detailed analysis, observed composition is andesite, latite, and/or trachyte.

Jurassic Sands Granite

The Sands Granite is a coarse grained, leucocratic granite that is pale-pink in color (Dunne, 1972). Within the map area of this study, it was only observed within the Powerline Canyon Shear Zone, where it has experienced variable degrees of shear and hydrothermal alteration. The age of the unit is uncertain, but was observed to intrude the probable Jurassic metavolcanics by Dunne (1977), indicating it is Jurassic or younger in age.

Shear Zone Matrix Rock

That rock that forms the matrix of the Powerline canyon shear zone is dark colored (green, blue, black) fine-grained, and resistant. Dunne (1972) describes it as being sheared rock derived from both sides of the shear zone, so it is a comminuted mass of Precambrian basement rocks and probably Jurassic metavolcanics that have experienced varying degrees of additional metamorphism. The unit is difficult to interpret because of the degree of deformation.

Note of Geochronology

Although there are no U-Pb dates presented in this paper, three samples were taken from the Jurassic volcanics, Jurassic Aztec and Jurassic Sands Granite. Due to equipment repair, the samples were not processed to completion and no geochronology data was obtained. However, the samples did pass through the majority of the mineral separation process for zircon, and if dated, could be very useful to the research in the area.

STRUCTURAL GEOLOGY

The Mojave Desert and Old Dad Mountain have experienced a very complex tectonic history, resulting in the superposition of structures from several episodes of different kinds of deformation. Three major first order structures are located in the map area along with other minor structures, and will be discussed in this section.

Powerline Canyon Shear Zone

The Powerline Canyon Shear Zone is a 300-450 m wide zone of brittle and ductile shear that juxtaposes Precambrian rocks on the east against Jurassic metavolcanic and plutonic rocks on the west. It appears to be near vertical, dipping steeply to the east between 70-90 degrees. Within the shear zone is a dark colored matrix rock that has experienced significant shear, and is probably a mixture of the rocks on either side of the shear zone (Dunne, 1977). In this study, it was observed to surround pods of less-sheared Paleozoic limestone on the eastern half and Jurassic Sands Granite on the western half, although Dunne (1977) also describes pods of gneiss and volcanic rocks to be present. Pods of limestone within the shear zone are commonly marble, and contain a fabric that appears to be foliation. From pod to pod, orientations of this fabric were measured to strike between 290-345° with a dip of 70-88° degrees to the east.

The Powerline Canyon Shear Zone is interpreted to accommodate a significant amount of left lateral slip (Dunne, 1977). Evidence for this lies in the complicated network of braided faults within the shear zone (some illustrated in the map, Fig 3), the presence of rocks within the shear zone that do not appear directly on either side of it, and the presence of Sands Granite within the shear zone, which is located ~ 1 km to the S of its appearance within the shear zone (Fig. 3; Dunne, 1977). This relationship indicates a minimum of ~ 1km of slip. Dip-slip movement could have also occurred along the shear zone, but no direct evidence for dip slip was observed. Two z-folds were observed within the limestone pods; one with a trend of 120° and plunge of 72°, and another that was more difficult to accurately measure, but that trended 143°. These structures would generally indicate dextral rather than sinistral shear, but could be located along an antithetic fault (R' shear) or could have occurred during a different period of deformation. At its northernmost exposure, the Powerline Canyon Shear Zone disappears beneath the Playground Thrust (Fig 3).

Playground Thrust Fault

The Playground Thrust Fault places Paleozoic Bird Springs Limestone on top of Jurassic volcanic and metavolcanic units. It is hard to constrain the overall orientation of the fault, as measurements of strike and dip on exposed surfaces were highly variable and not necessarily representative of the entire fault contact between Paleozoic and Jurassic rocks, probably due to later deformation in the Cenozoic (Fig 4A, stereonet). Dunne (1977) recorded a fault dip of 10-15 degrees east; however, its current dip does not represent the orientation of the fault at the time of deformation, as it was later tilted due to Cenozoic normal faulting on the Old Dad Fault. Dunne (1977) described the nature of the fault as a thin zone of ductile deformation within the

bottom few centimeters to a meter of the hanging wall being. Hanging wall rocks are recrystallized and transposed, but some outcrops of the fault within the map area of this study displayed evidence for both brittle and ductile deformation. Large-scale drag folds are present in the weak carbonate rocks of the hanging wall, but pencil cleavage and fault gauge were also observed.

Kinematic indicators, including drag folds, mullions, slickenlines, pencil cleavage, and questionable Reidel shears point to SE directed slip. A large drag fold near the SW corner of the existing hanging wall has limbs oriented at $200^{\circ};24^{\circ}$ and $65^{\circ};84^{\circ}$, indicating a SE vergence direction (Fig 5A). An anticline, syncline pair in the Bird Springs directly above the fault on the W side of Old Dad has S-SE vergence direction (Fig 5B). Multiple lineation measurements, displayed in the Stereonet in Fig 4B, were taken on mullions, pencil cleavage, and slickenlines. Their average trend is NW-SE, and the plunge is highly variable and probably inconclusive due to Cenozoic tilting. To the east, the Playground Thrust is truncated by Old Dad Fault (Fig 3).

Old Dad Fault

The Old Dad Fault is a large normal fault on the eastern flank of the range. It juxtaposes Precambrian basement rocks in the footwall next to Paleozoic and younger rocks in the hanging wall. The fault is mostly covered by Quaternary deposits, but insight on the orientation and style of deformation were gained from a few outcrops in the very NE portion of the map area and drag folds in the Bird Springs Limestone. Based on only a few measurements, the fault strikes SE and dips steeply $\sim 60\text{-}70^{\circ}$ to the NW, roughly in agreement with Dunne (1977). Two large drag folds within the hanging wall are the most reliable indicator of fault kinematics in the map area. The beds within the first fold are striking between $130\text{-}133^{\circ}$ and increase in dip from 50° to 5°

overturned as they approach the fault (Fig 6A). The second fold is similar, with strikes between 120° and 140° and dips gradually increasing to the E from 80° to 5° overturned (Fig 6B). The two folds, as well as a fault plane outcrop (location on map Fig 3) suggest that Old Dad Fault strikes between 120-160° and fault movement down to the W-SW. The tilting of the hanging wall block may indicate that the fault may have a listric geometry.

Western Normal Fault

In the western-most portion of the map area, an additional normal fault trending N-NW is interpreted, which Dunne (1977) refers to as a gravity-induced landslide based on his interpretation of the structure. There are no clear exposures of the fault; however, on the eastern side of the drainage there are Jurassic volcanic rocks, and directly on the other side of the drainage, a fairly coherent block of Paleozoic Bird Springs Limestone. The orientation of the fault and units cut by the fault are similar to the Old Dad Fault, so they are probably associated with the same period of deformation.

STRUCTURAL DEVELOPMENT

The timing of structural development at Old Dad Mountain can be interpreted on the basis of observed cross-cutting relationships combined with published knowledge of regional deformational events. The Powerline Shear Zone truncates and incorporates the Jurassic Sands Granite and Jurassic metavolcanics units, and is truncated to the north by the Playground Thrust. The Powerline Canyon Shear Zone must therefore have a minimum age in the Jurassic and must be older than the Playground Thrust that is most likely late Cretaceous in age. Large Cretaceous age thrust faults within the Eastern Mojave Desert, specifically from Clark Mountain to the Old

Woman Mountains, were described by Walker et al. (2002) to be part of the Sevier thrust belt. The Playground Thrust is likely part of that deformation, activity on which is dated ~98-85 Ma (Fleck and Car, 1990; Flecher and Karlstrom, 1990; Karlstrom et al., 1993). Old Dad Fault truncates both the Playground Thrust and the Powerline Canyon Shear Zone. The truncation of the Powerline Canyon Shear Zone lies to the south of the mapped area, but is described by Dunne (1977). Old Dad Fault, as well as the smaller normal fault in the western part of the map, is probably associated with Miocene Basin and Range extension.

DISCUSSION

Mapping for this study was mostly consistent with Dunne (1977). Dunne (1977) interpreted the down dropped block of Bird Springs on the western side of the map area to be a gravity induced landslide deposit, based on his criteria that a fault must be associated with ductile deformation. Although no fault outcrops were found, juxtaposition of the Paleozoic Bird Springs unit next to the Jurassic volcanic and metavolcanic units with the observed orientations and mostly coherent block of Paleozoic limestone seems to indicate the presence of brittle faulting, not just slumping/landslide. It was probably a smaller fault associated with the same period of deformation that formed the Old Dad Fault.

It seems unlikely that the Soda-Avawatz fault is exposed in the area mapped. Originally, we were curious if the Powerline shear zone or the Old Dad fault could be part of this system. The mapping and structural development described above makes this unlikely. Rather, the Powerline shear zone is probably an older Mesozoic structure similar to the Kokoweef fault (Burchfiel and Davis, 1971). The Kokoweef fault is a north-northwest trending structure that

juxtaposes Paleozoic clastic and carbonate rocks on the west next to Precambrian crystalline rocks on the east. It is cut by the Keystone Thrust that is associated with Sevier deformation much like the Playground Thrust cuts the Powerline Canyon shear zone. It is thought to possibly accommodate lateral strain near an obliquely converging margin (Burchfield and Davis, 1975). The Powerline Canyon Shear Zone could represent a similar phenomenon (Dunne, 1977).

SUMMARY

The units and structures exposed at Old Dad Mountain display the complex geologic history of the eastern Mojave Desert. The major structures at Old Dad include 1) the Powerline Canyon Shear Zone that is probably mid-late Mesozoic in age and may be associated with lateral strain accommodation for an obliquely converging margin, 2) the southeast-vergent Playground Thrust that places Paleozoic units atop Jurassic units and is part of the Sevier thrust belt, and 3) the Late Cenozoic Old Dad normal fault that is most likely associated with Miocene Basin and Range extension. By investigating the geology and kinematics at Old Dad mountain that lies to the east of the southern continuation of the Soda-Avawatz Fault Zone, insight into a few of the outstanding questions within the Mojave Desert region was gained:

- 1) The cross-cutting relationship observed between the Powerline Shear Zone and the Playground Thrust in which the former is truncated by the latter requires the Powerline Canyon Shear Zone to be Cretaceous or older in age. This rules out the possibility that it is an active strand involved in Soda-Avawatz Fault Zone deformation.
- 2) The structural development inferred for Old Dad Mountain, specifically the juxtaposition of Precambrian basement and Mesozoic rocks by a shear zone that is later cut by Cretaceous thrust faulting is similar to the relationships observed at Clark Mountain

(Burchfield and Davis, 1971) and other localities in the Eastern Mojave Desert. This might be a subject for further investigation.

- 3) The kinematic and fault relationship data acquired at Old Dad mountain can be combined with age data from the samples taken and published data from other localities to gain a better understanding of the geologic history and deformation in the Mojave Desert. This, in turn, will aid in a better understanding of the tectonic development of the Mojave Desert as a whole, as well as the western margin of North America.

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