Characterizing the deformation history of the southern Mina Deflection: field and structural studies in the Huntoon Mountains, California-Nevada

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CHARACTERIZING THE DEFORMATION HISTORY OF THE SOUTHERN MINA DEFLECTION: FIELD AND STRUCTURAL STUDIES IN THE HUNTOON MOUNTAINS, CALIFORNIA-NEVADA

A Thesis
Presented to
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In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Geological Sciences

by
Joseph Bodie McCosby
July 2019
CENTRAL WASHINGTON UNIVERSITY
Graduate Studies

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Dean of Graduate Studies
ABSTRACT

CHARACTERIZING THE DEFORMATION HISTORY OF THE SOUTHERN MINA DEFLECTION: FIELD AND STRUCTURAL STUDIES IN THE HUNTOON MOUNTAINS, CALIFORNIA-NEVADA

by

Joseph Bodie McCosby

July 2019

New geologic mapping and structural studies in the Huntoon Mountain area (HMA), California-Nevada document the volcanic and deformation histories across the south-central Mina Deflection (MD). Our work allows us to (a) test whether present-day GPS predicted sinistral slip rates are the same as geologic slip rates in the southern MD, and (b) determine the kinematics of fault slip is transfer through the MD. The HMA exposes primarily Miocene andesitic-dacitic volcanic rocks overlain by the 12.114 ± 0.006 Ma (40Ar/39Ar sanidine, Petronis et al., 2019) Tuff of Jack Spring and the 11.399 ± 0.041 Ma (40Ar/39Ar plagioclase, Nagorsen-Rinke et al., 2013) latite ignimbrite. These units are overlain in buttress and angular unconformity by basalt lavas and mafic volcanic centers that range in age from 4.08 ± 0.10 (40Ar/39Ar groundmass plagioclase, Tincher and Stockli, 2009) to 2.996 ± 0.063 Ma (40Ar/39Ar groundmass plagioclase, DeLano et al., 2019). The oldest faults in the HMA are NE-striking, NW-dipping normal faults that cut Miocene volcanic rocks, but not Pliocene basalt lavas. The youngest faults in the HMA are ENE-striking sinistral faults and associated left-stepping releasing bend NW-striking normal-dextral faults that cut all units in the HMA and offset unconformities between Miocene volcanic rocks and Pliocene basalt lavas. Offset unconformities record
a minimum total Pliocene ENE sinistral and NW dextral slip rates of $0.8 \pm 0.4$ mm/yr and $0.3 \pm 0.1$ mm/yr, respectively. Summing our new ENE sinistral slip rate of $0.8 \pm 0.4$ mm/yr with Pliocene sinistral slip rates from other studies in the southern MD (Tincher and Stockli, 2009; Nagorsen-Rinke et al., 2013; DeLano et al., 2019), yields a minimum ENE sinistral slip rate of 1.9-3.0 mm/yr. Our new net minimum ENE sinistral slip rate of 1.9-3.0 mm/yr is within error of both GPS data constrained elastic block model sinistral shear rate of $\sim 2.4$ mm/yr (Bormann et al., 2016) and transrotational modeled rate of 2.1-3.2 mm/yr (DeLano et al., 2019). Our studies have determined that geologic and geodetic ENE sinistral slip rates are the same and the kinematics of fault slip transfer through the southwestern MD are characterized by vertical axis clockwise rotating blocks bounded by ENE sinistral faults.
ACKNOWLEDGMENTS

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CHAPTER I
INTRODUCTION

The Mina Deflection (MD) is a right-stepover in the NW-striking dextral Walker Lane (WL) and is defined by a series of ENE-striking sinistral faults. Comparison of geologic (long-term; $10^3$-$10^6$ years) and geodetic (present-day; $10^1$ years) fault slip rates in the south-central MD, California-Nevada reveal that long-term slip rates are less than present-day slip rates. The discrepancy between geologic and geodetic slip rates implies one of two things: (1) there is “missing” long-term slip along faults of the MD that have gone undocumented or, (2) the MD is experiencing a present-day strain transient whereby the region is undergoing a present-day pulse of fault slip that is higher than the geologic slip rate averaged over $10^3$-$10^6$ years.

Examination of 30+ year published geologic maps, Google Earth imagery, aerial imagery, and field reconnaissance mapping of the Huntoon Mountain area (HMA), within the south-central MD, suggest the presence of various volcanic markers in this region that if offset by faults could record the missing fault slip (Figs. 2 and 3). Documenting long-term fault slip rates in the southern MD might explain the discrepancy between geodetic and geologic slip rates, as well as allow us to characterize the deformation history, fault slip transfer mechanism (Fig 4), and tectonic development across the MD. To test the hypothesis that the faults of the HMA record undocumented, or missing slip, we completed new geologic mapping, structural studies, and $^{40}$Ar/$^{39}$Ar geochronology (in progress) in a ~150 km² region in the south-central MD, California-Nevada. Plates 1 and 2 show a 1:24,000 scale geologic map and geologic cross sections, respectively, of the HMA field area and Plate 3 presents a stratigraphic column that
includes outcrop and petrographic descriptions, and geochronologic ages of the mapped units.

New geologic mapping shows that the HMA primarily consists of Paleozoic and Mesozoic basement rocks that are unconformably overlain by Miocene volcanic and sedimentary units which, in turn, are unconformably overlain by Pliocene basalt flows. Faulting in the HMA can be divided into two main groups: (1) NE-striking normal faults cut all units in the HMA except the Pliocene basalt flows, and (2) sinistral and dextral faults that cut all units in the HMA except the youngest Quaternary deposits. Data presented here are used to document a middle Miocene to early Pliocene NW-SE extension along the NE-striking normal faults and a Pliocene and younger phase of ENE sinistral and NW dextral fault slip. Using ages of offset units and magnitude of offset, we calculate fault slip rates that allow us to document the deformation history across the HMA, to characterize the kinematics of fault slip transfer through the MD, and to assess the tectonic development of the southwestern MD.
CHAPTER II
LITERATURE REVIEW

About 25% of the relative motion between the Pacific-North American plates is accommodated across the Walker Lane (WL), an intracontinental zone of NW-striking dextral faults that is superimposed upon the western margin of the Basin and Range extensional province (e.g. Dokka and Travis, 1990; Dixon et al., 1995; Oldow, 2003). The Mina deflection (MD), a 125 km long 45 km wide right stepover within the dextral WL, is defined by ENE-striking sinistral faults (e.g. Wesnousky, 2005; Petronis et al., 2009; Nagorsen-Rinke et al., 2013; Bormann et al., 2016; DeLano et al., 2019). It is hypothesized that fault slip is transferred from the NW-striking faults of the southern WL into the southwestern MD, however the mechanism by which this deformation is accommodated within the MD is poorly understood (McKenzie and Jackson, 1983, 1986; Oldow, 1992, 2003; Oldow et al., 1994; Oldow et al., 2003; Nagorsen-Rinke et al., 2013; DeLano et al., 2019). The deformation history of the MD is not completely characterized. Studies in the southwestern MD suggest at least one deformation event prior to the onset of slip along the dominant ENE sinistral faults; however, concrete evidence for such a deformation event is lacking (Tincher and Stockli, 2009; Nagorsen-Rinke et al., 2013; DeLano et al., 2019). Recent studies in the southern MD document Pliocene volcanic markers offset along the ENE-striking sinistral faults of the MD showing ENE sinistral slip rates of ~0.4 mm/yr along the Coaldale fault (Tincher and Stockli, 2009), 0.4-0.5 mm/yr in the Adobe Hills area (Nagorsen-Rinke et al., 2013), and 0.7-0.9 mm/yr in the River Spring area (DeLano et al., 2019). Combining these rates yields a net minimum geologic ENE sinistral fault slip rate of 1.4-1.8 mm/yr since the middle Pliocene across the southern MD.
Recent GPS data constrained elastic block modelling suggests a present-day ENE sinistral shear rate of ~2.4 mm/yr across the southern MD (Bormann et al., 2016), which is greater than the sum of sinistral geologic fault slip rates. Nagorsen-Rinke et al. (2013) and DeLano et al. (2019) hypothesize that this slip discrepancy can be explained by undocumented geologic fault slip rates within the MD. We test this hypothesis using a geologic mapping and structural geology study across the Huntoon Mountain Range, California-Nevada. Our studies document a Miocene to Pliocene volcanic history, are the first to provide clear evidence for post middle Miocene to early Pliocene horizontal extension, and document Pliocene dextral and sinistral fault slip.
Characterizing the deformation history of the southern Mina Deflection: Field and structural studies in the Huntoon Mountains, California-Nevada

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INTRODUCTION

Strike-slip fault zones commonly include extensional or contractional stepovers between distinct subparallel faults. These stepovers transfer slip between the distinct subparallel strike-slip faults and form complex zones of deformation (e.g. Wilcox et al., 1973; Crowell, 1974; Aydin and Nur, 1982; Cunningham and Mann, 2007). Geologic features observed in extensional stepovers include normal faults (Fig. 1a), pull-apart basins, extensional strike-slip duplexes, and transtensional oblique faults (Fig. 1b) and structures observed in contractional stepovers include thrust faults, push-up ridges, positive flower structures, and contractional strike-slip duplexes (Cunningham and Mann, 2007). Less commonly, these stepovers can include a component of rotation where rigid, fault-bound blocks rotate in the direction of shear imposed across the subparallel strike-slip faults (Fig. 1c). As a result, the faults bounding these rotation rigid blocks record sense of slip opposite of the slip along the subparallel strike-slip faults that bound them (McKenzie and Jackson, 1983, 1986; Dickinson, 1996) (Fig. 1c).
Figure 1: Block models illustrating the different fault types proposed to accommodate fault slip transfer across the MD. (A) The displacement-transfer model whereby an extensional stepover, defined by normal faults, transfers slip across the stepover (Oldow, 1992; Oldow et al., 1994). (B) The transtensional model whereby a combination of sinistral and normal slip along connecting faults transfers slip across the stepover (Oldow, 2003). (C) The clockwise block rotation model in which sinistral slip bounding clockwise rotating rigid blocks transfers fault slip (McKenzie and Jackson, 1983; McKenzie and Jackson, 1986; Wesnousky, 2005; Nagorsen-Rinke et al., 2013). Single-barbed arrows show dextral fault motion across faults of the central and southern WL and sinistral motion along faults in the Mina deflection; half-circle double-barbed arrows indicate clockwise rotating fault blocks; solid ball is located on the hanging wall of normal slip faults; thin short lines indicate slip direction on fault surfaces. Modified from Delano et al. (2019).
The Walker Lane (WL) is a ~130-175 km wide NW dextral shear zone located in eastern California and western Nevada (Fig. 2). The WL includes a number of right-stepping extensional stepovers, such as the Deep Springs and Queen Valley normal faults (Lee et al., 2001; 2009), and right-stepping, clockwise rotational stepovers such as the Carson Domain (Cashman and Fontaine, 2000) and the Mina Deflection (MD) (e.g. Wesnousky, 2005; Delano et al., 2019; Petronis et al., 2019). Paleomagnetic data from across the ~40 km long Carson Domain (Cashman and Fontaine, 2000) formed the foundation for a kinematic model whereby translation and clockwise rotation of rigid fault blocks bounded on either side by sinistral faults accommodated NW-dextral slip. In contrast to the Carson domain, the kinematics of fault slip transfer across the larger MD (125 km long by ~30 km wide) is not as well understood (cf. Bradley, 2005; Wesnousky, 2005; Lee et al., 2006; Nagorsen-Rinke et al., 2013; Bormann et al., 2016; DeLano et al., 2019).

During the last ~20 years, three different fault slip transfer models have been proposed for the MD: (1) the displacement transfer model (Oldow, 1992; Oldow et al., 1994), (2) the transtensional model (Oldow, 2003), and (3) the clockwise block rotation model (Wesnousky, 2005; Nagorsen-Rinke et al., 2013; DeLano et al., 2019) (Fig. 1). Geologic map, structural, and seismic data from the MD form the basis for Oldow’s (1992) and Oldow et al.’s (1994) displacement transfer model, an extensional step-over defined by a series of normal faults that accommodate the transfer of slip (Fig. 1a). In contrast, earthquake focal mechanisms, fault-slip inversion data sets, and GPS velocity data led Oldow (2003) to propose the transtensional model whereby fault slip is accommodated on the sinistral faults of the MD through a combination of both sinistral and normal slip (Fig. 1b). The clockwise block rotation model accounts for the transfer of
Figure 2: Simplified tectonic map of the western part of the US Cordillera showing the major geotectonic provinces and modern plate boundaries. ECSZ (Eastern California Shear Zone) and WL (Walker Lane) in light gray; Basin and Range province in medium gray; MD (Mina Deflection) in dark gray. Red box shows location of Figure 3. Modified from DeLano et al. (2019).
fault slip through the central MD by the clockwise rotation of crustal blocks bounded by faults that accommodate sinistral slip (McKenzie and Jackson 1983, 1986) (Fig. 1c). The clockwise block rotation model is supported by Wesnousky’s (2005) observations of sinistral offset, fault geometry, and paired basins at the ends of active ENE-striking sinistral faults of the MD. Nagorsen-Rinke et al. (2013) reached the same conclusion based on the geometry and offset observed along Pliocene faults in the southwestern MD. Paleomagnetic data from across the MD indicates variable degrees of clockwise block rotation ranging from 5-104° since the late Miocene-Early Pliocene (Petronis et al., 2009; Grondin et al., 2016; Petronis et al., 2019). Building on Petronis and colleagues work, DeLano et al. (2019) proposed a clockwise rotation model for the southwestern MD whereby ~22-31° of clockwise rotation of blocks bounded by sinistral faults accounted for the documented long-term summed sinistral slip rate of 1.4-1.8 mm/yr.

We completed new geologic mapping, structural, and geochronologic studies in the Huntoon Mountain area (HMA), California-Nevada, south-central MD in order to document how fault slip is accommodated in stepover systems dominated by sinistral faults, to build upon the transrotational and irrotational kinematic models for the southwestern MD, and to compare geologic fault slip rates to GPS-derived slip rates. Examination of satellite and aerial imagery, 30+ year old geologic maps, and field reconnaissance suggests the presence of Miocene and Pliocene volcanic rocks in the HMA that are offset by a series of sinistral faults and associated extensional and compressional step-overs that had not been documented. Our studies document the geometry, magnitude, and timing of pre-Pliocene extension and deformation and Pliocene sinistral and dextral fault slip in the HMA ultimately leading to tighter constraints on the spatial-temporal accommodation of fault slip across major stepover systems within
intracontinental strike-slip shear zones (Oldow et al., 1994; Dickinson, 1996; DeLano et al., 2019).

This work presents the results of geologic investigations in the HMA. Plate 1 shows a 1:24,000 scale geologic map, Plate 2 shows accompanying cross sections and a palinspastic restoration, and Plate 3 shows a stratigraphic column that includes outcrop and petrographic descriptions, and geochronologic ages of the units mapped in this investigation. We use these data to calculate a NW-SE middle Miocene to early Pliocene minimum extension rate of ~0.1 mm/yr between 12-4 Ma as well as minimum long-term Pliocene ENE sinistral and NW dextral slip rates of 0.8 ± 0.4 mm/yr and 0.3 ± 0.1 mm/yr, respectively, since ~4 Ma. Our minimum long-term ENE sinistral slip rates of 0.8 ± 0.4 mm/yr, summed with Pliocene ENE-sinistral slip rates calculated in surrounding field areas within the MD (Tincher and Stockli, 2009; Nagorsen-Rinke et al., 2013; DeLano et al., 2019), yields a minimum ENE sinistral slip rate of 1.9-3.0 mm/yr across the south-central MD. This ENE geologic sinistral slip rate is within error of the GPS data constrained elastic block model sinistral shear rate of ~2.4 mm/yr across the central MD (Bormann et al., 2016).

REGIONAL GEOLOGIC SETTING

Geologic and geodetic studies indicate the Pacific Plate moves NW relative to a stable North American continent at a rate of ~50 mm/yr (e.g. Dokka and Travis, 1990; Dixon et al., 1995; Oldow, 2003) (Fig. 2). About 25% of the relative motion between the Pacific-North American plates is accommodated across the WL, an intracontinental ~25-100 km wide zone of NW-striking dextral faults across the eastern flank of the Sierra Nevada and the western margin of the Basin and Range province (e.g.
Dokka and Travis, 1990; Dixon et al., 1995; Bennett et al., 2003; Faulds and Henry, 2008) (Fig. 1). Dextral slip from the NW-striking faults of the southern WL is concentrated on two main fault systems, the Fish Lake fault zone and the Owens Valley-White Mountains fault zone. These two fault zones transfer dextral slip into the sinistral MD, a ~125 km long ~45 km wide right-step within the WL, where it is accommodated by ENE-striking sinistral faults and associated extensional and compressional step-overs (Oldow et al., 1994; Wesnousky, 2005; Lee et al., 2009; Nagorsen-Rinke et al., 2013; DeLano et al. 2019) (Figs. 3 and 4).

Field studies in surrounding areas have documented a minimum net geologic ENE sinistral slip rate of 1.4-1.8 mm/yr across the southern MD (Tincher and Stockli, 2009; Nagorsen-Rinke et al., 2013; DeLano et al., 2019). In contrast, recent elastic block modelling based on GPS velocity data across the MD predicts a present-day geodetic ENE sinistral shear rate of ~2.4 mm/yr across the central MD (Bormann et al., 2016). The documented geologic ENE sinistral slip rate is only ~58-82% of the present-day GPS measured sinistral shear rate (Bormann et al., 2016). The discrepancy between geodetic and geologic slip rates implies one of two things: (1) there is “missing” slip along the ENE-striking sinistral faults of the MD that has not been documented or, (2) the MD is experiencing a strain transient where the region is undergoing a pulse in sinistral shear today that is higher than the average long-term (10^3-10^6) geologic slip rate (Rockwell et al., 2000; Peltzer et al., 2001; Oskin et al., 2007; Pérouse and Wernicke, 2017). Recent mapping and structural studies from surrounding areas have documented slip rates along many, but not all, of the ENE-striking sinistral and NW-striking oblique (normal-dextral) faults of the MD (e.g. Bradley, 2005; Tincher and Stockli, 2009; Nagorsen-Rinke et al., 2013; DeLano et al., 2019). Here, we prefer the “missing” slip hypothesis where
Figure 3: Shaded relief map of the Walker Lane Belt and northern part of the eastern California shear zone showing the major Quaternary faults, the Carson domain, Mina deflection (MD), and the Silver Peak–Lone Mountain extensional complex (SPLM). Figure shows geographic information for paleomagnetic data discussed in the text. Light-blue squares show locations of GPS sites that bound the Mina deflection (Bormann et al., 2016); the solid ball is located on the hanging wall of normal faults; arrow pairs indicate relative motion across strike-slip faults; white dashed box outlines location of Figure 4. Abbreviations: AH–Adobe Hills field area; BSF–Benton Springs fault; CF–Coaldale fault; CVF–Clayton Valley fault; DSF–Deep Springs fault; DVFC–Death Valley–Furnace Creek fault zone; EPF–Emigrant Peak fault; FLVF–Fish Lake Valley fault; GHF–Gumdrop Hills fault; HLF–Honey Lake fault; HMF–Hunter Mountain fault; LMF–Lone Mountain fault; MVF–Mohawk Valley fault; OVF–Owens Valley fault; PLF–Pyramid Lake fault; PSF–Petrified Springs fault; PVF–Panamint Valley fault; QVF–Queen Valley fault; RVF–Round Valley fault; SAF–San Antonio Mountains range front fault; SLF–Stateline fault; SNFFZ–Sierra Nevada frontal fault zone; TPF–Towne Pass. fault; WMFZ–White Mountains fault zone; WRF–Wassuk Range fault; WSFZ–Warm Springs fault zone. Modified from DeLano et al. (2019).
Figure 4: Shaded relief map of the southern Mina Deflection and the southern Walker Lane. Dark black lines represent major Quaternary faults with solid back balls indicating the hanging wall of normal faults and arrow pairs indicating relative motion across strike-slip faults. Heavy arrow in the NW corner of map indicates the trend of present-day motion of the Sierra Nevada relative to a stable North America (Dixon et al., 2000). Location of areas mapped during previous studies shown by yellow dashed boxes. Field area discussed in this report indicated by dashed blue box. Fault abbreviations: CF-Coaldale fault; CSF-Coyote Springs Fault; WMFZ-White Mountain fault zone; QVF-Queens Valley fault; SNF-Sierra Nevada fault. Modified from Nagorsen-Rinke et al. (2013).
additional, previously undocumented, fault slip has been accommodated on the ENE sinistral and NW dextral faults in the HMA that have not been mapped in 30+ years.

Previous geologic mapping in the HMA showed abundant volcanic units with an apparent range in age (Crowder et al., 1972; Stewart et al., 1981) that, if offset by ENE-striking sinistral faults, might record magnitude of sinistral offset. Magnitude of offset measurements and radiometric ages on offset volcanic rocks will allow us to calculate sinistral slip rates in this region. These data will potentially resolve the discrepancy between geologic (long-term; $10^3$- $10^6$ years) sinistral fault slip rates and the present-day GPS (short-term; $10^1$ years) modeled sinistral shear rates (cf. Nagorsen-Rinke et al., 2013; Bormann et al., 2016; DeLano et al., 2019). In this study, we combine geologic mapping, structural studies, and $^{40}$Ar/$^{39}$Ar geochronology to document the volcanic and deformation histories of the HMA and to test the hypothesis that sinistral slip rates are the same as the present-day GPS data constrained elastic block model rate (Bormann et al., 2016).

**GEOLOGIC MAPPING AND STRUCTURAL STUDIES**

Geologic mapping and collection of structural data, kinematic data, petrographic samples, and geochronologic samples were completed across a 7.5-minute quadrangle (~150 km$^2$) sized area straddling the Jack Spring 7.5-minute quadrangle to the north and Truman Meadows 7.5-minute quadrangle to the south (Plate 1). Mapping of the ~150 km$^2$ area was completed during June – August 2018 by J. Bodie McCosby and field assistant Grant Nussbaum; this mapping was based upon reconnaissance mapping in 2002 by Jeff Lee. Detailed field mapping of the area was completed at 1:12,000 scale on translucent mylar sheets overlain on National Agriculture Imagery Program (NAIP) digital orthophoto quadrangles printed with 10 m contour lines created in ESRI ArcMap.
using U.S. Geological Survey, 10 m National Elevation Dataset (NED) registered to the WGS 1984 UTM Zone 11 projection. Printed 1:12,000 scale base maps were coded and referenced to a grid before being cut into a field manageable size. While in the field, 1:12,000 scale tiles were compiled at 1:24,000 scale to assess the regional context of detailed field mapping. Previous published geologic maps of the HMA and surrounding areas (Crowder et al., 1972; Stewart et al., 1981; Tincher and Stockli, 2009; Nagorsen-Rinke et al., 2013; DeLano et al., 2019) were used to provide the framework for identifying and mapping units as well as for completing parts of the map area (Plate 1) that were not accessed during the June – August field season. Field maps were compiled by scanning coded 1:12,000 scale tiles and referencing them to the pre-defined grid.

Scans were then scaled to 1:24,000 and digitized in Adobe Illustrator. Structural data include strike and dip of sedimentary bedding, flattened fiamme, flow foliation, and planes to poles of columnar cooling joint intersections (Plate 1) (Fig. 5).

**GEOLOGIC ROCK UNITS AND GEOCHRONOLOGY**

Our geologic mapping in the HMA documents Paleozoic and Mesozoic basement units overlain by Miocene, Pliocene, and Quaternary units (Plates 1, 2, and 3). Paleozoic basement consists of metasedimentary units that have been intruded by Mesozoic granite all of which are nonconformably overlain by Miocene volcanic and volcaniclastic rocks. Pliocene volcanic rocks overlay Miocene units in angular and buttress unconformity which are, in turn, overlain by Quaternary alluvial, aeolian, and landslide deposits.

To constrain the age of volcanic units and fault history within the HMA, six samples were collected from Miocene and Pliocene volcanic rocks (units Mtjs, Pbp, Pbn, Pbol, and Pbx) for \(^{40}\text{Ar}^{39}\text{Ar}\) geochronology. Samples were processed following the
Figure 5: Lower hemisphere, equal area stereonet plots of structural data. (A) Plot of great circles of fiamme, flow foliation, and calculated plane to pole of cooling column intersections collected in unit Mlt. (B) Plot of great circles of fiamme, bedding, and calculated plane to pole of cooling column intersections collected in unit Mtjs. Heavy black great circles in (A) and (B) shows the average plane for unit Mlt and Mtjs, respectively.
methods described in Nagorsen-Rinke et al. (2013). Cleaned separates of sanidine and
groundmass will be dated using incremental heating technique following the methods
described in Dalrymple and Duffield (1988) and Nagorsen-Rinke et al. (2013). $^{40}$Ar/$^{39}$Ar
geochronology was scheduled to be completed in time for the submission of this report,
however the government shut down this winter postponed this work which is now
scheduled to be completed by August 2019.

**Geologic Rock Units**

**Paleozoic and Mesozoic Basement**

Paleozoic and Mesozoic basement rocks consist of the marine metasedimentary
units Cambrian marble (Cm) and the Ordovician Palmetto Formation (Op) which have
been intruded by the Jurassic granite of Pellisier Flats (Japg) (Plates 1, 2, and 3). Cm
consists of fine to medium grained white to gray marbles which are tentatively correlated
to the Poleta Canyon Formation (Crowder et al., 1972; Tincher and Stockli, 2009). Unit
Op is characterized by small knobby outcrops of intensely folded black siltstone and slate
with minor marble and quartzite. Though not observed in the HMA, Op is structurally
juxtaposed against unit Cm and Cambrian phyllites along a low-angle thrust plane
thought to be associated with the Paleozoic Roberts Mountain thrust (Crowder et al.,
1972; Stockli et al., 2003; Tincher and Stockli, 2009). These Paleozoic metasedimentary
rocks are intruded by unit Japg, a phaneritic hornblende + biotite granite tentatively dated
to $\sim$157 Ma (K/Ar on biotite) (Evernden and Kistler, 1970). Locally, units Cm and Japg
form paleo-topographic highs with are overlain by Miocene and Pliocene volcanic rocks
in buttress unconformity.
**Oligocene-Miocene Units**

Exposed across an ~1.5 km² area in the northeast part of the map area and unconformably overlying Op are two cooling units of the Candelaria Junction tuff of Speed and Cogbill (1979) with lower and upper cooling units denoted as Mt₅a and Mt₅b, respectively. Unit Mt₅ is a cliff forming, pale grey to red, phenocryst bearing (plagioclase + sanidine + quartz + sparse biotite) ash-flow tuff with fiamme (Speed and Cogbill, 1979; Stewart et al., 1981). Unit Mt₅ is dated between 22 and 24 Ma by K/Ar on biotite, sanidine, and plagioclase (Speed and Cogbill, 1979). This area was not visited during the field season, so unit relations and descriptions are taken from Stewart et al. (1981).

**Miocene Units**

Nonconformably overlying Paleozoic and Mesozoic basement rocks are a series of Miocene andesitic to dacitic lahars, debris flows, volcaniclastic sediments, lava flows, and shallow intrusions. The sequence of Miocene units in the northern part of the field area is different from the southern part. Because the middle part of the HMA is largely covered by Pliocene basalts, we were unable to determine the stratigraphic relations between the Miocene units in the northern HMA vs. the southern HMA.

Unit Mdbₓ outcrops in the northern HMA and is dominated by debris flows and lahars. The unit consists of subangular to subrounded, millimeter to meter-sized clasts of hornblende-bearing dacite to andesite. Debris flows and lahars are commonly matrix supported with a light brown to gray muddy matrix with hornblende, sanidine, plagioclase, and quartz. Mdbₓ commonly has interbedded well sorted, laminated silt, fine to coarse-cross-bedded sand, and conglomerate layers all primarily composed of volcaniclastic sediments and volcanic debris. In one location, a 5-15 m thick zone of
rounded river cobbles was observed suggesting a small paleochannel developed in the lahar and debris flows.

A phenocryst rich andesite lava flow and a hornblende dacite debris flow, units Maf and Mdh, respectively, were first identified in the River Spring field area southwest of the HMA. Unit Maf is crystal rich (~40%) phenocryst-bearing (plagioclase + pyroxene + hornblende + minor biotite) andesite lava flow. Unit Mdh is a weakly consolidated, ~15 m thick, poorly sorted, nearly clast supported debris flow with occasional thinly bedded (~10 cm mud layers. Clasts in unit Mdh range in composition from andesitic to dacitic and are subrounded, 2-30 cm in size with infrequent meter scale boulders within a fine grained light grey ashy matrix. DeLano et al. (2019) report a groundmass plagioclase $^{40}$Ar/$^{39}$Ar recoil age of 14.695 ± 0.816 Ma for unit Mdh.

Also, unconformably overlying the Paleozoic and Mesozoic basement rocks are Miocene debris flows (Mdf) and volcaniclastic sediments (Mas). Unit Mdf is a clast supported debris flow consisting of poorly sorted subangular to sub-rounded clasts of a phenocryst-bearing (plagioclase + pyroxene) glassy black andesite in a heavily weathered ashy matrix. Unit Mdf is characterized by infrequent knobby outcrops at the base of unit Mas. Conformably overlying unit Mdf is a ~20 m thick section of moderately to well sorted cross-bedded volcaniclastic sediments (Mas) (Fig. 6). Clasts consist of pumice, quartz, plagioclase feldspars, pyroxene, sub-rounded lithics and occasional silicified woody material. Units Mdf and Mas are compositionally similar and occur in close proximity to one another making it likely that they originated from the same volcanic source.

Conformably overlying units Mas and Mdf is a two-pyroxene andesite lava flow (Mal). Unit Mal is ledge forming, dark grey on fresh surfaces, dark purple-brown on
Figure 6: Field photograph showing Miocene volcaniclastic sediments (unit Mas) in outcrop with boulders of Mlt from upslope. Bedding planes in unit Mas are highlighted with green lines. Inset shows close-up photograph of bedding and crossbedding in unit Mas.
weathered surfaces, and has randomly oriented cooling joints. Unit Mal is porphyritic with plagioclase, clinopyroxene, orthopyroxene, and occasional glomerocrysts the same minerals (Fig. 7a). The groundmass in unit Mal consists of elongate swallowtail plagioclase, pyroxene, Fe-Ti oxides, and dark brown glass (Fig. 7a).

Units Mdbx, Mdf, Mas, and Mal are intruded by hornblende + two-pyroxene shallow andesite intrusions and lava domes (Mai). Unit Mai is lacks vesicles and is light grey on fresh surfaces, brown-grey on weathered surfaces, and occurs as large dome-like outcrops suggesting it is a shallow intrusion. Unit Mai is phenocryst bearing (plagioclase + clinopyroxene + orthopyroxene + minor hornblende) and has a holocrystalline groundmass of plagioclase + pyroxene + Fe-Ti oxides.

Unconformably overlying unit Mdbx is the Tuff of Jack Spring (Mtjs). In the HMA field area, Mtjs is a latite, poorly to moderately welded, and ridge forming (Figs. 8 and 9). In hand sample, Mtjs contains easily visible phenocrysts of plagioclase and sanidine (up to 5 mm) and biotite (up to 2 mm) in a light gray ashy matrix with frequent centimeter scale pumice and occasional fiamme as well as millimeter to centimeter scale volcanic lithic fragments (rhyolite to andesite) (Fig. 7b). In thin section, Mtjs is phenocryst bearing (sanidine + plagioclase + biotite + hornblende + clinopyroxene + quartz) with prevalent 1-2 mm unaltered sanidine crystals (Fig. 7b). Sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology yields an age of 12.114 ± 0.006 Ma (Petronis et al., 2019).

A Miocene latite tuff (Mlt) occurs in the southern half of the HMA and, similarly to unit Mtjs, unconformably overlies older Miocene volcanics. Unit Mlt is ridge forming with a bulbous outcrop pattern, pinky gray on fresh surfaces, and dark brown-purple or brick red on weathered surfaces. Mlt has large (1-35 cm) fiamme, occasional subrounded lithics of various volcanic composition, and infrequent petrified wood (Fig. 10). In hand
Figure 7: Annotated photomicrographs of several Cenozoic units (A) Andesite lava flow (unit Mal). (B) Tuff of Jack Spring (unit Mtjs). (C) Latite ignimbrite (unit Mlt). (D) Glomerocrystic basalt lava flow (unit Pbg). (E) New-basalt lava flow (unit Pbn). (F) Basalt lava flow (unit Pbml). All photomicrographs are in cross-polarized light except B in plane-polarized light. Mineral abbreviations: bio, biotite; cpx, clinopyroxene; opx, orthopyroxene; pl, plagioclase; sa, sanidine; ol, olivine; qtz, quartz.
Figure 8: (A) Field photograph showing outcrop pattern of the Tuff of Jack Spring (unit Mtjs) within the Huntoon Mountain area. Yellow line indicates the thinly laminated white ash layer separating the dark-colored upper and light-colored lower cooling units of Mtjs. A-Inset showing a close-up image of this thinly laminated white ash layer. (B) Field photograph showing the partially welded dark-colored upper cooling unit with cooling columns (denoted by vertical blue lines) and the unwelded light-colored lower cooling unit of the Tuff of Jack Spring (unit Mtjs). B-inset shows a close-up image of crossbedding (denoted by green lines) in the basal ash flow layer of unit Mtjs.
Figure 9: Field photograph showing ridges of unit Mtjs (bounded by pink lines) cut by a NE-striking, NW-dipping pre-Pliocene normal fault in the northern section of the Huntoon Mountain area.
Figure 10: (A) Field photograph showing boulders of the Miocene latite ignimbrite (unit Mlt) weathering to dark brown-purple or brick red. Blue arrows point large (1-35cm) fiamme. (B) Field photograph of Mlt outcrop with blue arrows highlighting the side view of large (1-35cm) fiamme.
sample, Mlt has easily visible plagioclase and sanidine (1-2 mm with a few up to 8 mm) and diagnostic euhedral (pseudo-hexagonal) biotite (~1 mm). In thin section, Mlt is phenocryst bearing (plagioclase + sanidine + biotite + clinopyroxene + Fe-Ti oxides + minor hornblende) with common glomerocrysts of clinopyroxene and plagioclase in a matrix of dark drown glass (Fig. 7c). Plagioclase $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology yielded an age of $11.399 \pm 0.041$ Ma (Nagorsen-Rinke et al., 2013). Though no direct contacts between units Mlt and Mtjs were observed in the field, we use their $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology ages to determine their relative age (Nagorsen-Rinke et al., 2013; Petronis et al., 2019) (Plates 1, 2, and 3).

**Pliocene Units**

The next section describes Pliocene basalt units observed in the HMA. In general, basalt flows are ridge forming and interfingered. All Pliocene basalt flows overlie Miocene volcanic rocks in buttress and angular unconformity.

The likely oldest basalt flow in the HMA, unit Pbp, is the informally labeled Picto-basalt named for an outcrop with Paleoamerican pictographs. Pbp uncomfortably overlies Miocene volcanics in buttress unconformities and occurs as the first Pliocene unit filling valley created by paleorelief in Miocene units (Plate 1). Pbp weathers to a buff brown to grey color, and is phenocryst bearing (orthopyroxene + olivine) with an unaltered fine to medium grained groundmass. $^{40}\text{Ar}/^{39}\text{Ar}$ groundmass plagioclase geochronology is currently in progress, but based on petrographic and stratigraphic observations, unit Pbp likely correlates to Tincher and Stockli’s (2009) oldest basalt unit Tb with a $^{40}\text{Ar}/^{39}\text{Ar}$ groundmass plagioclase age $4.08 \pm 0.10$ Ma.

Unit Pbg is ridge forming with a bulbous outcrop pattern and infrequent cooling columns, silvery-grey on fresh surfaces, and buff brown to tan on weathered surfaces.
Unit Pbg is phenocryst bearing (olivine + orthopyroxene + clinopyroxene + plagioclase) with a medium gray and medium grained groundmass with frequent glomerocrysts (olivine + orthopyroxene + clinopyroxene + plagioclase) (Fig. 7d). Unit Pbg and Pbp are separate, petrographically distinct units that are stratigraphically correlated based on their relation to underlying Miocene units.

Conformably overlying unit Pbp is a Pliocene andesitic basalt lava flow (Pba). Pba is ridge forming, silvery grey on fresh surfaces, dark brown to purple on weathered surfaces, and has ‘snowflake’ texture that appears at the center of flows with ‘a’a texture occurring at flow tops. Pba is phenocryst bearing (clinopyroxene + olivine + infrequent plagioclase) and has a medium to coarse grained matrix consisting of pyroxene and plagioclase easily visible in hand sample.

Conformably overlying unit Pba and in buttress unconformity on Miocene volcanic units is a plagioclase-bearing Pliocene basalt lava flow (Pbn). Unit Pbn is ridge forming with infrequent cooling columns, silvery gray on fresh surfaces, reddish buff brown on weathered surfaces, and has frequent large (up to ~5 mm) vesicles throughout the unit. Pbn is phenocryst bearing (plagioclase + olivine + clinopyroxene + orthopyroxene) with a fresh silvery grey medium grained groundmass (Fig. 7e). $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of groundmass plagioclase from this unit is in progress.

Conformably overlying unit Pbn is a Pliocene weakly phyric basalt lava flow (Pbm₁). Pbm₁ is ridge forming, has common flow foliation defined by alternating light and dark bands, silvery gray to dark gray on fresh surfaces, and tan to dark brown on weathered surfaces. Pbm₁ is phenocryst bearing (olivine + clinopyroxene) with a fresh silvery grey to dark grey fine-grained groundmass (Fig. 7f). Groundmass plagioclase
$^{40}\text{Ar}/^{39}\text{Ar}$ geochronology on a flow in Pbm$_1$ yields an age of $3.544 \pm 0.007$ Ma (DeLano et al., 2019).

Interfingering with unit Pbm$_1$ is a phenocryst rich olivine basalt lava flow (Pbol). Unit Pbol is ridge forming with a bulbous outcrop pattern, rare cooling columns, silvery grey on fresh surfaces, and dark grey brown on weathered surfaces. Unit Pbol is phenocryst bearing (olivine + clinopyroxene + minor plagioclase) with a silvery grey coarse-grained matrix. $^{40}\text{Ar}/^{39}\text{Ar}$ groundmass plagioclase dating of this unit is in progress.

Conformably overlying unit Pbol is a two-pyroxene basalt (Pbx). Unit Pbx is ridge forming with a blocky columnar outcrop pattern, dark grey on fresh surfaces, and red-purple on weathered surfaces. Unit Pbx is phenocryst bearing (clinopyroxene + orthopyroxene + minor olivine). $^{40}\text{Ar}/^{39}\text{Ar}$ groundmass plagioclase dating of this unit is in progress.

Unconformably overlying the Miocene volcanic rocks and interfingering with units Pbol and Pbx is an aphanitic medium grained basalt lava flow (Pbb). Unit Pbb has flaggy columnar outcrop pattern, dark grey on fresh surfaces, and tan-brown on weathered surfaces. Unit Pbb is weakly-phyric with minor olivine phenocrysts.

Conformably overlying the Pliocene basalt lava flows are Pliocene cinder cones, volcanic centers, cinder-scoria deposits, and associated dikes (Pvc and Pbc). Unit Pvc is defined by cone shaped exposures composed of angular red breccia blocks, cobble to pebble sized basalt cinder, and rare volcanic bombs. Unit Pbc is defined by red basalt scoria and cinder deposits ranging from sand to boulder sized. Unit Pbc is sourced from nearby volcanic centers and cinder cones. $^{40}\text{Ar}/^{39}\text{Ar}$ groundmass plagioclase from a dike cross-cutting unit Pvc in the River Spring area yields an $^{40}\text{Ar}/\text{Ar}$ model recoil age of $2.996 \pm 0.063$ Ma (DeLano et al., 2019).
**Quaternary Units**

Active Quaternary units mapped include landslide deposits (Qls), playa deposits (Qp), aeolian sands covered with pebble- to cobble-sized obsidian sourced from the Mono and Inyo craters (Qos), and seasonally active streams (Qal). Unit Qls is characterized by alluvium and colluvium surrounding slumped blocks of local units (most commonly Pliocene basalts) frequently occurring along large fault scarps. Unit Qp is easily recognized by semi-circular white flats made up of evaporites and dried mud with frequent mud cracks. Unit Qos consists of aeolian sands made up of mostly fine-grained volcaniclastic sediments with angular obsidian fragments, ranging from millimeter to centimeter scale, exposed on its surface. These obsidian fragments occur throughout the field area in unit Qos, with a higher density in the southern portion of the HMA field area and are likely sourced from the Mono and Inyo craters to the west (Reheis et al., 2002; Nagorsen-Rinke et al., 2013; DeLano et al., 2019). Exposed in the southcentral part of the field area, a consolidated sample of Qos was collected with small wood twigs in it. This sample is a candidate for carbon dating. Unit Qal consists of alluvium from seasonally active stream beds and channels most commonly made up of reworked unconsolidated sands and gravels from surrounding units. Map unit Qal includes vegetated flats between outcrops and other undifferentiated Quaternary deposits.
FAULT STYLE, GEOMETRY, AND MAGNITUDE OF OFFSET WITHIN THE HUNTOON MOUNTAIN AREA

Introduction

To document the style, geometry, relative timing, and magnitude of deformation within the HMA, we completed new detailed geologic mapping and structural studies across the Jack Springs and Truman Meadows quadrangles (Plates 1, 2, and 3). We combine geochronology results on key volcanic units with fault offset magnitude measurements to calculate geologic fault slip rates (Tincher and Stockli, 2009; Nagorsen-Rinke et al., 2013; DeLano et al., 2019; this study). Exposed faults within the HMA can be divided into two subcategories: 1) NE-striking, NW-dipping normal faults associated with pre-Pliocene extension and deformation that cut all pre-Pliocene units in the HMA and 2) ENE-striking near vertical sinistral faults, and NW-striking normal-dextral faults defined by large, left-stepping extensional step-overs associated with sinistral faults, both of which cut all units in the HMA except the youngest Quaternary deposits (Fig. 11).

The northern section of the HMA is defined by NE-striking, NW-dipping normal faults that cut Miocene and older units but not the overlying Pliocene units (Plate 1 and 2). These normal faults represent an extensional deformation event that pre-dates the emplacement of Pliocene basalts. The rest of the HMA is defined by ENE-striking sinistral faults and NW-striking normal-dextral faults that define large extensional step-overs along the sinistral faults. Sinistral and dextral faults of the HMA are characterized by linear valleys, extensional and compressional step-overs, pull apart basins, and laterally offset volcanic markers including subvertical basalt flow contacts, angular unconformities, and buttress unconformities (Plates 1 and 2; Figs. 12, 13, and 14). Pleistocene and Holocene fault scarps are infrequently observed and, similar to
Figure 11: Map of the Huntoon Mountain area superimposed on digital orthophotographs, National Elevation Dataset (NED) generated slope shade, with all units removed to highlight the different fault systems in the field area. Red lines show pre-Pliocene NE-striking, NW-dipping normal faults; blue lines show ENE striking sinistral and NW-striking dextral-normal faults of the Jack Spring extensional stepover (JSE); yellow lines show ENE-striking sinistral and associated extensional stepovers of the faults of McBride Flats (MBF); purple line in the SE corner shows the Coaldale fault (CF). Solid ball on hanging wall of normal fault; arrow pairs indicate relative motion for strike-slip faults.
**Figure 12:** Detailed geologic map superimposed on digital orthophotographs, National Elevation Dataset (NED) generated slope shade, and 10 m contours showing sinistral offset of a buttress unconformity between a Pliocene new-basalt lava flow (unit Pbn) and a Miocene latite ignimbrite (unit Mlt) (offset markers 1-1’, 2-2’, and 3-3’). The offset buttress unconformity is a sub-vertical contact between paleorelief developed in Mlt and the sub-horizontal Pbn. The buttress unconformity is denoted by the thick blue line offset across three ENE-striking sinistral faults. All units except Pbn and Mlt have been removed for simplicity. For the error associated with the measured offset, see Table 1.
**Figure 13:** Detailed geologic map superimposed on digital orthophotographs, National Elevation Dataset (NED) generated slope shade, and 10 m contours showing dextral offset of an angular unconformity between a Pliocene basalt lava flows (units Pbg and Pbx) and the Miocene Tuff of Jack Spring (unit Mtjs) (offset markers 5-5' and 6-6'). The offset angular unconformity is a sub-vertical contact between Mtjs, which dips ~13° to the SE, and the horizontal Pliocene basalt flows Pbg and Pbx (Fig. 5b). The angular unconformity is denoted by the thick red line offset across two NW-striking dextral-normal faults. Lateral offset along normal fault in the far east corner is apparent only. All units except Pbx, Pbg, and Mtjs have been removed for simplicity. For the error associated with the measured offset, see Table 1.
Figure 14: Detailed geologic map superimposed on digital orthophotographs, National Elevation Dataset (NED) generated slope shade, and 10 m contours showing sinistral offset of an angular unconformity between Pliocene basalt lava flows Pbol and Pbx (offset marker 4-4'). The angular unconformity is denoted by the thick yellow line offset across one ENE-striking sinistral fault. All units except Pbol, Pbx, and Pvc have been removed for simplicity. For the error associated with the measured offset, see Table 1.
interpretations in the Adobe Hills and River Spring areas (Reheis et al., 2002; Nagorsen-Rinke et al., 2013; DeLano et al., 2019), the most recent fault scarps have likely been covered with primary fallout and windblown volcanic ash, small lithics, and obsidian fragments (unit Qos) from Mono and Inyo Craters to the west.

Fault Geometries and Deformation Events

Observations of vertical contacts between Miocene units Mdh and Mlt, tilted flow foliation measurements in unit Mlt, and paleorelief of Miocene units in field areas surrounding the HMA suggested the occurrence of at least one pre-Pliocene deformation event (Nagorsen-Rinke et al., 2013; DeLano et al., 2019). Further evidence of paleorelief developed in Miocene units was observed in the HMA through Pliocene buttress and angular unconformities with the older Miocene units. In contrast to surrounding field areas (Nagorsen-Rinke et al., 2013; DeLano et al., 2019), we observe Miocene normal faults and in turn, direct evidence for pre-Pliocene deformation in the HMA.

The first deformation event, exposed in the northern section of the HMA, is characterized by NE-striking, NW-dipping normal faults that cut and tilt units Mdbx and Mtjs ~15° southeastward; these faults are, in turn unconformably overlain by horizontal Pliocene units (Plate 1 and 2). No fault planes were observed in the field but fault traces, measured from mapping, yield an average strike of ~60°. Our field observations provide the first concrete evidence for a middle Miocene to early Pliocene extensional deformation event that explains published observations of tilting and paleorelief in Miocene units (Nagorsen-Rinke et al., 2013; DeLano et al., 2019; this study). In addition, tilting and paleorelief development in Miocene units explains the high angle contacts and buttress unconformities with younger Pliocene units we observed in the HMA and were
also observed in surrounding field areas in the southwestern MD (Nagorsen-Rinke et al., 2013; DeLano et al., 2019).

The second deformation event, exposed throughout the HMA, is defined by a dominant set of # near vertical ENE-striking sinistral faults and a subordinate set of four steeply NW-striking, SW-dipping normal-dextral faults. The latter fault set is exposed in the west-central HMA as part of a large (~7 km-long) extensional stepover between two ENE-striking sinistral faults. These faults cut all units in the HMA except the youngest Quaternary deposits (Plates 1 and 2). Pliocene sinistral and normal-dextral faults of the HMA share mutual crosscutting relationships suggesting sinistral and normal-dextral fault slip occurred contemporaneously.

**Magnitude of Extension and Extension Rates**

To calculate the magnitude of extension, we palinspastically restored unit Mtjs along cross section B-B’ (Plates 1 and 2). Palinspastic reconstruction of slip along normal faults and restoration of SE-dipping Mtjs to an original subhorizontal orientation along the northwestern third of cross-section B-B’’ yields a NW-SE extension magnitude of ~0.7 km between 12.114 ± 0.006 (age of unit Mtjs from Petronis et al., 2019) and ~4.1-3.0 Ma (ages of overlying uncut basalts from Tincher and Stockli, 2009; Nagorsen-Rinke et al., 2013; DeLano et al., 2019). Thus, the northern part of the HMA field area records a late Miocene to middle Pliocene NW-SE extension rate of ~0.1 mm/yr (Plate 2).

**Magnitude of Sinistral Offset and Fault Slip Rates**

Our new geologic mapping in the south-central HMA documents 15 sinistral faults and five normal-dextral faults, and six Cenozoic geologic markers offset by these faults (Plate 1, offset markers 1-6; Figs. 12, 13, and 14; Table 1). Offset geologic markers include sub-vertical basalt flow contacts, buttress unconformities, and angular
unconformities. Offset measurements were made using the 1:24,000 scale geologic map in Plate 1 in Adobe Illustrator by projecting offset marker contacts onto fault traces when necessary and measuring offset magnitude using the Measure Tool. Errors associated with lateral offset measurements include visually defining the location of intersection between the offset marker and fault and the geometry of the marker (strike and dip) relative to the faults. We assign an error of 15% for a well-defined intersection, such as a sub-vertical depositional contact (e.g. buttress unconformity) cut and offset by a vertical fault, and a more conservative error of at least 30% for less well-defined intersections such as moderately dipping contact cut and offset by a sub-vertical fault. Fault slip rates were calculated from the measured offset and age of youngest offset unit, and the error in fault slip rate is the standard deviation of associated offset and age error. Calculated fault slip rates are minimums since the late Pliocene (Table 1).

Pliocene sinistral slip is accommodated along three main fault systems in the HMA. From south to north, these faults are: 1) the Coaldale fault, 2) faults of McBride Flats, and 3) the Jack Springs extensional step-over (Plate 1; Fig. 11). No offset markers were found along the Coaldale fault in the HMA, but eastward near Montgomery Pass, Tincher and Stockli (2009) report ~1.2 km of sinistral offset of unit Tbc (basaltic scoria vent) across the Coaldale fault. Dividing the ~1.2 km of sinistral offset by the reported groundmass $^{40}\text{Ar}/^{39}\text{Ar}$ age of 3.14 ± 0.03 Ma for unit Tb(c) yields a long-term minimum sinistral slip rate of ~0.4 mm/yr along the Coaldale fault near Montgomery pass (Tincher and Stockli, 2009).

To the north of the Coaldale fault, the next sinistral fault system, herein called the faults of McBride Flats, records ENE-sinistral fault slip along three faults that offset the same buttress unconformity between the petrographically distinct basalt unit Pbn and unit
Mlt. The buttress unconformity is observed best on the southern side of Huntoon Mountain and defined by subhorizontal Pbn flows that abut a sub-vertical erosional escarpment developed in Mlt (Plates 1 and 2). Our observation that Pbn is in direct contact with Mlt in buttress unconformity provides strong evidence for paleorelief of Miocene volcanic rocks and is indicative of a pre-Pliocene deformation event. The buttress unconformity is offset along three east ENE-striking sinistral faults that, in total, record 1.6 ± 0.2 km of sinistral offset (Plate 1, offset markers 1-3; Fig. 12). Offset markers 1-1’ and 3-3’ have the highest confidence (15% error estimate in offset magnitude) while offset marker 2-2’ has relatively low confidence (30% error estimate in offset magnitude) (Plate 1; Fig. 12; Table 1). 

$^{40}$Ar/$^{39}$Ar groundmass plagioclase geochronology for unit Pbn is currently in progress, but its age can be preliminarily constrained between 3.544 ± 0.007 (DeLano et al., 2019) to 4.08 ± 0.10 Ma (Tincher and Stockli, 2009). Dividing the measured offset by the preliminary age range for unit Pbn yields a minimum long-term ENE-sinistral slip rate of 0.4 ± 0.2 mm/yr.

**Table 1.** Calculated sinistral and dextral slip rates in the Huntoon Mountain area

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<th>Age (Ma)</th>
<th>Age Source</th>
<th>Offset Type</th>
<th>Magnitude (m)</th>
<th>Slip Rates (mm/yr)</th>
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<td>5</td>
<td>3.544 ± 0.007-4.08 ± 0.10</td>
<td>1, 2</td>
<td>dextral</td>
<td>860 ± 130</td>
<td>~0.2</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>3.544 ± 0.007-4.08 ± 0.10</td>
<td>1, 2</td>
<td>dextral</td>
<td>300 ± 90</td>
<td>~0.1</td>
<td>13</td>
</tr>
<tr>
<td>N/A</td>
<td>3.14 ± 0.03</td>
<td>1</td>
<td>sinistral</td>
<td>~1200</td>
<td>~0.4</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Offset markers described in text and are shown in Plate 1 and Figures 12-14.
1Tincher and Stockli (2009).
2DeLano et al. (2019).
The next fault system, the Jack Spring extensional stepover, is a sinistral fault system on the north side of Huntoon Mountain that partitions slip along the main ENE-striking sinistral fault splay on the north side of Huntoon Mountain into a large NW-striking extensional stepover comprised of four main faults that also accommodates some dextral slip (Plate 1, offset markers 5-6; Fig. 13). Sinistral offset magnitude is measured from an offset sub-vertical basalt flow contact between units Pbol and Pbx. The offset basalt contact between these two units is exposed on the north side of a large volcanic center (Plate 1, offset marker 4; Fig. 14). This offset marker records 1.3 ± 0.2 km of sinistral offset. $^{40}\text{Ar}^{39}\text{Ar}$ groundmass plagioclase geochronology for units Pbol and Pbx is currently in progress, but its age can be preliminarily constrained between 2.996 ± 0.063 (DeLano et al., 2019) and 4.08 ± 0.10 Ma (Tincher and Stockli, 2009). Dividing the measured offset by the preliminary age range for unit Pbol yields a long-term ENE-sinistral slip rate of 0.4 ± 0.2 mm/yr.

**Magnitude of Dextral Offset and Fault Slip Rates**

Pliocene dextral offset markers are observed in two localities within the HMA along the northern terminuses of two of the large NW-striking normal-dextral extensional stepover faults. These dextral faults offset an angular unconformity between units Mtjs and Pbx/Pbg and record a total of 1.2 ± 0.3 km of NW dextral offset (Plate 1; Fig. 13; Table 1). Unit Mtjs dips 13° to the SE on average whereas, in general, Pliocene basalt flows are horizontal (Plate 1; Fig. 5b). $^{40}\text{Ar}^{39}\text{Ar}$ groundmass plagioclase geochronology for unit Pbx is currently in progress, but its age can be preliminarily constrained between 3.544 ± 0.007 (DeLano et al., 2019) and 4.08 ± 0.10 Ma (Tincher and Stockli, 2009). Dividing the magnitude of offset by this age range for Pbx yields a long-term minimum dextral slip rate of 0.3 ± 0.1 mm/yr.
DISCUSSION

Our new geologic mapping and structural studies in the HMA, south-central MD, build upon published work in the southwestern MD (Wesnousky, 2005; Tincher and Stockli, 2009; Nagorsen-Rinke et al., 2013; DeLano et al., 2019) and provides insight into the volcanic and deformation histories recorded in the MD. Exposed within the HMA are Miocene andesitic-dacitic volcanic and volcaniclastic rocks overlain by two Miocene ignimbrites all of which are unconformably overlain by interfingered Pliocene basalt lava flows (Plates 1, 2 and, 3). These rocks record two distinct deformation events: (1) middle Miocene-early Pliocene NW-SE extension and (2) Pliocene ENE sinistral and NW dextral fault slip. Palinspastic reconstruction of unit Mtjs in the northern HMA yields a horizontal extension magnitude of ~0.7 km and a horizontal extension rate of ~0.1 mm/yr from the middle Miocene-early Pliocene (Plate 2). Laterally offset Pliocene volcanic markers indicate a net minimum total ENE sinistral offset of 2.9 ± 0.4 km and NW dextral offset of 1.2 ± 0.1 km yielding minimum Pliocene sinistral and dextral slip rates of 0.8 ± 0.4 mm/yr and 0.3 ± 0.1 mm/yr, respectively.

Middle Miocene Extension

The first deformation event recorded in the HMA is a middle Miocene-early Pliocene NW-SE extensional event. In the southwestern MD, tilted Miocene units and paleorelief developed therein, overlain by subhorizontal Pliocene basalt and andesite lava flows led Nagorsen-Rinke et al. (2013) and DeLano et al. (2019) to suggest at least one deformation event prior to the emplacement of Pliocene units. However, the structures that resulted in tilting and paleorelief development were not exposed (Nagorsen-Rinke et al., 2013; DeLano et al., 2019). In the northern HMA, we mapped a series of NE-striking NW-dipping dextral-normal faults cutting southeast tilted Miocene units unconformably
overlain by subhorizontal Pliocene units (Plate 1 and 2; Figs. 9, 11, and 13). In addition to this, we mapped angular and buttress unconformities between Miocene and Pliocene units (Plate 1 and 2; Figs. 12 and 13). Normal faults and unconformable contacts between Miocene and Pliocene units provide the first clear evidence for at least one pre-Pliocene deformation event in the southwestern MD. Palinspastic reconstruction of normal faults that cut the Tuff of Jack Spring reveals an extension magnitude of ~0.7 km, yielding a middle Miocene to early Pliocene extension rate of ~0.1 mm/yr from 12.1 and ~4.1-3.0 Ma.

Recently published paleomagnetic data from unit Mtjs ~4 km north of the HMA reveal spatially variable components of clockwise vertical axis block rotation ranging from 25° - 104° with an average rotation of 60° ± 23° since the emplacement of unit Mtjs in the middle Miocene (Petronis et al., 2019). Rotating the NE-striking NW-dipping normal faults documented in the HMA anticlockwise to account for this average rotation yields an average NS-strike. This pre-rotation fault orientation indicates E-W extension between the middle Miocene and early Pliocene (Fig. 15).

The middle Miocene to early Pliocene E-W extension history in the HMA we documented can be explained by modifications to a tectonic model proposed across the MD by Tincher and Stockli (2009) (Fig. 15). Based on mapping across the Queen Valley region and studies across the central WL, these authors suggested that between 10-15 Ma the MD acted as a right lateral accommodation zone between the east-dipping Wassuk Range front normal fault to the north and the west-dipping White Mountain normal fault zone to the south (Fig. 15). In their model Tincher and Stockli (2009) suggest that E-W extension was expressed as dextral offset along ENE-striking faults just east of Queen Valley from 12-5.5 Ma. This was followed by dominantly ENE sinistral faulting with the
Figure 15: Modified tectonic model proposed by Tincher and Stockli (2009) illustrating the Miocene-Pliocene tectonic evolution of the MD. Active faults denoted by solid black lines; inactive faults denoted by solid grey lines and are provided for geographic context; large black arrows indicate general stress acting on the MD; fault symbols defined in figure 2. (A) Between ~15-10 Ma dextral slip along NE-striking faults and E-W extension along NS-striking faults in the MD define an accommodation zone that links the oppositely dipping normal faults of the Wassuk Range to the north and White Mountains to the south. (B) The White Mountains fault zone reactivates as a dextral fault at ~3 Ma. To the north, this dextral slip is partitioned into normal slip along the NE-striking Queen Valley normal fault and clockwise transrotational sinistral slip along ENE-striking sinistral faults. Older, inactive NS-striking normal faults (see A) rotate ~60° clockwise to a NE-SW strike. See text for further discussion. Modified from Tincher and Stockli (2009).
reactivation of the White Mountain fault zone as a dextral fault in the Pliocene (Tincher and Stockli, 2009) (Fig. 15). Tincher and Stockli (2009) did not include any E-W extension accommodated on NS-striking normal faults within the MD in their model. However, our investigations in the HMA show an episode of E-W extension across the MD between 12.1 and ~4.1-3.0 Ma. This can be explained by a modified version of the Tincher and Stockli (2009) model where right lateral accommodation between oppositely dipping Wassuk Range front normal fault and White Mountain normal fault zone is expressed as both E-W extension along NS-striking normal faults north of Queen Valley and dextral offset along ENE-striking faults to the east of Queen Valley (Fig. 15).

While our mapping constrains the age of normal faulting to between 12.1 and ~4.1-3.0 Ma, previous thermochronologic and structural studies on the White Mountain fault zone suggested that the MD acted as a right-lateral accommodation zone between 10-15 Ma (Stockli et al., 2003; Tincher and Stockli, 2009) (Fig. 15). These age constraints suggest that the timing of east-west extension across the HMA is bracketed between 12.1 Ma and 10 Ma. Using these age bounds yields an E-W extension rate of ~0.3 mm/yr across the HMA.

**Kinematics of Pliocene fault slip transfer across the MD.**

During the Pliocene, the deformation style across the MD changed to one dominated ENE-striking sinistral faults that define major right-stepover in the NW-striking dextral WL. Three kinematic models for slip transfer across the right-stepping MD in the dextral fault dominated WL have been proposed: (1) the displacement transfer model (Oldow, 1992; Oldow et al., 1994), (2) the transtensional model (Oldow, 2003), and (3) the clockwise block rotation model Wesnousky, 2005; Nagorsen-Rinke et al., 2013; DeLano et al., 2019) (Fig. 1). Similarly to the Adobe Hills (Nagorsen-Rinke et al.,
2013) and River Springs (DeLano et al., 2019) field areas, our new mapping did not
document normal motion along Pliocene ENE sinistral faults. These observations,
combined with Wesnousky’s (2005) field observations, which he interpreted as indicating
clockwise rotation, and Petronis et al.’s (2019) and Grondin et al.’s (2016) paleomagnetic
data indicating clockwise rotations, lead us to suggest that the displacement transfer (Fig.
1a) and the transtensional (Fig. 1b) models are not applicable to the southwestern MD at
least since the Pliocene. Our interpretation follows that of Nagorsen-Rinke et al. (2013)
and DeLano et al. (2019). In this interpretation, deformation is accommodated in the
southwestern MD by a series of clockwise rotating blocks bounded by ENE-striking
sinistral faults as described in the clockwise block rotation model (McKenzie and
Jackson, 1983, 1986; Dickinson, 1996; DeLano et al., 2019) (Fig. 1c and 16).

Delano et al. (2019) propose a transrotational model to assess the magnitude of
block rotation and the associated ENE sinistral slip rates on block bounding faults in the
southwestern MD. Here we assess this model by integrating our new geologic mapping
and structural data, and minimum fault slip rates with data from published studies across
the southern WL and southwestern MD (Bradley, 2005; Kirby et al., 2006; Lee et al.,
2006, 2009a; Tincher and Stockli, 2009; Nagorsen-Rinke et al., 2013; Lifton et al., 2013;
DeLano et al., 2019). Additionally, we compare rotation values from nearby
paleomagnetic studies (Petronis et al., 2009; Rood et al., 2011; Grondin et al., 2016;
Petronis et al., 2019) with the rotation value calculated by DeLano et al. (2019).

**Transrotational Model**

Geologic observations (e.g. lack of oblique fault striations, near vertical sinistral
faults) in the HMA, Adobe Hills (Nagorsen-Rinke et al., 2013), and River Spring
(DeLano et al., 2019) along with field observations from Wesnousky (2005) of sinistral
offset, fault geometry, and paired basins at ends of active fault zones suggest that deformation across the MD is characterized by vertical axis clockwise fault block rotation. Paleomagnetic data from across the MD support this interpretation; Miocene-Pliocene age rocks record variable degrees of clockwise rotation. In the eastern MD, Petronis et al. (2009) reported clockwise rotation rates of ≥4-6°/Ma since the late Miocene-early Pliocene (Fig. 3 for geographic reference). In the Bodie Hills region, west of the MD, Rood et al. (2011) reported rotation rates ~5°/Ma since the middle Miocene (Fig. 3 for geographic reference). In the western MD, ~4 km north of the HMA, Petronis et al. (2019) reported rotation rates 4.9 ± 1.9°/Ma since the middle Miocene (Fig. 3 for geographic reference). Furthermore, elastic block modeling of GPS data from across the central WL predicts present-day clockwise vertical axis rotation of fault blocks bounded by ENE-striking sinistral faults in both the MD and Carson domain (Bormann et al., 2016) (Fig. 3 for geographic reference). For these reasons, it is highly likely that deformation in the central MD is characterized by vertical axis clockwise block rotation and therefore should be considered when discussing the kinematics of fault slip transfer into and through the southwestern MD.

To account for clockwise vertical axis block rotation and further assess ENE sinistral slip rates in the southwestern MD, DeLano et al. (2019) utilize Dickinson’s (1996) pinned transrotational model to calculate ENE sinistral slip rates across the southwestern MD (Fig. 16). Since the model area from DeLano et al. (2019) includes the HMA, their results apply directly to this study. While other transrotational models proposed by Dickinson (1996) can be used to assess rotation and sinistral slip in the southwestern MD, Dickinson (1996) preferred the pinned model, thus we use it here. In the pinned model, the rotating block is pinned at its midline to the edges of the shear zone.
Figure 16: Pinned transrotation model showing clockwise rotating blocks (gray blocks), bounded by sinistral faults, within a zone of dextral shear across the southern WL and southwestern MD, California-Nevada. Heavy arrow shows the present-day azimuth of the motion of the Sierra Nevada block with respect to the central Great Basin (SN-CGB) (Bennett et al., 2003). WMFZ – White Mountain fault zone. VTBRAV – Volcanic Tableland–Benton Range–Adobe Valley faults. Modified from Dickinson (1996) and DeLano et al. (2019). See text for discussion and description of variables.
which allows the shear zone width, \( W \) (\( W_o \) and \( W_n \), where \( o \) and \( n \) are pre-rotation and post-rotation, respectively) and rotating block width, \( P \) (\( P_o \) and \( P_n \)) to vary during rotation while the length of the rotating block (\( L_c \)) remains fixed (Dickinson, 1996; DeLano et al., 2019) (Fig. 16). To calculate the magnitude of sinistral slip, the initial clockwise angle \( \phi \) between the rotating block and the shear zone boundary is calculated where: \( \alpha \) = post rotation angle between the rotating block and the shear zone boundary and \( S \) = total dextral slip in kilometers (Dickinson, 1996) (Fig. 16).

\[
\phi = \arccos\left(\frac{S \cdot \sin \alpha}{W_n} + \cos \alpha\right)
\]

(1)

Given a \( \phi \) value, the magnitude of sinistral slip (\( R \)) can be calculated using:

\[
\text{sinistral slip} = R = P_n (\cos \phi - \cos \alpha)/\sin \alpha
\]

(2)

DeLano et al.’s (2019) transrotational modeling was completed under the following simplifications and assumptions. (1) The geometry of faulting is simplified so that the dextral shear zone is bounded by two NW-striking fault zones, the dextral White Mountain fault zone to the east and the dextral Volcanic Tableland–Benton Range–Adobe Valley faults to the west (DeLano et al., 2019) (cf. Figs. 4 and 17). (2) The sinistral fault bounded blocks in the southwestern MD are simplified into one clockwise rotating fault block (cf. Figs. 17 and 18). (3) The maximum shear zone width (\( W_n \)) is 20 km. (4) All 2.8 mm/yr of dextral slip on the Owens Valley fault is partitioned onto the White Mountains fault zone and the Volcanic Tableland, and then transferred north into the sinistral faults in the southwestern MD (cf. Fig. 17). (5) Decomposing the 2.8 mm/yr
Figure 1: Kinematic fault slip model across the transition from the northwestern eastern California shear zone to the southwestern MD (cf. Fig. 3). Dashed black line bounds the Volcanic Tableland; blue dashed polygons show the locations of map areas Black Mountain (south) (DeLano et al., 2019), River Spring (middle) (DeLano et al., 2019), Adobe Hills (Nagorsen-Rinke et al., 2013) (northwest), and Huntoon Mountain area (this study) (northeast); heavy arrow in the northwest corner of the maps shows the present day azimuth of motion of the Sierra Nevada block with respect to the central Great Basin (SN-CBG) (Bennett et al., 2003) Fault symbols defined in Figure 2; fault abbreviations are defined in Figures 2 and 3. Modified from Delano et al. (2019) Nagorsen-Rinke et al. (2013) and Lee et al. (2009). See text for discussion.
Figure 18: Detailed kinematic fault slip model of the southwestern MD (cf. Figs. 3 and 17). Blue dashed polygons show the locations of map areas northern Black Mountain (south) (DeLano et al., 2019), River Spring (middle) (DeLano et al., 2019), Adobe Hills (Nagorsen-Rinke et al., 2013) (northwest), and Huntoon Mountain area (this study) (northeast); heavy arrow in the northwest corner of the maps shows the present day azimuth of motion of the Sierra Nevada block with respect to the central Great Basin (SN-CBG) (Bennett et al., 2003). Fault symbols defined in Figure 2; JSE – Jack Spring extensional step-over; MBF – faults of McBride Flats; other fault abbreviations are defined in Figures 2 and 3. Modified from Delano et al. (2019). See text for discussion.
toward 323° (cardinal direction of SN-CGB vector) yields a dextral shear rate of 2.7 mm/yr across the simplified dextral shear zone. (6) Age bounds for dextral shear are 3.5 Ma to 3.0 Ma, which yields total dextral slip (S in equation 1) of 9.5 km and 8.1 km (DeLano et al., 2019). (7) The post rotation angle between the rotating block and the shear zone boundary ranges from 75-89° (α in equation 1).

Using the aforementioned values to solve equations 1 and 2 yields sinistral slip (R) magnitudes ranging from 8.1-9.5 km (DeLano et al., 2019). Dividing R by our age range of 3.5-3.0 Ma yields ENE sinistral slip rates of 2.1-3.2 mm/yr. This calculated transrotational ENE sinistral slip rate is within error of both the GPS data constrained elastic block model strain rate of ~2.4 mm/yr (Bormann et al., 2016) and our new net minimum ENE sinistral fault slip rate of 1.9-3.0 mm/yr. Overlap of the modeled transrotational ENE sinistral slip rate with both GPS data constrained elastic block model sinistral shear rates and our new documented net minimum geologic fault slip rates suggests that the pinned model is a reasonable assessment of the transrotation in the southwestern MD.

Finally, differencing α and φ values yields angle of rotation values ranging from 22-31° since 3.5-3.0 Ma (DeLano et al., 2019). These rotation values are consistent with rotation values from the central MD of 19-35° (Petronis et al., 2009) and are well within the 5-60° clockwise rotation values from Pliocene basalt lavas in the Adobe Hills (Grondin et al., 2016) (Figs. 3 and 4 for geographic reference). However, our modeled clockwise rotation values are considerably lower than 60°±23° reported by Petronis et al. (2019) from unit Mtjs north of the HMA. Petronis et al. (2019) suggest that unit Mtjs records clockwise rotation in the region since the middle Miocene while units from the central MD (Petronis et al., 2009) record clockwise rotation since the latest Miocene-
earliest Pliocene. In contrast to Petronis et al. (2019), we suggest that all clockwise rotation in the MD has occurred since the Pliocene and the variability of clockwise rotation magnitude is best explained by small blocks with variable magnitudes of clockwise rotation (e.g. Nelson and Jones, 1987).

**Irrotational Kinematic Models**

To provide a first order approximation for how fault slip is transferred from the NW-striking dextral faults of the southern WL into the ENE-striking sinistral faults of the southwestern MD, DeLano et al. (2019) assessed the validity of two irrotational kinematic models (Fig. 17). DeLano et al.’s (2019) irrotational kinematic models are a simplification of the more complicated natural fault geometries, kinematics, and rates, and is based on the following assumptions (Fig. 17). (1) Fault geometries and orientations have been simplified (cf. Figs. 3, 4, and 17). (2) All fault slip rates have remained constant through time. (3) Published and new minimum fault slip rates in the models are treated as absolute rates and do not consider the errors in slip rate estimates. (4) The models are rotationally static in that vertical axis rotations are not considered. (5) The models assign a dextral slip rate of 2.8 mm/yr to the northern Owens Valley fault, the minimum rate reported by Kirby et al. (2008) (Fig. 17).

In the first irrotational model, all of the 2.8 mm/yr of dextral slip along the Owens Valley fault is transferred northward onto the White Mountain fault zone (Delano et al., 2019). In the second model, 1.9 mm/yr of dextral slip along the Owens Valley fault is transferred northward onto the White Mountain fault zone (Delano et al., 2019) (Fig. 17). In this model, the remaining Owens Valley fault slip is partitioned northwestward into E-W extension across the Volcanic Tableland and NNW-dextral slip along the Round Valley fault (DeLano et al., 2019) (Fig. 17). The irrotational models proposed by DeLano
et al. (2019) predicted fault slip rates in the transition zone from the dextral southern WL to the sinistral southwestern MD but they did not predict fault slip rates in the central part of the MD. Our newly documented Pliocene slip rates from the central MD provide additional constraints for how fault slip is accommodated within the MD and will allow for the improvement of these models.

To assess these models, we add $0.4 \pm 0.2 \text{ mm/yr}$ of ENE-sinistral slip documented along the faults of Mcbride Flats (MBF in Fig. 18) and $0.4 \pm 0.2 \text{ mm/yr}$ of ENE sinistral slip and $0.3 \pm 0.1 \text{ mm/yr}$ of NW dextral slip documented along the faults of the Jack Spring extensional step-over (JSE in Fig. 18) to the models (Nagorsen-Rinke et al., 2013; DeLano et al., 2019) (Plate 1; Figs. 11-14, 17 and 18; Table 1). To maintain strain compatibility, the sinistral slip rates along the faults of the Mcbride flats suggest $0.4$-$0.7 \text{ mm/yr}$ of NE-SW compression along the Coyote Springs fault (DeLano et al., 2019) (Figs. 17 and 18). The $0.4 \pm 0.2 \text{ mm/yr}$ of ENE sinistral slip documented along the southern ENE sinistral fault of the JSE suggests that some of the documented $0.7$-$0.9 \text{ mm/yr}$ ENE sinistral slip from the northeastern River Spring field area (Delano et al., 2019) has been partitioned into ENE-WSW extension in the JSE (Fig. 18). We can calculate the ENE-WSW extension rate along to NW-striking dextral-normal faults of the JSE by differencing the slip rate documented along the sinistral faults in the northeastern River Spring field area and the slip rate documented along the southern ENE sinistral fault of the JSE (Fig. 18). This yields an ENE-WSW extension rate of $0.3$-$0.5 \text{ mm/yr}$. Additionally, along these same dextral-normal faults of the JSE, $0.3 \pm 0.1 \text{ mm/yr}$ of NW dextral slip was documented. This new NW dextral slip rate is subparallel to and, within error of, NW dextral rates of $0.3 \pm 0.1 \text{ mm/yr}$ documented in the River Spring field area (DeLano et al., 2019) (Figs. 17 and 18). Our new documented sinistral and dextral
Pliocene fault slip rates help to confirm the predictions made by the irrotational kinematic models proposed by Nagorsen-Rinke et al. (2013) and DeLano et al. (2019) as well as place new constraints for fault slip rates in the central MD.

Additionally, summing our new minimum ENE sinistral fault slip rates of 0.8 ± 0.4 mm/yr from the HMA with previously published rates in the southern MD of ~0.4 mm/yr along the Coaldale fault (Tincher and Stockli, 2009), 0.4-0.5 mm/yr in the Adobe Hills area (Nagorsen-Rinke et al., 2013), and 0.7-0.9 mm/yr in the River Spring area (DeLano et al., 2019) yields a net minimum ENE sinistral geologic fault slip rate of 1.9-3.0 mm/yr parallel to N50-60E across the southern MD since the middle Pliocene. This revised net ENE sinistral slip rate is within error of GPS data constrained elastic block model shear rates of ~2.4 mm/yr (Bormann et al., 2016) (Fig. 18). This supports ours and DeLano et al.’s. (2019) hypothesis that the discrepancy between modeled geodetic and documented geologic fault slip rates was due to undocumented fault slip within the central MD, of which, most (all?) has been found in the HMA.

Geologic vs Geodetic Rates

In regions with constant strain rates, geologic and geodetic fault slip rates should be similar (Bennett et al., 2003; Lee et al., 2009b). However, discrepancies between geodetic and geologic slip rates can be explained by: (1) documented geologic slip rates underestimate the true fault slip rate, (2) not all geologic slip in the region has been documented, or (3) the region is experiencing a pulse of slip that is greater than the average geologic slip rate known as a strain transient (DeLano et al., 2019). Summed geodetic strain rates calculated parallel to Pacific-North American plate motion (313º) (Dixon et al., 2000) across the southern WL at a latitude of ~36.5º, are the same, within error, as geologic slip rates at ~9.3 mm/yr (cf. Bennett et al., 2003; Lee et al.,
2009b) (Fig. 3). Across the southern WL ~140 km to the north, at a latitude of ~37.5°, Lifton et al. (2013) showed that the sum of late Pleistocene fault slip rates was ~3.0-5.9 mm/yr which is only ~27-58% of the modeled geodetic strain rate of 10.6 ± 0.5 mm/yr. More recently, DeLano et al. (2019) hypothesized that newly published geologic fault slip and previously unconsidered slip may account for the discrepancy between geodetic and geologic fault slip rates across the southern WL. Accounting for variable amounts of slip on the White Mountain fault zone (Kirby et al., 2006; Lifton et al., 2013; DeLano et al., 2019), DeLano et al. (2019) presented three new geologic slip rates summed along a transect orthogonal to 323° from the San Antonio Mountains, Nevada southwest to the Sierra Nevada, California of 7.5 +1.2/-0.8 mm/yr, 8.5 +1.3/-0.9 mm/yr, and 9.3 +1.2/-0.8 mm/yr. The first two account for 60-97% of the geodetic rate and the latter is within error of the modeled GPS rate for the southern WL (cf. Lifton et al., 2013; DeLano et al., 2019).

While the work of DeLano et al. (2019) rectifies the discrepancy between geodetic and geologic fault slip rates in the southern WL, it does not adequately explain the same issue in the southwestern MD. Previously summed geologic ENE sinistral slip rates through the southwestern MD were 1.4-1.8 mm/yr which is ~58-82% of the present-day GPS data constrained estimate of ~2.4 mm/yr of sinistral shear (Bormann et al., 2016; DeLano et al., 2019). DeLano et al. (2019) hypothesized that the discrepancy between geodetic and geologic fault slip rates in the southwestern MD can be explained by either: (1) documented minimum geologic fault slip rates underestimate the true slip rate or (2) there is fault slip on sinistral faults in the MD that has not yet been documented. Our newly documented ENE sinistral fault slip rates in the HMA allow us to address this discrepancy.
Summing our new ENE sinistral fault slip rates of 0.8 ± 0.4 mm/yr parallel to N50-60E with previously published ENE sinistral fault slip rates in the southwestern MD (Tincher and Stockli, 2009; Nagorsen-Rinke et al., 2013; DeLano et al., 2019) yields a net minimum ENE geologic sinistral fault slip rate of 1.9-3.0 mm/yr (Fig. 18). This ENE sinistral geologic fault slip rate is within error of the GPS data constrained elastic block model sinistral shear rate of ~2.4 mm/yr (Bormann et al., 2016). Thus, the MD is not experiencing a strain transient but rather undocumented fault slip explains the discrepancy between geodetic and geologic slip rates in the southern MD.

**SUMMARY**

New geologic mapping, structural, and soon to be completed geochronology studies spatially and temporally characterize the volcanic and deformation histories in the HMA, south-central MD. The HMA exposes primarily Miocene andesitic-dacitic lava flows, debris flows, and lahars overlain by the 12.114 ± 0.006 Ma (\(^{40}\text{Ar}/^{39}\text{Ar}\) sanidine, Petronis et al., 2019) Tuff of Jack Spring in the northern HMA and the 11.399 ± 0.041 Ma (\(^{40}\text{Ar}/^{39}\text{Ar}\) plagioclase, Nagorsen-Rinke et al., 2013) latite ignimbrite in the southern HMA. These units, in turn, are overlain in buttress and angular unconformity by the 4.08 ± 0.10 (\(^{40}\text{Ar}/^{39}\text{Ar}\) groundmass plagioclase, Tincher and Stockli, 2009) to 2.996 ± 0.063 Ma (\(^{40}\text{Ar}/^{39}\text{Ar}\) groundmass plagioclase, DeLano et al., 2019) basalt lavas, volcanic centers, and scoria deposits.

Our study is the first to document evidence for extensional deformation along now NE-striking, NW-dipping normal faults that cut Miocene and older units, but not the Pliocene and younger units. This deformation event resulted in the development of paleorelief in Miocene units observed across the southwestern MD. Palinspastic
restoration of unit Mtjs reveals a horizontal extension magnitude of ~0.7 km between 12.114 ± 0.006 (Petronis et al., 2019) and ~4.1-3.0 Ma (Tincher and Stockli, 2009; DeLano et al., 2019) yielding a minimum NW-SE extension rate of ~0.1 mm/yr.

Paleomagnetic data on unit Mtjs from Petronis et al. (2019) suggest that these normal faults have since been rotated clockwise from their original NS strike.

Our investigations also documented Pliocene ENE sinistral and NW dextral offset markers north of the Coaldale Fault in the HMA (Nagorsen-Rinke et al., 2013; DeLano et al., 2019). ENE-striking faults offset a buttress unconformity and sub-vertical basalt flow contact 2.9 ± 0.4 km, and dextral slip along NW-striking faults offset an angular unconformity 1.2 ± 0.3 km. Combining magnitude of offset measurements with ages for offset volcanic markers yields ENE sinistral and NW dextral slip rates of 0.8 ± 0.4 and 0.3 ± 0.1 respectively.

Our results suggest the HMA underwent E-W extension during the middle Miocene to early Pliocene followed by clockwise vertical axis rotation and dominantly ENE-striking sinistral faulting in the Pliocene. Summing published ENE sinistral slip rates from northern Queen Valley (Tincher and Stockli, 2009), Adobe Hills (Nagorsen-Rinke et al., 2013), and River Springs (DeLano et al., 2019) areas with our ENE sinistral slip rate of 0.8 ± 0.4 mm/yr yields a minimum ENE sinistral slip total geologic sinistral slip rate of 1.9-3.0 mm/yr which is within error of the GPS sinistral shear rate of ~2.4 mm/yr (Bormann et al., 2016) and the modeled transrotational rate of 2.1-3.2 mm/yr (DeLano et al., 2019). Results presented here, combined with those from surrounding field areas, suggest that dextral slip transferred northward into the southwestern MD is accommodated by clockwise rotating blocks bounded by ENE-striking sinistral faults (Fig. 1c). Additionally, the discrepancy between geodetic and geologic slip rates in the
southwestern MD has been resolved through documentation of new ENE sinistral fault slip rates within HMA.
CHAPTER IV

CONCLUSIONS

New geologic mapping, structural, and geochronology studies (in progress) characterize the spatial and temporal kinematics of fault slip transfer through the HMA, south-central MD. This study is the first to document pre-Pliocene E-W extension of ~0.1 mm/yr from 12.1 Ma to 4.1-3.0 Ma as well as Pliocene dextral and sinistral offset markers and long-term fault slip rates in the HMA. New mapping documents a series of pre-Pliocene normal faults, two ENE sinistral offset markers, and one NW dextral offset marker. Identified pre-Pliocene normal faults found in the HMA help confirm speculations of pre-Pliocene deformation from Nagorsen-Rinke et al. (2013) and DeLano et al. (2019) as well as strengthen the tectonic model proposed by Tincher and Stockli (2009) that suggests the present-day MD was acting as a right lateral accommodation zone between oppositely dipping range frontal faults. Results here also suggest a long-term dextral slip rate of 0.3 ± 0.1 mm/yr and long-term sinistral slip rate of 0.8 ± 0.4 mm/yr since ~3.5 Ma across the HMA. Fault slip in the southern MD is characterized by three additional datasets: (a) a mapping project along the Coaldale Fault, Tincher and Stockli (2009), (b) a mapping project in the Adobe Hills, southwestern MD, Nagorsen-Rinke et al. (2013), and (c) a mapping project in the Black Mountains and River Spring area, southwestern MD, DeLano et al. (2019). Summing published ENE sinistral slip rates from these studies with our ENE sinistral slip rate of 0.8 ± 0.4 mm/yr yields a net minimum ENE sinistral slip rate of 1.9-3.0 mm/yr which is within error of the GPS data constrained sinistral shear rate of ~2.4 mm/yr (Bormann et al., 2016). This suggests that sinistral fault slip across the southern MD has been consistent throughout its slip history. Lack of observed Pliocene normal motion and horizontal Pliocene units lead us to the
same conclusion as Nagorsen-Rinke et al. (2013) and DeLano et al. (2019), that the kinematics of fault slip transfer across the present-day MD best fit the clockwise block rotation model where ENE sinistral fault slip is accommodated along faults that bound clockwise rotating blocks.
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