# CHAPTER 3

# Geologic map of the east-central Meadow Valley Mountains, and implications for reconstruction of the Mormon Peak detachment fault, Nevada

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## ABSTRACT

The role of low-angle faults in accommodating extension within the upper crust remains controversial, because their existence markedly defies extant continuum theories of how crustal faults form, and once initiated, how they continue to slip. Accordingly, for many proposed examples, basic kinematic problems like slip direction, dip angle while active, and magnitude of offset are keenly debated. A prime example is the Mormon Peak detachment and overlying Mormon Peak allochthon of southern Nevada, whose origin and evolution have been debated for several decades.

Here, we use geologic mapping in the Meadow Valley Mountains to define the geometry and kinematics of emplacement of the Mormon Peak allochthon, the hanging wall of the Mormon Peak detachment. Identifiable structures well suited to constrain the geometry and kinematics of the detachment include a newly mapped, Sevier-age monoclinal flexure in the hanging wall of the detachment. The bounding axial surfaces of the flexure can be readily matched to the base and top of the frontal Sevier thrust ramp, which is exposed in the footwall of the detachment to the east, in the Mormon Mountains and Tule Springs Hills.

Multiple proxies, including the mean tilt direction of hanging wall fault blocks, the trend of striations measured on the fault plane, and other structural features, indicate that the slip direction along the detachment is approximately S75W (255°). Given the observed separation lines between the hanging wall and footwall, this slip direction indicates c. 12 to 13 km of displacement on the Mormon Peak detachment, lower than a previous estimate of 20 to 22 km, which was based on erroneous assumptions in regard to the geometry of the thrust system. Based on a new detailed map compilation of the

region, simple palinspastic constraints also preclude earlier suggestions that the Mormon Peak allochthon is a composite of diachronously emplaced, surficial landslide deposits. Although earlier suggestions that the initiation angle of the detachment in the central Mormon Mountains is c. 20-25° remain valid, the geometry of the Sevier-age monocline in the Meadow Valley Mountains and other structural data suggest that the initial dip of the detachment may steepen markedly to the north beneath the southernmost Clover Mountains, where the hanging wall includes kilometer-scale accumulations of volcanic and volcaniclastic strata.

## INTRODUCTION

In materials obeying Byerlee or Coulombic failure laws, the shear stress required for both the initiation and continued slip on normal faults dipping less than 30° is greater than the shear strength of the rock, assuming the maximum principal stress direction is sub-vertical (e.g. Collettini and Sibson, 2002; Axen, 2004). Extensional detachments (nominally, low-angle normal faults with displacements of kilometers to tens of kilometers), are widely described in the literature and currently accepted by most geologists as fundamental tectonic elements. However, they are problematic, not only from a mechanical point of view, but also from the point of view of historical seismicity, which is dominated by slip on planes steeper than 30° (e.g. Jackson and White 1989; Wernicke, 1995; Elliott et al, 2010). Thus, despite general acceptance, the very existence of low-angle normal faults continues to be challenged, even on geological grounds (e.g. Miller et al, 1999; Anders et al, 2006; Wong and Gans 2008).

For example, a frequently cited example of an upper-crustal normal fault that both initiated and slipped at low angle (20-25°) throughout its evolution is the middle Miocene Mormon Peak detachment of southern Nevada, which localized near the frontal thrust ramp of the Cretaceous Sevier orogeny (Wernicke et al, 1985; Wernicke and Axen, 1988; Axen et al, 1990; Wernicke, 1995; Axen, 2004; Anderson et al, 2010). This interpretation has been challenged by several workers who contend that the hanging wall of the detachment constitutes one or more large-scale rock avalanche deposits (e.g. Carpenter et al, 1989; Anders et al. 2006; Walker et al. 2007).

Because the detachment is superimposed on the frontal ramp of a decollement thrust belt, numerous potential structural markers, such as (1) the axial surfaces of the frontal ramp syncline and anticline, (2) footwall cut-offs of Paleozoic and Mesozoic stratigraphic units by the ramp zone, and (3) stratigraphic mismatch between footwall and hanging wall units of the detachment, provide constraints on both the initial dip and net displacement along the detachment. Although some of these features were previously described in detail from the footwall of the detachment in the Mormon Mountains and Tule Springs Hills area (Wernicke et al., 1985; Axen et al 1990), potential offset counterparts in the Meadow Valley Mountains, immediately to the west of the Mormon Mountains, have to date only been mapped in reconnaissance (Tschanz and Pampeyan, 1970; Pampeyan 1993). These maps depict a large-scale, monoclinal flexure in Paleozoic and Mesozoic strata overlain in angular unconformity by a succession of mid-Tertiary lacustrine and volcanic strata. Based on the regional geology of the frontal Sevier ramp zone in southern Nevada (Longwell et al., 1965; Burchfiel et al, 1974; Burchfiel et al. 1982; Carr, 1983; Axen, 1984; Burchfiel et al, 1997), this flexure constrains the geometry of the frontal thrust ramp (e.g. Axen et al. 1990). In this paper, we present new 1:24,000 scale mapping of the Meadow Valley Mountains targeted toward documenting the heretofore poorly constrained geometry of the frontal ramp zone, and examine its implications for the existence, geometry, and kinematics of the Mormon Peak detachment.

## GEOLOGIC SETTING

The Sevier front in the southern Nevada region is primarily expressed by a decollement thrust that initiated within Middle Cambrian dolostones along a strike length of >200 km (Burchfiel et al., 1982). In the northern 50 km of exposure, the thrust trace is comparatively straight, striking NNE, except where strongly overprinted by Miocene faulting (Figure 1). The most readily identifiable structural element along the entire trace is the frontal ramp, where the thrust cuts upsection in the footwall from lower Paleozoic to Jurassic strata. The ramp zone is variably accompanied by a footwall syncline and thin duplex slices. The hanging wall of the thrust is invariably detached within a restricted stratigraphic interval within Middle Cambrian dolostones, near the boundary between the Papoose Lake and Banded Mountain members of the Bonanza King Formation (Burchfiel et al., 1982; Bohannon, 1983 ; Wernicke et al., 1985; Axen et al., 1990). The three structural elements that are most useful as potential offset markers include (1) the base of the ramp and associated ramp syncline; (2) the intersection of the ramp and the top of footwall Mississippian strata; and (3) the top of the ramp and associated ramp anticline (Figure 2). Based on previous mapping, the position of the first two of these elements is relatively well known, but any trace of the ramp anticline had not been recognized (Figure 2).

The Paleozoic and Mesozoic strata involved in thrusting lie along the eastern margin of the Cordilleran miogeocline. The hanging wall of the frontal thrust contains a section transitional between thin cratonic facies to the east and thick continental shelf deposits to the west (e.g. Burchfiel et al., 1974). Among a number of systematic across-strike stratigraphic variations near the thrust ramp is the westward erosive pinchout of some 400 m of Permian carbonates (Toroweap and Kaibab Formations) below an unconformity at the base of the Lower Triassic Virgin Limestone Member of the Moenkopi Formation (Burchfiel et al., 1974; Tschanz and Pampeyan, 1970). The pinchout occurs within the west-facing monoclinal flexure formed by the ramp, best exposed in the Spring Mountains, Nevada, and the central Meadow Valley Mountains.

The Mormon Mountains are a topographic and structural dome, veneered by klippen of the Mormon Peak detachment (Figure 1). The footwall geology of the detachment is a ~6 to 8 km thick, variably east-tilted crustal section through the frontal thrust ramp zone. Below the detachment, the structurally deeper, western part of the range exposes autochthonous Proterozoic basement and nonconformably overlying Cambrian through Mississippian strata. In the central part of the range, Middle Cambrian strata of the Mormon thrust plate are thrust over Mississippian strata. In the eastern part of the range, the thrust ramps upward at an angle of ~30° relative to bedding in the autochthon.

The hanging wall of the Mormon Peak detachment, hereafter referred to as the Mormon Peak allochthon, is composed of moderately to strongly tilted imbricate normal fault blocks (Figure 3). The fault blocks are composed primarily of Cambrian through Pennsylvanian carbonates derived from the Mormon thrust plate. Along the northern flank of the range, the Pennsylvanian carbonates are concordantly overlain by interstratified gravels, rock avalanche deposits and volcanic strata of Tertiary age, locally as much as 2000 m thick (Anderson et al., 2010). Most of these strata are coeval with eruption of the Middle Miocene Kane Wash Tuff (c. 14-15 Ma), but locally strata as old as the Late Oligocene Leach Canyon Tuff (c. 24 Ma) are preserved in the Tertiary section.

In general, stratal tilt directions within the Mormon Peak allochthon are quite systematic. The eastern and northern part of the allochthon contains blocks tilted to the E or NE, and the westernmost part contains blocks tilted to the W or SW (Figure 3). Where the boundary between the E- and W- tilted domains intersects the northwest boundary of the range, Tertiary strata are disconformable on Bird Spring strata and show both E and W tilts. Hence the difference in tilt direction is primarily a consequence of Tertiary deformation.

The Meadow Valley Mountains, immediately to the west of the Mormon Mountains, contain two structurally distinct domains. In the southern part of the range, the ramp syncline is characterized by folded upper Paleozoic strata no younger than the Kaibab Formation, overlain in angular unconformity by the Kane Wash Tuff (Pampeyan, 1993). Farther north, strata as young as the Petrified Forest Member of the Triassic Chinle Formation are preserved beneath the sub-Tertiary unconformity, suggesting at least a 1500 m difference in structural level near the axis of the syncline. In this area, strata on the east limb of the syncline are overlain in angular unconformity by the Leach

Canyon Tuff and younger strata. The sub-Tertiary unconformity ultimately cuts downsection to the Bird Spring Formation of late-Paleozoic age in the eastern part of the range. Similar to the relationship in the adjacent northern Mormon Mountains, Tertiary strata in the easternmost Meadow Valley Mountains lie concordantly, or in mild angular unconformity, on the Bird Spring Formation.

## METHODS

Geologic mapping of part of the Meadow Valley Mountains (Figure 4) was done during the spring of 2011 and spring of 2012, using 1:12,000 base maps. The following maps and field sheets were digitized in ArcGIS: the Meadow Valley Mountains field sheets (this report), Wernicke et al., (1985), Axen et al., (1990), Axen (1991), Axen (1993), Taylor (1984), Ellis (1985), Olmore (1971), Skelly (1987), unpublished mapping (Skelly, Axen, and Wernicke, 1987), and unpublished mapping (Wernicke, Ellis, and Taylor, 1983). Stereographic projections of bedding and foliations within the field areas were projected using Allmendinger's Stereonet 8 program (Cardozo and Allmendinger, 2013; Allmendinger et al., 2013).

## STRUCTURES

Faults within the mapped areas of the Meadow Valley Mountains (Figure 4) are predominantly NNE-trending to NNW-trending high-angle normal faults, with moderate offsets (10s to 100s of meters). Tertiary volcanic units are truncated by these faults, indicating a Tertiary age. There is a tight, pre-Tertiary anticline with a NW trend in the central part of the mapped area. Subvertical orientations of the Permian beds directly underlie subhorizontal Tertiary strata.

The general orientations of strata within the southwestern half of the map area are different from the northeastern half, with the transition occurring across a zone of ~N-S trending faults located in the middle of the map area (Figure 4). The Paleozoic and Mesozoic units in the western half form a homocline that uniformly dips ~40° NW, overlain by subhorizontal Tertiary strata. In the eastern half, dips of pre-Tertiary strata are more variable, but average 10-20° NE. Tertiary strata generally dip c. 25-50 ° NE, somewhat more steeply than underlying pre-Tertiary strata.

The oldest exposed Tertiary units are lower Quichapah volcanics (i.e. Leach Canyon and Bauer tuffs), locally overlying basal Tertiary conglomerate or limestone beds. Leach Canyon tuffs overlie tilted Triassic Chinle Formation in the west and cut down-section to the middle of the Permian red beds in the east. In the northeastern corner of the mapped area (Figure 4), Leach Canyon and Harmony Hills directly overlie Bird Spring Formation strata, but it is unclear if the contact is depositional or faulted.

There appears to be a slight angular unconformity beneath and within Kane Wash units, suggesting some tilting may have occurred between individual flows, but the difference in dip is too slight to be definitive.

Two cross-sections drawn perpendicular to the strike of Tertiary bedding (Figure 5, a and b) show the increase in Tertiary dips towards the east. Reconstructions that untilt Tertiary strata and restore Tertiary fault offsets (Figure 5, c and d) show an eastward decrease in angle between the pre-Tertiary and Tertiary strata from west to east. Thus the area records the formation of a WNW-facing monoclinal flexure prior to deposition of the Tertiary section (Figure 5, b and d). After deposition, the flexure was overprinted by a NNW-trending, extensional rollover structure, imparting an ENE dip onto the shallowly west-dipping limb of the pre-Tertiary flexure.

Orientations of bedding in the hanging wall of the Mormon Peak detachment show an abrupt transition from predominantly east dips to predominantly west dips, in both the Meadow Valley Mountains and the Mormon Mountains (Figure 3). The boundary between predominantly east-dipping beds and predominantly west-dipping beds has an apparent separation of ~5 km left-laterally across a narrow swath of alluvial cover in Meadow Valley Wash (Figure 3). The strike of bedding in fault blocks on the northwestern edge of the Mormon Mountains, closest to the Meadow Valley Wash, is more westerly than in the interior of the Mormon Mountains, with the dip direction transitioning gradually between the two areas.

The hanging wall of the Mormon Peak detachment is divided into 8 sub-domains (including the eastern Meadow Valley Mountains), with each sub-domain denoted with variously colored and numbered enclosures (Figure 3). Each klippe of the detachment is shown separately, except those with fewer than 20 measurements, which were combined with nearby klippen. Stereograms showing a total of 717 attitudes of bedding show a strong fabric in tilt directions oriented ENE-WSW. The main exception to this overall pattern is the strong E to ESE tilt in the northernmost Mormon Mountains (domain 8, Figure 3).

## RECONSTRUCTIONS

In addition to the restorations of cross-sections through the Meadow Valley Mountains (Figure 5, b and d), restoration of the orientations of pre-Miocene strata in the greater hanging wall area of the Mormon Peak allochthon also define a flexure in upper Paleozoic and Mesozoic strata (Figure 6). Sub-domains 7 and 8 (Figure 3) in the northern Mormon Mountains, and the eastern and western portions of the Meadow Valley Mountains (domain 6, Fig. 3 and an un-numbered domain, respectively), all have Tertiary strata in depositional contact with underlying Paleozoic units. We calculated the mean Tertiary attitude in each domain, and used it to estimate attitudes of bedding in Paleozoic and Mesozoic units in each domain prior to Tertiary deposition (Figure 6). These restored dips define a WNW-facing monocline between domains, with dips shallowing to a subhorizontal orientation in the northwestern Mormon Mountains (domain 7, Fig. 3). Restored dips in the westernmost Meadow Valley Mountains average ~35° NW, the eastern Meadow Valley Mountains ~20° NW, and the northwestern Mormon Mountains <10°. The reconstructed dips from the northernmost Mormon Mountains (sub-domain 8) vary from this pattern, dipping ~25° S. Regardless of this complexity, the observation that the Tertiary section everywhere rests on lower part of the Bird Spring Formation throughout the northern Mormon Mountains suggests limited overall structural relief east of the monoclinal flexure.

We can relate the hanging wall and footwall structure of the Mormon Peak detachment by combining various footwall stratigraphic and structural cutoffs, exposed in the Mormon Mountains, with a downward projection of the cross sections in the Meadow Valley Mountains (Figure 7). The geology of the Mormon Mountains and Tule Springs Hills in the footwall of the Mormon Peak detachment is taken from Axen et al. (1990), with the Meadow Valley Mountains geology modified using structural cross sections from this study.

## DISCUSSION

### Transport direction on the Mormon Peak detachment

A precise direction of displacement is necessary in order to get an accurate measurement of the net offset across the Mormon Peak detachment. A number of independent lines of evidence suggest that the transport direction averages about S77°W (Table 1). The first is based on a compilation of attitudes of bedding within the hanging wall of the detachment that indicate the tilt directions within the Mormon Peak allochthon (Figure 3). Studies of imbricate normal fault blocks suggest that the mean tilt direction tends to parallel slickenlines and other transport indicators (e.g. Anderson et al, 1971**;** Davis et al, 1980**;** Davis and Hardy, 1981). Thus, the tilt direction of bedding is often used as a proxy for maximum elongation direction in extensional allochthons, and for the transport direction on underlying detachments, assuming bedding was subhorizontal at the onset of extension.

All 717 structural measurements in Figure 3 are combined in Figure 8, and reveal a strong preferred orientation. Figure 8a shows the modern orientations of pre-Tertiary strata that were subhorizontal prior to extension (i.e. excluding units from the Sevier thrust ramp in the western Meadow Valley Mountains). The density contours and maximum density of these data show a well-defined ENE-WSW trend, with the best-fit circle through them oriented 251/86 (Figure 8b), suggesting a maximum elongation direction and slip direction along the detachment of 251° (S71W). In addition, the averages for each spatial sub-domain (Figure 3) define an array that also aligns along an ENE-WSW trend that strikes ~245°, excluding sub-domain 8. Subdomain 8 is at the extreme northern edge of the Mormon Mountains. It contains a larger proportion of syntectonic strata, and may have experienced complex vertical-axis rotations due to Tertiary strike-slip faulting and/or folding, as suggested by Anderson et al. (2010) and discussed further below.

In Figure 8c, poles to bedding for 90 attitudes measured in Tertiary units in the hanging wall of the Mormon Peak detachment are plotted, along with domainal averages (Figure 3). A unimodal maximum in poles to bedding occurs at 60° towards S59W (60->239), corresponding to a mean attitude of N31W 30NE (329/30). This implies an extension direction and transport of the allochthon towards ~239° (Figure 8d).

Twenty-six striations on or near the detachment plane, broadly distributed over the surface trace of the Mormon Peak detachment in the Mormon Mountains, are shown on Figure 9 (Walker, 2008). The east plunging determinations were all measured on the east-dipping trace of the detachment in the eastern Mormon Mountains, which was rotated eastward in Tertiary time along imbricate normal fault blocks of the Tule Springs detachment system (Axen et al., 1990; Axen, 1993). These faults cut, and are therefore younger than, the Mormon Peak detachment.

Walker et al. (2007) suggested that each of the individual klippe of the Mormon Peak allochthon represent individual surficial gravity slide masses that moved at different times radially off of the modern topographic dome defined by the Mormon Mountains, and by the structural contours of the Mormon Peak detachment. They based their hypothesis on the claim that the striations everywhere indicate motion of the klippe down the modern dip direction of the detachment.

Across the eastern half of the topographic and structural dome, the substrate of the detachment is the Mormon thrust plate. The radial gravity slide hypothesis of Walker et al. (2007) is readily falsified by the observation that the oldest strata at the base of the fault blocks across the eastern half of the dome is everywhere younger than the age of strata in the footwall of the detachment above the Mormon thrust. Across this area, the detachment is a footwall decollement riding about 100-200 m stratigraphically below the base of the Dunderburg Shale Member of the Upper Cambrian Nopah Formation (see Axen, 1993, for stratigraphic nomenclature). The east-tilted normal fault blocks above the detachment across the eastern 2/3 of the Mormon Mountains are predominantly Ordovician through Pennsylvanian strata, unconformably overlain by Tertiary volcanic and sedimentary strata, with only local preservation of the upper part of the Nopah Formation in some of the fault blocks, mainly in the westernmost blocks well to the west of the range crest (Figure 10). The detachment level at the base of the hanging wall blocks is thus stratigraphically at least 100-200 m above the basal beds of "unit Cbb4" (the black marker horizon in the upper part of the Banded Mountain Member of the Bonanza King Formation, as defined in Wernicke, 1984, Wernicke et al., 1985, Wernicke et al., 1989, Axen et al., 1990, and Axen, 1993), ruling out derivation of any of these blocks to the *west* of their present location, as required by the gravity-slide model. The basal Cbb4 footwall decollement of the detachment can be confidently traced on geologic maps from the northeasternmost Mormon Mountains across the East Mormon Mountains and Tule Springs to Jumbled Mountain (Axen et al., 1990; Swanson et al., submitted). In the Tule Springs Hills, a few kilometers east of the Jumbled Mountain exposure, the detachment is observed to cut rapidly upsection from its Cbb4 decollement, cutting upward across the Dunderburg Shale Member and into Upper Cambrian and younger strata (Axen, 1993). Hence, simple palinspastic constraints unambiguously define a simple stratigraphic separation across the detachment, independent of arguments based on offset structural markers of Sevier age. This stratigraphic separation constraint indicates that the pre-detachment substrate of fault blocks in the Mormon Peak allochthon lies in the Tule Springs Hills, east of the footwall cutoff of the Dunderburg Shale, requiring the allochthon in its entirety to have been displaced generally westward, not radially off the crest of the structural and topographic dome in the Mormon Mountains.

This simple "statigraphic separation" argument is supported by the observations that (1) the tilted fault blocks in the eastern Mormon Mountains are bounded by faults that cut the Mormon Peak detachment, restoring its initial trajectory to dip uniformly westward (Wernicke et al., 1985; Axen et al., 1990), (2) the structural continuity between the northwest Mormon Mountains and the Meadow Valley Mountains, both of which are composed of ENE tilted fault blocks of Kane Wash Tuff and older Tertiary strata resting unconformably on the lower part of the Bird Spring Formation (Figures 2, 3 and 6); requiring that (3) all of the blocks in the Mormon Peak allochthon, which are continuously exposed across the northern flank of the range and do not contain any thrust repetitions, are derived from the hanging wall of the Mormon thrust, as noted above; and (4) the overall structural continuity of >700 measurements of stratal rotations in the allochthon, which form a coherent fabric traceable across all of the klippen (Figure 3);

and (5) in both hanging wall and footwall, the structural and stratigraphic position of the detachment descends to the west.

A further difficulty with the surficial sliding model is the presence of a c. 2000 m-thick Tertiary section within the Mormon Peak allochthon in the northernmost Mormon Mountains/southern Clover Range (Anderson et al., 2010). This section is steeply tilted to the east, and contains within it interstratified rock avalanche deposits. The implication of the gravity slide model is that a slide block on the crest of the dome was first a kilometer-scale depocenter receiving scarp breccias that was later uplifted and then slid into a newly developed depression.

The only evidence cited in support of radial gravity sliding are the 28 slickenline data, of which approximately 11 measurements (c. 1/3 of the data collected, mainly along the NW flank of the range) plot in the NW quadrant of a stereogram (Figure 9). As elaborated further below, this evidence is at best a weak basis for ignoring basic palinspastic constraints, and the slickenline data are in any event best interpreted as supporting the arguments based on the structural coherence and tilt directions within the allochthon.

Commensurate with the palinspastically constrained westward displacement of the allochthon relative to its substrate, we assume all of the striations plotted on Figure 9 reflect upper plate displacement toward the western hemisphere of the stereogram. Neglecting the effect of post-detachment tilt along the eastern flank of the range, we interpret the western hemisphere polarity of each of the measured striations to reflect the slip direction. A histogram of the western polarities (Figure 8) demonstrates that the striations cleanly define a unimodal population with the highest frequency orientations near 270°, with an estimated standard deviation of +/- 37°.

Additional lines of evidence for the maximum elongation direction during extensional deformation in the Mormon Mountains (Wernicke et al., 1985) include (1) the observation that two intersecting normal faults in the footwall of the detachment do not offset each other, implying both have a slip direction along or near the trend and plunge of their intersection, which is S82W 25 (262/25); and (2) the trend of the obtuse bisectrix between two sets of syn-detachment, small-displacement high-angle faults in the footwall of the detachment interpreted to be conjugate fractures, suggesting that the least principal stress direction along the crest of the structural dome during fracture was S80W (260); and (4) The long axis of structurally domiform detachments is generally a reliable proxy for the extension direction along detachment faults (e.g. Davis and Coney, 1979; Spencer and Reynolds, 1989; Livaccari et al., 1993). the orientation of the long axis of the structural dome defined by the detachment, which is also approximately WSW (c. 250; e.g. Walker et al., 2007, their Fig. 1).

A summary of all available slip direction indicators is presented in Table 1. The mean orientation of these proxies is S75W (255°). This extensional slip direction is highly oblique (c. 40°) to the dip direction of the thrust ramp (298°), requiring caution in interpreting two-dimensional cross sections depicting the interaction between Sevier-age and Miocene tectonic elements. Below, we present data bearing on the offset of Mesozoic features by the detachment in map view, so as to better assess the three-dimensional complexities of structural restoration.

**Locations of three offset Sevier-age structural markers**

***Above the Mormon Peak detachment.*** The geometry of the Sevier-aged thrust ramp is defined by the west-dipping monocline in the western part of the mapped area (Figures 1 and 4). The monoclinal section between the axial surfaces of the bounding folds ranges from at least the lower Bird Spring Formation (Pennsylvanian) to the Moenave Formation (Jurassic). As measured between points R and R' on Figure 4, the section dips on average 40° WNW, over an across-strike, horizontal distance of 7000 m, with little difference in the elevation of the Miocene erosion surface that overlies it (Figure 4). These constraints require a minimum structural relief of 4500 m.

Structural relief of 4500-5000 m accords well with the value predicted by the structural relief on the frontal Sevier thrust ramp, which is the thickness of Middle Cambrian through Jurassic units, as measured in the footwall of the thrust. According to footwall cross-sections from the Tule Springs Hills and Beaver Dam Mountain to the east, the section is c. 5000 m thick (e.g., Plate 1 in Axen, 1993; Plate 2A in Hintze, 1986). A value near 5000 m is inconsistent with placing the base of the frontal thrust ramp in Mississippian strata, as depicted in the reconstruction of Axen et al (1990). This placement predicts structural relief of only 3000 m in the hanging wall of the thrust. Their reconstruction was based on the occurrence of a Cambrian-on-Mississippian decollement segment of the thrust exposed in the central Mormon Mountains, which is cutoff by the detachment. The exposed decollement segment is only about 2 km wide in the thrust transport direction. In the northern part of the range, the Mississippian decollement may die out altogether. A narrow footwall decollement segment within the Mississippian, however, appears to be useful as a structural marker, because it predicts significant structural effects in the hanging wall of the thrust, as elaborated on below.

A northward pinchout of a footwall decollement segment in Mississippian strata is supported by a change in the exposed structural level that occurs between the southern Meadow Valley Mountains and the area mapped in this study. Along strike to the south of the area of Figure 4, the sub-Tertiary unconformity, rather than resting on strata as young as Jurassic, instead rests on strata only as young as the Permian Kaibab Limestone. This difference in stratigraphic position suggests a 1500-m difference in total structural relief on the ramp to the south, from c. 4500 m to 3000 m. This difference is readily explained by a lateral ramp in the thrust, where a decollement riding on top of the Mississippian structurally descends to Middle Cambrian to the north, dropping the structural level of the thrust plate toward the north by about 1500 m, about the stratigraphic difference both between the Kaibab and Jurassic strata in the hanging wall, and the Banded Mountain Member and the upper Mississippian strata in the footwall.

Given these constraints, the first structural marker is delineated by the western edge of the monocline (ramp syncline; Figure 2), which is complicated by the East Vigo thrust and other structural complexities identified by Pampeyan (1993), but it is clear that the structural low is defined by a narrow outcrop belt of Jurassic strata (point R, Figure 4). The match in structural relief exposed in the eastern Meadow Valley Mountains and the relief on the footwall ramp also suggests that the axial trace of the syncline is located near exposures of Jurassic strata (point R), because a location further west would require more structural relief than could be generated by the entire Cambrian through Jurassic section. Additional structural relief would require somehow building up structural relief in the footwall with additional thrusts or other structures, which are not observed in extensive exposures of footwall rocks in the region. Therefore we interpret the ramp syncline to be located at the western edge of the Moenave Formation exposures mapped here, near point R.

The second structural marker, which constitutes the most significant complication in the otherwise homoclinal section from lower Bird Spring to Moenave strata, is a relatively tight “backfold” that affects the central part of the section, which may have a relationship with the structures below the detachment.

The third structural marker, the trace of the ramp anticline, is located at the top of the ramp where the dip of the reconstructed pre-Tertiary units shallows from 40° to subhorizontal. Within the Meadow Valley Mountains, reconstructed pre-Tertiary units shallow eastward from 40° to 15°, but do not reach 0°, indicating that the anticline is located just east of the easternmost Meadow Valley Mountains exposures (Figure 5). Consistent with this hypothesis, a stereonet plot of reconstructed dips, which includes sub-Tertiary units in the Mormon Mountains, indicates that the hinge of the anticline is located between the Meadow Valley Mountains and the westernmost Mormon Mountains (Figures 3, 4 and 8).

***Below the Mormon Peak detachment.*** In the footwall, the first structural marker is the base of the ramp, i.e., the intersection of the axial surface of the ramp syncline with the Mormon thrust,. It can be constrained only by its easternmost possible position, because the detachment mainly cuts downward across the thrust autochthon and into Proterozoic basement (Wernicke et al., 1985). The map-view position of the undisturbed, autochthonous base of the Middle Cambrian Banded Mountain Member of the Bonanza King Formation (the detachment horizon for the thrust decollement), marks the eastern possible limit of the base of the ramp (Figure 2).

The second Sevier-age structural marker below the detachment is the location of the westward cutoff of footwall Mississippian strata by the thrust ramp described above (Figure 2). As described above, where the thrust fault remains within the Mississippian for at least 2 kilometers across strike, and is cutoff by the Mormon Peak detachment (Figures 1 and 7). In the hanging wall, we infer that the presence of a narrow Mississippian decollement segment of the thrust is genetically related to the relatively tight anticlinal "backfold" within the Permian strata (Figure 4), as indicated by the reconstruction in Figure 7.

The third marker below the detachment is the top of the thrust ramp, which is well exposed in the Tule Springs Hills near Jumbled Mountain. To the west, the decollement ramps at a moderate angle across upper Paleozoic and lower Mesozoic strata, whereas to the east, the thrust plate is everywhere thrust over the Jurassic Kayenta Formation (Axen, 1993).

**Offset Estimates**

Offset along the detachment is, in part, based on the six positions of three Sevier-age structural markers described above, and summarized in Figure 2: Above the detachment, the axial traces of the ramp anticline and ramp syncline, and the axial trace of a small "backfold" we infer to be related to a narrow decollement segment of the thrust. Below the detachment, the base and top of the thrust ramp, and the intersection or cutoff of Mississippian strata along the thrust ramp. In present geometry, the anticline at the east edge of the Meadow Valley Mountains is 24 kilometers away, as measured along the detachment slip direction, from the top of the thrust ramp at Jumbled Mountain (Figure 2). This includes the combined offset of (1) the Mormon Peak detachment, and (2) younger faults in the footwall of the Mormon Peak detachment, predominantly along the Tule Springs detachment system of Axen et al. (1990) and Axen (1993). Axen et al. (1990) estimated approximately 11 km of slip on these faults based on restoration of cross sections. Subtracting that figure from the 24 km of total separation of the ramp anticline, leaves 13 kilometers of slip on the Mormon Peak detachment.

The ramp syncline in the hanging wall is 12 kilometers WSW of the east limit of its position in the footwall (Figure 2). There may be minor strike-slip offset along the Meadow Valley Wash, but this is at high angle to the detachment slip direction. Therefore, based on this marker alone, we estimate a maximum of 12 kilometers of displacement on the detachment at this location. The position of the truncation of the Mississippian by the Sevier thrust and its narrow ramp zone, and its counterpart projected in the subsurface in the Meadow Valley Mountains, also suggests about 12 km of slip on the detachment.

Anderson and others (2010) also proposed 10-15 kilometers of offset across the northern part of the Mormon Mountains, which they attribute to displacement on an inferred strike-slip fault. Within the Kane Springs volcanic units, they find deposits from landslides containing interbedded Cambrian- and Jurassic-aged material. They note that the nearest location where such disparate ages could have been simultaneously exposed to a fault scarp is in the Tule Springs Hills, 10-15 kilometers to the ENE. These landslides and interbedded Kane Wash volcanics both dip 70° to the east, a direction that would be expected from block rotation above the Mormon Peak detachment.

Independent of these structural markers, as mentioned above in regard to displacement direction of the detachment, the stratigraphic offset of the Dunderberg Shale Member of the Nopah Formation is defined by the east limit of Nopah Formation exposures above the detachment and the truncation of the Dunderberg below the detachment. The stratigraphic separation in the direction of transport is at least 22 km. Again, subtracting approximately 11 km of offset along the younger Tule Springs detachment system, the net offset along the Mormon Peak detachment is at least 11 km.

**Initial Dip of the Detachment**

The initial dip of the detachment may be estimated by comparing its orientation with those of various elements in the thrust system with which it interacts, as well as its reconstructed angle with respect to the basal Tertiary unconformity in the area, which pre-dates formation of the detachment (e.g. Wernicke, 1995).

The dip of the Paleozoic units thrust over the ramp should correspond fairly closely to the dip of the ramp, assuming a simple reconstruction (Figure 7). Bedding within the western Meadow Valley Mountains dips an average of 40° NW. The base of the thrust ramp is not unambiguously exposed in the footwall in the Mormon Mountains, indicating that it has been (largely or) wholly excised the detachment, which cuts directly into autochthonous basement in the westernmost Mormon Mountains (Wernicke et al., 1985; Axen et al., 1990). Either detachment is, overall, slightly steeper than the thrust ramp, or the detachment is shallower than the ramp, but the base of the ramp is “relayed” westward via the narrow decollement at the top of the Mississippian described earlier (Wernicke et al., 1985). Whatever the case in the central and southern Mormon Mountains where most of the detachment footwall is exposed, relief across the monocline in the Meadow Valley Mountains demands that the ramp cut upward more-or-less uninterrupted from Middle Cambrian through Jurassic strata, at least in the northernmost Mormon Mountains and southern Clover Mountains, where this area palinspastically restores (Figures 2 and 7). Hence, if the Mormon Peak detachment tends to parallel the ramp, then the initial dip of the Miocene detachment in this area should be c. 40°, according to our restored Mesozoic ramp structure (Figure 7).

This estimate is approximately 15° steeper that the 25° intial dip proposed for the central Mormon Mountains (e.g. Wernicke et al., 1985; 1995). Hence, if we presume that the detachment tends to follow the thrust ramp to the north, its initial dip must steepen by about 15° along strike toward the north, from about 25° to 40°. Alternatively, if the angle between the detachment and autochthonous section is presumed to remain constant to the north, a detachment that is overall steeper than the ramp would require significant variation in the dip of the detachment along strike. A steeper detachment to the north would also tend to promote the development of deep supradetachment basins and promote the generation of scarp breccias, as observed in the northernmost Mormon Mountains.

As mentioned above, our map compilation indicates that the detachment fault within the northernmost Mormon Mountains is closely parallel to the thrust ramp there.

For at least 6.6 kilometers of map extent in the inferred transport direction, the detachment is confined to the lower part of unit Cbb4 of Wernicke et al (1985). This suggests that the Mormon Peak detachment is closely parallel to the Mormon thrust ramp, at least in the northern part of the Mormon Mountains.

As mentioned above, the Mormon thrust also shows significant variation in geometry along strike. The difference in structural relief between the northern and southern parts of the Meadow Valley Mountains is most simply explained by the presence of a lateral ramp in the thrust, between an extensive Cambrian flat in the north and a significant Mississippian flat in the south. This lateral ramp would occur between the central and northernmost Mormon Mountains, and may have influenced the initial dip of the detachment, with steeper dip to the north (honoring the reconstruction in Figure 7) and shallower dip to the south (honoring the reconstruction of Axen et al., 1990).

In addition to possible variations in initial dip for the detachment along strike, there may also be significant variation in the dip of the detachment and/or thrust as a function depth. The ~ 42° dips within the Moenkopi and Chinle may reflect a steeper lower part of the thrust ramp, while the ~35° dips of the Permian red beds may reflect a shallower upper ramp.

**Post-Miocene Faulting**

There is the potential for a few kilometers of left-lateral strike-slip motion to be accommodated by a fault or faults buried within Meadow Valley Wash. This is suggested by (1) ~5 km apparent offset of the boundary between east- and west- dipping strata noted earlier (Figure 3); (2), the apparent sinistral vertical-axis rotation of strata at the northwesternmost edge of the Mormon Mountains, closest to the Meadow Valley Wash. Possible right-lateral faulting in the northernmost Mormon Mountains is suggested by apparent dextral drag folding on an E-W trending fault. The existence and timing of motion of these faults is speculative, as none of them have been identified in the field, but other N-trending, left-lateral faults, active after regional Miocene normal faulting, have been identified in the region. These include the Kane Wash fault on the western edge of the Meadow Valley Mountains, and the Tule Corral fault in the central part of the Tule Springs Hills (e.g. Axen, 1993).

**Other interpretations of the Mormon Peak detachment**

Recently, some researchers have questioned, firstly, whether the Mormon Peak detachment is a "rooted" crustal fault, as opposed to a system of landslide deposits (e.g. Anders et al, 2006); and secondly, whether all the apparent thinning of the Mormon Peak allochthon is due to faulting (Anderson et al., 2010). Multiple lines of evidence indicate that the fault is rooted and accommodates regional extension: 1) stable isotopic data presented by Swanson et al., (2012) indicates rapid circulation of meteoric fluids from a depth of at least 4 kilometers, too deep to explain with a landsliding mechanism; 2) the substrate of the basal Tertiary unconformity is uniformly lower Bird Spring Fm. east of the Sevier-age monocline in the Meadow Valley Mountains, and remains on the Bird Spring Fm., uninterrupted, across Meadow Valley Wash and into the Mormon Mountains; 3) the 2-km thick section of landslide debris interbedded with the Kane Wash

Tuff in the hanging wall, and its 70 degree dip towards the east (see Anderson et al, 2010), is consistent with syntectonic deformation, and remains unexplained by the landslide theory, as described earlier; 4) the structural level of the Permian units in the easternmost Meadow Valley Mountains, their Tertiary cover, and their internal structural pattern, is the same as the nearby hanging wall of the detachment in the Mormon Mountains, and highly dissimilar to the exposed basement rocks below the detachment. Interpreting the Meadow Valley Mountains block as part of the detachment footwall requires two faults, the toe of the landslide which fortuitously contains the same units and structures, and a pre-existing high-angle fault with kilometers of offset (see Walker, 2008) to be concealed beneath the ca. 2-km width of alluvial cover between the two ranges.

Evidence against it being a rooted fault mostly hinges on the radial orientations of fault striations on the detachment (Walker et al., 2007). However, such a distribution of slip directions does not preclude the detachment being a rooted fault. Singleton (2013) described kinematic indicators on corregations of the Buckskin-Rawhide detachment showing a radial pattern, which he interpreted as a reflection of a late-stage compressional event perpendicular to the extension direction. As argued in Wernicke et al. (1985), it is likely that the north-south component of the Mormon dome resulted from regional NS shortening during extension and emplacement of the Mormon Peak allochthon.

The determination of the amount of displacement and thinning accommodated by slip on the detachment, versus dissolution of the hanging wall (e.g. Anderson et al. 2010; Diehl et al., 2010), is more difficult to address directly with this data. We present here a kinematic model based on palinspastic constraints and other structural data, and it is beyond the scope of this paper to address this long-standing problem.

## CONCLUSIONS

Based on the mapping of structures within the Meadow Valley Mountains and a regional compilation of geologic data in the neighboring Mormon Mountains, East Mormon Mountains and Tule Springs Hills, we correlate Sevier-age contractile structures across the Mormon Peak detachment, and provide a new, independent estimate of 12 to 13 km of displacement. This measurement is in the interpreted slip direction, S75W (azimuth 255), based on multiple lines of structural evidence (Table 1).

The observations presented here are broadly consistent with the model of Axen et al. (1990), where a Sevier-age thrust flat-ramp-flat is overprinted and distended by the Mormon Peak detachment as well as structurally lower, younger detachments. However, our data indicate several significant modifications to their geometric and kinematic model of the detachment. First, structural relief indicates that the flat at the base of the ramp is in Cambrian, not Mississippian strata, within the northernmost Mormon Mountains. Second, the total displacement on the Mormon Peak detachment is approximately 12-13 km, not 20-22 km as indicated in the earlier reconstruction. Third, assuming the detachment initiated along the thrust ramp, it would have had a steeper initial dip (35-40°) to the north, although the dip direction would have likely been oblique to a much more shallowly plunging, left-oblique slip direction.

## APPENDIX. DESCRIPTION OF MAP UNITS

Unit descriptions are heavily modified from Pampeyan (1993). All potassium-argon (K-Ar) ages cited have been recalculated using 1977 constants (Steiger and Jager, 1977), resulting in ages about 2.7 percent older than the original published data. Color terminology used in the following descriptions is from the National Research Council Rock Color Chart (Goddard et al., 1948).

Qal: Alluvium (Holocene)-Unconsolidated stream-channel and fan deposits of clay- to cobble-size. Commonly less than a few meters thick but probably exceeds 10 m in major washes.

Tal: Alluvium (Pleistocene? and Pliocene)-Mildly consolidated streamchannel and coarse basin deposits of sand- to cobble-size, crudely stratified. Commonly present on former drainage terrace surfaces or perched on older alluvial or lacustrine deposits. Thickness is 100 meters at the mouth of Vigo Canyon, but usually thinner.

KANE WASH TUFF (Miocene)- Divided into Unit 2, Unit 1, Unit W, and Unit O. Adularescent sanidine is diagnostic of this tuff.

Tku2: Unit 2-Thin blue-gray to blue-green devitrified tuff about 1 m thick overlain by brownish-gray-weathering, devitrified ash-flow tuff. Lithic component is mostly flattened pumice. It ranges from a few meters to about 90 m thick. K-Ar age, 14.1 Ma (Novak, 1984).

Tku1: Unit 1-Cliff-forming, crystal-rich, rhyolitic to trachytic ash-flow tuff grading upwards from densely welded, reddish-brown to less welded, brownish-gray lithic-crystal tuff. Contains flattened pumice fragments as large as 2.5 by 15 cm. Sanidine crystals as long as 10 mm, many of them adularescent, decrease in size, but increase in abundance, upwards. K-Ar age, 14.1 Ma (Novak, 1984). May be as thick as 120 m in scarp along Kane Springs Wash.

Tt: Trachyte (Miocene)·-Black to grayish-purple, blocky weathering trachyte lavas, with a microcrystalline to glassy matrix that locally shows flow banding. On this map, it is defined by the very hard layer that crops out in an otherwise poorly exposed slope. The flow is about 5 m thick in its only exposure in the mapped area. This flow is not considered part of the Kane Wash tuff, but is found between Unit W and Tku1.

Tkw: Unit W-Pinkish-gray, pale-yellowish-brown-weathering, rhyolite ash-flow tuff. Lower four-fifths of unit lithic tuff with non-compacted pumice fragments as much as 15 cm across and cavities and few crystals; upper one-fifth of unit is pink to pale-violet, moderately to densely welded cliff-forming devitrified lithic tuff. Thickness ranges from 137 m to zero. K-Ar age, 14.7 Ma (Novak, 1984).

Tko: Unit O-Largely moderate brown to reddish-brown, densely welded, rhyolite ash-flow tuff easily recognized as forming a thin dark cliff under a thick light colored slope. Eutaxitic structure is unique to most of this unit, and the flattened pumice fragments can be used for dip measurements. Maximum thickness of unit is about 79 m in Kane Springs Wash scarp decreasing to 0 along south edge of volcanic terrane. K-Ar age, 15.6 Ma (Novak, 1984).

Tb1: Basalt Unit 1 (Miocene)- Dark-gray to grayish-black, brownish-black-weathering olivine basalt in compact to amygdaloidal flows. Single(?) aphanitic flow as much as 4 m thick exposed in vicinity of Hackberry Canyon, lies between the Hiko Tuff (Th) and crystal tuff (Tku) of the Kane Wash Tuff. This basalt locally is coarsely amygdaloidal with epidote- and quartz-lined amygdules up to 1 cm long.

Th: Hiko Tuff (Miocene)-Pinkish- to brownish-gray, brown-weathering, moderately welded vitric crystal to crystal ash-flow tuff, becoming slightly less welded towards top of unit. Basal 10 to 15 m, where exposed, is white to pale greenish-yellow and light-gray, partially welded, punky lithic-crystal tuff. In upper half of section there are local lenses of coarse impure sandstone or wacke as thick as 3 m. Maximum thickness is 0-43 m near Vigo. The Hiko Tuff has yielded K-Ar ages of 18-20 Ma (Armstrong, 1970; Noble and McKee, 1972 ; Marvin and others, 1970).

Thh: Harmony Hills Tuff (Miocene)-Brownish-gray to pale yellowish-brown, reddish-brown weathering, crystal-rich, biotite ash-flow tuff. Abundance and size of biotite crystals are diagnostic characteristics as the unit contains more euhedral biotite than any other ash-flow tuff in this region, usually in books as much as 3 mm in diameter and 1-2 mm thick. Total thickness of the Harmony Hills Tuff is about 81 m in Hackberry Canyon, where it rests on a basalt flow-breccia (Tbb). Radiometric analyses of the Harmony Hills Tuff from the surrounding region yielded an average age of 21 Ma (Armstrong, 1970; Noble and McKee, 1972; Marvin and others, 1973).

Tbb: Basalt breccia (Miocene)-Thick, dark-purple, red, black, monolithologic basalt flow-breccias and flows. Well exposed in Hackberry Canyon and along south edge of volcanic terrane. The thickness of this unit is highly variable, with a maximum thickness reported by E.F Cook (1965) as 289 m in area 3 km west of Vigo; average thickness is closer to 100 m thinning to zero away from Hackberry Canyon.

CONDOR CANYON FORMATION (Miocene)-In this area, consists of Leach Canyon and Bauers, Lacustrine Limestone, and Conglomerate

Tlc: Leach Canyon Formation and Bauers Tuff, undivided (Miocene)-The Bauers Tuff is a pale purple, highly welded tuff up to 8 m thick, but is too thin to show separately and is included with the underlying Leach Canyon Formation (Tic). Leach Canyon Formation consists of a pale-lavender ash-flow tuff. Consists of two cooling units locally separated by lenses of light gray, orange-mottled lacustrine limestone up to 5 m thick. Total thickness about 74 m west of Vigo (E.F Cook, unpub. data, 1955, 1956). Age of the

Leach Canyon Formation, based on K-Ar analyses of samples from the surrounding region, is about 24.6 Ma (Armstrong, 1970; Rowley and others, 1975 ).

Tl: Lacustrine limestone (Oligocene?)-Light-gray freshwater limestone in beds 10 to 30 cm thick, commonly containing algal structures. Thickness ranges from 5 to 30m; typically 20 m thick. Occurs at base of the volcanic section, resting unconformably on pre-Tertiary sedimentary rocks, and locally on, or interlayered with, prevolcanic conglomerate (Tc). Age considered to be late Oligocene inasmuch as strata underlie lower Miocene tuffs (Ekren and others, 1977).

Tc: Conglomerate (Tertiary)-Reddish-orange- to reddish-brown-weathering, poorly sorted, synorogenic(?) conglomerate occurring in isolated patches filling low areas on pre-volcanic erosion surface. Appears to interfinger locally with lower lacustrine limestone (Tl). Mainly well-rounded cobbles in a silty to coarse sandy matrix, but pebble- to small-boulder-size clasts are present, all consisting of Paleozoic carbonate rocks, quartzite, and some chert. Thickness ranges from 0 to about 50 m.

CHINLE FORMATION (Upper Triassic)-Consists of Upper Sandstone, Upper Conglomerate, Petrified Forest, and Shinarump units.

Trcu: Upper sandstone member-Moderate-red to dark-red, fine-grained, nonmarine, silty sandstone and shaley sandstone present in scattered outcrops along south edge of volcanic terrane. Upper contact is not observed within this area, but a thickness of 740 m has been estimated for this unit (Tschanz and Pampeyan, 1970) based on size of outcrop area and better exposures near Mormon Mountains. This unit may be part of the Petrified Forest member, but is mapped separately here for its redder color.

Trcc: Upper conglomerate-Grayish-red, dark-brown-weathering, ridge-forming, fine-grained sandstone and chert-pebble conglomerate. Some sandstone is crossbedded and quartzitic. Approximate thickness of 25 meters. This unit may be a conglomerate bed within the Petrified Forest member.

Trcp: Petrified Forest member-Moderate-red to dusty-red, fine-grained, nonmarine, silty sandstone and shaley sandstone present in scattered outcrops along south edge of volcanic terrane. Thickness is 365 m.

Trcs: Shinarump Member-Grayish-red, dark-brown-weathering, ridge-forming, fine-grained sandstone and chert-pebble conglomerate. Some sandstone is crossbedded and quartzitic. Fossil wood common elsewhere in the Shinarump was not seen here, and overall texture of member is finer than in exposures farther east. The Shinarump Member is observed to be 40 m thick in its sole outcrop within the map area.

Trm: Moenkopi Formation (Middle? and Lower Triassic)- Predominantly gray, pale-brown, yellowish-brown, grayish-yellow- to grayish-orange-weathering, even-bedded, dense marine limestone, with interbedded red, orange, and brown silty and shaley limestone giving large outcrops a color-banded aspect. The Moenkopi rests with angular discordance on a variety of units, including br, Pku, Pkl, and locally lies directly on Pr5. Dark-brown-weathering, chert-rich, sedimentary or karst breccia is locally present in lenses along the base of the Moenkopi. Upper contact with the Shinarump Member (Trcs) of the Chinle Formation is poorly exposed in an isolated outcrop, but 985 m of Moenkopi is present in a homoclinal section 5 km west of Vigo.

Pk: Kaibab Limestone (Lower Permian)- Gray limestone with approximately 50% brown-weathering chert. Chert is commonly bedded, but can occur as elongate nodules. Thickness ranges from 40 m to zero.

Pt: Toroweap Formation (Lower Permian)- Pinkish-gray to light gray, cliff-forming limestones with minor chert. Minimum thickness of 60 m lies unconformably between the Moenkopi Formation (Trm) and Permian red beds (Prb).

RED BEDS (Lower Permian)- Permian red sandstone unit, subdivided here into units 1-5. Complete red-beds section is exposed, with a total thickness of about 552m. Red-beds unit correlates approximately with strata mapped as Coconino Sandstone, Queantoweap Sandstone, and Pakoon Limestone of McNair (1951 ) in Beaver Dam Mountains to the east (Reber, 1952**;** Langenheim and Larson, 1973 )

Pr5: Unit 5: Slope-forming, even-bedded, red, coarse-grained sandstone and silty sandstone. Lower contact is drawn at base of prominent gray carbonate marker bed that is overlain by yellow sandstone beds. Upper contact is drawn at discordant contact with overlying chert breccia of the Toroweap and Kaibab Formations (Pkl and Pku) and carbonate beds of the Moenkopi Formation. Unit is about 123 m thick.

Pr4: Unit 4: Upper 90 m is red, slope-forming, coarse-grained sandstone containing some interlayered red siltstone layers, as well as minor resistant beds of gray, fossiliferous limestone. These beds are darker red and more resistant than the sandstone beds of Pr5, and have significantly less carbonate that Pr3. The lower part of this unit consists of badland-weathering, contorted beds of red and yellow shaley sandstone and siltstone with interlayered beds of gypsum. Gypsiferous beds up to 6 m thick occur in an area about 1,100 m long by 305 m wide (Jones and Stone, 1920) and appear to represent deformed evaporite basin deposits. The thickness of this unit is about 242 m.

Pr3: Unit 3: Even-bedded, pink, white, and gray sandstone and shale, with lesser gray limestone and sandy limestone, cross-bedded buff sandstone. Contains more pink beds and fewer carbonate beds than Pr1 and Pr2. The upper contact is defined above the last carbonate bed. This unit is about 90 m thick.

Pr2: Unit 2: Pink, white, and gray sandstone, gray limestone and sandy limestone, cross-bedded buff sandstone, pinkish shale, sandstone, and sandy limestone, with calcareous beds increasing downwards. This unit contains a higher percentage of gray carbonate beds than units Pr1 and Pr3. About 50 m thick

Pr1: Unit 1: Even-bedded, pink, white, and gray sandstone, gray limestone and sandy limestone, cross-bedded buff sandstone, with lesser pinkish shale, sandstone, and sandy limestone. This unit has more white carbonate beds than units Pr2 and Pr3, and is more pink in color than Pr2. Basal contact drawn at the lowest red sandy bed. About 45 m thick.

BIRD SPRING FORMATION (Pennsylvanian to Mississippian)- divided into units 1-3

MPb3: Unit 3: Light to dark-gray limestone, with very little chert. Looks very similar to the top of MPb1, and is often distinguished solely on stratigraphic position. About 30 m thick.

MPb2: Unit 2: Very fine-grained, brown-weathering sandy limestone. Well exposed in Meadow Valley Wash near Galt. About 30-45 m thick.

MPb1: Unit 1: Interlayered beds of light to dark-gray limestone, pinkish-gray cherty limestone, reddish-brown sandy, calcareous, and dolomitic limestone, and white to reddish-brown, fine-grained sandstone. Limestone is fine- to medium-crystalline, thin- to medium-bedded, and fossiliferous. Sandy beds, some of which are quartzitic, form brownish- to reddish-weathering ledges in even-bedded step-like outcrop. Upper limestone and cherty limestone are middle Wolfcampian in age. The lowermost limestones and cherty limestones are Morrowan in age. A complete continuous section is not exposed in anywhere in the Meadow Valley Mountains, but unit was previously estimated to be about 1,310 m thick (Tschanz and Pampeyan, 1970); however, it may be closer to 2,000m thick in the southern Meadow Valley Mountains.

**REFERENCES**

Allmendinger, R. W., Cardozo, N. C., and , and Fisher, D., 2013, Structural Geology Algorithms: Vectors & Tensors: Cambridge, England, Cambridge University Press, p. 289.

Anders, M. H., Christie-Blick, N., and Walker, C. D., 2006, Distinguishing between rooted and rootless detachments: A case study from the Mormon Mountains of southeastern Nevada: Journal of Geology, v. 114, no. 6, p. 645-664.

Anderson, R. E., 1971, Thin-skin distension in Tertiary rocks of southeastern Nevada: Geological Society of America Bulletin, v. 82, p. 43-58.

Anderson, R. E., Felger, T.J., Diehl, S.F., Page, W.R., Workman, J.B., 2010, Integration of tectonic, sedimentary and geohydrologica processes leading to small-scale extension model for the Mormon mountains area north of Lake Mead, Lincoln County, Nevada, *in* Umhoefer, P. J., Beard, L.S., Lamb, M.A. (Eds.), ed., Miocene Tectonics of the Lake Mead Region, Central Basin and Range, Geological Society of America Special Paper 463, p. pp. 395-426.

Armstrong, R. L., 1970, Geochronology of Tertiary igneous rooks, eastern Basin and Range province, western Utah, eastern Nevada, and vicinity, USA: Geochimica et Cosmochimica Acta, v. 34, p. 203-232.

Axen, G. J., 1984, Thrusts in the Eastern Spring Mountains, Nevada - Geometry and Mechanical Implications: Geological Society of America Bulletin, v. 95, no. 10, p. 1202-1207.

-, 1991, Tertiary extension, magmatism, and thrust reactivation in the southern Great Basin, and a mechanical model for detachment faulting [Ph.D.: Harvard University, 235 p.

Axen, G. J., 1993, Ramp-flat detachment faulting and low-angle normal reactivation of the Tule Springs thrust, southern Nevada: Geological Society of America Bulletin, v. 105, p. 1076-1090.

Axen, G. J., 2004, Mechanics of low-angle normal faults, *in* Karner, G. D., Taylor, B., Driscoll, N. W., and Kohlstedt, D. L., eds., Rheology and deformation of the lithosphere at continental margins: New York, Columbia University Press, p. 46–91.

Axen, G. J., Wernicke, B. P., Skelly, M. F., and Taylor, W. J., 1990, Mesozoic and Cenozoic tectonics of the Sevier thrust belt in the Virgin River valley area, southern Nevada Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir, v. 176, p. 123-153.

Bohannon, R. G., 1983, Mesozoic and Cenozoic tectonic development of the Muddy, North Muddy, and northern Black Mountains, Clark County, Nevada: Geological Society of America Memoir, v. 157, p. 125-148.

Burchfiel, B. C., Cameron, C. S., and Royden, L. H., 1997, Geology of the Wilson Cliffs-Potosi Mountain Area, Southern Nevada: International Geology Review, v. 39, no. 9, p. 830-854.

Burchfiel, B. C., Fleck, R. J., Secor, D. T., Vincelette, R. R., and Davis, G. A., 1974, Geology of the Spring Mountains, Nevada: Geological Society of America Bulletin, v. 85, p. 1013-1022.

Burchfiel, B. C., Wernicke, B., Willemin, J. H., Axen, G. J., and Cameron, S. C., 1982, A new type of decollement thrust: Nature, v. 300, p. 513-515.

Cardozo, N., and Allmendinger, R. W., 2013, Spherical projections with OSXStereonet: Computers & Geosciences, v. 51, no. 0, p. 193 - 205.

Carpenter, D. G., Carpenter, J. A., Bradley, M. D., Franz, U. A., and Reber, S. J., 1989, Comment on "On the role of isostasy in the evolution of normal fault systems": Geology, v. 17, p. 774-776.

Carr, M. D., 1983, Geometry and structural history of the Mesozoic thrust belt in the Goodsprings district, southern Spring Mountains, Nevada: Geological Society of America Bulletin, v. 94, p. 1185-1198.

Collettini, C., and Sibson, R. H., 2001, Normal faults, normal friction?: Geology, v. 29, no. 10, p. 927–930.

Cook, E. F., 1965, Stratigraphy of Tertiary volcanic rocks in eastern Nevada: Nevada Bureau of Mines and Geology Report, v. 11, p. 67 p., (incl. geologic map, scale 61:500,000).

Davis, G. A., Anderson, J. L., Frost, E. G., and Shackelford, T. J., 1980, Mylonitization and detachment faulting in the Whipple-Buckskin-Rawhide Mountains terrane, southeastern California and western Arizona: Geological Society of America Memoir, v. 153, p. 79-130.

Davis, G. H., and Hardy, J. J., 1981, The Eagle Pass detachment, southeastern Arizona: Product of mid-Miocene listric (?) normal faulting in the southern Basin and Range: Geological Society of America Bulletin, v. 92, p. 749-762.

Ekren, E. B., Orkild, P. P., Sargent, K. A., and Dixon, G. L., 1977, Geologic map of Tertiary rocks, Lincoln County, Nevada, scale 1:250,000.

Elliott, J. R., Walters, R. J., England, P. C., Jackson, J. A., Li, Z., and Parsons, B., 2010, Extension on the Tibetan plateau: recent normal faulting measured by InSAR and body wave seismology: Geophysical Journal International, v. 183, no. 2, p. 503-535.

Ellis, B. J., 1985, Thin-skinned extension superposed on frontal Sevier thrust faults, Mormon Mountains, southern Nevada [M.S.: Syracuse University.

Goddard, E. N., Trask, P. D., De Ford, R. K., Rove, O. N., Singewald, J. T., and Overbeck, R. M., 1948, Rock color chart: Geological Society of America.

Jackson, J. A., and White, N. J., 1989, Normal faulting in the upper continental crust: observations from regions of active extension: Journal of Structural Geology, v. 11, no. 1/2, p. 15-36.

Jones, J. C., and Stone, R. W., 1920, Deposits in Southern Nevada, *in* Stone, R. W., and others, ed., Gypsum deposits of the United States, Volume 697, U.S. Geological Survey Bulletin, p. 155-160.

Langenheim, R. L., Jr., and Larson, E. R., 1973, Correlation of Great Basin stratigraphic units: Nevada Bureau of Mines and Geology Bulletin v. 72, p. 36.

Longwell, C. R., Pampeyan, E. H., Bowyer, B., and Roberts, R. J., 1965, Geology and mineral deposits of Clark County, Nevada: Nevada Bureau of Mines and Geology Bulletin, v. 62, p. 218.

Marvin, R. F., Byers, F. M., Mehnert, H. H., Orkild, P. P., and Stern, P. W., 1970, Radiometric ages and stratigraphic sequence of volcanic and plutonic rocks, southern Nye and western Lincoln Counties, Nevada: Geological Society of America Bulletin, v. 81, p. 2657-2676.

McNair, A. H., 1951, Paleozoic stratigraphy of part of northwestern Arizona: American Association of Petroleum Geologists Bulletin, v. 35, p. 503-541.

Miller, E. L., Dumitru, T. A., Brown, R. W., and Gans, P. B., 1999, Rapid Miocene slip on the Snake Range–Deep Creek Range fault system, east-central Nevada: Geological Society of America Bulletin v. 111, no. 6, p. 886–905.

Noble, D. C., and McKee, E. H., 1972, Description and K-Ar ages of volcanic units of the Caliente volcanic field, Lincoln County, Nevada and Washington County, Utah: Isochron/West, no. 5, p. 17-24.

Novak, S. W., and Collected Reprint, S., 1984, Eruptive History of the Rhyolitic Kane Springs Wash Volcanic Center, Nevada, 1984, Calderas and Associate Igneous Rocks, American Geophysical Union., p. 8603-8615.

Olmore, S. D., 1971, Style and evolution of thrusts in the region of the Mormon Mountains, Nevada [Ph.D: University of Utah, 213 p.

Pampeyan, E. H., 1993, Geologic map of the Meadow Valley Mountains, Lincoln and Clark Counties, Nevada, scale 1:50,000.

Reber, S. J., 1952, Stratigraphy and structure of the Beaver Dam Mountains: Intermt. Assoc. Pet. Geol. Guidebook, v. 7, p. 101–108.

Rowley, P. D., Anderson, J. J., and Williams, P. L., 1975, A summary of Tertiary volcanic stratigraphy of the southwestern high plateaus and adjacent Great Basin, Utah: U.S. Geological Survey Bulletin, v. 1405-B, p. B1-B20.

Skelly, M. F., 1987, The geology of the Moapa Peak area, southern Mormon Mountains, Clark and Lincoln Counties, Nevada [M.S.: Northern Arizona University, 150 p.

Steiger, R. H., and Jager, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters v. 36, no. 3, p. 359-362.

Styron, R. H., and Hetland, E. A., 2014, Estimated likelihood of observing a large earthquake on a continental low-angle normal fault and implications for low-angle normal fault activity: Geophysical Research Letters, v. 41, no. 7, p. 2342-2350.

Swanson, E. M., Wernicke, B. P., Eiler, J. M., and Losh, S., 2012, Temperatures and Fluids on Faults Based on Carbonate Clumped-Isotope Thermometry: American Journal of Science, v. 312, no. 1, p. 1-21.

Taylor, W. J., 1984, Superposition of thin-skinned normal faulting on Sevier orogenic belt thrusts, northern Mormon Mountains, Lincoln County, Nevada [M.S.: Syracuse University, 80 p.

Tschanz, C. M., and Pampeyan, E. H., 1970, Geology and mineral deposits of Lincoln County, Nevada, scale 1:250,000.

Walker, C. D., 2008, A gravity slide origin for the mormon peak detachment: Re-examining the evidence for extreme extension in the Mormon Mountains, southeastern Nevada, U.S.A. [Doctor of Philosophy: Columbia University.

Walker, C. D., Anders, M. H., and Christie-Blick, N., 2007, Kinematic evidence for downdip movement on the Mormon Peak detachment: Geology, v. 35, no. 3, p. 259.

Wernicke, B., 1995, Low-angle normal faults and seismicity: A review: Journal of Geophysical Research, v. 100, no. B10, p. 20159.

Wernicke, B., Walker, J. D., and Beaufait, M. S., 1985, Structural Discordance between Neogene Detachments and Frontal Sevier Thrusts, Central Mormon Mountains, Southern Nevada: Tectonics, v. 4, no. 2, p. 213-246.

Wernicke, B. P., and Axen, G. J., 1988, On the role of isostasy in the evolution of normal fault systems: GEOLOGY, v. 16, p. 848-851.

Wong, M. S., and Gans, P. B., 2008, Geologic, structural, and thermochronologic constraints on the tectonic evolution of the Sierra Mazatán core complex, Sonora, Mexico: New insights into metamorphic core complex formation: Tectonics, v. 27, no. 4.

## Tables

**Table 1**: summary of slip direction data

| DATA TYPE | INFERRED SLIP DIRECTION |
|---|---|
| Tilt direction in hanging wall Paleozoic strata | 251° |
| Tilt direction in hanging wall Tertiary strata | 239° |
| Mean trend of striations on fault surface | 270° |
| Obtuse bisectrix, footwall conjugate fault fabric | 260° |
| Intersecting faults | 262° |
| Long axis of dome in detachment | 250° |

## Figures

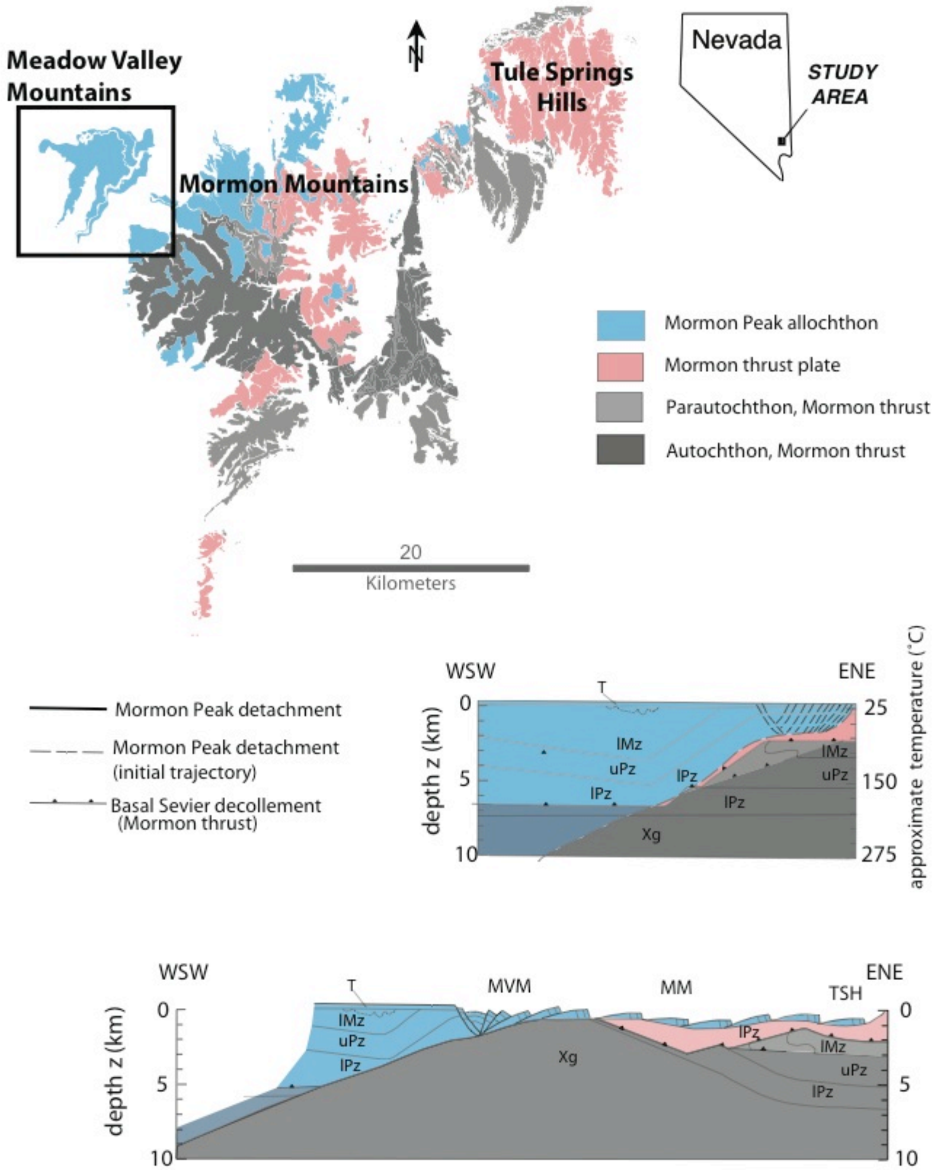



Figure 1. Structural map and schematic cross-sections of the Meadow Valley Mountains (MVM), Mormon Mountains (MM), and Tule Spring Hills (TSH) of Nevada. Location shown on inset map of the state. Black outline indicates area of Figure 4.

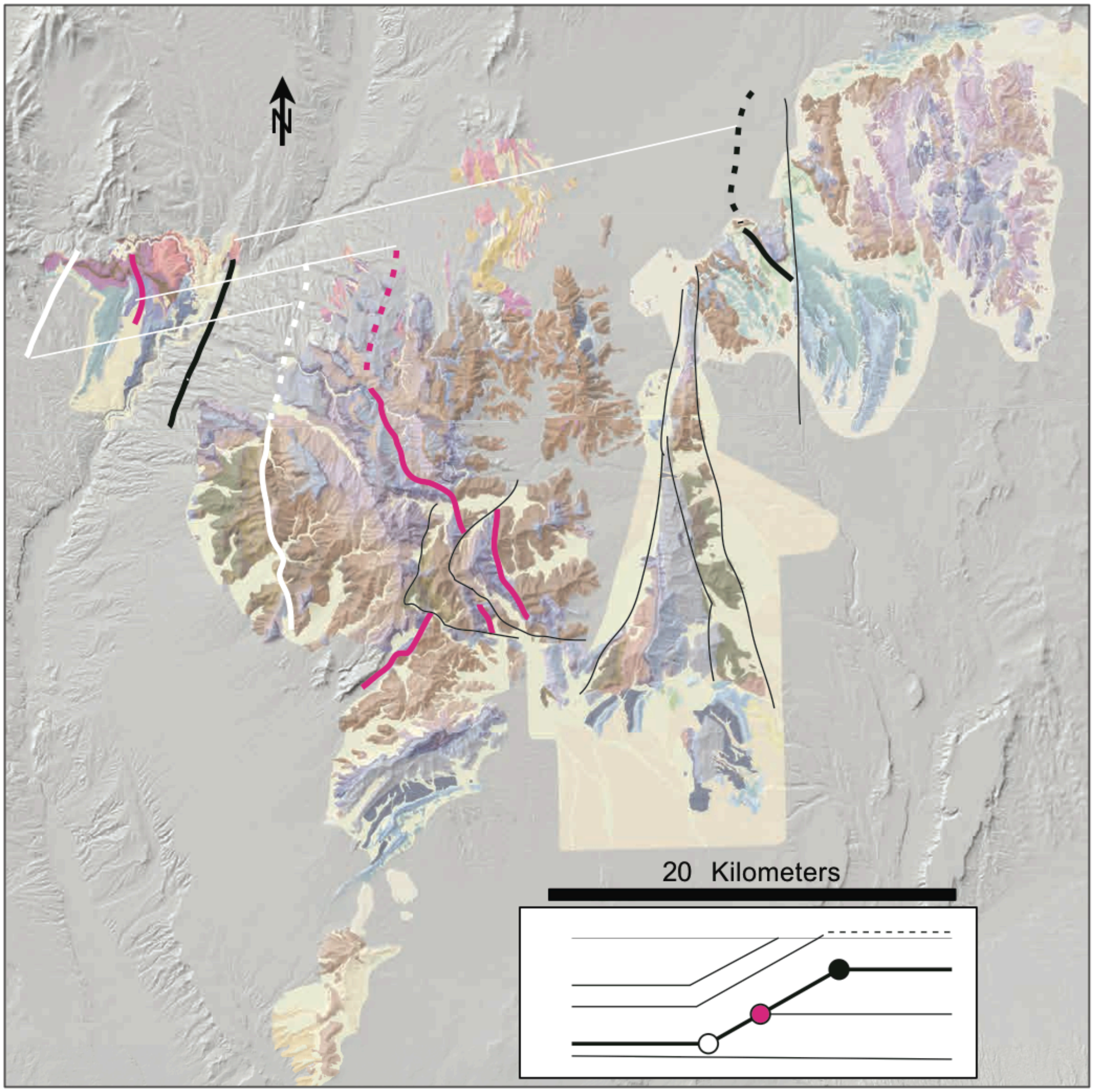



Figure 2. Map showing locations of ramp syncline (white line), thrust truncation of top of Mm (pink line), and ramp anticline (thick black line). Dotted where projected. Thin black lines show major post-detachment faults. Thin white lines show correlation of structural features along the Mormon Peak detachment slip direction. Inset shows schematic cross-section, showing location of thrust ramp features.

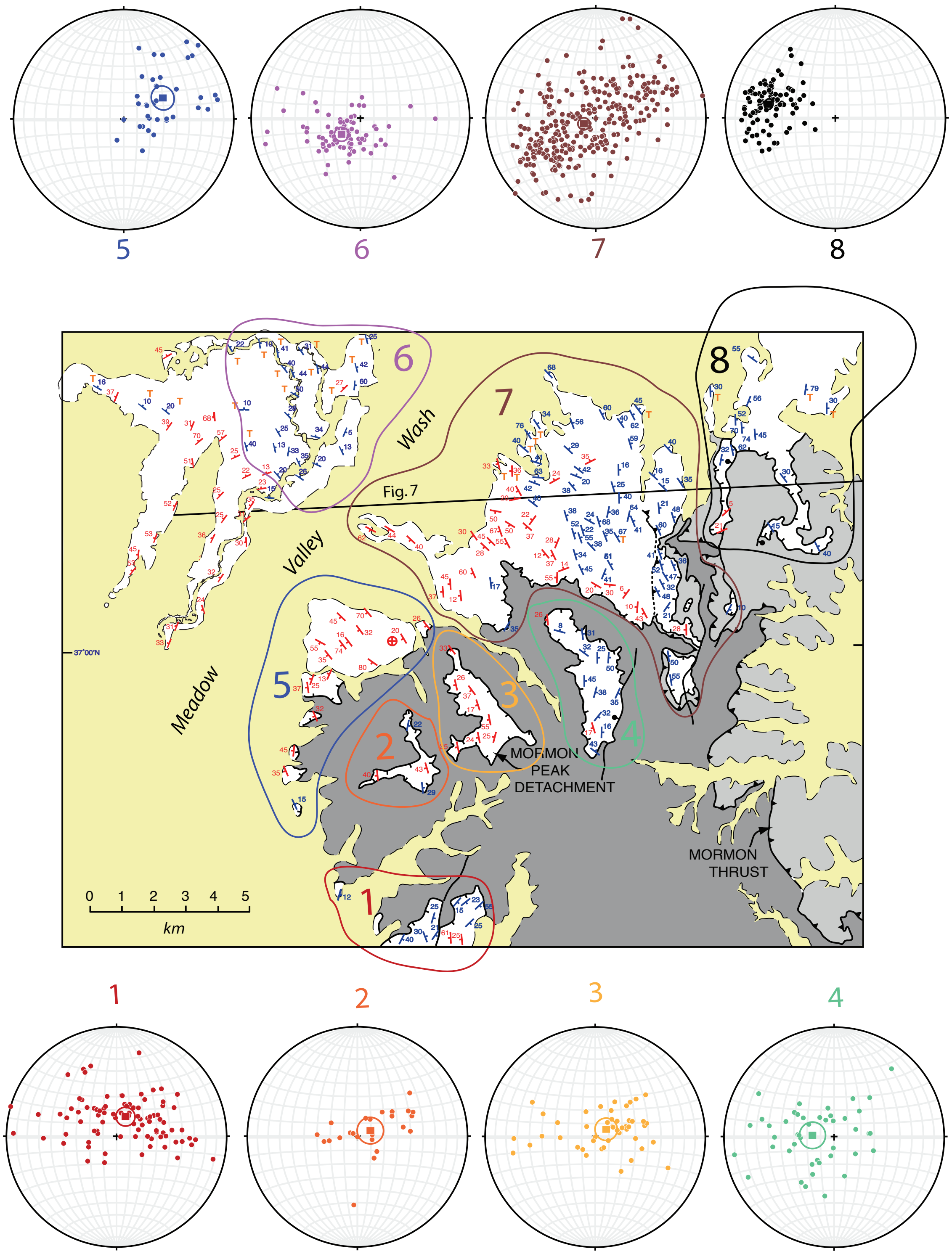



Figure 3. Orientations of hanging wall strata. Red symbols indicate west-dipping strata, blue symbols indicates east-dipping strata. Measurements within Tertiary strata labeled with an orange T. Stereonet plots are orientations of poles to bedding, with each area marked on map by loop of the same color and number.

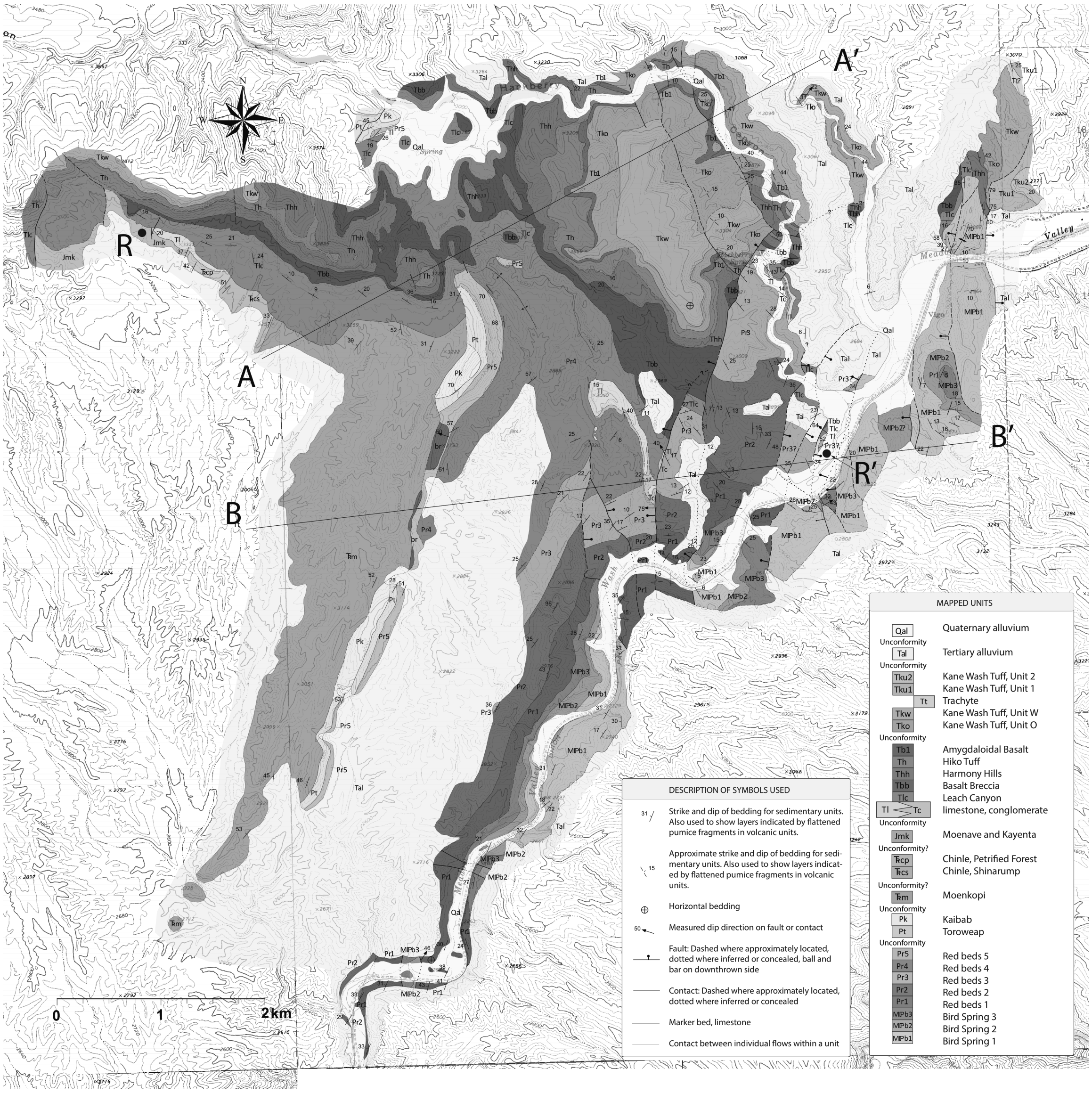



Figure 4. Geologic map of the Meadow Valley Mountains. See Figure 1 for location. Cross-sections A-A' and B-B' are shown in Figure 5. R and R' show locations used to measure structural relief (see text).

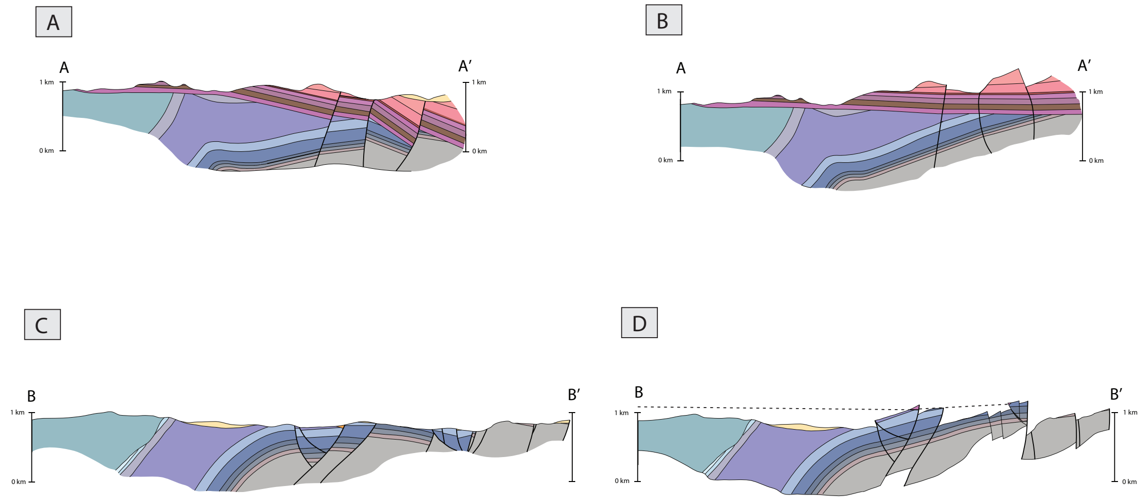



Figure 5. Cross-sections and through the Meadow Valley Mountains, and reconstructions to early Miocene geometries. A, cross-section through A-A'; B, reconstruction of A-A'; C, cross-section along line B-B'; D, reconstruction of B-B'. See Figure 2 for legend.

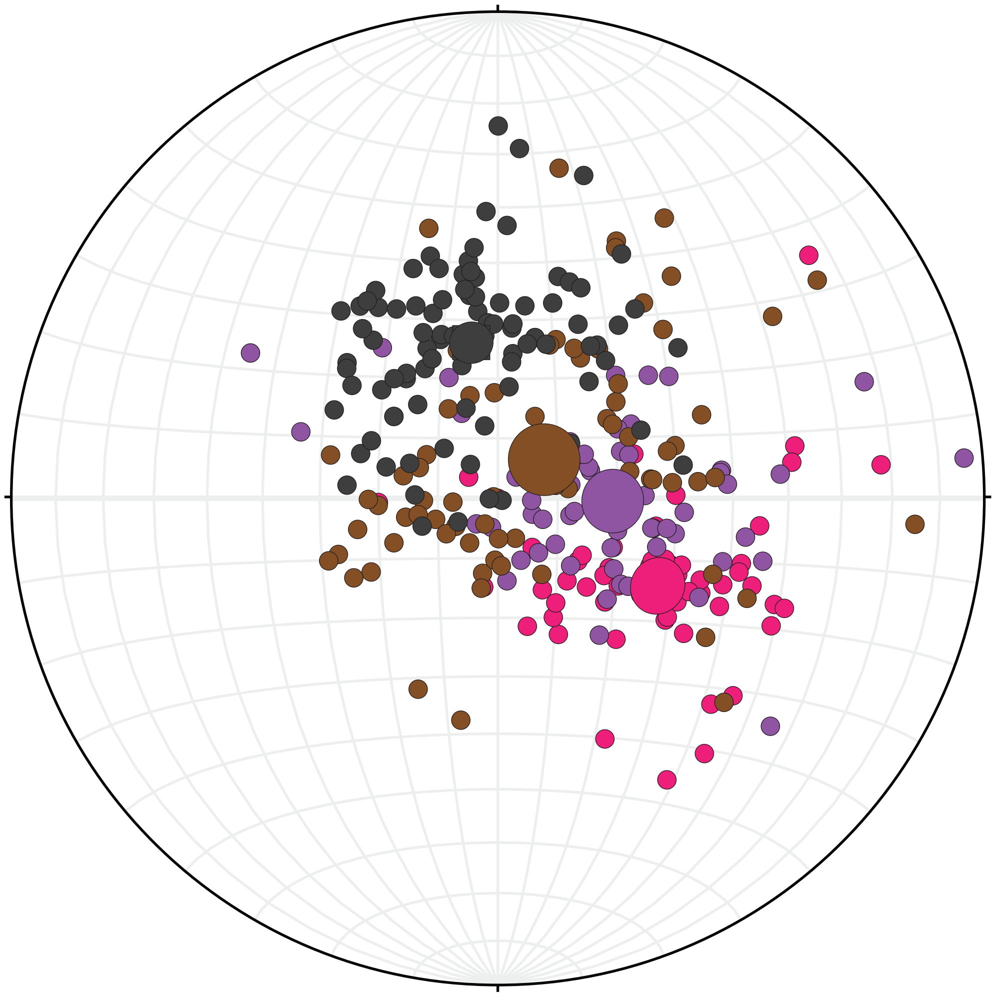


Figure 6. Restored poles to pre-Tertiary bedding, taken from areas where Tertiary strata are exposed in the Mormon Peak allochthon. From west to east, magenta (western Meadow Valley Mountains), purple (domain 6, Fig. 3), brown (domain 7, Fig. 3), and black (domain 8, Fig. 3). Attitudes were restored by rotating nearby Tertiary units to the horizontal about the strike of bedding. The larger circles are the average orientation within each group, with the circle diameters scaled to the scatter within the dataset. Data define a NE-trending anticlinal flexure. Sources: this study (purple and pink groups), Wernicke et al. (unpublished data, brown group), and Anderson et al. (2010, black group).

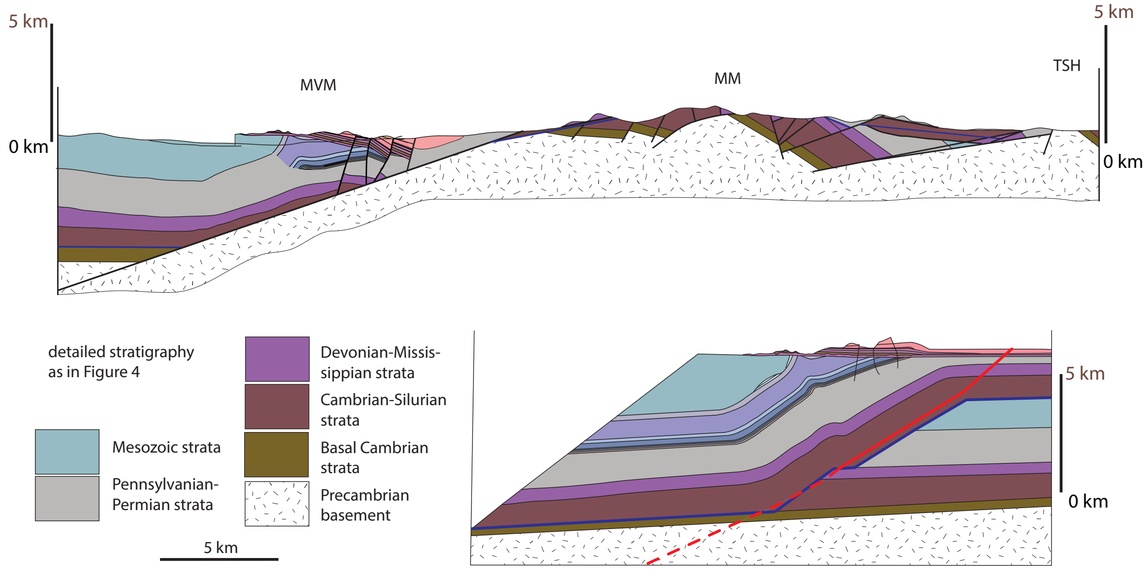



Figure 7. Regional reconstruction of the Meadow Valley Mountains (MVM), Mormon Mountains (MM), and Tule Springs Hills (TSH), drawn NW-SE, perpendicular to Sevier structures. Blue line is the Mormon Mountain thrust, red line is the Mormon Peak detachment. Detachment footwall geometry from Axen and others, 1990.

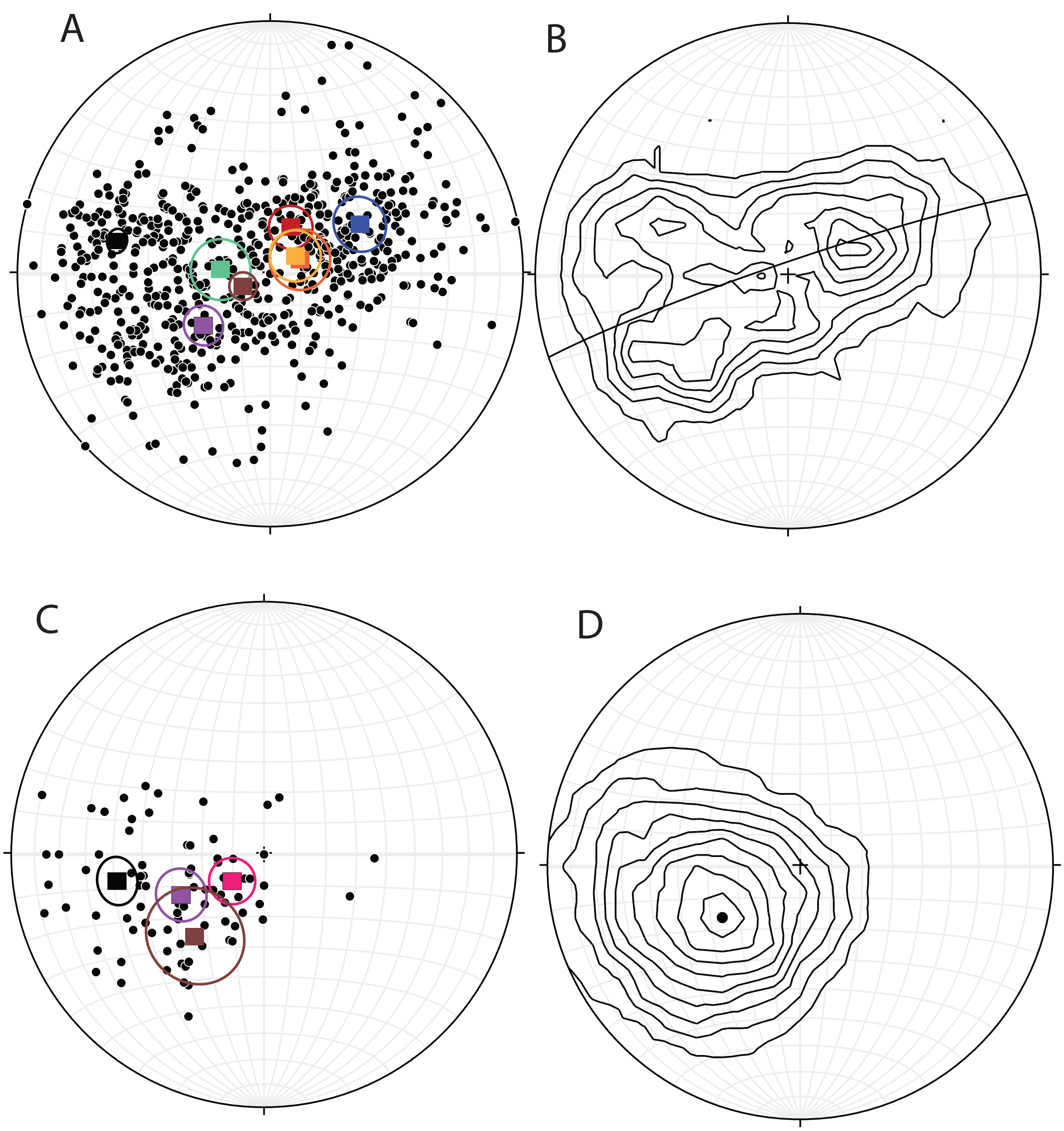
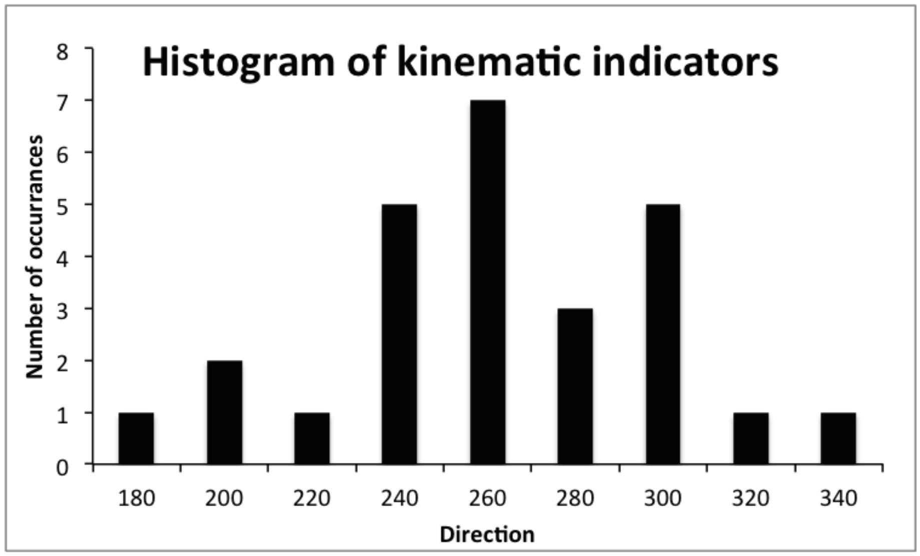



Figure 8. Equal-angle stereonet plots of orientations of strata within the hanging wall of the Mormon Peak detachment. A, poles to bedding of Paleozoic units, small black dots; squares are averages by region, as in Figure 3. Circles show relative spread of data within each subset; B, contours of all points in A, and best-fit plane of 251/86; C, poles to bedding of Tertiary units, small black dots; squares are averages by region, as in Figure 3, with the addition of magenta for the western Meadow Valley Mountains. Circles show relative spread of data within each subset; D, contour plot of points in C, with center at 61 -> 239.

A




B

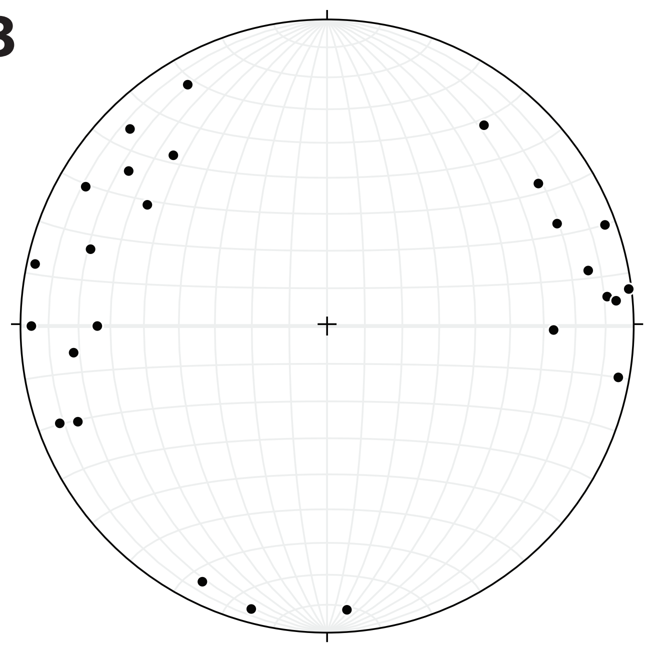


Figure 9. Histogram and stereonet plot of kinematic indicators based on data in Walker (2008). A, Histogram of kinematic orientation directions, binned in 20 degree increments; B, equal-angle stereonet projection, showing orientations of kinematic indicators.

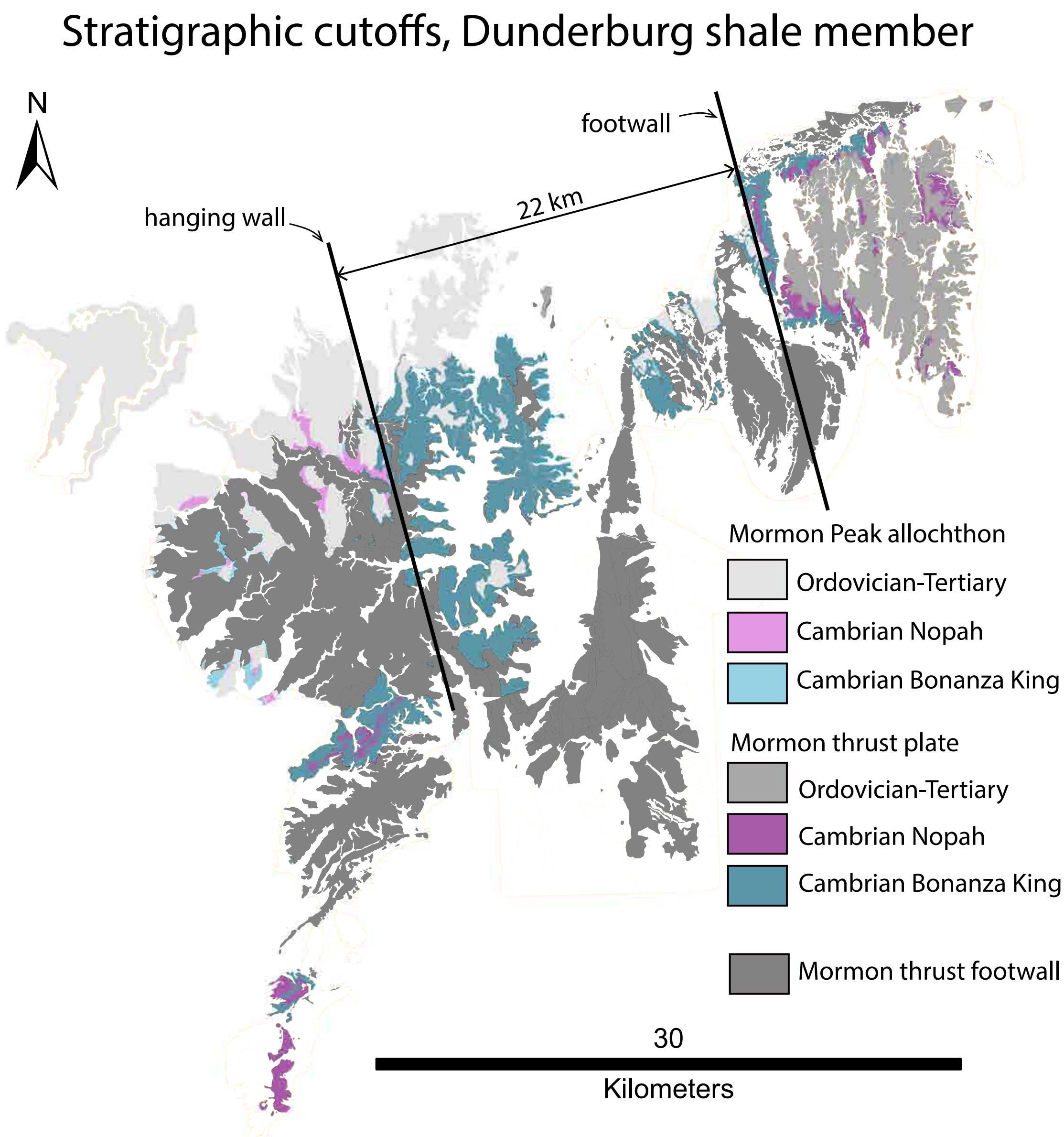



Figure 10. Map of distribution of Cambrian Bonanza King and Nopah strata, showing 22 km separation between occurrence of Nopah strata between the hanging wall and footwall of the Mormon Peak detachment.