CALIFORNIA GEOLOGICAL SURVEY

FAULT EVALUATION REPORT FER-262

THE HELENDALE FAULT

in the Apple Valley North, Fairview Valley, Fifteenmile Valley, Lucerne Valley and Cougar Buttes 7.5 Minute Quadrangles, San Bernardino County, California

By

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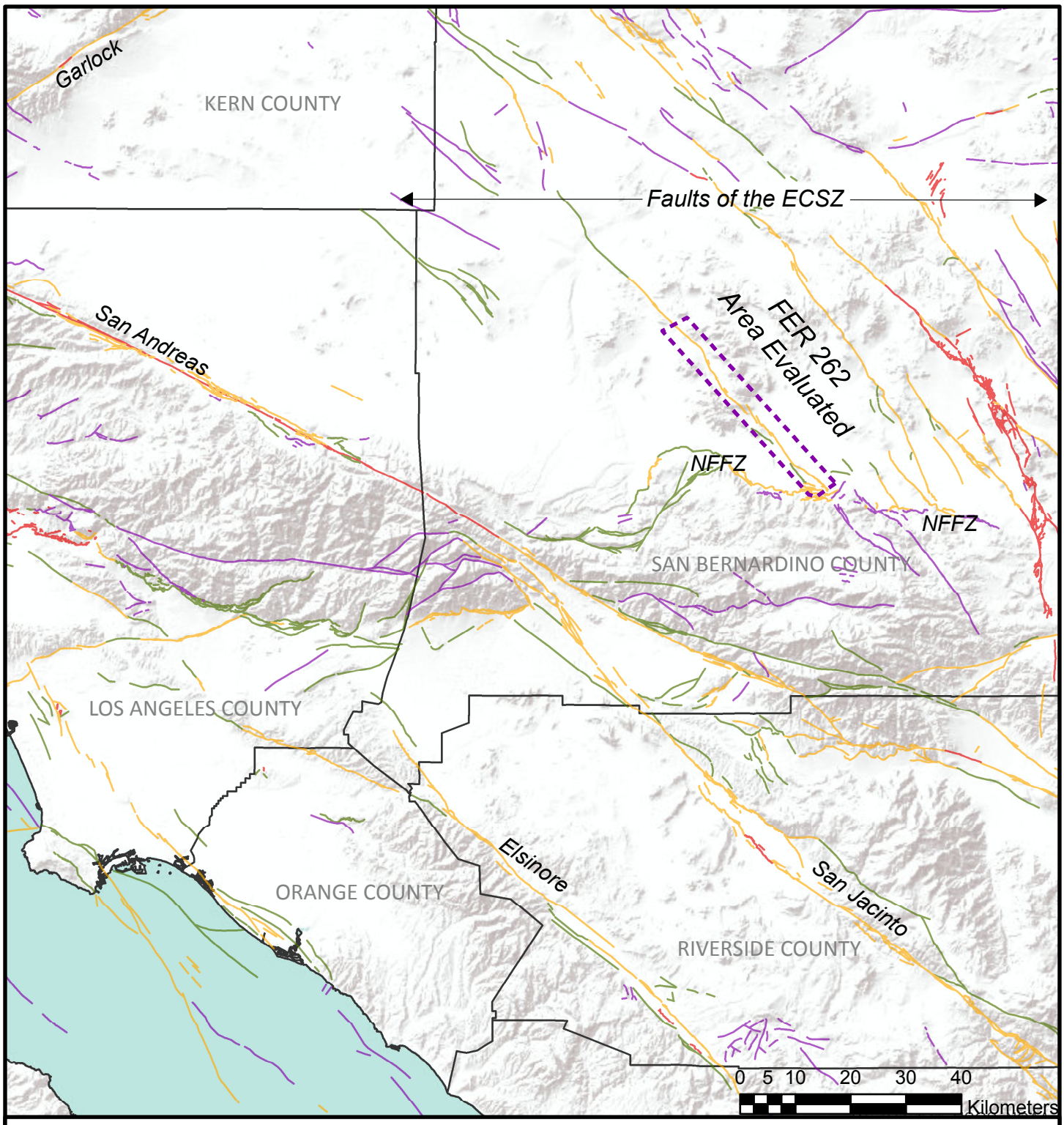
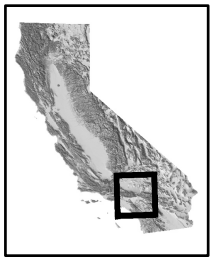
INTRODUCTION

The Helendale fault lies within the western portion of the Eastern California Shear Zone (ECSZ), Mojave Desert, California (Figure 1). The fault extends roughly 75 kilometers from the Kramer Hills (about 35 kilometers west of Barstow) southeastward to north front of the San Bernardino Mountains (Figure 2). The northern portion of the fault is thought to merge with the southern extent of the Lockhart fault. The fault system is comprised of discontinuous, sub-parallel to parallel en echelon strands forming a zone that can be as much as 1.5 kilometers in width. The first maps depicting portions of the Helendale fault were developed by Vaughan (1922), Thompson (1929, Fig. 17, p.616), and the fault was named by Bowen (1954). The entire length of the Helendale fault was mapped by Dibblee (1960a, 1960b, 1961, 1964, and 1973), and by Morton et al. (1980). The sense of displacement on the Helendale fault is dextral, with a lesser component of vertical displacement (Miller and Morton 1980; Morton et al., 1980). No evidence of historic surface rupture exists on the Helendale fault. Bryan and Rockwell (1994) and Bryan (1995) excavated trenches in Lucerne Valley, exposing evidence of as many as three earthquakes in about 16.5 thousand years before present (ka), with the most recent event occurring after about 2.3 ka. Recent studies on the slip-rate of the Helendale fault indicate a relatively low rate of 0.8 +/- 0.3 mm/yr (Oskin et al., 2008) using maximum measured offset of late Pleistocene alluvial fan deposits. Segments of the Helendale fault are considered active based on the work by Morton et al. (1980) and subsequent fault evaluation by CGS (Manson, 1986).

The Helendale fault has been previously evaluated in Fault Evaluation Reports 176 and 182. FER 176 considered segments of the Helendale fault from Astley Rancho 7.5-minute Quadrangle to the Cougar Buttes 7.5-minute Quadrangle. In FER 176, Manson (1986) identified that the Helendale was sufficiently active and well defined from the western edge of the Turtle Valley Quadrangle, southeast to the Cougar Buttes Quadrangle. In FER 182, Bryant (1986) considered the southern-most segment of the Helendale fault within the Big Bear City and Rattlesnake Canyon Quadrangles. This current re-evaluation is being made because new academic and consulting studies, modern high-resolution imagery, and detailed



Portion of Helendale Fault Evaluated in FER-262

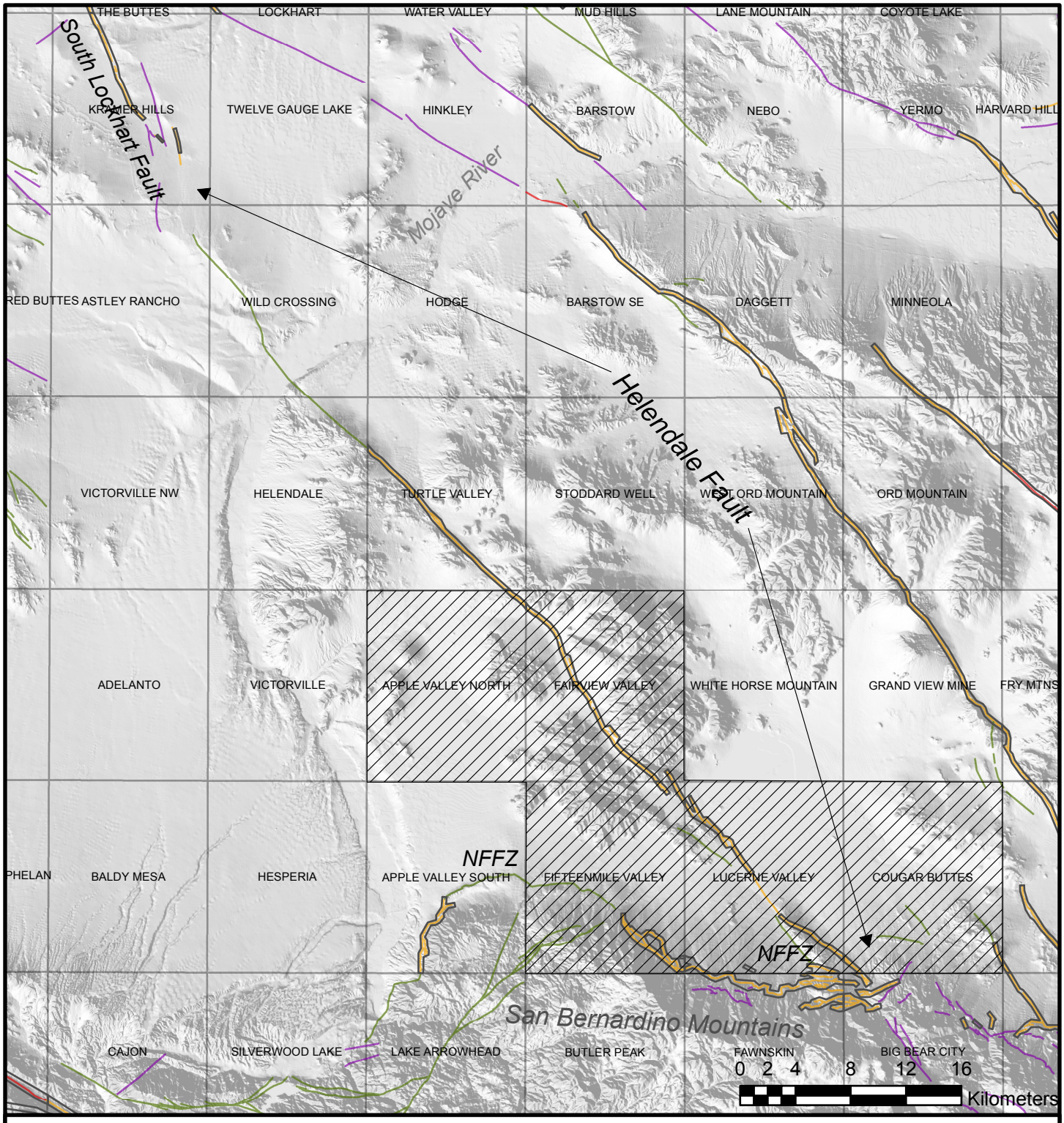


Fault Activity
- Historic
- Holocene
- Late Quaternary
- Quaternary

ECSZ - Eastern California Shear Zone
NFFZ - North Frontal Fault Zone

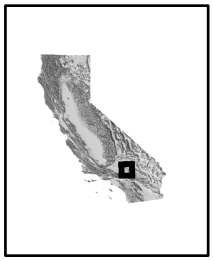
N W E S

Figure 1



Geographic Extent of Helendale Fault and Existing APEFZ

(USGS 7.5-minute quadrangles evaluated for FER-262 shown in black hatch pattern)



Fault Activity

- Historic
- Holocene
- Late Quaternary
- Quaternary

NFFZ - North Frontal Fault Zone

Figure 2

topography based on light detection and ranging (LiDAR), have become available since the original evaluation in 1986. This report includes re-evaluation of the Helendale fault from the Apple Valley North Quadrangle in the north to the Cougar Buttes 7.5 Minute Quadrangle in the south (USGS Quadrangles evaluated are shown on Figure 2).

SUMMARY OF AVAILABLE DATA

Compilation of faults and related features from regional studies are shown on Plate Ia through Ie.

Regional Setting and Geometry

The Helendale Fault is comprised of a complex series of both right and left stepping en echelon strands and associated folds and basins, that extend from the Helendale-South Lockhart fault zone north of the Mojave River, to the San Bernardino Mountains in the south. The fault is considered the western most active structure in a series of faults that make up the Eastern California Shear Zone (Dokka and Travis, 1990). The entire length of the Helendale fault was mapped by Dibblee (1960a, 1960b, 1961, 1964 and 1973), and by Morton et al. (1980).

Regional Geologic Mapping

Geologic mapping of the Black Mountain area by Stone (2006) covers the northern most portion of the Apple Valley North and Fairview Valley Quadrangles. This map shows north facing scarps in alluvium thought to be Tertiary to Quaternary in age, with alluvium of late Pleistocene age also being affected. The fault is shown as concealed where it is projected across areas underlain by alluvium of Holocene age.

Hernandez and Tan (2007) show the trace of the Helendale fault in the Apple Valley North Quadrangle as approximately located and breaking older alluvium (Qoa). This map also shows another fault in the northern portion of Sidewinder Valley that juxtaposes very old alluvium with Cretaceous monzogranite. However, this fault is mapped as a discontinuous feature in older alluvium.

Miller and Matti (2001) mapped the geology of the Fifteenmile Quadrangle. This map shows the furthest west strand of the Helendale fault trending through bedrock of the Granite Mountains. No faults along this trend are shown to break alluvium of late Pleistocene and Holocene age.

Sadler (1982) mapped portions of twelve 7.5 minute Quadrangles along the north flank of the San Bernardino Mountains. Within the Lucerne Valley and Fifteenmile Valley Quadrangles, Sadler shows the general distribution of bedrock units and faults. Faults shown on the Fifteenmile Valley Quadrangle are east trending, confined to the range front, and associated with the north frontal fault zone. Within the Lucerne Valley Quadrangle, Sadler shows several approximately located northwest trending faults in young alluvium around the town of Lucerne Valley, Rabbit Springs, and Sunset Cove (Plates Ic and Id). Numerous northwest trending bedrock faults are mapped within the southern portion of the Granite Mountains and along the margins of the bedrock ridge east of Pitzer Buttes.

Regional Fault-Specific Mapping

Bull (1976) studied the tectonic geomorphology of the Mojave Desert and used quantitative geomorphology coupled with the identification of surficial geologic deposits to explain the tectonic activity of mountain ranges. Five differential equations are used to provide a quantitative index that relates uplift, erosion, and deposition along streams that cross mountain fronts. These equations are used to separate ranges into three classes: Class 1 range fronts occur in highly active tectonic settings characterized by active folding and faulting during the Pleistocene and Holocene; Class 2 range fronts generally include faulted Pleistocene, but not Holocene deposits; Class 3 range fronts have been tectonically inactive during the Quaternary. Bull also used measurements of mountain front sinuosity and valley-floor width in order to develop maps of relative uplift in the Mojave Desert. Five locations along the Helendale fault were assessed. Bull assigned tectonic activity Class 1 to the Helendale from southern Fairview Valley to northern Sunset Cove, southern Sunset Cove to Rabbit Springs, and to the western and eastern margin of the unnamed northwest trending ridge in southern Lucerne Valley.

Morton et al. (1980) used black and white, low-sun-angle air photos to identify young-looking fault features along the trend of the Helendale fault. Their strip map is annotated with interpreted features, such as tonal lineaments, alignments of scarps, and aligned notches. These features were not field checked by the authors. However, Manson (1986) field inspected most of these features in order to assess the recency of activity. Manson's observations are annotated on the strip map published by Morton et al. (1980) on Figure 4 of FER 176 (Manson, 1986).

Askoy (1986) mapped young looking fault features and geology along the fault from Brisbane Valley to Lucerne Valley (See Plates Ia-e). Mapping also included a provenance study of offset alluvial sediment of Quaternary age, as well as gravity surveys within Lucerne and Fairview Valleys. Askoy noted features, such as scarps, beheaded stream courses, faceted spurs, and aligned notches and springs. He also noted up to 200 meters of right-lateral offset of stream courses. The provenance study describes clast lithology and percent of each clast type within alluvial deposits of probable Pleistocene and Holocene age. Several alluvial fan deposits on the west side of Helendale fault are described as having distinct sources that occur in specific drainages to the south and east. Gravity surveys within Fairview and Lucerne Valleys presented in this thesis indicate strong regional gradients with contours that parallel the Helendale fault, suggesting that the Helendale fault is a vertical structure at depth. Askoy concluded that initiation of the Helendale fault occurred in Pleistocene time, but that based on the continuity of younger alluvium across the trace of the Helendale fault and the lack of historic seismicity, Holocene offset could not be demonstrated.

Bryan (1995) studied the tectonic geomorphology of the southern portion of the Helendale fault from Sunset Valley to Cushenbury Springs. This MS thesis includes a tectonic strip map of the Helendale fault as well as fault trenching and the identification of paleo surface rupture events. Bryan's sequence of latest Pleistocene and Holocene

surface rupture events are the sole source of paleoseismic data for the Helendale fault system. These are described in subsequent sections.

In addition to the references provided above, CGS also reviewed in-progress geologic mapping conducted by Mr. Howard Brown from within the Fairview Valley Quadrangle.

Groundwater Investigations

Groundwater availability in the Lucerne Valley region has been a long lasting concern for the Mojave Water Agency and local farmers. Schaefer (1978) used the groundwater basin nomenclature developed by the California Department of Water Resources (DWR, 1967 and 1975). Locally, from west to east, these are identified as the Fifteenmile Valley, Rabbit Springs, and Lucerne Lake subasins. According to Schaffer (1978), fairly distinct changes in groundwater elevation occur across the northwest trending Helendale fault and a parallel fault named the Lucerne Lake fault to the east of the Helendale. The Rabbit Springs subbasin lies between these parallel strands. Groundwater elevation differences ranging from 60 to 100 ft are present along the Helendale fault. Based on 1976 data, groundwater differences range from near zero, south of State Route 247 (CA-247), to as great as 12 meters lower on the east side of the Lucerne Lake fault just north of CA-247. Gravity data used to model basin geometry in the Lucerne Valley suggest a strong linear gradient along the Helendale fault (Askoy, 1986; Surko, 2006) that coincides with groundwater elevation differences between the Fifteenmile and Lucerne subbasins. In contrast, Daily (2012) used very low frequency and magnetic geophysical transects to identify the location of the Helendale fault within Fairview and Lucerne valleys. Within Lucerne Valley, Daily (2012) concluded that the fault zone itself contains water, may be a conduit for subsurface flow from higher elevations, and that it is the juxtaposition of dissimilar geologic units across the fault that create a groundwater barrier.

Investigations into groundwater resources of Fairview Valley have not been conducted. However, several private wells exist with depth to water documented by the California Department of Water Resources (DWR). In the southern end of the valley, depth to groundwater was on the order of 86 meters below ground surface (bgs) in 2014 (DWR, 2015), near the intersection of Wallew and Cahuilla Roads. On the northeast side of the Fairview playa near the terminus of Oldenburg Road, groundwater was on the order of 50 meters bgs in 2014 (DWR, 2015). However the density and distribution of groundwater wells, as well as the lack of historic data, do not lend themselves to a detailed understanding of the effects of faulting on groundwater levels.

Consulting Studies

Given the sparse population along the trend of the Helendale fault and the relative lack of development, few fault investigations have been conducted within the Alquist-Priolo Fault Zone established in 1988. The study by Bryan (1995) included three trenches within the zone, but was an academic study and therefore not intended to develop fault setbacks for structures of human occupancy (See trench locations on

Plates Ic and Id). An APEFZ geologic/fault investigation was conducted by Terra Geosciences at 32687 Hwy. 18 (APN No. 450-371-06), dated June 3, 1998. This investigation was located east of the photo lineament identified as the fault by Manson (1986). Two trenches up to 3.4 meters deep exposed alluvial sediments thought to be as old as early Holocene to Pleistocene in age, based on carbonate development (See trench locations on Plate Id). No faults were identified in these trenches, consistent with their location east of the fault.

Timing and Sense of Movement

Right-lateral faulting in the Mojave Desert is thought to have initiated in middle-to-late Miocene time based on observations of offset units on the Calico-Blackwater fault, and faults near Death Valley (Dokka and Travis, 1990). However, the currently active right lateral faults of the ECSZ are thought to have initiated in the early Pleistocene (1.5 to 0.7 Ma) based on cross-cutting relationships between northwest trending shears and reverse faults of the north frontal fault zone (Meisling and Weldon, 1989). The sense and total slip on the Helendale fault has been a subject of debate over the years. Dibblee (1961) identified metavolcanic rocks on the west side of the fault north of Victorville that may be displaced several miles. Dibblee also noted vertical displacements along the fault are “reversed,” but concluded that these displacements are small. Garfunkel (1974) used small-scale mapping compiled by Rogers (1967) to identify piercing points along the Helendale fault, and suggested a total 10 to 15 km of right-lateral offset. Askoy (1986) reviewed the measurements conducted by Garfunkel (1974) and found that additional metavolcanic outcrops are found along the Helendale fault that were not used by Garfunkel to constrain the total slip on the fault. Askoy (1986) concludes that Mesozoic basement and Pleistocene alluvial deposits have the same separation of about 2 km, indicating right-lateral faulting initiated in the Pleistocene. This view is also shared by Miller and Morton et al. (1980) who performed potassium-argon dating on a petrologically distinct pluton on either side of the Helendale fault (at the fault intersection with I-15). Miller and Morton (1975) concluded that total right-lateral slip on the Helendale fault may not be more than 1 or 2 km. Jachens et al. (2002) used offset magnetic anomalies along the Helendale fault that suggest total slip of 4.3 km in the south, and 3 km in the north. Askoy (1986) suggested that right-lateral faulting continued through Pleistocene as evidenced by varying amounts of offsets in older alluvial units and stream courses, but also stated that movement appears to have ceased during the Holocene based on the continuity of young alluvial units.

Recency

In the area of Rabbit Springs, Bryan and Rockwell (1994) excavated a single trench to a depth of 4.5 m, exposing lacustrine, alluvial and colluvial strata (Plate Id). Brittle deformation within the exposed strata was not observed, but significant warping and plastic deformation was present. At the time, ^{14}C dating was conducted but results were not available for the report. Based on correlation with studies conducted on playa margins in the region, the lacustrine strata at the base of the trench were thought to be

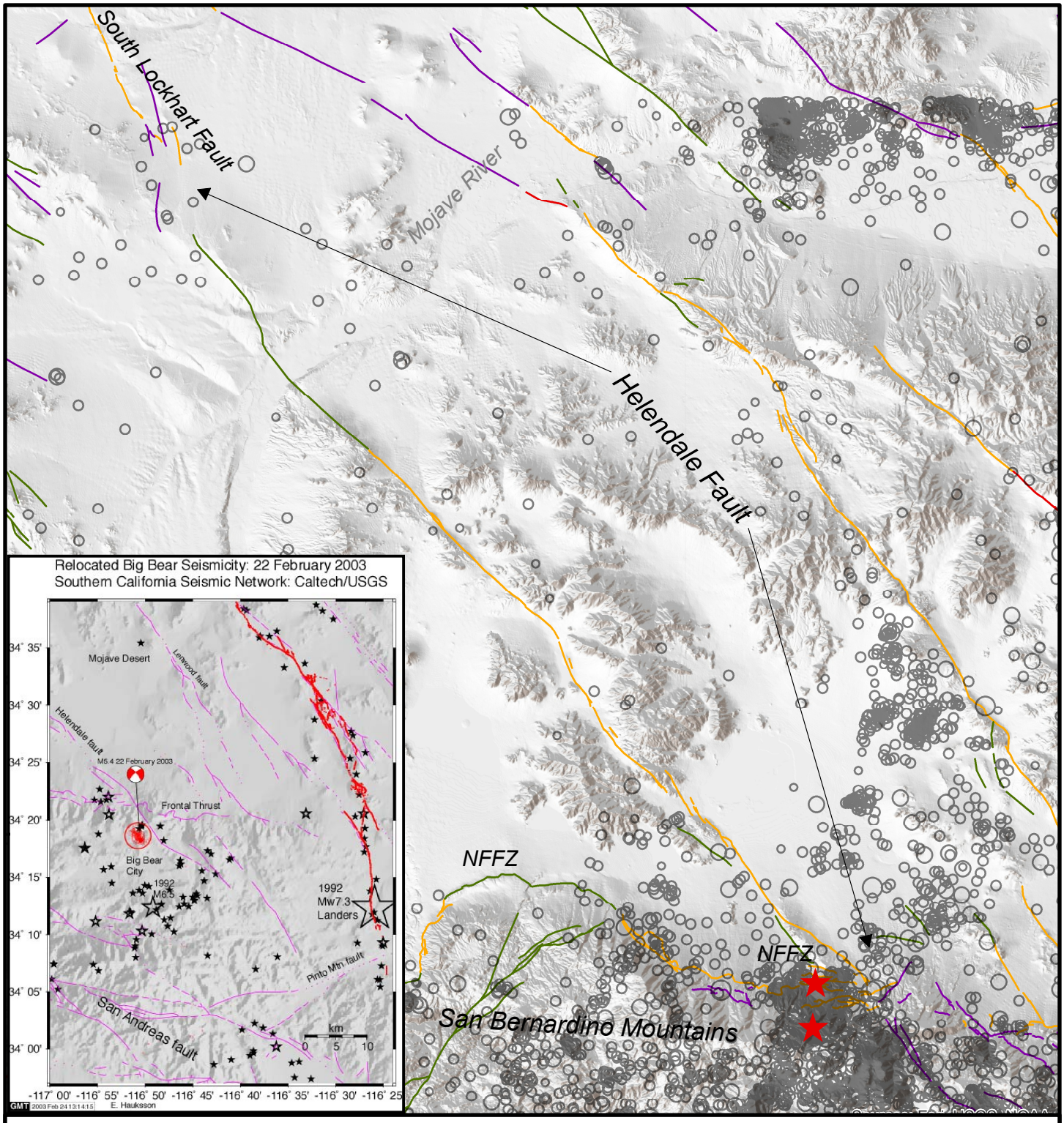
9.5 to 10 ka in age. Fractures in the strata were not filled, suggesting they are relatively young and not exposed at the surface. In continuation of this thesis study, Bryan (1995) excavated an additional two trenches across the trace of the Helendale fault in Sunset Cove (See Plate Ic) exposing evidence of as many as three earthquakes since about 16.5 ka. The most recent event (MRE) is estimated based on dating of detrital charcoal within offset alluvial strata, yielding calibrated ages of 4,415 +445/-494 (T-3 in Sunrise Cove) and 2,330 +28/-189 (T-1 at Rabbit Springs). However, Bryan (1995) concludes that the MRE is younger than the 2.3ka date at Rabbit Springs because the detrital charcoal sample was not the stratigraphically highest unit deformed by faulting.

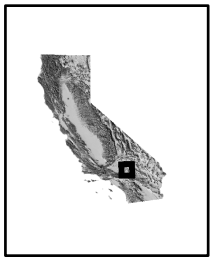
Slip Rate

Several workers have developed slip rates for the Helendale fault. Clark et al. (1984) reported a slip rate of about 1 mm/yr, based on 1-2 km dextrally offset pluton boundary of Mesozoic age (Miller and Morton, 1980). This slip rate is suggested to be representative of the long-term rate (post 20 Ma) based on the once continuous southern boundary of Miocene detachment strata, now offset by several faults of the ECSZ (Dokka, 1983). However, as with total slip estimates on this fault, the method Dokka (1983) used to extend the total slip from 1-2 km of Miller and Morton (1980), to 3 km is unclear. Petersen and Wesnousky (1994) reported a preferred slip rate of 0.8 /yr based on the 3 km dextral offset reported by Dokka (1983) and Dokka and Travis (1990) and also assumed initiation of offset between 2 Ma and 20 Ma. For the probabilistic seismic hazard assessment for the State of California, the slip rate assigned by Petersen et al. (1996) was 0.6 mm/yr, with minimum and maximum assigned slip rates of 0.2 mm/yr and 1.0 mm/yr, respectively. Askoy (1986) suggested that offset Pleistocene strata have about the same total slip as Mesozoic strata (~1.9 km) and he concluded that this possibly indicates onset of faulting during the Pleistocene epoch. Oskin et al. (2008) investigated slip rates on several faults within the ECSZ, including the Helendale fault. Within the Turtle Valley area, mapping of offset alluvial surfaces of Pleistocene age coupled with numeric age dating yielded a slip rate of less than or equal to 0.8 +/- 0.3 mm/yr. The Working Group for California Earthquake Probabilities using a slip rate of <0.8mm/yr, with a maximum of <1.3 mm/yr and a minimum of <0.6 mm/yr (Oskin et al., 2008; Field et al., 2013).

Slip Rate and Tectonic Geomorphology

The identification of active faulting that is well defined at the surface requires understanding of surficial geology; that is, the general distribution of Quaternary deposits. Sharp (1972) showed recently active breaks along the San Jacinto fault, highlighting associated tectonic geomorphic features, such as: scarps, truncated spurs, linear gullys, troughs, aligned notches, offset drainage channels, closed depressions and ponded alluvium. Morton et al. (1980) used Sharp’s classification to identify relative young looking fault related features along the Helendale fault zone. The expression of these features can be related to the slip rate of the fault as well as the rates of primary





Historic Seismicity Epicenters
(moment magnitude scale; quarry blasts removed)

- 1.0 to 1.9
- 2.0 to 2.9
- 3.0 to 3.9
- 4.0 to 4.9
- 5.0 to 5.9

N W E S

0 5 10 Km

Data Source:
Hutton, K., Woessner, J., and Hauksson, E., 2010, Earthquake monitoring in southern California for seventy-seven years (1932–2008): Bulletin of the Seismological Society of America, v. 100(2), pp. 423-446.

Figure 3

surficial processes, such as erosion and deposition by rainfall runoff, and gravitation movement. Secondary surficial processes, such as eolian deposition may also influence the surface expression of faulting.

Seismicity

Earthquake data from the Southern California Seismic Network (SCSN) catalog (Hutton et al., 2010) show a clustering of earthquakes north of Big Bear City and west of Cushenbury Canyon (Figure 3). North of the San Bernardino Mountains epicenters become scattered with some perhaps aligning with the Helendale fault in the Lucerne Valley, and few aligning with the Helendale fault northwest of Lucerne Valley. This observation is fairly consistent with regional earthquake distribution in the Mojave Desert; most of the seismicity does not clearly align with the mapped traces of ECSZ faults, with exception being the Landers Mw 7.3 sequence (Petersen and Wesnousky, 1994).

Three hours after the Landers earthquake in 1992, the Ms 6.4 Big Bear earthquake occurred at a depth of about 5 kilometers about 1.6 kilometers from the Helendale fault. Black (2008) concluded that the Big Bear earthquake could not be directly attributed to the Helendale, but the Helendale could not be ruled out as the source due to the proximity. According to Hauksson et al. (2003), the Helendale fault produced a ML 5.4 earthquake on February 22, 2003 that was located 3.2 kilometers north of Big Bear City at a depth of about 6 kilometers. This earthquake was not preceded by foreshocks, but was followed by 116 aftershocks during the first 6 hours, with the five larger aftershocks ranging from M 4.0 to M 4.5. According to Hauksson et al. (2003):

> The mainshock exhibited strike-slip faulting (horizontal movement) on a steeply dipping (80 degrees) plane striking N40W, sub-parallel to the local strike of the Helendale fault. This mechanism is consistent with the mainshock being near the Helendale fault, a more than 64 km long, late Quaternary fault in the Mojave Desert. Preliminary locations of the aftershocks appear to form a 3.2 kilometers long, northwest striking trend, located 3.2 km to the west of the main surface trace of the Helendale fault. Hence, this sequence may be occurring on a small sub-parallel fault, adjacent to the Helendale fault.

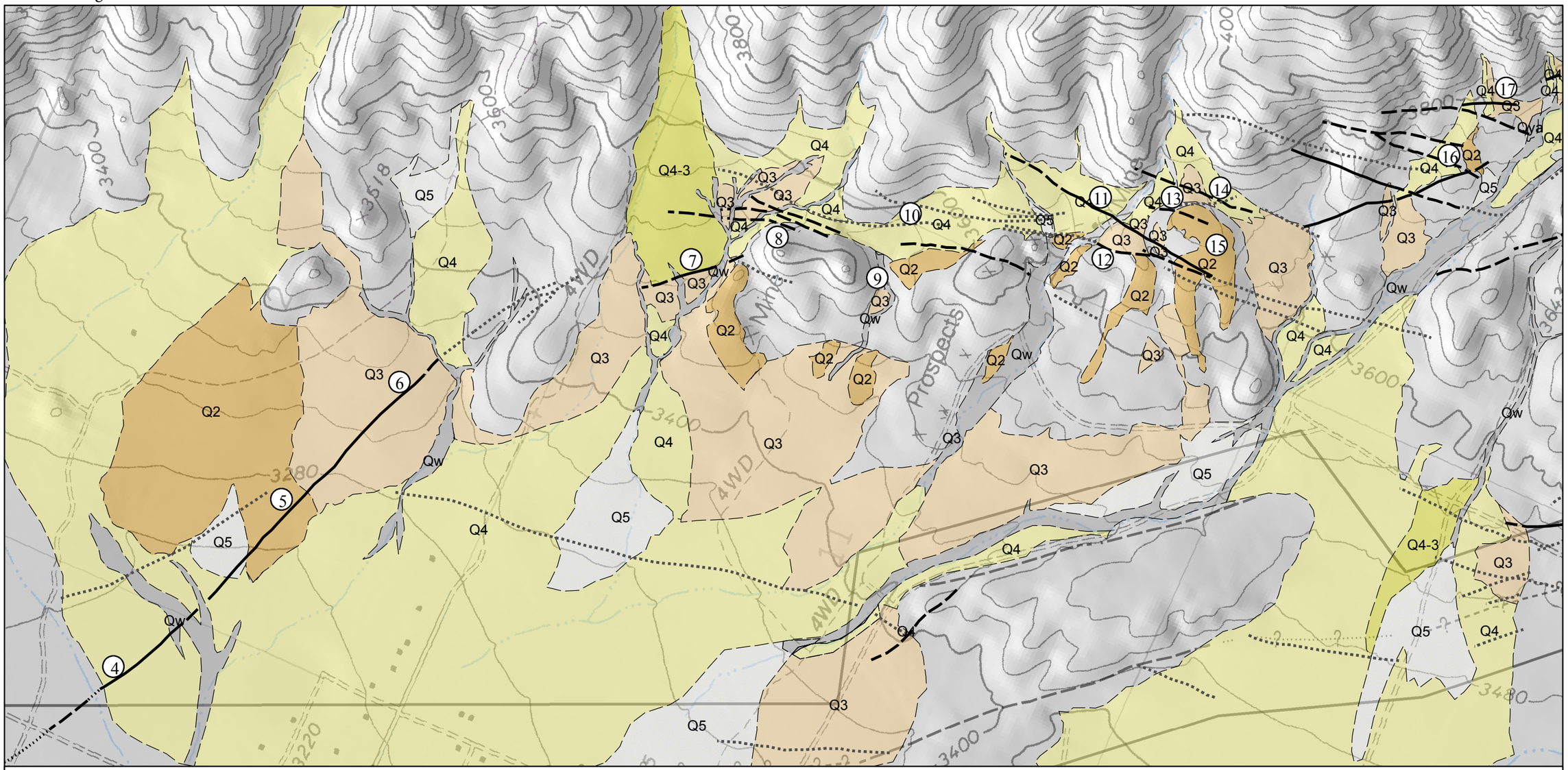
GEOMORPHOLOGY, AERIAL PHOTO INTERPRETATION AND FIELD RECONNAISSANCE

Interpretation of aerial photographs, LiDAR and MASTER are shown on Plates IIa-e with the image/data source following the geomorphic feature observed. Additional details related to observed geomorphic features are provided on Table 1. Within the southeastern portion of the Fairview Valley Quadrangle, geomorphic mapping was conducted using ADS-40 imagery to identify the general distribution of Quaternary alluvial surfaces and the extent to which fault related features disrupt the these surfaces (Figure 4 and 5). Limited field reconnaissance was conducted over three days in December 2014 and three days in March of 2015.

Table 1: Geomorphic features observed

(Numbers keyed to locations on Plates IIa through IIe)

1. Plate IIa: Scarp, 0.5 to 1 meter high in Holocene alluvial fan deposits. Trace relocated based on LiDAR.
2. Plate IIa: Fault mapped by Manson 1986, appears to be the result of erosion near the lakebed margin due to eolian processes.
3. Plate IIb: Linear break in slope flanking small ridge.
4. Figure 4: Scarp in Q_4 alluvium based on LiDAR. See profile based on LiDAR DEM, shown on Figure 5.
5. Figure 4: Back-facing scarp in Q_2 alluvium. See profile based on LiDAR DEM, shown on Figure 5.
6. Figure 4: Linear gully with no apparent source area in Q_3 alluvium.
7. Figure 4: Back-facing scarp in Q_3 alluvium with ponded alluvium upslope.
8. Figure 4: Series of scarps, tonal and vegetation lineaments in Q_3 and Q_4 alluvium.
9. Figure 4: Wind gap that once conveyed Q_2 and Q_3 alluvium. Channel currently disconnected from former sediment sources. Channel eroding headward into Q_4 ponded alluvium upslope.
10. Figure 4: Ponded alluvium in graben.
11. Figure 4: Fault identified in Quarry, Paleozoic dolomite faulted against Q_3 alluvium with apparent down to east sense of offset. Scarp continues in Q_4 alluvium on the north side of quarry. (See Figure 6)
12. Figure 4: Fault juxtaposes Q_3 alluvium with Q_2 alluvium and Paleozoic dolomite.
13. Figure 4: Graben separating mountain front from Q_2 terrace surface.
14. Figure 4: Topographic and tonal lineament in Q_3 and Q_4 alluvium.
15. Figure 4: Q_2 terrace surface has been uplifted, removed from deposition, and is strongly dissected.
16. Figure 4: Complex intersection of topographic (back-facing scarps) and vegetation lineaments. Uplifted and abandoned alluvial units.
17. Figure 4: Fault scarp with apparent down to the west sense of displacement. Bedrock fault scarp exposed truncating older alluvium found on both sides of the fault.
18. Plate IIb: Lineament associated with bedrock contact/fault in Triassic monzonite and diorite.
19. Plate IIb: Right laterally deflected drainage of Askoy 1986, not verified.
20. Plate IIc: linear valley with numerous aligned troughs and ponded alluvium. Faulting appears to follow bedrock contacts.
21. Plate IIc: linear valley with numerous aligned troughs and ponded alluvium. Faulting appears to align with bedrock contacts.
22. Plate IIc and Figure 8: Right-laterally offset drainages, side-hill bench with ponded alluvium.
23. Plate IIc: Trace not verified based on review of multiple imagery sources.
24. Plate IIc: Tonal lineaments in distal fan and lacustrine deposits. Both lineaments are continuous for about 400 meters north of the lakebed margin.
25. Plate IIc: Lineament follows alignment of vegetation and mounding of eolian sand.
26. Plate IIc: Lineament noted on multiple imagery sources. Appears to run parallel to contours and therefore liquefaction origin cannot be precluded.
27. Plate IIc: Linear valley and tonal contrast. Granitic bedrock faulted against Pleistocene fan deposits.
28. Plate IId: Tonal lineament extends south from known fault locations near Rabbit Springs.
29. Plate IId: Tonal contrasts showing en-echelon pattern in MASTER imagery.
30. Plate IIe: Scarp noted as truncation of older alluvium. Photos predate development of aggregate quarry.
31. Plate IIe: Scarp along base of slope affecting older colluvium, alluvium, and loci of active fan deposition.
32. Plate IIe: Scarp showing approximately 20 meters of vertical throw in alluvial fan deposits.
33. Plate IIe: Scarp and linear ridge in alluvial fan deposits, nearly parallel with axial drainage.
34. Plate IIe: Scarp disrupting drainage patterns in coarse textured alluvial fan deposits.



Interpreted Faults and Lineaments

Photo Lineament

Interpreted Fault, solid line where accurately located; long dash where approximately located.

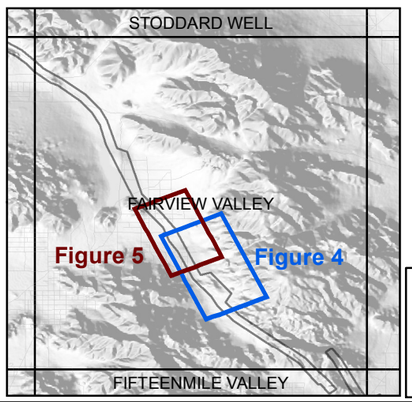
1988 Alquist-Priolo Earthquake Fault Zone Boundary and fault traces (Shown in light gray)

Official Alquist-Priolo Fault Zone

Fault, solid line where accurately located; long dash where approximately located; short dash where inferred; dotted where concealed; query (?) indicates additional uncertainty.

Interpreted Geomorphic Units

Qw	Geomorphically active alluvial wash
Q5	Geomorphically active alluvial fans and valley alluvium
Q4	Abandoned alluvial fans (Holocene)
Q4-3	Abandoned alluvial fans (Late Pleistocene to Holocene)
Q3	Relict alluvial fans (Late Pleistocene)
Q2	Relict alluvial fans (Pleistocene)



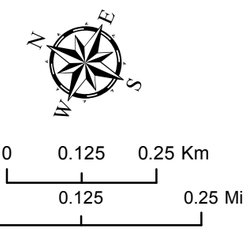


Figure 4
Geomorphic Interpretations
Southeastern Fairview Valley

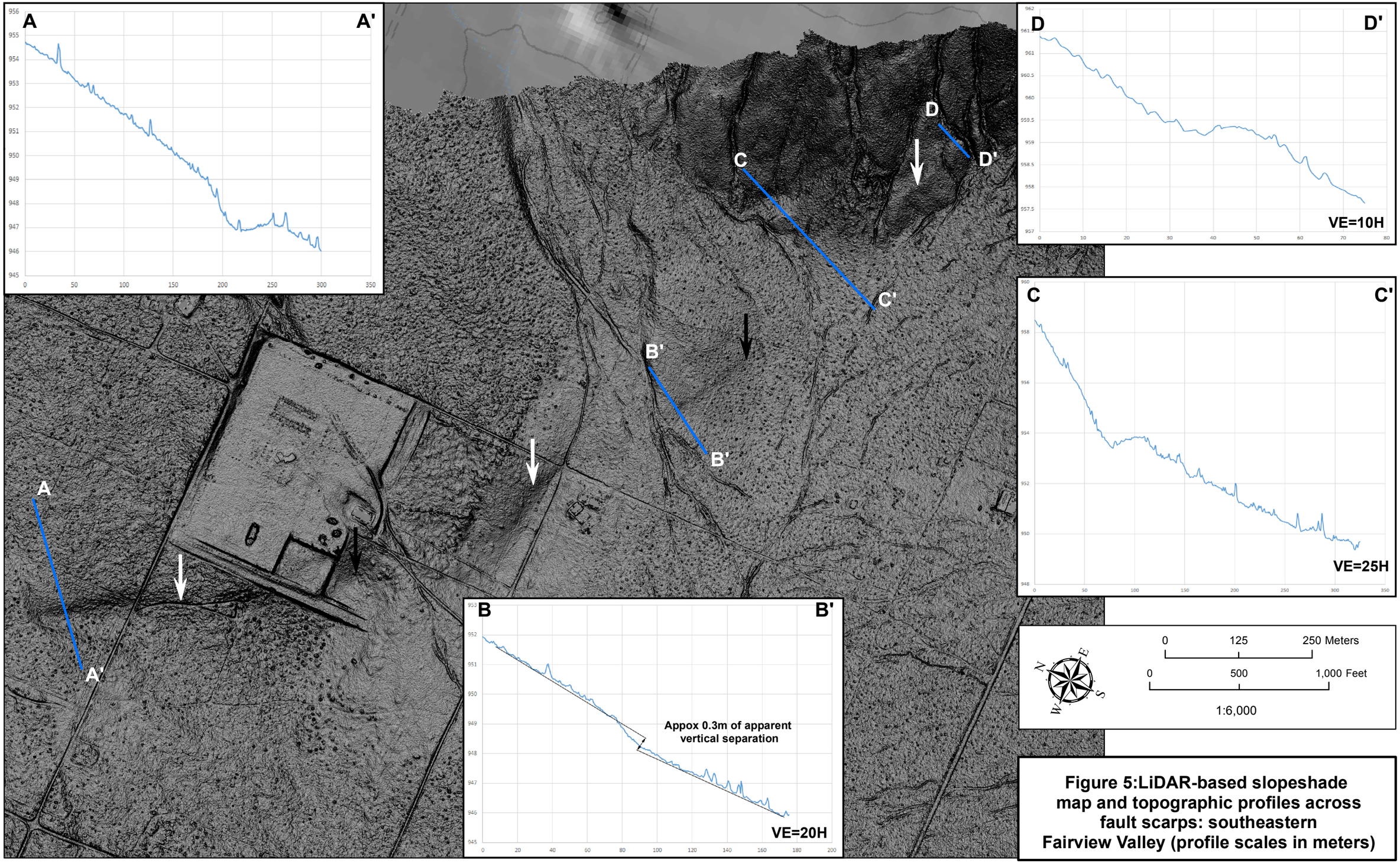


Figure 5:LiDAR-based slopeshade map and topographic profiles across fault scarps: southeastern Fairview Valley (profile scales in meters)

Apple Valley North Quadrangle

The existence and location of the Helendale fault is suggested by a shutter ridge comprised of older alluvium in contact with younger alluvium (Plate IIa). The northern base of the shutter ridge has been faulted against a series of Pleistocene and Holocene alluvial fans that emanate from Black Mountain to the east. The alluvial fans mapped as unit Qia (Stone, 2006) are thought to be largely of Pleistocene age, appear moderately dissected, and have a reddish brown color on color aerial photos (San Bernardino County, Google Earth image dated 01/31/2009). In this area, Holocene fan deposits overlie and are inset into the dissected Pleistocene fan surface. A road to the Black Mountain Quarry traverses the eastern base of the shutter ridge and obscures the expression of the fault at the ground surface. North of Quarry Road, the fault trace is expressed as a low lying scarp in an inset alluvial fan deposit that is likely Holocene-age. The fault traverses Holocene alluvium to the southeast where is expressed in in another series of shutter ridges.

In addition to previously mapped fault traces, a linear trough with ponded alluvium forms a lineament just south of the main fault trace (Plate IIa). The lineament is aligned subparallel to the main trace, but based on available geologic mapping (Hernandez and Tan, 2007) and LiDAR, does not extend into alluvium of Holocene age.

Fairview Valley Quadrangle

The Helendale fault is expressed in a series of shutter ridges south of Black Mountain within the northwest corner of Fairview Valley 7.5 minute Quadrangle. The fault trace crosses the Black Mountain Quarry rail alignment and is exposed within the railway cut. The fault is expressed as a series north facing scarps and linear ridges extending for about 1.5 km to the northwest where it then becomes concealed in active alluvial fan deposits over a distance of about 0.35 km. From Johnson Road to the Fairview Valley playa, the fault traverses alluvial fan deposits of Holocene age and is expressed as a series of low, west-facing scarps. Alluvial surfaces on the east side of the fault are abandoned and moderately incised with through-flowing channels within those surfaces crossing the fault trace. Because the abandoned alluvial surfaces on the east side of the fault have not experienced significant soil development, the fault trace is not readily apparent based on review of USDA, BLM and MASTER imagery. However, LiDAR provides a strong basis for identification and accurate location of this fault trace. As the fault enters the Fairview Valley playa from the north, it appears to form a scarp that has forced north-to-south flowing distributary channels to the west side of the valley (Plate IIa, location 1). LiDAR topography shows subdued expression of faulting within the active playa deposits at the south side of the playa. This subdued expression of the fault in the south is consistent with the activity of alluvial deposition and eolian degradation and deposition in the area. However, the existence and location of the fault is also apparent from tonal contrasts and vegetation lineaments on USDA and MASTER imagery. Previously mapped fault related features (Manson, 1986) on the east margin of the playa do not align with fault traces to the north and south (Plate IIa, location 2) and appear to result from eolian degradation.

As the Helendale fault exits the southern end of the Fairview Valley playa it traverses alluvium and the eastern margin of a low-relief inselberg. Several west facing scarps indicate the existence and location of the fault in this area (Plate IIb, location 3). In addition, a linear gully with ponded alluvium on the east flank of the inselbergs indicates the location of the fault. As described above, in this area, topographic features related to faulting are modified by eolian erosion and deposition. Between Oldenburg and Mountain View Roads the Helendale fault is expressed as west facing fault scarps as high as 1 meter. In this area the fault expression appears to control the location of alluvial fan apexes resulting from abrupt change in relief along the fault trace.

Complexity of surface expression increases to the southeast of Mountain View Road (See Figures 4a and 5). Near the intersection of Mountain View and Wallew Roads. Here the surface trace of the Helendale fault splits into a western and eastern strand.

Western Strand: The western strand is concealed in late Holocene alluvium for about 1.3 km but becomes better expressed in alluvium east of Chicago Road. The fault trends into a northwest trending ridge that lies within the center of the valley. This ridge is bounded by parallel strands of the fault. On the east side the fault is expressed as a linear break in slope on the flank of the ridge that is modified in part by stream erosion. On the west side, faulting is indicated by a linear gully and a west facing break in slope, accompanied by vegetation lineaments and tonal contrasts. Further south, the eastern strand is less apparent in alluvial fan deposits of probable Holocene age. In contrast, the western strand is expressed as a series of vegetation lineaments and tonal contrasts that become more pronounced as the trace enters the hills to the south.

Eastern Strand: The eastern strand makes a bend toward the mountains in the east where its existence and location is indicated as a low south facing scarp (0.3 m) in alluvial fan deposits that are likely Holocene age (Figure 4, Note No. 4; and Figure 5). This topographic feature extends for about 1.2 kilometers, becoming a north facing scarp and linear gully in Pleistocene deposits (Figure 4, Notes 5 and 6). This is a key feature in the recognition of potentially active faults along the steep range-front of the Granite Mountains. For a distance of about 2 km the range front is comprised of steep catchments that extend about 1 km into the range. Drainage networks within these catchments are comprised of linear first-order streams. These drainages are disrupted by a series of outlying ridges (shutter ridges) that have deflected them in an apparent right-lateral sense. Mapping of alluvial surfaces along the range front indicates that units Q2 and Q3, of probable Pleistocene age, have been faulted, laterally translated, uplifted and removed from the modern drainage source (Figure 4, notes 12 and 15). Fault offset of unit Q3 was observed in a quarry (Figure 4, location 11; Figure 6) and scarps were observed in adjacent fan surfaces (Q4), of probable Pleistocene and Holocene age. Faulting of Q4 surfaces also lead to ponding of the unit against

outlying ridges in an apparent graben, uplift/removal and incision, fault scarps (See Figure 7) and vegetation lineaments. The existence and location of these faults are observed on ADS40, MASTER, and USDA imagery, but become less apparent to the south end of the steep range front (Figure 4, Notes 7 through 17).

At southern most end of the Fairview Valley, the alluvial plain terminates and is surrounded by a ridge of Mesozoic granite. This ridge forms the drainage divide between Fairview Valley to the north and Sunset Cove (part of Lucerne Valley) to the south. In this region, several parallel canyons have been attributed to faulting. These canyons drain south into Sunset Cove and are labeled as features A, B and C on Plate IIc. Although Canyon A has been attributed to faulting by past workers (Dibblee, 1986; Askoy 1986), there are no features suggestive of faulting in alluvial deposits along this trend in the upper Sunset Cove area. A sidehill bench is noted in Mesozoic granite, but an extension of this linear feature into alluvium is not apparent in LiDAR, or the referenced imagery. A large landslide (0.06 km^2) present on the east side of this valley, may be responsible for obscuring fault related features. The existence and location of the Helendale fault in Canyon B is demonstrated by a series of aligned notches that connect to opposing drainages in the north and south. The existence and location of the Helendale fault in Canyon C is demonstrated by a series of linear troughs, tonal contrasts, ponded alluvium and side hill benches.

Figure 6: Photo looking south from channel bed. Older alluvial fan gravels in fault contact with bedrock comprised of Paleozoic dolomite. Graben formed with apparent up to the west and up to the east displacement. Exposure us approximately 3.5 meters in height. Location: T5N, R2W, Sec 12 (SW corner); 34.5345°N, 117.0487°W.

Figure 7: Photo looking east from topographic break between mountain front and alluvial fan on east side of Fairview Valley. Apparent up to the east bedrock fault scarp exposed (denoted by black arrows) that truncates older alluvium found on both sides of the fault. Location: T5N, R2W, Sec 13 (NE corner); 34.5280°N, 117.0413°W.

Fifteenmile Valley Quadrangle

The existence and location of the Helendale fault extending from canyon B (Plate IIc) is demonstrated by scarps, shutter ridges, and right laterally deflected drainages. However, this strand may be decreasing in activity to the south. It is progressively less apparent in Quaternary alluvium to the south and cannot be located with certainty at about 0.4 kilometers north of where its trend would intersect with Cove Road. In contrast, the existence and location of the branch of the Helendale fault that extends from canyon C (Plate IIc) is demonstrated by linear features including side hill benches, right laterally deflected drainages and ponded alluvium (Plate IIc, location 22; Figure 8). Linear features in Quaternary alluvium include east-facing scarps, tonal contrasts and vegetation lineaments. This eastern trace appears to become the main trace of the Helendale fault that extends south into Lucerne Valley.

Figure 8: Photo looking west at the Granite Mountains where the eastern branch of the Helendale fault enters Canyon C (Plate IIc). Location: 34.5034°N, 117.0117°W; Image: NASA, dated 01/01/2015, viewed in Google earth.

Lucerne Valley Quadrangle

The Granite Mountains terminate where they intercept a broad piedmont with landforms comprised of alluvial fans, alluvial washes and inselbergs that form on the north flank of the San Bernardino Mountains. From northwest to southeast, the Helendale fault crosses the broad alluvial plain of Sunset Cove (Plate IIc). The existence and location of the Helendale fault in this area is expressed as east-facing scarps, tonal contrasts and vegetation lineaments. The trace of the Helendale then traverses the margin of an outlying ridge of the Granite Mountains, roughly paralleling Cove Road and the margin of Lucerne Lake. Here the fault trace is expressed as a

series of scarps, side hill benches, and aligned notches. The fault continues south from this ridge into an area where alluvial, lacustrine and eolian processes have modified the landscape. The existence and location of the Helendale is expressed as a series of springs, east facing scarps, side hill benches and vegetation lineaments for over 2 km. These features are bounded by a flood control channel on the east that partially obscurres fault related features. South of CA-18, the fault trace is concealed by active alluvial fan deposits for about 2.7 km. However, several tonal contrasts appear in MASTER imagery that suggest the fault may be present in the shallow subsurface (Plate IId, location 29). Where the fault trace crosses Meridian Road, it forms a linear ridge with attendant tonal contrasts and right laterally deflected drainages. This trace, along with an accompanying western parallel strand, is visible in 1953 USDA imagery, LiDAR (to a lesser degree) and within the Hi-Grade Materials aggregate quarry east of Meridian Road. East of the quarry, the Helendale is strongly expressed in an unnamed ridge that extends northwest from the San Bernardino Mountains range front. The aforementioned western parallel strand bounds the western side of the unnamed ridge and is expressed as a series of scarps, opposing drainages, aligned notches and right-laterally deflected drainages (Plate IIe, locations 30, 31 and 33). The expression of faulting is concealed in alluvial washes on the western margin of the ridge. The eastern trace of the Helendale forms a deep linear canyon through the nose of the ridge, then trends toward the eastern flank of the ridge where it is expressed as a series of scarps and aligned notches and springs (such as the Box S Spring; Plate IIe, location 34). From about the latitude of Box S Spring, the western and eastern traces of the Helendale appear to interact with faults of the North Frontal Fault Zone.

Lucerne Lake Fault

The Lucerne Lake fault forms a parallel trace to the Helendale, extending from the north side of the playa, near Venada Road, to the south side of the playa near Gobar Road (Plate IIc and IId). The existence and location of this fault is demonstrated by tonal contrasts and lineaments in distal alluvial fan and playa deposits (Plate IIc, locations 24 and 25); an eroded scarp at the base of a northwest trending ridge in the middle of the Lucerne playa; and, tonal lineaments in playa deposits at the south end of the Lucerne Lake. CGS is not aware of documentation on the connection, or lack thereof, between the Lucerne Lake fault and the Helendale fault.

Cougar Buttes Quadrangle

Within the southwest corner of the Cougar Buttes Quadrangle the surface trace of the Helendale extends toward Cushenbury Springs. Faulting is expressed as scarps, aligned springs and tonal lineaments. Several scarps and lineaments in this area trend nearly perpendicular to the northwest trending Helendale fault, suggesting interaction between the Helendale and the North Frontal Fault system.

CONCLUSIONS

The Helendale Fault zone extends approximately 75 kilometers from the Kramer Hills in the north to Cushenbury Springs at the southern end of Lucerne Valley. The fault

is thought to be primarily right-lateral strike-slip with up to 2 km of total slip. Several overlapping strands result in folds and uplifted ridges. The most recent calculated slip rate of 0.8 +/- 0.3 mm/yr is based on offset alluvial fan surfaces and drainages at the southern end of Turtle Mountain (Oskin et al., 2008). Bryan (1995) found evidence for three ruptures since about 16.5 ka, with the most recent event occurring post 2.3 ka. As discussed by Manson (1986), the Helendale fault is well defined at the surface from Cushenbury Springs to just north of I-15. However, as noted by Manson (1986) and Askoy (1986), segments of the Helendale fault are concealed in young alluvium within the Fairview and Lucerne Valleys.

Within the northernmost portion of the evaluated area, the Helendale fault is expressed as a single strand, from northern Fairview Valley to the southern margin of the Fairview Valley playa. South of the playa, fault complexity increases with apparent right steps from the main trace. Drainages issuing from the eastern range front are disrupted and right-laterally offset. These disrupted drainages, shutter ridges, wind gaps, and ponded alluvium delineate the active strand of the fault. Taking this interpreted active strand into account, the distance between the western and eastern strand is nearly 1.5 kilometers. Fault complexity continues south from Fairview Valley through the drainage divide with Lucerne Valley. The western strand is nearly continuous through northwest trending bedrock ridges that show right laterally deflected drainages, scarps, aligned notches and opposing drainages, but appears to lose expression in Quaternary alluvium of Sunset Cove. In contrast, the parallel eastern strand in Fairview Valley is discontinuous through the Granite Mountains. It becomes continues feature within a linear canyon (Canyon C, Plate IIc), marked by tonal contrasts, linear troughs, ponded alluvium, side hill benches and saddles. This eastern strand enters Sunset Cove and is continuously expressed in Quaternary alluvium as a series of scarps, tonal contrasts, vegetation and tonal lineaments. Because the western strand appears to die out and the eastern strand is strongly expressed, this suggests an eastward stepover. The fault trace continues southeast along the western margin of Lucerne Lake, traversing an outlying ridge of the Granite Mountains. Surface expression along this segment includes scarps, side hill benches, aligned notches and tonal contrasts. As the fault enters the alluvial plain to the south, overlapping strands occur in the vicinity of Rabbit Springs. Surface expression of faulting include scarps, tonal lineaments and aligned springs. Bryan and Rockwell (1994) excavated a fault trench northwest of the intersection of Kendall Road and Rabbit Springs Road, finding that Holocene age lacustrine deposits were warped along the trend of a mapped lineament. They attributed the warping to a rupture event along the Helendale. Southeast from Rabbit Springs to State Route 18, the surface trace of the Helendale is expressed as a geomorphic monocline, with an uplifted plateau on the west, bounded by an east-facing linear scarp with aligned springs, side hill benches and vegetation lineaments. This feature loses expression north of State Route 18 where the fault is concealed in active alluvial fan deposits. However, several tonal contrasts on MASTER imagery extend from State Route 18 toward the High-Grade aggregate quarry on Meridian Road. The Helendale fault is exposed in the walls of the High-Grade quarry as

a western and eastern trace. The western trace is expressed as a series of scarps and tonal contrasts in Quaternary alluvium and opposing drainages, aligned notches and right-laterally deflected drainages within the northwest trending ridge to the south. The eastern trace is strongly expressed as scarps, a deep linear canyon with opposing drainages, right-laterally offset drainages, side hill benches, aligned notches and tonal contrasts. As the eastern strand approaches Cushenbury Springs, it forms an east facing scarp with aligned springs within alluvial fan deposits of Pleistocene age. As both the western and eastern strand approach the North Frontal Fault Zone the trend of fault related geomorphic features become more easterly, suggesting that there is strong interaction between the NFFZ and the Helendale fault system.

The connection between Helendale fault and the Lucerne Lake fault is unknown, however, the existence of the Lucerne Lake fault is demonstrated by the presence of scarps, tonal and vegetation lineaments in deposits of Pleistocene and Holocene age.

RECOMMENDATIONS

Recommendations for establishing Earthquake Fault Zones are based on the criteria of "sufficiently active" and "well-defined" (Bryant and Hart, 2007). Recommended traces to be included in the Helendale APEFZ are shown on Plates IIIa-e.

The Helendale fault was previously reviewed by Manson (1986) and was determined to be sufficiently active and well-defined from Brisbane Valley in the north (north of I-15) to Cushenbury Springs in the south. This current study reevaluates the Helendale from the northern end of Fairview Valley to the southern end of the Lucerne Valley. Based on the interpretation of aerial photographs, LiDAR data, stereo ADS-40 imagery and MASTER imagery, several areas of unrecognized fault complexity exist within the evaluated area. These include fault-related scarps in the Quaternary alluvium within the southeastern Fairview Valley and a western strand of the fault expressed as a series of scarps, opposing drainages, and tonal contrasts within, and along the base of the northwest trending ridge adjacent to Meridian Road in southern Lucerne Valley. Identification of additional fault traces sub-parallel to the main trace along the entire length of the fault evaluated herein was made possible by the use of detailed sub-meter resolution topography and sub-meter resolution ADS 40 stereo imagery. The previously zoned traces, shown in black on Plates Ia through Ie have been reviewed and revised as necessary based on new information. All additional traces and those included or revised from the original zoned traces, considered sufficiently active and well-defined, are shown on Plates IIIa through IIIe.

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PG 7692, CEG 2379
November 16, 2015

reviewed
recommendations approved
Chris J. Hill

AERIAL PHOTOGRAPHS AND IMAGERY USED

United States Department of Agriculture (USDA)

1952 Flight AXL-20K black/white 9”x9” scale 1:20,000, frames 179, 180, dated: 11/28/52

1952 Flight AXL-21K black/white 9”x9” scale 1:20,000, frames 29-31, dated: 11/28/52

1952 Flight AXL-22K black/white 9”x9” scale 1:20,000, frames 108-110, dated: 12/11/52

1952 Flight AXL-23K black/white 9”x9” scale 1:20,000, frames 93-95, 167-169, dated: 12/15/52

1953 Flight AXL-25K black/white 9”x9” scale 1:20,000, frames 34-38, 195-198, dated: 1/9/53

1953 Flight AXL-43K black/white 9”x9” scale 1:20,000, frames 48-51, dated: 2/16/53

1953 Flight AXL-47K black/white 9”x9” scale 1:20,000, frames 33-35, dated: 2/22/53

United States Bureau of Land Management (BLM)

1978 Flight CAHD77-7-28 black/white 9”x9” scale 1:30,000, frames 11-14, dated: 7/5/78

1978 Flight CAHD77-8-29 black/white 9”x9” scale 1:30,000, frames 7-10, dated: 7/5/78

1978 Flight CAHD77-8-30 black/white 9”x9” scale 1:30,000, frames 6-10, dated: 7/5/78

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North West Geomatics Ltd. and Fugro Earthdata, Inc., 2005, Digital stereo imagery flown for the USDA National Agriculture Imagery Program (NAIP), approximate ground sample distance (GSD; aka pixel dimension) 0.81 to 0.87 meters:

Image line L106182046 (Frames 7 and 8), flown 6/04/2005

Image line L106191911 (Frames 8 through 10), flown 6/19/2005

Image line L106182035 (Frames 6 through 9), flown 6/18/2005

Image line L108231657 (Frames 5 through 7), date unknown

MASTER Imagery:

MASTER which is the acronym for MODIS/ASTER Airborne Simulator records 50 spectral bands ranging from the visible to the thermal region of the electromagnetic spectrum with bandwidths ranging from 0.04 to 0.70 µm and spectral resolution of 5 to 50 meters (Hook et al., 2000). The MASTER data (Southern California Faults Special Project) is downloadable from the JPL/NASA website (http://masterweb.jpl.nasa.gov/).

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TOPOGRAPHIC MAPS

U.S. Geological Survey: Apple Valley North Quadrangle 1970, 7.5-minute series (1:24,000) (photo revised 1993); Fifteen Mile Valley Quadrangle 1993, 7.5-minute series (1:24,000); Fifteen Mile Valley Quadrangle 1971, 7.5-minute series (1:24,000) (photo revised 1975); Lucerne Valley Quadrangle 1971, 7.5-minute series (1:24,000) (photo revised 1994); Cougar Buttes Quadrangle 1971, 7.5-minute series (1:24,000) (photo revised 1994).

DIGITAL ELEVATION DATA

Earth Scope LiDAR (Survey Date: 04/02/2007 - 04/26/2007): Material is based on services provided to the Plate Boundary Observatory by NCALM (http://www.ncalm.org). PBO is operated by UNAVCO for EarthScope (http://www.earthscope.org) and supported by the National Science Foundation (No. EAR-0350028 and EAR-0732947). Acquired March 2015 (Average point density 4.61 pts/m^2; raster resolution 0.5 m)

NCALM LiDAR (Survey Date: 11/01/2003): LiDAR data acquired by the National Center for Airborne Laser Mapping on behalf of Dr. Mike Oskin (UC Davis) and Dr. Lesley Perg (University of Minnesota) as part of their National Science Foundation funded-project (No. EAR-0337263): Testing tectonic geodesy from fault slip rates across the eastern California shear zone. Acquired March 2015 (Average point density 1.67 pts/m^2; raster resolution 0.5 m)

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