Mapping landforms with applications to geomorphology and earthquake geology

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Introduction

Active faulting may be investigated using multiple methods which can be separated into different measured quantities over different length scales and over different time scales. Geodetic methods (GPS and InSAR) might be used to measure the interseismic strain accumulation over several years to decades or to characterize the coseismic motion in a single earthquake. Seismology may measure short term (at most decades) strain release via the distribution and magnitude of earthquakes in a region. On the other end of time scales of investigation (10^5-10^6 yr), geologic relationships may be used to record the total deformation in a region. In between, the landscape may record deformation over intermediate time scales (10^2-10^4 yr). This is the time scale over which to see most fault sources active, but also over which we don't expect significant structural evolution.

These two exercises take advantage of high resolution topography (~1m/pix) from airborne lidar mapping and age dating of markers to explore the record of deformation in the landscape. The student will gain practical experience examining spectacular tectonic landforms along a strike-slip fault (Wallace Creek) and an active fold over a blind reverse fault (Wheeler Ridge) from two classic areas along the San Andreas Fault System in California (see location map).

The exercises have a brief introduction to the location goals of the activity followed by a list of tasks. The tasks are best done in pairs or small groups and students should draw and annotate the indicated figures. We have made a rough estimate of the time required for each task.

Location map showing Wallace Creek and Wheeler Ridge situation within south-central California. Los Angeles is at the southeast portion of the map area.

I. Mapping the San Andreas Fault (SAF) near Wallace Creek California

Rarely are tectonic landforms as well expressed and dated as they are at Wallace Creek along the San Andreas Fault in south-central California (Figure I.1). In the area surrounding Wallace Creek are examples of most of the classic geomorphic features of strike-slip faults (Figures I.2 and I.3). These landforms were noted by numerous geologists through the early and mid 1900s as indicating horizontal motion along the SAF. The seminal work at the site was by Sieh and Jahns, 1984 and Sieh and Wallace, 1987.

Goals--After completing this exercise, you should have these basic skills:

- Use large scale aerial photography, topographic maps, and other topographic data to delineate landforms.
- Identify tectonic landforms along a strike-slip fault system and estimate offsets if appropriate.
- Interpret simple logs of excavations (trenches) to determine the ages of landforms.
- Estimate the slip rate along the San Andreas Fault and consider the implications for earthquake timing.

Tasks

Using the aerial photographs, topographic maps, and trench logs provided (see Figures I.3-I.6), please do the following (best done in pairs). Use Figure I.4 to do your mapping and make your measurements and notations:

1. Familiarize yourself with the major landforms (look at Figure I.2 for ideas) of the area and discuss them with your colleague. [10 minutes]
2. Using the suggested mapping symbology (and others you might need to supplement—Figure I.5), delineate the major geomorphic elements of the area. Try to keep the delineation as descriptive as possible without interpreting history. Don't put the fault(s) in yet--do it after you mapped the features (next step). Emphasize the area shown in Figure I.4--note that it has a 0.5 m contour interval. [20 minutes]
3. Looking at Figure I.2, neatly label the major features that you have mapped and discuss with your colleague. Feel free to label other features of interest and map the SAF. It does not have to be a single line. [10 minutes]

Look for landforms and structures such as

- Beheaded drainages
- Offset drainages
- Sags
- Shutter ridges
- Scarps
- Different terrace levels (hint: look for terraces preserved near deeply incised channels)
- Fault traces

4. Looking at Figures I.3 and I.4 and your mapping, measure several offsets, including the one for the main Wallace Creek channel and record your measurements and calculations in the table. Using the trench logs from Figure I.6, determine the age of the two surfaces that were cut by the trenches. Use the table below. If you assume they date the last deposition in the beheaded channel, how do they constrain the age of the active channel? [20 minutes].

Upstream feature (type/location)	*Downstream feature (type/location)*	*Offset measurement (m)*	*Age (Years BP)*	*Slip rate (offset/age)*

5. What sources of error must be considered in the offset channel measurements you made and in the estimates of offset rate? [10 minutes total]

6. If you look to the southeast of the main Wallace Creek offset, there are some small offsets that hopefully you noticed (?). How much are they offset? They are inferred to have formed in the last major earthquake here which was 1857. Given the slip rate you calculated, how long would it take to accumulate the slip that was released in 1857 here?

If you assume that the next earthquake might recur after the same amount of slip has accumulated as was released in the last earthquake, when would you expect the next to occur? How valid is that estimate for earthquake hazard assessment?

Acknowledgments
The Wallace Creek exercise presented here is based on earlier versions developed by Jeri Young, Ramón Arrowsmith, and Roland Bürgmann starting in 2003 for the International Quality Network paleoseismology courses at the University of Potsdam. Encouragement from and discussions with Manfred Strecker and Angela Landgraf have been helpful in its further refinement. Development of the current version was partially supported by the STRATEGY project at Potsdam University.

The B4 Lidar Project collected lidar point cloud data of the southern San Andreas and San Jacinto Faults in southern California. Data acquisition and processing were performed by the National Center for Airborne Laser Mapping (NCALM) in partnership with the USGS and Ohio State University through funding from the EAR Geophysics program at the National Science Foundation (NSF). Optech International contributed the ALTM3100 laser scanner system. UNAVCO and SCIGN assisted in GPS ground control and continuous high rate GPS data acquisition. A group of volunteers from USGS, UCSD, UCLA, Caltech and private industry, as well as gracious landowners along the fault zones, also made the project possible.
https://doi.org/10.5069/G97P8W9T. Processed at and downloaded from http://www.opentopography.org/.

References
Bevis, M., Hudnut, K., Sanchez, R., Toth, C., Grejner-Brzezinska, D., Kendrick, E., … Coloma, F. (2005). The B4 Project: Scanning the San Andreas and San Jacinto Fault Zones. *American Geophysical Union, Fall Meeting 2005, Abstract #H34B-01*.

Sieh, K. E., & Jahns, R. H. (1984). Holocene activity of the San Andreas fault at Wallace Creek, California. *Geological Society of American Bulletin*, *95*, 883–896.

Sieh, K. E., & Wallace, R. E. (1987). The San Andreas Fault at Wallace Creek, San Luis Obispo County, California. In M. L. Hill (Ed.), *Geological Society of America Centennial Field Guide--Cordilleran Section* (pp. 233–238). Boulder, Colorado: Geological Society of America.

Vedder, J. G., & Wallace, R. E. (1970). Map showing recently active breaks along the San Andreas and related faults between Cholame valley and Tejon Pass, California. U.S. Geological Survey Miscellaneous Geologic Investigations Map I-574, scale 1:24,000.

Figures for Wallace Creek exercise

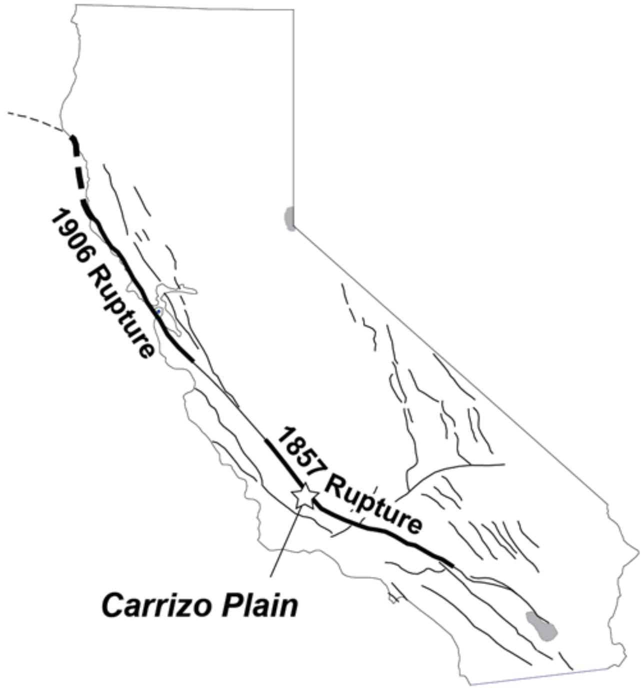


Figure I.1*. Location map.*

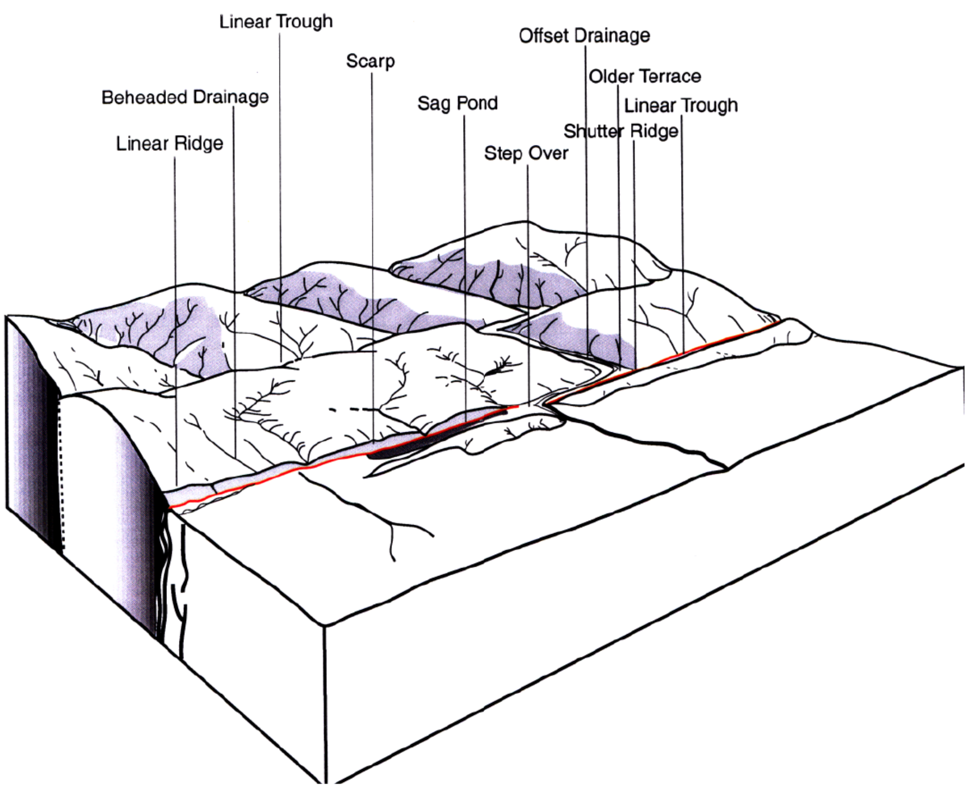


Figure I.2*. Block diagram showing landforms produced along recently active strike-slip faults (modified from Vedder and Wallace, 1970 by Jeri Young).*

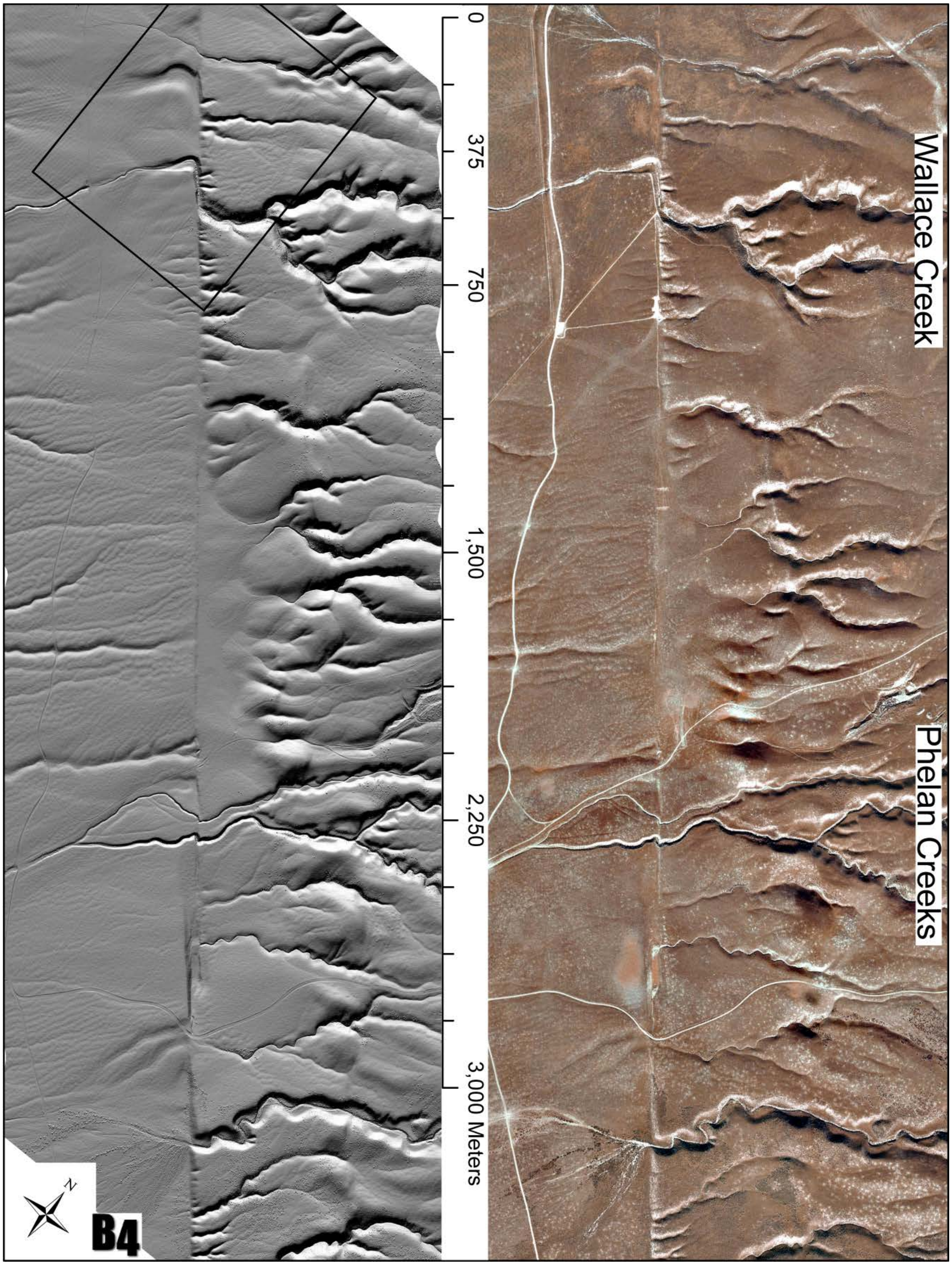
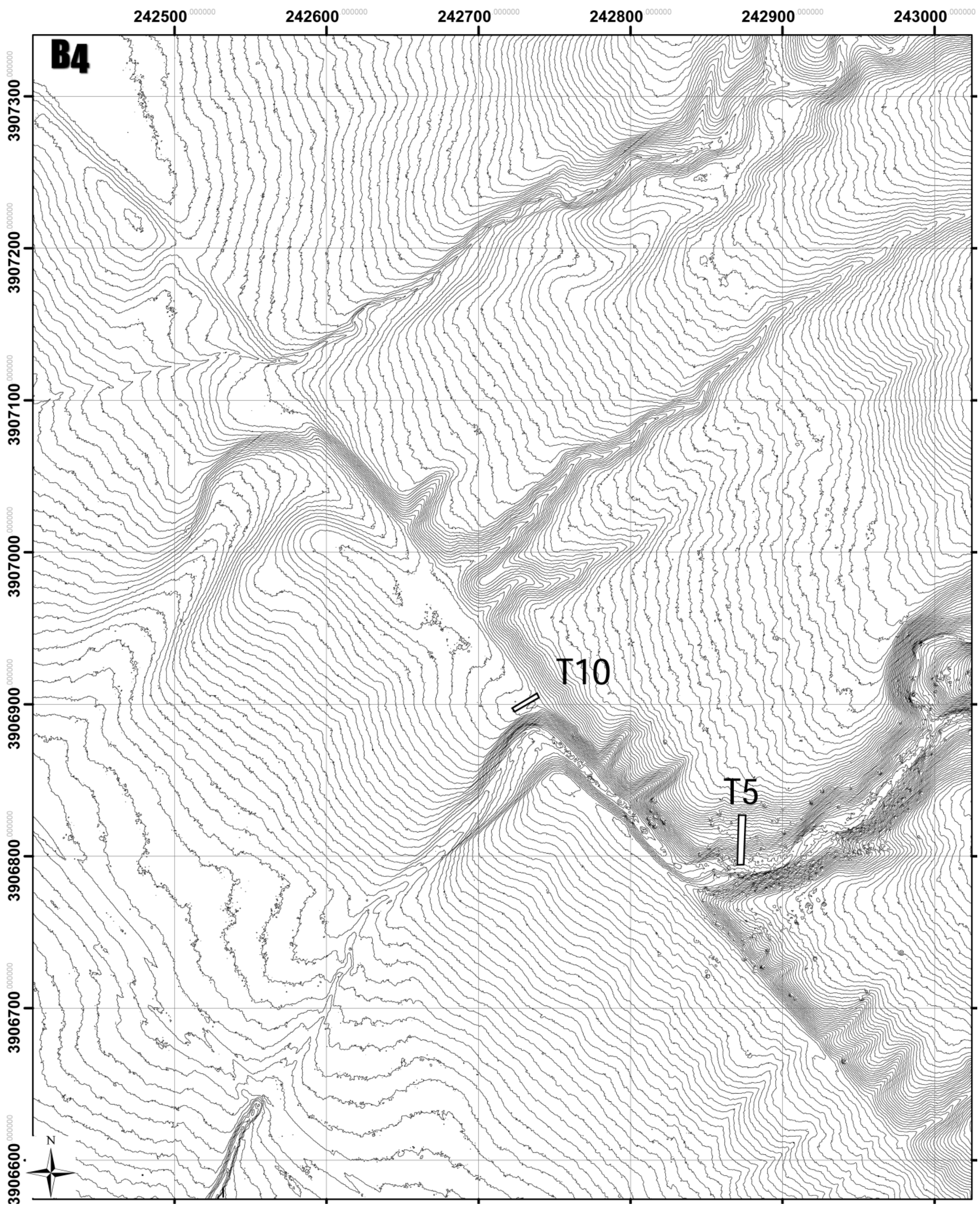
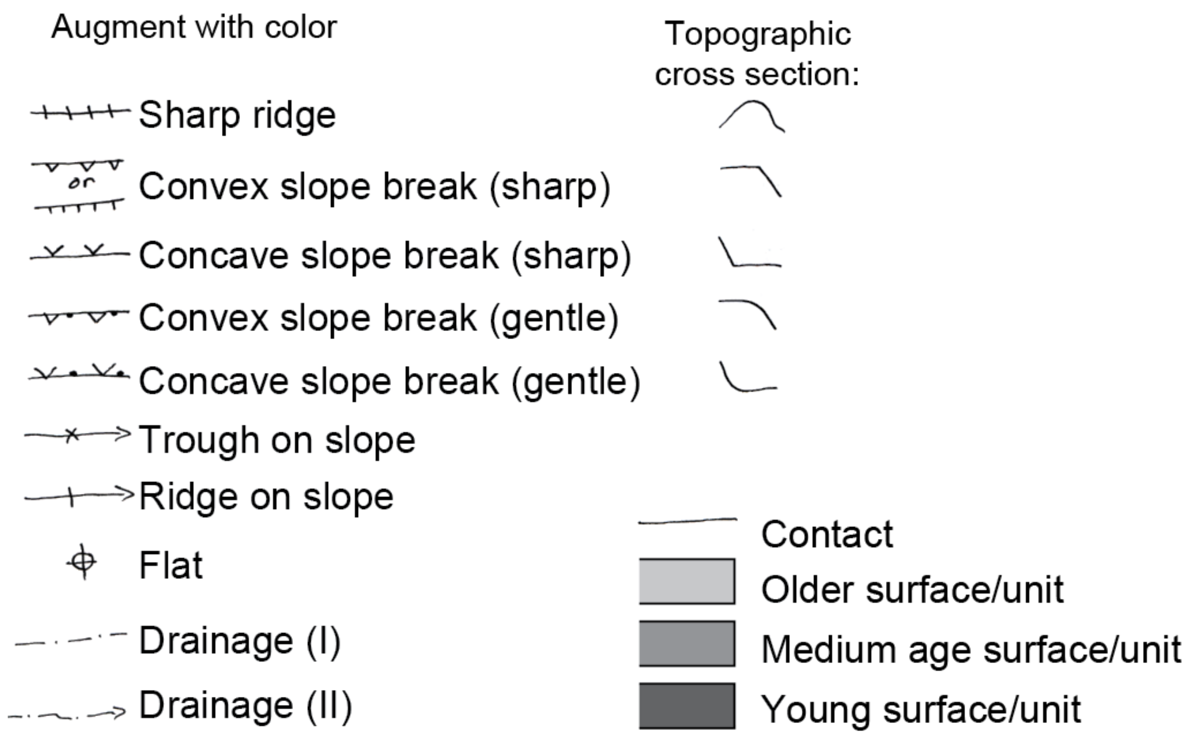


Figure I.3. *Wallace Creeks to Phelan Creeks B4 lidar topography (Bevis, et al., 2005; hillshade illuminated from the northwest) and aerial photographic data (US BLM). Box on northwest end of hillshade indicates location of Figure I.4. Sieh and Wallace, 1987 present a field guide to this portion of the San Andreas Fault.*


B4
242500
242600
242700
242800
242900
243000
3907300
3907200
3907100
3907000
3906900
3906800
3906700
3906600
T10
T5
N

*Previous page: **Figure I.4**: 0.5 m contour interval topographic map of the area around Wallace Creek. Note the larger offsets (~100s m) and the small ones (to the southeast ~10s m). The locations of T5 and T10 (Figure I.6; Sieh and Jahns, 1984) are indicated. The surrounding grid is 100 m interval UTM zone 11 WGS84. Data are from the B4 survey of the southern San Andreas Fault (Bevis, et al., 2005) processed at http://www.opentopography.org/. See Figure I.3 for location. Draw and label your features on this map.*

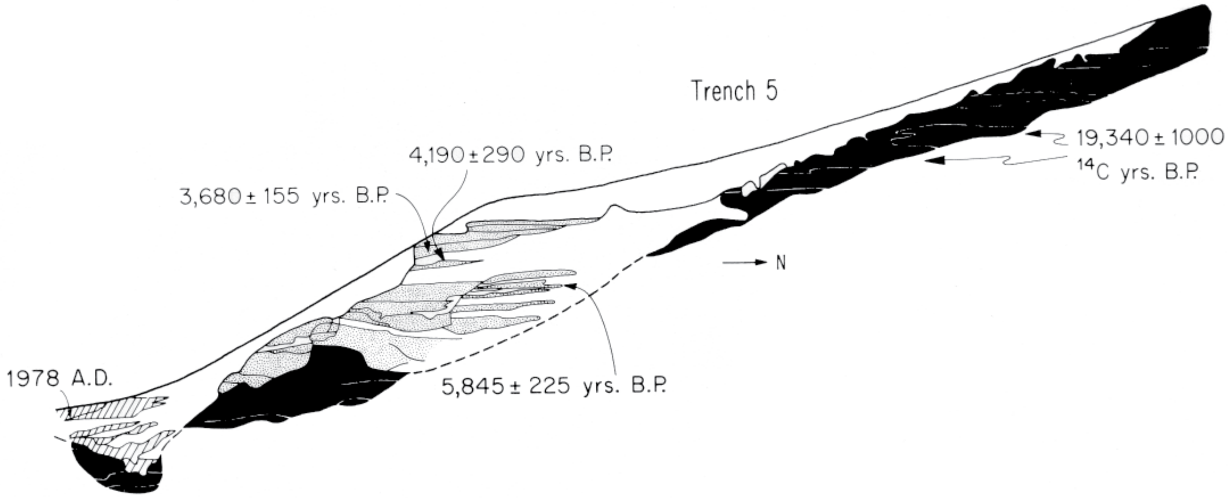


Line work guided by topographic breaks

Line work only

Additional interpretation (valley floor) and fault zone

***Figure I.5**: Suggested morphologic mapping symbology. Use this mapping "language" to indicate the positions and extents of the morphologic elements that comprise the landforms. Feel free to create new ones as you need; just be consistent and put it on an explanation for the map. Use colors where you can for emphasis. The lower sequence of images shows an example of the mapping in the northwest portion of Figure I.4.*



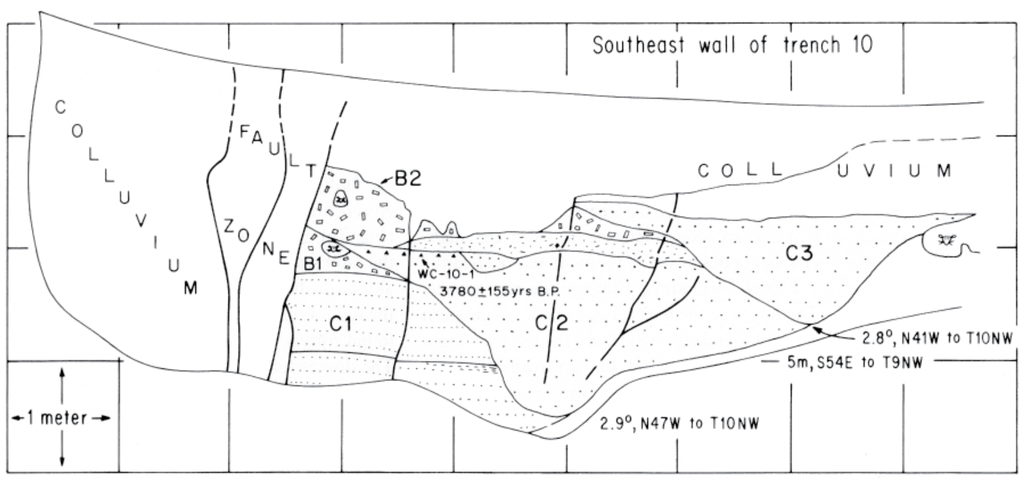


***Figure I.6**: Logs from trenches 5 and 10 from Sieh and Jahns 1984. Use these ^{14}C ages to estimate the time of <u>last</u> deposition of these materials and hence the ages of the surfaces they are associated with. Note their locations on Figure 3. Units B1-B2 are scarp derived colluvium. C1-C3 are fluvial sands and gravels.*

II. Examining an uplifting landscape: Wheeler Ridge, California
(developed in collaboration with Emily Kleber)

Evidence of surface uplift due to active folding is unsual. It is well manifest at Wheeler Ridge in south-central California (Figures II.1-3). The landscape shows the interaction between north flowing drainages and the eastward propagating, progressively uplifting fold (Figures II.2-3). As the fold lifts, the original fan is eroded as the surface processes respond to the increase in relief. Wheeler Ridge has been the subject of numerous studies. Shelton, 1966 presented oblique aerial photography documenting key landforms (Figure II.2). Keller, et al., 1998 presented the seminal geomorphology and initial Quaternary age control. Most recently Kleber, 2015 completed a study examining the classic features with a fresh high resolution view enable from new high resolution topography and new geochronologic results. In this activity, we use the mapping and approach from Kleber, 2015 in combination with the published age control for landforms on Wheeler Ridge.

Goals--After completing this exercise, you should have these basic skills:

- Use high resolution topographic data to delineate tectonic landforms over an active fold.
- Given ages of deformed landform elements, estimate the surface uplift rate where possible.
- Interpret the pattern of fold growth.

Tasks

Using the aerial photograph, topographic and geomorphic maps as well as the geochronology table provided (see Figures II.2-II.6 and Table II.1), please do the following (best done in pairs). Use Figure II.5 to do your mapping and make your measurements and notations on Figure II.6:

1. Familiarize yourself with the major landforms (look at Figure II.2 for ideas) of the area and discuss them with your colleague. [10 minutes]
2. Using the features indicated on the oblique aerial photo of Figure II.2, label the same and additional interesting landforms on the southward view of Figure II.3 (e.g., wind gap, water gap, deflected drainage, paleo fan, modern fan, etc.). *Note: a water gap is a narrowed valley still able to convey drainage while a wind gap is a formerly active drainage pathway (most likely a water gap).* [10 minutes]
3. Using the suggested mapping symbology (and others you might need to supplement—Figure II.4), delineate the major morphologic elements of the area. Try to keep the delineation as descriptive as possible without interpreting history. [20 minutes]
4. Looking at your labeling of features on II.3, neatly label and name the major geomorphic features that you have mapped on Figure II.5 and discuss with your colleague. Feel free to label other features of interest and map the fold axis as defined by this geomorphology. [10 minutes]
5. Figure II.6 shows the paleofan surfaces as mapped by Keller, et al., 1998 and modified by Kleber, 2015. The units increase in relative age from Q1 (modern-Holocene) to Q5 (late Pleistocene). Comparing with your morphologic mapping on Figure II.5, what simple topographic and geomorphic evidence supports their interpretations? [10 minutes]

6. Adjacent to the Figure II.6 map are topographic profiles parallel (below) and perpendicular to the fold axis. They should be used to estimate the surface uplift (hint: use Q1 as the reference undeformed shape and measure the vertical distance to the current elevation of the paleosurface). Using the table below fill in the vertical uplift you have just measured and the age of the surface in kiloyears before present (Table II.1). Compute the vertical uplift rate for each surface.

Quaternary surface	*Surface uplift (m)*	*Surface age (ka)*	*Surface uplift rate (m/kyr)*
Q1			
Q2			
Q3			
Q4			
Q5			

7. Using the surface ages and the distance along the fold (parallel profile on Figure II.6) compute the horizontal propagation rate of the fold (hint. Assume that the tip of the fold is now at Q1 on the parallel topographic profile and that it was in an equivalent position at the time of activity—the age—of the other surfaces).

Quaternary surface	*Horizontal distance (m)*	*Surface age (ka)*	*Horizontal propagation rate (m/kyr)*
Q1			
Q2			
Q3			
Q4			
Q5			

Acknowledgments
Development of this exercise was partially supported by the STRATEGY project at Potsdam University. Emily Kleber's research was partially supported by the Southern California Earthquake Center.

Wheeler Ridge lidar data acquisition and processing completed by the National Center for Airborne Laser Mapping (NCALM). NCALM funding provided by NSF's Division of Earth Sciences, Instrumentation and Facilities Program. EAR-1043051. https://doi.org/10.5069/G99K485N. Processed at and downloaded from http://www.opentopography.org/.

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Keller, E. A., Zepeda, R. L., Rockwell, T. K., Ku, T. L., Dinklage, W. S., Barbara, S., & Street, G. (1998). Active tectonics at Wheeler Ridge , southern San Joaquin Valley , California. *Geological Society of America Bulletin*, *110*(3), 298–310.

Kleber, E. J. (2015) Surface Response to Slip Along a Propagating Blind Thrust Fault Wheeler Ridge, California. M.S. thesis: Arizona State University, 95 pp.

Shelton, J. S. (1966). Geology Illustrated. San Francisco: Freeman, 434 p.

Figures for Wheeler Ridge exercise

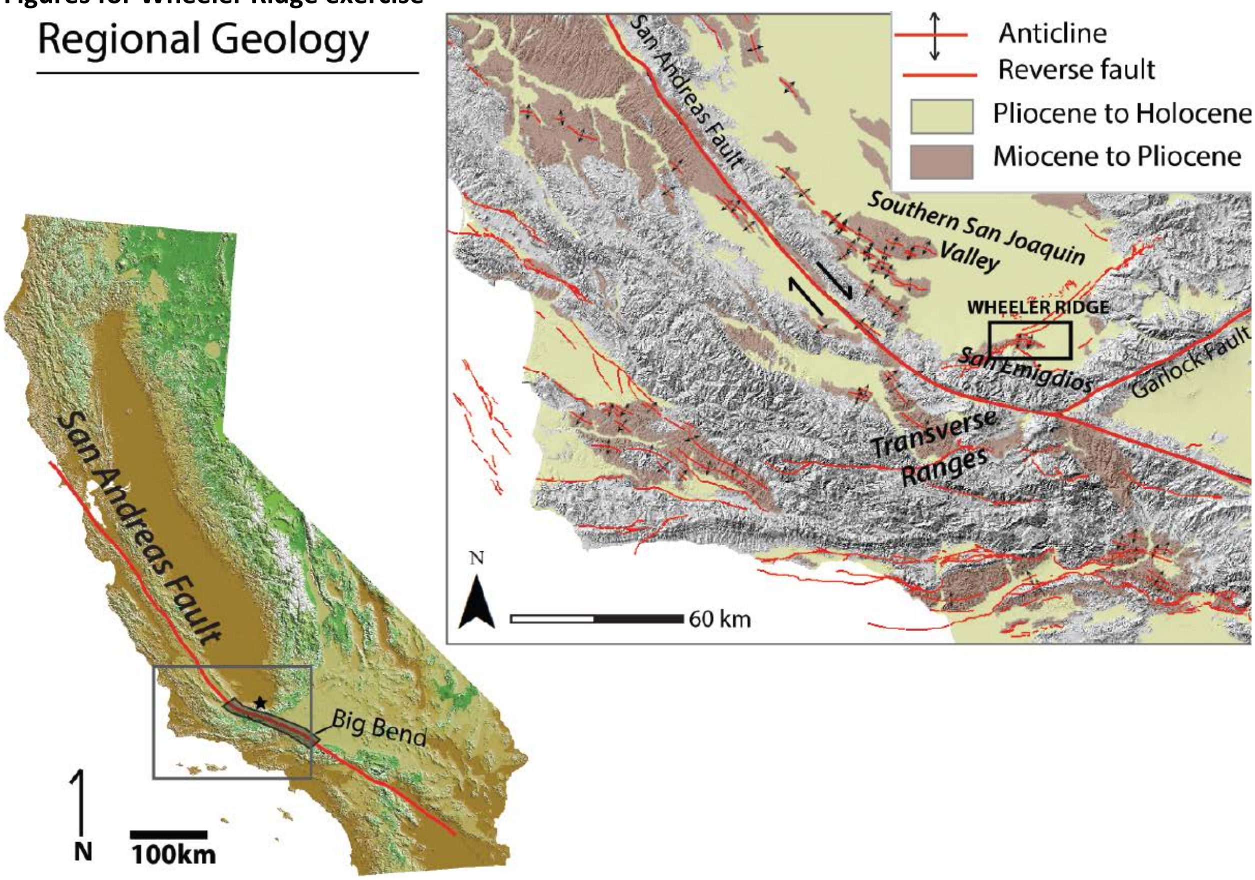


Figure II.1. *Location map and geologic setting for Wheeler Ridge. Regional tectonic setting is dominated by transpression north of the Big Bend in the San Andreas Fault, California. Bold black lines are reverse faults and folds that have been active in the Quaternary and deforming Miocene and younger sedimentary deposits. Our study focuses on Wheeler Ridge, which is part of the San Emigdio fold and thrust belt at the base of the San Joaquin Valley. Wheeler Ridge is a tectonic and geomorphic boundary separating the flat topography of the San Joaquin Valley from the faulted and uplifted San Emigdio Mountains to the south. The blind thrust tip of Wheeler Ridge is verging north and propagating east through ~4.5 km of Tertiary to Quaternary sediments deposited in the Southern San Joaquin Valley (from Kleber, 2015).*

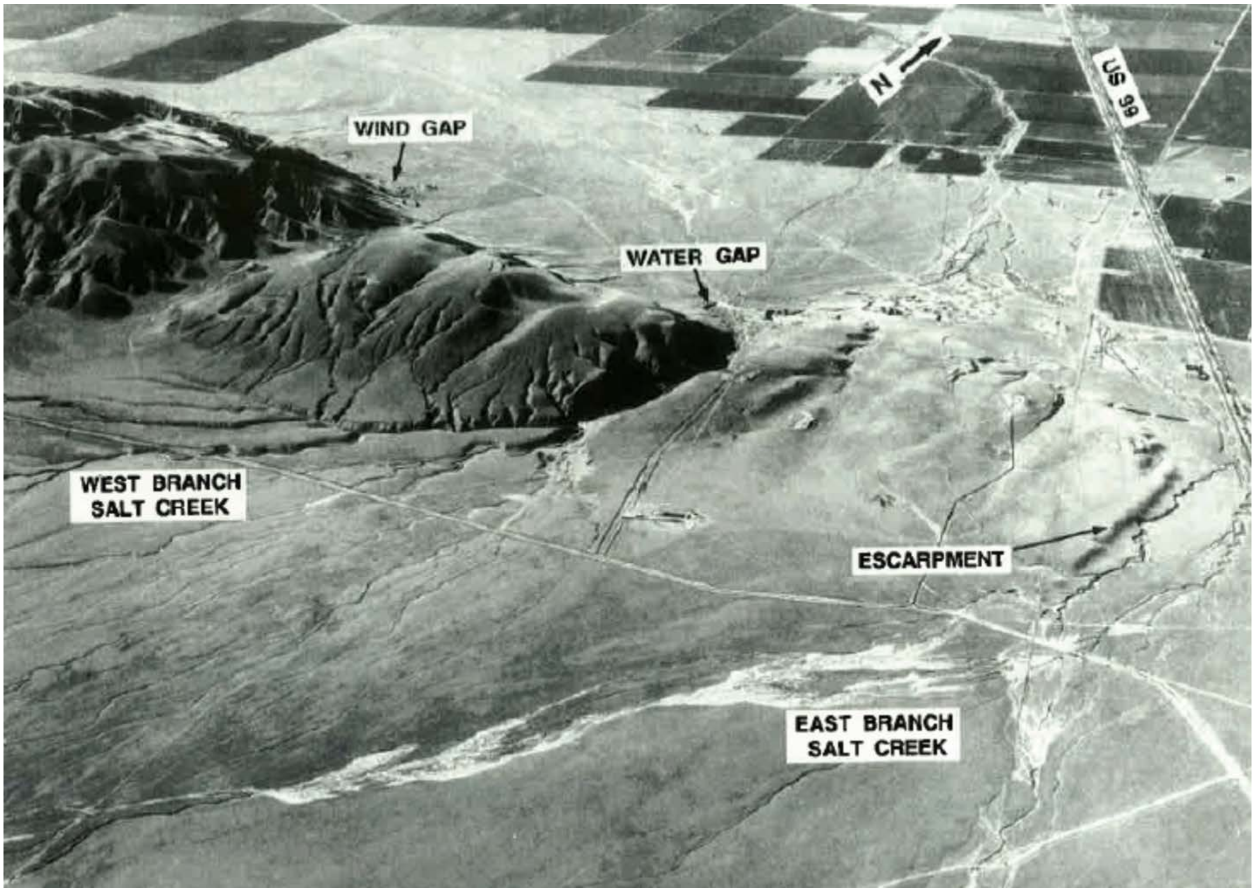


Figure II.2. *Low angle aerial photo from Shelton (1966) over the eastern portion of Wheeler Ridge pointing out the wind and water gaps and their positions relative to the northward flowing branches of Salt Creek. View to the northwest.*

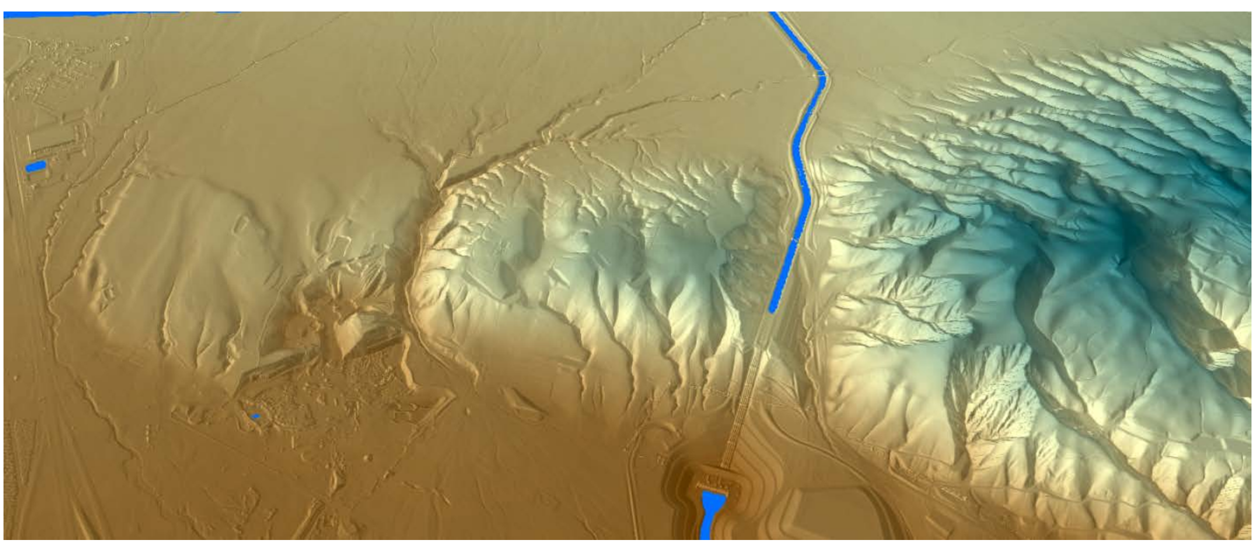


Figure II.3. *Oblique view to the south over the east end of Wheeler Ridge. Despite the anthropogenic modifications, numerous landforms indicating progressive uplift of the surface and disruption of the north flowing drainages are evident. Data are from 1 m digital elevation model (https://doi.org/10.5069/G99K485N).*

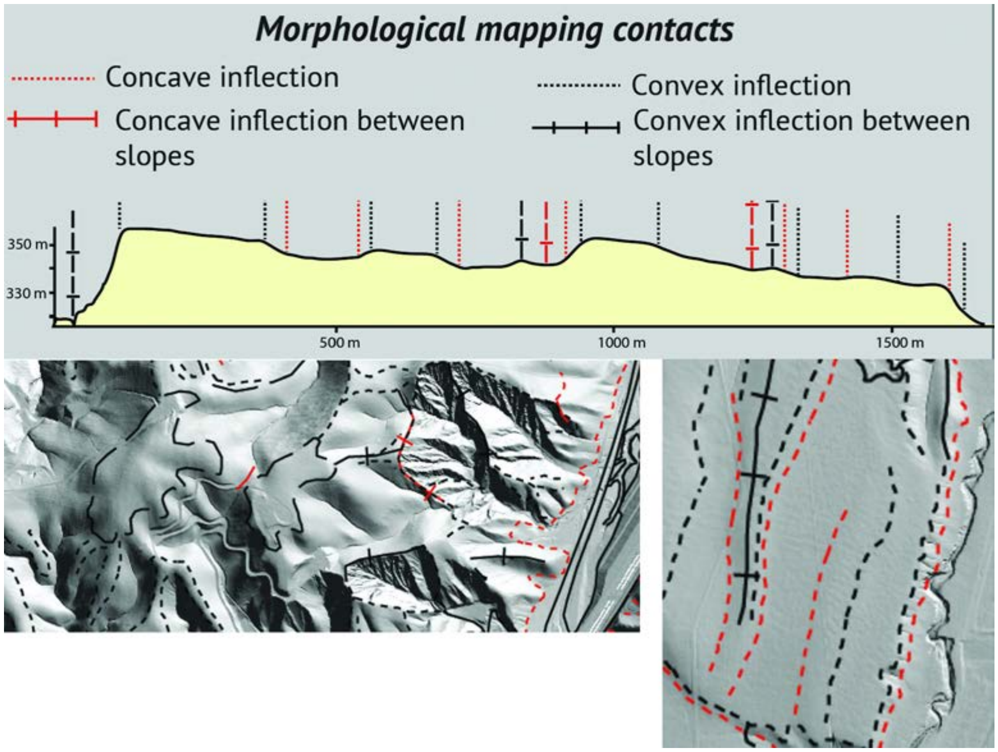
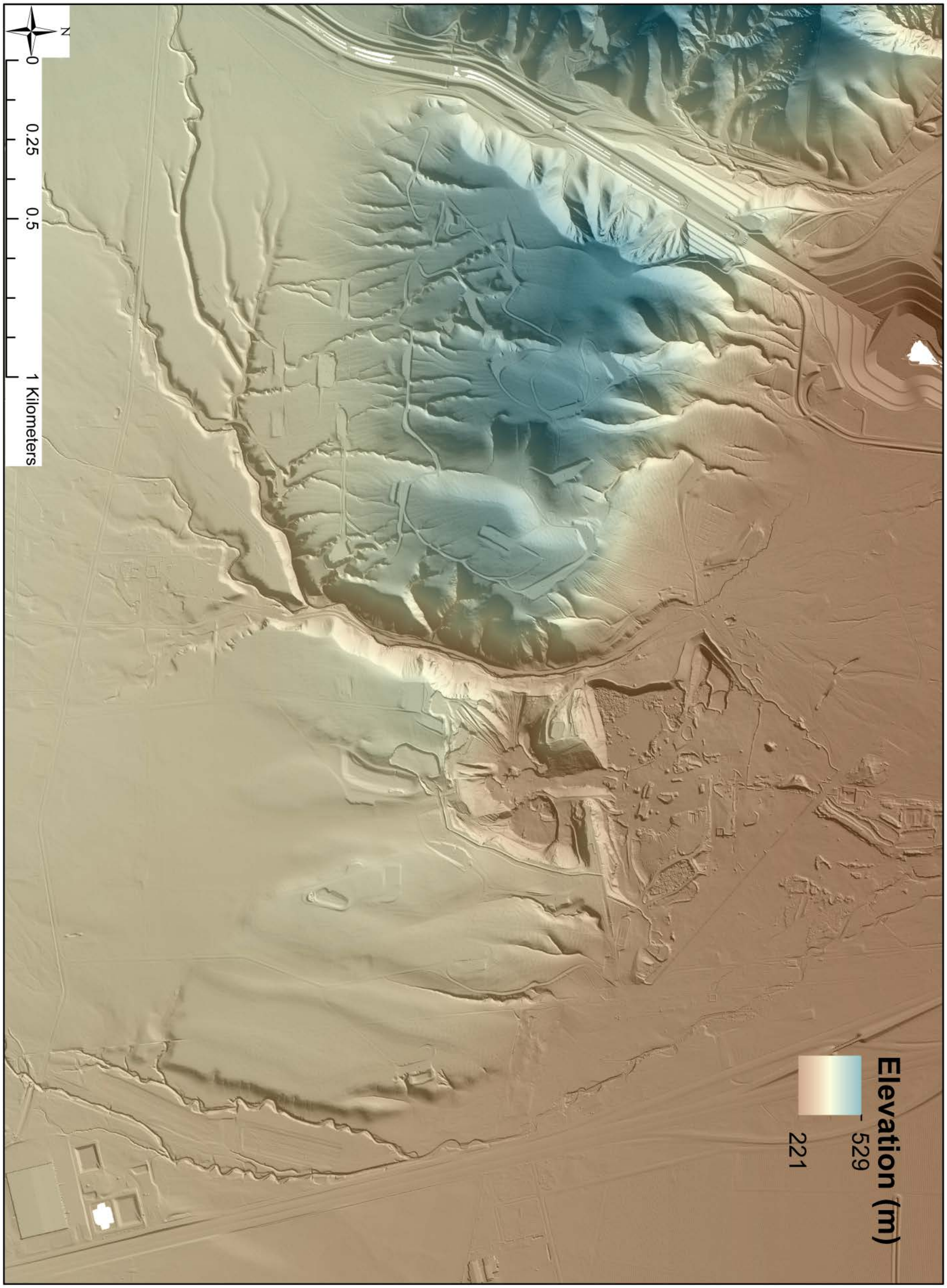
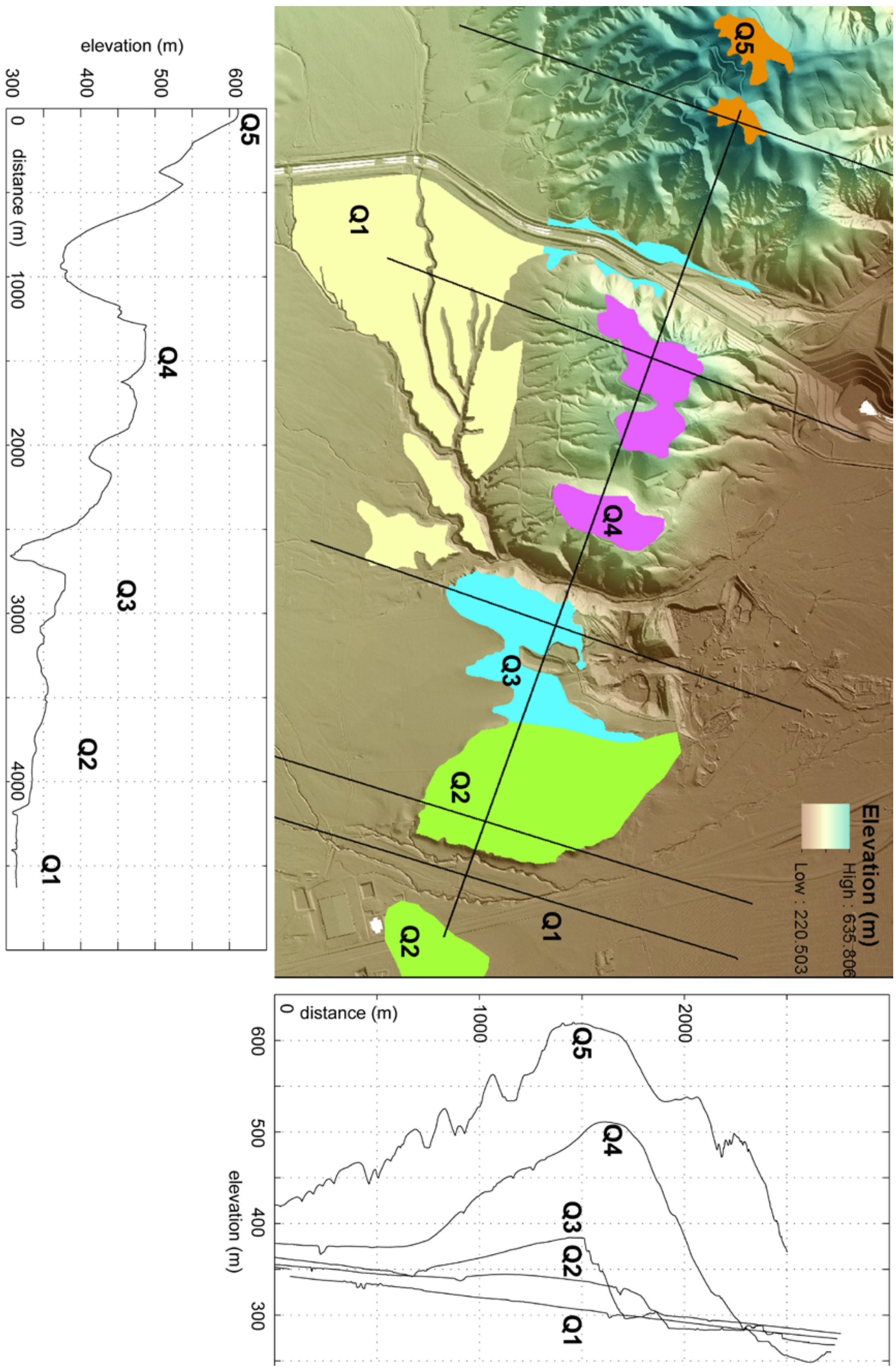


***Figure II.4**. Suggested morphologic mapping symbology. Use this mapping "language" to indicate the positions and extents of the morphologic elements that comprise the landforms. Feel free to create new ones as you need; just be consistent and put it on an explanation for the map. Use colors where you can for emphasis. The upper panel shows map and cross section views of the morphologic features while the bottom two panels provide examples. Modified from Kleber, 2015.*

*Next page. **Figure II.5**. Digital elevation model colored by elevation (see scale) with artificial shading (illuminated from the northwest). Draft your morphologic mapping (Figure II.4) on this map. Use the blank space on this page for an explanation. Label the principal landforms (e.g., wind gap, water gap, paleo fan surface, modern fan, etc.). Data are from 1 m digital elevation model (https://doi.org/10.5069/G99K485N)*

Explanation of symbols and colors:


N
0
0.25
0.5
1 Kilometers
Elevation (m)
529
221


Elevation (m)
High : 635.806
Low : 220.503
Q1
Q2
Q3
Q4
Q5
elevation (m)
distance (m)

Previous page. ***Figure II.6****. Digital elevation model colored by elevation (see scale) with artificial shading (illuminated from the northwest). Colored polygons show extents of paleo-fan units with increasing relative age Q1 (modern-Holocene) to Q5 (late Pleistocene). See Table II.1 (Approximate age of deposits). The adjacent topographic profiles parallel (below) and perpendicular can be used to estimate the surface uplift (hint: use Q1 as the reference undeformed shape). Profile locations are indicated by black lines on the map.*

Table II.1*: Wheeler Ridge chronosequence (from Keller, et al., 1998). Approximate age of deposits information is needed for the exercise.*

WHEELER RIDGE SOIL CHRONOSEQUENCE

Geomorphic surface*	Solum thickness (m)	B Horizon Type	Moist color†	Texture	Structure	Clay films	Carbonate stage§	Approx. elevation (m)	Approximate age of deposits (ka)
Q1	0.5–0.8	AC to Cambic B	10YR 3/3	Sandy to sandy loam	Primary fluvial stratification to massive	None	Weak I	295–299	Holocene#
Q2	2.4+	Argillic	10YR 4/4	Sandy loam	Moderate coarse subangular blocky	Many thin and moderately thick on pebble-matrix interfaces	I–III	318–335	17**
Q3	2.7+	Argillic	10YR 4/4	Loam to sandy loam	Weak medium subangular blocky	Many moderately thick on pebble matrix interfaces	II–III	335–378	60††
Q4	3.1+	Argillic	7.5YR 4/6	Sandy loam	Massive breaking to fine subangular blocky	Continuous thick on pebble-matrix interfaces	III	425–500	105 or 125§§
Q5	N.A.	B horizon stripped and/or engulfed by carbonate					Strong IV	600–650	185##

Note: N.A.—not available.
*We assume that the geomorphic age is approximately the age of the deposits.
†Color terms follow Munsell Color Company (1975) notation.
§Carbonate stage terms follow Gile et al. (1966) and Bachman and Machette (1977).
#Based on soil development and ^{14}C.
**Based on ^{14}C and uranium-series.
††Based on extrapolation of fold propagation and soil development.
§§Based on uranium series.
##Based on rate of fold propagation—may be as old as 400 ka.