Map of Topographic Lineaments Interpreted as Recent Surface Ruptures from Faulting and Distributed Deformation along the Bennett Valley and Southern Maacama Fault Zones, Sonoma County, California

By Suzanne Hecker

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Cover. Photograph of a tree growing on the fault scarp along the Spring Valley strand of the Bennett Valley fault zone, view to the north. U.S. Geological Survey photograph taken by Suzanne Hecker.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
yard (yd)	0.9144	meter (m)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)

Map of Topographic Lineaments Interpreted as Recent Surface Ruptures from Faulting and Distributed Deformation along the Bennett Valley and Southern Maacama Fault Zones, Sonoma County, California

By Suzanne Hecker

Introduction

This study documents lidar-illuminated topographic lineaments interpreted as evidence of recent surface fault ruptures and surface ruptures related to distributed deformation along the Bennett Valley Fault Zone and the southernmost Maacama Fault Zone in the northern San Francisco Bay area (fig. 1, on map sheet). Together, these fault zones form a structural connection across a right stepover between the main Maacama Fault Zone and the Rodgers Creek Fault, overlapping principal strands of the San Andreas plate boundary system north of San Francisco Bay (figs. 1, 2, on map sheet) that accommodate about a quarter of the ~40 millimeters per year of regional dextral tectonic slip (Parsons and others, 2013).

Although much of the Bennett Valley Fault Zone is seismically active (McLaughlin and others, 2012; Sowers and others, 2010), only the north end of the fault zone (the "Spring Valley strand," indicated on southern map panel of map sheet and labeled "D" in figure 2, on map sheet) was previously known to have youthful geomorphic expression and to displace Holocene deposits (McLaughlin and others, 2008; Sowers and others, 2010; Sowers and others, 2016). Holocene activity along the length of the Bennett Valley Fault Zone and southernmost Maacama Fault Zone, with possible implications for rupture propagation, continuity, and slip transfer, had not been identified. However, fault splays that project eastward from the Rodgers Creek Fault have been mapped and hypothesized to accommodate slip transfer to the Bennett Valley Fault Zone (Hecker and Randolph Loar, 2018). The generally subtle and distributed nature of surface-rupture evidence along the Bennett Valley and southernmost Maacama Fault Zones, and extensive vegetation cover, had left recent faulting previously unmapped along most of the zone.

The map presented here represents a new compilation of inferred surface-rupture features detected using high-resolution topographic lidar data from an airborne lidar survey of Sonoma County, California (OpenTopography, 2014). These data, which enable subtle topographic features to be discerned, indicate that recent (likely Holocene) surface ruptures extend throughout the Bennett Valley and southernmost Maacama Fault Zones.

The rupture-lineament map was created using a GIS (geographic information system) framework and is included herein as an image map at a scale of 1:36,000 and as digital datasets (included as supplemental information to this report). The mapping is intended to lay the groundwork for future studies designed to better characterize how plate-boundary slip is accommodated on this important and complex system of faults.

Approach and Scope

This study identifies topographic lineaments interpreted as surface fault ruptures and distributed off-fault deformation from visual inspection of lidar-derived aerial images (for example, figs. 3–5, on map sheet). Hillshades, slopeshades, and slope and elevation maps of the region encompassing the Bennett Valley and southernmost Maacama Fault Zones were generated using a 3-foot bare-earth digital elevation model (DEM) from a high-density (13.7 cloud points and 2.8 ground points per square meter) 2013 airborne lidar survey of Sonoma County (OpenTopography, 2014). The various terrain representations provided a more complete depiction of the geomorphology associated with faulting. A hillshade with low (30°) sun-angle illumination from the northeast was advantageous for viewing lineaments within these generally north–northwest striking fault zones, whereas a hillshade with low sun-angle illumination from the northwest proved to be useful where rupture-lineament orientation is transverse to the overall zone. Three-dimensional aerial and satellite imagery hosted on Google Earth (available at https://www.google.com/earth/versions/#earthpro) in areas without tree canopy provided additional evidence of surface ruptures.

Lidar mapping of recently active traces of the Rodgers Creek Fault (Hecker and Randolph Loar, 2018), which used the same high-resolution airborne lidar dataset as this study, facilitated identification of similar, though generally subtler, topographic lineaments having characteristics consistent with recent surface ruptures along the Bennett Valley and southernmost Maacama Fault Zones. The geomorphic features targeted in this study, although generally not as well defined, also bear some resemblance to historical surface ruptures, such as those produced by the M_w 6.0 2014 South Napa Earthquake (Ponti and others, 2019) and visible in post-earthquake lidar topography (OpenTopography, 2015). The fine-scale topographic lineaments observed and mapped in this study are interpreted to reflect mainly Holocene activity, appearing to not have been severely degraded by surficial processes.

This map presents topographic features interpreted as produced by tectonic shear deformation; however, the map does not differentiate primary fault rupture from secondary (off-fault) ruptures related to bulk deformation of the shallow crust. Although geomorphic features that exhibit characteristics diagnostic of landslides were generally not mapped, lineaments that appear to be at least partly the result of gravitational ridge spreading (fig. 3*B*, on map sheet) are included on the map. These lineaments are semi-continuous with probable tectonic surface ruptures and therefore may have been driven from below by tectonic displacement. Landsliding is extensive in some areas and may have contributed locally to the formation of ruptures identified as tectonic. Fault traces that can be reasonably inferred from larger-scale geomorphic expression (such as valley-margin linearity) or from continuity with mapped ruptures, but that lack small-scale topographic evidence of recency, were omitted from the map.

This map is designed to capture the spatial extent of surface ruptures but does not fully resolve ruptures that diverge and extend beyond the study area (dashed outlines on map and fig. *2*, on map sheet), delimited to encompass the main zones of surface ruptures. Not uncommonly, such strands project toward and in some cases coincide with other Quaternary faults (as identified in U.S. Geological Survey and California Geological Survey, 2022), indicating that these faults too may have experienced Holocene activity. Mapping extends ~50 kilometers (km) from the south end of the Bennett Valley Fault Zone north to where latest Quaternary activity was previously recognized on the Maacama Fault Zone (fig. 2, on map sheet). The Knights Valley Fault Zone converges with the Maacama Fault Zone from the east at the northern boundary of the map (fig. 2, on map sheet), and, together with the collinear Franz Valley Thrust, it was used to delimit the extent of mapping in this area, where the zone of identified surface ruptures is particularly broad and densely distributed.

A classification scheme is systematically applied to surface-rupture strands in the GIS database based on their observed characteristics (tables 1 and 2). Surface rupture is classified by clarity of expression (well, moderate, or poor) and by the likelihood it resulted, directly or indirectly, from tectonic shear deformation (high, moderate, or low confidence); the latter category is represented on the image map. Surface ruptures mapped from lineaments with particularly subtle topographic expression and (or) uncertain origins are typically assigned a “low” confidence. Uncertain, low-confidence strands may include those that are relatively short and isolated, have a discordant or crosscutting orientation, and (or) can be reasonably attributed to landsliding or to differential erosion along bedding planes or older faults in bedrock identified on geologic maps or interpreted from the lidar topography. The observed geomorphic evidence, along with possible non-rupture interpretations, is described in the attribute table, though typically in a cursory manner.

The attribute table includes a field for how closely the mapping represents the location of rupture (either “accurately located” to within ~20 meters [m], or “approximately located” to within ~60 m), which also indicates the maximum width of the zone of observed features (tables 1 and 2). Another field indicates if the mapped rupture appears to be part of a broader, more diffuse zone of rupture not represented by additional mapping. Surface ruptures that coincide with a previously mapped fault, or ruptures that cross a mapped or lidar-observed landslide are noted in the attribute table comments. When combined, the Mark West Spring 7.5’ quadrangle (McLaughlin and others, 2004), the Napa and Bodega Bay 30’ x 60’ quadrangles (compiled by Wagner and Gutierrez, 2017), and the Healdsburg 7.5’ quadrangle (Delattre, 2011) cover the study area and provide a complete picture of previously mapped faults and other geomorphic features.

Table 1. Surface Rupture Mapping Attribute Fields

Field Name	Field Description
FID	Unique record identifier*
Shape	Feature geometry*
FltName	Fault name**
QFltID	Fault identification number**
FtrDescrip	Description of rupture features
FtrClarity	Clarity of features (well, moderately, or poorly expressed)
FtrCom	Comment on feature origin and clarity
RupConf	Rupture confidence (high, moderate, or low confidence)
RupLocCert	Location certainty (accurately or approximately located)
RupZoneWid	Width, if part of broader zone (30-60 m; 60-100 m; >100 m)
RupLocCom	Comment on location certainty and context

*internal to Esri ArcGIS (Esri, 2020)

**adopted from U.S. Geological Survey and California Geological Survey, 2022

Table 2. Representative Examples of Attribute Records

Field Name	Value	
	Example 1	Example 2
FID	171	5
Shape	Polyline	Polyline
FltName	Maacama fault zone, southern section	Bennett Valley fault zone
QFltID	30b	229
FtrDescrip	subtle topographic lineaments	sharp topographic lineaments (mainly base of steep slope below ridgeline and narrow subtle benches); closed depression
FtrClarity	poorly expressed	well expressed
FtrCom	north end is better expressed and located (possible drainage feature?)	<Null>
RupConf	low confidence	high confidence
RupLocCert	approximately located	accurately located
RupZoneWid	<Null>	<Null>
RupLocCom	lies near toe of mapped landslide	<Null>

Geomorphic Evidence of Surface Ruptures

The geomorphology of ruptures within the Bennett Valley and southernmost Maacama Fault Zones is broadly consistent with lateral shear, although vertical motion is evident on some strands (for example, likely compression or transpression along the north flank of the Sonoma Mountains [fig. 5*A*, on map sheet] as well as transtension along the north-south-trending Spring Valley strand [labeled on southern map panel of map sheet]). Vertical offsets in areas of topographic relief may also reflect a component of gravitational deformation. The most conspicuous, and highest confidence, surface-rupture lineaments consist of relatively linear and continuous features that cut across topography, commonly expressing small landforms such as scarps, sidehill benches (uphill-facing scarps), and linear troughs (figs. 3*A* and 4*A*, on map sheet). Such lineaments commonly show abrupt along-strike and across-fault changes in slope and aspect, as would be expected from lateral juxtaposition of discordant landscape elements. Other lineaments have discernable en echelon or zigzag configurations (the latter interpreted as likely linked en echelon steps and restraining bends) indicative of lateral slip or have somewhat sinuous or anastomosing geometries (figs. 3*B* and 4*C*, on map sheet). Zones of anastomosing lineaments may represent overlapping assemblages of Riedel-type shears and other subsidiary fractures. Most surface ruptures, however, were interpreted simply from continuity of inflections in slope apparent in the lidar terrain and are described generically as topographic lineaments.

Drainage channels clearly offset by faulting are relatively uncommon along the Bennett Valley and southernmost Maacama Fault Zones at the scale of individual mapped strands (example shown in figure 3*C*, on map sheet). This apparent lack of offset drainages likely has to do with the distributed nature of slip, coupled with slope and erosional processes that affect the evolution of channel bends. However, large-scale drainage disruption is apparent along the southernmost Maacama Fault Zone, particularly along Mark West Creek and its tributaries (fig. 6, on map sheet). Small drainages (mainly ravines and gullies) and shallow local landslides have developed where ruptures cut across sloping terrain (fig. 3*A*, on map sheet); these common forms of erosion may also mask or mimic the presence of rupture, hampering mapping accuracy.

Distribution and Pattern of Recent Surface Ruptures within the Bennett Valley and southernmost Maacama Fault Zones

Mapping of fine-scale topographic lineaments reveals that the entire length of the Bennett Valley and southernmost Maacama Fault Zones has experienced recent (likely Holocene) rupture, illuminating a surface connection between the Rodgers Creek Fault and the main Maacama Fault Zone. The assemblage of lineaments inferred to be rupture-related is broad and complex, up to ~4–7 km wide, and locally wider than the previous representation of these Quaternary faults (fig. 2, on map sheet). About half of the mapped strands have been classified as either moderate or high confidence, with a distribution similar to the overall zone, and appear to demarcate multiple pathways of slip accommodation.

The southern portion of the Bennett Valley Fault Zone permeates and bounds the Sonoma Mountains (labeled in figure 6, on map sheet), a large-scale topographic feature that lies on the northeast side of a broad 16° left-restraining bend in the Rodgers Creek Fault. The complex network of surface ruptures in this area, which includes transverse and radial geometries, and its spatial association with substantial relief and seismicity indicate that the Sonoma Mountains are being actively uplifted and internally deformed, and moreover that they manifest a long-term process of contractional deformation. Large, deep-seated landslides have developed on the west side of the range (labeled in figure 6, on map sheet) where rupture is particularly complex and links to the Rodgers Creek Fault. The disordered and discontinuous nature of surface ruptures in this area is suggestive of landslide activity as well as tectonic deformation. Farther south, strands of the Bennett Valley Fault Zone converge with the Rodgers Creek Fault at low angle, and at its southern terminus, the Bennett Valley Fault Zone lies adjacent and subparallel to the Rodgers Creek Fault.

Surface ruptures along the northeastern side of the Sonoma Mountains broadly follow an intramountain ridge, where gravitational ridge spreading is evident, and continue to the northwest as a relatively narrow and locally well-expressed zone that climbs the steep southwest flank of Bennett Mountain (peak labeled in figure 6, on map sheet). This zone connects with the north-south-trending Spring Valley strand, previously identified as having Holocene activity (McLaughlin and others, 2008; Sowers and others, 2010; Sowers and others, 2016). Newly mapped rupture lineaments, mostly short (<0.5 km long), poorly defined and scattered, appear to be a southward extension of the Spring Valley strand and join a better-defined rupture lineament that branches northward from the Rodgers Creek Fault. To the north, where the Spring Valley strand projects across the highly urbanized Rincon Valley, geomorphic evidence of surface faulting is subdued and discontinuous.

Northward from this low-lying area, the Bennett Valley Fault Zone transitions to the southernmost Maacama Fault Zone (U.S. Geological Survey and California Geological Survey, 2022) and resumes a northwesterly strike. The southernmost Maacama Fault Zone traverses the moderate-relief terrain of the Mayacamas Mountains; the rupture zone is at least 3 km wide throughout this area. This broad "rupture corridor" has a moderately developed topographic grain defined by northwest-trending ridgelines and drainages (apparent on slopeshade elevation map; fig. 6, on map sheet). Surface ruptures are more densely distributed north of where the rupture zone makes a slight westward bend north of Porter Creek Road. This bend occurs approximately where a west northwest-striking undifferentiated Quaternary fault, the Petrified Forest Thrust (labeled "C" in figure 2, on map sheet), intersects the southernmost Maacama Fault Zone from the east. The configuration of mapped ruptures in this area is locally complex and includes narrow zones of transverse (west northwest- to southwest-trending) strands, some extending beyond the southernmost Maacama Fault Zone (such as along the western section of the Petrified Forest Thrust; identified on northern map panel of map sheet) and others bounding sets of short northwest-trending strands. The latter geometric arrangement indicates that small-scale block rotation, possibly augmented by landsliding, may be contributing to the complexity of surface rupture. The fabric of recent faulting near the southern terminus of the southernmost Maacama Fault Zone is similarly influenced by west northwest-striking Quaternary faults that continue eastward beyond the limits of the study area; some of these faults have been identified as being part of the Maacama Fault Zone (thicker line-weight strands near ~38° 30' N; fig. 2, on map sheet).

Implications for Rupture in Individual Earthquakes

The interpreted lineament dataset presented herein is a composite record of many spatially overlapping surface-rupturing earthquakes that have likely occurred over the past several thousand years and longer. Surface expression of any one earthquake is presumably geographically extensive and complex but does not reach the breadth or density of mapped lineaments (which includes lower confidence features that may not be ruptures). Original rupture traces were likely more continuous than represented by mapping, owing to discontinuities in preservation and truncations caused by recurrent faulting.

An important hazard implication of this mapping is the potential size of earthquakes on the Bennett Valley and southernmost Maacama Fault Zones. The complexity and distributed nature of surface ruptures indicate that geometric, structural, or rheological impediments may limit rupture propagation and confine earthquakes to portions of the zone. Larger earthquakes involving the main Maacama Fault Zone or Rodgers Creek Fault could possibly nucleate or terminate here. Additionally, ruptures could involve other contiguous faults beyond the study area. Future investigations employing geomorphic field studies, paleoseismology, and diverse geophysical datasets are needed to elucidate past rupture patterns and the factors that may control rupture propagation. Also, further work, including detailed field mapping, may allow primary fault ruptures to be distinguished from secondary ruptures and from primarily gravity-driven ground deformation. The extensive geomorphic evidence presented in this study indicates that the Bennett Valley and southernmost Maacama Fault Zones are an active avenue of slip transfer between more discrete, regional-scale faults of the plate-boundary system.

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