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Map of Recently Active Traces of the Rodgers Creek Fault, Sonoma County, California

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Introduction

The accompanying map and digital data identify recently active strands of the Rodgers Creek Fault in Sonoma County, California, interpreted primarily from the geomorphic expression of recent faulting on aerial photography and hillshade imagery derived from airborne light detection and ranging (lidar) data. A recently active fault strand is defined here as having evidence consistent with slip during the Holocene epoch (approximately the past 11,700 years). The purpose of the map is to update the fundamental fault dataset for characterizing surface-rupture hazard, siting slip-rate and paleoseismic studies, and studying the geometry and evolution of slip. To serve a range of users, the map is presented in several formats: as an image map, as a digital database for use within a geographic information system (GIS), and as a KML file for visualizing the fault using virtual globe software.

Important outcomes of this mapping revision include the following: (1) a northward 17-km increase in the known length of Holocene-active faulting to include most of the Healdsburg Fault, a structural continuation of the Rodgers Creek Fault northwest of a bend in the fault at Santa Rosa; (2) first-time identification of fault strands across the Santa Rosa Creek floodplain in central Santa Rosa (Hecker and others, 2016); (3) increases in the known width and complexity of faulting; and (4) identification of fault splays that project toward the Bennett Valley-Maacama Fault system to the east and toward an active extension of the Hayward Fault to the south beneath San Pablo Bay, recently mapped by Watt and others (2016) and previously inferred from shallow microseismicity (Lienkaemper and others, 2012).

The Rodgers Creek Fault is a principal strand of the San Andreas Fault system north of San Francisco Bay (fig. 1, on map sheet) that accommodates 6–10 millimeters per year (mm/yr) of plate-boundary motion (Schwartz and others, 1992). The 30-year mean probability of a magnitude (M)$\geq$6.7 earthquake on the combined Rodgers Creek-Hayward Fault, estimated at 33 percent, is the highest among faults in the region (Field and others, 2015; Aagaard and others, 2016). The most recent surface-rupturing earthquake on the Rodgers Creek Fault was likely between 1715 and 1776 (Hecker and others, 2005), indicating that the elapsed time may have reached or exceeded the poorly constrained average recurrence of large earthquakes on the fault, estimated to be 130–370 years (Schwartz and others, 1992). More research is needed to clarify other aspects of the fault's behavior, such as timing of earlier events, lengths of earthquake ruptures, and amounts and distribution of displacement through time. Aseismic shallow fault slip, or creep, a phenomenon documented along many parts of the San Andreas Fault system in northern California, has been recognized along the Rodgers Creek Fault, from Santa Rosa northward, only relatively recently (Funning and others, 2007; Lienkaemper and others, 2014; McFarland and others, 2016; Jin and Funning, 2017).

Fault Nomenclature

The nomenclature of the Rodgers Creek Fault system has varied over time and with point of view. The fault north and south of Santa Rosa is shown on early fault-activity and geologic maps (for example, Brown, 1970; Huffman and Armstrong, 1980) as separate faults (the Healdsburg Fault and Rodgers Creek Fault, respectively), reflecting discontinuities in the geometry of faulting across the Santa Rosa Creek floodplain. However, other fault-activity maps and more recent publications have regarded the southern part of the Healdsburg Fault (southward from the vicinity of Windsor; fig. 2*A*, on map sheet) as part of the modern Rodgers Creek Fault because of the continuous nature of Holocene faulting (Herd and Helley, 1977; Jennings, 1994; Hart, 1998a, b; Working Group on Earthquake Probabilities, 2003; U.S. Geological Survey and California Geological Survey, 2006). Our revised mapping indicates that Holocene faulting is indeed continuous across the Santa Rosa Creek floodplain (Hecker and others, 2016) and extends along most (at least 80 percent) of the length of the Healdsburg Fault, as well as along the Rodgers Creek Fault south of Santa Rosa, suggesting that the two faults operate as a single, integrated seismic source. To reflect this new understanding, we herein refer to the Holocene-active fault in its entirety simply as the Rodgers Creek Fault and adapt the original nomenclature to refer to the sections of the fault north and south of Santa Rosa.

Approach and Scope

This publication builds upon prior mapping of recently active traces of the Rodgers Creek Fault by Hart (1982, 1992) and Bryant (1982), prepared under California's Alquist-Priolo program of fault-rupture hazard zoning (fig. 2*B*, on map

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[1] U.S. Geological Survey.

[2] Stantec Consulting Services, Inc.

sheet). These maps, prepared at a scale of 1:24,000, utilized existing fault mapping, interpretation of fault geomorphology from aerial photography, and limited field inspection to identify fault strands that are sufficiently active and well defined to meet the criteria of the Alquist-Priolo regulatory zones. We also consulted earlier (1970–1971) unpublished 1:24,000-scale mapping of recently active traces from the vicinity of Santa Rosa southward by R.D. Brown of the U.S. Geological Survey, as reproduced in Hart (1982, fig. 5*A*, *B*).

Similar to previous efforts, our mapping of the Rodgers Creek Fault relies largely on the interpretation of fault traces from remote sensing imagery. An aerial perspective is advantageous for identifying geomorphic features indicative of active strike-slip faulting, such as scarps, tonal lineaments, linear troughs and drainages, hillside benches, offset drainages, and closed depressions (fig. 3, on map sheet; also Wallace, 1990), and for judging the continuity of these features. For this latest effort, we checked, revised, and extended the existing mapping of the Rodgers Creek Fault primarily using hillshade imagery generated from a 3-ft bare-earth digital elevation model (DEM) derived from a high-density (13.7 points per square meter) 2013 airborne lidar survey of Sonoma County.[1] This dataset provided the best view of the geomorphology along the fault. We also used (1) 0.5- and 1.0-m-resolution hillshade imagery generated from airborne lidar collected in 2007 within an approximately 1-km-wide strip along the fault;[2] (2) stereographic inspection of low-elevation (1:6,000-scale), low sun angle, color aerial photography flown along the Rodgers Creek and southern Healdsburg sections of the fault for the U.S. Geological Survey (1991); (3) inspection of smaller scale (≤1:20,000-scale) aerial photography, including low sun angle, color photography (U.S. Geological Survey, 1973, 1974; California Division of Mines and Geology, 1976) that was utilized by Hart (1982 and 1992); (4) three-dimensional aerial imagery provided by Google Earth; and (5) field mapping along the southern quarter of the Rodgers Creek section of the fault (Randolph Loar, 2002; fig. 2*B*, on map sheet). Although field observations are important for verifying the faulting origin of some features, we were able to field check remotely mapped fault strands along only a few stretches of the fault. Future improvements to mapping will come from additional on-the-ground inspection of less-confidently identified features and incorporation of exploratory trench data from unpublished geotechnical reports. We generally limited the mapping area to the 1-km-wide swath of the 2007 lidar survey, as we found that this footprint includes most of the zone of distributed shear.

For this revision, we also incorporated faults identified from geologic mapping (fig. 2*B*, on map sheet) that are within or near the zone mapped as recently active. Geologically mapped faults provide a longer-term context for recent surface faulting and, despite lacking geomorphic evidence of recency, may have been active during the Holocene, as demonstrated by the 2014 *M*6 South Napa earthquake (DeLong and others, 2016). In places where the geomorphically mapped active traces lie in the vicinity of these framework faults, we generally show the latter only where they are farther than a few tens of meters from the more conspicuously active traces, although we note the spatial correspondence in the database attribute records of the mapped strands.

Database Structure and File Formats

The mapping data for this study is being released as GIS map layers to be viewed and queried using analysis software such as Esri ArcGIS or ArcReader. As with all GIS data, the reader must keep in mind the resolution limitations associated with the sources of data. For less technical applications, we are providing a KMZ (zipped Keyhole Markup Language) file of fault traces and data that may be viewed interactively in Google Earth and other similar software and a fixed image of the map at a scale of 1:36,000.

The basic structure of the digital database derives from guidelines developed for a prototype community fault map database for the San Francisco Bay area (Graymer, personal communication, 2004). The database design for the Rodgers Creek Fault includes attribute fields that record information related to fault-strand age and rank, geomorphic expression, location certainty, and mapping sources (table 1). We have not included site-specific data such as locations of fault-trench exposures. However, we identify in the attribute records the few fault strands that have been trenched for paleoseismic research (table 2) and some strands that have been trenched as part of the Alquist-Priolo program (mainly in Healdsburg).

Fault strands interpreted from geomorphic evidence of recent activity are assumed to be Holocene in age; geologically mapped faults that lack sufficient evidence of activity are regarded as potentially having been active in the Holocene. Fault strands described as accurately located in this study are estimated to be within 10 m of their true locations; mapped strands that are approximately located (the majority) are judged to be within 50 m of their true locations, although sections of these strands may be more accurately located. Holocene faults are reported as inferred where they are projected between geomorphically identified strands. In some places, a single mapped fault represents multiple strands visible on imagery but too closely spaced to feasibly map separately. Where this is the case, it is commonly noted in the comment field for location certainty (table 1). All of the geologically mapped faults not identified as recently activity are portrayed as approximately located (or inferred) to reflect uncertainty in the location of possible rupture during the Holocene. The lengths of digitized fault

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[2] This material is from the EarthScope Northern California Lidar Project, 2007 (https://doi.org/10.5069/G9057CV2) and 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).

Table 1. Fault-strand database attribute fields.

[Information includes fault-section name, fault-strand age estimate, location certainty, geomorphic expression, relative importance in accommodating slip, and source(s) of mapping]

Field name	Field description
FID	Unique feature identifier*
Shape	Feature geometry*
FltName	Fault section name
QFltID	Fault section identification number**
LocCert	Location certainty description (accurately located, approximately located, or inferred)
LocCertCom	Comment on location certainty
FltRank	Fault-strand rank [either part of (1) principal, (2) distributed, or (3) long-term displacement zone, or (4) questionable]
FltRankCom	Comment on fault-strand rank
FltAge	Age estimate (Holocene or potentially Holocene)
FltAgeCom	Comment on age estimate
FltMappBy	Citation for fault-strand mapping
FltMappCom	Comment on fault-trand mapping
FtrMapped	Geomorphic evidence of recent activity
FtrMappBy	Citation for geomorphic evidence
FtrMappHow	Method of observing geomorphic evidence
FtrMappCom	Comment on geomorphic evidence

*Internal to Esri ArcGIS

**Adapted from U.S. Geological Survey and California Geological Survey, 2006

Table 2. Fault strands trenched for purpose of paleoseismic study

Database fault-strand identifier (FID)	Study reference
Rodgers Creek section	
114	Budding and others (1991); Schwartz and others (1992)
186	Randolph Loar and others (2004)
192	Randolph Loar (2002)
205	Schwartz and others (1992); Hecker and others (2005)
429	Givler and Baldwin (2016)
613	Givler and Baldwin (2016)
Healdsburg section	
12	Swan and others (2006)

strands in the database are somewhat arbitrary or are inherited from source datasets.

A field for displacement hierarchy is included in the database (fault-strand rank; table 1). This parameter is intended to convey relative importance in accommodating slip and differentiates between strands that appear to be part of the principal displacement zone and those that form the remainder of the distributed displacement zone. We surmise that the latter may include older principal strands, as well as secondary strands and discrete off-fault deformation. Geologically mapped strands that lack geomorphic evidence of recency are indicated as being part of the long-term displacement zone. Strands mapped from features that are fault-like in appearance but whose origins are equivocal are given a rank of "questionable." Such equivocal features may be produced by ridge-top spreading (sackungen) or landsliding, by differential erosion along older faults or bedrock contacts, or by grading for roads. Because landslide scarps may resemble fault scarps, fault strands mapped through landslide terrain are commonly flagged as such in the comment field. Additional database documentation can be found in the metadata of the GIS files.

Notable Aspects of Revised Mapping

The detail that can be observed using high-resolution lidar topography allowed us to map fault traces at a finer scale than had been attempted previously and was indispensable for identifying geomorphic evidence of active faulting in forested and urban environments (see, for example, fig. 3, on map sheet; Hecker and others, 2016). The improved topographic resolution afforded by lidar reveals the Rodgers Creek Fault to be wider (locally >1 km in width) and more structurally complex than previously thought. This led us to differentiate strands that are relatively well developed and that we interpret to be part of the principal, through-going zone of displacement from strands that make up the broader zone of deformation.

We caution that interpretation of discrete fault traces involves significant uncertainty in some areas owing to one or more of the following factors: (1) faulting is complex and distributed; (2) faulting is obscured by land development or by landsliding or other surficial processes; (3) in steep terrain, landslide scarps, especially those related to sackungen, may be mistaken for faults; and (4) landforms indicative of faulting are discontinuous or near the limit of image resolution. These conditions give rise to mapping inaccuracies and to a non-unique representation of the pattern of faulting. This uncertainty is reflected in part by the "approximately located" designation assigned to most fault strands in the dataset.

The revised map increases the known extent of Holocene rupture by 17 km, with strands identified as far north as the hills southwest of Geyserville, northwest of Healdsburg (fig. 2*A*, on map sheet), for a total Holocene fault length of at least 73 km. This result substantiates the work of early mappers who cited evidence consistent with geologically young surface rupture to delineate the Healdsburg Fault as active in the Quaternary (for example, Gealey, 1951; Huffman and Armstrong, 1980). Evidence of Holocene activity along essentially the entire length of the Healdsburg Fault section is consistent with the results of interferometric synthetic aperture radar (InSAR) studies (Funning and others, 2007; Jin and Funning, 2017) showing that shallow creep, at preferred rates in the range of 1.9–6.7 mm/yr, is occurring along the fault between Santa Rosa and Healdsburg. We observed field evidence of creep on the Healdsburg section of the fault at a location in Santa Rosa (strand FID 518) and east of Healdsburg (strand FID 614). The new mapping also corroborates the findings of geotechnical consulting studies that indicate the presence of Holocene faulting within northern Healdsburg (for example, Hart, 1998b, and as noted in the age-estimate comments for some strands in the database).

Splays of the Rodgers Creek Fault (some of equivocal origin) project or continue beyond the eastern boundary of the map area in several locations and may accommodate transfer of slip to the Bennett Valley-Maacama Fault system to the east (fig. 2*A*, on map sheet). In particular, several fault strands on the southeast side of Taylor Mountain branch northward toward the Spring Valley fault strand, a section of the Bennett Valley Fault Zone that displaces latest Pleistocene and Holocene deposits (McLaughlin and others, 2008; Sowers and others, 2016; fig. 2*A*, on map sheet). Other strands that appear to connect the Rodgers Creek Fault with the Bennett Valley Fault Zone and associated unnamed faults (U.S. Geological Survey and California Geological Survey, 2006; Hecker, unpublished mapping) lie within a broad restraining bend in the Rodgers Creek Fault along the southwest side of Sonoma Mountain (fig. 2*A*, on map sheet), as well as farther south where the Bennett Valley Fault Zone approaches to within 1.5 km of the Rodgers Creek Fault. On the north side of Santa Rosa, several northward-trending strands connect to a broader zone of Quaternary faulting associated with the Rodgers Creek Fault (fig. 2*A,* on map sheet). Farther north, near Windsor, strands of the fault branch to the southeast toward a section of the Alexander-Redwood Hill Fault Zone identified as active in the latest Quaternary (U.S. Geological Survey and California Geological Survey, 2006; fig. 2*A*, on map sheet).

At its south end, the Rodgers Creek Fault bifurcates, and the eastern branch of the fault, expressed as pop-up features in the mudflats fringing San Pablo Bay, has been identified as the south end of the mapped trace (for example, Hart, 1992). The western branch has been interpreted as a late Quaternary strand (U.S. Geological Survey and California Geological Survey, 2006), or as primarily an erosional feature (Hart, 1992). It strikes south-southeast and projects toward active strands of the Tolay fault in the area of Sears Point (Hecker, unpublished mapping) and toward a recently discovered strand of the Hayward Fault beneath San Pablo Bay (Lienkaemper and others, 2012; Watt and others, 2016).

Our results indicate that the Rodgers Creek Fault is longer, wider, and more structurally complex than previously known and, therefore, presents a greater hazard to the built environment. Although the new map provides a substantial refinement in the representation of recently active traces, it also shows first-order agreement with previous maps. In particular, the principal displacement zone that we've delineated based primarily on geomorphic expression interpreted from lidar imagery generally follows the main active traces identified by Hart (1982, 1992), Bryant (1982), and earlier workers. This is evidence that, although in detail the configuration of surface faulting is complex and likely evolves through time, the Rodgers Creek Fault is fundamentally well developed, with a relatively stable locus of slip during the Holocene.

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