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Reassessment of the 1906 San Andreas Fault Rupture in Portola Valley, California, from Synthesis of LiDAR and Historical Data

by Chester T. Wrucke, Robert T. Wrucke, and Ted Sayre

Abstract During the 1906 magnitude 7.8 earthquake, surface rupture along the San Andreas fault propagated through the Town of Portola Valley on the San Francisco Peninsula. Subsequently, a number of studies came to conflicting conclusions regarding the exact location and nature of the 1906 surface rupture through the area. Our study provides new evidence for correctly locating the 1906 rupture within the town using field observations, a detailed analysis of 3D, bare-earth Light Detection and Ranging (LiDAR) images, and a review of photographs and other historical documents related to the 1906 rupture. Our composite images combine LiDAR views with historical photographs to aid in locating the 1906 fault trace and a previously unrecognized splay of the fault. Both the main fault trace and newly proposed splay-fault locations are significantly different from interpretations of the 1906 surface rupture developed over the last 50 years. Assembled evidence shows that the primary rupture in 1906 occurred only on the western of two main fault traces, rather than stepping to the eastern trace as proposed previously, and that a major section (about 2.6 km) of the western trace has been inaccurately mapped. From LiDAR-image analysis, we demonstrate that the previously mapped 1906 trace in the southern part of Portola Valley cuts through a homoclinal sequence of strata. These moderately dipping strata form prominent bedding lineaments have been mapped previously as quaternary fault traces.

Introduction

The devastating magnitude M_w 7.7–7.9 San Francisco earthquake of 18 April 1906 brought the San Andreas fault to world attention (Wallace, 1968; Prentice, 1999; Zoback, 2006). The earthquake, now well known for being one of the most important seismic events to take place in the United States in recorded history, created a rupture at least 435 km long in northwestern California, from Shelter Cove in the north to San Juan Batista in the south. On the San Francisco Peninsula, the rupture passed through the village of Portola (now Portola Valley), located about 70 km southeast of San Francisco and 30 km west of San Jose (Fig. 1).

In Portola Valley, the earthquake produced a variety of geologic features, well exposed in many areas, though poorly expressed in some critical places (Fig. 2). As a result of relatively easy access, professors, students, and photographers came to the town shortly after the earthquake from Stanford University, only 13 km away, and from nearby cities to study the damage and geologic features produced in the event. Their work resulted in a rich written and photographic record of the great earthquake and of the San-Andreas-fault zone in Portola Valley.

Included in this wealth of information from 1906 is an unpublished, hand-drawn map by J. C. Branner (Fig. 3) that shows the location of the furrow made by the fault in Portola Valley. Branner, who was Professor of Geology at Stanford at the time, andbecame the third president of the Seismological Society of America (Howell, 2002), contributed his and his student's observations of the 1906 fault rupture to the California Earthquake Commission for inclusion in a major compilation of the cause and effects of the earthquake in the state (Lawson *et al.*, 1908). That compilation, which contains a seminal record of the earthquake, includes photographs, maps, and text addressing the 1906 rupture in the Portola-Valley area. Taber (1906) also provided observations of surface faulting in the town, including details of the zone of disruption, the right-lateral displacement, and the location and trend of the rupture.

Although one of the main conclusions from these studies made soon after the earthquake was that the 1906 event resulted in a single fault trace through Portola Valley, a map published of that trace in Lawson *et al.* (1908, map 22) contains substantive errors of the fault location in Portola Valley. Those errors have caused confusion in subsequent geologic studies in Portola Valley, including postulated stepping between multiple fault traces.

More than 50 years passed after the great earthquake and the compilation of the Earthquake Commission report (Lawson *et al.*, 1908) before studies of the San Andreas fault

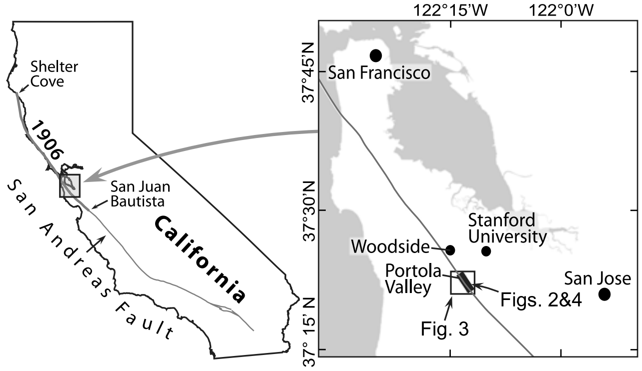


Figure 1. Map showing the location of the study area in relation to the San Andreas fault and surface rupture of 1906. Inset map shows the fault traverse south of San Francisco, the outline area of several figures, and the localities mentioned in the report.

in the Portola Valley area resumed. Most of the new studies focused on the faults that make up the rift zone (Dibble, 1966; Dickinson, unpublished report, 1970, see Data and Resources; Brown, 1972; Taylor *et al.*, 1980; Price *et al.*, 6 1984; Page, 1983; Brabb *et al.*, 1998; Hall *et al.*, 2001). Some of the new geologic maps identified the 1906 fault trace, others did not. Several studies concluded that the 1906 faulting locally resulted in complicated traces, and they advanced the concept of left stepping during the earthquake between two fault traces that in places are 250 m apart. Conclusions in these studies contrast to the simple trace and consistent right-lateral offset of the San Andreas fault reached by the studies made shortly after the earthquake. These are conflicting concepts and show, thereby, that significant differences in interpretation of the 1906 faulting have been reported and need to be resolved.

The combination of studies that were undertaken shortly after the 1906 earthquake, together with those conducted in the 1960s and later, has made Portola Valley a focal area of geologic research on the San Andreas fault on the San Francisco Peninsula. Recognition of major unresolved problems regarding the location and movement history of the 1906 fault trace in Portola Valley make the town a logical place for further study.

The location of the 1906 rupture of the San Andreas fault in Portola Valley and the movement mechanics during the rupture are important for developing the geologic record of this major tectonic plate boundary. Accurate siting of the fault is especially important to the Town of Portola Valley because it is imperative to know the exact location of the 1906 rupture in order to prevent unsafe development proximate to that trace, as future movement will likely follow the same path as before (Lawson *et al.*, 1908; Cluff, 1968; Wallace, 1968). Because the fault extends through the town for about 4.6 km, Portola Valley had the foresight a few years after its incorporation in 1964 to appoint a town geologist with the objectives of assessing such geologic hazards as may exist within the community and of producing a geologic

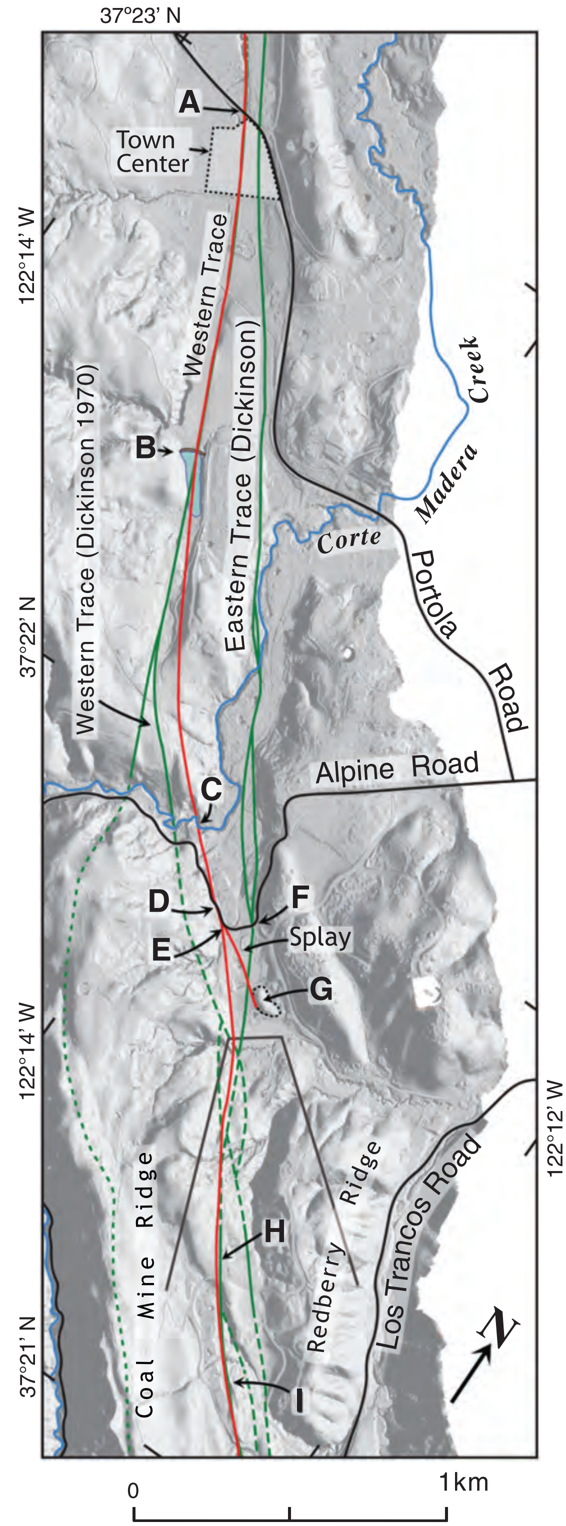
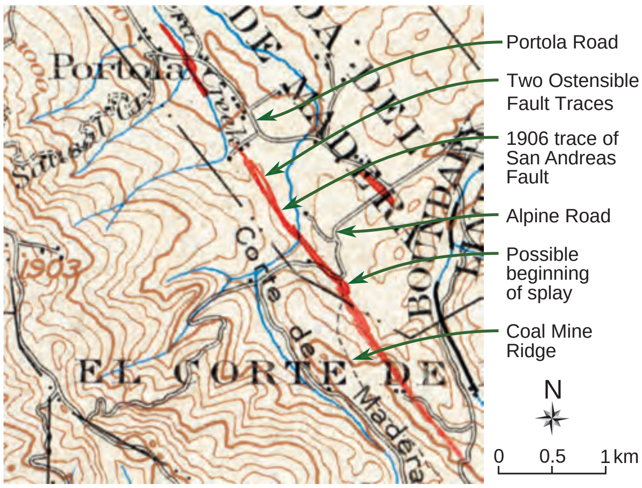


Figure 2. Simplified map on LiDAR base of the San Andreas 2
Fault zone, Portola Valley. (A) 1906 fault trace at Portola Road. (B) Sausal Pond dam. (C) 1906 fault trace at Corte Madera Creek. (D) 1906 fault crossing at Alpine Road. (E) Southeast end of the 1906 fault trace along Alpine Road. (F) Eastern trace of the fault at Alpine Road. (G) Bovet Hill. (H) Trench. (I) En echelon furrows. The red line shows the current interpretation of the 1906 fault rupture and splay. The green lines show fault traces of Dickinson 3
(unpublished report, 1970, see Data and Resources).



4 **Figure 3.** Annotated enlarged portion of a map by J. C. Branner (unpublished map, 1906, see Data and Resources) showing red lines he drew for the 1906 fault rupture in the area that became the Town of Portola Valley. Wide gaps in the fault trace in the upper part of the map are parts of a dashed fault line. Short red line east of the main fault is the trace of disrupted ground in 1906 near the intersection of Alpine Road and Portola Road. Hill 1903 near the west border is labeled Windy Hill on the U.S. Geological Survey 1980 edition of the Mindego Hill quadrangle. The map base is the 1902 U.S. Geological Survey Santa Cruz quadrangle.

map as an official town document useful in land-use planning (Mader *et al.*, 1988). Portola Valley is probably the first municipality in California to have taken such a step, and its geologist is charged with maintaining the map and advising the town government on matters of geology and seismic hazards.

Building setback requirements from faults were enacted by the Town of Portola Valley prior to passage of the California Alquist–Priolo Special Studies Zones Act in 1972 and were more stringent (Mader *et al.*, 1988). The Alquist–Priolo Act established certain minimum setbacks for designated active faults. Maps required by the act to identify the location of special study zones and certain faults within them were prepared for areas that include Portola Valley (Slosson, 1974a,b). Those maps show faults discussed here.

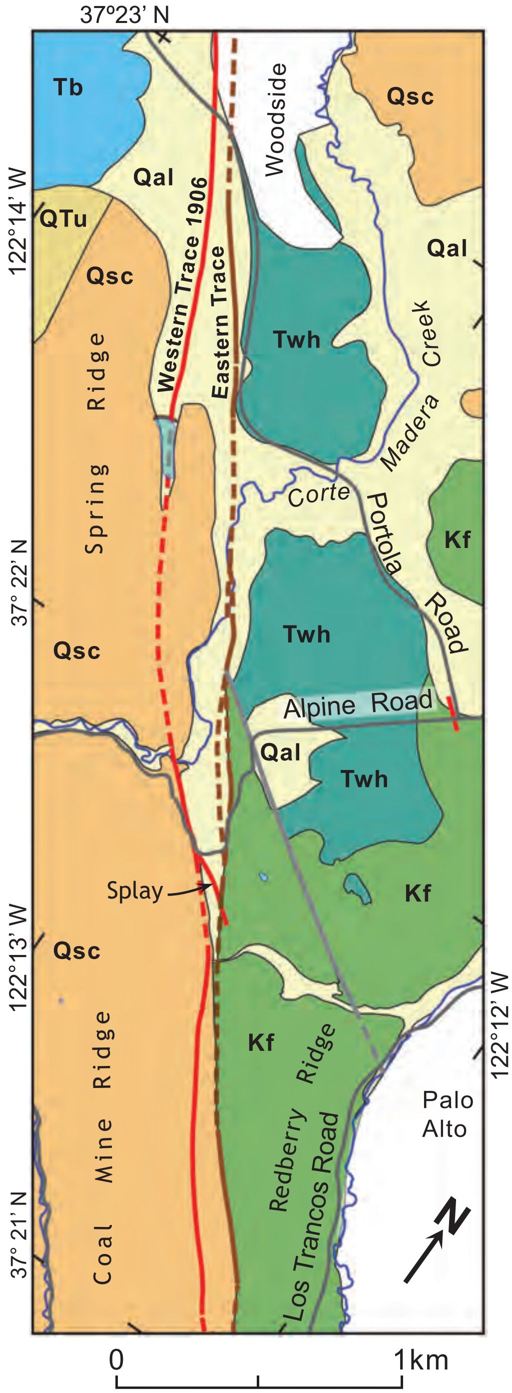
Our paper addresses three fundamental questions about the San Andreas Fault in Portola Valley: (1) where was the location of the 1906 surface rupture; (2) was the 1906 movement on a single main trace or on multiple traces; and (3) why are interpretations of the location and movement history made shortly after the great earthquake different from most of those made during the 1960s and later? To answer these questions, the paper examines photographic and other archival records related to the 1906 earthquake, as well as geologic papers from 1906 to the present. Our study also utilizes LiDAR (Light Detection and Ranging) (Schmidt *et al.*, 2008; see Data and Resources) data to determine the location of the 1906 fault trace in Portola Valley and provide an understanding of the geologic structure of an important area nearly devoid of outcrops. We also review evidence of single- and multiple-trace offset interpretations of fault rupture in Portola Valley to clarify the mechanics of ground movement during the 1906 seismic event in the town. We include a forensic analysis to show how misinterpretations of 1906 photographs led some investigators to reach erroneous geologic conclusions.

Previous Geologic Studies in Portola Valley

The first geologic study that includes Portola Valley is of the Santa Cruz 1:125,000-scale quadrangle and was conducted between 1892 and 1905 (and therefore prior to the earthquake), but not published until 1909 (see Branner *et al.*, 1909, Introduction). The task of mapping the fault zone and 7
other geologic details in the quadrangle was enormously difficult, as the area was large, the onshore portion was nearly 1,789 km^2 in size, had dense undergrowth, abundant soil cover, numerous landslides, and intricately and complexly broken rock units (e.g., Branner *et al.*, 1909, p. 9). For these reasons, and probably because of time constraints as well, the authors were forced to generalize the geology significantly. The report that accompanies the map, however, acknowledged that several fault traces were found in the San-Andreas-fault zone but were not mapped. They chose to show only one fault in the San-Andreas-rift zone, one that had strong geomorphic expression that resulted from the juxtaposition of different rock units. Despite having been published three years after the earthquake, the report's geologic map was not updated to show the 1906 break, possibly because the manuscript was in an advanced state of preparation.

The trace of the San Andreas fault in the geologic map of the Santa Cruz quadrangle (Branner *et al.*, 1909) is significantly different from our interpretation of the 1906 fault trace, and in Portola Valley it is as much as 250 m farther to the east (Fig. 4). In much of the town, the 1906 fault rupture is within the Santa Clara formation rather than between different rock units as shown in Branner *et al.* (1909).

Lawson *et al.* (1908) showed the 1906 rupture as a single, through-going trace that extended the length of the San Francisco Peninsula. Unfortunately, two maps of the fault trace in the original 1908 version of Lawson *et al.* (1908, maps 4 and 22) do not agree with each other in detail (Figs. 5, 6). Map 4 has a black and white, highly generalized topographic base for the Portola Valley area that lacks roads and buildings, but shows the fault close to the location given by Branner's hand-drawn map (Fig. 3). Map 22, in contrast, is in color and shows the fault trace on a detailed U.S. Geological Survey base engraved in 1902 that has contours, roads, streams, and buildings (Fig. 5). The use of color and the detailed base give the impression that this is the primary and most accurate map depicting the fault-surface rupture. The location of the fault trace as shown on map 22, however, does not match that shown in Branner's hand-drawn map (Fig. 3). Map 22 shows the fault along the base of Coal Mine Ridge at Alpine Road about 80 m to the west of where Branner placed it. Possibly because of the higher quality



8 **Figure 4.** Simplified geologic map of Portola Valley. Qal stands for alluvium, Quaternary. QTu stands for undefined units, Quaternary and Tertiary. Qsc stands for Santa Clara formation, Pleistocene and Pliocene. Tb stands for Butano formation, Eocene. Twh stands for Whiskey Hill formation (Eocene). Kf stands for Franciscan formation, Cretaceous. The red faults show the current interpretation of the 1906 surface rupture of the San Andreas Fault (western trace) and a short fault trace at the junction of Alpine Road and Portola Road (dashed where approximately located). The brown fault is the eastern trace of the San Andreas fault, mostly from Branner et al. (1909) (dashed where approximately located). The gray fault is unnamed. The map shows the eastern trace defined by juxtaposition of contrasting rock units. The western trace of the fault is entirely in the Santa Clara formation.

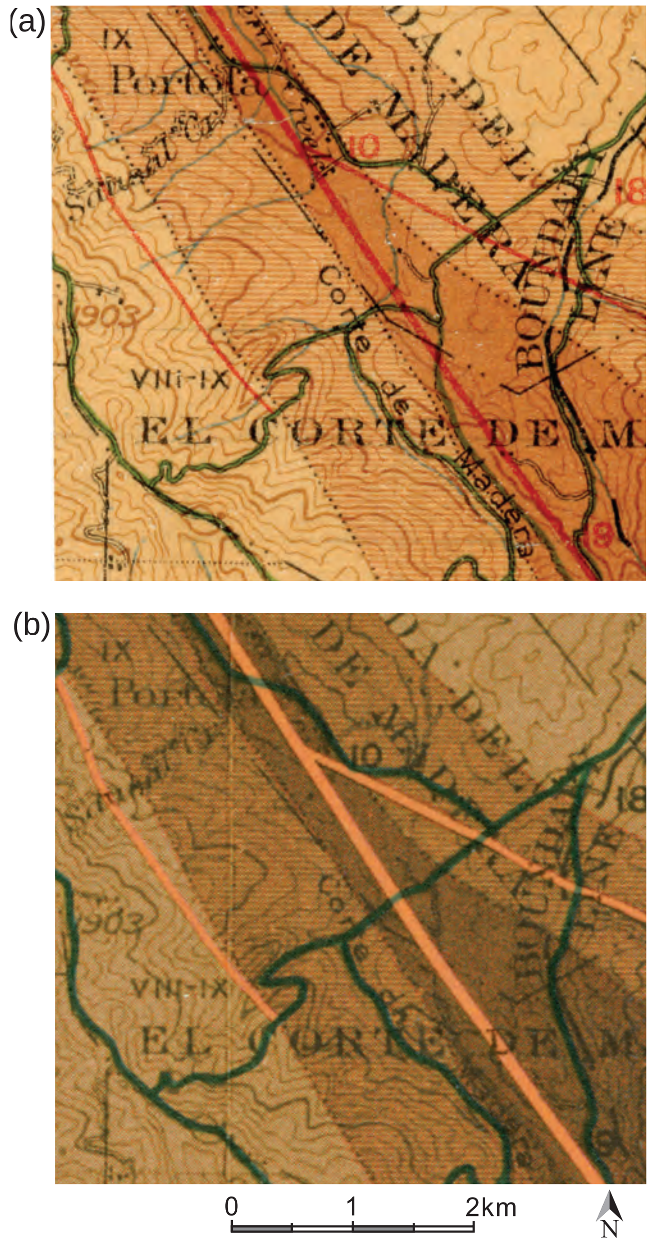


Figure 5. Two versions of map 22 of Lawson et al. (1908). (a) Enlarged part of the map from the original printing, showing the location of the 1906 fault rupture at Alpine Road. (b) Enlarged part of the map from the second printing of 1970, showing the same area as in (a).

of the map-22 base, geologists working in the 1960s and 1970s may have assumed that it correctly depicted the location of the 1906 trace. Regrettably, Branner's map (Fig. 3) probably was unknown to most people who studied the geology of Portola Valley from 1960 to the present.

An important complication regarding map 22 is that on close inspection, the reprinted version of 1970 (Fig. 5b) was found to differ from the original map of the first printing of 1908 (Fig. 5a). The 1970 reprinted version shows, with a wider line, the 1906 fault trace in most of Portola Valley

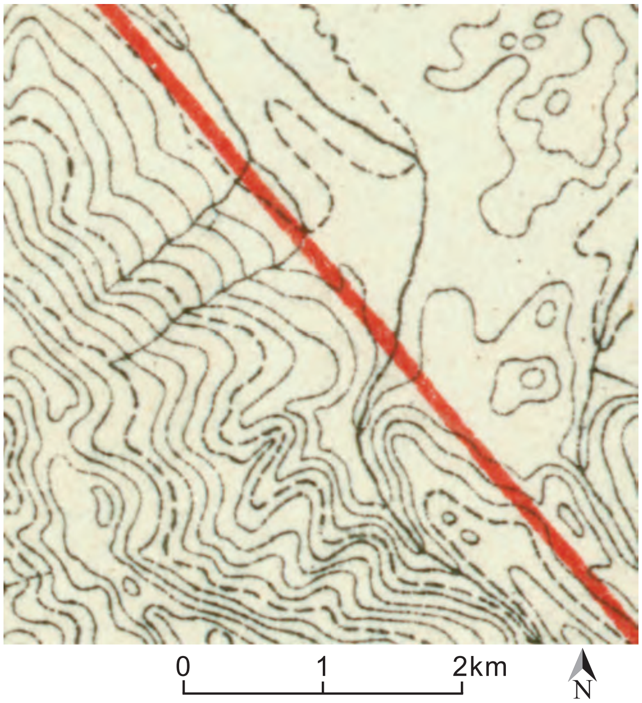


Figure 6. Enlarged part of map 4 of Lawson *et al.* (1908) showing the 1906 fault rupture in approximately the same area as in Figure 5a,b, but on a topographic base with no roads and a contour interval of 100 feet (30 m).

slightly to the east of the location in the original version, although the two versions are about the same at Alpine Road.

A compilation map by Schlocker *et al.* (1965) shows the single 1906 rupture as printed in the original version of map 22, but plotted on a base made from modern 7.5′ topographic quadrangles. The Schlocker *et al.* (1965) map, unfortunately, advances the conclusion that the fault location provided by the original map 22 was correct.

Most geologic maps produced after 1965, as noted earlier, show the San-Andreas-fault zone in Portola Valley as consisting of multiple traces (e.g., Dibblee, 1966; Dickinson, unpublished report, 1970, see Data and Resources; Slosson, 1974a,b; Page, 1993; Pampeyan, 1993; Brabb *et al.*, 1998, 2000), some of which show an anastomosing pattern locally. 9 Except for Pampeyan (1993), these maps either do not identify the 1906 trace or do not identify its location anywhere in the map area.

Dickinson (unpublished report, 1970, see Data and Resources) used stereo aerial photographs and field observations to locate the fault in Portola Valley (Fig. 2) and concluded that in 1906 the ground ruptured on two traces, but did not describe the full extent of the disruption on each of those traces. North of Alpine Road, the eastern of his traces, which he referred to as the Trancos trace, is similar to the trace shown in Branner *et al.* (1909). Part of his western trace, which he named the Woodside trace, follows the fault location as shown in the original map 22 of Lawson *et al.* (1908; Fig. 5a). In the northern part of the town,

Figure 7. 1906 photograph showing a fence offset about 2 feet (60 cm) at the side of a house on Portola Road (Lawson *et al.*, 1908, p. 106). The house exists today, although modified since 1906. The location of the photograph was identified by the late Dwight Crowder of the U.S. Geological Survey (Dickinson, unpublished report, 1970, p. 22, see Data and Resources).

Dickinson mapped the western trace along the side of a house on Portola Road, a well-documented location of the 1906 rupture (Fig. 2, Locality A; Fig. 7). From there he showed the trace as crossing the road at a prune orchard (Fig. 8) and continued to the southeast along strong and locally complex geomorphic features through a field and to Sausal Pond Dam (Fig. 2, Locality B). From Sausal Pond south to Alpine Road, Dickinson's trace diverges from the map 22 location as interpreted by Schlocker *et al.* (1965) and follows geomorphic features farther to the west. To the south of Alpine Road, Dickinson's Woodside trace differs significantly from the trace in map 22 in Lawson *et al.* (1908). He believed the western trace rupture in 1906 extended at least as far to the south as Portola Road and possibly to the town center, but the movement transferred to the eastern trace somewhere north of Alpine Rd. Dickinson's work is reflected in subsequent regional maps that include Portola Valley (Brown, 1972; Slosson, 1974a,b; Price *et al.*, 1984; Brabb *et al.*, 1998, 2000).

Taylor *et al.* (1980) follows Dickinson (unpublished report, 1970, see Data and Resources) in concluding that the San-Andreas-fault zone in Portola Valley consists of two main fault traces (here called the western and eastern traces) and that movement during the 1906 earthquake took place on the western trace in the northern part of the town and transferred onto the eastern trace in the south. Taylor *et al.* interpreted the faulting as having followed the western trace southward to about 50 m south of Portola Road, then it stepped to the eastern trace beginning about 100 m south of that road. Because Taylor *et al.* found no record of faulting in several exploratory trenches dug southeast of Portola Road and only weak geomorphic expression of the trace in that area, they concluded that the fault movement stepped left

Figure 8. 1906 photograph of view to the south from the front of the house pictured in Figure 7. This scene was described in Lawson *et al.* (1908, p. 106), probably by Branner, as "Where the fault crosses the road, the fences on both sides were torn in two, and in the prune orchard south of the road the rows of trees were displaced in some instances about 2 feet [61 cm]. The cracks in the road were about 6 inches [15 cm] wide, approximately parallel, and running nearly north-south, while the direction of the fault line itself was about northwest–southeast."

to the eastern trace and continued to the south across Alpine Road at the position mapped by Dickinson (Fig. 2, Locality F). Page (1993) also concluded that left stepping between the eastern and western traces had taken place in Portola Valley, but did not indicate whether this movement was from 1906 or otherwise. Pampeyan (1995) recorded evidence for left stepping from several sources. Interpretations of 1906 movement on more than one trace, as well as the complicated fault pattern of some maps (Dickinson, unpublished report, 1970, see Data and Resources; Brown, 1972; Price *et al.*, 1984; Brabb *et al.*, 1998, 2000), differ significantly from the single active-trace interpretation of Branner (Fig. 3) and Lawson *et al.* (1908), and more recently from those of Hall *et al.* (2001) and Graymer *et al.* (2006). Wetenkamp (2008, pp. 36–37), after reviewing evidence of faulting discovered in research trenches dug in the northern part of Portola Valley and reported by Fisher *et al.* (2002) and by others in unpublished reports, questioned whether there was left stepping in 1906.

Hall *et al.* (2001) showed on a generalized map of Portola Valley that movement took place only on the western trace in 1906. Their interpretation differs from ours on where the fault crossed Alpine Road and on the location of the fault to the south of the road.

Our Interpretations

The portion of the San Andreas fault in Portola Valley that is the focus of this study is located between the Sausal Pond Dam, at Locality B (Fig. 2) in the north, and an

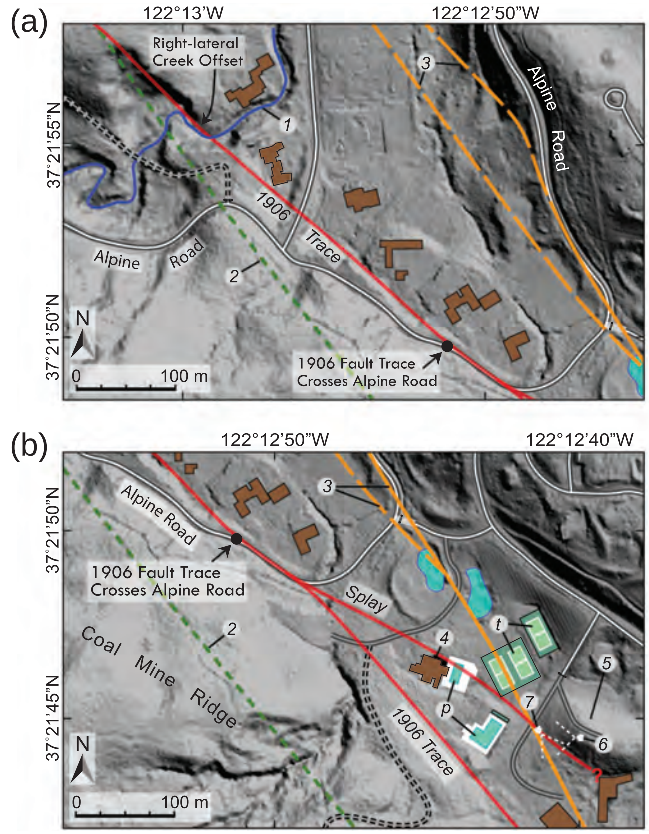


Figure 9. Maps on LiDAR base showing traces of the San Andreas fault in the vicinity of Alpine Road and the proximity of the 1906 rupture and splay to existing houses and other structures. (a) 1906 fault rupture from Corte Madera Creek to the crossing at Alpine Road: *1*–Corte Madera Creek; *2*–map 22 fault trace in Lawson *et al.* (1908); *3*–Eastern traces of the San Andreas fault. (b) Area southeast of Alpine Road (southeast terminus of the splay not known): *2*–map 22 fault trace in Lawson *et al.* (1908); *3*–Eastern traces of the San Andreas fault; *4*–Recreation center and office; *5*–Bovet Hill; *6*, *7*–Camera locations of 1906 photographs shown, respectively, in Figures 17 and 25; *p*–swimming pools; and *t*–tennis courts. 11

exploratory trench excavated in 1989 across the 1906 rupture 2.6 km to the south at Locality H (Hall and Wright, 1993).

Our first indication of the need to revise interpretations of the San Andreas fault in Portola Valley made after 1960 resulted from observing a straight segment of Corte Madera Creek (Fig. 2, Locality C; Fig. 9a); about 30 m long and bounded at each end by a right-angle bend, suggestive of right-lateral fault offset. The straight segment trends to the northwest toward the location of the 1906 rupture Dickinson (unpublished report, 1970, see Data and Resources) mapped at Locality B. This segment of the creek could be a result, at least in part, of the creek having followed weakened bedrock along the fault. This important geomorphic feature is not shown on the town's geologic map (Price *et al.*, 1984) and appears to have been overlooked by all geologists since 1960, with the exception of Carol Prentice, coauthor of Graymer *et al.* (2006; personal comm., 2010) and possibly 10
of Dibblee (1966). The straight segment of the creek is not

Figure 10. 1906 photograph to the southeast, showing the fault disruption at Alpine Road. The photograph, included in Lawson *et al.* (1908, plate 63A), was taken shortly after the earthquake. The fault broke along the south side of the road, as described by
13 Branner (see text). Large fracture in the foreground is interpreted here as an en echelon fault break. This photograph was printed in reverse by Taylor *et al.* (1980).

Figure 11. 1906 photograph of a well-dressed man and woman at the Alpine Road fault crossing. Trees in the background are also shown in Figure 10. The minimal road repairs of the main break confirm this photograph was taken after Figure 10. Enlargement shows buttons on the right side of the man's jacket, correct for male attire, thus confirming this photograph and Figure 10 were not reversed (as discussed in the text). 14

Figure 12. 1906 photograph to the southeast showing a horse with a saddle and the fault disruption at Alpine Road. The photograph was taken shortly after the earthquake and has the same large tree in the background as in Figures 10, 11, and 13.

depicted on any edition of the U.S. Geological Survey topographic maps of the area, or on the town's geologic map, and the creek locality is obscured in aerial photographs by dense overhanging trees. This offset stream, however, is clearly visible in bare-earth images constructed from LiDAR data (Fig. 9a).

The straight, offset segment of Corte Madera Creek aligns well with our interpretation of the location at which the 1906 trace crosses Alpine Road, about 260 m to the southeast at Locality D. The rupture at Locality D is consistent with 1906 photographs of the fault at Alpine Road (Figs. 10–13) and with the following description, written by J. C. Branner of Stanford University (Lawson *et al.*, 1908, p. 107), in which he states that the main-fault trace crossed the road 0.75 mile[s] (1.2 km) south of the intersection of Alpine Road and Portola Road:

> Here the road was so badly broken and cracked that it was not possible to drive [a carriage] across the fracture until the place was repaired. The fracture followed along the south side of the road for a distance of 300 feet [90 m] tearing up the bank with cracks, some of which were a foot [30 cm] or more across. Where the road bends toward the south, the fracture crost [sic] to the north side of the road, making cavities several feet deep.
> 12 These cracks continued toward the northwest through the underbrush, pulling apart a barbed wire fence and leaving many well-marked furrows through the adjoining fields. About 30 feet [9 m] north of the road, a white oak, somewhat weakened by decay and fire, was jerked off by the violence of the shock. To the southeast the fault-line is traceable by a well-marked furrow thrown up in the fields. Where the fracture crosses the Alpine Road, there appears to have been an uplift of about 2 feet [60 cm] on the northeast side of the fault. This appearance may be due to the settling of a part of the ridge of incoherent materials to the south, or it may be due to the lateral thrust [transpression] along a sloping surface.

Branner's description, together with 1906 photographs, a hand-drawn map, a student notebook, and an analysis of changes to Alpine Road provide valuable clues that we believe confirm the location of that important crossing. But because numerous interpretations have been made that

Figure 13. 1906 photograph of a man and boy standing on Alpine Road about 150 feet (46 m) southeast of where the fault rupture crossed the road. The man is standing on the fault fracture that extends along the southwest side of the road. The large tree in the background is also visible in Figures 10, 11, and 12.

differ from these early records of where the fault crossed Alpine Road, we have made a detailed analysis of the available clues.

Branner's description, for example, tells us that the fault followed along the south side of Alpine Road and trended to the southeast from the fault crossing to a well-marked furrow in fields. Figure 13 shows the 300-feet (90-m) fracture on the side of the road, and Figures 10–12 provide a clue for the trend of that part of the road. The clue is provided by the short, faint segments of ridge crests seen above the roadway alignment (Fig. 14). Through field and map studies we have identified these ridges and found they are to the southeast of the fault crossing, thereby confirming the southeast trend of the fault and the road, as described.

Some of Branner's directions seem imprecise and may have confused future workers. His references to the fault on the south side of the road for 300 feet (90 m) and to a bend in the road to the south cannot be exact. There are no bends to the south, and, if the fault trends to the southeast, as just discussed, the fault would have been on the southwest side of the road. Along the road segment trending to the southeast, references to the north and south sides of the road do identify opposite sides, but more precise headings for the sides of the road would have been to the northeast and southwest. Branner's description clearly indicates that the fault crossed Alpine Road at a bend to the south, but, if our interpretation of the location is correct, it would have been more accurate to state that, when traveling northwesterly, the road at the fault crossing bends to the west.

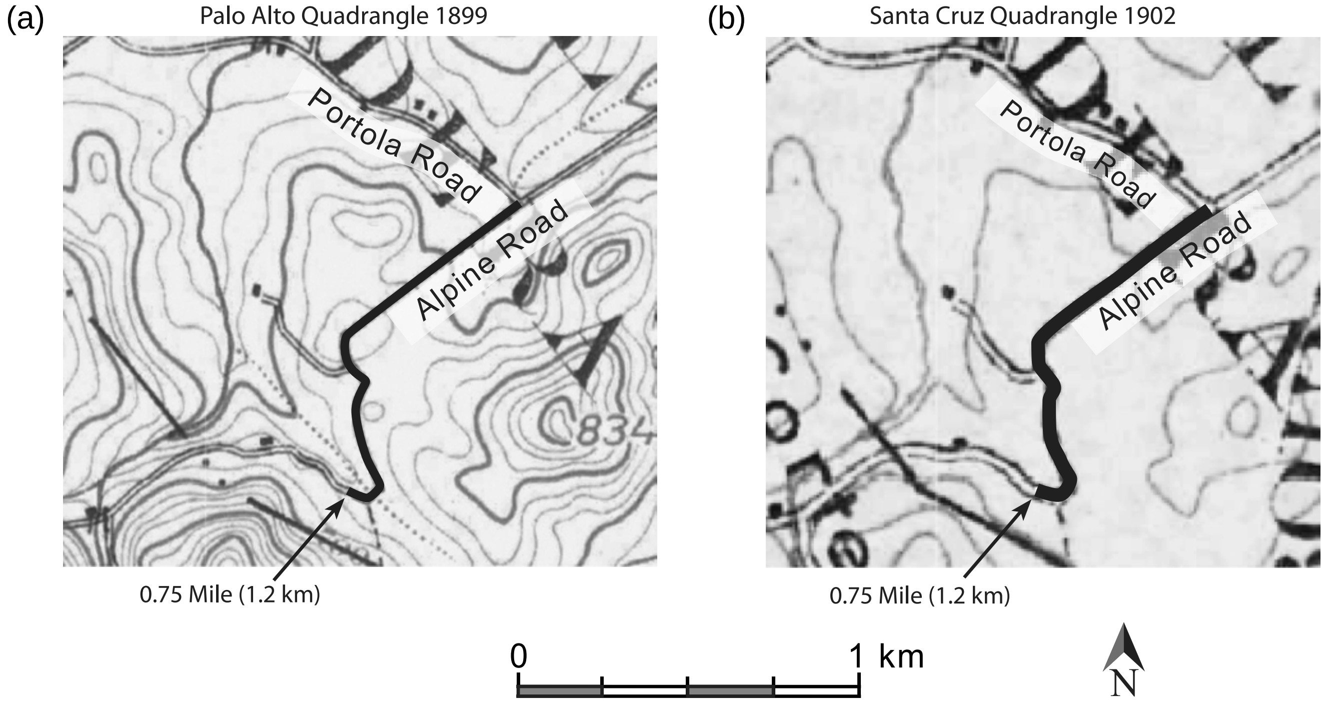
Branner's description that the fault crossed Alpine Road 0.75 miles (1.2 km) from the intersection with Portola Road

Figure 14. Enlarged view from Figure 10 of the center skyline and the far end of Alpine Road, showing ridge profiles. The lower profile is Redberry Ridge, the upper profile is a more distant ridge. The view of the ridges is obscured today by trees in the field southeast of Locality E, but the ridges can be seen from that field.

should be helpful in identifying the location of the fault crossing. Branner, however, did not describe how the measurement was made. When we measured the distance along Alpine Road by tape, we found that the 0.75-mile distance almost reached the curve at Locality E (Fig. 2). This curve cannot be where the fault crossed the road because there is no straight segment of the road to the southeast, as Branner described. When we measured the historic alignment of Alpine Road shown in the 1899 edition of the Palo Alto quadrangle (Fig. 15a) using a computer program (see Appendix A), the 0.75-mile distance was found to be essentially coincident with Locality D (Fig. 2). When the same computer measure- 15
ment was made using the 1902 edition of the Santa Cruz quadrangle, the base map used by Branner to make his hand-drawn map (Fig. 3), the same result was achieved (Fig. 15b).

Branner's description of the many well-marked furrows on the north side of Alpine Road may describe en echelon breaks. The prominent fracture that crosses the road diagonally in Figure 10 is probably an en echelon break, reflecting a change in offset style from the straight segment (Fig. 12) to the southeast along the side of the road as described by Branner to en echelon breaks to the northwest.

The adjoining fields Branner described as northwest of the fault crossing, we suggest, consisted of the area shown as



16 **Figure 15.** Maps showing the 0.75-mile (1.2 km)-long portion of Alpine Road, as measured on each map, west from the intersection with
17 Portola Road (see text). (a) Enlargement of a part of the 1899 Palo Alto quadrangle. (b) Enlargement of a part of the 1902 Santa Cruz quadrangle. Both maps are of the U.S. Geological Survey.

an orchard in aerial photographs of 1939 and 1953 (Fig 16a, b), and includes the area between the southern edge of the orchard and Alpine Road. The fields can be seen in a pre-1920 photographic view to the south along the future site of Willowbrook Drive, as shown in a book on the history of Portola Valley (Lund and Gullard, 2003, p. 206).

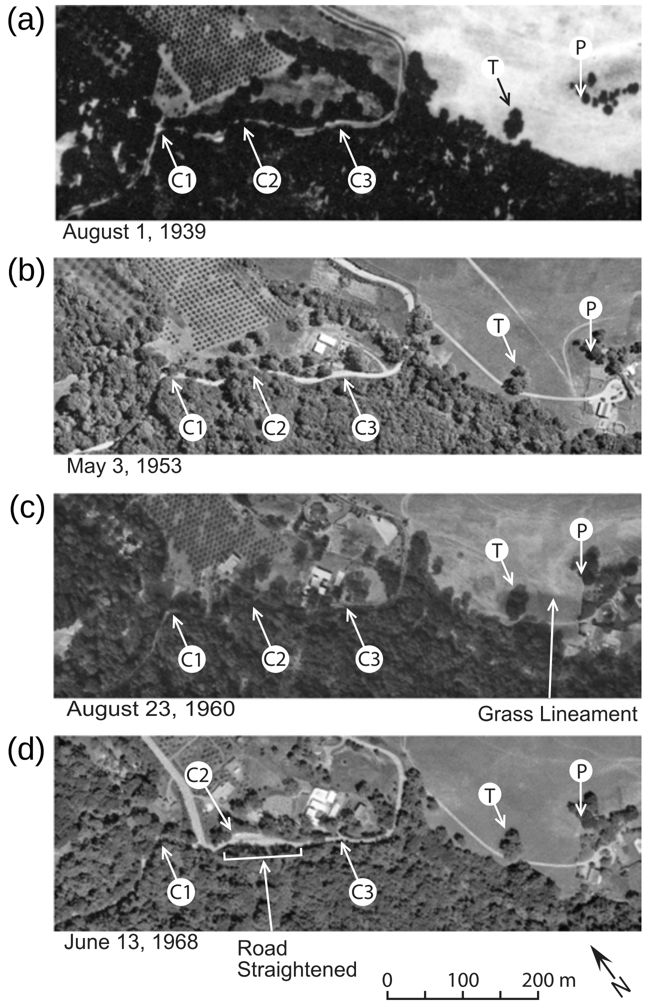
We interpret the field Branner described as southeast of the fault and having a furrow was southeast of localities D and E (Fig. 2) and is shown in the 1906 photograph taken from Bovet Hill (Fig. 17; Fig. 18). Aerial photographs show the field remained covered in grass for several decades after 1906 (Figs. 16a–d).

Our interpretation of the crossing location on Alpine Road is based in part on 1906 photographs (Figs. 10–12). These photographs show the crossing at the end of a straight
20 segment of the road, where ridgelines, discussed earlier, are visible to the southeast beyond the far end of the road. The photographs also show the fault rupture at a bend in the road at the northwest end of the straight road segment. To find where these photographs were taken, we made a map of the alignment of Alpine Road in 1906, using data from a road survey of 1894 (Fig. 19a; see Appendix B). We identified only three places on the 1906 alignment of Alpine Road where there are curves of the proper orientation with straight sections to the southeast. These curves are on the part of the road on the northeast flank of Coal Mine Ridge. The three curves are labeled C1, C2, and C3 in Figures 19a–c.

In 1906, these curves were sharper than they are today, as expected of a narrow, unpaved and a single-lane road for horses and buggies, as shown in Figures 10–13. The 1894 road survey suggests the road closely followed the curvature of the hillside, probably for ease of construction. Despite widening and realignment for the paved road of today, the curves of 1906, although modified, are still recognizable, as shown in Figure 19a–c.

We define Curve C1 as the sharp bend present today in Alpine Road about 55 m west of the intersection with Willowbrook Drive (Fig. 19c). In the highly generalized 1902 base map used by Branner (Fig. 3) and Lawson *et al.* (1908, map 22; see Fig. 5a), the house shown adjacent to Alpine Road probably was near Curve C1. That house, now gone, is important to this discussion, because the original map 22 in Lawson *et al.* shows the fault rupture at that location, whereas Branner (Fig. 3) shows the fault farther to the northeast.

Curve C1 could not have been where the 1906 fault rupture crossed Alpine road because the distant ridges shown in the background in Figures 10–12, and 14 cannot be seen from there. Just beyond the end of the straight section to the southeast from C1, the hillside of Coal Mine Ridge rises about 10 m, blocking the view of the distant ridges. Also at Curve C1, there are no adjoining fields to the north, as mentioned by Branner (Lawson *et al.*, 1908, p. 107), because of nearby incisions of Corte Madera Creek. To the southeast there is no field for more that 500 m. The intersection of Alpine Road and Portola Road is more than a mile (1.6 km) distant, rather than 0.75 miles (1.2 km), as described by Branner; and the curve is not aligned with the trend of



18 **Figure 16.** Aerial photographs showing a segment of Alpine Road in Portola Valley. C1, C2, and C3 are important curves on Alpine Road. P shows the location of the 1906 photograph taken from Bovet Hill (Fig. 17). T shows the trees present in 1906 (shown in Fig. 17). (a) 1939 aerial photograph (oldest known of the area) taken prior to the construction of Willowbrook Drive, shows the
19 orchard mentioned in the text. (b) 1953 aerial photograph of the same area as (a) but sharper and showing Alpine Road more distinctly. (c) 1960 aerial photograph showing contrasting gray tones from different vegetation on opposite sides of the splay. (d) 1968 aerial photograph showing Willowbrook Drive and gentler curves on Alpine Road than shown in earlier aerial photographs. The aerial photographs are from the U.S. Geological Survey.

the straight section of Corte Madera Creek (Fig. 9a) that we interpret as following the 1906 surface rupture.

Curve C2 (Figs. 19a–c) in 1906 was located where today a parking lot exists, adjacent to the northeast side of Alpine road, about 50 m southeast of the intersection with Willowbrook Drive. The curve was part of the road alignment that existed prior to a significant straightening of this part of the road in 1962. Old patches of pavement from the prior alignment can be found today in the parking area.

In 1906, Curve C2 was sharp, and the relatively straight segment of the road to the southeast had a gentle bend. Today

Figure 17. 1906 photograph of westerly view from Bovet Hill, showing the furrow of the fault splay in a field.

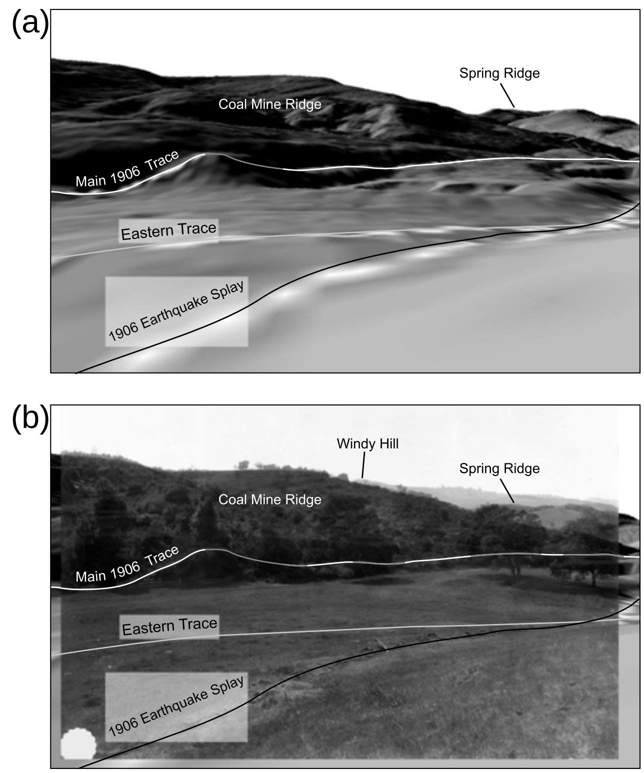


Figure 18. (a) Oblique, bare-earth LiDAR image of the same scene as Figure 17, showing the fault splay, eastern and 1906 traces of the San Andreas fault, Coal Mine Ridge, and Spring Ridge. The diffused white dashes show the final adjusted fault trace locations transposed to a perspective camera view, as explained in Appendix C. Windy Hill does not appear in (a), because it was not included in the LiDAR survey. (b) Composite view of the 1906 photograph overlain on the LiDAR image of (a). The close registration of the LiDAR image and the 1906 photograph is evidence of the accuracy of our assessment of the alignment of the furrow and the location of the photograph. The view shows the 1906 fault splay crosses the eastern trace of the San Andreas fault. The splay joins the main 1906 trace to the right of the photograph. The north knob of Windy Hill is shown in the background.

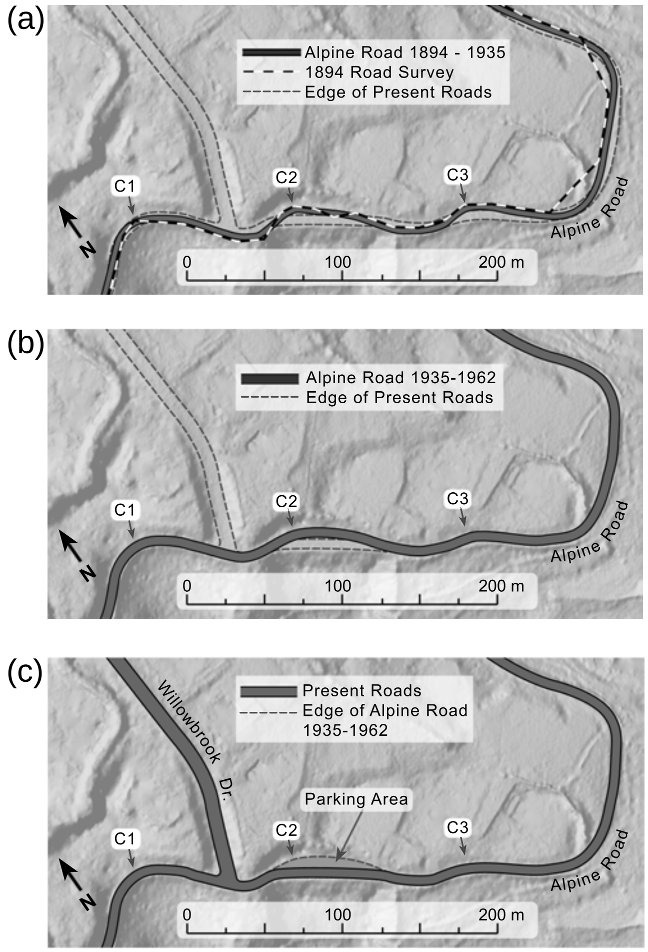


Figure 19. Alpine Road on LiDAR base, 1894 to 2012. (a) Map showing 1894 road survey (see Data and Resources), our interpretation of the narrow 1894 road alignment, and the 2012 road alignment. (b) 1936–1962 road alignment based on aerial photographs (Figs. 16a–c). (c) Alignment of Alpine Road in 2012 based on LiDAR and Figure 16d.

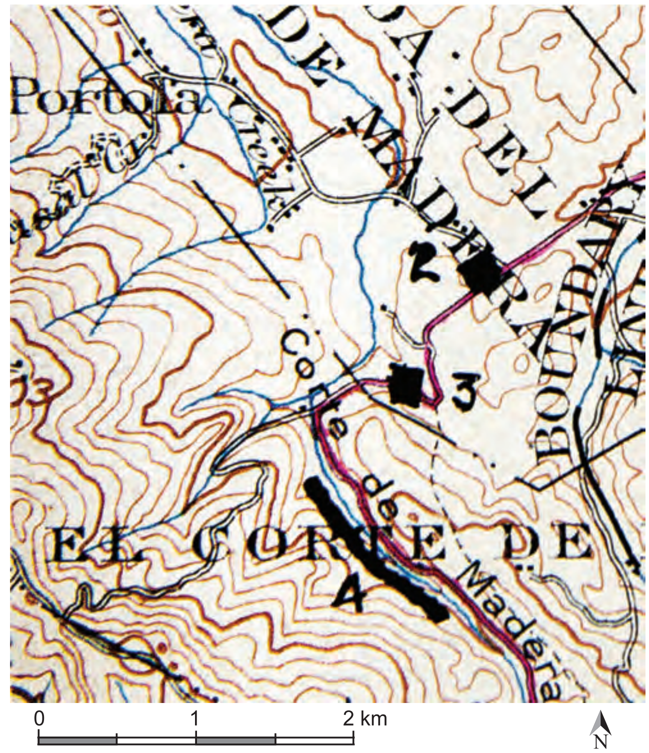


Figure 20. Part of a map in a 1906 field notebook by F. W. Turner (see Data and Resources) showing a large black square, labeled number 3, at the location of the fault rupture on Alpine Road. The base map used by Turner was the 1902 edition of the Santa Cruz quadrangle of the U.S. Geological Survey. His notes for station number 3 read "NWN cracks about 1 or 2 inches [2.5 or 5 cm] wide, earth shoved up about 4 or 5 inches [10 or 13 cm]. Big tree down." The crack dimensions are smaller than those described by Branner shortly after the earthquake, as shown in Figures 10–13, probably because the road had been repaired when Turner recorded his observations in September 1906, five months after the earthquake.

the view to the southeast from C2 is toward a sharp curve and a forest-covered slope of Coal Mine Ridge that gently rises at least 7 m in the line of sight above Alpine Road. If the forest density above that slope in 1906 was similar to the vegetation shown in Figures 10 and 12, the view to the distant ridges would have been through a slot in the forest canopy over 120 m long. We believe such a slot was unlikely.

Despite the probability that the view to the southeast was restricted in 1906, Curve C2 is consistent with some of the qualifying characteristics of where the surface rupture crossed the road. We interpret the area north and northwest of and adjacent to Curve C2 as containing the adjoining fields Branner described (Lawson *et al.*, 1908, p. 107).

Shortly after the 1906 earthquake, F. W. Turner, a student of J. C. Branner at Stanford University, glued a large black symbol on part of the 1902 topographic map of the
21 Santa Cruz quadrangle to his field notebook to mark the location where he saw the surface rupture of the fault at Alpine Road (Fig. 20). He also noted, as did Branner (Lawson *et al.*, 1908, p. 107) that a big tree had fallen nearby, suggesting he was at the same location described by Branner. Turner's symbol, unfortunately, covers a significant section of the road between the house near Curve C1 and the major bend in the road at Locality E (Fig. 2) and, therefore, does not pinpoint the fault crossing location precisely. The center of Turner's large symbol, however, could be interpreted to be located at Curve C2, as recognized by Pampeyan (1995).

Although the presence of the fields to the north and the symbol used by Turner are consistent with potential fault rupture at Curve C2, the intervening slope of Coal Mine Ridge and the overlying forest cover at the end of the straight section strongly suggest this curve is not the locality of the fault crossing.

A 1906 photograph of the fault rupture on Alpine Road provides an important clue that the crossing was not at Curve C2. From an on-site analysis of the hillside along the side of the road immediately south of the curve, we find the hillside has a much steeper and higher rise than the one shown on the right side of the photograph in Figure 12. Of the three curves, only Curve C3 has a gently rising hillside on the south side, as shown in the photograph.

We conclude that the bend in the road at C3 and the straight segment trending southeast from there conforms best to evidence of where the fault rupture crossed Alpine Road in 1906, and where photographs of Figures 10–13 were taken. These photographs show the crossing in the near ground at a curve in the road that is sharper than Curve C3 today, and that it is at the northwest end of a straight segment of the road. Today the distant ridges shown in Figures 10–12 and 14 cannot be seen from Curve C3. Unlike the curves C1 and C2 where the view of the ridges are blocked by a slope of Coal Mine Ridge or 120 m of forest, the view at Curve C3 is now blocked be a few trees. We believe the trees are too young to have existed or to have interfered with the view of the ridges in 1906.

Curve C3 today is a gentle bend in the road. This may be a reason why the curve has been overlooked as the site of the fault crossing. Based on our analysis of the 1894 survey (Fig. 19a), the curve of the road closely followed the curvature of the hillside, and this is consistent with photographs of the roadway in 1906 (Figs. 10–12).

Today the distant ridges shown in Figures 10–12 cannot be seen from Curve C3. Unlike Curves C1 and C2, however, where the view of the ridges are blocked by a slope of Coal Mine Ridge or 120 m of forest, the view at Curve C3 is now blocked only by a few trees. We believe the trees are too young to have existed or to have interfered with the view of the ridges in 1906.

Just as at Curve C2, we interpret the area adjacent to and northwest of Curve C3 as the one containing Branner's adjoining fields. As discussed earlier, southeast of the end of the straight segment of Alpine Road from Curve C3 is the field Branner described as containing a furrow.

The correct position where the 1906 rupture crossed Alpine Road at Curve C3, as we interpret it here, is closely aligned not only with straight segments of the road and of Corte Madera Creek, but also with the place to the southeast where the fault begins to climb Coal Mine Ridge. The segment of the 1906 rupture from Curve C3 to where the rupture is seen in LiDAR on Coal Mine Ridge (Fig. 21) matches Branner's hand-drawn location of the fault (Fig. 3). Figure 4 summarizes our interpretation of the location of the surface trace of the 1906 rupture that matches all available evidence. Our interpretation of where the fault rupture crossed Alpine Road is supported by Branner's hand-plotted field map, a profile in Lawson *et al.* (1908) (Fig. 22), and a field notebook of F. W. Turner (Fig. 20).

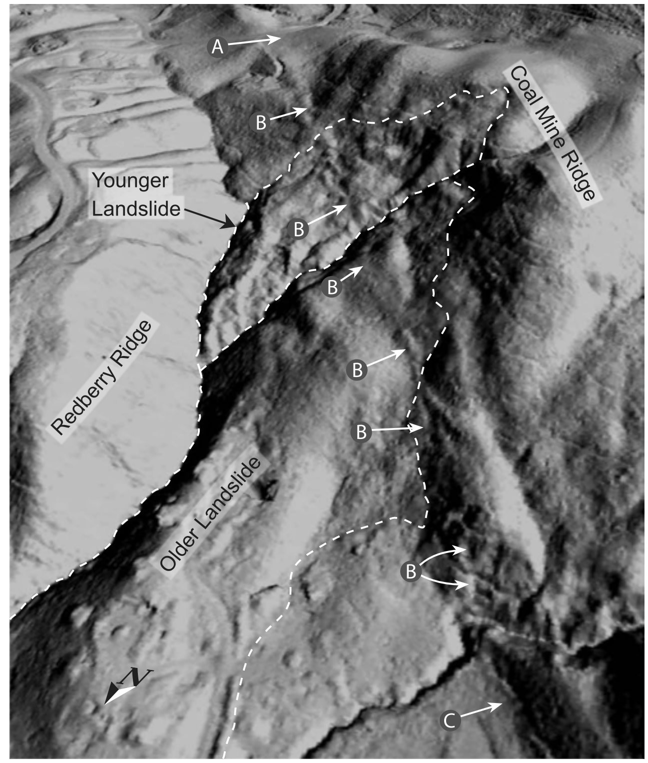


Figure 21. Oblique bare-earth LiDAR view to the southeast showing the east flank of Coal Mine Ridge and the western trace of the San Andreas fault. The view shows where the fault crosses landslides identified as older and younger based on surface roughness. A–Location of a trench identified at Locality H (Fig. 2). B–Geomorphic features of the fault trace. C–Fault trace at the base of Coal Mine Ridge. The fault trace extends to the northwest, beyond the base of the figure, to the crossing at Alpine Road (Fig. 2, Locality D).

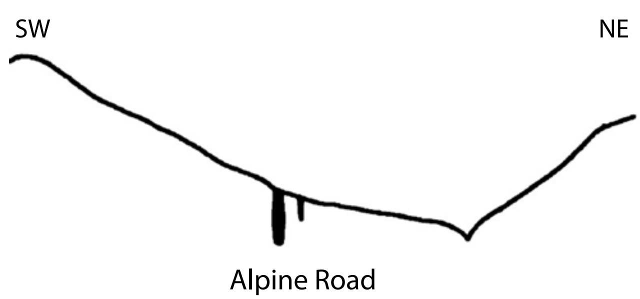


Figure 22. Profile of the land surface at Alpine Road from Lawson *et al.* (1908, p. 105, fig. 41), showing the location of the 1906 surface rupture of the San Andreas fault on a hillside.

Analysis of 1906 Photographs

We became suspicious that movement on the San Andreas fault in Portola Valley in 1906 might not have stepped from the western to the eastern trace after discovering that Taylor *et al.* (1980) had printed a 1906 photograph of the fault at Alpine Road in reverse from the image of the same photo (Fig. 10) as printed by Taber (1906) and Lawson *et al.* (1908, plate 63A). Dickinson (unpublished report, 1970, see Data and Resources) apparently believed the reversed photograph to be correct, as he used it in an unpublished report he coauthored with Johnson and Ellen (unpublished report, 1968, see Data and Resources). Taylor *et al.* and Dickinson based their conclusion that the 1906 fault trace crossed Alpine Road at Locality F (Fig. 2) in part on the observation that curves in Alpine Road, as depicted in the reversed photograph, closely resemble those seen today when the road is viewed looking north from that locality. We conclude, however, that the photograph taken looking to the southeast should not have been reversed, and that it is correctly printed here as Figure 10, the same way it appeared in Taber (1906) and Lawson *et al.* (1908), based on the following observations.

At least six historical photographs (four shown here) were taken at the location where the 1906 fault crossed Alpine Road; all show the same trees and bushes (Figs. 10–13). All support the way Figure 10 was printed in Lawson *et al.*
22 (1908) and Taber (1908). These photographs were taken at different times (because fractures in the road are fresh in some, worked over in others) and were made by different photographers. All of these photographs could not reasonably have been printed in reverse.

Additional evidence indicating that the photograph of Figure 10 should not have been reversed results from our analysis of Figure 11, which shows a well-dressed man and woman. In the photo, taken close to Figure 10, the man's coat is partly unbuttoned, revealing that the coat buttons are on his right side, correct for male attire; thus, the figure as we have it printed is of correct orientation. Moreover, by matching specific trees and bushes in the background of Figures 10–13, we can see that Figure 10 was printed cor-
23 rectly in Lawson (1908).

Further indication that the photograph in Taylor *et al.* (1980) should not have been reversed relates to the ridges that are barely visible in the background of the print. Today, ridges are not visible to the north from the location where Taylor believed the photograph was taken (Fig. 2, Locality F). The prominent high ridge in photographs of Figures 10–12 and 14 is located southeast of Los Trancos Road, and below it in the photographs is another ridge crest that matches Redberry Ridge (Fig. 2). Today, both ridges can be seen a short distance to the southeast of Locality E, as mentioned
24 earlier. An additional piece of evidence that the fault could not have crossed Alpine Road at Locality F is provided by a profile in Lawson *et al.* (1908, p. 105, fig. 41) and in our Figure 22. The ground is shown to rise immediately to the southwest, suggesting the crossing was on the part of Alpine Road that is at the base of Coal Mine Ridge.

We have shown from several lines of evidence that the photograph of Figure 10 should not have been reversed, thereby supporting our conclusion that the place where the fault surface rupture crossed Alpine Road in 1906 was at Locality D (Curve C3).

The following information from study of other old photographs and LiDAR images provides additional support for the conclusion that the 1906 fault trace did not cross Alpine Road at Locality F, as Taylor *et al.* and Dickinson concluded.

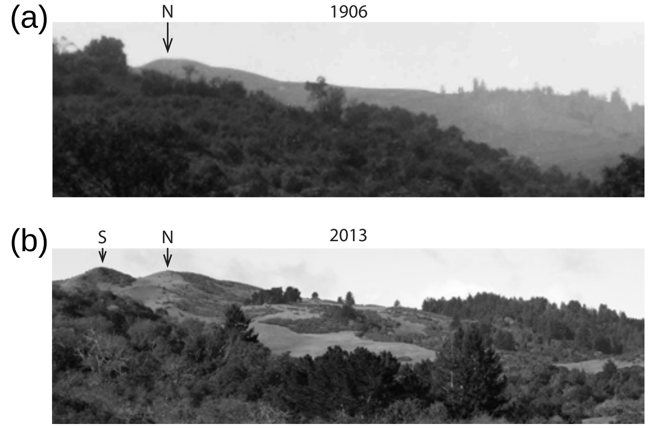


Figure 23. Photographs of Windy Hill and Coal Mine Ridge from the vicinity of Bovet Hill. (a) Enlargement of a portion of the 1906 photograph in Figure 17, taken from near the top of Bovet Hill, showing the north knob of Windy Hill and the crest of Coal Mine Ridge. (b) 2013 photograph taken from 50 m east of Bovet Hill, showing a view similar to (a). N—the north knob of Windy Hill. S—the south knob of Windy Hill.

The Use of LiDAR Technology and Old Photographs in Fault Identification

Dickinson (unpublished report, 1970, p. 22, see Data and Resources) referred to a fault-produced furrow south of Alpine Road that he interpreted as the eastern trace of the San Andreas fault. This furrow, not mapped as the primary rupture by Branner (Fig. 3), is shown in a 1906 photograph in Lawson *et al.* (1908, plate 16B) and in Figure 17. Our suspicions that the furrow did not trend toward the road crossing at Locality F, as Dickinson interpreted, led us to seek a means of determining the azimuth and location of the furrow. Changes in vegetation as well as new construction since 1906 have prevented us from making new photographs of views that duplicate the old photographs, but new interpretations of LiDAR images provided a substitute.

We started by searching for the location where the photograph in Figure 17 was taken. An important clue can be found in the background of the photograph, where the northern knob of grass-covered Windy Hill (Figs. 3 and 23a) is visible, but not the southern knob. Windy Hill is a prominent landmark near the western border of Portola Valley. During an on-site investigation, we concluded that the photograph was taken on or near the top of Bovet Hill (Fig. 2, Locality G; Fig. 9b, Locality 5) because this is the only place where the southern knob of Windy Hill is hidden by Coal Mine Ridge, but the northern knob can be seen, as well as the area where there was the field with the 1906 fault furrow.

Using software that draws upon 3D LiDAR data to produce maps and oblique bare-earth views, we tested whether the furrow in the 1906 photograph was the eastern trace of the fault trending toward Locality F. We did this by adding the eastern trace as mapped by Dickinson (unpublished

Figure 24. January 2010 photograph of a westerly view from near the top of Bovet Hill. The view is close to that of the 1906 photograph in Figure 17, although the row of pine trees obscures parts of Coal Mine Ridge and Spring Ridge. The boundary between the taller vegetation in the middle ground and the grass in the near ground is along the trace of the 1906 splay.

Figure 25. 1906 photograph view to the southeast from the base of Bovet Hill, showing the furrow of the fault splay, a man on a ridge top, and Redberry Ridge.

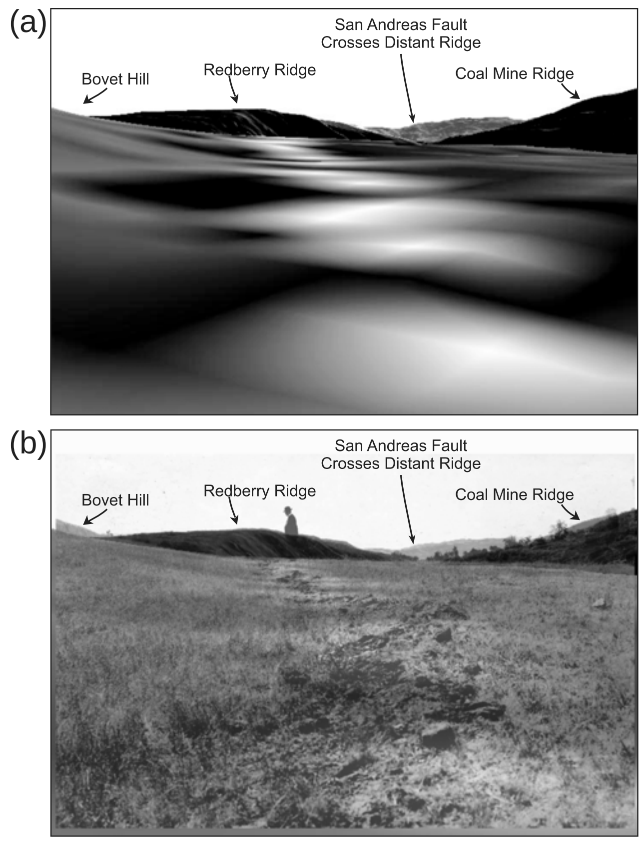


Figure 26. (a) Oblique bare-earth LiDAR view of the same scene as Figure 25. The diffused white dashes show the final adjusted fault trace locations transposed to a perspective camera view, as explained in Appendix C. (b) Composite view of the 1906 photograph overlain on the image of (a).

report, 1970, see Data and Resources) to a virtual map in the software, and used the map to make an oblique bare-earth LiDAR image of the scene shown in the 1906 photograph (Fig. 18a). The results demonstrate that the furrow does not coincide with the eastern trace because the alignment of the furrow and eastern trace do not match. We next tried to determine the location of the furrow in the photograph. To do this, we added a hypothetical trace to the virtual map and created a new oblique LiDAR image of the scene (Fig. 18a). The accuracy of the assumed trace position was checked by making a composite image (Fig. 18b) consisting of a semi-transparent copy of the 1906 photograph superposed over the LiDAR image. We adjusted the plotted fault trace and the viewer's location in repeated LiDAR images until a good match was achieved with the furrow (see Appendix C). After achieving the match, we concluded where the photograph was taken (Fig. 9b, Locality 6), and that the furrow was located along the northwest side of Bovet Hill (Fig. 2, Locality G). This location of the furrow is visible today as the boundary between different grasses and other vegetation (Figs. 16c, 24) (see Appendix D). The furrow trends northwest from the base of Bovet Hill toward Alpine Road at Locality E and, therefore, is not coincident with the eastern trace (see Figs. 9b and 18b).

Confirmation that the furrow trended toward Locality E followed from our analysis of a second 1906 photograph of the furrow (Fig. 25), one not used by Dickinson. We conclude that this photograph, also made in the Bovet Hill area (Fig. 9b, Locality 7), shows a view of the same furrow in Figure 17, but now viewed looking to the southeast. Using the same virtual map and alignment of the furrow determined in our analysis of Figure 17, we made a new oblique bare-earth LiDAR view (Fig. 26a) to match the second 1906 photograph (see Appendix C). The close match between the LiDAR image of Figure 26a and the photograph of Figure 25, as shown in the composite Figure 26b, confirm that the furrow alignment used to produce Figures 18a and 26a is correctly located. The location and trend of the furrow, however, differ considerably from those of the primary 1906 fault rupture, suggesting that the furrow is a splay

25 that diverged from the main fault (see Figs. 2 and 9b). If the furrow had been the main 1906 trace, a sharp bend south of Bovet Hill (or stepping) would be required in order to transit to someplace on the western trace where 1906 movement had been verified, as, for example, at Locality I (Fig. 2; Hall and Wright, 1993). If the splay had been the main trace in 1906, the large discrepancy between the location and alignment of the splay and the trace mapped by Branner (Fig. 3) farther to the west as a continuous fault between our Localities E, H, and I would have to be explained. From several lines of evidence discussed previously, Branner's trace is here considered to have been the main path of rupture in 1906.

We identified geomorphic features that we interpret as indicating the location of the primary 1906 surface rupture of the San Andreas fault south of Alpine Road by using another oblique bare-earth LiDAR view of the San-Andreas-fault zone (Fig. 21). This image is a view to the southeast from above Locality D. About 250 m southeast of Locality D, the trace lies near the northeastern base of Coal Mine Ridge (Fig. 2); farther southeast, where a seasonal stream flows from Coal Mine Ridge, the fault begins to climb the side of the ridge toward the next known position of the fault at Locality H (Fig. 2). The trace of the fault, as it climbs the ridge, is visible in the LiDAR image (Fig. 21, Locality A), despite the hummocky topography indicative of landslides. The signature of the fault trace across landslide terrain testifies to the geologic recency of the faulting. The location of the fault shown in Figure 21 is supported by Branner's map (Fig. 3).

The path of the fault on the east side of Coal Mine Ridge differs markedly from the complicated, anastomosing pattern shown on Portola Valley's official town geologic map (Price *et al.*, 1984) and other maps (Dickinson, unpublished report, 1970, see Data and Resources; Brown, 1972; Brabb *et al.*, 1998, 2000). The nearly complete absence of exposed bedrock on Coal Mine Ridge, the presence of numerous landslides, and the extensive, dense cover of chaparral and other vegetation, including poison oak, have been significant impediments to previous geologic work. Fortunately, geomorphic features typically associated with strike-slip faults are clearly evident in LiDAR images of the east side of the ridge, where they are well preserved beneath the thick vegetation canopy. Between Corte Madera Creek and Sausal Pond, however, LiDAR provides no apparent clue to the location of the active fault trace. Although bedrock in this area is the same poorly consolidated Santa Clara formation as on Coal Mine Ridge, physiographic evidence of the fault rupture is missing, we believe largely because the ground has been trampled by decades of cattle grazing. Fault rupture evident to Branner in this area in 1906 probably was thereby destroyed soon after the earthquake. In most of Portola Valley, however, bare-earth LiDAR has been enormously helpful in providing us with a means of revealing geomorphic features, especially in poorly exposed terrain like that of Coal Mine Ridge, and in showing, convincingly, that the principal 1906 movement of the San Andreas fault was along a single trace. Several research trench studies of the western trace have been done north of Sausal Pond (Hall *et al.*, 2001, p. 202) and in the southern part of the town, starting at Locality H (Hall and Wright, 1993), but none have been done between these two areas. Trenching could prove useful in locating the fault where geomorphic features are absent, as between Sausal Pond and Corte Madera Creek, and between Locality E and the first appearance of the fault to the south in LiDAR.

The San Andreas Fault near the Southern End of Portola Valley

The southernmost area of Portola Valley, beginning about 1 km southeast of where the fault leaves Alpine Road at Locality E, contains well-preserved geomorphic features associated with the fault that ruptured in the 1906 earthquake. A research trench in that area, dug at locality H (Fig. 2; Hall and Wright, 1993) during early planning for a housing development, revealed the western trace of the San Andreas fault to be exactly where Dickinson (unpublished report, 1970, see Data and Resources) had mapped it. Beginning about 80 m south of the research trench, this fault trace follows a straight gully about 5 m deep, 25 m wide, and 230 m long. A small stream course that crosses the gully has a right lateral offset of about 5 m. Remnants we interpreted as en echelon breaks trending about 35° to the gully axis are preserved at Locality I, suggesting an origin in 1906. We saw these features in 2010. At that time they consisted of moderately numerous, linear, north-trending, shallow depressions preserved on the northeast side of the gully. Hall and Wright (1993, plate B4) described them as 26
"north-trending, left-stepping extensional cracks." Localities H and I are supported by Branner's hand-drawn map (Fig. 3).

Discussion

The 1906 Trace in Portola Valley

We conclude that the primary fault-surface rupture in 1906 took place only along the western trace of the San Andreas fault, as shown on Figures 2 and 4. This conclusion is based on our analysis of 1906 photographs, including analysis of 1906 photographs taken at Alpine Road; mapping by Dickinson (unpublished report, 1970, see Data and Resources); other archival materials; field studies; and LiDAR images of the fault trace. Our location of the 1906 trace agrees with mapping by Branner (Fig. 3).

The 1906 trace enters Portola Valley from the north on the western trace and passes on the side of a house on the north side of Portola Road (Fig. 2, Locality A; Fig. 7). Southeast of the house, the fault crosses Portola Road (Fig. 8) and continues to the southeast to Sausal Pond on the southwest side of the topographic basin in central Portola Valley. This trace was identified by Branner in field studies (Fig. 3) by Dickinson (unpublished report, 1970, see Data and Resources) from local geomorphic features, and by research trenches dug at numerous localities (Hall *et al.*, 2001; Wetenkamp, 2008). The trenches added precision to the location of the fault and suggest that the actual trace may be a few meters west of Dickinson's mapped location and approximately along Branner's trace, as shown on a smaller-scale map.

From the dam at Sausal Pond (Fig. 2, Locality B) to Corte Madera Creek at Locality C, our evidence indicates that the 1906 surface rupture does not coincide with the western trace mapped by Dickinson; instead the trace trends toward the right-lateral offset of the creek. In this area the fault is entirely within the weakly consolidated Santa Clara formation (Fig. 4). Branner would have seen the furrow left by the fault, but no geomorphic evidence of the fault trace remains in this area, and probably was obliterated after the earthquake by trampling from cattle that grazed the area for decades.

Evidence that the surface rupture between Sausal Pond and Corte Madera Creek is entirely within the Santa Clara formation results from our examination of a rock exposure on the east side of the creek at Locality C. Between the two right-angle bends at this locality, Brabb *et al.* (2000) show rock on the east side of the creek at this locality (and farther to the north and south) as the Whiskey Hill formation of Eocene age. We, however, found this excellent bedrock exposure contains coal seams typical of the Santa Clara formation of Pleistocene and Pliocene age. Because this is the only exposure of bedrock we have found in the area Brabb *et al.* mapped as Whiskey Hill, we conclude this rock unit should have been mapped as Santa Clara. Dibblee (1966) and Price *et al.* (1984) mapped the rocks on both sides of the western trace from Sausal Pond to the south border of the town as the Santa Clara formation.

Southeast of Corte Madera Creek, the fault crosses Alpine Road at Curve C3, based on our analysis of 1906 photographs, a notebook by Turner (Fig. 20), as well as on careful scrutiny of a description of the fault crossing by Branner in Lawson *et al.* (1908). Southeast of the Alpine Road crossing, Branner's hand-drawn map (Fig. 3) and LiDAR data (Fig. 21) show the 1906 trace as climbing Coal Mine Ridge to Locality H. Continuing southeast to the border of the town, the 1906 trace is evident today from geomorphic features.

We have interpreted a 1906 furrow in the field southeast of Alpine Road as a splay from the main trace. The ground disruption was weaker along the splay than described by Taber (1908) for the main 1906 trace, and our analysis suggests that the splay diverges at a significant angle from the main trace as shown by Branner (Fig. 3), and differs from the trend of the eastern trace of the San Andreas fault. Our estimation of the location and trend of the splay is from analysis of both LiDAR data and 1906 photographs. This analysis has aided in solving a controversy as to whether fault movement in 1906 was on the eastern trace in the vicinity of Alpine Road.

Was There Stepping between the Eastern and Western Traces?

We conclude that there was no stepping from the western to the eastern trace in Portola Valley because we found no historic documentation in support of movement anywhere on the eastern trace in 1906. This conclusion differs from that of Dickinson (unpublished report, 1970, see Data and Resources) and Taylor *et al.* (1980, p. 60), who concluded that in 1906 there was left stepping between the two traces. They based their conclusions on their interpretation that in 1906 the fault crossed Portola Road on the western trace at Locality A and crossed Alpine Road on the eastern trace at Locality F. Dickinson was not clear as to where the stepping took place between Localities A and F. Taylor *et al.* believed the stepping onto the eastern trace was about 100 m south of where the western trace crosses Portola Road (Fig. 2, Locality A). Collective evidence and analysis supports the conclusion that a single, through-going surface rupture occurred on the western trace, as originally mapped by Branner in 1906 (Fig. 3).

Origins of Conflicting Interpretations

We conclude that much of the confusion regarding where the 1906 rupture is located in Portola Valley, and whether fault movement stepped from one trace to another, may have come from map 22 in Lawson *et al.* (1908). The original version of the map and the 1970 reprinted version (Fig. 5a,b) show the fault as crossing Alpine Road at a location not supported by Branner's description in Lawson *et al.* (1908), or by the 1906 photographs of the scene, and are significantly to the west of Curve C3 that we regard as correct. The locations where the fault crossed Alpine Road indicated by the center of the lines used in the original map 22 and in the reprinted version (Fig. 5a,b) could not have been the 1906 active trace because the distant, faint ridgelines shown in Figures 10–12, and 14, and discussed earlier, 27
cannot be seen from either location, as the side Coal Mine Ridge obscures the view. In addition, no field exists (as mentioned by Branner) northwest of and adjacent to the Alpine Road crossing shown in map 22.

Reversing the 1906 photograph of the fault at Alpine Road, as indicated by Dickinson (unpublished report, 1970, see Data and Resources) and shown by Taylor *et al.* (1980), supports a transfer of the 1906 rupture to the eastern trace through Locality F. This image reversal seems to solve the problem of the location of the fault crossing if stepping to the eastern trace is accepted. Although we have shown that left stepping did not take place, the fault at Locality F is real (Fig. 2). It is an older fault in the San-Andreas-fault zone in Portola Valley (Price *et al.*, 1984; Fisher *et al.*, 2002; Wetenkamp, 2008; Fig. 4).

Confusion as to the location of the 1906 active trace of the San Andreas fault in Portola Valley may have resulted to some degree from the unfortunate errors made in printing the two versions of map 22 in the Lawson *et al.* (1908) report

(Fig. 5a,b). More disruptive was the hypothesis that the dislocation stepped left from the western to the eastern trace, which resulted in a significant deviation in the course of understanding the location and mechanics of the 1906 offset. However, probably the most important failure of the published literature on the location of the active 1906 trace of the San Andreas fault in Portola Valley was the poor attention given the location of the fault as mapped by J. C. Branner soon after the earthquake. It is unfortunate that his contribution was not published to exacting standards in Lawson *et al.* (1908) or elsewhere, but it nevertheless was available and is included here.

Importance of Correct Location of the 1906 Trace

Our conclusions regarding the location of the 1906 fault rupture in the Town of Portola Valley are in accord with observations made by Branner (Fig. 3) and indicate that the observed rupture traversed the entire length of the town as a single trace (Fig. 4). Our location of the 1906 trace along Alpine Road is as much as 110 m to the east of the western trace crossing of the road as mapped by Dickinson (unpublished report, 1970, see Data and Resources) and Price *et al.* (1984; Fig. 2). This is a critical difference because our location of the western trace is close to modern buildings and recreational facilities and portends seismic risk to those structures. Because fault displacements commonly follow earlier fault movements (Cluff, 1968, p. 55 and p. 66; Wallace, 1968, p. 16), the trace identified here should be considered the most probable location of future surface movement along the San Andreas fault in Portola Valley.

The Geologic Structure of Coal Mine Ridge

Evaluation of 3D LiDAR images clearly reveal, for the first time, the geologic makeup and structure of Coal Mine Ridge, the main landmass traversed by the San Andreas fault in the study area in southern Portola Valley (Fig. 2). Although several faults and many lineaments have been mapped on the ridge (Dickinson, unpublished report, 1970, see Data and Resources; Price *et al.*, 1984; Pampeyan, 1995), the nearly complete absence of exposures of the underlying Santa Clara formation of Pliocene and Pleistocene age has made geologic interpretation difficult. Rare outcrops reveal poorly consolidated sandstone and conglomerate, but little of bedding attitudes. Most of the ridge is covered by slope wash and landslide deposits, but an inclined LiDAR view of the west side of Coal Mine Ridge clearly shows that the ridge consists of a homocline of gently east-dipping strata (Fig. 27).

Dickinson (unpublished report, 1970, see Data and Resources) and Price *et al.* (1984) show a fault along the crest of Coal Mine Ridge from the south end of Portola Valley to their version of the western trace of the San Andreas fault north of Corte Madera Creek. Along the crest of Coal Mine Ridge, the fault coincides with a lineament shown by Pampeyan (1995). The lineament is a trench that might be considered a sackung (Zischinsky, 1969), a structure developed at a ridge crest by gravitational spreading from creep down the flank of a steep ridge. We have found no evidence of creep along the lineament, or of an associated steep fault on the west side of Coal Mine Ridge. We interpret the linear trench not as a fault trace, but as mostly curved elements of bedrock stratigraphy.

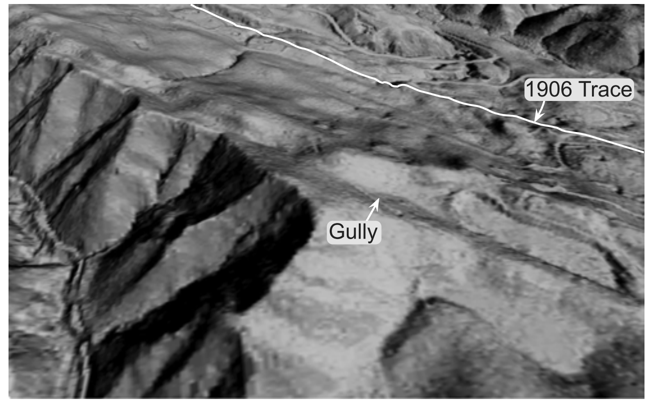


Figure 27. Oblique bare-earth LiDAR view to the north of the west side of Coal Mine Ridge, showing easterly dipping strata of the Santa Clara formation of Pliocene and Pleistocene age and the 1906 trace of the San Andreas fault. Gully near the spine of the ridge was considered part of a fault trace by Dickinson (unpublished report, 1970, see Data and Resources) and Pampeyan (1993) (see text), but is interpreted here as mostly curved elements of bedrock stratigraphy. 28

Conclusions

Field studies, the interpretation of 3D LiDAR images, and composite images made from LiDAR views in conjunction with 1906 photographs enabled us to estimate the location of the 1906 rupture of the San Andreas fault in a part of Portola Valley where mapping efforts of recent decades have proved inadequate. Confusion as to where the fault rupture occurred in 1906 near Alpine Road may have originated from inconsistencies in the fault location shown in the original and in the reprinted versions of a geologic map in Lawson *et al.* (1908) and from conclusions drawn from the incorrect reversal of a 1906 photograph. We show that the primary rupture in 1906 in the town was along the western of two main traces of the San Andreas fault. The location of the western fault trace is supported by an archived map and a field notebook, both made by investigators who witnessed the surface rupture associated with the 1906 earthquake. Identifying the correct location of the 1906 surface rupture is important because the rupture occurred on a single trace (plus a splay) that is closer to buildings and recreational facilities than previously believed. Our analysis also shows that there was no step over within the town to another trace and thus clarifies the movement mechanics of the fault during the 1906 earthquake. LiDAR images suggest that Coal Mine Ridge is a gently east-dipping homocline of sedimentary rocks with multiple lineaments attributed to bedding features, rather than to multiple traces of the San-Andreas-fault zone.

Data and Resources

An unpublished hand-drawn map by J. C. Branner showing the location of the main 1906 surface rupture of the San Andreas fault can be found in an album he compiled entitled "Photographs illustrating the Effects of the Earthquake of April 18, 1906." The album is available in the Bancroft Library archives, University of California, Berkeley, California. An enlarged portion of this map is shown in Figure 3.

The unpublished report by W. R. Dickinson, "Commentary and reconnaissance photogeologic map, San Andreas rift belt, Portola Valley, California", was prepared for the Town of Portola Valley in 1970. It is available in the Branner Library, Stanford University, California, and the U.S. Geological Survey Library, Menlo Park, California.

A. M. Johnson and S. D. Ellen prepared an unpublished report in 1968, "Preliminary evaluation of the interaction between engineering development and natural geologic processes on the Bovet Property, Town of Portola Valley, California, with a section on the San Andreas Fault by William R. Dickinson." The report was prepared for the Town of Portola Valley, California, and is available at the Branner Library, Stanford University, California, and the U.S. Geological Survey Library, Menlo Park, California.

The LiDAR data we used was obtained from a survey conducted in 2007 by the EarthScope Northern California LiDAR Project, available at http://www.opentopography.org (last accessed April 2013). This material is based on services provided to the Plate Boundary Observatory (PBO) by NCALM (http://ncalm.org; last accessed April 2013). PBO is operated by UNAVCO for EarthScope (http://earthscope.org; last accessed April 2013) and is supported by the National Sciences Foundation (No. EAR-03w50028 and EAR-0732947) URL: http://dx.doi.org/10.5069/G9057CV2, last accessed April 2013). The Northern California LiDAR Project was part of a program to survey the entire San Andreas fault in California. In Portola Valley, the LiDAR survey covered a northwest-trending area about 1.5 km wide, centered on the San-Andreas-fault zone.

San Mateo County, in 1894, obtained a deed that transferred to the county the portion of Alpine Road in the San-Andreas-fault zone. That deed contained details of a survey of the 1894 road and is recorded in Road Map Book No. 2, as "67 Deed 582." The deed is referred to in a county map entitled "Right-of-way map, Alpine Road—County Road No. 75, Map Sheet 21," dated 1977 (updated 1980). The map and deed are available at the San Mateo County Department of Public Works, Redwood City, California.

F. W. Turner recorded observations about the 1906 earthquake five months after the event in an unpublished field notebook available in the Stanford University Archives Library, J. C. Branner Collection, Stanford, California (see Fig. 20).

Acknowledgments

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Appendix A

Measurement on Alpine Road

To measure the 0.75-mile (1.2-km) distance along Alpine Road from the Portola Road intersection to the fault crossing, as Branner described (Lawson *et al.*, 1908, p. 107), we used a software program that took into account the scale and projection of the two maps by the U.S. Geological Survey available in 1906. The maps were the 1899 edition of the 1:62,500-scale Palo Alto quadrangle (Fig. 15a), the most detailed map available, and the 1:125,000-scale Santa Cruz quadrangle (Fig. 15b), the map Branner (Fig. 3) and Lawson *et al.* (1908; Fig. 5) used to show the main 1906 fault rupture. For each map, a line was added that followed Alpine Road. The line ended where the software program indicated it represented 0.75 miles (1.2 km) from Portola Road, as shown in Figures 15a and b.

Appendix B

Alpine Road Survey of 1894

Data for the survey line shown in Figure 19a for Alpine Road in 1894 came from the Public Works Department of San Mateo County, at Redwood City, California (see Data and Resources). Unfortunately, the data do not include information on where each survey point is located relative to the side or center of the road; nor does it include radius or arc data to define the alignment of large curves. A note included in the survey, however, is helpful in stating that the survey points are mostly not on the road centerline. The 1906 photograph of Alpine Road in Figure 13 provides additional helpful information showing that the road was a single, narrow lane. The map of the 1894 alignment in Figure 19a was created first by plotting a line from the survey data onto a bare-earth LiDAR (Light Detection and Ranging) base map. Most of the data points were found to be on the side of the current road alignment, thereby allowing us to interpret the narrow 1906 alignment relative to the survey line, as shown in Figure 19a.

Appendix C

LiDAR Images

In the ground-level, oblique, bare-earth LiDAR images in Figures 18a and 26a, the poor resolution of the foreground and the diffused character of the white dashes, representing fault traces, are the result of the way the software program created the images. The oblique images were made from 3D vertical bare-earth LiDAR data for the area defined in a vertical map view. The amount of detail shown in the foreground of Figures 18a and 26a was determined by the resolution in the map-view image from which the oblique views were made. In an extreme oblique view that simulates standing on the ground, as in Figures 18a and 26a, the foreground is greatly magnified from the map-view image. This magnification caused lines (actually made of fine dots) for the fault traces in the map view to become large, poorly defined dots in the oblique foreground view, but smaller and better defined in the distance. Details such as grass and dirt clods, which would be helpful to see in the enlarged foreground of Figures 18a and 26a, are completely missing because they are smaller than the limit of resolution in the original LiDAR map view. Despite the poor resolution in the foreground of the inclined views of these figures, the images are sufficient to approximate the scenes of the 1906 photographs (Figs. 17 and 25) and to determine the location of the furrow in the photographs, as well as to show in

Figure 9b the relation of the furrow to the eastern trace and the main traces of the San Andreas fault.

Appendix D

Vegetation Lineament

A lineament defined by different grasses and other vegetation is evident today in certain seasons of the year along the location of the 1906 splay, as shown in Figure 16c. When we visited the area of the splay in the winter of 2010, the vegetation had been left to grow undisturbed and was 30–40 cm higher and of slightly different composition on the southwest side of the lineament compared to the northeast side (Fig. 24). The vegetation shown in the 1906 photographs of the splay and field (Figs. 17, 25), by contrast, is short and similar on both sides of the splay and appears to have been trampled, or cut short, probably from grazing. The grazing is here considered to have eliminated any contrast that might have resulted if the vegetation had remained undisturbed. Grazing, as well as seasonal changes, also may explain why a lineament is not evident in some aerial photographs of the field that contained the 1906 splay (Fig. 16).

30 Cima Way
Portola Valley, California 94028-7812
(C.T.W., R.T.W.)

Cotton, Shires and Associates, Inc.
330 Village Lane
Los Gatos, California 95030
(T.S.)

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