Final Technical Report

REFINING THE HOLOCENE SLIP RATE ON THE GREENVILLE FAULT ZONE

EASTERN SAN FRANCISCO BAY AREA, CALIFORNIA

Award 03HQGR0108

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ABSTRACT

This study refines the rate of Holocene right slip on the Greenville fault zone by constraining lateral offsets of, and improving age constraints for, a latest Pleistocene to early Holocene alluvial channel-fill sequence exposed in trenches excavated in northeastern Livermore Valley. Our research builds on detailed knowledge of the fault and the alluvial deposits at this site previously documented by Sawyer and Unruh (2002). The 1980 Livermore earthquake sequence produced minor ground cracking along more than 6 km of the northern Greenville fault, including one of the most extensive rupture traces that offset the pavement of Laughlin Road and continued northwest through the trench site. For the present study, we excavated two trenches parallel to and on opposite sides of the 1980-fault trace of the northern Greenville fault, and one trench normal to and across the fault trace.

In total, the lateral offset of the channel-fill sequence across the fault trace was constrained by four fault-parallel trenches and one fault-normal trench, and the location and geometry of the fault were constrained by exposures in three fault-normal trenches and in one “fault-parallel” trench. The three-dimensional geometry of the channel-fill sequence on either side of the Greenville fault was precisely constrained at the “Laughlin Road” trench site by re-occupying existing survey monuments established by Sawyer and Unruh (2002). Specifically, the channel-fill sequence consists of three distinct and laterally restricted stratigraphic units that are right-laterally offset from 16.3 to 21.6 m across the fault trace. The duration of fault offset is bracketed by numerous photon-stimulated luminescence dates on sand-sized separates of bulk-sediment samples collected from the channel-fill sequence that range in age from 13.45 $\pm$0.79 to 10.64 $\pm$0.85 ka (Berger Sawyer, and Unruh, 2010). In combination, these data and their associated uncertainties constrain the rate of right slip across the 1980-rupture trace of the northern Greenville fault zone during the past 9 to 12 ka at 1.9 $\pm$0.3 mm/yr.

This Holocene slip rate estimate is nearly identical to the creep rate of 2 mm/yr based on 46 years of trilateration surveys of the Green triangulation net, located about 3 km to the southeast near Highway 580, which agrees with preliminary creep rate estimates based on 2000-2010 continuous global positioning system (GPS) observations (Lienkaemper et al., 2012). The Holocene rate estimate also agrees with the long-term average late Cenozoic slip rate of 2 $\pm$1 mm/yr, estimated south of Livermore Valley in the Northern Diablo Range (Peterson et al., 1996; Working Group on California Earthquake Probabilities, 2004—hereafter WG2004). However, our Holocene slip rate estimate is significantly lower than the secular rate of 5.4 $\pm$0.6 mm/yr derived from analysis of GPS data collected between 1993 and 2003 (D'Alessio et al., 2005).

We note that this is a minimum rate that does not account for offsets along a second Holocene-active fault was previously documented in two AP trenches approximately 30 m, or less, east of the 1980-fault trace at the Laughlin Road trench site. Thus, the Holocene slip rate may be somewhat higher than 1.9 $\pm$0.3 mm/yr across both traces of the northern Greenville fault zone.

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1.0 INTRODUCTION

The approximately 45 to 58 km-long (Hart, 1981; Unruh and Sawyer, 1998; Working Group, 2004) Greenville fault is the easternmost right-lateral strike-slip fault zone of the San Andreas fault system at the latitude of the San Francisco Bay area. The fault strikes north-northwest- to northwest through the Northern Diablo Range and along the eastern margin of Livermore Valley (Fig. 1). The Greenville fault was first mapped by Vickery (1925), who referred to it as the Riggs Canyon fault, and subsequently by Huey (1948), Rodgers (1966), Herd (1977), Hart (1981a, b), Cotton (1972), Dibblee (1980a, b, c), Wagner et al. (1990), and Unruh and Sawyer (1998). These previous workers have documented right-lateral offsets and evidence suggestive of lateral slip on the Greenville fault, including: large-scale offsets of an ultramafic body and magnetic anomalies in the Northern Diablo Range, intermediate offsets and/or deflections of drainage channels, fault-bounded shutter ridges, numerous sag ponds including the one at Frick Lake (approximately 250 m southeast of the Laughlin Road trench site)(Fig. 2), possible offset of late Pleistocene terrace remnants, offset alluvial fans, sub-horizontal slickensides on exposed fault planes, earthquake focal mechanisms, results of GPS-geodetic studies, and minor right-lateral surface rupture during the January 1980 Livermore earthquake sequence ($M_L \leq 5.8$), and the 11 mm of transient shear strain recorded during the subsequent 4 years at the Green triangulation net adjacent to I-580 on the south (Lienkaemper et al., 2012).

The January 1980 Livermore earthquake sequence produced minor right-lateral surface rupture discontinuously along more than 6 km of the northern Greenville fault (Hart et al., 1980; Bonilla et al., 1980; Woodward-Clyde Consultants, 1980, Hart, 1981; 1982)(Fig. 2). Principally the sequence began with a M_L 5.5 event on January 24th that ruptured unilaterally to the southeast along the Greenville fault over a subsurface

distance of 15 km. This event produced discontinuous surface ruptures along approximately 6.2 km of the northern Greenville fault, from near the Alameda—Contra Costa county line southeastward to near I-580 (Fig. 2), and a maximum of 2.5 cm of right slip and 5 cm of vertical offset. The M_L 5.8 event on January 27th occurred 14 km to the south of the first principal event, near the termination of the January 24th rupture zone, and extended the zone of surface ruptures about ½ km southeastward. Many of the ruptures had a left-stepping *en echelon* pattern and most individual were less than 100 m in length (CDMG Staff, 1980; Woodward-Clyde Consultants, 1980; Bonilla et al., 1980). However, one of the most laterally continuous rupture zones, approximately 300 m in length, formed a series left-stepping *en echelon* cracks across Laughlin Road and extended northwest through the trench site investigated herein. At Laughlin Road 0.2 cm of right-lateral offset was measured after the 24th event, and a total of 0.7 cm offset was measured following the January 27th event (CDMG Staff, 1980; Hart, 1981; 1982).

The January 24th earthquake occurred on a N39°W-striking plane dipping 70° to the northeast, whereas, the January 27th event occurred on a near-vertical N13°W-striking plane (Bolt et al., 1981). Mechanisms for both events indicate predominantly right-lateral strike-slip faulting with relative northeast side up dip-slip motion (Bolt et al., 1981). The second principal event had a subordinate reverse component, which is consistent with the region transpressional setting. Seismicity associated with the northern part of the fault is characterized by a sub-vertical alignment of epicenters extending to depths of approximately 17 to 18 km (Bolt et al., 1980; Hill et al., 1990; Oppenheimer and Macgregor-Scott, 1992). Focal mechanisms indicate primarily dextral strike-slip motion on northwest-striking nodal planes (Oppenheimer and Macgregor-Scott, 1992).

1.1 TECTONIC SETTING AND PREVIOUS WORK

The Greenville fault has the potential to generate earthquakes of M_w 6.7 to 7.1 (e.g., Petersen et al., 1996; Unruh and Sawyer, 1998) with a characteristic earthquake of M_w 6.9 (Working Group on California Earthquake Probabilities, 2004—hereafter WG2004; WG2007). Yet there is no record of the rate or recency of Holocene activity on the Greenville fault (Schwartz, 2008).

A late Cenozoic sip-rate estimate for the Greenville fault of 2 $\pm$ 1 mm/yr is based on a 10 km right-lateral offset of a Mesozoic ultramafic body in the northern Diablo Range (Peterson et al., 1996). The slip rate estimate apparently is predicated on the assumption that offset began about 3 to 10 Ma. Sweeney (1982) interpreted bedrock and subsurface geologic relations as evidence for approximately 2 km of displacement on the modern, active branch of the Greenville fault during the past 4.5 Ma. These relations suggest the long-term average slip rate may be as high as approximately 0.5

mm/yr. Wright et al. (1982) estimated a minimum, late-Pleistocene slip rate of 0.5 to 0.7 mm/yr based on relative-dating of Pleistocene stream terraces in southeastern Livermore Valley that they concluded are displaced approximately 90 m along a single fault trace in a broad fault zone.

Recent geodetic studies suggest similar to considerably higher slip rates. The Green triangulation net spans much of the width of the Greenville fault south of I-580 (Fig. 2). Modeling results based on triangulation data collected between 1965 and 2009 indicate a right-slip rate of 2 mm/yr (Lienkaemper et al., 2012), comparable to the late Cenozoic slip rate of 2 ±1 mm/yr (Peterson et al., 1996). However, the full rate may be higher at this location because the array does not appear to span the entire width of the Greenville fault zone (Fig. 2). D'Alessio et al. (2005) modeled 200 GPS-derived surface velocities, determined from data collected between 1993 and 2003, to estimate a secular rate of 5.4 ±0.6 mm/yr for the Greenville fault. However, as stated in Lienkaemper et al. (2012), much or all of this apparent rate may reflect loading on other faults in the region, like the Calaveras fault.

Unruh and Sawyer (1998) identified a site, the "Laughlin Road" trench site, straddling one of the more continuous traces of 1980 ground cracks that they demonstrated had the potential to provide slip-rate information for the northern Greenville fault. The fault is expressed at the site by low scarplets, a deflected ephemeral drainage, and seasonally prominent vegetation lineaments. Sawyer and Unruh (2002) excavated four trenches and identified a laterally restricted alluvial-channel-fill sequence that had been right-laterally offset from 17 to 25 m along the 1980-fault trace, but found limited detrital charcoal or organic materials only in the youngest surficial deposits. Subsequently, they attempted to constrain rates of Holocene fault activity by radiocarbon dating secondary or pedogenic carbonate nodules collected from offset alluvial deposits. The pedogenic carbonate dates are interpreted as mean-residence dates providing minimum-limiting age constraint for the channel-fill sequence. Sawyer and Unruh (2002) used these data to estimate a preliminary maximum-limiting slip rate of 4.1 ±1.8 mm/yr on the northern Greenville fault.

In addition to the "western" fault trace, a second Holocene-active fault was identified in a private consultant's trenches approximately 30 m to the east (Berloger Geotechnical Consultants, 2000).

1.2 METHODOLOGY

The primary goal of the present research is to refine the preliminary Holocene rate of right-lateral strike-slip movement on the northern Greenville fault estimated by Sawyer

and Unruh (2002) at the Laughlin Road site, by better constraining lateral offsets and by obtaining reliable age constrains for offset channel-fill sequence.

Three exploratory trenches were excavated in the present study at the Laughlin Road site to: 1) re-expose key sections of a paleo-channel and associated laterally restrictive alluvial deposits that Sawyer and Unruh (2002) identified as right-laterally offset across the fault; 2) better constrain the three-dimensional geometry of the paleo-channel and alluvial-fill sequence across the fault; and 3) provide an opportunity for Dr. Glenn W. Berger, then Director of the E.L. Cord Geochronology Laboratory, Desert Research Institute, University of Nevada to collect sediment samples for luminescence dating. (An additional task to document the rate of right slip across the "eastern" Holocene fault trace at the site was not funded and, therefore, not conducted as part of the present research.) Two trenches were excavated parallel to and on opposite sides of the western or 1980-fault trace and the third trench was excavated normal to and across the fault trace. The fault-parallel trenches were excavated between the previous fault-parallel trenches of Sawyer and Unruh (2002) and the fault trace, thereby limiting lengths of "piercing-point" projections. The third trench was excavated perpendicular to the fault, north of the two earlier fault-normal trenches, to precisely locate the fault trace through the northern part of the site. In all, seven exploratory trenches were excavated at the site, four parallel and three perpendicular to the fault (Fig. 4).

After cleaning the trench walls with hand tools and a commercial pressure washer, color-coded flagging was used to mark fault planes, fractures, stratigraphic contacts, sample locations, soil horizons, and other noteworthy features. The trench walls were logged at a scale of 1 in/1 m (~1:39) using a Topcon AP-L1A robotic total-station to precisely locate each flag in the various trenches and utilizing a single project-based coordinate system. Graphical logs of the three trenches are presented in Plate 1. As anticipated the exposed deposits did not yield organic materials suitable for radiocarbon dating, therefore, a luminescence dating program was conducted by Dr. Berger.

Six sediment samples were collected from trenches 3A and 4A (Plate 1) for estimating burial ages using several photon-stimulated-luminescence (PSL) sediment-dating procedures applied to the sand and silt fractions of exposed deposits. In addition several smaller samples were collected adjacent to and approximately 20 cm above and below each of the six luminescence samples. The smaller samples were employed for measurement of *in situ* water and elemental concentrations, required for dose-rate calculations. Luminescence samples were extracted using light-tight tins after removing 8 to 20 cm of the trench wall. Only the ends of the blocks within each tin were exposed to light during sampling. Consequently, about 1 cm of this end material was removed

under filtered (dim orange) laboratory lighting before processing of the interior of the samples for luminescence measurements. These results, which are presented in a following section of this report, represent the first application of single-grain-quartz (SGQ) PSL dating of deposits from this region. The methodology, results and limitations of the PSL burial ages from the Laughlin Road site are presented and discussed in detailed in Berger et al. (2010).

To provide objectivity in our research, we conducted one formal and several informal field reviews of the trench site and trench exposures attended by personnel from the U.S. Geological Survey, Lawrence Livermore National Laboratories, California Division of Mines and Geology (i.e., California Geological Survey), various university researchers and students, private consultants, local residents, and other interested participants (see Acknowledgements for partial listing of reviewers).

2.0 LAUGHLIN ROAD SITE

2.1 Geologic and Geomorphic Characteristics

The Laughlin Road site straddles the western- or 1980-trace of the northern Greenville fault at the eastern edge of the Livermore Valley, Livermore, California. The fault crosses and offsets a small alluvial fan fed by a short ephemeral drainage (Figs. 3 and 4). The site is approximately 190 m northwest of Laughlin Road (T.2S., R.2E., NE$^1/_4$, Sec. 26), in an area of continuous ground cracks produced by the 1980 Livermore earthquake sequence (CDMG Staff, 1980; Bonilla et al., 1980; Hart, 1981; 1982) (Figs. 2 and 4).

Based on previous NEHRP research studies (Unruh and Sawyer, 1998; Sawyer and Unruh, 2002), three Alquisto-Priolo study ("AP") trenches (Berloger Geotechnical Consultants, 2000) and the distribution of 1980 ground cracks (CDMG Staff, 1980; Bonilla et al., 1980; Hart, 1981), the linear western fault trace strikes approximately N36°W through the Laughlin Road site. Here the fault is marked by low scarps and scarplets and seasonally distinct vegetation ('star thistle') lineaments. The vegetation lineaments, in conjunction with trench observations, indicate the fault zone forms a groundwater barrier, or impends the westward flow of shallow groundwater, which is consistent with water-well information to the southeast in the vicinity of Frick Lake (p.c. Mr. Frick, 8/01), a large sag pond south of Laughlin Road (Fig. 3).

Of possible importance a second Holocene fault, approximately 30 m or less east of the 1980-fault trace was exposed in two AP trenches by Berloger Geotechnical Consultants

(BGC, 2000; p.c., G. Borchardt, 8/01)(Fig. 4). This subparallel fault strikes approximately N50°W and truncates the surficial-soil B horizon. A-horizon materials were found to be mixed with gravel downslope of the fault, forming a colluvial wedge (p. 14, BGC, 2000; personnel communication, Kevin Ryan, BGC, 8/01), which was subsequently confirmed by the acting Alameda County Geologist, Dr. Glen Borchardt (p.c., G. Borchardt, 8/01). No other traces of the Greenville fault are suspected in the vicinity of the Laughlin Road trench site based in nearly 3,700 linear-meters of AP trenches extending from 85 m northeast (e.g., Fig. 4) to about 800 m southwest of the 1980-fault trace (BGC, 2000).

The eastern trace of the northern Greenville fault is sufficiently active to control the distribution of erosion and sedimentation along the ephemeral drainage passing through the Laughlin Road site. Upstream of this fault trace the drainage is incised into indurated sandstone of the Miocene Cierbo Formation (Wagner, et al., 1990; Crane, 1988; Graymer et al., 2010) and has only thin discontinuous alluvial deposits along its entire ½ km-long reach. The apex of the small alluvial fan is co-spatial with where the drainage crosses the fault (Fig. 4). Thus, the pattern of erosion and deposition along the ephemeral stream indicates that recent alluvial-fan deposition has been controlled by late Holocene down-to-the-southwest vertical displacement on the eastern fault trace, consistent with exposed soil-stratigraphic relations and the fault-activity assessment by BGC (2000).

Although the eastern trace noticeably influences fluvial-geomorphic processes at the site, the western trace appears to be the dominant trace of the northern Greenville fault at this location. This inference is based on the western trace having a more prominent and continuous geomorphic expression, apparently forms a shallow groundwater barrier/impediment, and ruptured during the 1980 Livermore earthquake sequence whereas no rupture was reported along the eastern trace. The western fault trace further controls the distribution of late Holocene alluvial-fan deposition and right-laterally offsets the topographic or geomorphic axis of the low-gradient alluvial fan.

Projected eastward across the 1980-fault trace, the alluvial-fan axis does not align with its source channel, but rather projects into a colluvial slope roughly 25 m north of the stream channel, based on analysis of a two-foot contour map produced by Sawyer and Unruh (2002) (Fig. 4). As a consequence of being right-laterally offset, active (i.e., late Holocene) deposition only occurs on the south flank of the alluvial fan (a.k.a. “conveyor belt tectonics”). Based on these observations and a generally comparable amount of stratigraphic offset, Sawyer and Unruh (2002) concluded that the entire alluvial-fan landform has been laterally translated to the northwest along the western trace of the

Greenville fault from 17 to 25 m, which agrees with the range determined in the current study (discussed below).

2.2 Trench Stratigraphy

All three trenches excavated at the Laughlin Road site (fault-parallel trenches 3A and 4A, and fault-normal trench 5; Fig. 4), revealed the same sequence of alluvial fan and paleo-channel deposits that were exposed in the exploratory trenches of Sawyer and Unruh (2002). The exposed stratigraphy is floored by sandstone of the Miocene Cierbo Formation, which is overlain by a late Pleistocene alluvial unit (CP), a latest Pleistocene to early Holocene channel-fill sequence (unit G0, three Holocene alluvial deposits (units W, YC and L), and a late(st?) Holocene colluvial unit (C). Another late Pleistocene alluvial deposits (unit PG) was previously exposed in trench 3 of Sawyer and Unruh (2002) as a thin channel-fill deposit scoured into unit CP, but was not exposed during the current study.

Alluvial units were correlated across the fault based on their relative stratigraphic position, unique stratigraphic and pedogenic characteristics, and matching transverse stream-channel morphology. The exposed stratigraphic sequence is briefly described herein, from oldest to youngest (see Sawyer and Unruh, 2002 for more details).

Cierbo Formation—The stratigraphic characteristics of the Cierbo Formation were found in this study and by Sawyer and Unruh (2002) to differ markedly across the fault, evidently due to significant lateral juxtaposition along the Greenville fault. The Cierbo Formation was exposed east of the fault in trenches 1, 3 and 3A and east of the fault in trenches 4, 4A and 5 (Plate 1). As revealed in trench 3A, the formation consisted of well consolidated, light brown, bedded to massive, sandstone and pebbly sandstone. West of the fault near the floor of trenches 4A and 5, however, the formation consisted of highly weathered massive sandstone lacking pebbles. The Cierbo Formation was previously exposed in fault contact with older alluvial deposits juxtaposed on the west (see log of trench 1 in Plate 1 of Sawyer and Unruh, 2002) indicating a down-to-the-southwest vertical component to offset on the western fault trace.

Alluvial Unit CP—Unit CP, the stratigraphically lowest alluvial deposit, was exposed only east of the fault in the northwestern half of trench 3A and, likewise, previously was exposed in trench 3 also east of the fault. This unit is scoured into, and backfilled against, a channel margin cut into the Cierbo Formation (Plate 1). The deposits are composed of gravelly to locally cobbly alluvium with a silty clay loam matrix, engulfed by pedogenic carbonate. The abundance of pedogenic carbonate and secondary clay in this paleosol reflect a protracted period of soil formation prior to its subsequent burial,

indicating a late Pleistocene age for unit CP. Sawyer and Unruh (2002) obtained AMS radiocarbon dates on pedogenic (i.e., secondary) carbonate from unit CP that range in age from 14.1 to 8.4 ka. Because of the problems associated with radiocarbon dating of pedogenic carbonate (discussed below), Sawyer and Unruh (2002) considered these dates to underestimate the age of the engulfed deposit, in this case of unit CP.

Alluvial Unit G— Unit G is scoured and channelized into the Cierbo Formation and into the unit-CP paleosol. Unit G consists of an interbedded sequence of alluvium that infilled a paleo-channel scoured into unit CP and the Cierbo Formation (Plate 1). Unit G contains two distinct and laterally restrictive layers of gravel, sub-unit Gb and underlying sub-unit Go. Both layers have rather abrupt and distinct southern pinch outs, particularly sub-unit Gb (Plate 1), that are used as piercing points to constrain amounts and styles of movement along the western trace of the northern Greenville fault (discussed below).

Sub-Unit Gb—Sub-unit Gb is a 2 to 20 cm thick gravel layer within the upper part of unit G, as exposed in trenches 3A and 4A (and previously in trenches 2, 3 and 4 of Sawyer and Unruh, 2002). The gravel-sized clasts are composed of chert, quartz, metavolcanic rock, and moderately consolidated sandstone that were locally derived from the Cierbo Formation. The sandstone clasts are angular to subrounded, whereas the siliceous clasts are very well rounded. The basal contact of sub-unit Gb exhibits evidence of scouring, locally including small-scale channels. Sub-unit Gb pinches out to the south near Stn. 9.2W in trench 3A and near Stn. -9.5 E in trench 4A (Plate 1).

Sub-Unit Go—Gravel layer Go is 5 to 20 cm thick and contained within the lower-middle part of the unit-G paleo-channel-fill sequence. This sub-unit has the same clast composition as sub-unit Gb. The scoured basal contact of sub-unit Go has as much as 10 to 20 cm of local relief across small-scale channel forms. The southern pinchout of this layer is well defined in trench 3A but is less distinct in trench 4A where it tends to be somewhat discontinuous. The sub-unit pinches out southward near Stn. 9W in trench 3A and between Stn. -9.5W and -11.5W in trench 4A (Plate 1).

Alluvial Unit W—Exposed in all seven trenches, unit W is a southwestward thickening layer, up to about 2 m thick, composed of dark reddish brown to black (5YR2.5/2 to 5YR2.5/1) clay to sandy clay that is hard to extremely hard when dry. This unit exhibits properties of a vertisol or "self-churning" soil including wide desiccation cracks, strong coarse to extremely coarse, prismatic to columnar soil structure and, locally pedogenic slickensides on soil-ped faces resulting from differential movement resulting from the highly expansive nature of this clayey soil. Unit W is the youngest faulted deposit exposed at the trench site. The basal contact exhibits about 40 cm down-to-the-west,

vertically separation of across a high-angle fault exposed in trench 5, whereas, the upper contact is planar over the fault. Thus either the most-recent faulting event (MRE) at this site occurred during deposition of unit W or the upper part of unit W, along with a presumed MRE fault scarp, were striped by erosion. The abrupt southwest-thickening across the fault (Plate 1) shows unit W likely was truncated by erosion prior to burial by colluvial unit C.

Alluvial Unit YC—A narrow, nearly 1 m-deep erosional channel, incised through unit W and into unit G, was recently backfilled with unit YC deposits (Plate 1). The generally fining upward sequence consists of pebbly, cross-bedded sand in the lower approximately $^{2}/_{3}$ of the channel deposits (sub-unit YC1) grading to sandy silt (sub-unit YC2). Bedding and lamina locally have been disrupted by bioturbation. Sub-unit YC1 is the oldest unit exposed at the Laughlin Road site that we found to contain detrital charcoal. A detrital-charcoal sample from sub-unit YC1 in trench 3 yielded a “modern” AMS radiocarbon age (Sawyer and Unruh, 2002).

Alluvial Unit L—The uppermost alluvial deposit exposed at the site, unit L, is fine sandy loam to silty fine sand exposed in trench 3A and the overlapping portion of trench 4, as well as previously in the southern part of trench 3. Unit L represents a recent depositional lobe on the south flank of the alluvial fan at the site, based on the distribution and southward-thickening of this surficial layer combined with geomorphic relationships.

Alluvial Unit C—Only one colluvial unit was encountered at the Laughlin Road site shed southwestward from a gradual colluvial slope that, based on geomorphic relations, appears to partly bury the topographic axis of the offset alluvial fan. In addition, unit C thins to the south and southwest and buries unit W in trenches 4A and 5 (Plate 1) and, previously in the northernmost parts of trenches 3 and 4. The wedge-shaped unit is composed of reddish brown, clayey matrix supporting gravel-sized clasts. Unit G appears to un-faulted in trench 5.

3.0 RESULTS AND DATA ANALYSIS

3.1 Previous Age Constraints

Unit YC contains scattered, small fragments of detrital charcoal that have yielded modern AMS radiocarbon dates (Sawyer and Unruh, 2002). No other source of suitable charcoal was found for AMS dating in any of the seven trenches excavated at the Laughlin Road site.

AMS radiocarbon dating of pedogenic carbonate subsequence was conducted to provide, at best, minimum age constraints for two key trench units. Sawyer and Unruh (2002), with the assistance of Dr. Gordon Seitz, then of the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratories (CAMS-LLNL; currently at California Geological Survey), collected pedogenic carbonate (filaments, cemented nodules, ped coatings, and rhizoliths) from the calcic soils developed in units G and PG for AMS radiocarbon dating.

AMS radiocarbon dating of pedogenic carbonate is problematic because the material starts accumulating upon stabilization of the overlying geomorphic surface, and continues to accumulate as long as the deposit lies within the depth of wetting. Therefore, calcic soils contain a mixture of modern and possibly relatively old pedogenic carbonate and, thus, likely provide mean-residence ages for the calcic soil.

Paleosols are relic soils that generally have been buried below the depth of soil formation, however. Therefore, paleosols incorporate both an initial mean-residence age, as well as, the elapsed time since removal from soil-formation processes. We regarded these as “time-dependent” mean-residence ages that at some time in the past started recording actual elapsed time.

In any case, Sawyer and Unruh (2002) regarded the AMS radiocarbon dates on pedogenic carbonate as providing minimum-limiting age constraints on the pedogenic soils and associated engulfed deposits. Secondary carbonate no longer accumulates in the unit-PG paleosol, which is buried to a depth of 2 m. The paleosol yielded pedogenic carbonate AMS dates ranging from 14.1 to 8.5 ka. Whereas, pedogenic carbonate may still accumulate in the unit-G calcic soil, which yielded AMS ages ranging from about 2.5 to 4.1 ka.

The pedogenic carbonate AMS ages are considerable younger than ages provided by PSL luminesinence dating techniques for the same trench units (discussed in the following section).

3.2 New Age Constraints

To improve the previous age constraints, we applied photon-stimulated-luminescence (PSL) sediment-dating procedures to both polymineral fine silt and quartz sand fractions of 6 samples (Berger et al., 2010). All of the sediment samples were collected by Dr. Glenn W. Berger, then Director of the E.L. Cord Geochronology Laboratory, Desert Research Institute (DRI), University of Nevada. The sediment samples are from a stratigraphic column in trench 3A spanning from upper-most unit L, unit W, sub-units Gb

and Go, and basal unit G, near the paleo-channel margin. An additional sample was collected from unit W in trench 4A (Plate 1). Multigrain, single-aliquot-regenerative-dose (SAR) and pulsed-diode multigrain SAR-P PSL-dating procedures were applied to constrain the burial age of the 5 samples from trench 3A. In addition, micro-focused-laser technology was used in single-grain-quartz or SGQ-dating of the 3 samples from sub-units Gb and Go and basal unit G.

The polymineral fine-silt multi-aliquot age estimates are generally inaccurate, but the SAR ages from quartz sand grains are in stratigraphic sequence. The SAR ages range from 125 ±11 yrs (before 2005) within the surficial layer (unit L) to 13.45±0.79 ka in the base of the lowermost channel-fill of unit G in trench 3A (Table 1). The PSL-sediment-dating results are discussed below, and a complete description of the PSL-sediment dating procedures, results, and limitations is provided in Berger et al. (in press).

Unit L — PSL-sample LVM03-5 was collected from the youngest depositional lobe, unit L, of the alluvial fan at the Laughlin Road site, which overlies a deposit (unit YC1) AMS-radiocarbon dated as modern. The weighted mean SAR age of this sample is 125 ±11 yrs (Table 1), consistent with the modern AMS dates, its stratigraphic position, and the absence of obvious soil development.

For the purpose of constraining the slip rate on the Greenville fault, the SAR age of unit L is considered to be a “zero-set” age that has been subtracted from SAR ages of the older units. This practice reflects our uncertainty that the sediment samples were totally luminescence-bleached prior to deposition having been transported ½ km, or less, along ephemeral drainage channel.

Unit W —Sample LVM03-4 is from unit W in trench 3A and sample LVM03-6 is from the same unit exposed in trench 4A (Plate 1). Each sample was analyzed using the same four separate PSL sediment-dating procedures. Sample LVM03-4 also was analyzed using SGQ procedure, which appears to provide the age constraint for unit W of 4.31 ±0.23 ka. The weighted mean SAR age of sample LVM03-6 is 2.37 ±0.16 ka (Table 1).

Unit G —Unit G yielded three stratigraphically ordered SAR dates. The uppermost sample (LVM03-3) was collected within the fining-upward sequence of sub-unit Gb and provides a preferred age for this unit of 10.64 ±0.85 ka. Sample LVM03-2 is from a second fining-upwards layer, sub-unit Go (Plate 1). The weighted-mean SAR age of 11.12 ±0.55 ka provides the preferred age estimate of sub-unit Go (Table 1).

Sample LVM03-1 is from the lowermost paleo-channel section of unit G, where the southeast margin is cut into sandstone of the Miocene Ciebro Formation (Plate 1). The SGQ age appears to provide the best age constraint for the basal section of unit G of 13.45 ±0.79 ka (Table 1).

Discussion of PSL-Age Constraints —SAR PSL-age estimates constrain the latest Pleistocene through Holocene depositional and erosional history of an alluvial-fan sequence exposed in trenches at the Laughlin Road site. The ephemeral-drainage channel scoured into the Ciebro Formation and into older channel-fill unit CP prior to about 13.5 ka, or younger. Subsequently, the paleo-channel progressively backfilled to about 10.6 ka (or less) with sub-units Go and Gb.

Unit W fills a younger channel incised nearly 1.5 m into unit G, as exposed in trench 3A. Hence following backfilling of the paleo-channel and prior to deposition of unit W the drainage again incised its channel, after about 10.6 ka and before about 4.3 ka.

Alluvial-fan deposition resumed at approximately 4.3 ka, or earlier, and continued until at least 2.4 ka. The historical period is represented in the trenches by incision of a narrow erosional channel, apparently backfill in the past 125 years by unit YC deposits, capped by the most-recent constructional lobe of the alluvial fan at the Laughlin Road site.

3.2 Analysis of Stratigraphic Offsets

The amount and style of movement along the 1980-rupture trace of the northern Greenville fault is recorded by an offset paleo-channel and two associated infilled layers, and was constrained by total-station surveying. For these three offset stratigraphic datum, the horizontal component of fault offset is illustrated in map view in Figure 5, and both the horizontal and vertical components of fault offset are illustrated in cross-sectional view, constructed parallel to the fault, in Figure 6.

On either side of the fault, the southeastern margin of the paleo-channel is cut on sandstone of the Ciebro Formation and buried by the lowermost section of unit G (e.g., see log of trench 3A, Plate 1). East of the near-vertical fault plane the geometry of the channel margin is constrained by exposures in both walls of fault-parallel trench 3 and in the southwest wall of trench 3A. Similarly west of the fault, the channel-margin geometry is defined by exposures in trenches 4 and 4A (Fig. 5). These exposures show that the paleo-channel is oriented at a high-angle to the fault, suitable for use as a stratigraphic piercing “point”. Sub-unit Go and, particularly, sub-unit Gb abruptly “pinch out” to the southeast as exposed in trenches 3A, 3, 4A, 4 and in the southeast wall of

fault-normal trench 2 (e.g., Plate 1). In the fault-parallel trenches, these stratigraphic terminations are stacked one nearly directly above the other and, thus, similarly defining a high-angle of incidence with the fault plane (Fig. 5). Based on these relations, the northern margin of the unit-G paleo-channel and abrupt, southeastern terminations of the sub-units Go and Gb are used to constrain the amount of recent offset across the fault trace.

The three offset datum or piercing points are projected from 0.6 to 1.1 m westward and from 2.4 to 4.3 m eastward to constrain right-lateral offset across the 1980-fault trace that ranges from 16.3 to 21.6 m. The margin of the unit-G paleo-channel expresses the full range of uncertainty, and reveals little or no vertical displacement across the 1980-rupture trace of the northern Greenville fault (Fig. 6). The southern pinch outs of sub-units Gb and Go are defined as diverging northeastward towards the fault, adding to uncertainties in constraining lateral offset (Fig. 5), however, sub-unit Gb is considered to have the best geometric constraints of the three datum. Considering the stratigraphic and geometric relationships, sub-unit Gb has been offset from 18.9 to 20.7 m in a right-lateral sense across the fault with a preferred amount of 20.7 m. Sub-unit Go is offset nearly the same amount, from 18.2 to 20.7 m (Table 2).

Stratigraphic constraints reveal little vertical separation or apparent dip-slip displacement, if any, considering natural irregularities over the lengths of offset-datum projections (Fig. 5). Discrete fault offsets and/or associated near-surface folding appear to account for roughly 0.1 to 0.4 m of down-to-the-southwest vertical separation of sub-units Gb and Go across the fault. The northern margin of the unit-G channel may be separated 0.38 to 0.65 m down to the southwest. Nonetheless, the uncertainties appear to exceed or equal our estimates of the vertical separation of the projections.

The apparent dip-slip displacement is consistent with down-to-the-southwest vertical separation of stratigraphic units exposed in all three fault-normal trenches at this site and in other nearby trenches in either direction along the fault (BGC, 2000). The down-to-the-southwest apparent dip-slip displacement also is consistent with the fault motions determined for the principal events of the 1980 of the Livermore earthquake sequence, and with the overall geomorphic expression of the Greenville fault along the eastern margin of the Livermore Valley, which delineates a deep sedimentary basin, and at the western front of the Altamont Hills, a region of Quaternary tectonic uplift.

Hence, the 1980-rupture trace of the northern Greenville fault is characterized by a dominantly right-lateral strike-slip style of faulting having little, if any, consistent vertical displacement at the Laughlin Road trench site.

3.3 Slip Rate Estimates and Uncertainties

We estimate the Holocene slip rate for the 1980-rupture trace of the northern Greenville fault zone using PSL-sediment ages of Berger et al., (2010) coupled with estimates of lateral offset along the fault trace, and their associated uncertainties. The rate estimates range from 1.4 to 2.2 mm/yr. Sub-unit Gb provides the best geometric constraints on the amount of offset and provides slip-rate estimates ranging from 1.6 to 2.2 mm/yr, with a mean of 1.9 mm/yr (Table 2).

Discussion of Right-Slip Rates—There is good agreement among the results described above despite the slip-rate estimates being determined independently from three unique geometric datum offset across the northern Greenville fault. Overall, minimum slip-rate estimates range from 1.4 to 1.6 mm/yr, maximum estimates range from 2.1 to 2.2 mm/yr, and mean slip-rate estimates for each datum range from 1.8 to 1.9 mm/yr.

Herein, we report that the average rate of right slip across the 1980-rupture trace of the northern Greenville fault during the past 9-12 ka as 1.9 $\pm$0.3 mm/yr (Table 2). Our preferred rate, which is based on the relatively well-constrained offset of sub-unit Gb, also is 1.9 mm/yr.

It must be noted, however, that this slip rate characterizes only the 1980-rupture trace of the northern Greenville fault, and does not account for the second recognized Holocene fault trace. Therefore, we regard the rate of 1.9 $\pm$0.3 mm/yr as the *minimum* rate of right slip across the entire width of the northern Greenville fault.

4.0 ACKNOWLEGEMENTS

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5.1 Publications of this Study

Berger, G.W., Sawyer, T.L. and Unruh, J.R., 2010, Single- and Multigrain Luminescence Dating of Sediments Related to the Greenville Fault, Eastern San Francisco Bay Area, California: Bulletin of the Seismological Society of America, Vol. 100, No. 3, pp. 1051–1072.

TABLE 1
AGE-DATING RESULTS

Sample ID (in strat. order)	**Strata**	**AMS ^{14}C Age1** (ka)	**PSL-SAR Age[2]** (ka; sigma 1)
LVM03-5	Unit L	"modern"	0.125 ±0.011
LVM03-4	Unit W	-	4.31 ±0.23
LVM03-6		-	2.37 ±0.16
LVM03-3	Sub-unit Gb[3]	4.1 – 8.5 (min. age)	10.64 ±0.85
LVM03-2	Sub-unit Go[3]		11.12 ±0.55
LVM03-1	Unit G (lowermost)		13.45 ±0.79

[1] Radiocarbon dates from Sawyer and Unruh (2002); modern date on charcoal; 4.1 – 8.5 ka mean-residence dates on pedogenic carbonate.

[2] PSL-SAR luminescence dating results from Berger et al. (2010).

[3] The basal contacts of sub-units Gb and/or Go delineate the section of the unit-G channel margin used to estimate amounts of fault offset (e.g., see Table 2).

TABLE 2
GREENVILLE FAULT SLIP RATE ESTIMATES, LAUGHLIN ROAD SITE

Offset Datum	**Amount of Right Slip** (m)			**Duration of Slip**[2] (ka)			**Right-Lateral Slip Rate** (mm/yr)			
	Min.	Max.	Prefer.	Min.	Max.	Prefer.	Min.	Max.	Prefer.	Mean
Sub-unit Gb[1]	**18.9**	**20.7**	**20.7**	**9.3**	**11.5**	**10.4**	**1.6**	**2.2**	**1.9**	**1.9 ±0.3**
Sub-unit Go	18.2	20.7	--	10.0	11.7	10.9	1.6	2.1	--	1.8
Unit-G Channel Margin	16.3	21.6	--	9.3	11.7	--	1.4	2.2	--	1.8

[1] We consider that sub-unit Gb provides the best datum, based on available geometric constraints, to estimate amounts and rates of right slip across the 1980-rupture trace of northern Greenville fault.

[2] We estimates slip duration utilizing PSL-age assignments of Berger et al., (2010). Minimum slip duration is calculated as the minimum PSL age of stratigraphic unit, less interseismic interval estimated by USGS Seismic Hazards Maps-Fault Parameters (2002) of 537 yrs; "Preferred" duration is based on mean PSL age of stratigraphic unit, less ½ the inferred interseismic interval (269 yrs). Maximum slip duration is assumed equal to the maximum PSL age (at 1 sigma) of stratigraphic unit.

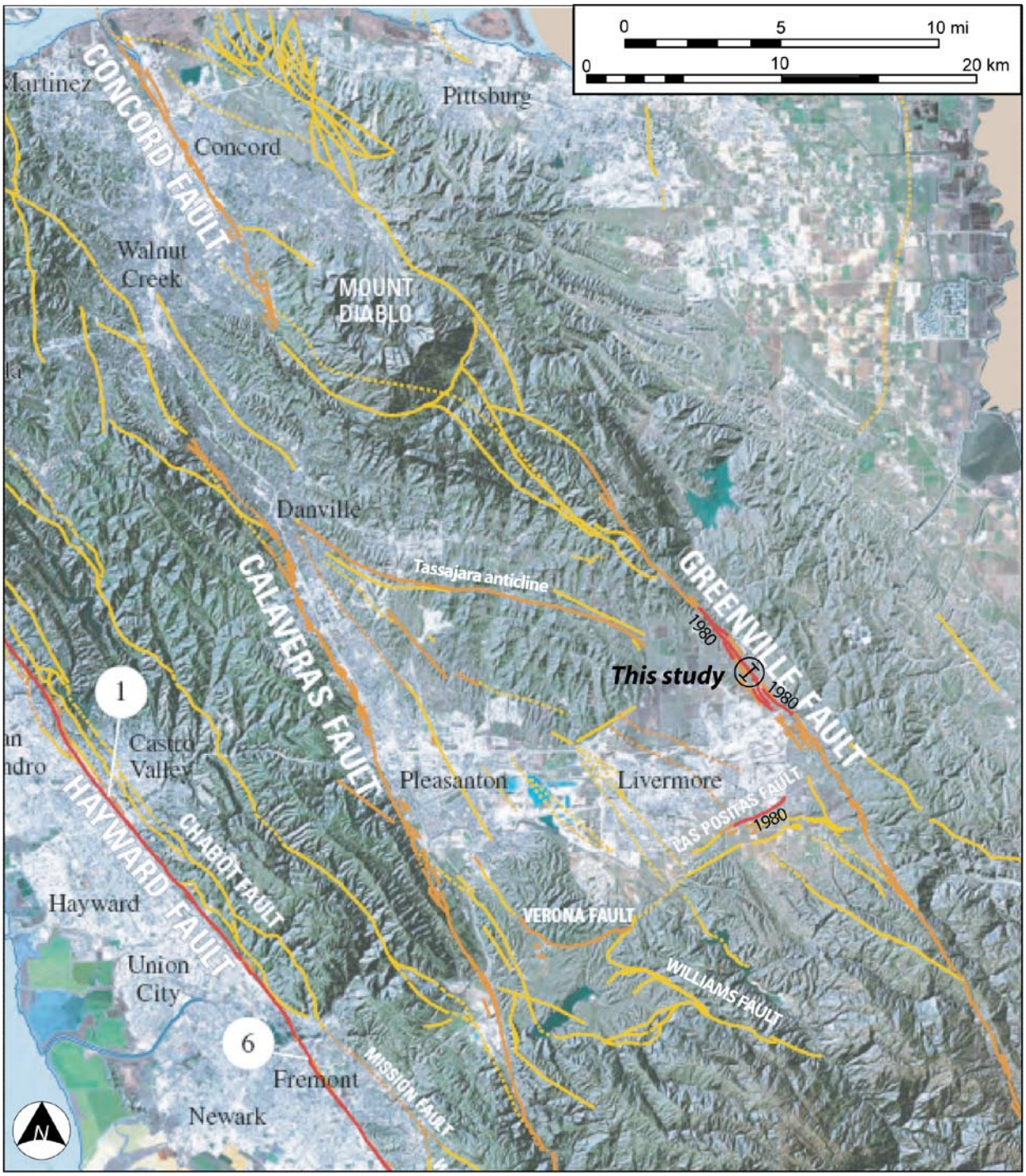

Figure 1 —Quaternary fault and fold map of the Livermore Valley region showing approximate location of the present paleoseismic study on the northern Greenville fault (source: U.S. Geological Survey; modified this study).

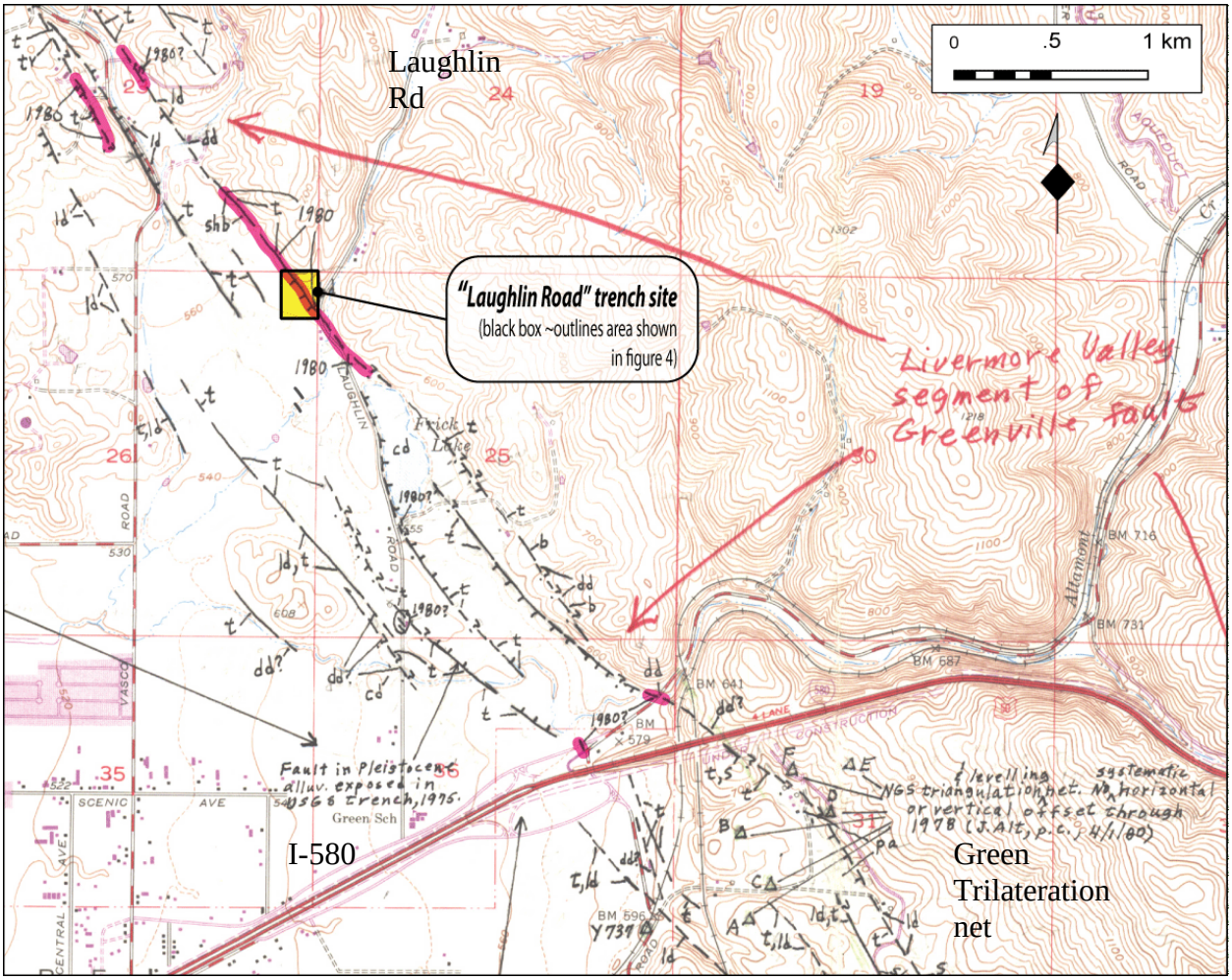

Figure 2 —Map of the northern Greenville fault by Hart (1981a, b) showing areas of fault rupture and ground cracking during the 1980 Livermore earthquake sequence. Also shown is the "Laughlin Road" trench site that straddles one of the most-continuous 1980-fault appear to span the full width of the Greenville fault zone as mapped by Hart (1981), nor as we have mapped this section of the fault (see Fig. 3).

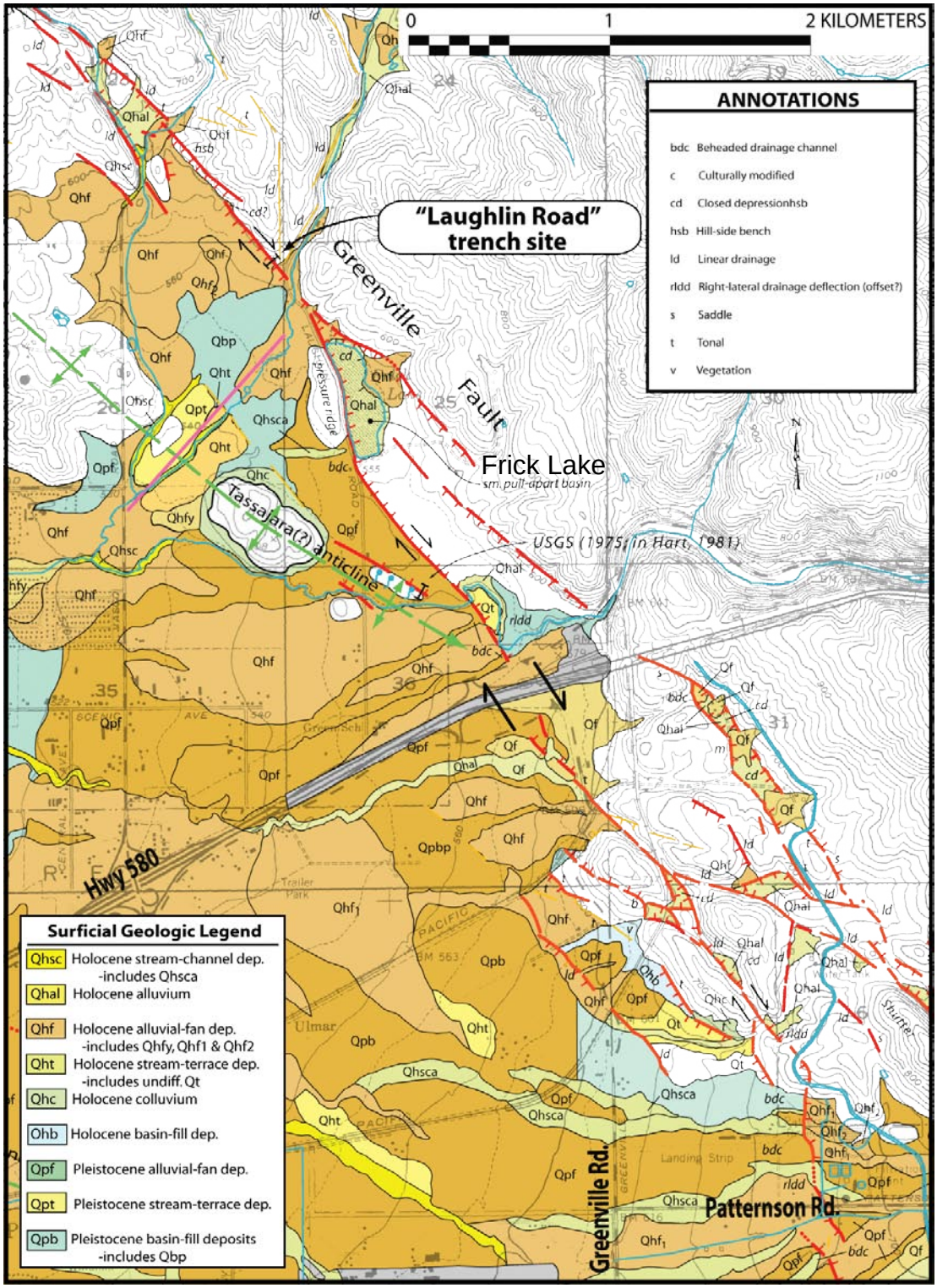

Figure 3 —Quaternary surficial geologic map of eastern Livermore Valley showing the northern Greenville fault. The Laughlin Road trench site is at the eastern edge of Livermore Valley, near Laughlin Road, where a Holocene alluvial fan and associated deposits have been offset during the past 9 to 12 ka across the northern Greenville fault.

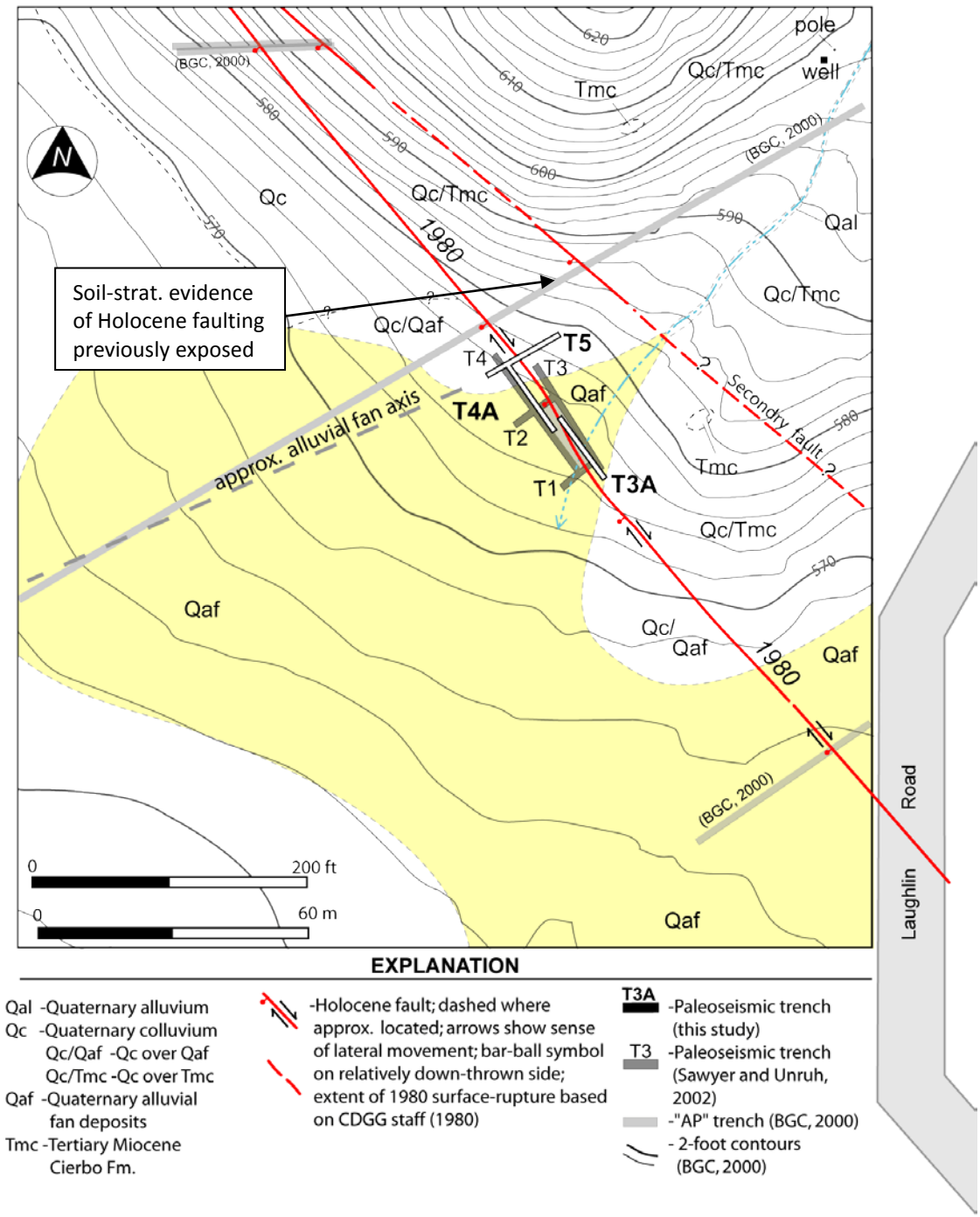

Figure 4 —Topographic map (2' contours) of the Laughlin Road trench site and vicinity showing Holocene alluvial-fan deposits (shown in yellow) offset (e.g., note north margin) along the 1980-trace of the northern Greenville fault. Trenches T3A, T4A and T5 were excavated as part of the present study, whereas trenches T1, T2, T3, and T4 previously were excavated by Sawyer and Unruh (2002).

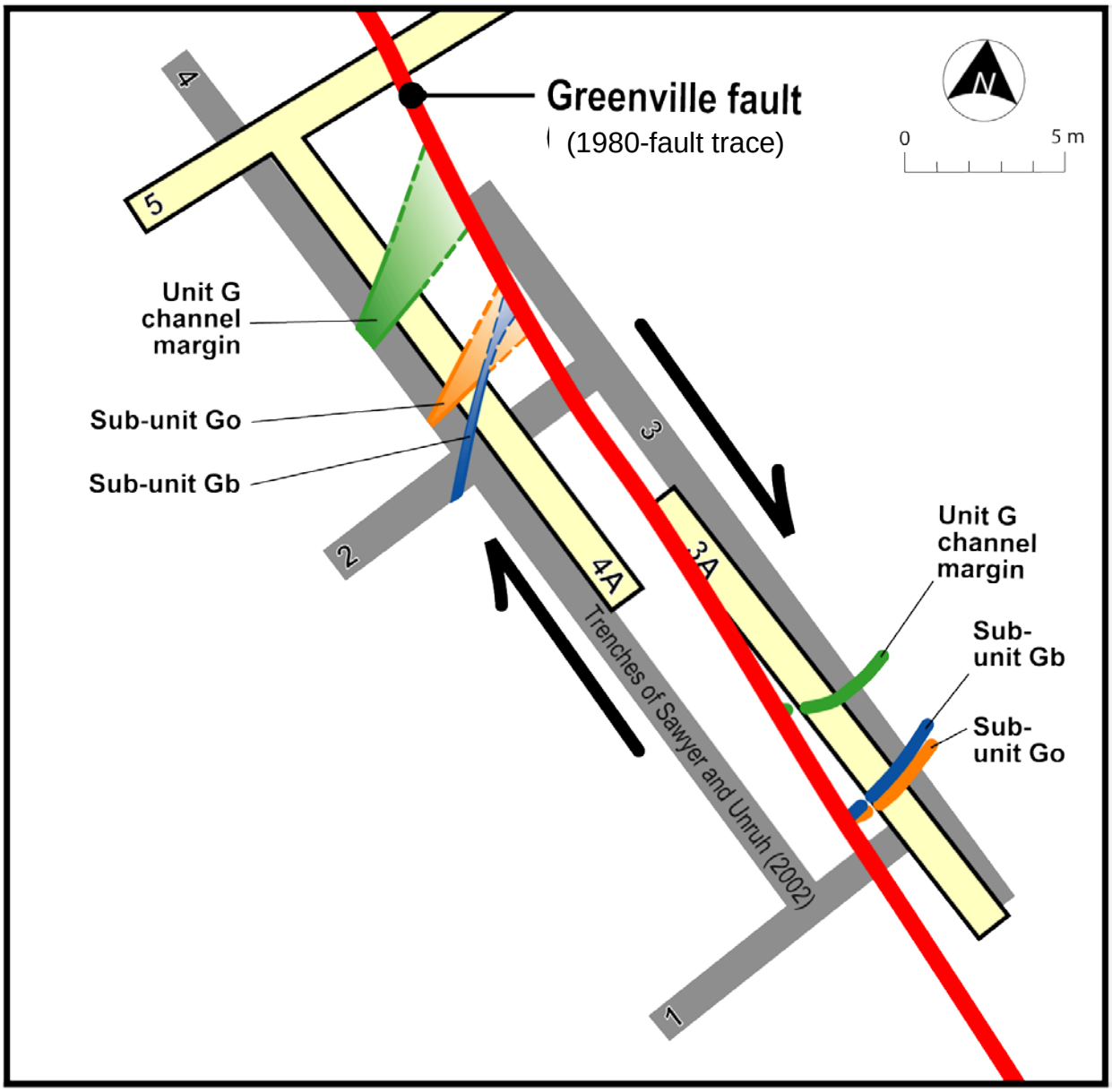

Figure 5 —Simplified map of the Laughlin Road trenches showing three stratigraphic datum utilized in this study to constrain the amount of right slip on the 1980-trace of the northern Greenville fault. The intersection of these datum with the fault is relatively well constrained on the east side of the fault trace, whereas there is more natural variability and longer projections of the stratigraphic datum on the west side.

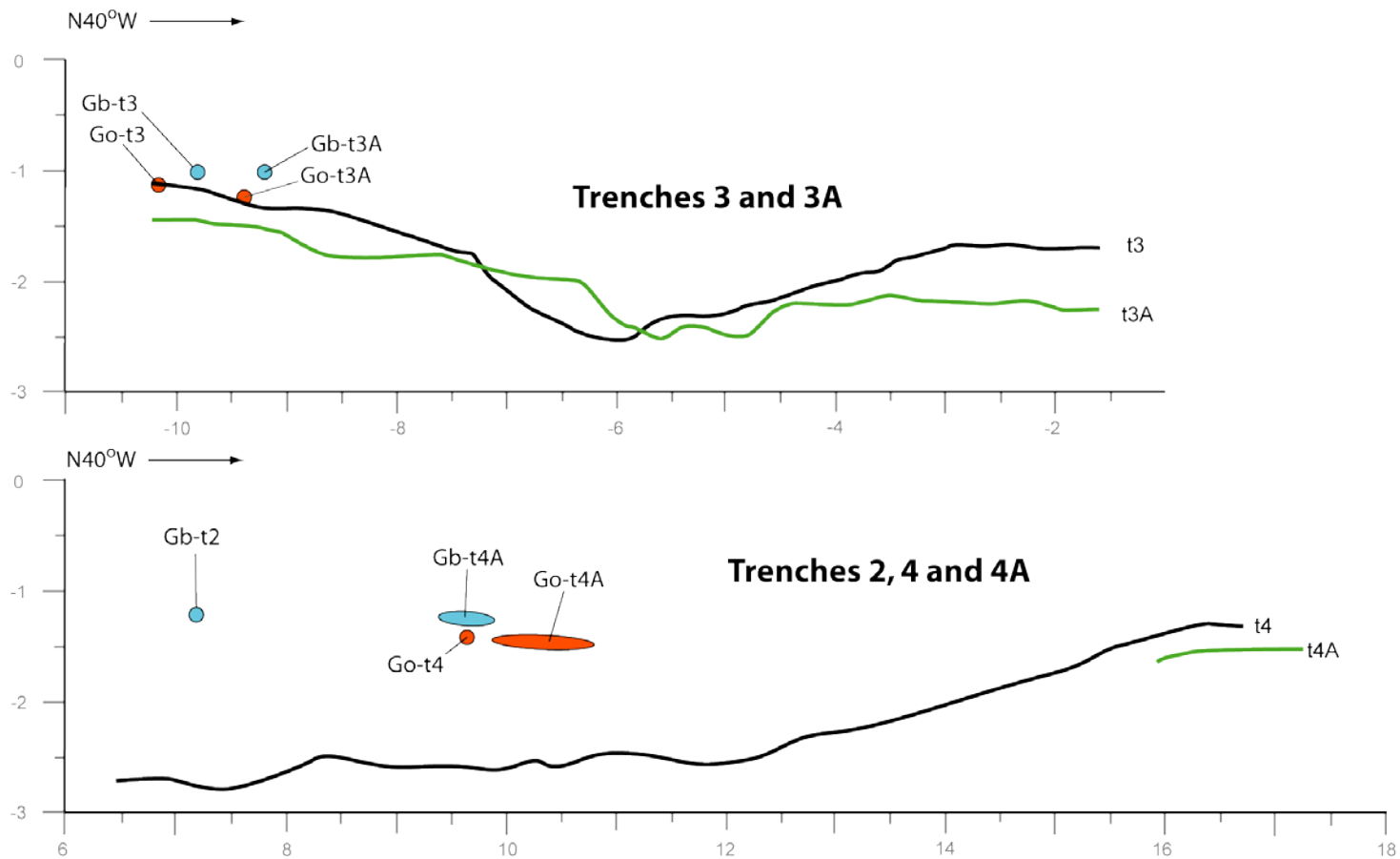

Figure 6 —Cross-section views in the plane of fault, showing offset of the three stratigraphic datum as constrained by precise surveying of exposures in five trenches, including three from the previous study (Sawyer and Unruh, 2002)—note there is a break in the horizontal scale between the sections. The outline of the northern unit-G channel margin is shown in green relatively close to the fault plane in trenches t3A and t4A, and in black further away from the fault in trenches t3 and t4. The relative geometric position of the stratigraphic terminations or pinchouts of sub-units Gb and Go are constrained based on exposures in all four fault-parallel trenches, and that of sub-unit Gb also is constrained by previous trench t2 exposures.

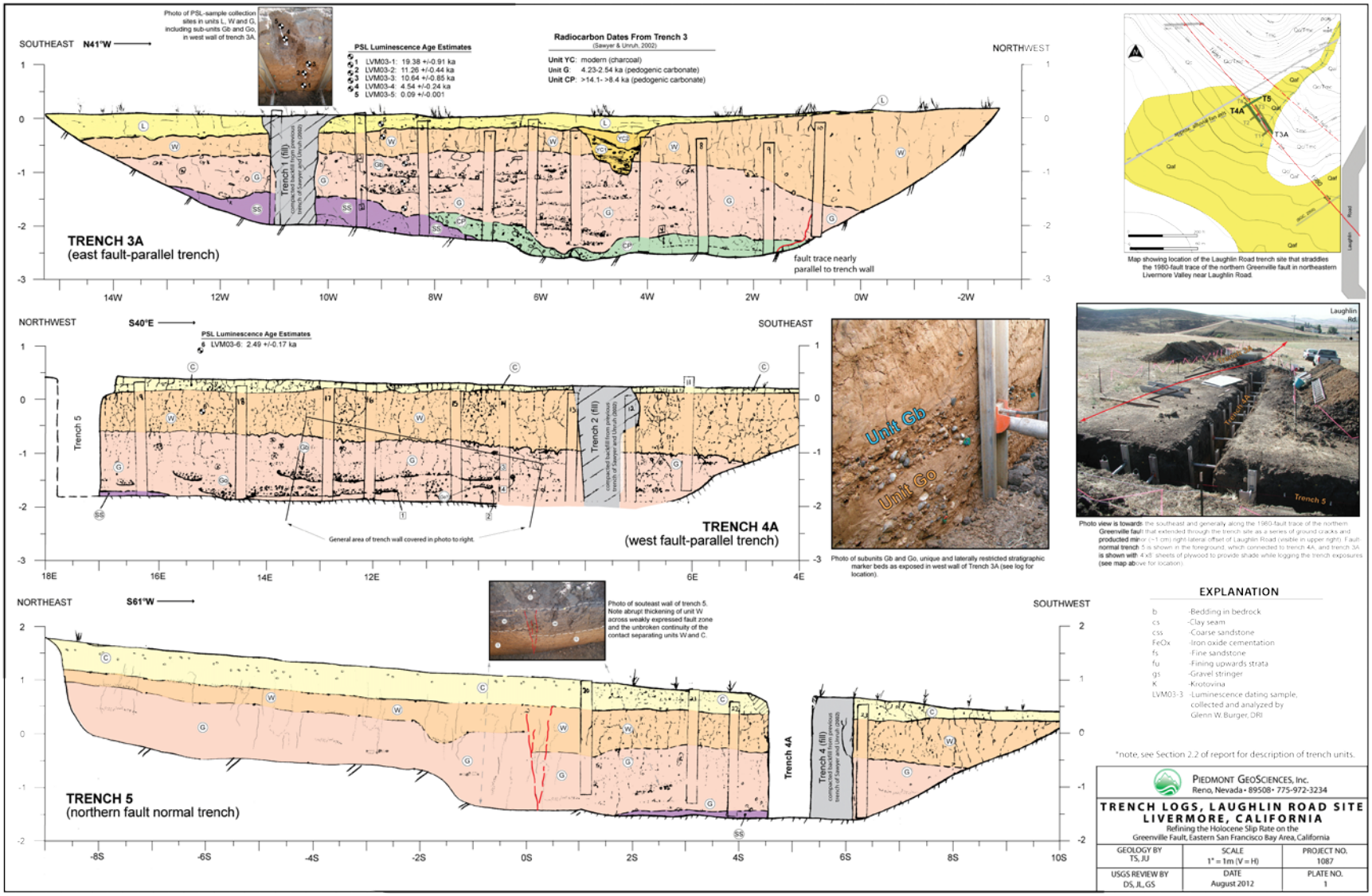
Plate 1
Photo of PSL-sample collection sites in units L, W and G, including sub-units Gb and Go, in west wall of trench 3A.
PSL Luminescence Age Estimates
1 LVM03-1: 19.38 +/-0.91 ka
2 LVM03-2: 11.26 +/-0.44 ka
3 LVM03-3: 10.64 +/-0.85 ka
4 LVM03-4: 4.54 +/-0.24 ka
5 LVM03-5: 0.09 +/-0.001
Radiocarbon Dates From Trench 3
(Sawyer & Unruh, 2002)
Unit YC: modern (charcoal)
Unit G: 4.23-2.54 ka (pedogenic carbonate)
Unit CP: >14.1- >8.4 ka (pedogenic carbonate)
SOUTHEAST N41°W
NORTHWEST
Trench 1 (fill)
TRENCH 3A
(east fault-parallel trench)
fault trace nearly parallel to trench wall
14W
12W
10W
8W
6W
4W
2W
0W
-2W
Map showing location of the Laughlin Road trench site that straddles the 1980-fault trace of the northern Greenville fault in northeastern Livermore Valley near Laughlin Road.
NORTHWEST
S40°E
SOUTHEAST
PSL Luminescence Age Estimates
6 LVM03-6: 2.49 +/-0.17 ka
Trench 5
Trench 2 (fill)
General area of trench wall covered in photo to right.
TRENCH 4A
(west fault-parallel trench)
18E
16E
14E
12E
6E
4E
Unit Gb
Unit Go
Photo of subunits Gb and Go, unique and laterally restricted stratigraphic marker beds as exposed in west wall of Trench 3A (see log for location).
Laughlin Rd
Trench 5
Photo view is toward: the southeast and generally along the 1980-fault trace of the northern Greenville fault that extended through the trench site as a series of ground cracks and producted minor (~1 cm) right-lateral offset of Laughlin Road (visible in upper right). Fault-normal trench 5 is shown in the foreground, which connected to trench 4A, and trench 3A is shown with 4 x 8' sheets of plywood to provide shade while logging the trench exposures (see map above for location).
NORTHEAST
S61°W
SOUTHWEST
Photo of souteast wall of trench 5. Note abrupt thickening of unit W across weakly expressed fault zone and the unbroken continuity of the contact separating units W and C.
Trench 4A
Trench 4 (fill)
TRENCH 5
(northern fault normal trench)
-8S
-6S
-4S
-2S
0S
2S
4S
6S
8S
10S
EXPLANATION
b -Bedding in bedrock
cs -Clay seam
css -Coarse sandstone
FeOx -Iron oxide cementation
fs -Fine sandstone
fu -Fining upwards strata
gs -Gravel stringer
K -Krotovina
LVM03-3 -Luminescence dating sample, collected and analyzed by Glenn W. Burger, DRI
*note, see Section 2.2 of report for description of trench units.
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TRENCH LOGS, LAUGHLIN ROAD SITE
LIVERMORE, CALIFORNIA
Refining the Holocene Slip Rate on the Greenville Fault, Eastern San Francisco Bay Area, California
GEOLOGY BY TS, JU
SCALE 1" = 1m (V = H)
PROJECT NO. 1087
USGS REVIEW BY DS, JL, GS
DATE August 2012
PLATE NO. 1