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Late Quaternary deformation and slip rates in the northern San Andreas fault zone at Olema Valley, Marin County, California

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Abstract

Quaternary sedimentary deposits along the structural depression of the San Andreas fault (SAF) zone north of San Francisco in Marin County provide an excellent record of rates and styles of neotectonic deformation in a location near where the greatest amount of horizontal offset was measured after the great 1906 San Francisco earthquake. A high-resolution gravity survey in the Olema Valley was used to determine the depth to bedrock and the thickness of sediment fill along and across the SAF valley. In the gravity profile across the SAF zone, Quaternary deposits are offset across the 1906 fault trace and truncated by the Western and Eastern Boundary faults, whose youthful activity was previously unknown. The gravity profile parallel to the fault valley shows a basement surface that slopes northward toward an area of present-day subsidence near the head of Tomales Bay. Surface and subsurface investigations of the late Pleistocene Olema Creek Formation (Qoc) indicate that this area of subsidence was located further south during deposition of the Qoc and that it has migrated northward since then. Localized subsidence has been replaced by localized contraction that has produced folding and uplift of the Qoc. This apparent alternation between transtension and transpression may be the result of a northward-diverging fault geometry of fault strands that includes the valley-bounding faults as well as the 1906 SAF trace. The Vedanta marsh is a smaller example of localized subsidence in the fault zone, between the 1906 SAF trace and the Western Boundary fault. Analyses of Holocene marsh sediments in cores and a paleoseismic trench indicate thickening, and probably tilting, toward the 1906 trace, consistent with coseismic deformation observed at the site following the 1906 earthquake.

New age data and offset sedimentary and geomorphic features were used to calculate four late Quaternary slip rate estimates for the SAF at this latitude. Luminescence dates of 112–186 ka for the middle part of the Olema Creek Formation (Qoc), the oldest Quaternary deposit in this part of the valley, suggest a late Pleistocene slip rate of 17–35 mm/year, which replaces the unit to a position adjacent to its sediment source area. A younger alluvial fan deposit (Qqf; basal age ~30 ka) is exposed in a quarry along the medial ridge of the fault valley. This fan deposit has been truncated on its western side by dextral SAF movement, and west-side-down vertical movement that has created the Vedanta marsh. Paleocurrent measurements, clast compositions, sediment facies distributions, and soil characteristics show that the Bear Valley Creek drainage, now located northwest of the site, supplied sediment to the fan, which is now being eroded. Restoration of the drainage to its previous location provides an

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estimated slip rate of 25 mm/year. Furthermore, the Bear Valley Creek drainage probably created a water gap located north of the Qqf deposit during the last glacial maximum ~18 ka. The amount of offset between the drainage and the water gap yields an average slip rate of 21–30 mm/year. Finally, displacement of a 1000-year-old debris lobe approximately 20 m from its hillside hollow along the medial ridge indicates a minimum late Holocene slip rate of 21–25 mm/year. Similarity of the late Pleistocene rates to the Holocene slip rate, and to previous rates obtained in paleoseismic trenches in the area, indicates that the rates may not have changed over the past 30 ka, and perhaps the past 200–400 ka. Stratigraphic and structural observations also indicate that valley-bounding faults were active in the late Pleistocene and suggest the need for further study to evaluate their continued seismic potential.
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Keywords: San Andreas fault; Slip rate; Quaternary; Stratigraphy; Structure; Gravity

1. Introduction

About 25 km north of San Francisco, a 45-km-long section of the San Andreas fault (SAF) lies within a continuous, linear valley between the Point Reyes Peninsula and the west Marin County mainland (Fig. 1). This section of the SAF last moved during the great 1906 San Francisco earthquake. The largest amount of horizontal displacement (about 5–6 m) during the 1906 event was measured by G.K. Gilbert near Olema (Lawson, 1908). A paleoseismologic study on the 1906 trace of the SAF south of Olema (Fig. 1C) revealed a time-averaged minimum dextral slip rate of 24 ± 3 mm/year during the past 2000 years and an average recurrence interval for large 1906-type earthquakes of 221 ± 40 years (Niemi and Hall, 1992). Within the valley are many fault-related landforms, including sag ponds and linear ridges. G.K. Gilbert's descriptions of these features following the 1906 earthquake (Gilbert, 1907a,b, 1908a,b) remain an excellent source of information about the fault valley. There is currently no fault creep and little seismicity along this locked segment (Hill et al., 1990; Galehouse, 2002).

The 1906 SAF trace lies in the center of a valley with edges defined by other fault strands that Galloway (1977) named the Eastern and Western Boundary faults (Fig. 1C). These faults probably extend the length of the valley, although they are in some locations obscured by alluvial fans, stream or landslide deposits, or vegetative cover. Terraces of mixed fluvial and marine origin on the eastern flank of Inverness Ridge and the western flank of Bolinas Ridge (Fig. 1C) with clasts from the other side of the valley (Galloway, 1977; Niemi, 1992) attest to progressive uplift of the ridges and narrowing of the fault valley. A recent study of marine terraces on the western flank of Inverness Ridge demonstrated increasing rates of ridge uplift with increasing proximity to the Western Boundary fault (Scherer, 2004).

In this paper we report geophysical and sedimentological data collected from the San Andreas fault zone in Olema Valley. These data provide details about the geometry of the valley and the history of late Quaternary deformation along this segment of the SAF. Quaternary sedimentary deposits and geomorphic features in the valley provide an excellent opportunity to investigate the history of movement within the SAF zone during the past several hundred thousand years. Our analyses of fault zone deformation have direct application to assessing future seismic behavior of the San Andreas fault, clarifying its rupture mechanisms, and refining earthquake probabilities on separate traces within the fault zone. Understanding the slip history at a location where the SAF carries about one half of the ~49 mm/year Pacific–North America plate motion (Argus and Gordon, 2001) can improve estimates of seismic hazard for the densely populated San Francisco Bay Area.

2. Regional geologic setting

The region of western Marin County is divided into three structural blocks, represented in the study area by the Point Reyes Peninsula, Bolinas Ridge, and the SAF valley. The Point Reyes Peninsula is part of the Salinian terrane, a displaced fragment of con-

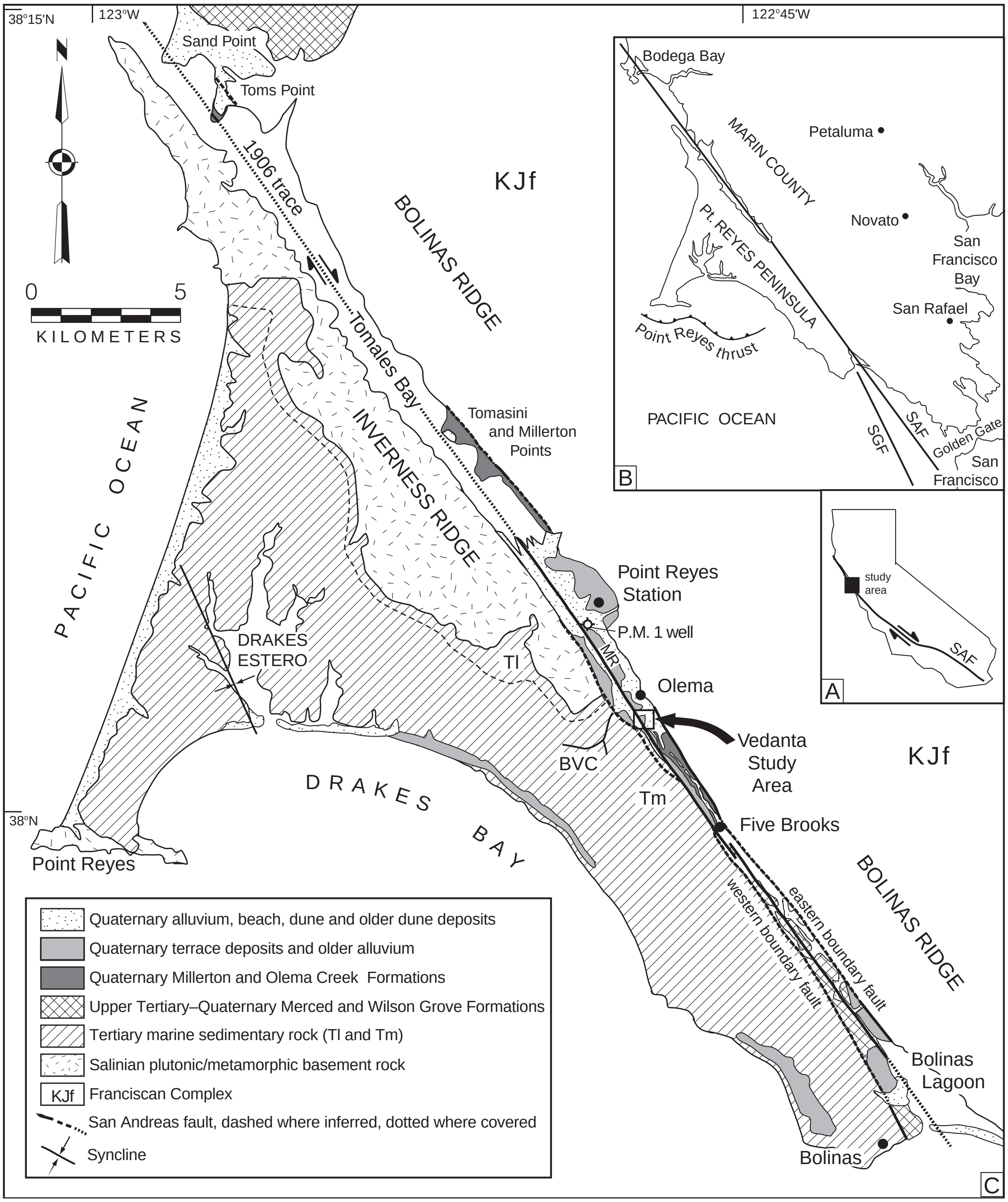


Fig. 1. (A) Location of study area in California. SAF = San Andreas fault. (B) The Point Reyes Peninsula, separated from Marin County mainland by SAF. The San Gregorio fault (SGF) joins SAF south of study area. Offshore faults from McCulloch (1989). (C) Generalized geology map modified from Galloway (1977) and Clark and Brabb (1997). MR = medial ridge. Tl = Laird Formation (thin sandy unit overlying Salinian plutonic/metamorphic basement rock). Tm = Monterey Formation (extensive siliceous shale unit on Inverness Ridge west of study area). BVC = Bear Valley Creek drainage.

tinental crust that consists of Cretaceous plutonic and older metamorphic rock overlain by over 4 km of lower Eocene to Pliocene marine sedimentary rock (Clark et al., 1984; Clark and Brabb, 1997) and Quaternary stream, beach, and dune deposits. The geologic units have been folded into a broad synclinorium flanked by two antiforms (Point Reyes to the southwest and Inverness Ridge to the northeast; Lajoie, 1996) that have been truncated, apparently by motions on the Western Boundary fault (WBF) and the offshore Point Reyes reverse fault (McCulloch, 1989). Analyses of marine terraces on the western flank of Inverness Ridge suggest that active folding and uplift of the peninsula continues. Age data and elevations from the lowest terrace (see linear bands of Quaternary sediments between Drakes Estero and Bolinas in Fig. 1C) indicate post-80 ka uplift rates that increase from 0.2 mm/year near the center of the syncline to 1.0 mm/year near the WBF (Grove, 2003; Scherer, 2004). Since 1906, the only >3 magnitude earthquake in the Point Reyes region was a M5 event in 1999 that resulted from reverse motion on a fault near Bolinas (NCEDC, 2004) that was probably the WBF.

Bolinas Ridge consists of highly deformed Mesozoic-aged Franciscan subduction-complex rock that is primarily sandstone between Bolinas and Millerton Point, and melange with inclusions of greenstone, chert, serpentinite, and sandstone between Millerton and Toms Points (Blake et al., 1974). North of Toms Point, the Franciscan Complex is overlain by the upper Miocene–Pliocene Wilson Grove Formation, an erosional remnant of a formerly extensive deposit of shallow-marine sandstone (Fox, 1983). The accordant summit of Bolinas Ridge is part of a subplanar erosional surface cut on Wilson Grove and Franciscan rocks that extends to the northwest and southeast of the study area (Mendocino Plateau of Fox, 1983). After the late Miocene, the plateau was uplifted and streams drained the block from east to west (Fox, 1983). According to Dickinson (1922), subsequent eastward tilting caused the lower parts of these streams on the uplifted western edge (adjacent to Tomales Bay) to incise canyons into the underlying Franciscan bedrock and the uppermost parts to begin draining eastward into the valley east of Petaluma (Fig. 1B). The plateau increases in elevation from the north end of Tomales Bay to Mount Tamalpais, located along the coast between Bolinas and San Francisco.

Between Inverness and Bolinas Ridges lies a valley created by the SAF zone. About 25 km of the fault's length is covered by waters of Tomales Bay and Bolinas Lagoon; the remaining 20 km is exposed on land between the two bays (see Fig. 1C). The narrowest part of the SAF valley, at Five Brooks, is a topographic and structural high where Franciscan basement is exposed at the land surface. South of this high, Franciscan basement is overlain by the Plio-Pleistocene Merced Formation, a fossiliferous shallow-marine and nearshore deposit (Clifton et al., 1988). Portions of both the basement and Pleistocene units are fault slices offset from rocks located east of the SAF on the San Francisco Peninsula to the south.

The SAF fault valley extends south of Bolinas Lagoon into the offshore. Analyses of high-resolution seismic reflection data by Bruns et al. (2003) show that the 1906 trace of the SAF lies in the middle of a Holocene basin that is bounded on the east by the Golden Gate fault and on the west by the Potato Patch fault (a splay of the San Gregorio fault). Both the Potato Patch fault and the Golden Gate fault can be traced to the seafloor, display flower structure geometry, and have large apparent stratigraphic discontinuity across them. The offshore San Gregorio fault appears to correlate with the onshore WBF and the Golden Gate fault extends onshore to the Eastern Boundary fault (EBF). The 1906 trace of the fault mapped in the offshore near Bolinas appears to be quite youthful, without large stratigraphic offset (Bruns et al., 2003).

In the north end of the SAF fault valley (north of Five Brooks; Fig. 1C), the Franciscan basement is mostly covered by an extensive suite of upper Quaternary deposits. The faulted medial ridge (MR in Fig. 1C) divides the northern end of Olema Valley into two northwest-trending alluviated valleys, each filled by sediment of distinct provenance. Bear Valley and Gravel Creeks lie west of the medial ridge and contain clasts derived from the western Salinian terrane, whereas Olema Creek lies east of the medial ridge and contains clasts derived predominantly from the eastern Franciscan Complex. The 1906 SAF trace lies within Quaternary deposits in the center of the valley.

3. Late Quaternary stratigraphy and structure of the Olema Valley

Information about the stratigraphy and structure of the Olema Valley was obtained by studying surface outcrops and topographic features, analyzing water and oil well logs, and collecting detailed gravity data.

3.1. Olema Creek Formation and younger alluvial units

Filling in the valley above the Franciscan Complex bedrock are Quaternary sediments that are progressively younger toward the northwest. The oldest unit is the Pleistocene Olema Creek Formation (Qoc), which is exposed in the incised banks of Olema Creek between Five Brooks and about 1 km south of the Vedanta site. The Qoc has been deformed into broad upright folds with northwest-oriented hinges (Grove et al., 1995). Bedding dips more steeply (up to 65°) at the southern end of the outcrop belt and less steeply (5–10°) at the northern end. The Qoc is truncated by the EBF, which forms a distinct topographic lineament in the landscape. The Qoc is apparently truncated on the west by the 1906 strand of the SAF, and much of the unit is covered by younger fluvial terrace deposits (Figs. 2 and 3).

The Qoc consists of estuarine and lacustrine mud, fluvial sand and gravel, fine-grained marsh and pond deposits, and alluvial fan sand and gravel derived from Inverness Ridge to the west (Grove et al., 1995). Four luminescence dates from Qoc sediments that range from 112 to 186 ka (Grove et al., 1995; L. Owen, 2000, personal communication), are evidence that the unit was deposited during marine isotopic stages 5 and 6. Estuarine mud that contains marine diatoms was probably deposited about 125 ka, when sea level was about 6 m higher than it is today (Chappell and Shackleton, 1986), and marine water may have inundated the valley as far south as Five Brooks. During times of lower sea level, alluvium was deposited by streams that transported sediment northward along the axis of the valley, and in fans that accumulated sediment shed from the western ridge. Marsh and pond mud settled out in low areas between the stream channels and fans.

Sediments of the Qoc were deposited in a broad valley that has been subsequently compressed and narrowed (Grove et al., 1995), as recorded by three fluvial terrace levels that bevel the Qoc and record progressive uplift of the valley between Olema and Five Brooks (Figs. 1 and 3). The Qoc marine deposits are presently over 60 m above sea level along the southern limit of the outcrop belt. Sediments that match Qoc types have been encountered in water wells throughout the Olema Valley (unpublished logs from the California Water Resources Department) and at 35–280 m depth in the P.M.1 oil well (Fig. 1C; CDOG, 1992).

Sediments of similar age and facies to the Qoc reappear at the surface to the northwest, along the eastern edge of Tomales Bay (Millerton Formation—Qm). We have obtained three luminescence ages of 125–155 ka from the Qm (Grove et al., 1995; L. Owen, 2000, personal communication), which probably grades into the Qoc in the subsurface (Fig. 4). The Qm contains interbedded alluvial and estuarine sediments, with a higher percentage of marine facies than the Qoc because of its closer proximity to the Pacific Ocean.

South of Tomales Bay the Qoc grades upward into the Qoa (older alluvium unit) of Hall and Hughes (1980), which makes up the medial ridge that bisects the valley from the Vedanta Retreat northward to the head of Tomales Bay. The Qoa unit of sand and gravel also contains a tephra bed (the Olema Ash) identified by Hall and Hughes (1980) that correlates to an ash bed dated to 55–75 ka in cores from Clear Lake (Sarna-Wojcicki et al., 1988). The Qoa sediments probably extended across the valley prior to the last glacial maximum (LGM) and sea level lowstand about 18 ka, when the valley was incised, and the alluvial deposits were eroded to create the remnant medial ridge. Because the 1906 fault strand cuts through the medial ridge, its remnant shape may be partially controlled by fault-related deformation (Hall and Hughes, 1980). Fluvial incisions prior to the LGM have produced a complicated stratigraphy in the medial ridge, and younger inset deposits include the Quarry fan gravel that is discussed below. During the Holocene transgression, younger alluvium filled the lower parts of Olema Valley, particularly where it widens near the head of Tomales Bay.

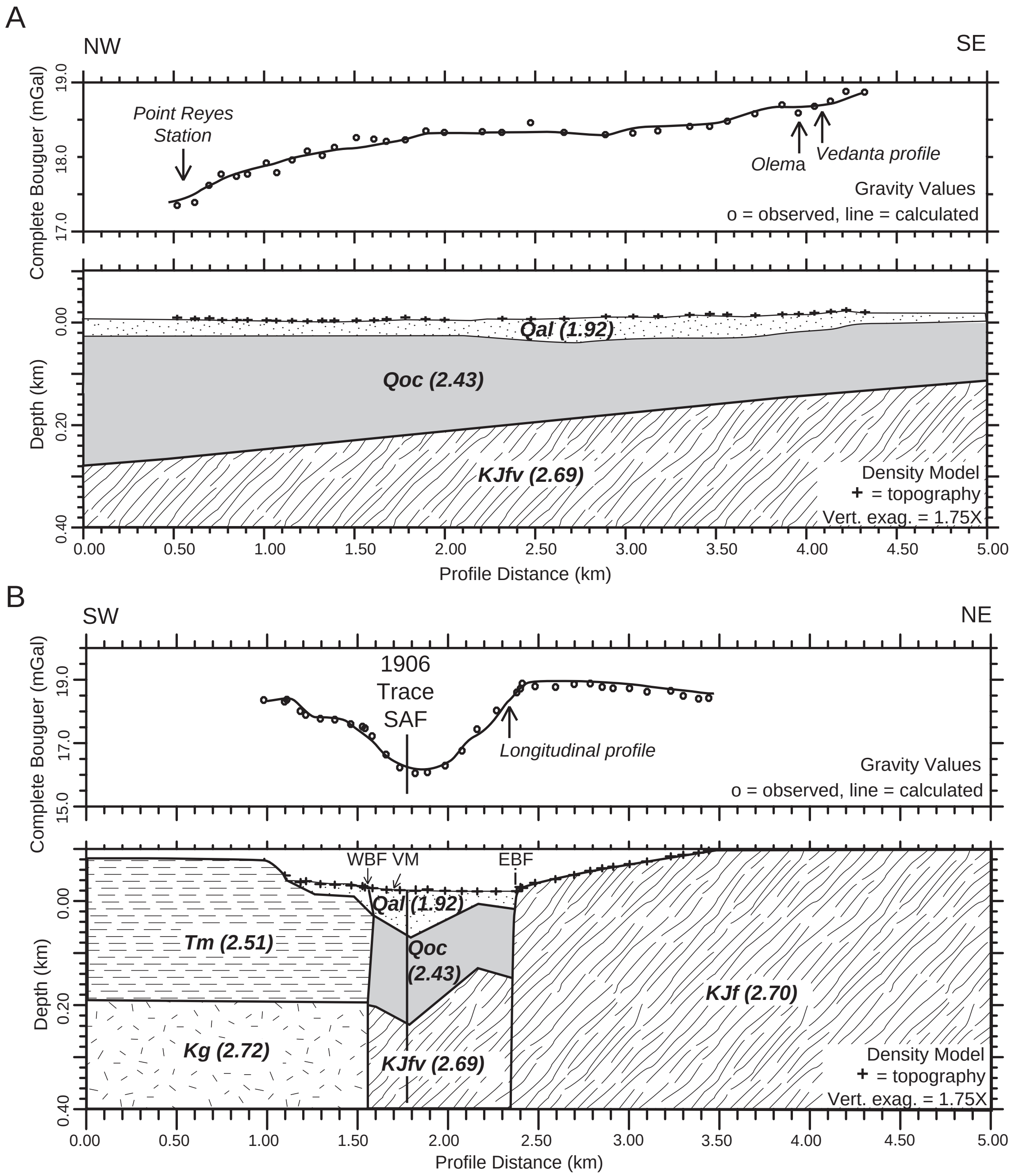


Fig. 2. (A) Longitudinal gravity profile parallel to SAF along eastern edge of valley, between Point Reyes Station and Olema. KJfv = Franciscan Complex in valley. Qoc = Olema Creek Formation. Qal = alluvium (Qoa, older alluvium, not differentiated). Numbers in parentheses are density values used in models, in g/cm^3. Modeling was carried out to a total depth of 21 km (including 5 km of underplated oceanic crust), and a total width of 10 km. The models are only shown to 0.4 km depth and 5.0 km width to provide detailed geometry of shallow units. (B) Vedanta gravity profile perpendicular to SAF through town of Olema and Vedanta Retreat (transect location in Fig. 3), showing three structural blocks in study area. KJf = Franciscan Complex east of fault valley. Tm = Miocene Monterey Formation. SAF = San Andreas fault (1906 trace); WBF = Western Boundary fault; EBF = Eastern Boundary fault; VM = Vedanta marsh. Other abbreviations as in Fig. 2A.

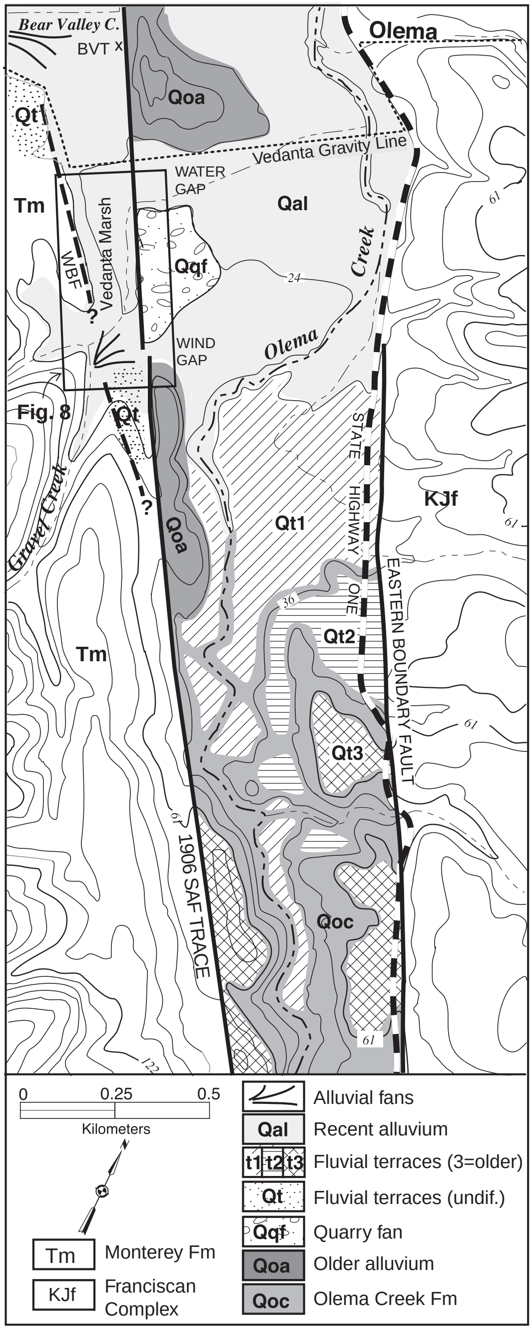


Fig. 3. Topographic and geologic map of northern end of Olema Creek Formation (Qoc) and study areas at Quarry fan (Qqf) and Vedanta marsh. Contour interval: 12 m. BVT=Bear Valley Creek trench site. WBF=Western Boundary fault. Tm=Monterey Formation. KJf=Franciscan Complex.

3.2. High-precision gravity experiment

We conducted a gravity experiment in the alluviated fault valley to obtain more information about the subsurface geometry of the Franciscan Complex bedrock and overlying Quaternary units. A high-precision technique, including 130 stations with an average spacing of 100 m, was used to show details of the basement surface below the fault valley, which is not a visible feature on regional gravity maps (Clement, 1965). Stations were positioned with a 5 arc-second precision total station surveying instrument, and relative gravitational attraction was measured with a LaCoste and Romberg D-type gravimeter, read to a precision of 0.001 mGal. Terrain, Free-air, and Bouguer corrections were calculated and applied to all station measurements and far-field corrections were calculated by the U.S. Geological Survey. The forward modeling program (HYPERMAG) of Saltus and Blakely (1993) was used to fit density profiles to the Bouguer gravity values (Quinn and Grove, 1994).

In this paper, we present two of our four gravity profiles. One profile was collected parallel to the San Andreas fault along Highway 1 (eastern side of Olema Valley; longitudinal profile in Fig. 2A), and the second profile was collected perpendicular to the fault through Olema and the Vedanta Retreat (Fig. 2B; location shown in Fig. 3).

Gravity values in the longitudinal profile that decrease gradually toward the northwest (Fig. 2A) are consistent with surface and subsurface observations of a northwestward-increasing depth to Franciscan basement rock, which is exposed at the surface south of Five Brooks. The bedrock surface appears to slope gently northward to near Point Reyes Station, where it was found at about 280 m depth in a well (P.M.1 well in Fig. 1C). The depth to bedrock of about 200 m at the Vedanta Retreat (Fig. 2) was determined by interpolating between the surface exposure at Five Brooks and the 280 m depth in the P.M.1 well, assuming a constant slope to the northwest. The accommodation space created by the northwest-deepening bedrock surface has been filled by Quaternary sediments that are thicker in the northwest direction (units Qoc and Qal in Figs. 2A and 4). Our gravity model also suggests that the SAF valley is underlain by sheared Franciscan Complex bedrock that has a

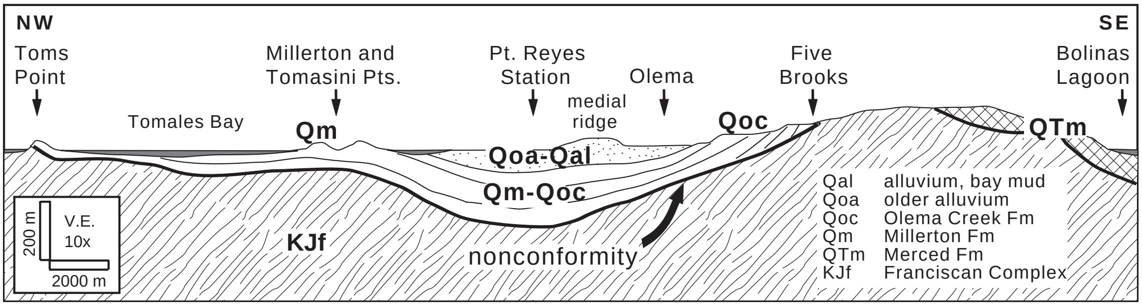


Fig. 4. Interpretation of subsurface geology along length of SAF valley. Constraints are surface geology, an oil well log at the latitude of Point Reyes Station, water well logs in the valley between Point Reyes Station and Five Brooks, and gravity data between Point Reyes and Olema.

slightly lower density value compared to the bedrock of Bolinas Ridge.

According to our fault-perpendicular gravity model (Fig. 2B), Franciscan basement rocks are overlain at this part of the valley by about 200 m of Qoc sediments, a thickness consistent with the minimum thickness of 175 m measured in outcrop nearby (Grove et al., 1995). The overlying Qoa alluvium that makes up the medial ridge is not visible as a discrete unit in the gravity model because the measurement line crossed the valley through an eroded gap in the ridge (Fig. 3). Alluvium (Qal) in the gravity model includes Holocene marsh and valley-fill deposits and the older alluvium (Qoa) that overlie the Qoc. The irregularities of the Quaternary deposits in Fig. 2B reflect a complex history of faulting and stream incision and the real geometry is certainly different in detail from that shown in the gravity model. The 1906 trace of the SAF cuts through Quaternary deposits, which are truncated to the east and west by faults that are the EBF and WBF. Our study suggests that a portion of the strain must be partitioned from the 1906 SAF trace onto these border faults. This may account for why the geologic measurements of slip during the 1906 earthquake are less than the geodetic slip (Thatcher et al., 1997).

3.3. Implications for Late Quaternary deformation of the valley

The present-day geometry of the geologic units in the fault valley is a result of a basin that has migrated northwestward in response to contraction and uplift (Fig. 4). The depositional basin was located farther south when the Qoc was deposited, and it has migrated progressively northwestward to its position today near the head of Tomales Bay (Grove et al., 1995). A similar northwestward migration of a depocenter between fault strands was documented in the San Gregorio basin offshore of the Golden Gate south of Bolinas Lagoon (Bruns et al., 2003).

The migrating system has created an offlapping sedimentary fill geometry and sediment younging to the northwest, and structural uplift to the south. The alternating transtension and transpression in the valley may be a result of fault-strand geometry that converges to the southeast and diverges to the northwest (Grove et al., 1995). This proposed control by fault geometry implies a series of active strands, including the EBF and WBF, which have strong tectonic geomorphic expression of active faulting (e.g. sag ponds, deflected drainages, linear topographic hills) and which truncate late Pleistocene sediments. No trenches have yet been excavated across the boundary faults in this area to study their slip rates or records of paleoearthquakes.

Whereas the valley south of the Vedanta Retreat has been uplifted, the valley to the north has been subsiding, as shown by the depth to Qoc sediments that were formed at near-sea-level elevations and the location where present-day sedimentation is localized (Fig. 4). Terraces that bevel the flanks of the Bolinas and Inverness Ridges on the eastern and western sides of the fault valley suggest that the valley-narrowing process has been ongoing for some time, and that the ridges have continued to rise with respect to the valley between them. Studies of marine terraces on the western flank of Inverness Ridge confirm the ongoing uplift of this ridge (Scherer, 2004).

4. Late Quaternary slip rates

4.1. Evidence from the Pleistocene Olema Creek Formation (Qoc)

Clasts in the Qoc are entirely granitoid compositions derived from Inverness Ridge plutonic basement rock, which is now located about 3 km north of the northernmost surface exposure of the Qoc. All of the streams in the fault valley north of Five Brooks today flow toward the north and so the basement rock on Inverness Ridge must have been located farther south during the time of Qoc deposition. Even if streams were flowing southward at that time, the present-day configuration would cause Monterey Formation (Tm) clasts to be introduced into streams, as they are in Bear Valley Creek (BVC) today. Based on our luminescence dates of 112–186 ka from within the Qoc, the oldest part of the formation near Five Brooks was probably deposited 200–400 ka. If the southern end of the plutonic basement exposure is moved 7 km southeast, to be aligned with the southern end of the Qoc at Five Brooks, long-term slip rates of 17–35 mm/year are obtained (assuming 200–400 ka age). Seven kilometers is the minimum amount of fault slip necessary to bring plutonic source rocks to the watershed of the Olema Creek basin. Palinspastic reconstructions of plutonic basement locations farther south than Five Brooks would increase our calculated slip rate. If the Olema Creek Formation is older than our conservative age estimate of 400 ka, than the slip rate would be less than reported here. Furthermore, granitoid compositions of Qoc clasts imply that a ridge partitioned the valley and prevented Franciscan Complex clasts from entering the valley from the east, much as a medial ridge partitions the valley today and prevents Franciscan clasts from entering the BVC drainage. These data indicate that the present medial ridge morphology is a manifestation of a long-term structural deformation style.

4.2. Evidence from Pleistocene Quarry fan gravel (Qqf)

The Qoc grades upward into the older alluvium (Qoa) unit exposed in the medial ridge. At the Vedanta Retreat, the older alluvium has been eroded away and the low areas filled with younger alluvial-fan deposits (Qqf) that were derived from Inverness Ridge to the west. Whereas, like the Qoc, the older Qoa unit contains primarily granitoid clasts, the younger fan deposits contain primarily Monterey Formation (Tm) clasts. Both units were incised during the LGM, creating wind and water gaps at the Vedanta Retreat, and they together make up the remnant medial ridge.

Because the Monterey Formation clasts in the Qqf alluvium make good road-building materials, this part of the medial ridge has been quarried to construct gravel roads throughout the Vedanta Retreat. The quarrying has created excellent three-dimensional exposures of the fan sediments, hereafter referred to as the Quarry fan. The northwestern edge of the Quarry fan has been truncated by displacement along the 1906 strand of the SAF and the deposit has been separated from its sediment source area. We studied the sedimentology of these deposits to test the hypothesis that the alluvial fan was supplied with sediment via the same drainage that now supplies sediment to Bear Valley Creek (BVC) and to use the offset between the fan and source drainage to calculate a slip rate for the SAF extending back to the late Pleistocene.

At the quarry site exposures, we analyzed sedimentary characteristics of the alluvial fan to determine the environments of deposition and site paleogeography (Domrose et al., 2000). We described grain sizes, bedding styles, and sedimentary structures of individual units. We measured paleocurrent directions from preferred orientations of clasts, and clast compositions in both Quarry fan gravel and gravel in modern BVC. Finally, we collected a fine-grained sand sample for optically stimulated luminescence (OSL) dating of fan deposits.

The Qqf deposits are composed of sand and gravel beds interbedded with fine-grained silt and clay (Fig. 5A). We used the classification system of Harvey (1984) to divide the fan deposits into four facies: debris-flow sand and gravel, sheet-flow sand and gravel, channel sand and gravel, and silt and clay. Debris flows are poorly sorted deposits associated with viscous gravity flows. Sheet flows were deposited by rapid, unchannelized flow, and channel deposits formed by stream flow restricted to channels. Silt and clay units were formed as overbank deposits in the floodplain.

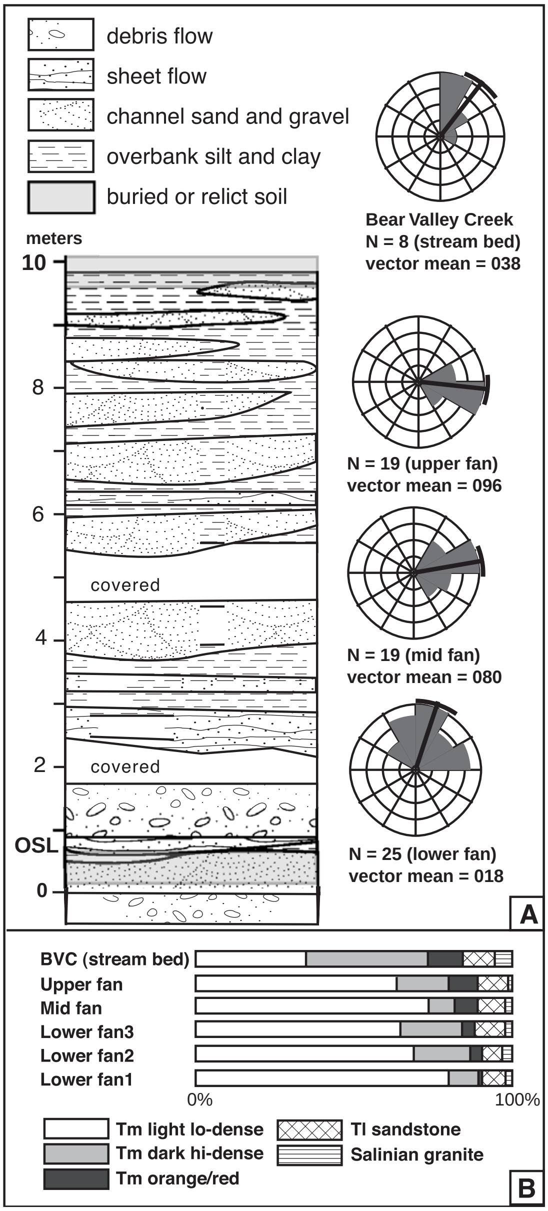


Fig. 5. (A) Generalized stratigraphic column of quarry deposits, showing facies sequence and paleocurrents. Current directions measured on clasts in active stream bed of Bear Valley Creek also shown. OSL = location of sample site for optically stimulated luminescence date. (B) Clast compositions in Quarry fan gravels and in Bear Valley Creek ($n = 100$).

At the quarry site, debris-flow deposits are found only in the lower parts of the fan (about 11-m thickness exposed; see Fig. 5A). Both channel and overbank deposits are more common in the upper part of the fan. A buried soil, distinguished by clay films on the undersides of clasts, weak ped development, and a remnant organic horizon, occurs near the bottom of the deposits. The debris-flow deposits and coarser-grained sediment in lower fan beds suggest a proximal fan position, whereas the finer-grained deposits in the upper fan beds suggest a reduction in flow energy and a more distal fan position, probably as the source area was carried farther away by fault slip. Soil development within the fan indicates a period of relative quiescence, and the surface soil indicates some period of elapsed time since the fan was last active.

Sheet-flow gravels contain many flattened, imbricated clasts. We measured the orientations of these clasts throughout the fan to obtain the approximate direction of the paleocurrents during fan development. These data show that the predominate current direction changed with time from a more northeasterly direction to a more southeasterly direction (Fig. 5). This trend is consistent with the northwest translation of the source drainage by the SAF.

Clast composition counts indicate that clast types in the fan are the same as those in the modern bed of BVC. The dominant clast types (83–90%) are beige to tan laminated, low-density shale, and grey to black higher-density chert from the Monterey Formation, which is the primary rock type on Inverness Ridge west of the study site. The other clast types are sandstone from the Laird Formation (6–10%) and granite from Salinian basement rock (1–5%), which are also exposed in bedrock outcrops west of the valley. We conclude that the Qqf gravel clasts were derived from the west via the BVC drainage. The variation in clast-type percentages could result from drainage changes in the watershed over time, as the bedrock units continued to erode to deeper stratigraphic levels.

A thin layer of fine-grained sand about 1.5 m above the base of the exposed Qqf deposits was sampled for OSL dating. The date obtained for this sample is 25 ± 2 ka (L. Owen, 2000, personal communication). This date is corroborated by a radiocarbon age of 28,100 ± 2600 years B.P. (CAMS #51328) determined on detrital charcoal from a colluvial layer shed from the lower west side of the Quarry fan ridge and exposed in the top layer of a paleoseismic trench. Since the OSL date is above the base of the Qqf deposit, we estimate that the base of the sedimentary sequence may be slightly older at approximately 30 ka.

The wide, shallow channel deposits in the Qqf deposits do not provide good piercing lines across the fault like the narrow, steep channels adjacent to the Hayward fault that Borchardt and Lienkaemper (1999) could use to calculate a long-term slip rate on that fault. However, changing paleocurrent directions in the fan sequence are consistent with continued dextral-fault motion, and we have used these data to reconstruct the fan position during phases of aggradation and fluvial incision (Fig. 6).

If the eastern end of the BVC drainage is restored southeastward until it is adjacent to the Qqf deposits (about 750 m), and these deposits are assumed to be 30 ka, we obtain an average slip rate during the past 30 ka of 25 mm/year (Fig. 6B). Channels at that time were flowing toward the east. The lowest deposits (beneath the buried soil that may indicate a period of fan quiescence) have paleocurrents directed toward the north–northeast, and the fan was probably located farther southwest at that time (Fig. 6A). Reconstruction of 1000 m offset since 40 ka yields a slip rate of 23 mm/year.

Fig. 6C shows the fan position during deposition of upper deposits, when paleocurrents were directed toward the east–southeast. It was probably during or shortly after the LGM that BVC cut through the medial ridge to create a water gap and ceased to supply sediment to the Quarry fan (Fig. 6C,D). As dextral fault motion continued, BVC was diverted and began to flow northwestward along the SAF trace (Fig. 6D). Gravel Creek was also diverted and began to flow through the gap that had been created by

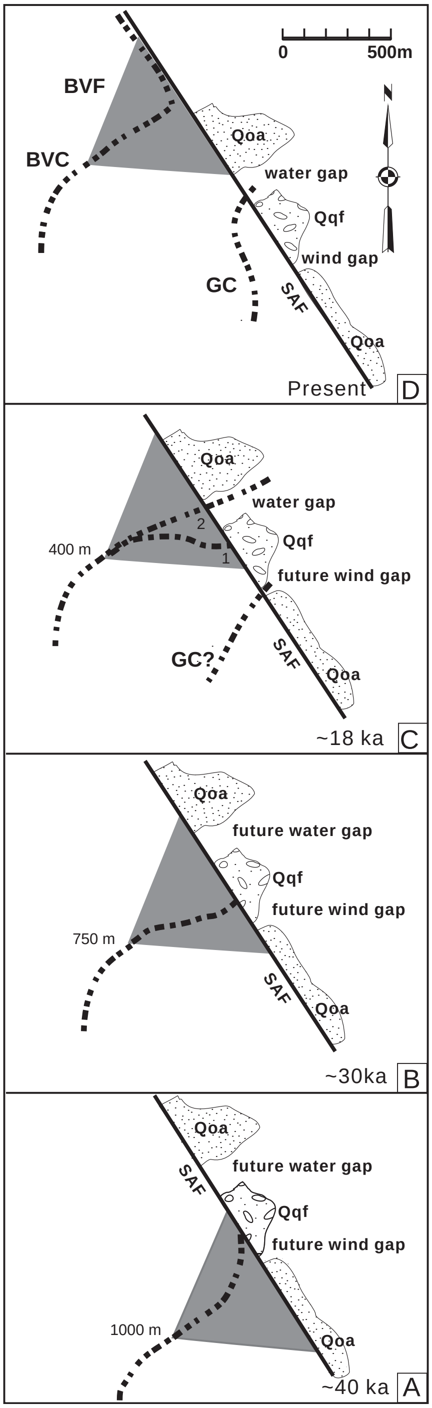


Fig. 6. Model for Quarry fan (Qqf) evolution. BVC=Bear Valley Creek. BVF=Bear Valley fan. GC=Gravel Creek. Qoa=older alluvium in medial ridge. Qqf=Quarry fan sediments. SAF=San Andreas fault (1906 trace). (A) BVC position during deposition of lower Qqf. If fan apex was at this position 40 ka (based on luminescence date), the time-averaged rate of northwest displacement is 23 mm/year. Sediments flow toward northeast. (B) Motion on SAF has moved fan apex northwestward and sediments flow to site in a more easterly direction. (C) SAF motion continues and sediments flow southeasterly to fan (channel 1). BVC incises fan deposits and cuts water gap (channel 2). GC cuts water gap sometime between C and D. Qqf deposits become isolated from BVC source. (D) Present configuration showing distinct left bend in Bear Valley Creek. Between C and D, subsidence west of SAF creates vertical scarp along western edge of Qqf deposits. GC is diverted to north, occupying water gap cut by BVC and creating wind gap south of Qqf.

BVC. A combination of subsidence west of the fault and erosional downcutting created a straight west-facing scarp along the western edge of the Quarry fan deposits. The eastern edge of the Quarry fan deposits has been eroded into a sinuous shape by meanders of the Olema Creek (Niemi and Hall, 1996).

Data from the Quarry fan suggest that the 1906 trace of the SAF has been active for at least the past 30 ka and that it has continued to slip at a rate of about 25 mm/year. Niemi (1992) also estimated a 21–30 mm/year longer-term slip rate, based on the approximate 460 m (± 150 m) offset of BVC from the 150-m-wide water gap in the medial ridge that it probably cut during the LGM about 18 ka. The soil at the top of the Quarry fan deposits developed during the nearly 20 ka since the ridge was incised and the fan became inactive.

4.3. Evidence from Holocene sediments in paleoseismic trenches

To determine a Holocene slip rate, two trenches were excavated across the 1906 trace of the SAF and the straight southwestern margin between Qoa medial ridge deposits and the Bear Valley fan (BVT in Fig. 3). At this site several geomorphic units are exposed at the surface. The slopes of the medial ridge, here composed of granitic colluvium derived from the Qoa deposits, are pervasively disrupted by landsliding. This is seen in hillside landslide scars and hollows, colluvial aprons, and landslide debris at the base of the ridge (Fig. 7A). West of the medial ridge and the SAF trace are the gentle slopes of the Bear Valley alluvial fan. Along the fault between the fan and the ridge is a linear depression formed by localized coseismic subsidence (Fig. 7B).

The Bear Valley (BV) trench 1 site was chosen at a location where a small landslide debris lobe apparently has been offset from a hillside scar by repeated movement on the SAF. Detailed topographic mapping of the site shows that the debris lobe has been offset about 20 m from the hillside hollow. The active trace of the SAF is clearly exposed in the trench. The fault juxtaposes light-colored, ridge-derived debris to the west against dark-colored, organic-rich, gravelly, sandy silt to the east (Fig. 7B). Repeated slip on the fault at this location has caused a localized zone of subsidence between the debris lobe and the ridge where the organic-rich deposits collected. A second fault trace is located west of and stratigraphically below the debris lobe. Detailed mapping of the structures exposed in the Bear Valley (BV) trench 2 within the landslide debris hollow revealed a complex series of shears within a Qoa slice or slide block (Fig. 7C).

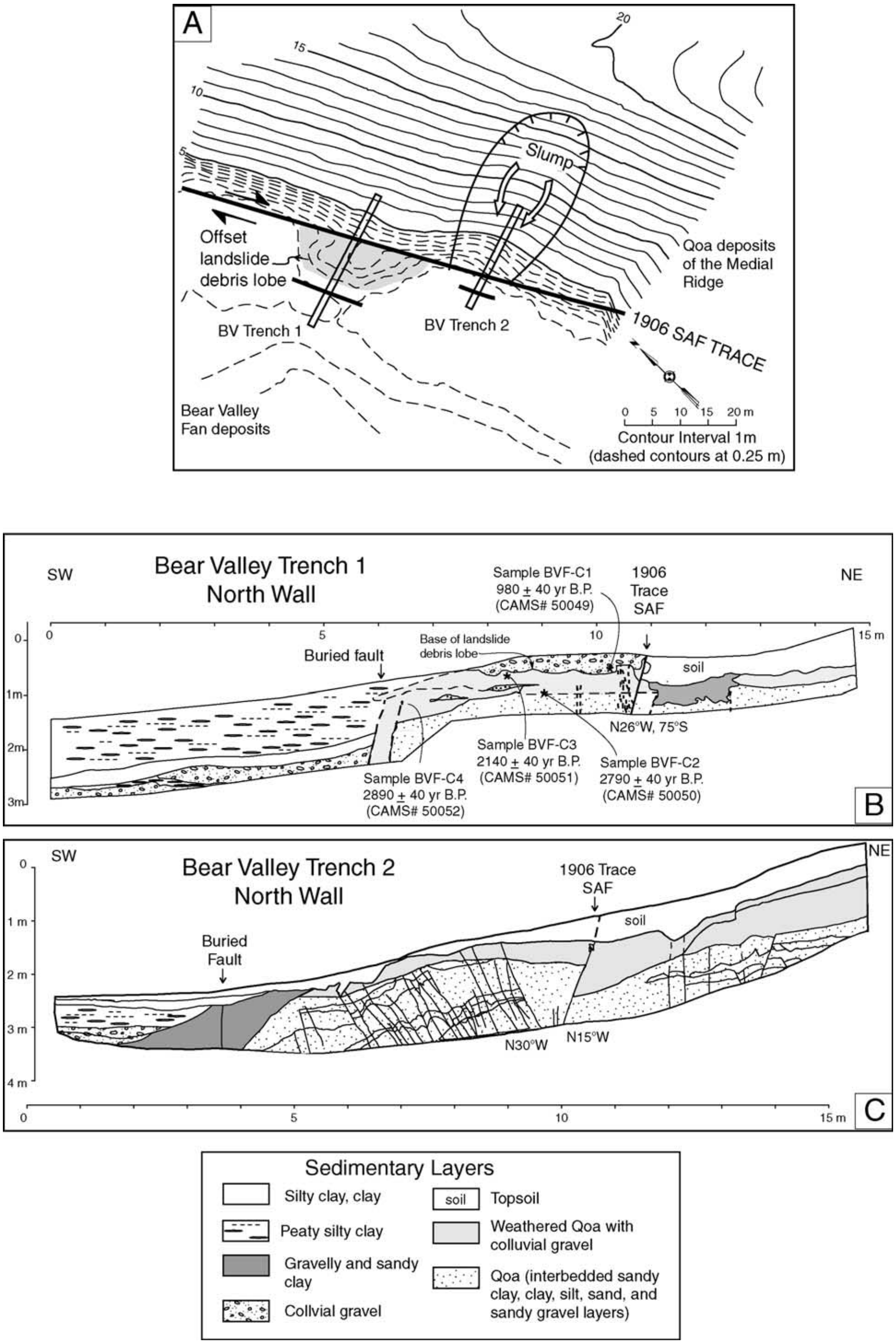
Radiocarbon dating on charcoal from sediment at the base of debris lobe yielded an age of 980 ± 40 years B.P. (962–790 cal B.P. using Method A of Radiocarbon Calibration Program version 4.3; Stuiver and Reimer, 1993). Because the detrital charcoal is older than the sediments in which it is found, this radiocarbon age suggests a maximum potential age of the debris lobe. Using the range 962–790 cal B.P. for the age of the landslide deposition and 20 m as the amount of horizontal translation, we calculated a minimum slip rate of 21–25 mm/year. Additional fault strands located to the west of the landslide debris lobe further indicate that this is a minimum rate.

4.4. Comparison with other slip-rate studies

The slip rate estimates we present in this paper for the late Pleistocene offset of the granitoid source area from Qoc (17–35 mm/year), offset of the BVC fan source from Qqf (23–25 mm/year), offset of the BVC channel from the Vedanta water gap (21–30 mm/year), and for the late Holocene offsets of a landslide debris lobe from the hillslope scarp (21–25 mm/year) agree

Fig. 7. (A) Detailed topographic map of Bear Valley fan trench site. The medial ridge is located along east side of the SAF and consists of older Quaternary alluvium (>30 ka, Qoa). Active trace of the SAF offsets debris lobe about 20 m northwest along the SAF from a hillside landslide scar. Map shows location of two paleoseismic trenches—Bear Valley (BV) trench 1 and BV trench 2. One-meter contours are labeled every 5 m and given in a relative elevation datum. Dashed contours are spaced every 25 cm. (B) Graphic log of north wall of Bear Valley trench 1 that was excavated through a small debris lobe and across the SAF. Two fault traces were exposed. The eastern SAF trace has translated the landslide debris lobe northwestward. A small depression has formed along this trace. The western SAF trace lies beneath base of landslide debris lobe and juxtaposes peaty silty clay against ridge-derived colluvium. (C) Graphic log of north wall of Bear Valley trench 2 excavated at base of hillside landslide scar and across the SAF. A pervasively sheared and folded block of the older alluvium (Qoa) is found between 1906 strand of SAF and a buried fault trace.

with other estimates at this location of 24 ± 3 mm/year (Niemi and Hall, 1992) and at other sites in northern California. Global Positioning System (GPS) velocities from a network across the SAF system in northern California from 1993 to 1995 produced an estimated slip rate of 39.6 + 1.5 − 0.6 mm/year for



faults of the 80-km-wide SAF system (Freymueller et al., 1999). About one half of this slip rate is thought to be accommodated on the SAF. Prentice et al. (2000) reported a slip rate of 15–22 mm/year, based on offset of an abandoned ~5 ka Mill Creek channel at Fort Ross, 60 km north of Olema. They also estimated slip rates of 18–19 mm/year based on offset of a late Pleistocene stream that is incised into oxygen-isotope stage 5e terrace deposits and offsets across a landslide. Farther to the north at Point Arena, estimates of a Alder Creek channel offset range from a maximum rate of 21–25 mm/year for the late Holocene (Prentice, 1989) to 17–28 mm/year for the late Pleistocene (Prentice et al., 2000). Offset marine terrace inner edges at Point Arena yield slip rates between 16 and 24 mm/year (Prentice et al., 2000). At the northernmost terminus of the 470-km-long 1906 San Francisco earthquake rupture, Prentice et al. (1999) determined a minimum slip rate of 14 mm/year for the past 13 ka.

5. Constraints on structural deformation from the Vedanta marsh

Details of the geologic history of the Vedanta marsh (Figs. 1 and 3) and its structural contact with the late Quaternary deposits of the medial ridge were obtained from air photo analyses, field mapping, and sedimentologic study of five sediment cores drilled into the marsh and paleoseismic trenches excavated across the SAF. The marsh is a 90-m-wide and 340-m-long basin formed between the 1906 trace of the SAF fault (northeast margin) and the WBF (southwest margin; Fig. 8). Our gravity model indicates that Qoa and Qal sediments thicken from 40 m along the WBF to about 80 m along the SAF across the Vedanta marsh (VM).

Information about the subsurface stratigraphic sequence in the VM was obtained from five cores extracted from the marsh during October 1998 using an all-terrain-vehicle mounted with a hydraulic, hollow-stemmed auger (Fig. 8). Cores were retrieved in 1.5-m unlined sections. Core recovery was good except in the upper 2 m of the section. Two cores—VM1a (4.8 m) and VM1b (20.8 m)—were recovered from the eastern margin of the marsh adjacent to the SAF and the paleoseismic trenches. Two cores—VM3 (4.8 m) and VM4 (16.0 m)—were obtained from the center of the marsh. A fifth 4.8-m-long core (VM2) was located approximately 50 m north of VM3 and VM4 in the center of the marsh, and had only 43% core recovery.

The stratigraphic sequence in the VM1b and VM4 cores can be divided into a lower coarse-clastic fluvial section and an upper fine-grained, peaty section of marsh deposits (Fig. 8B). These data indicate a major shift in depositional style. The boundary between the upper and lower sequence lies about 8.5 m below the surface in theVM4 core, but deeper, around 11.8 m, in the VM1B core. This elevation difference may indicate tectonic tilting of the marsh to the northeast, toward the 1906 trace of the SAF.

Radiocarbon dating of an insect wing, seed, bark, and charcoal collected from the bottom of core hole VM1b at a depth of 20.8 m yielded ages that cluster around 11,200 years B.P. These data suggest an average accumulation rate of 1.8–1.9 mm/year. A radiocarbon age of 8830 years B.P. from a depth of 14.7 m in VM4 suggests an average accumulation rate of 1.7 mm/year. Some peat deposition at the base of the VM1b core at a depth of 20.8 m indicates that subsidence has occurred along the VM for at least the past 12 ka. The slightly higher sediment accumulation rates along the 1906 trace of the SAF, compared to the center of the marsh, is consistent with other evidence of northeast tilting.

Active tectonic subsidence of the VM was observed at the time of the 1906 earthquake (Lawson, 1908), when a lane of water ponded against the rupture trace. Niemi (1992) used archival data, including historical descriptions, sketches, and photographs of the 1906 rupture, to precisely locate the fault trace and to document the style of coseismic deformation at the marsh (Gilbert, 1907a,b, 1908a,b; notebooks at U.S.G.S. archive, Denver; J.C. Branner photography, Stanford Univ. Archive). The 1906 faulting through the marsh was on a straight, narrow trace near the western base of the Quarry fan ridge and on a sidehill bench trace on the ridge southeast of the marsh (Fig. 8A). The secondary coseismic geomorphic changes at this site included: (1) a zone of secondary cracking 3.0 to 4.5 m wide, (2) local subsidence that temporarily reversed the flow of Gravel Creek and ponded water 70 cm deep along the fault trace, and (3) slump failure along the west

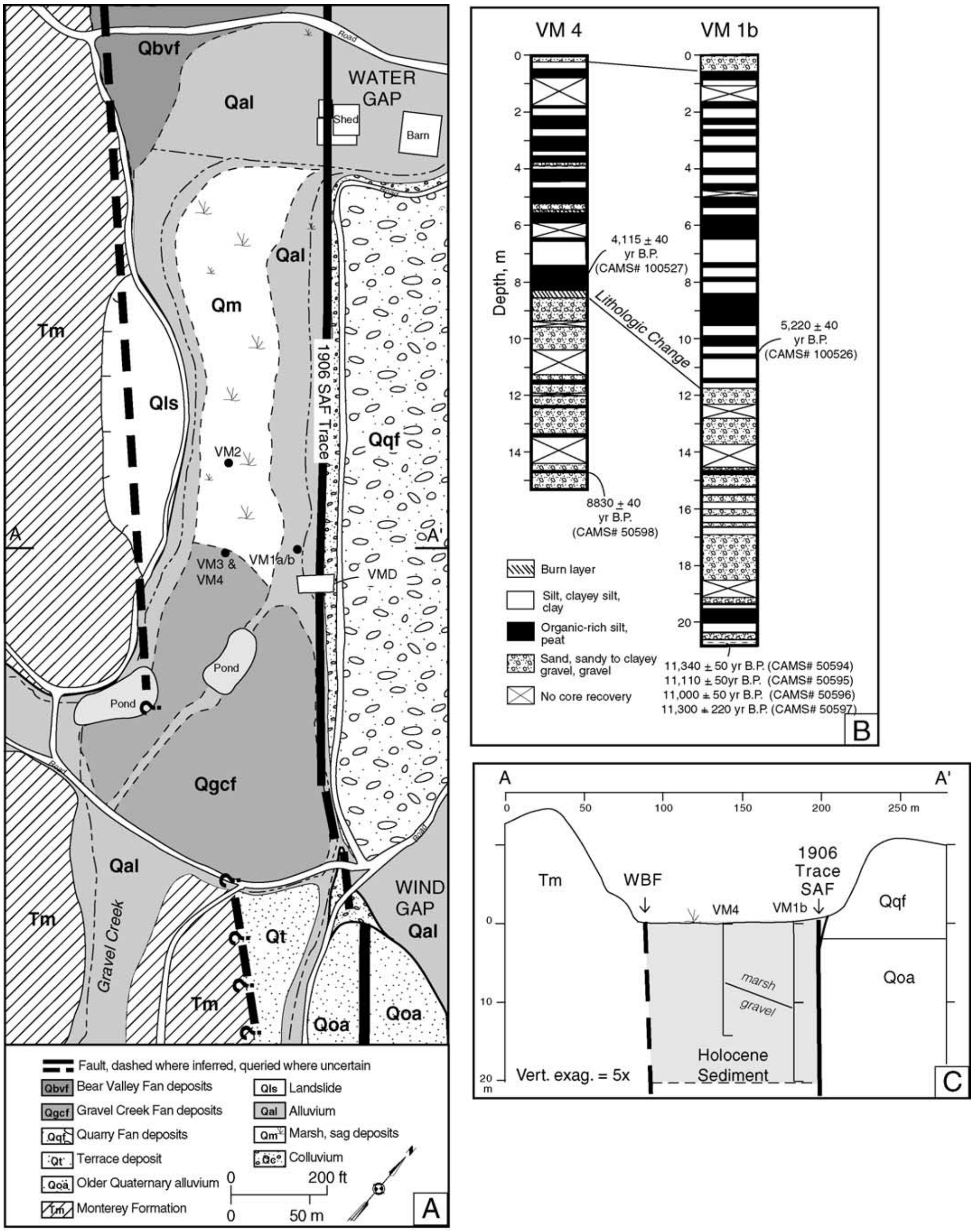


Fig. 8. (A) Surficial geologic map of Vedanta marsh showing location of sediment cores and paleoseismic trench (VMD). Alluvial fan deposits from Bear Valley Creek (Qbvf) to the north and Gravel Creek (Qgcf) to the south limit the extent of marsh deposition. Subsurface trenches into Gravel Creek fan indicate that fan deposits thin to the north and east (Niemi, 1992). Alluvium flanks areas where drainage channels traverse the marsh. Colluvium lies at the base of slopes of Quarry fan deposits (Qqf), which are topographcally higher. (B) Stratigraphic section of two cores taken from Vedanta marsh. Radiocarbon dates are shown with laboratory numbers from Lawrence Livermore National Lab. (C) Schematic cross section across the Vedanta marsh showing location of Western Boundary fault (WBF) and 1906 trace of San Andreas fault (SAF). Lithostratigraphic correlation between core VM4 in the middle of the marsh with VM1b along the SAF suggests northeast tilting of the basin.

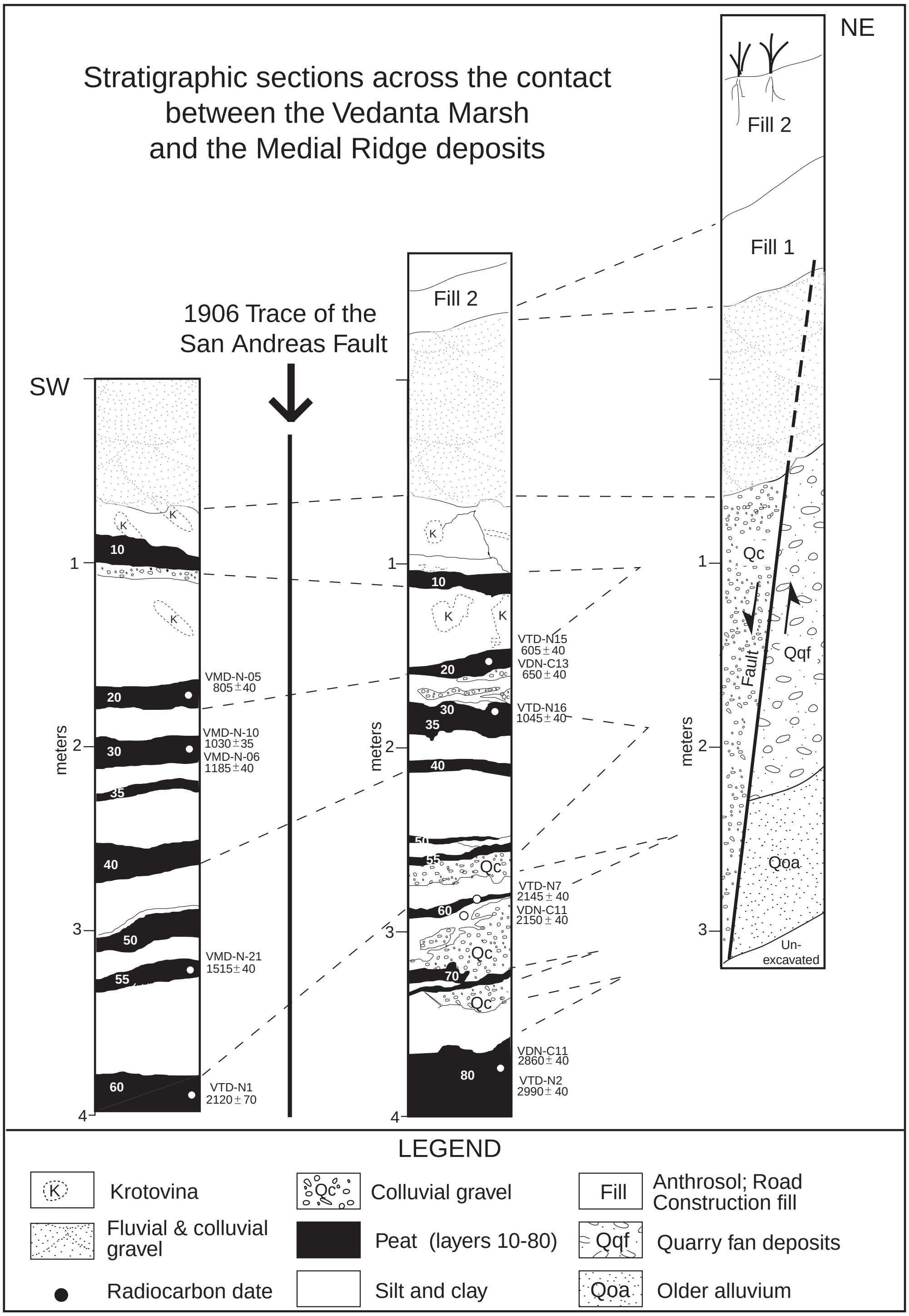


Fig. 9. Stratigraphic sections across Vedanta marsh and medial ridge deposits exposed in VM Ditch paleoseismic trench (VMD in Fig. 8A). A clear, vertical transition from predominantly fine-grained marsh deposits to coarse clastic sediment occurs about 1–2 m below ground surface. This was probably caused by historical logging and other land use changes in the watershed. Radiocarbon data are given in Table 1.

side of the ridge that caused the embankment of a dirt road to slide into the marsh. Trenching in the wind gap area at the south end of the VM also confirmed the existence of localized subsidence along the 1906 fault trace (Niemi and Hall, 1992).

Additional constraints on active deformation of the VM deposits and the nature of their contact with Qoa and Qqf sediments were obtained by studying paleoseismic trenches excavated perpendicular to the SAF (Niemi et al., 2002; Zhang et al., 2003). The late Holocene stratigraphic section in the trenches consists of marsh peat, clay, and silt overlain by fluvial and colluvial gravel (Fig. 9). The 1906 trace of the SAF is a 2-m-wide zone of upward-branching fault splays within the VM sediment, which interfingers with colluvial gravel from the medial ridge that is in fault contact with late Quaternary Qqf (~30–18 ka) and Qoa (>30 ka) deposits (Fig. 9). This secondary zone of faulting is located about 4 m east of the 1906 trace and has apparent normal separation (Fig. 9). The Qqf–Qoa contact east of the fault occurs about 1.3 m below the present VM surface (Fig. 8C) and indicates that base level at the time of deposition of the Qqf was similar to the current level. Our observations suggest a tectonic control for the VM basin. However, the amount of base level lowering and Qoa/Qqf sediment removal from the VM during the last glacial maximum is not known. Deeper drilling and recovery of longer cores within the VM basin would help to determine the relative amounts of tectonic subsidence and erosion at this site.

The rate of differential subsidence across the active 1906 trace of the SAF can be estimated by using the top of peat layer 60 as a marker (Fig. 9). The top of peat 60 has an apparent vertical separation across the fault of 90 cm. Radiocarbon analysis on organic material from the layer yielded a radiocarbon age of ca. 2100 years B.P. (Table 1, samples VTD-N7 and VTD-N1). These data suggest a 0.4 mm/year tectonic subsidence rate. Successively younger peats have progressively less vertical separation. The calculated subsidence rate for peat 60 is less than the sediment accumulation rate calculated for the 3.3-m-thick section of marsh deposits. This suggests that the amount of vertical separation may include apparent offset due to lateral slip of units, and thus may not represent the full tectonic subsidence. The rate of 0.4 mm/year is comparable, however, to the late Quaternary subsidence rates for San Francisco Bay of approximately 0.2–0.4 mm/year (Atwater et al., 1977). These data suggest that the ratio of vertical slip to strike slip across the 1906 trace of the SAF at this site is relatively small. Subsidence is probably accommodated on the secondary fault that juxtaposes colluvium and interfingering marsh sediment against Qqf and Qoa sediment. The amount of tectonic

Table 1
Radiocarbon data from the Vedanta paleoseismic trench (VMD)

Sample name	Lab #	Location[I]	Sample material	Layer	Depth[II]	$\sigma^{13}C$	Fraction Modern	$D^{14}C$	^{14}C age
Vedanta marsh ditch									
VTD-N15-wd	CAMS #80518	DN, E	wood	20	173	−25	0.9272 ± 0.0045	(−78.5) ± 4.5	605 ± 40
VDN-C13	CAMS #90669	DN, E	twig/wood	20	178	−25	0.9225 ± 0.0045	(−77.5) ± 4.5	650 ± 40
VMD-N-05	CAMS #90675	DN, W	leaf	20	186	−25	0.9044 ± 0.0045	(−95.6) ± 4.5	805 ± 40
VTD-N16-wd	CAMS #80519	DN, E	wood	21	184	−25	0.8779 ± 0.0042	(−127.5) ± 4.2	1045 ± 40
VMD-N-06	CAMS #90674	DN, W	leaf	30	214	−25	0.8629 ± 0.0038	(−137.1) ± 3.8	1185 ± 40
VMD-N-10	CAMS #90676	DN, W	leaf/twig	30	225	−25	0.8797 ± 0.0038	(−120.3) ± 3.8	1030 ± 35
VMD-N-21	CAMS #90671	DN, W	twig	55	332	−25	0.8281 ± 0.0040	(−171.9) ± 4.0	1515 ± 40
VMD-N-18	CAMS #90670	DN, W	twig	60	380	−25	0.8356 ± 0.0037	(−164.4) ± 3.7	1445 ± 40
VTD-N7	CAMS #80512	DN, E	peat	60	309	−25	0.7655 ± 0.0037	(−239.2) ± 3.7	2145 ± 40
VTD-blk-N1-290-295mm	CAMS #80507	DN, W	peat	60	422	−25	0.7685 ± 0.0060	(−236.3) ± 6.0	2120 ± 70
VDN-C10	CAMS #90667	DN, in, E	twig	61	384	−25	0.7655 ± 0.0049	(−234.5) ± 4.9	2150 ± 60
VDN-C11	CAMS #90668	DN, E	twig	80	368	−25	0.7002 ± 0.0034	(−299.8) ± 3.4	2860 ± 40
VTD-N2f	CAMS #80511	DN, E	peat	80	377	−25	0.6892 ± 0.0034	(−315.1) ± 3.4	2990 ± 40
Detrital Qqf									
VT98-2S-26	CAMS #51328	T2S, W	charcoal	4	65	−25	0.0302 ± 0.0098	(−969.8) ± 9.8	28,100 ± 2600

subsidence on this fault cannot be estimated due to a lack of stratigraphic match across the structure.

6. Conclusions

Investigations of late Quaternary sediments that were deposited in the San Andreas fault (SAF) zone in Olema Valley provide new data about the style of deformation and about deformational changes through time in this strike-slip tectonic setting, which is well known because of the large offset that occurred during the great 1906 San Francisco earthquake. Newly obtained ages from luminescence and radiocarbon dating, combined with sedimentary unit and geomorphic reconstructions, provide slip rates extending into the late Pleistocene. High-resolution gravity data, coring, and paleoseismic trenches provide the subsurface data for interpreting fault geometry at valley-wide and more local scales.

Luminescence ages for the oldest Quaternary units in the valley are 112–186 ka for the Olema Creek Formation (Qoc) and 125–155 ka for the Millerton Formation (Qm), suggesting that these units are time correlative but now separated at the surface because of subsidence and overlap by younger sediments. Analyses of surface exposures and subsurface well log and gravity data suggest that this area of subsidence has migrated northward during the past several hundred thousand years, from a location near Five Brooks when the Qoc was deposited to its present position near the head of Tomales Bay. The Qoc sediments have subsequently been deformed into broad folds and truncated by movement on the valley-bounding Eastern Boundary fault, which has a strong topographic expression in the landscape. The apparent alternation between transtension and transpression in the valley appears to be the result of fault strand geometry that diverges northward, and includes motion on valley-bounding faults as well as the 1906 strand of the SAF. Paleoseismic studies on the valley-bounding faults are needed to better understand their slip rates and their records of paleoearthquakes.

Reconstruction of the Qoc to a position adjacent to its sediment source area provides a long-term slip rate of 17–35 mm/year. Reconstruction of the Quarry alluvial fan (Qqf; basal age ~30 ka) to a position next to the Bear Valley Creek that supplied it with sediment yields an estimated slip rate of 25 mm/year, which is consistent with an estimated slip rate of 21–30 mm/year obtained by matching the creek with other geomorphic features, such as a water gap probably formed during the LGM ~18 ka. Reconstruction of a ~1000-year-old debris lobe to its source position yields a slip rate of 21–25 mm/year. The consistency among rates obtained from these late Pleistocene–Holocene units, and from previous paleoseismic studies in the area, points to persistent dextral slip in the vicinity of the 1906 SAF strand. These rates are also consistent with rates obtained from studies along the SAF farther north in California.

The Vedanta marsh is a basin formed in part by localized subsidence along the SAF zone. It is bounded on the northeastern side by the 1906 trace and on the southwestern side by the Western Boundary fault. Sediments at the base of cores from the marsh are dated at ~13 ka, with peat deposits prevalent since ~5 ka. The subsurface core stratigraphy suggests tectonic tilting toward the northeast, toward the 1906 trace. This is consistent with observations of subsidence along the fault after the 1906 earthquake, and with apparent normal separation of horizontally bedded peat layers mapped across the fault in paleoseismic trenches. Although the rate of vertical offset across the 1906 trace is very small compared to the rate of horizontal offset, the rate of vertical offset across the Western Boundary fault may be much greater, given the elevation of Inverness Ridge on the western side of this fault.

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