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Historical Changes in the Tidal Marsh of Tomales Bay and Olema Creek, Marin County, California

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ABSTRACT

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Maps of the Tomales Bay and Olema Valley region, located 65 km north of San Francisco, were first published about 1860. We compared these maps with more recent topographic maps to determine geomorphological changes in the tidal marsh at the head of Tomales Bay and within the lower reach of Olema Creek, one of its tributaries. The accumulation of a significant volume of sediment in Tomales Bay is documented by shoreline progradation between 1862 and 1954, with the bulk occurring before 1918. This deposition probably reflects landscape instability caused by the introduction of livestock, agriculture, and non-native vegetation and by intensive logging within the watershed. The depositional history of Tomales Bay is undoubtedly similar to that of Bolinas Lagoon, another submerged part of the San Andreas fault zone closer to San Francisco.

Map comparisons show that the downstream reach of Olema Creek actively meandered across its floodplain until the early 1920's. Stratigraphic evidence for a late Holocene channel of Olema Creek 300 m west of its present position was exposed in trenches near the town of Olema. This buried channel and its associated overbank deposits confirm that until recently the Olema Creek floodplain was a naturally aggrading environment. Presently, the channel of Olema Creek is entrenched several meters into its floodplain. This incision probably was triggered by artificially straightening the channel near its mouth, causing the gradient to increase.

ADDITIONAL INDEX WORDS: *Coastal environmental change, marshland, human impact, stream incision.*

INTRODUCTION

One of the most challenging aspects of research within the coastal environment is assessing the impact of human activity on the rate that erosion and deposition alter this naturally evolving estuarine ecosystem. In this paper, we document the major geomorphic changes that have occurred in the past 150 years at the head of Tomales Bay and along one of its major tributary drainages, Olema Creek.

Tomales Bay, located approximately 65 km north of San Francisco in Marin County, California, occupies a submerged valley developed along the San Andreas fault. The Tomales Bay region has a long Miwok Native American cultural history, although their occupation appears not to have significantly altered the environment. This region was first explored by the Spanish in the 16th Century and was developed into ranches in the mid-19th Century. Development of the region has been minimal compared with other parts of coastal California. A flourishing oyster industry is evidence that water quality within the bay remains high. However, the morphology of Tomales Bay, its marshland, and its tributaries have significantly changed in the past 150 years.

In Marin County, the San Andreas fault zone has left a prominent, linear mark on the landscape—a 45-km-long depression oriented northwest-southeast (Figure 1). The north and south parts of the fault zone currently are submerged beneath Tomales Bay and Bolinas Lagoon, respectively (Figure 1b). West of the fault, Inverness Ridge has a maximum elevation of 430 m. It is cored by Mesozoic granodioritic basement rocks of the Salinian Block overlain by folded Tertiary sedimentary rocks (BLAKE *et al.*, 1974; GALLOWAY, 1977; CLARK *et al.*, 1984). East of the fault, the rounded hills of Bolinas Ridge consist of Franciscan graywacke, greenstone, serpentinite, and mélange, a subduction zone complex of Mesozoic age (GLUSKOTER, 1969; BLAKE *et al.*, 1974). The

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juxtaposition of these rocks having markedly different tectonostratigraphic histories is due to cumulative right-lateral offset of at least 300 km across the San Andreas fault system, which began in the early Tertiary (*e.g.*, GRAHAM *et al.*, 1989). Within the study area, the San Andreas fault zone is marked by streams with locally deflected channels and by ponded drainages or sags, all of which attest to the intricate relationship between fault slip and drainage pattern evolution (HALL and HUGHES, 1980; BROWN and WOLFE, 1972). Geomorphic changes in the drainages caused by the 5 m of dextral offset across the fault in the 1906 San Francisco earthquake were documented by G.K. GILBERT (1908).

In this study, we assess historical changes in the geomorphology of both the tidal marsh of Tomales Bay and its tributary drainage systems since about 1860 by comparing several generations of maps of the study area. We also present sedimentologic data that document changes that have occurred in the Olema Creek floodplain, one of the major drainages that flow into the south end of the bay. These data and resulting interpretations are compared to other studies of the Tomales and Bolinas regions.

PHYSIOGRAPHIC ASPECTS

Tomales Bay

Tomales Bay is a 20.4-km-long, shallow (mean depth of 3.1 m) estuary with a total watershed area of 570 km^2 (LMER, 1992). Two large drainage basins supply fresh water to Tomales Bay from the east—Walker Creek near the mouth and Lagunitas Creek near the head of the bay (Figure 1). A third large drainage that follows the trend of the San Andreas fault to the south of the bay is the Olema and Bear Valley creek system. These north-flowing streams are tributary to the mouth of Lagunitas Creek, joining it at the head of Tomales Bay. Short, northeast-flowing streams from Inverness Ridge west of the fault and southwest-flowing streams from Bolinas Ridge east of the fault also drain into the bay.

Tomales Bay has a restricted connection to the Pacific Ocean through the waters of Bodega Bay (Figure 1). The granodioritic rock that forms Tomales Point at the northwest tip of the Point Reyes Peninsula extends northwest to Bodega Head as a shallow, submerged ridge. This ridge has three gaps eroded across its trend. The main connection of Tomales Bay with the Pacific Ocean is the southernmost, 2.3-km-wide gap, which has a sill depth of 24 meters below sea level (mbsl) and lies offshore of Tomales Point (DAETWYLER, 1966). This shallow connection with the Pacific Ocean indicates that with only a relatively small drop in sea level, Tomales Bay changes from an estuary to a subaerial river valley. Given the well-documented changes in sea level that have accompanied the Pleistocene climatic fluctuations, this environmental transformation must have occurred several times in the past two million years.

Olema and Bear Valley Creeks

Olema Creek is a perennial stream within a linear drainage basin that follows the eastern margin of the San Andreas fault zone for 13.7 km and has a drainage area of 40 km^2 (Figure 1). The watershed of Olema Creek lies predominantly within the Franciscan rocks of Bolinas Ridge. Tributary drainages from Bolinas Ridge are short, ephemeral, consequent streams that flow nearly perpendicular to the fault zone. Gravel Creek and several other perennial, spring-fed streams from Inverness Ridge west of the fault also are tributary to Olema Creek. The drainage basins of these western tributaries lie entirely with Monterey Formation shales of Miocene age.

The longitudinal profile of Olema Creek shows three pronounced knickpoints (Figure 2). The first, approximately 4.3 km south (upstream) of the mouth of the stream, probably represents the headward migration of an erosional pulse triggered when the channel was artificially straightened in the early 1920's. The second step in the profile occurs at Five Brooks, where the creek has been dextrally offset by the San Andreas fault (HALL *et al.*, 1986). The third knickpoint occurs in the headwaters region and marks the change in gradient between the first-order drainage on the fault valley floor and the second-order tributaries that drain the adjacent ridges.

Bear Valley Creek is a perennial stream that drains a 12-km^2 area of Inverness Ridge and whose downstream reach follows the western margin of the fault valley. This creek makes a pronounced deflection to the northwest, where it intersects the 1906 trace of the San Andreas fault (Figure 1). Farther downstream, Bear Valley Creek flows parallel to the lower reach of Olema Creek. It is separated from it by a low ridge of probable tectonic origin in the middle of the fault zone. The linearity of these subparallel drainages indicates that they are subsequent streams whose location

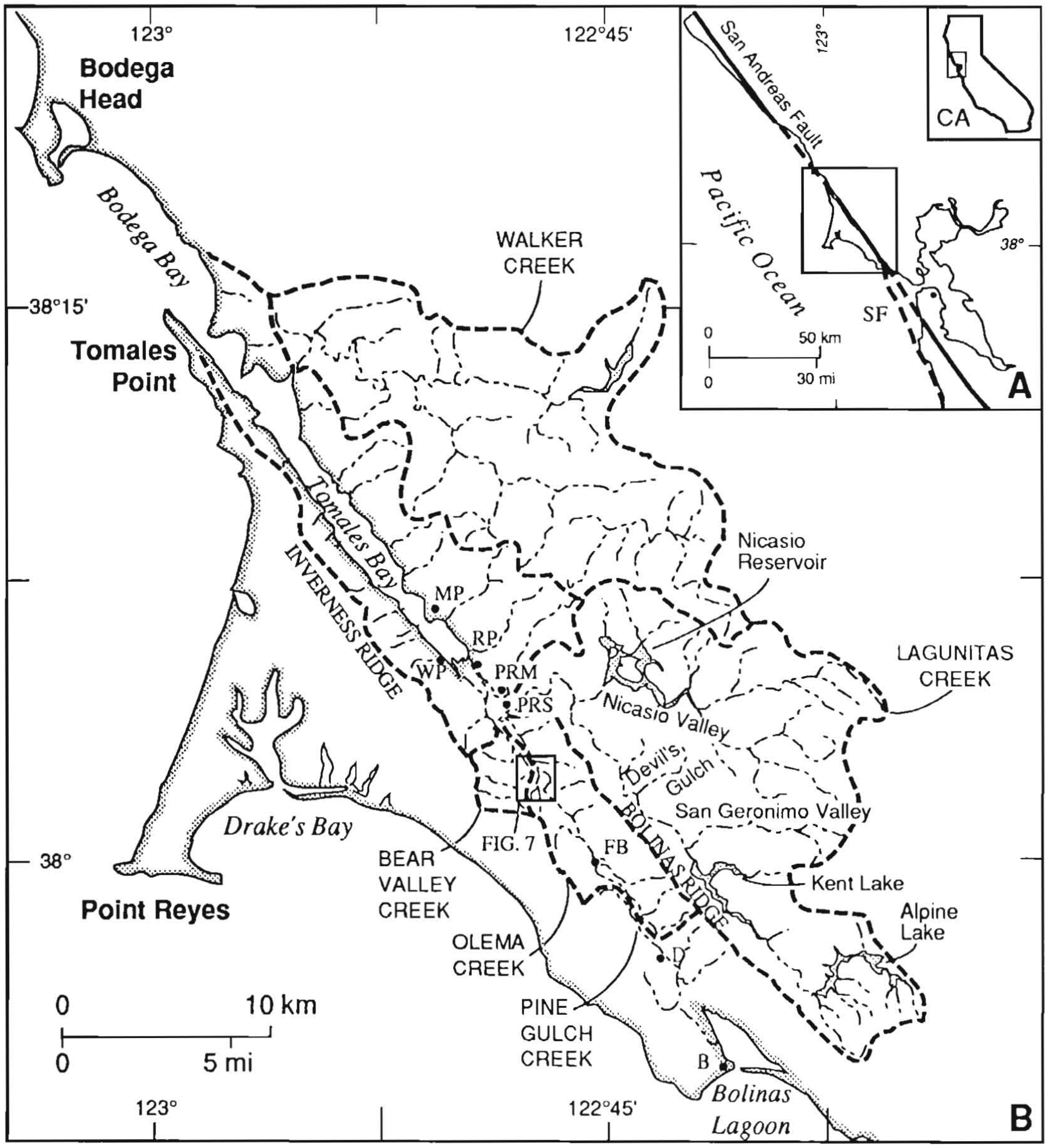

Figure 1. Map showing the drainage basins tributary to Tomales Bay. A) Tomales Bay is located along the San Andreas fault north of San Francisco (SF) east of Point Reyes Peninsula. B) The watershed of Tomales Bay and its subdivisions are outlined with a bold dashed line. The major drainage basins contributing to Tomales Bay are Walker Creek basin near the mouth of the bay and Lagunitas Creek basin near the head of the bay. Two drainage basins, Olema Creek and Bear Valley, join Lagunitas Creek in the tidal marsh. Short northeast- and southwest-flowing drainages flank the sides of the bay. Place names mentioned in the text are labeled or have the following abbreviations: B = Bolinas, D = Dogtown, FB = Five Brooks, MP = Millerton Pt., PRM = Point Reyes mesa, PRS = Point Reyes Station, RP = Railroad Pt., and WP = Willow Pt.

is ultimately controlled by horizontal and vertical slips along the San Andreas fault. Both Olema and Bear Valley creeks flow into the southeast end of Tomales Bay via Lagunitas Creek.

Lagunitas Creek

Lagunitas Creek (also called Papermill Creek) is a perennial stream that drains an area of 211 km^2 east of the San Andreas fault (ANIMA *et al.*, 1988), including the Nicasio and San Geronimo valleys (Figure 1). Sediments from this stream and its southern tributaries, Olema and Bear Valley creeks, have accumulated in the southeast end of Tomales Bay, forming a prominent delta. This delta region is marked both by a mudflat, which is emergent only at low tides, and by a vegetated salt marsh, which is subject to flooding during high tides.

Marin Municipal Water District has built three dams across Lagunitas Creek for local water supply purposes. The resulting reservoirs, Kent Lake, Alpine Lake, and Nicasio Reservoir, have greatly reduced the suspended sediment that this drainage system contributes to Tomales Bay. Where it enters the tidal marsh of Tomales Bay, the mouth of Lagunitas Creek is regulated by a fourth dam that diverts fresh water from the creek into leveed ditches, which drain a part of the marsh and convert it into pasture for dairy cattle.

HISTORICAL DRAINAGE CHANGES

We assessed recent changes in the geomorphology of the tidal marsh at the southern end of Tomales Bay and the local tributary drainage systems by comparing several generations of historical maps. The most accurate early maps of the head of Tomales Bay and the Olema Creek drainage are the 1862 U.S. Coast Survey map of Tomales Bay and the 1858 land grant map prepared for Andrew Randall (Figures 3 and 4). A boundary map was one of the requirements for acquiring a land grant from the Mexican government between 1834 and 1846 and for verifying the claim to the U.S. government after 1850 (DEWEY LIVINGSTON, *personal communication,* 1991). The 1858 *Plat of the Rancho Punta de los Reyes (Sobrante)* was surveyed for Andrew Randall by R.C. MATHEWSON (1858) and filed with the U.S. Surveyor General in San Francisco in August 1858 (Figure 4). This map was drawn at a scale of 40 chains to the inch (40 chains equals 0.5 mile or 0.8 km) and appears to be the base for subsequent boundary maps. Trees along the banks of Olema Creek were

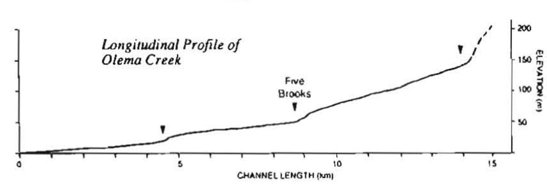

Figure 2. Longitudinal profile of Olema Creek. Three pronounced knickpoints, marked by triangles, separate segments of the stream with different gradients. Profile was drawn from USGS topographic maps, scale 1:24,000.

used as reference points in the 1858 survey, a common practice at that time. These can be seen on the map in Figure 4.

The 1865 boundary map of property belonging to Rafael Garcia, entitled *Plat of the Rancho of Tomales y Baulines* (SAN FRANCISCO SURVEYOR GENERAL, 1865), was compiled from notes and maps at the Surveyor General's office in San Francisco. An 1871 map showing the subdivisions of the *Rancho Punta de Los Reyes* in Marin County, California, also appears to be based on the earlier (1858) survey along Olema Creek. It contains original survey data only for areas west of Five Brooks along a drainage that extends toward the Pacific Ocean and along Bear Valley Creek.

During his field investigation in 1906–1907 of the surface rupture on the San Andreas fault after the April 18, 1906 San Francisco earthquake, G.K. Gilbert sketched the fault within the drainage basins of Olema and Bear Valley creeks and where it was exposed at low tide in Tomales Bay (Figure 5). From these sketches (GILBERT, 1908), we obtained additional information about both the position of the channels of Olema and Bear Valley creeks and the appearance of the marshlands at the head of Tomales Bay. Because these sketch maps were not based on surveyed data nor drawn to scale, they provide only a qualitative picture of geomorphic conditions at the time of the earthquake.

The first U.S. Geological Survey (USGS) topographic map of the area is the Point Reyes 15 minute quadrangle, issued in 1918 and revised in 1954. The old boundary of the land grant of *Rancho Punta de los Reyes (Sobrante)* and *Rancho Tomales y Baulinas* is marked as a dashed line on these maps. Because the land grant essentially coincided with the course of Olema Creek in the 1860's, the USGS maps record the position of its channel at that time. The 1918 topographic map

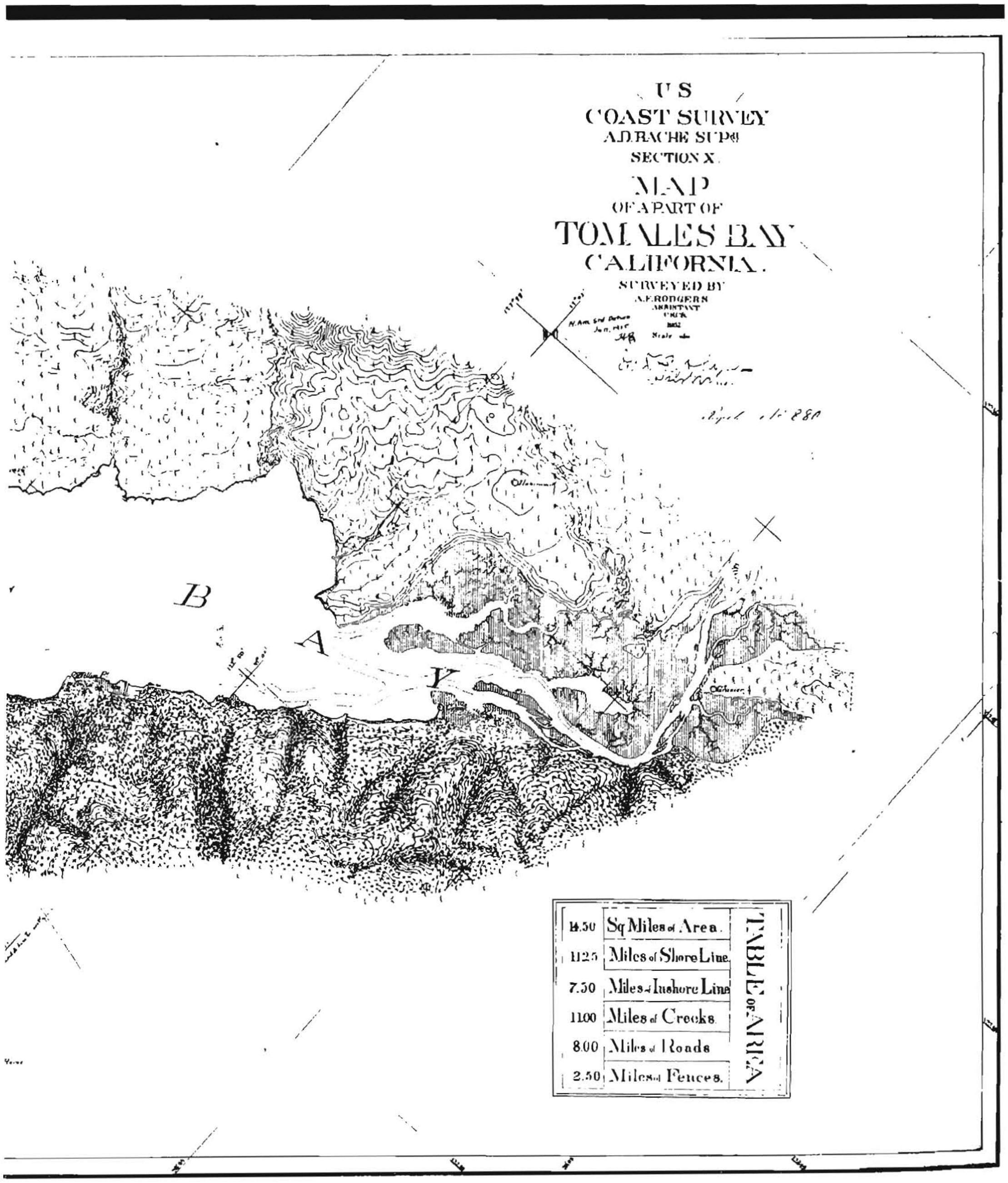

Figure 3. U.S. Coast Survey map of a part of Tomales Bay, dated 1862 (Section X, surveyed by A.F. Rodgers).

also documents the changes in the course of Olema Creek and the marshland areas of Tomales Bay from the 1860's to 1918. The 1954 edition of this quadrangle map records changes from 1918 to 1954.

"Olema canal" first appears on the 1925 map of Marin County. The canal was built after the area was surveyed in 1915–1916 for the 1918 USGS topographic map and before the 1925 map. Willow thickets along the lower reach of Olema Creek

Figure 4. Historic map of the Olema and Bear Valley Creeks, dated 1858. Olema Creek was the northeast boundary of the land grant of *Rancho Punta de los Reyes (Sobrante)* confirmed to Andrew Randall.

were cleared, and a canal was dug in about 1920 to 1922 to convert the swampy land to pasture and to control flooding (LIVINGSTON, 1991). The meandering stream channel was artificially straightened between the town of Olema and Lagunitas Creek, a distance of approximately 3.0 km.

To track the changing positions of Olema Creek and the growth of the marshlands at the head of Tomales Bay, we superimposed the 1862 U.S. Coast survey map and the 1918 and 1954 editions of the USGS 15 minute topographic map using a zoom transfer scope. Prominent headlands along Tomales Bay, including Railroad Point, Millerton Point, the "points" of Point Reyes Station and Point Reyes Mesa on the east and Willow Point on the west (Figures 1 and 6), were used, along with latitude and longitude, to register the maps.

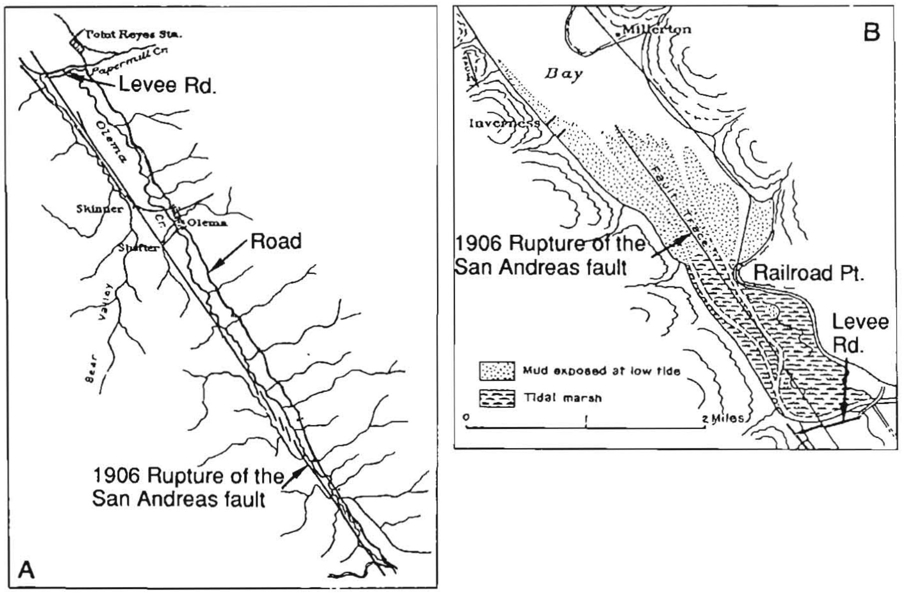

Figure 5. G.K. Gilbert's sketch map of the 1906 surface rupture of the San Andreas fault within the drainage basins of Olema and Bear Valley creeks and Tomales Bay. A) This sketch nicely illustrates the deflected drainages along the San Andreas fault. Also note the exaggerated meanders of the lower reaches of both Olema and Bear Valley creeks (GILBERT, 1908). B) Sketch of the head of Tomales Bay showing the location of the San Andreas fault rupture and the offset of the Levee road (Sir Francis Drake Boulevard) (Figure 24 in GILBERT, 1908). Note the boundary between the "tidal marsh" and "mud exposed at low tide" just northwest of Railroad Point. By 1918, as represented on the USGS topographic map, this boundary had propagated slightly farther northwestward.

The 1858 Randall map (Figure 4), which shows the position of Olema Creek, was not re-registered to the compilation map because the location of the land grant survey, which closely follows the stream course, is printed on the 1918 and 1954 editions of the USGS 15 minute Point Reyes quadrangles. Because of limited historical data, the changes in channel location of Bear Valley and Gravel creeks are shown only between 1918 and 1954. In the following section, we summarize the primary changes in the channel of lower Olema Creek and the marshlands of Tomales Bay that occurred during the time intervals 1860 to 1918, 1918 to 1954, and 1954 to 1982.

Interval 1860 to 1918

Perhaps the most dramatic and pervasive changes in landscape and land use occurred during this time:

(1) Siltation at the head of Tomales Bay caused the tidal marsh to prograde more than a kilometer to the northwest (Figure 6), from 0.5 km northwest of Point Reyes Mesa to Railroad Point (two prominent ridges on the east shore of Tomales Bay).

(2) As shown in the 1862 map, only one tidal channel connected with Lagunitas Creek at that time (Figure 3). A second fork connected to the main tidal channel from the northwest, but not to the southeast to Lagunitas Creek. A third tidal channel extended to Tomassini Canyon between Point Reyes Station and Point Reyes Mesa. It appears that subsidence associated with 1906 strike-slip faulting and described by GILBERT (1908) caused the second tidal channel to connect with Lagunitas Creek (Figure 5). By 1918, however, deposition had changed this tidal channel into an isolated, closed depression.

(3) It is clear that Olema Creek migrated westward during this interval, but the maps available from this period lack the detail necessary to evaluate whether the incision that characterizes the present channel also occurred before 1918.

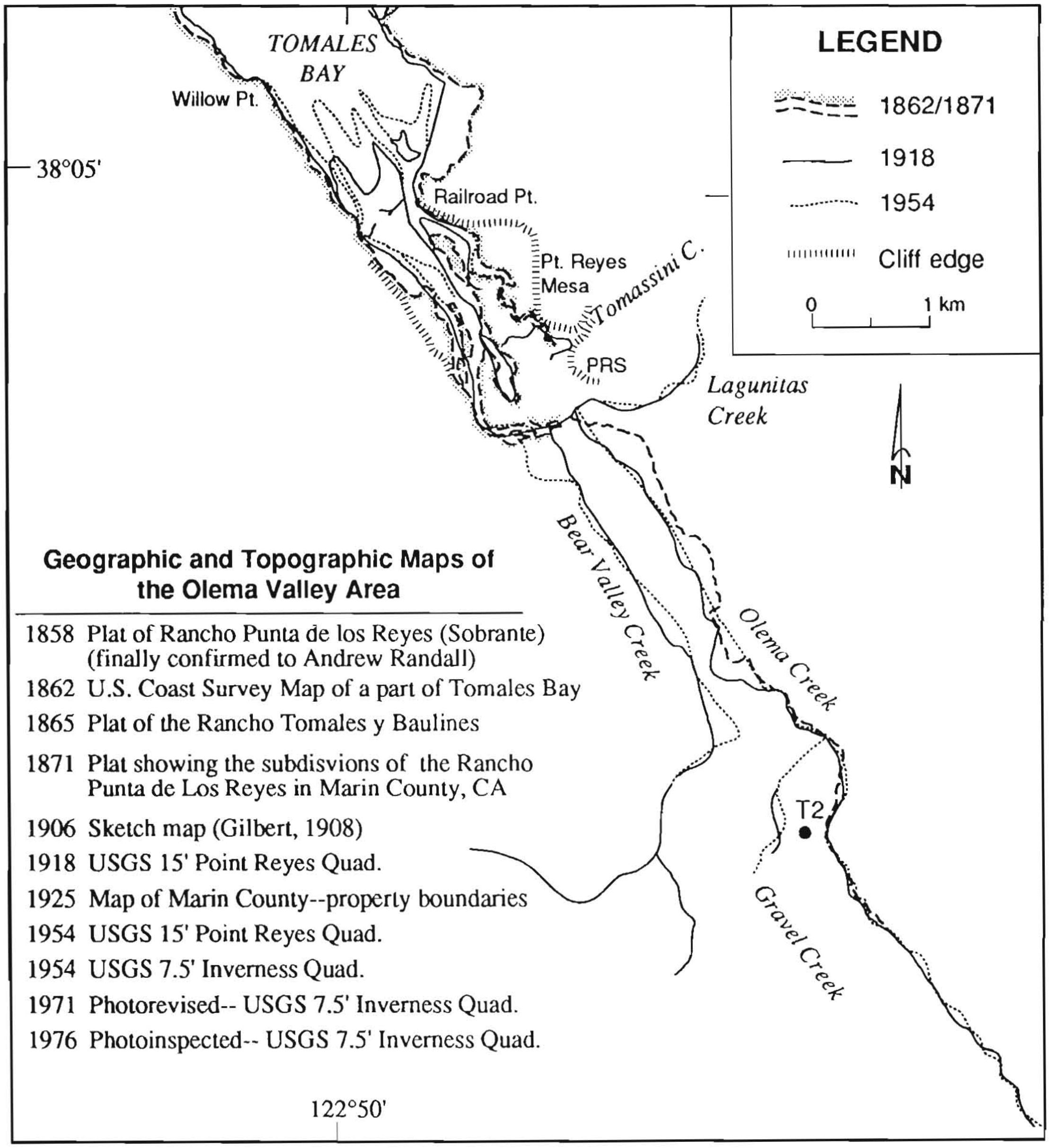

Figure 6. Comparison of the 1862/1871, 1918, and 1954 maps of the head of Tomales Bay and the northern reach of Olema Creek. T2 marks the location of Trench 2 where evidence of a prehistoric position of Olema Creek was uncovered.

(4) Several historical accounts suggest the presence of an "Arroyo Olemus Lake" or Olema Lake (D. LIVINGSTON, *personal communication*, 1991), whose most likely location is the low-lying stretch of Olema Creek between the town of Olema and Lagunitas Creek. This flood-prone area was most recently inundated in the storm of January 6, 1982 (ANIMA *et al.*, 1988).

Several structures were built within the study area between 1860 and 1918. Landscape and veg-

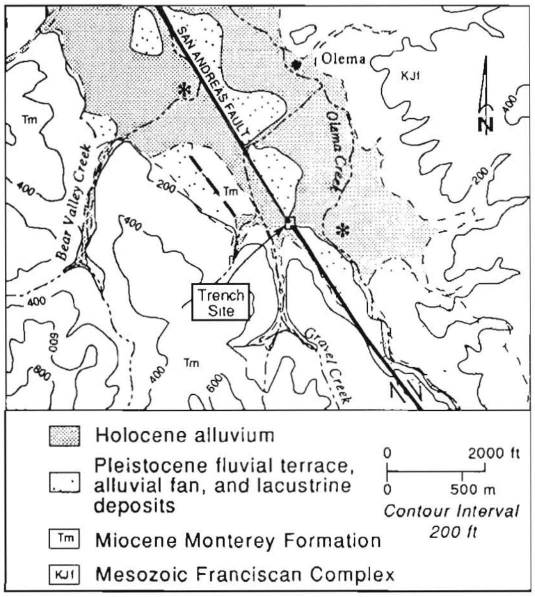

Figure 7. Map of Olema Valley showing the location of the trench site where a stratigraphic section of Olema Creek deposits was exposed. The asterisks mark the site of the right-angle bend in the channel of Bear Valley Creek and also the sharp bend in Olema Creek. Location of this detailed map is given on Figure 1. Contours from U.S. Geological Survey Inverness 7.5 minute quadrangle. Geologic mapping based on HALL and HUGHES (1980).

etative cover modifications that probably accelerated the rate of sedimentation into Tomales Bay also occurred during this interval. In 1856–1857, four lawyers, Oscar and James Shafter, Trenor Park, and Solomon Heydenfeldt, acquired more than 50,000 acres of land on the Point Reyes Peninsula (SHAFTER, 1915). The land was subdivided into ranches, stocked with sheep and dairy cattle, and leased to tenants. Raising livestock and European crops introduced non-native grasses and weeds into the local ecology, changing forever the vegetative cover of the land. Intensive logging also occurred during this period. Redwoods were removed from the Lagunitas Creek basin, and Douglas fir trees were cut in Olema Valley basin for cordwood (MASON, 1976). In the 1860's, Samuel Taylor built a paper processing mill on Lagunitas Creek several kilometers upstream from Tomales Bay (MUNRO-FRASER, 1880). In 1873–1874, the North Pacific Coast Railroad track was completed along Lagunitas Creek and north along the east shore of Tomales Bay (DICKINSON, 1967). A county road, now known officially as Sir Francis Drake Boulevard and locally as the Levee road, also was built along the south levee of Lagunitas Creek at the head of Tomales Bay sometime after 1892 (D. LIVINGSTON, *personal communication,* 1991). All of these cultural activities must have contributed to the destabilization of the hillslopes and adjacent stream channels. Destabilization undoubtedly promoted soil erosion, local incision of streams, and increased deposition at the head of Tomales Bay, causing the mudflats there to prograde to the northwest.

Interval 1918 to 1954

During this period, several artificial channels were dug that changed the drainage pattern of the lower reach of Olema Creek and several of the tidal channels that fed and drained the Tomales Bay marshland. Some of these changes include:

(1) The marshland at the head of Tomales Bay prograded an additional 500 to 800 m to the northwest. Deposition in the marsh was concentrated along tidal channels, producing linear spits at their mouths.
(2) Part of the Tomales Bay marshland was converted into pastures by construction of levees along tidal inlets and a series of seasonal dams along Lagunitas Creek.
(3) In about 1921, a straight, 3.0-km-long canal was excavated for Olema Creek between the town of Olema and Sir Francis Drake Boulevard (Levee Road).
(4) A prominent right-angle bend of Bear Valley Creek where it intersects the active (1906) trace of the San Andreas fault is first noted. The channel had been previously mapped as having a gentle curve to the northwest in this area, suggesting that it had either been artificially straightened or meandered to the southeast (Figure 7).

Modification of the lower Olema Creek floodplain and the marshlands at the southeastern end of Tomales Bay was extensive between 1918 and 1954. Because marshes usually act as traps for suspended sediments, artificial regulation of tidal circulation promoted sedimentation at the mouths of the tidal channels. The headwaters of Lagunitas Creek was dammed in 1919 to form Alpine Lake (Figure 1; D. LIVINGSTON, *personal communication,* 1992).

Interval 1954 to 1982

According to the 1976 "photoinspected" USGS

7.5 minute Inverness quadrangle, "no major cultural or drainage changes [were] observed." Two additional reservoirs in the Lagunitas Creek drainage basin were built in this interval: Kent Lake in 1954, and Nicasio Reservoir in 1959 (D. LIVINGSTON, *personal communication*, 1992). These reservoirs must have further reduced the sediment contribution of Lagunitas Creek to the Tomales Bay marshland.

Small deltas formed at the mouths of streams along both the east and west sides of Tomales Bay, and waters filled the floodplain region of the lower reach of Olema Creek during the extensive flooding that accompanied the 100-year storm of January 1982 (ANIMA *et al.*, 1988). A study of sediment traps placed in Olema Creek, air photo interpretation, and a survey of Olema Creek drainage by a consultant to Point Reyes National Seashore (QUESTA ENGINEERING, 1990) showed that except for the effects of the 1982 storm, there has been little change in sedimentation rates along this creek in the past few decades.

HUMAN IMPACT ON SEDIMENTATION

The rapid progradation of the tidal marsh of Tomales Bay that occurred between 1860 and 1918 corresponds to the time that European ranches developed in the region. Similar changes in the coastal environment during this period have been well documented in stratigraphic records of Bolinas Lagoon (Figure 1). Analyses of pollen and sediments from a 1.88-m-long core taken from the tidal flat area of Bolinas Lagoon north of the mouth of Pine Gulch Creek (Figure 1) documented the effects of large-scale logging on the coastal environment (BERGQUIST, 1977). The introduction of non-native species (eucalyptus trees, around 1870 and the European weeds, sheep sorrel and ribwort, probably in the 1850's) by settlers of Bolinas area has left a clear signature in the pollen record that was used by BERGQUIST (1977) to date the core.

During the redwood lumbering and cordwood logging periods (1849 to 1880), marsh sediments record an increase in grain size and organic debris, including redwood chips, and a corresponding decrease in bivalves and pollen from marsh plants. The period from the 1850's to 1900 marks the denudation of the watershed with its resulting slope instability and erosion, which is reflected in the high sediment accumulation rate of 1.3 to 1.9 cm/yr in Bolinas Lagoon. By 1880 the forest "had long since been chopped out," according to MUNRO-FRASER (1880). This author estimated that 15 million board feet of Douglas fir (*Pseudotsuga menziseii*) and redwood (*Sequoia sempervirens*) lumber was cut in the immediate vicinity of Bolinas between 1849 and 1858. As the slopes revegetated in the early 20th century, the sediment once again began to accumulate in the lagoon at the long-term Holocene sedimentation rate of 0.3 to 0.4 cm/yr (BERGQUIST, 1977).

We interpret a similar depositional history for a paleoseismic research site on the San Andreas fault in the hamlet of Dogtown, which is located 2 to 3 km north of Bolinas Lagoon (Figure 1). At this site, the 3.5-m-thick stratigraphic section exposed in backhoe trenches (COTTON *et al.*, 1982) consists of a basal clay unit overlain by 2 to 2.5 m of gravel with interstratified silts and sands deposited by Pine Gulch Creek on its floodplain. Eight concordant radiocarbon dates on detrital wood reported by COTTON *et al.* (1982) from the basal dark gray clay (an overbank/sag pond deposit) yield a weighted-average age of 260 ± 28 yr BP (NIEMI, 1992). Using the tree-ring calibration curves of STUIVER and REIMER (1987), the age range for the top of the basal clay layer is A.D. 1528 to 1784. The Dogtown sedimentologic data indicate both a shift toward deposition of coarser clastics within the past two centuries and a pronounced increase in the sediment accumulation rate to 0.8 to 1.0 cm/yr, a pattern identical to the latest Holocene deposition in Bolinas Lagoon. In the early part of this century, the slopes surrounding the Dogtown site were revegetated, reducing the sediment supply to Pine Gulch Creek. Today, its meandering channel is incised several meters into the floodplain deposits.

OLEMA CREEK INCISION

The lowermost 4.3 km of Olema Creek flows in a channel that is incised up to 3 to 4 m into its floodplain deposits. The 3 km of channel closest to Tomales Bay is relatively straight, whereas the upstream 1.3-km-long segment is characterized by entrenched meanders. By contrast, the maps of 1858 and 1918 show that during this interval Olema Creek meandered across the entire lower reach of its floodplain (Figure 6). A sketch of the creek between the town of Olema and Tomales Bay made by G.K. GILBERT in 1906 confirms the map data (Figure 5) and provides a basis for comparing former channel locations and geometry with the modern channel.

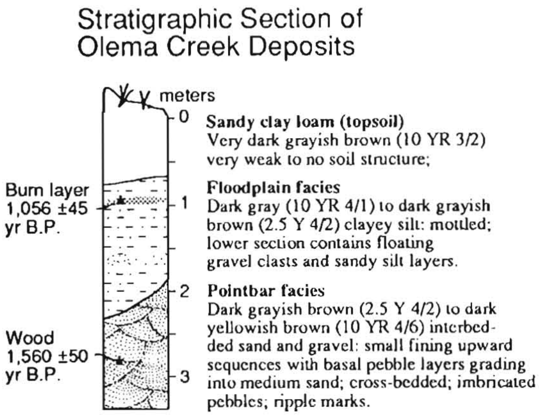

Figure 8. Schematic columnar section of the stratigraphy exposed in Trench T2. Location of T2 is given on Figures 6 and 7.

Stratigraphic evidence that Olema Creek meandered within its 500- to 600-m-wide valley was found in paleoseismic research trenches excavated along the San Andreas fault 300 m west of the modern channel near the town of Olema (Figure 7). A prehistoric position of the Olema Creek channel along the west side of the floodplain is preserved within a 3.0- to 3.5-m-thick stratigraphic sequence of fluvial deposits in Trench 2 (T2) (NIEMI and HALL, 1992; NIEMI, 1992). The base of the exposed section consists of cross-bedded pebble gravel to coarse-grained sand that grades up-section into fine sand and silt. We interpreted this fining-upward sequence as point bar sediments that accumulated within a former meander loop of Olema Creek (Figure 8). The top of the sequence slopes to the west, reflecting the original depositional geometry of the point bar. The composition of sediments in the buried sequence matches that in the modern creek. The erosional contact (buttress unconformity) separating the point bar sequence from older fine-grained overbank sediments to the west represents the buried cutbank meander scar.

Detrital wood from the point bar has a radiocarbon age of 1,560 ± 50 yr BP (Beta 30549). The point bar sequence is overlain by 1.7 to 2.2 m of sandy to clayey floodplain silt (Figure 8). An *in situ* burn layer less than 90 cm below the surface and approximately 1 m above the top of the point bar sediments yielded a weighted average radiocarbon age of 1,056 ± 45 yr BP. (See Table 1 for data and explanation of weighted averages.) The point bar sequence indicates that by about 1,400 yr BP, Olema Creek had meandered near the western margin of its floodplain. By 1,200 yr BP, this channel was abandoned or had migrated toward the east. The deposition of approximately 1 m of the floodplain silt above the point bar within a ca. 500-year interval indicates a sedimentation accumulation rate of 0.2 cm/yr. Although the site is located near the San Andreas fault (Figure 7) where sedimentation may reflect episodes of tectonic disruption, the sediment overbank accumulation rate is comparable to the average Holocene depositional rate for Tomales Bay. This latter rate is based on work of DAETWYLER (1966), who established that 23 m of estuarine sediments have accumulated in Tomales Bay in the past 10,000 yr BP. This similarity in rates is probably not coincidental, because both Olema Valley and Tomales Bay are adjoining parts of the erosional valley developed along the San Andreas fault zone.

SUMMARY OF DRAINAGE CHANGES

The floodplain of Olema Creek and the estuary of Tomales Bay both experienced episodes of aggradation and erosion during the Holocene. However, the responses to perturbations in sediment supply and hydrologic conditions are significantly different within these two adjoining estuarine and floodplain environments. The response of the lower reach of Olema Creek to European cultural intervention seems to have been incision. Given the evidence that Olema Creek meandered for at least the past 1,000 years and continued to do so until about 1918, the modern channel incision appears to have been the result of historical human impact within its drainage basin, and/or of direct alteration of the downstream end (*i.e.*, the channel straightening). The stratigraphic record recovered at Dogtown indicates that Pine Gulch Creek first responded to lumbering within its watershed by depositing sediment on its floodplain. As revegetation began to stabilize the denuded hillslopes in the early part of this century, the sediment supply diminished and the creek downcut into its deposits, forming entrenched meanders. Olema Creek may have responded in a similar fashion. Clearly, channel incision was accelerated in the early 1920's when the lower 3 km of Olema Creek was constrained to flow in a shorter, steeper channel between Olema nd Tomales Bay. The knickpoint created by this human intervention is still migrating upstream.

Table 1. *Radiocarbon ages from Trench T2 in the Olema Creek floodplain.*

Sample No.	Lab No.[1]	Type	$^{13}C/^{12}C$	Adjusted ^{14}C (yr B.P. $\pm 1\sigma$)[2]	Calendar Year[3]
			Burn Layer		
VT2-C9	Beta 30548	charcoal	−22.7	1,230 ± 120	660–953 A.D.
VT5-C4	Beat 30551	charcoal	−25.0	1,050 ± 130	880–1153 A.D.
VT6-C3	Beta 28705	charcoal	−25.8	1,600 ± 50*	406–535 A.D.
VT8-C3	Beta 29102	charcoal	−27.2	1,200 ± 110	680–1270 A.D.
VT13-C2	Beta 39176	soil[4]	N/A	970 ± 60	1007–1157 A.D.
			Weighted Average[5]	1,055.5 ± 45.2	869–1037 A.D. 1141–1150 A.D.
			Buried Point Bar		
VT2-C14	Beta 30549	wood	−25.6	1,560 ± 50	424–555 A.D.

[1]Radiocarbon ages were determined by Beta Analytic Inc., Coral Gables, Florida, and are reported with $\pm 1\sigma$
[2]Adjusted radiocarbon yr B.P. are normalized to −25 per mil ^{13}C
[3]Tree-ring calibration of radiocarbon years to calendar years with $\pm 2\sigma$ from STUIVER and BECKER (1986) and converted using calibration program of STUIVER and REIMER (1987)
[4]Bulk sample of soil with abundant disseminated charcoal flecks
[5]An average age, weighted according to the precision of the measurement, was calculated according to LONG and RIPPETEAU (1974). Each age was compared to the weighted average age using the Chauvenet rejection rule modified for a population of five to account for the variance between the analytical age and the averaged age. Ages that lie beyond $\pm 1.65\sigma$ were defined as outliers, where σ is the square root of the square of the observed age minus the square of the average age. This method identified one age, Beta 28705*, as anomalously old

The rapid progradation at the southeastern end of Tomales Bay, documented by maps between 1862 and 1918, probably was the direct result of introducing livestock and exotic plant species, clearing land for agriculture, and intensive logging in the watershed regions in the later half of the 19th Century. We speculate that the late Holocene depositional history of Tomales Bay has been similar to that of Bolinas Lagoon, but remains to be documented by detailed core analyses. Our analysis of maps shows that the rate of marshland progradation at the head of Tomales Bay slowed after 1954. After reaching a peak in the late 1800's the suspended sediment load introduced into Tomales Bay was significantly reduced when several reservoirs were built along the Lagunitas Creek drainage and when tributary hillslopes became revegetated after logging ceased.

We speculate that both the Olema Creek and Tomales Bay geologic systems remain partially destabilized. Olema Creek and its tributaries are likely to continue to downcut, particularly in the upstream reaches. We also expect the Tomales Bay tidal flats to continue to prograde at rates higher than pre-1860's rates because of ongoing development in the region.

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