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Authors
Simms, Alexander
Reynolds, Laura C
Bentz, Michael
et al.

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Tectonic subsidence of California estuaries increases forecasts of relative sea-level rise.

Alexander Simms[1], *Laura C. Reynolds*[2], *Michael Bentz*[3], *Angela Roman*[4]

Department of Earth Science
University of California, Santa Barbara
1006 Webb Hall
Santa Barbara, CA 93106
+1 805-893-7292
1 asimms@geol.ucsb.edu, 2 lcreynolds15@gmail.com, 3 jmichaelbentz@gmail.com, 4 angela.n.roman@gmail.com

Thomas Rockwell[5], *and Robert Peters*[6]

Department of Geological Sciences
San Diego State University
MC-1020
5500 Campanile Dr.
San Diego, CA 92182-1020
5 trockwell@mail.sdsu.edu, 6 rpeters_geo1@skyhighway.com

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Abstract

Even along the generally uplifting coast of the Pacific US, local geologic structures can cause subsidence. In this study we quantify Holocene-averaged subsidence rates in four estuaries (Carpinteria Slough, Goleta Slough, Campus Lagoon, and Morro Bay) along the southern and central California coast by comparing radiocarbon-dated estuarine material to a regional sea-level curve. Holocene-averaged rates of vertical motion range from subsidence of 1.4+/-2.4 mm/yr, 1.2+/-0.4 mm/yr, and 0.4+/-0.3 mm/yr in Morro Bay, Carpinteria Slough, and Goleta Slough, respectively, to possible uplift in Campus Lagoon (-0.1+/-0.9 mm/yr). The calculated rates of subsidence are of the same magnitude as rates of relative sea-level rise experienced over the late Holocene and effectively double the ongoing rates of relative sea-level rise experienced over the last five decades on other parts of the coast. The difference in rates of vertical motion among these four estuaries is attributed to their geological settings. Estuaries developed in subsiding geological structures such as synclines and fault-bounded basins are subsiding at much higher rates than those developed within flooded river valleys incised into marine terraces. Restoration projects accounting for future sea-level rise must consider the geologic setting of the estuaries and, if applicable, include subsidence in future sea-level rise scenarios, even along the tectonically uplifting US Pacific Coast.

1. Introduction

Subsidence along coastal margins can exacerbate ongoing rates of relative sea-level rise (Kolker et al. 2011). In some places, subsidence is the dominant driver of relative sea-level change (Tornqvist et al. 2008; Kolker et al. 2011) and coastal wetland loss (Tornqvist et al. 2006). However, subsidence has largely been ignored across the Pacific Coast of California, possibly due to the uplifting nature of the coast (Brew and Williams 2010). In this study, we determine the importance of subsidence along the southern and central California coast by quantifying the rates of vertical motion in four estuaries (Fig. 1) and investigate the role of geologic setting on the rates of subsidence within each estuary.

Relative sea-level change is a function of several factors including the volume of water in the oceans, glacial-isostatic adjustments, compaction and dewatering of unconsolidated sediments, local steric affects such as multi-annual changes in wind and oceanographic patterns, and tectonically-driven subsidence and uplift. Over the past 20 kyr, global sea level has risen an average of 120-130 m due to an increase in ocean water volume primarily derived from the melting of the continental ice sheets and thermal expansion of ocean water during deglaciation (Bard et al. 1996; Lambeck et al. 2002). However, modeling studies have suggested that local glacial-isostatic adjustments caused by the deformation of the solid Earth and its geoid have resulted in only 90-110 m of sea-level rise expressed along the southern and central California coast since the Last Glacial Maximum (Clark et al. 2014; Reeder-Meyers et al. 2015; Simms et al. 2016). Reynolds and Simms (2015) provide one of the few data-based sea-level reconstructions for the southern and central California coast. They compiled the tectonically-corrected elevations of 132 ^{14}C dated sea-level indicators from along the southern California coastline to produce a record of regional sea-level change over the past 15 kyr, which includes the impacts of global ocean volumes, glacial-isostatic adjustments, and local long-term steric affects. They showed that sea-level rise was rapid from 15 ka to between 8 and 6 ka and slowly decelerated to a rate of ~0.8 +/- 0.3 mm/yr over the last 4 ka. This sea-level reconstruction provides an important datum for measuring rates of tectonic uplift and subsidence along the California Coast.

In order to determine if subsidence is an important process operating within the estuaries along the active US Pacific Coast, we acquired seven new radiocarbon ages from specimens of the gastropod *Cerithidea californica* in marsh deposits buried beneath Carpinteria Slough, Goleta Slough, and Campus Lagoon as well as one previously reported radiocarbon age from Morro Bay in a study by Gallagher (1996)(Fig. 1). We compare the elevations of these specimens within each estuary to the regional sea-level curve of Reynolds and Simms (2015) for southern California. The difference in the two elevations at the same age is a measure of the total vertical motion experienced within the marsh, which is a function of shallow compaction as well as deep-seated tectonic subsidence or uplift along structural features. We used the gastropod *Cerithidea californica* as an index point because of its prevalence in southern and central California estuaries and its relationship to known tidal datums – between 1.2-2.1 m above Mean Lower Low Water (MLLW)(Sousa 1983). After quantifying the Holocene-averaged rates of subsidence in these four estuaries we investigate the role of tectonic processes in driving subsidence by comparing their geologic settings.

2. Geologic Setting

The southern and central California coast lies along the active transform plate boundary between the North American and Pacific Plates. As a result of active tectonics, the shelf and coastal plain are narrow and bordered by mountains (Draut et al. 2009; Sommerfield et al. 2009) that extend to the coastline except where active faults and synclines intersect the coast. Consequently, few estuaries have developed along the southcentral California coast - the few that have are generally smaller than equivalent features along the US Atlantic and Gulf Coasts and most other passive margins across the globe. Extant California estuaries are found in four geologic settings: (1) structural basins (low areas of the Earth's crust, of tectonic origin, in which sediments have accumulated – Jackson, 1997), (2) flooded river valleys or incised valleys, (3) back-barrier lagoons, and (4) drowned river mouths (Fig. 2).

Although larger in the past, Carpinteria Slough currently contains approximately 0.9 km^2 of mudflats, tidal channels and marsh (Ferren, 1985). The Slough lies within the Pleistocene Carpinteria Basin, an east-trending, north-verging, faulted syncline within the Santa Barbara Fold Belt (Jackson and Yeats 1982)(Fig 3), is bounded to the south by the Rincon Creek Fault, and overlies more than 1200 m of Pleistocene fill (Jackson and Yeats 1982; Fig. 3a). South of the fault, Miocene-aged rocks form a prominent bedrock wave-cut platform that hosts a kelp reef (Page et al. 2008) and is thought to correlate with a 45-50 ka marine terrace onshore (Lajoie et al. 1979; Jackson and Yeats 1982).

Goleta Slough is an approximately 1.4 km^2 expanse of tidal channels, mud flats, and marsh (Lohmar et al., 1980). Prior to rapid filling caused by anthropogenic activities and a series of large floods in the 1860s, it covered an area of approximately 50 km^2 and contained subtidal bay environments (Lohmar et al., 1980). Similar to Carpinteria Slough, Goleta Slough lies within an east-trending, south-verging faulted syncline within the Santa Barbara Fold Belt (Minor et al. 2009; Gurrola et al. 2014). This basin is bounded on the south by the More Ranch Fault (Fig. 3b), which separates the slough from an uplifted marine terrace reaching elevations as high as 12 m (Minor et al. 2009). The faulted block has been breached at its southern end by the combined drainages of the creeks flowing into the slough. Incision through the faulted block was likely driven by sea-level lowering during the Last Glacial Maximum approximately 20 ka (Lohmar et al. 1980)(Fig. 4). U-series, optically-stimulated luminescence, and ^{14}C ages constrain the age of the uplifted marine terrace to the south of the slough to around 50 ka (Gurrola et al. 2014).

Prior to the construction of a dam by the University of California, Santa Barbara to form an artificial lake, Campus Lagoon was a small (~0.1 km^2) expanse of mudflats and sandflats. Unlike Carpinteria and Goleta Sloughs, it did not form within a faulted syncline (Fig. 4). During the last lowstand in sea level, the axis of the lagoon hosted a small creek that incised into the 50 ka marine terrace on the opposite side of the More Ranch Fault from Goleta Slough. Subsequent sea-level rise flooded this valley, resulting in the formation of an estuary at the valley mouth. Morro Bay is an approximately 8.5 km^2 expanse of unvegetated mud flats flooded during high tides with deep (up to 12.5 m at their deepest) tidal channels fringed by vegetated marshes and shallower tidal channels (Gallagher, 1996). Morro Bay developed behind a large coastal spit within the onshore extension of Estero Bay (Fig. 4). The Estero Bay and Morro Bay basin is bounded to the north and south by the Cambria and Los Osos Fault Zones, respectively (Hanson et al. 1992; Lettis and Hall 1994; Wiegers 2009) (Fig. 4). Although Morro Bay formed within a structural basin, the Morro Bay sand spit isolated the bay from the ocean, enhancing accommodation. The break in marine terraces found to the north and south of Morro Bay, along with the deposition and preservation of 250 m+ of Quaternary sediment, suggest that subsidence is active within the basin (Lettis and Hall 1994)(Fig. 3).

3. Methods

Two cores from Goleta and Carpinteria Sloughs were acquired using a GeoProbe 7822DT. These cores were ~2.5 cm in diameter and reached a depth of 21 m in Goleta Slough and 13.7 m in Carpinteria Slough. A core from Campus Lagoon was collected using a 7.2 cm diameter vibracore aboard the *R/V TSII*, a portable coring raft. Descriptions of the cores included texture, color, and the presence of sedimentary structures, macrofauna, plant material, and bioturbation. The interpretations of sedimentary environments were based on the texture and macrofaunal similarity to modern environments observed in the field. Core-top elevations were determined using a TopCon Hyperlite+ GPS. Elevations were corrected to NAVD88 using the online NOAA OPUS site (www.ngs.noaa.gov/OPUS/; last accessed January, 2016).

Radiocarbon ages were obtained from specimens of the gastropod *C. californica* within the cores. Only the shells in the most pristine condition were dated. Shells that were worn, bleached, chipped, or contained holes were avoided.

Accurate radiocarbon ages of inorganic carbon require correction for a radiocarbon reservoir. Holmquist et al. (2015) obtained an average delta R (difference between global marine carbon reservoir and the local carbon reservoir) of 171+/-154 ^{14}C years based on radiocarbon dates of 20 historically collected (pre-bomb) specimens of *Cerithidea californica* from 4 different estuaries in southern and central California. This reservoir correction was applied to the radiocarbon ages from Carpinteria Slough, Goleta Slough, and Campus Lagoon. For Morro Bay, we applied an estuary-specific delta R of 43+/-23 obtained from Morro Bay by Holmquist et al. (2015). Calib 7.1 was used to calibrate our radiocarbon ages using the marine calibration curve (Reimer et al. 2013).

Magnitude of subsidence (S) was calculated by subtracting paleo-relative sea-level elevations derived from *C. californica* shells in estuarine cores (RSL_{cc}) from the regional relative sea-level curve of Reynolds and Simms (2015)(RSL_p) as follows:

$$S = RSL_p - RSL_{cc} \quad (1).$$

In order to determine RSL_p from times other than the index points in the compilation of Reynolds and Simms (2015), an exponential function of the form of:

$$RSL_p = a \times e^{bt} \quad (2)$$

was fit to the data, where *t* is the age of the index point, *a* and *b* are constants derived from fitting the exponential equation to the data, and *e* is the Euler number.

Following Reynolds and Simms (2015), we used the nearest open-ocean NOAA tide gauge to calculate *C. californica's* relationship to relative sea level in each estuary. For Carpinteria, Goleta, and Campus Lagoon, we used the Santa Barbara, California tide gauge (9411340). *C. californica* are found 1.2-2.1 m above MLLW (Sousa, 1983), which is equivalent to 0.8+/-0.45 m above Mean Sea Level (MSL) in Santa Barbara. Although the sea-level index point from Morro Bay was obtained from a *C. californica* shell, it was not found in muddy marsh sediments typical of *C. californica* habitat, but a sandy facies interpreted as a bayshore beach (Gallagher 1996). We therefore assign its indicative range (the vertical range over which the indicator occurs at present; Shennan 2015) as 0+/-1.1 m. 1.1 m is the tidal range (mean high water – mean low water) reported for the nearest NOAA tide gauge at Port San Luis (9412110). The paleo relative sea level represented of each specimen of *C. cerithidea* (RSL_{cc}) was calculated as follows:

$$RSL_{cc} = El_{cc} - IR_{cc} \qquad (3)$$

where El_{cc} is the elevation of the *C. californica* in the cores and IR_{cc} is the indicative meaning (vertical distance between a datable sedimentary horizon or formation and its local, contemporary, mean sea level; Zong and Sawai, 2015) of the *C. californica* (0.8 m).

We assumed an error of +/-3.8 m for the exponential fit (2) to the relative sea-level data of Reynolds and Simms (2015; RSL_p). A value of +/-3.8 m encompasses >95% of the vertical range of the observations in which the relative sea-level curve is based. The combined error (E_t) for the total magnitude of Holocene subsidence (*S*) was then calculated via:

$$E_t = (E_{rsl}^2+E_{obs}^2)^{0.5} \qquad (4)$$

where E_{rsl} is the error associated with the regional relative sea-level curve (+/-3.8 m) and E_{obs} is the vertical error associated with RSL_{cc} for each estuary. E_{obs} was determined via the following equation modified from Yu et al. (2012):

$$E_{obs} = (E_{cc}^2+E_s^2+E_{nv}^2+E_p^2+E_{gps}^2)^{0.5} \qquad (5)$$

where E_{cc} is the error associated with the indicative range of *C. californica* (0.45 m), E_s is the error associated with sampling (0.02 m), E_{nv} is the error associated with non-vertical drilling (0.01 x depth (m)), E_p is the error associated with the elevation of the top of the pushed pipe sections (0.1 m), and E_{gps} is the error of the GPS (0.05 m). For Morro Bay, E_{gps} was increased to 1.0 m because of the unknown uncertainties associated with the elevation measurements of Gallagher (1996).

The error on the Holocene-averaged subsidence rate (E_r) was determined by the following combination of the aforementioned errors:

$$E_r = (S/T_{cc}) \text{ x } ((E_{Tcc}/T_{cc})\hat{\ }2+(E_t/S)\hat{\ }2)\hat{\ }0.5 \qquad (6)$$

where T_{cc} is the age of the *C. californica* and E_{Tcc} is the error in the age of the *C. californica*.

4. Results

4.1 Stratigraphy

The core from Carpinteria Slough contains approximately 10 m of gray (7.5YR 5/1) to dark brown (7.5YR 3/2) silty mud with five 20-100 cm thick sand beds overlying a > 2m gray (7.5YR 4/1) sand bed at the base of the core (Fig. 5). The basal gray sand bed is composed of clean, moderately sorted sand with common marine shell fragments. The presence of marine shell fragments in these sands and modern estuarine-mouth sands within lower Carpinteria Slough and their absence in modern beach sands, suggests a subtidal marine or estuarine environment of deposition. Foraminifera from the mud beds within the core include *Jadammina* sp., and, along with the presence of *C. californica*, suggest deposition above MSL but below Mean High High Water (MHHW) in a marsh environment (Fig. 5). Four dark reddish gray (5YR 4/2), poorly sorted, muddy sand beds devoid of marine fossils are interbedded with the muds in Carpinteria Slough. These sand beds are interpreted as alluvial fan deposits prograding into the marsh from the small creeks entering Carpinteria Slough. A gray (Gley 1 5/N) sand bed similar to the basal sand bed occurs at a depth of 4.85 m below MSL, which in turn is overlain by another 2 m of gray to dark brown silty mud similar to the sediments found on the marsh surface today.

The core from Goleta Slough contains 21 m of alternating gray and dark brown sand and mud beds (Fig. 5). The lowest 2 m and upper 1 m of the core contains a gray and dark brown organic rich mud similar to the muds found within Carpinteria Slough. Between the two mud beds is ~16 m of alternating very dark greenish-gray (3/10Y) sands and muds with prevalent oyster shell fragments (Fig. 5) and one thin (< 1 m) return of the gray to dark brown muds. The upper and lower gray and dark brown muds are interpreted to represent a marsh environment while the interbedded very dark greenish gray sands and muds are interpreted to represent a more open-bay type environment.

The 1.8 m core taken from Campus Lagoon records a different type of depositional environment. The core contains two general sedimentary facies: a green gray (5/5GY) mud with scattered plant material and sparse *C. californica* shells and a greenish gray (5/10Y) laminated muddy sand to sand with scattered gypsum lamina, plant material, and mud rip-up clasts. These facies are interpreted to represent mud and sand flat environments, respectively.

The core from Morro Bay, described by Gallagher (1996), contains a sandy very dark grayish brown (10YR 3/2) mud with abundant organic material in the upper 2 m overlying a dark bluish gray and dark gray sandy mud overlying a gravelly poorly-sorted dark gray coarse sand with shell fragments. The upper very dark grayish brown mud is interpreted to represent a marsh deposit while the underlying dark and bluish gray sandy mud is interpreted to represent bay deposits. The lower gravely poorly-sorted sand and shells are interpreted to represent a bay shoreline-beach (Gallagher 1996).

4.2 Subsidence Rates

Holocene-averaged subsidence rates calculated based on the elevations of *C. californica* in the cores are highest in Morro Bay and Carpinteria Slough, at 1.4+/-2.4 mm/yr and 1.2+/-0.4 mm/yr, respectively, and negligible to negative at Campus Lagoon (-0.1 +/-0.9mm/yr), possibly indicating uplift (Table 1). Our best estimate for the subsidence rate in Goleta Slough is 0.4+/-0.3 mm/yr. However, the *C. californica* preserved in the core from Goleta Slough occurs at a time marked by rapid changes in the rate of sea-level rise and few sea-level index points (Fig. 2). However, several marine-limiting data points, which are largely derived from mollusk species that inhabit intertidal to marine environments (Nardin et al. 1981; Coan and Valentich-Scott 2012) and constrain the lower limit of relative sea level, do exist for this time period. The *C. californica* from Goleta Slough, which inhabit intertidal areas above MSL, plot within the trend of the marine-limiting data from southern California (Fig. 6). However, because *C. californica* inhabit intertidal areas above MSL, this supports ongoing subsidence of Goleta Slough, which would be required to lower paleo relative sea-level indicators below the regional curve.

5. Discussion

5.1 Comparison between Rates of Subsidence and Current Sea-Level Rise

Tide gauge data from Santa Barbara (between Goleta and Carpinteria Sloughs) and Port San Luis (~20 km south of Morro Bay) suggest ongoing rates of sea-level rise of 0.73+/-1.2 mm/yr from 1973-2014 and 0.74+/-0.4 from 1945-2014, respectively (http://tidesandcurrents.noaa.gov/sltrends/sltrends.html, last accessed September 2015). The magnitude of relative sea-level rise experienced at both tide gauges reflect not only global ocean volumes, but also glacial-isostatic adjustments, steric affects, and local tectonics. Rates based on these California tide gauge data are less than global average rates of relative sea-level rise experienced over the same time period likely due to wind stress associated with the Pacific Decadal Oscillation (Bromirski et al., 2011).

Morro Bay subsided through the Holocene at a rate nearly twice that of relative sea-level rise recorded at Port San Luis. The large errors associated with the tide gauge record at Santa Barbara, reflecting in part its relocation on two occasions and the discontinuous nature of the record, make it difficult to quantify the relationship between the rates subsidence in Carpinteria and Goleta Sloughs and ongoing rates of sea-level rise. However, rates of subsidence averaged over the Holocene at Carpinteria and Goleta Sloughs are of similar magnitudes as the rate of relative sea-level rise recorded in the tide gauge in Santa Barbara, while subsidence is negligible in Campus Lagoon.

5.2 Geologic Controls on Subsidence Rates

Rates of subsidence in Carpinteria Slough and Morro Bay differ by an order of magnitude with Campus Lagoon. Part of this difference is attributed to the geologic settings of the estuaries. Of the four estuaries studied, Morro Bay, Carpinteria Slough and Goleta Slough are located within structural basins (Dibblee, 1966; Jackson and Yeats, 1982; Lettis and Hall, 1994; Gurrola et al., 2014) while Campus Lagoon formed within a flooded river valley cut into an uplifting marine terrace (Dibblee, 1966; Gurrola et al., 2014). Marine terraces indicative of tectonic uplift plunge below the modern surface at the margins of Carpinteria Slough, Goleta Slough, and Morro Bay (Dibblee, 1966; Jackson and Yeats, 1982; Lettis and Hall, 1994; Gurrola et al., 2014). Similarly, oil exploration and water wells encounter shallow marine Quaternary deposits at depths of no less than 200 m beneath Morro Bay and up to 1000 m beneath Carpinteria and Goleta Sloughs (Fig. 3). The presence of Quaternary shallow marine deposits at depths far below the level of Quaternary oscillations in sea levels suggest ongoing active subsidence along the geologic structures hosting these estuaries (Dibblee, 1966; Jackson and Yeats, 1982; Lettis and Hall, 1994; Gurrola et al., 2014).

The magnitudes of Holocene-averaged subsidence determined in this study reflect both deep-seated tectonic subsidence as outlined above with a likely contribution from shallow compaction. The higher subsidence rates within the tectonically-controlled basins and the absence of subsidence outside the tectonically-controlled basins suggest tectonics plays a prominent role within the four estuaries studied. Although at present we cannot separate the relative importance of tectonic-subsidence and compaction in determining the magnitudes of subsidence in these estuaries; the two processes likely complement one another in that tectonic-induced subsidence provides more accommodation for the accumulation of compactable Holocene sediments.

5.3 Implications for Coastal Management

Not all estuaries are subsiding, but for those that are, subsidence can exacerbate the impacts of sea-level rise. The best way to determine which estuaries have experienced significant amounts of subsidence is to understand the geological framework in which the estuaries developed. For estuaries confined to structural basins such as Carpinteria and Goleta Sloughs, tectonic subsidence must be taken into account as a factor when planning for and predicting future rates of relative sea-level rise. Alternatively, in estuaries formed within flooded river valleys cut into uplifting marine terraces, tectonic subsidence is minimal or absent. In some cases, tectonic uplift decreases rates of relative sea-level rise compared to non-uplifting areas. Within drowned river mouth estuaries and back-barrier environments, the degree of subsidence depends on the geological setting of the system. If they lie within a structural basin, then subsidence rates are likely to be high as is the case of Morro Bay. If they lie outside of structural basins, they are likely to experience minimal tectonically-induced subsidence.

6. Conclusions

Subsidence is an important process operating within many US Pacific Coast estuaries, even along the tectonically uplifting southern and central California coast. Of the four estuaries examined in this study, three are subsiding at rates of 1.2+/-0.4 mm/yr in Carpinteria Slough, 0.4+/-0.3 mm/yr in Goleta Slough, and 1.4+/-2.4 mm/yr in Morro Bay. The difference amongst these rates of subsidence is largely attributed to their geologic settings. Both Carpinteria and Goleta Sloughs formed within a fault-bound estuary and are subsiding at very high rates. Although Morro Bay developed as a back-barrier estuary, it also sits atop a subsiding sedimentary basin bounded by two faults. Campus Lagoon, which formed as a flooded river valley cut into a marine terrace during a former lowstand in sea level, is the only estuary studied that is experiencing negligible subsidence (-0.1 +/-0.9 mm/yr), possibly even uplift due to the absence of a subsiding structural feature underlying the estuary. Restoration and mitigation plans which neglect the effects of variable subsidence in estuarine environments may not adequately prepare these environments, or the infrastructure they contain, for the effects of future sea-level rise.

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Table 1. Radiocarbon Ages and Subsidence Rates

Lab Number	Core	Depth in Core (m)	Observed RSL (m)	Error (m)	14C Age (yr)	Error (2 sigma)	Source	Calibrated** Mean (yr)	Range (yr)	Predicted RSL (m)	Error (m)	Subsidence (m)	Subsidence Error (m)	Subsidence Rate (mm/yr)	Error (mm/yr)	Estuary Average (mm/yr)	Error (mm/yr)
Goleta Slough																	
UCIAMS-151216	GS14-02	20.3	19.0	0.5	8385	25	This study	8745	8367-9138	15.3	3.8	3.7	3.8	0.4	0.4	0.4	0.3
UCIAMS-151217	GS14-02	20.4	19.1	0.5	8455	25	This study	8826	8434-9240	15.6	3.8	3.5	3.8	0.4	0.4		
Carpinteria Slough																	
UCIAMS-129080	CS13-02	9.4	8.7	0.5	4020	54	This study	3818	3399-4251	2.8	3.8	5.9	3.8	1.5	1.0	1.2	0.4
UCIAMS-129081	CS13-02	10.6	9.9	0.5	4520	54	This study	4489	4016-4881	3.5	3.8	6.4	3.8	1.4	0.9		
UCIAMS-129078	CS13-02	11.3	10.6	0.5	5240	54	This study	5405	4955-5771	5.1	3.8	5.5	3.8	1.0	0.7		
UCIAMS-129079	CS13-02	12.2	11.5	0.5	5730	56	This study	5953	5596-6280	5.9	3.8	5.6	3.8	0.9	0.6		
Campus Lagoon																	
D-AMS 005756	CL13-02	1.8	2.7	0.7	4358	58 (29)	This study	4267	3832-4723	3.2	3.8	-0.5	3.9	-0.1	-0.9	-0.1	-0.9
Morro Bay																	
Beta 60948	LO 5	4.8	3.8	1.5	2540*	70	Gallagher, 1996	1739	1971-2327	1.4	3.8	2.4	4.1	1.4	2.4	1.4	2.4

*fragments

**Using a delta R of 171+/-154 for Goleta Slough, Carpinteria Slough, and Campus Lagoon and a delta R of 43+/-23 for Morro Bay

Table 1. Radiocarbon Ages and Subsidence Rates

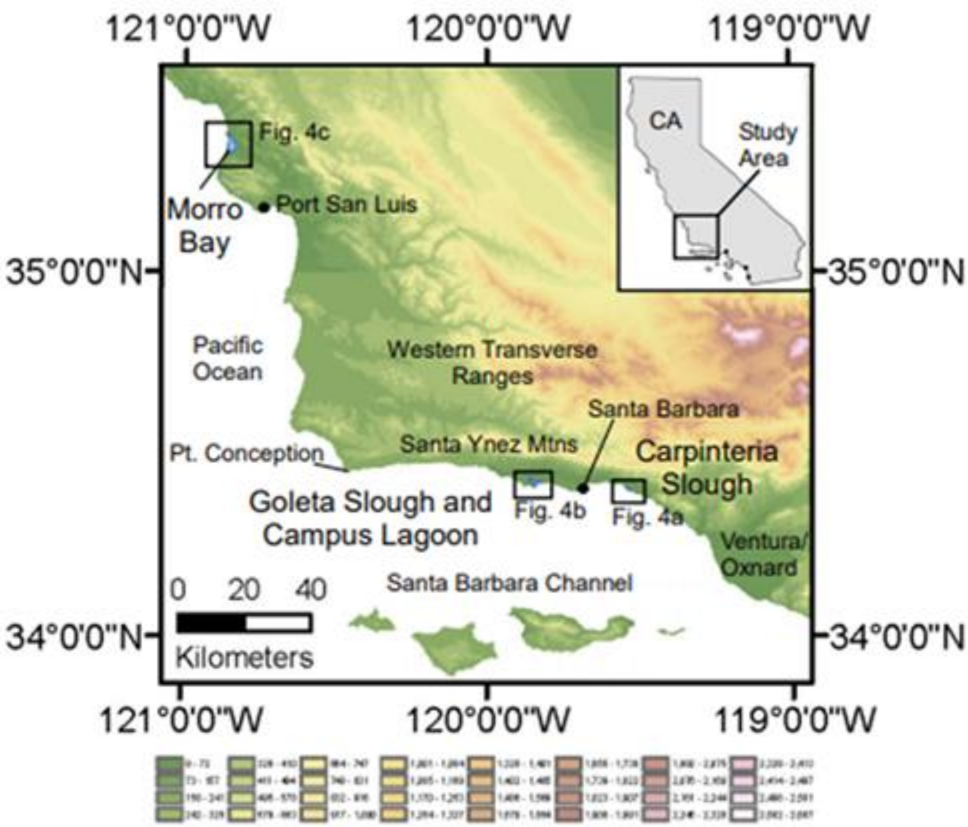

Figure 1. Digital elevation model in meters of the study area showing the locations of the features discussed in the text. Elevation data from the National Elevation Dataset (Gesch et al., 2002).

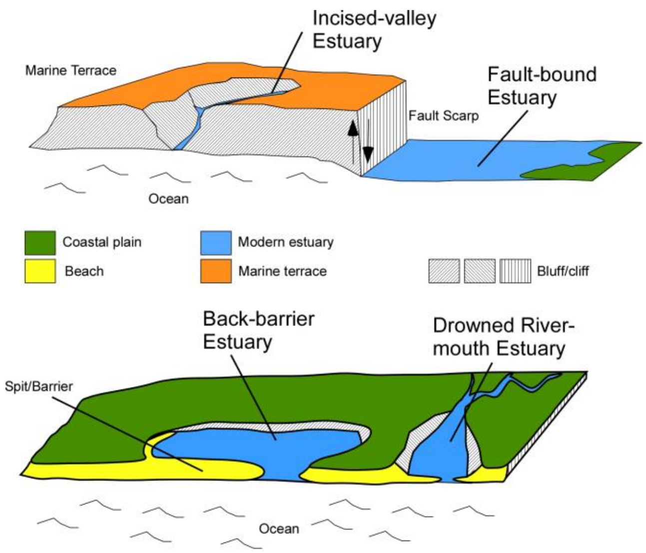

Figure 2. Model illustrating the different geologic settings for estuaries in southern and central California.

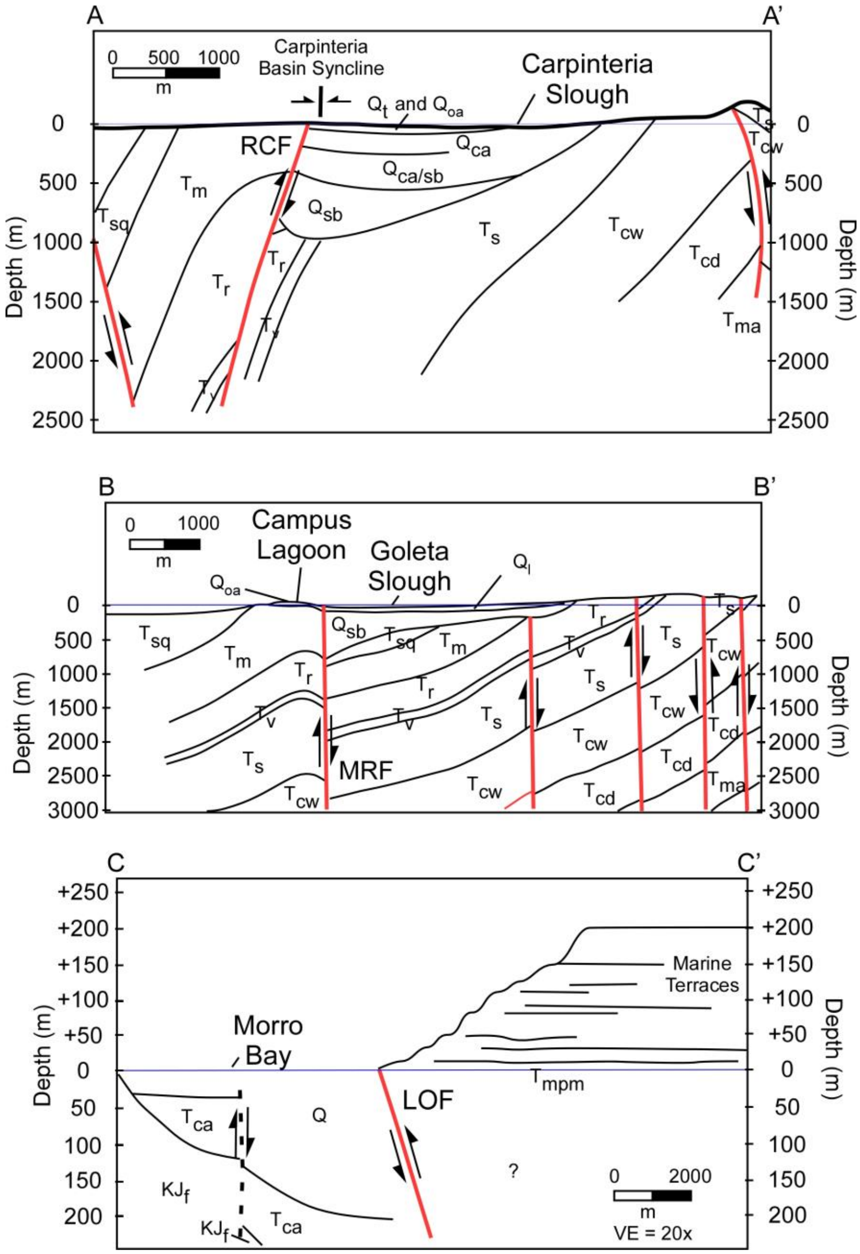

Figure 3. Geologic cross-section through A.) Carpinteria Slough (after Jackson and Yeats 1982), B.) Goleta Slough and Campus Lagoon (after Dibble 1966), and C.) Morro Bay (after Lettis and Hall 1994). See Figure 4 for cross-section locations. RCF = Rincon Creek Fault, MRF = Moore Ranch Fault, and LOF = Los Osos Fault Zone. T_{sq} = Sisquoc Formation, T_m = Monterey Formation, T_r = Rincon Shale, T_v = Vaqueros Formation, T_s = Sespe Formation, T_{cw} = Coldwater Sandstone, T_{cd} = Cozy Dale Shale, T_{ma} = Matilija Formation, Q_{sb} = Santa Barbara Formation, Q_{ca} = Casitas Formation, Q_{oa} = Quaternary marine terrace, Q_t, Q, Q_l = Late Quaternary (Pleistocene and Holocene) deposits. KJ_f = Franciscan Complex, T_{ca} = Careaga Sandstone, and T_{mpm} = Miguelito Member, Pismo Formation

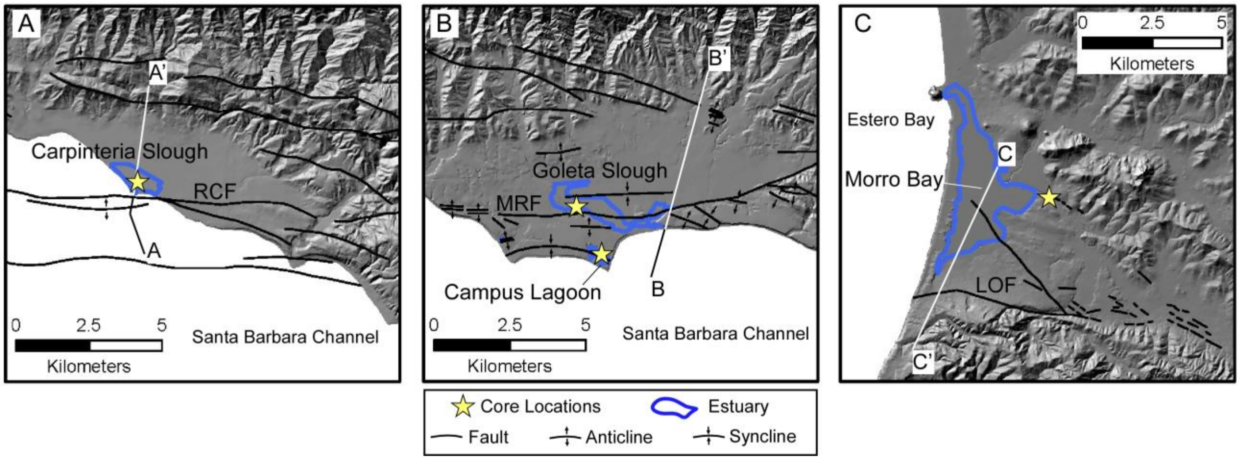

Figure 4. Hillshade maps illustrating the major geological structures for A.) Carpinteria Slough (after Jackson and Yeats 1982), B.) Goleta Slough and Campus Lagoon (after Gurrola et al. 2014), and C.) Morro Bay (after Lettis and Hall 1994). RCF = Rincon Creek Fault, MRF = Moore Ranch Fault, and LOF = Los Osos Fault Zone. Hillshade is based on the USGS National Elevation Dataset.

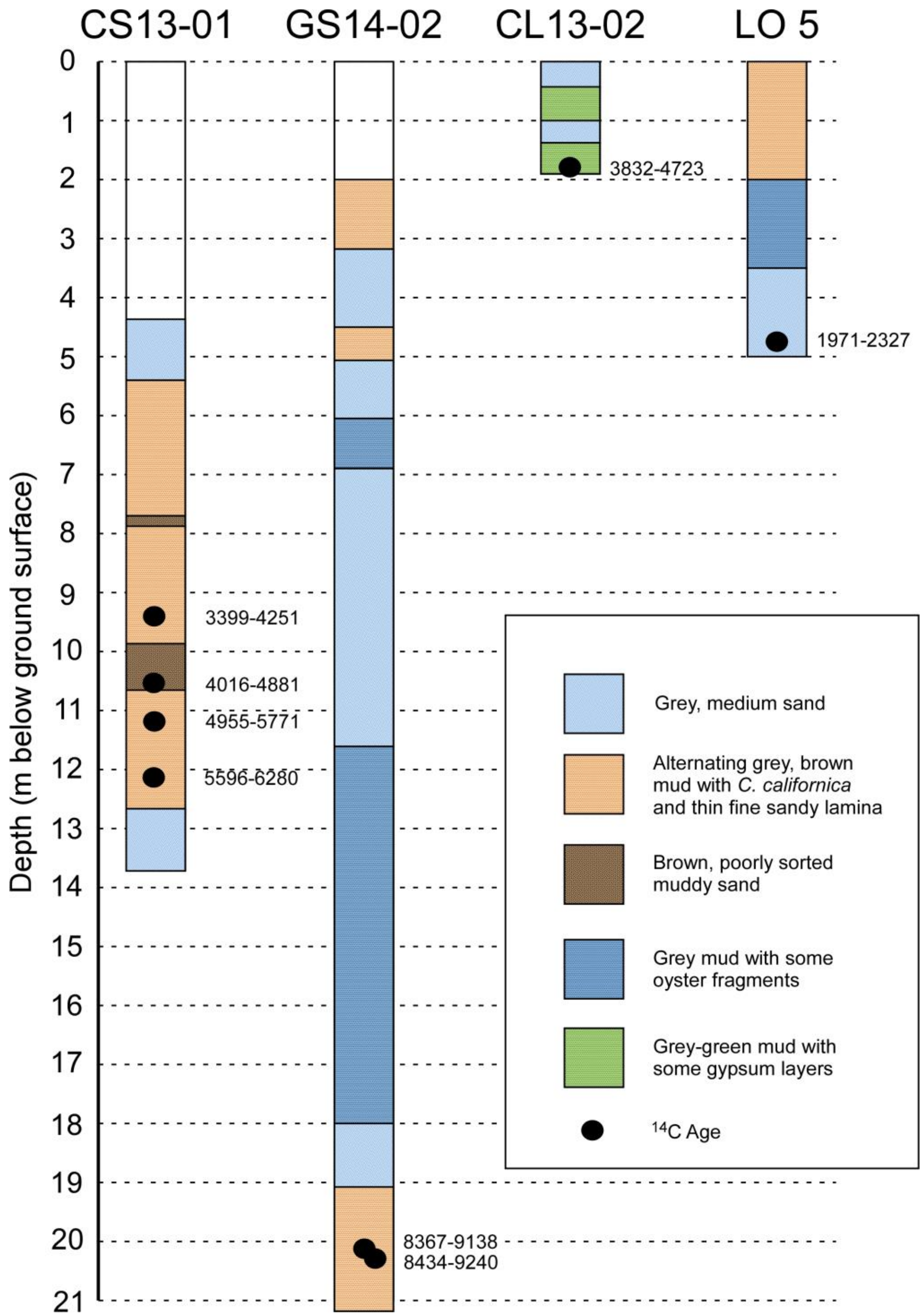

Figure 5. General core stratigraphy from Carpinteria Slough (CS13-02), Goleta Slough (GS14-02), Campus Lagoon (CL13-02), and Morro Bay (LO 5 – after Gallagher 1996). See Figure 4 for core locations.

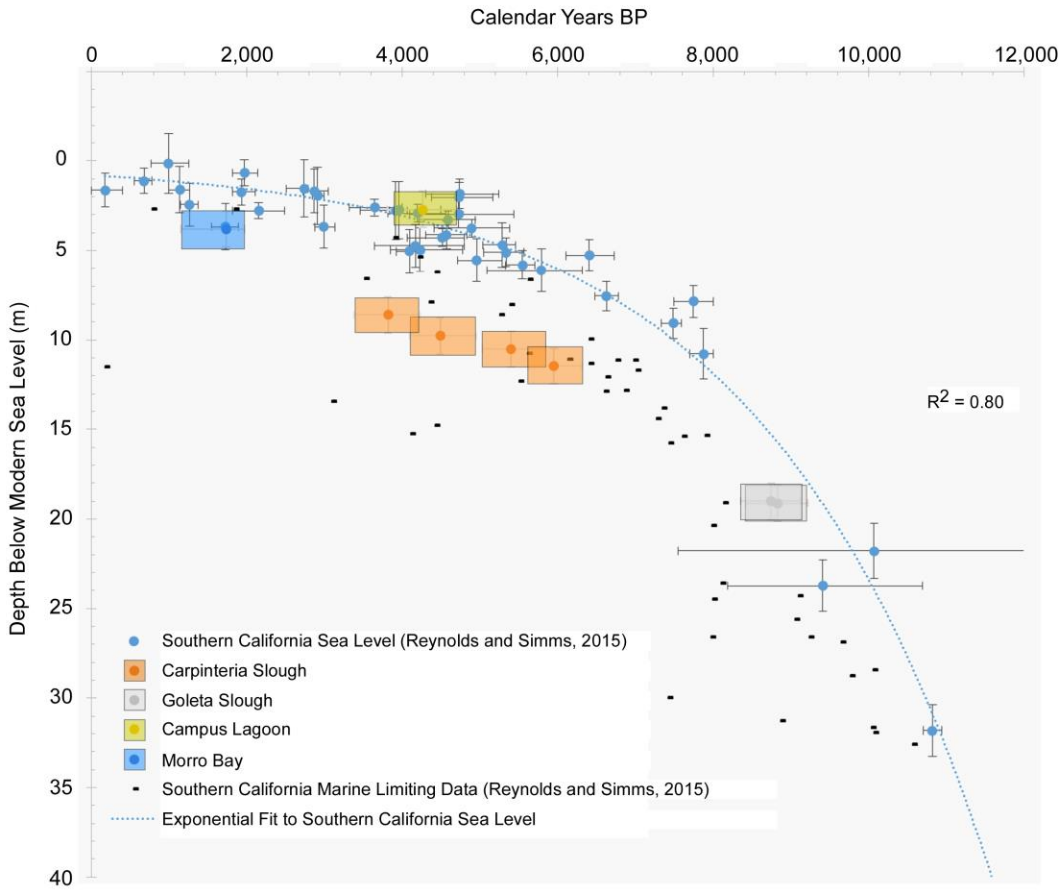

Figure 6. Graph illustrating the elevations of radiocarbon dated *Cerithidea californica* and sea-level index and marine limiting data from southern California (after Reynolds and Simms 2015) for Carpinteria Slough, Goleta Slough, Campus Lagoon, and Morro Bay.