# Implications of geometry, age and depositional history of a shallow confining layer in a coastal groundwater basin, Monterey County, California, USA

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[1] We mapped the geometry of a shallow confining layer within the Salinas Valley aquifer system, northern Monterey County, California, using indicator geostatistics. The confining layer was previously interpreted to be mainly Holocene in age, having been deposited as a single unit during post-Wisconsin sea-level rise. We interpret this layer in our field area to be associated with Isotope Stages 5 (84–121 kyr) based on three independent arguments: layer geometry, with three distinct clay units rather than one; $^{14}$C analyses of peat samples; and consideration of required rates of coastal uplift. The complex stratigraphy of the confining layer likely resulted from deposition over existing topography, erosion during exposure, and uplift during three intervals of sea level rise and fall. Similarly complex layering may occur in other coastal basins, influencing groundwater resource development, remediation and protection in these settings. *INDEX TERMS:* 1829 Hydrology: Groundwater hydrology; 8105 Tectonophysics: Continental margins and sedimentary basins; 1869 Hydrology: Stochastic processes; 4556 Oceanography: Physical: Sea level variations. **Citation:** Erskine, J. A., and A. T. Fisher, Implications of geometry, age and depositional history of a shallow confining layer in a coastal groundwater basin, Monterey County, California, USA, *Geophys. Res. Lett.*, *29*(24), 2178, doi:10.1029/2002GL015844, 2002.

## 1. Introduction

[2] Increasing agricultural and urban demand for groundwater in coastal areas presents challenges resulting from groundwater overdraft, contamination, and seawater intrusion. The Salinas Valley aquifer system (SVAS) in Monterey County, CA, contains a complex assemblage of Miocene to Holocene aquifer and confining units [e.g., *Greene*, 1970; *Dupré et al.*, 1991]. As in many coastal California basins, the shallow aquifer system comprises a series of interbedded, fining-upward, marine and non-marine units resulting from a combination of glacio-eustatic sea-level change and regional uplift [e.g., *Dupré*, 1975, 1990; *Tinsley*, 1975].

[3] We present a geostatistically-based stratigraphic analysis of the northwestern Salinas Valley and reassess the depositional nature of the SVAS. We combine three-dimensional mapping, new radiocarbon data and estimates of regional uplift rates. We focus on former Fort Ord in northern Monterey County, where closely-spaced well data provide a unique window into the origin of sediments in this coastal basin.


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## 2. Geologic and Hydrologic Setting

[4] Former Fort Ord is located adjacent to Monterey Bay, at the northwest end of the Salinas Valley (Figure 1a). The Salinas River is bounded by fluvial terraces and alluvial fans within the Salinas Valley [*Dupré*, 1990; *Greene*, 1990]. Fort Ord occupies a topographic highland, 30-m above the floor of the Salinas Valley, and overlies the SVAS, a groundwater basin stretching ~300 km to the southeast (Figure 1a).

[5] The base of the aquifer system at Fort Ord is the Miocene Monterey Formation, with overlying and interbedded Pliocene to Holocene, Paso Robles, Aromas Red Sands, valley fill, and dune deposits comprising the most important aquifer and confining units. The hydrogeologic units of primary interest are: (1) the two shallowest aquifers, the unconfined "A-aquifer" and confined "180-ft aquifer," and (2) the "Salinas Valley Aquiclude" (SVA), a confining unit that separates the two aquifers. The A- and (uppermost) 180-ft aquifers are typically associated with Pleistocene to Holocene dune sand and alluvial/fluvial valley fill deposits, respectively [*Tinsley*, 1975]. Within the Salinas Valley [*Tinsley*, 1975; *Greene*, 1977], the SVA is generally characterized as a single, laterally-extensive, estuarine and lagoonal, clay unit up to 35 m thick, pinching out near the ocean and to the south. The A-aquifer is rarely used for groundwater supply at present because of persistent water quality concerns, but the 180-ft aquifer comprises an important groundwater reservoir.

[6] Based on a stratigraphic correlation between the SVA and nearby soil profiles, and on a single $^{14}$C -dated wood fragment from overlying terrace deposits, *Tinsley* [1975] estimated a lower-limit age for the SVA of 6–18 ka, linking deposition to post-Wisconsin sea-level rise. Subsequent inter-basin and intra-basin correlations are consistent with this origin for the later [e.g., *Dupré*, 1990; *Dupré and Tinsley*, 1980; *Greene*, 1977]. The SVA may unconformably contact older transgressive clays within the Salinas Valley locally, due to tectonic downwarping and Wisconsin-age valley incision by the Salinas River [*Tinsley*, 1975], but the

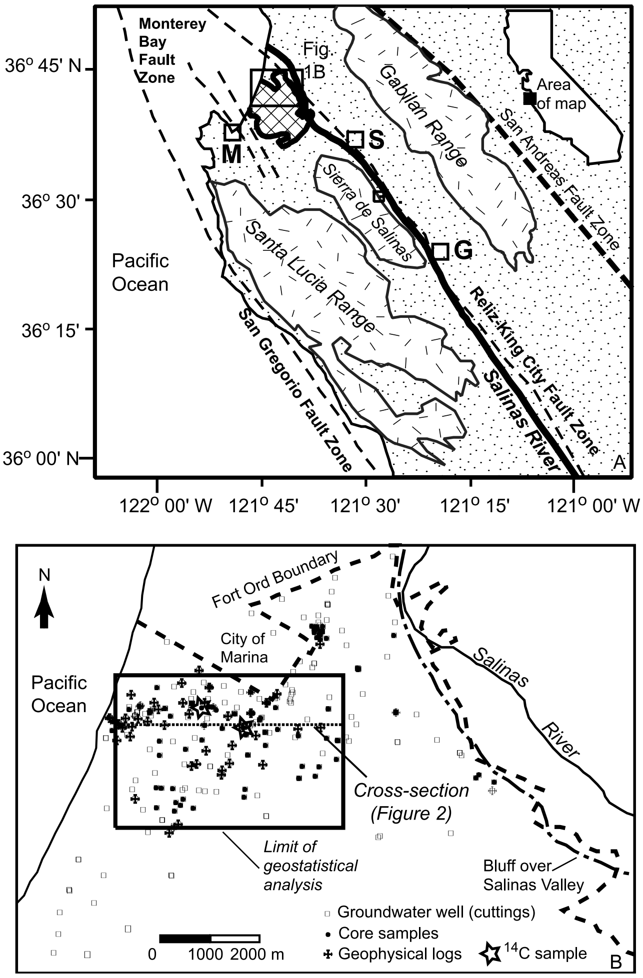


**Figure 1.** Study area and sample locations. (a) Index map of California, southern Monterey Bay, CA, former Fort Ord and detailed study area (Figure 1b). Squares show locations of cities: M = Monterey, S = Salinas, G = Gonzales. (b) Locations of wells, piezometers, and borings from which cuttings (open squares), cores (filled circles), and geophysical logs (crosses) were collected. $^{14}$C samples indicated with stars. Dotted line shows location of cross-section in Figure 2.

age of a stratigraphically equivalent layer at former Fort Ord remains unclear [e.g., *Dupré and Tinsley*, 1980; *Clark et al.*, 1997].

## 3. Field and Analytical Methods

[7] There were 283 wells and borings located within a 4.65-km$^2$ study area, installed over a 60-yr period (Figure 1b). Of 13.4 linear km of available well logs, 2.3 km (17%) are based on high-quality core samples from known depths, and the remainder are based on less reliable records of drill cuttings. We augmented these data with natural gamma-ray and induction resistivity geophysical logs collected through PVC casing at 0.15-m depth intervals in 55 wells. Natural gamma-ray logs are often used for stratigraphic correlation and as an indication of clay content, but we found this tool to be relatively insensitive to the lagoonal and estuarine clays common in the study area. In contrast, induction resistivity logs proved to be more useful, identifying clay-rich intervals at the 90% confidence level based on comparison with 306 core samples.

[8] We mapped the occurrence of the SVA within a volume 4.65 km$^2$ in area and 50 m thick, using indicator kriging to interpolate between observation points [*Erskine*, 1998]. We defined a binary indicator scheme whereby measurement points were assigned to either clay (SVA facies) or nonclay (aquifer facies) categories. We discretized all lithologic records at 0.6-m intervals, resulting in 22,000 observation points. Indicators based on core descriptions were assigned first, followed by those based on geophysical data. Indicators based on cuttings descriptions were assigned where no other data was available. Ordinary indicator kriging [*Johnson and Dreiss*, 1989; *Journel*, 1982] was used to estimate the mean probability of clay indicator occurrence at evenly-spaced grid points throughout the study volume. Grid spacing was 75 m horizontally and 0.6 m vertically. Ordinary indicator kriging uses the spatial statistics of the lithologic data (the degree of correlation), quantified with directional variograms, to interpolate indicator values between data locations. Directional variograms were determined experimentally to estimate characteristic correlation lengths and anisotropy. SVA dip was found to be statistically insignificant.

[9] Several hundred meters of archived core were examined and two hand-picked peat samples from the SVA were dated using $^{14}$C following careful processing (sand and shells separated, acid and based washed, converted to graphite). Samples were analyzed at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory using standard techniques [*Southon et al.*, 1990; *Vogel et al.*, 1984].

## 4. Results and Discussion

[10] Volume maps, fence diagrams and cross sections of clay probability illustrate the geometry of the SVA in the field area (Figure 2). A cross validation study, in which known data points were sequentially removed from the data set and observations were compared to predictions, demonstrated correct identification of clay and non-clay facies with 85% and 95% reliability, respectively.

[11] The SVA is thickens to the southeast, dips to the northwest, and has an irregular upper surface (Figure 2). Cross sections through the indicator model illustrate that the SVA in this area is composed of three distinct units (labeled I, II and III in Figure 2). These units are separated by nonclay (sand and gravel) units. Core samples from between SVA clay units at Fort Ord consist predominantly of well-sorted aeolian sands, with no evidence for coarse-grained channel lag material, wood fragments, ripples, cross-beds or other indicators of fluvial or tidally-influenced deposition. The SVA is considerably more homogeneous in the Salinas Valley to the north and east [*Dupré*, 1990; *Greene*, 1977; *Tinsley*, 1975].

[12] The interfingering of clay and nonclay units is consistent with a model for Quaternary deposition in which individual nonclay-clay sequences record distinct periods of sea-level rise and fall, and associated marine transgression and regression [*Dupré*, 1975; *Dupré et al.*, 1991; *Greene*, 1977; *Tinsley*, 1975]. Fine-grained, estuarine or lagoonal clay is deposited during a sea-level high stand. A blanket of

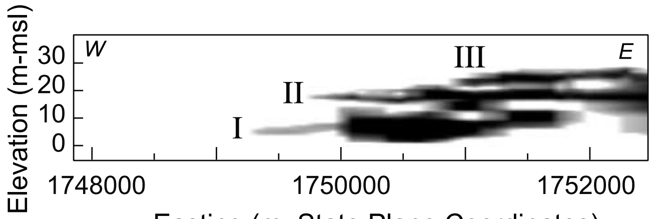


**Figure 2.** Cross section of SVA at Fort Ord, based on probability of clay occurrence. Black indicates highest probability of the presence of a clay indicator; white background indicates probability below cutoff. Three clay units are clearly visible (labeled I, II and III, oldest to youngest), with non-clay interlayers. $^{14}$C samples were collected from layers I and II. Vertical exaggeration = 30×.

dune sand deposited rapidly after sea level falls protects parts of the newly-exposed marine clay from erosion. As sea level rises again, a new layer of clay is draped over older deposits, resulting in hummocky relief.

[13] The two peat samples from SVA layers I and II were analyzed by AMS and revealed no measurable $^{14}$C, indicating an absolute age of at least 40 kyr. While this lower age limit is consistent with an earlier $^{14}$C analysis, indicating that the SVA is at least 6–18 kyr old [*Tinsley*, 1975], it is older than the range of ages commonly assigned to the SVA in the Salinas Valley [e.g., *Dupré and Tinsley*, 1980; *Dupré et al.*, 1991].

[14] Additional insight is provided by calculations of apparent uplift rates associated with different ages for the SVA. The present day surface elevation of the SVA is 0–20 m-msl at Fort Ord (Figure 2), and 0–10 m-msl in the SVA in the Salinas Valley [*Tinsley*, 1975]. Fossil assemblages indicate a lagoonal paleoenvironment and depositional depth of $\leq$10 m [*Tinsley*, 1975]. The $^{14}$C-tested peat samples we collected at Fort Ord were from 0 and 3 m-msl, and bivalve hashes were found in clay horizons at elevations $\leq$10 m-msl. Overlying clay samples are similarly unoxidized, organic-rich, and thickly bedded, and are laterally continuous on geostatistical cross sections with deeper clays, suggesting that these materials represent marine conditions at present elevations up to 20 m-msl.

[15] Minimum SVA uplift rates were estimated by subtracting paleo-sea level from current SVA surface elevations, and dividing by possible times since deposition. For instance, if the SVA at Fort Ord were deposited 18 kya, with sea level at approximately −120 m-msl, uplift of 6.6–7.8 mm/yr since deposition would be required (Figure 3). These are minimum uplift rates, assuming no erosion of the SVA since deposition. Quaternary marine terraces around Monterey Bay are more commonly interpreted to have uplifted at 0.1–0.4 mm/yr [e.g., *Anderson and Menking*, 1994; *Bradley and Griggs*, 1976; *Greene*, 1990], as have terraces along much of coastal California [*Dupré et al.*, 1991; *Grant et al.*, 1999]. Coastal terraces near Santa Cruz (northern Monterey Bay) may have uplifted recently at 1.1 mm/yr, but this area is unusually active seismically [*Perg et al.*, 2001]. It is unlikely that Salinas Valley sediments were uplifted at rates 3 to 40× faster than most of coastal California over the last 10–20 kyr, particularly since marine terraces are not preserved in this area.

[16] By dividing total uplift required for the SVA at Fort Ord by an average rate of 0.1–0.4 mm/yr, a more likely minimum age of ~80 kya is indicated (Figure 3). Younger ages require both greater uplift rates and deposition of distinct, laterally-continuous clay units (indicative of low-energy, estuarine conditions) separated by sand units during a single phase of sea level rise.

[17] Three of the lowest Santa Cruz terraces date from the last major interglacial period, Isotope Stage 5 (84–121 kyr), which comprises three glacio-eustatic transgression-regression events [*Anderson and Menking*, 1994; *Bradley and Griggs*, 1976; *Perg et al.*, 2001; Figure 3]. Each of these three terraces demarcates a paleo-shoreline at a transgression peak (Stages 5a, 5c, 5e). The SVA at Fort Ord likely represents the lagoonal or estuarine analog of these marine terraces. The SVA is thicker and more continuous north and east of Fort Ord, probably because of differences in water depth during deposition, and thus differences in sensitivity to modest changes in sea level.

[18] A young SVA composed of a single, thick layer would greatly impede inter-aquifer communication, whereas a multi-layered SVA deposited over a longer time, with intervening periods of erosion, is more likely to be laterally discontinuous. Some cross sections through our geostatistical model show gaps in individual layers. Erosion of thin SVA layers could occur during sea-level low stands, with exposed clay units being dissected by streams flowing from

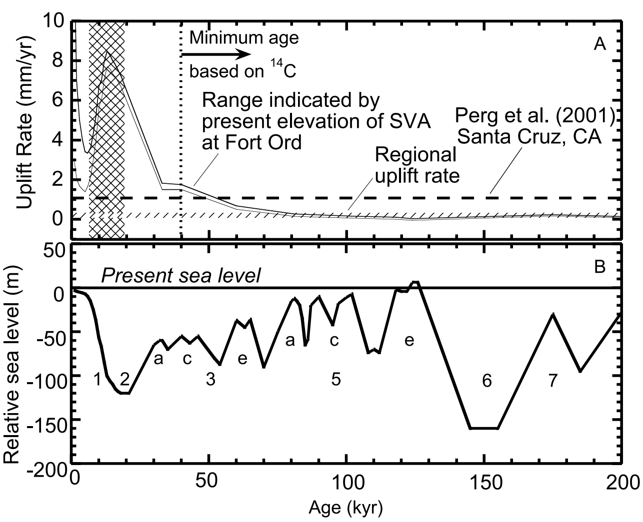


**Figure 3.** (a) Long term uplift rates required by present elevation of the SVA at former Fort Ord, assuming deposition at paleo-sea level and ages as shown. Solid lines indicate range of required uplift rates based on this study and *Tinsley* [1975]. Vertical cross-hatched band indicates 6–18 kya age range for SVA, requiring uplift rates of 1.5–8.0 mm/yr. Dotted line at 40 kyr indicates minimum age of SVA at Fort Ord based on $^{14}$C analyses. Horizontal hatched band indicates uplift rate of 0.1–0.4 mm/yr for the Monterey Bay region and much of coastal California [*Anderson and Menking*, 1994; *Dupré et al.*, 1991; *Greene*, 1990]. Horizontal dashed line indicates rate from recent analyses of terraces in Santa Cruz [*Perg et al.*, 2001]. (b) Composite sea-level curve used to derive long term uplift rates for the SVA [*Dupré et al.*, 1991; *Fairbanks*, 1989; *Lajoie et al.*, 1991].

elevated areas towards the Salinas Valley. A discontinuous SVA would be more conducive to exchange of fluids and solutes between shallow aquifers. Development of deeper aquifers within this system, in response to degradation of shallower resources, could result in groundwater flow through leaky confining layers, from shallower to deeper aquifers.

[19] Numerous other coastal and near-coastal California basins contain shallow sequences similar to those of the Salinas Valley, including the upper Merced Formation of northern California [*Dupré et al.*, 1991], and shallow deposits in basins of Santa Barbara and San Diego counties [e.g., *Berenbrock*, 1988; *Izbecki*, 1983]. Thin, discontinuous confining units are particularly likely near the edges of these coastal basins, because (1) deposition onto river terraces results in confining units that are thinner on the edges than in deeper parts of the basins, (2) multiple units may have been deposited in response to small fluctuations in sea level, and (3) adjacent highland areas may have generated streams that flowed across the basin edges, incising channels and penetrating the thin, fine-grained deposits. This hypothesis remains to be tested, basin by basin.

## 5. Conclusions

[20] A geostatistical assessment of sedimentary deposits in a coastal basin, in combination with $^{14}C$ analyses and consideration of regional uplift rates, suggests that the shallow confining layer in the study area is more complex stratigraphically and considerably older than previously thought. We interpret multiple clay units within a shallow confining layer to be associated with sea-level high stands during Isotope Stage 5 (84–121 kyr). This interpretation is consistent with the thin, discontinuous nature of the clay units, and has important implications for groundwater development, protection and remediation in this setting. Similar depositional interpretations may apply to other coastal basins experiencing uplift and repeated transgressive-regressive cycles. Hydrogeologic models developed near the centers of coastal basins should be applied with care on basin edges, since subtle differences in depositional conditions may result in significantly different hydrostratigraphy.

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