Article
Documenting the Evolution of a Southern California Coastal Lagoon during the Late Holocene

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Abstract: Coastal wetlands are declining globally, and although wetland restoration looks to offset these losses, its success relies on anticipating environmental response to external forces. The purpose of this study is to investigate the sedimentological record of Los Peñasquitos Lagoon to determine the processes that drive environmental transitions in a Southern California coastal wetland. For this project, we analyze three sediment cores from the wetland for grain size, total organic matter, and shell assemblages to reconstruct environmental change over the past ~4000 years. From the results, we find that the lagoon was initially an open embayment that persisted for >2000 years; however, at ~1000 cal yrs BP, a short-lived wet climatic period triggered a fluvial deltaic progradation at the head of the lagoon. As the wet period ended and drier conditions returned, the delta began to retreat, and the lagoon infilled as the estuarine mouth bar was permanently established. The permanent establishment of the mouth bar resulted in a transition to a marsh-dominated environment throughout the wetland. Ultimately, these environmental transitions were driven by climate variability, although evidence of human impacts was observed more recently in the record. Therefore, future restoration efforts must consider both natural climatic variability and anthropogenic influences if they intend to sustain coastal wetlands.

Keywords: coastal wetlands; sediments; grain size; stratigraphy; Southern California; Los Peñasquitos Lagoon

1. Introduction

Coastal wetlands are critical environments for a broad range of ecosystem services, such as flood and water quality management [1–3], sediment control [4–6], shoreline protection [7–9], biodiversity hotspots [10–12], nutrient cycling [5,10], and carbon sequestration [13,14]. Arguably, one of the greatest risks to coastal wetlands is rising sea level triggered by climate change [7,14–18]. Sea-level rise threatens to drown coastal wetlands worldwide if sedimentation rates cannot keep pace with rising sea levels [19] or if coastal wetlands do not have the space to migrate inland [20,21]. Due to human intervention via dam construction and urbanization, the sediment supply to many wetlands has been severely limited, if not cut off entirely [7,22,23]. Although coastal wetlands can adjust to incremental changes in climate, the combined impact of anthropogenic interference with climate change and sea-level rise may be too great [17,19], as over 50% of coastal wetlands have already been lost globally [7,24,25].

Coastal wetlands along the US Pacific coast are particularly vulnerable. The steep topography of the Pacific coastline and extensive coastal urbanization in areas such as Southern California limit the migration potential for these wetlands in response to sea level rise [26] and limit the space available for wetlands to become established in general. Although 90% of the Atlantic coastline is comprised of coastal wetland habitats, these areas make up only 10–20% of the Pacific coast [27,28] due to the active tectonic margin, which
leaves little room for expansive coastal plains [29–32]. These conditions exacerbate the effects of urbanization on coastal environments, particularly in Southern California, due to its high population density [33]. It is estimated that over 90% of California’s historic wetlands have already been lost to agriculture, industry, and urban development [34]. As urbanization overtakes Southern California coasts, wetlands experience phenomena such as coastal squeeze [35] and fragmentation [36]. Both phenomena disrupt the natural processes that maintain these environments and significantly inhibit the ecosystem services they provide.

Given the continued degradation of Southern California wetlands, conservation and restoration have become increasingly important. *Ostrea lurida* (Olympia oyster) habitats are one example of an important restoration endeavor in Southern California. There is evidence that Southern California wetlands were once better suited to support oyster communities [37,38]. However, as the wetlands evolved, these habitats transitioned to salt marsh or tidal creek systems, which are less conducive to oyster development [38,39]. Several previous studies have found evidence for oyster reef communities in the recent geologic past within Southern California coastal wetlands that today are dominated by tidal creeks and salt marshes [40,41]. This indicates that these environments were once better-suited to support filter-feeding bivalves but have transitioned away from conditions that are conducive to sustaining oyster populations and their associated reef communities. In fact, oyster shells found in sediment cores from Los Peñasquitos Lagoon (LPL) are dated between ~3000 and 6000 years ago, predating the stratigraphic shift from a lagoon/open embayment to a mudflat/marsh system [42]. This suggests that the loss of oyster communities may have resulted from natural processes driving widespread environmental change in the lagoon and not anthropogenic modification of coastal environments due to European colonization in the 18th century [43], estuarine habitat loss in the 18th and 19th centuries [44] or overfishing during modern times [45]. Although this stratigraphic transition in LPL has been previously documented, questions remain about when this transition occurred and what drove this environmental change, if it was not driven principally by human activities. With these questions unanswered, restoration efforts in LPL and within the greater region may prove difficult, especially in the face of climate change. For these efforts to be successful, we must better understand how wetlands respond naturally to environmental changes. Studying the evolution of modern-day coastal wetlands over the recent geologic past may provide important insight into coastal processes that can aid in restoration efforts.

Therefore, this study aims to better understand the processes and events that may have driven the shift in a Southern California coastal wetland from an open bay estuary with oyster-favorable habitats to a salt marsh with limited oyster-favorable habitat. To address this question, we investigate the sedimentological history of LPL, located in San Diego County. We take an in-depth look at the stratigraphy of three sediment cores, using grain size and total organic matter as paleoenvironmental indicators to reconstruct the evolutionary history of this lagoon. We also perform palaeoecological analyses on the shells present within the cores to establish the timing of habitat suitability for oysters and their associated community. Furthering our understanding of Pacific coastal wetland systems may provide insight into the natural environmental factors that may have contributed to the historical decline in the Olympia oyster and aid in future efforts to restore the species in Southern California.

2. Study Area

The LPL is a marine-dominated coastal wetland in San Diego County, California [40]. This lagoon rests at the end of the Los Peñasquitos watershed, a 260 km² drainage basin that borders the Torrey Pines State Reserve (Figure 1). Like most southern California lagoons, LPL originated as an estuary, formed by the rising postglacial sea level [40], but it has experienced several environmental shifts throughout its history. Before 6000 cal yrs BP, the surrounding coastal region was characterized by rocky, cobbly beaches that formed
following the postglacial sea-level rise [46]. Within the past 6000 years, regional sea-level rise slowed in Southern California [47], allowing the open embayments and lagoons in the San Diego County region to start infilling and developing sandy beaches [41,48,49]. Previous work by Scott et al. [50] indicated that there may have also been tidal flow restriction in LPL at this point. By ~2750 cal yrs BP, previous work interpreted a transition in LPL to a salt marsh environment that more closely resembles what we see today [41,42].

Figure 1. Images of the study area. (a) Satellite imagery of the study site, Los Peñasquitos Lagoon, located in San Diego County. The red markers indicate the three coring locations; the green dashed line marks the border of the Torrey Pines State Reserve. Core locations from previous work that are referenced in the text are shown as a white square and yellow star. (b) Photo of the specific core location for LPL07 and (c) shows an example of the core locations where LPL03 and LPL04 were collected. These photographs demonstrate the variability of habitats reflected at the surface of the cores.
This previous work by Cole and Wahl [41] provided essential insight into the paleoenvironmental evolution of the lagoon over the last ~3500 years. Below, we will summarize their interpretation of the evolution of LPL as well as how it fits with previous work by others in this area. Cole and Wahl [41] concluded that prior to ~3000 cal yrs BP, the lagoon was an open embayment infilling with predominantly sandy sediments. At ~2750 cal yrs BP, there was a transition within the lagoon to conditions in which grass pollen dominated and sediments were fine, suggesting the initiation of marsh-like conditions which continued up core through time [41]. Sedimentation rates increased by >3-fold during the 19th century following European settlement in the area [41], and this increase is consistent with other marshes in the region [43,51,52].

Additionally, there have also been two biological shifts that generally line up with changes in climate over the past ~3000 years. Mangrove and pondweed dominated the lagoon up through ~2750 cal yrs BP, at which point grass became more abundant [41,42]. This transition coincides with the shift from a wetter to drier climate. The subsequent biological shift occurred ~200 cal yrs BP, when *Erodium* and eucalyptus overtook grass [41,43], roughly coinciding with the shift to today’s arid climate. In should be noted, however, that eucalyptus and *Erodium* are also non-native plants in Southern California, and they are often interpreted as indicators of European settlement [41,43,53].

One factor in the natural history of LPL that has not been explored in depth is the presence of bivalve shells that have been deposited throughout the lagoon’s history. Previous studies have noted the presence of whole shells or shell fragments within the lagoon [40–42] and a shell hash layer containing whole and fragmented shells (M. Kirby, unpublished data). In these studies, shells were identified as *Ostrea lurida*, commonly known as the Olympia oyster. This is the only oyster species native to the Pacific coast [45,54–56]. The Olympia oyster was once a dominant North American Pacific coast fishery with a historic geographical range that encompassed Sitka, Alaska, south to Baja California del Sur [38]. Today, this species is only found from British Columbia down to the northern coast of Baja California, and even within this area, the population is sporadic at best [38]. Previous studies have shown that a key factor in the Olympia oysters’ ability to maintain a population is the availability of a solid substratum for cementing [39,57]. *Ostrea lurida* are free-swimming organisms for up to three weeks during their larval stage before they seek a hard surface to attach to for the rest of their lives [54]. In estuaries with heavy sedimentation, it can be difficult for oysters to find a stable surface for attachment. When sedimentation levels overwhelm an open bay, there is a subsequent loss of habitats for species such as *Ostrea lurida* that thrive in a brackish, open water environment [58]. Therefore, the loss of suitable habitat for the Olympia oyster in LPL does not necessarily require anthropogenic modifications to the system or overharvesting but rather the natural processes that caused the environmental shift from an open embayment to a restricted tidal marsh over the past ~3000 years may be a significant, if not primary, contributor.

3. Materials and Methods
3.1. Core Collection and Descriptions

Three sediment cores were collected from LPL (Figure 1) using a ~7.6 cm diameter vibracorer in January 2017 and October 2017. The cores ranged in length from ~2 to 3 m and were transported intact to California State University, Fullerton (CSUF) and stored in the CSUF Department of Geological Sciences refrigerated Core Repository prior to analysis. At CSUF, each core was split lengthwise, with one half designated as the working half and the other preserved unsampled as an archive in the core repository. We photographed the working half and created a detailed core description for each core to note qualitative characteristics such as sediment texture, changes in sediment color, apparent sedimentary structures, and the presence of organic matter, plant material, or shells. Following the core descriptions, we designated core LPL07 as our master core as it was the longest core, transitioned from a sandy base to a muddy core surface, and contained a >10 cm thick shell hash layer.
3.2. Grain Size Analyses

We sampled core LPL07, our master core, at 1 cm contiguous intervals; each sample was ~0.5 cm$^3$ of wet sediment, removed directly from the split, half-round, working half of the core using a small aluminum spatula and washed the sediment into a 50 mL centrifuge tube with deionized water. Cores LPL04 and LPL03 were sampled similarly, but every ~2–4 cm to document identifiable lithologic units, with samples taken every ~1 cm where there was a visible transition. For all the cores, each sample was pretreated with ~90 mL of 30% hydrogen peroxide ($\text{H}_2\text{O}_2$) to remove organic matter, 10 mL 1 N hydrochloric acid (HCl) to remove carbonate (CO$_3$), and 10 mL of 1M sodium hydroxide (NaOH) to remove any biogenic silica. After these three pretreatments, the sediment that remained should only consist of the lithogenic (mineral) fraction, free of any material that would have been deposited or chemically precipitated during or after deposition. Particle size distributions were measured using a Malvern Mastersizer 2000 laser diffraction grain size analyzer coupled to a Hydro 2000 G large-volume sample dispersion unit following the methodology described by Leidelmeijer et al. [59]. The grain size output from the Malvern Mastersizer 2000 was run through the GRADISTAT [60] Excel program. From the GRADISTAT analyses, we utilized the sorting ($\sigma$) and descriptive mean grain size results of the geometric (modified) Folk and Ward method [60] and also calculated the average sorting of each stratigraphic unit by determining the mean sorting value of all samples within the unit.

3.3. Loss-on-Ignition

Loss-on-ignition (LOI) is a widely used, semi-quantitative method for calculating total organic matter (TOM) and carbonate mineral content in sediments [61–63]. Only cores LPL07 and LPL04 were processed via this method; TOM for core LPL03 was estimated using clay content as a proxy (discussed in more detail in results). Each core was sampled at ~1 cm contiguous intervals; then, ~2–4 g of dry sediment (previously dried at 60 $^\circ$C overnight) was placed into individual pre-weighed porcelain crucibles for analysis. The crucibles were placed into a muffle furnace and combusted at 550 $^\circ$C for 2 h. During this process, the organic matter is oxidized into carbon dioxide and ash. The weight of the crucible following this procedure provides a measurement for the TOM in the sediment [63]. After determining TOM, the samples were returned to the furnace and combusted at 950 $^\circ$C for 2 h. In this stage, any carbonate matter present in the sediment undergoes thermal decomposition, which provides a quantitative measurement for total carbonate mineral content (TC) in the sediment [61,62].

3.4. Shell Analyses

Numerous paleontological studies have shown that it is possible to estimate the distance a shell assemblage has traveled based on a qualitative assessment of its physical condition [64–68]. In this study, the primary goal of this assessment was to determine whether the shell hash layer in LPL07 was an oyster reef in situ, suggesting an established reef community or a reworked lag deposit where shells from various spatial and temporal setting may have been brought together into a single deposit. The key taphonomic indicators we examined were the biofabric of the deposit (shell orientation, size- or shape-sorting, and close-packing) and the condition of the individual shells (i.e., visible breakage, abrasion, or potential causes of organism death such as boreholes). We defined the biofabric of the deposit following the methodology described by Kidwell, Fursich, and Aigner [66] through directly analyzing the shells and utilizing our core description and core photos. Then, the ~20 cm shell hash layer was fully extracted from both halves of the core (working and archive), and the shells were identified to the level of species and examined for physical features that may indicate whether the shells had been transported, as well as any visible mechanism of death.
3.5. Radiocarbon Dating

Organic samples were collected from each core for the purpose of radiocarbon dating. Nine samples were collected from LPL07: two charcoal samples from above and below the shell hash layer and seven shell samples from within the shell hash layer. The purpose of dating these samples in the core was to establish the ages of the shells both directly and within the stratigraphic sequence. One shell and one charcoal sample were collected from LPL04, and a single charcoal sample was collected from LPL03. The dating strategy in these cores was to compare shell ages to the shells in LPL07 and to obtain at least one age per core for stratigraphic correlations. All samples were analyzed at the W.M. Keck AMS Lab at UC Irvine and the samples were calibrated using the CALIB 8.20 Radiocarbon Calibration tools [69]. As part of this process, raw radiocarbon dates from shell samples were corrected for marine reservoir effect using a local $\Delta R$ value of $-43 \pm 40$ 14C yr [70].

4. Results

4.1. Core Description and Grain Size

In our master core, LPL07, we observed a clear color shift in the core around a depth of 160 cm, where the lower section of the core is greyer in appearance and the upper section is browner in color. The other most notable sedimentary structure observed was a sharp contact at ~83 cm, which marks the transition between dominantly coarse sediment below and fine sediment above (Figure 2e). Moving up through the core above 83 cm, we see interbedded sand layers and sand lenses decrease in frequency whereas organic inclusions and visible roots increase in frequency.

We separated the full grain size distribution of each sample into the following classifications: mud (i.e., clay and silt, 0–63 µm), fine sand (63–250 µm), and medium and coarse sand (250–2000 µm). From here on out, for the sake of brevity, we will refer to medium and coarse sand as “coarse sand.” We plotted the raw data for each sample on a ternary diagram (Figure 2a). From this plot, we see that the data generally clusters into four separate groups. Using these groups, we can manually define four distinct sedimentary units within the core (Table 1), each characterized by a unique grain size composition described below. Each unit was compared against all other units using a two-sample $t$-Test to determine that all units are significantly different (Table 2).

Table 1. Stratigraphic unit characteristics.

| Grain Size Distribution as Percentages of Total | Minimum | Maximum | Mean | Standard Deviation | n | Sorting |
|-----------------------------------------------|---------|---------|------|--------------------|---|---------|
| Unit 1                                        |
| Mud                                           | 8.6     | 39.6    | 23.4 | 8.5                | 91 | 2.5 µm  |
| Fine Sand                                     | 40.6    | 76.3    | 65   | 6.8                | 91 |         |
| Coarse Sand                                   | 3.4     | 32.9    | 11.6 | 6.4                | 91 |         |
| Unit 2                                        |
| Mud                                           | 5.7     | 66.3    | 24.8 | 15.6               | 59 | 3.7 µm  |
| Fine Sand                                     | 14      | 56.9    | 32.7 | 9.7                | 59 |         |
| Coarse Sand                                   | 14.4    | 67.4    | 42.5 | 14.1               | 59 |         |
| Unit 3                                        |
| Mud                                           | 48.4    | 73.1    | 63   | 7.3                | 15 | 3.1 µm  |
| Fine Sand                                     | 24.1    | 49.4    | 34.6 | 7.4                | 15 |         |
| Coarse Sand                                   | 0       | 7.1     | 2.4  | 1.6                | 15 |         |
Table 1. Cont.

| Grain Size Distribution as Percentages of Total | Minimum | Maximum | Mean  | Standard Deviation | n | Sorting |
|-----------------------------------------------|--------|---------|-------|--------------------|---|---------|
| Unit 4                                         |        |         |       |                    |   |         |
| Mud                                           | 73.7   | 99.9    | 91.8  | 6                  | 29|         |
| Fine Sand                                     | 0.1    | 18.8    | 7.2   | 5.2                | 29| 2.8 μm  |
| Coarse Sand                                   | 0      | 7.5     | 1     | 1.6                | 29|         |

Figure 2. Sedimentology of core LPL07. (a) Ternary diagram for LPL07 showing mud on the left, fine sand on the bottom, and coarse sand on the right. Unit boundaries are shown with a solid black line, and units are labeled such that “U” stands for “Unit.” Data markers also correspond with their respective units (+ for Unit 1, circles for Unit 2, diamonds for Unit 3, X for Unit 4); however, the open square samples are from the shell matrix, which plot in U2, but are characterized as U1 (see text for explanation). (b) Percentage of coarse sand as compared with shell abundance within the shell hash layer. The light blue shape behind the grain size graph illustrates the abundance of shells with its width—where the shape is wider, more shells were present. The corresponding stratigraphic units are shown to the right of the plot. (c) Complete sedimentary data for the core. All data are shown relative to core depth. The data from left to right include the percentage of mud, the percentage of fine sand, the percentage of coarse sand, the percentage of total organic matter (% TOM), and the stratigraphic column showing the different depositional units identified (from a) along with the location of shells and radiocarbon dates. Representative images from core photographs for each of the stratigraphic units are shown in d–f with the corresponding location highlighted on the stratigraphic column. (d) Unit 4 from the surface of the core, (e) highlights the sharp contact (yellow line) between Units 2 and 3, and (f) is Unit 1 from near the bottom of the core.
Table 2. Stratigraphic unit t-test comparisons.

| Unit | 1   | 2     | 3     | 4  |
|------|-----|-------|-------|----|
| 1    | -   | <0.001| <0.001| <0.001|
| 2    | -   | -     | <0.001| <0.001|
| 3    | -   | -     | -     | <0.001|
| 4    | -   | -     | -     | -   |

Unit 1 is poorly sorted (standard deviation 2.5 µm) and consists mainly of fine sand (averaging 70 ± 6% across all samples). Mud content averages 25 ± 8% across all Unit 1 samples, and coarse sand averages 10 ± 6%. The unit spans core depths from 313 cm up to 163 cm, making it the longest unit in this core, but there is variability in sediment texture within this unit. Although depths from 313 cm up to 270 cm are dominated by fine and coarse sand (Figure 2f), we see a noticeable shift to greater mud content at 269 cm. From 269 up to 200 cm, the mud content is consistently between 20 and 40% but decreases to 5–10% above 200 cm. There is a sharp increase in coarse sand from 30% at 191 cm to 50% at 185 cm with this coarse sand spike falling between the oyster shell samples at 191 cm and the rest of the shell hash layer, which spans 185 to 165 cm (Figure 2b). This dominantly coarse sand sublayer is represented in the ternary plot as open squares (Figure 2a) and technically might be more consistent with Unit 2 (see below); however, given the limited number of samples in this group and its stratigraphic position, we decided not to define it as a shift in sedimentary unit. Above the shell hash layer at 184 cm, coarse sand drops from 50% to 30%, fine sand increases from 45% to 60%, and mud increases from 5% to 10%. From 185 to 173 cm, coarse sand steadily decreases to 10%, mud increases to ~30%, and fine sand remains stable. Near the top of the unit at 163 cm and the transition into the bulk of Unit 2, the unit coarsens with increases in coarse sand and decreases in fine sand.

The main distinction between Units 1 and 2 is coarse sand: Unit 2 has the highest amount of coarse sand out of any other unit in the sequence. Coarse sand averages 40 ± 14%, whereas fine sand and mud average 30 ± 9% and 25 ± 15%, respectively. Unit 2 is more poorly sorted than Unit 1 (standard deviation 3.7 µm), and it is also the second thickest unit in the core, spanning depths from 162 to 85 cm. It is a complex sedimentary sequence that sees broad fluctuations in coarse sand and mud, whereas fine sand steadily decreases up core. Coarse sand and mud fluctuations are typically inverse throughout this section, creating a sequence of alternating muddy and coarse layers, yet the coarse-dominated sections are generally more expansive. A mud-dominated layer is located at depths from 162 to 149 cm and that is overlain by a coarse-grained layer from 148 to 116 cm (Figure 2c). Above this, from 115 to 103 cm, is another mud-dominated layer, overlain by the last coarse sand layer from 102 to 88 cm that lies below a thin mud layer from 87 to 85 cm at the transition to Unit 3 (Figure 2c).

Unlike Units 1 and 2, which are sand-dominated, Units 3 and 4 are mud-dominated. Unit 3 is the thinnest unit of all four (Figure 2c). This unit serves as a transition between the sandy lower half of the core and the muddy upper half (Figure 2e), as it is composed mainly of mud (60 ± 7%), with a moderate amount of fine sand (35 ± 7%) and very little coarse sand (5 ± 1%) (Figure 2c). It is poorly sorted (standard deviation 3.1 µm) but has relatively better sorting than Unit 2 below. This unit, which only encompasses depths between 84 cm and 59 cm, is also where we begin to see a more consistent fining-upward trend. Coarse sand decreases consistently throughout, reaching 0% at a depth of 59 cm, and fine sand and mud vary out of phase with each other (Figure 2c).

The primary difference between Units 3 and 4 is mud: Unit 4 contains the most mud out of all four units. This unit is poorly sorted (standard deviation 2.8 µm) and defined by a very high percentage of mud (90 ± 6%), followed by a very small amount of fine sand (10 ± 5%) and even less coarse sand (<1 ± 1%) (Table 1). This unit, which extends up core from 58 cm through to the top of the core (Figure 2d), continues the overall fining upward trend present in Unit 3. Coarse sand is almost consistently absent from this unit.
To apply the units defined from the master core (LPL07) to cores LPL03 and LPL04, we plotted the raw grain size data on a ternary diagram (Figure 3) with the same unit classifications defined from LPL07. From this plot, we recognize that only three of the four units defined in LPL07 are present in LPL03 and LPL04. LPL03 contains very little coarse sand and is instead composed primarily of mud and fine sand, which fluctuate inversely throughout the core. With a total length of 172 cm, LPL03 is also the shortest core (Figure 4a). The base of the core (172–148 cm) is characterized as Unit 1, and the unit is homogenous with an overall fining upward trend. The remainder of the core fluctuates between Units 3 and 4. Overlying Unit 1 is a four-centimeter-thick Unit 3 section (146 to 143 cm) dominated by mud, followed by a six-centimeter Unit 4 section (142 to 137 cm) that is also predominantly mud but contains about 10% less fine sand and 5% less coarse sand than the Unit 3 section below it. At 136 cm, the core shifts back to Unit 3, which extends through 119 cm (Figure 4a). Throughout this Unit 3 section, fine sand is steadily decreasing (30% to 25%) whereas mud increases (65% to 75%). This is overlain by an expansive Unit 4 section, spanning depths from 118 cm to 36 cm. Fine sand and mud fluctuate inversely throughout this unit with no discernable pattern, but mud remains dominant overall until fine sand starts to sharply increase at 40 cm. Lastly, the top of the core returns to a Unit 3 section for the final 35 cm.

Core, LPL04, is dominated by fine sand and mud. Its stratigraphic sequence is nearly identical to that of LPL03 (Figure 4b). The core begins with a Unit 1 section that spans from 289 cm to 159 cm and is dominated by fine sand (~70%) with a moderate amount of coarse sand (~25%) and a small amount of mud (~15%). Like LPL03, above the basal Unit 1 the core alternates between Unit 3 and Unit 4 sections with coarse sand continuing to decrease to the point where its presence is negligible, whereas fine sand and mud fluctuate inversely. Unit 1 is overlain with a Unit 3 section, which can be seen as a transition between a fine sand-dominated environment and a mud-dominated environment, and it spans depths from 159 cm up to 76 cm. The next section of the core is defined as Unit 4 and extends from 75 cm to 34 cm and contains a general trend of increasing mud content up core from ~80% to a maximum of ~90% at 46 cm. The final unit in this core is a return to Unit 3. Mud is still the predominant grain size (60%), but fine sand is more prevalent than in the previous unit (40%).
Figure 4. Sedimentology of cores (a) LPL03 and (b) LPL04. All data are shown relative to core depth. The data from left to right include the percentage of mud, the percentage of fine sand, the percentage of coarse sand, the percentage of total organic matter (% TOM), and the stratigraphic column showing the different depositional units identified along with the location of radiocarbon dates. Note that the % TOM for LPL03 is a proxy described in detail in the text.
4.2. Loss-on-Ignition

Loss-on-ignition analysis was performed on LPL07 and LPL04 to determine the percentage of total organic matter (TOM). With both cores, we see a general trend of increasing TOM moving upwards through the core (Figures 2c and 4). Throughout the lower ~2 m of LPL07, the TOM remains consistently below 10% (Figure 2c). At ~80 cm, there is a sharp increase to 10% TOM corresponding to the transition from Unit 2 to Unit 3. The TOM remains relatively constant at ~10% until the transition from Unit 3 to Unit 4 at 58 cm where it steadily increases up core through Unit 4, peaking at a value of ~30% just below the surface.

Core LPL04 shows a similar increasing trend, though the values remain much lower throughout the core (Figure 4b). For the first 80 cm of LPL04 through Unit 1 and half of the lower Unit 3, TOM is consistently low with values of 0–2%. Over the next meter, the TOM slowly increases to ~10% TOM moving upward through the lower Unit 3 and the overlying Unit 4. The transition from Unit 4 to the upper Unit 3 section shows a slight decrease in TOM, but in general TOM remains consistently ~10% for the top meter of the core. Although we did not perform loss-on-ignition analysis for core LPL03, the percentage of clay content can be used as a proxy due to its positive correlation with TOM ($R^2 = 0.755$, data not shown). The TOM proxy of LPL03 differs from the TOM of LPL07 and LPL04 in that it does not steadily increase moving upwards through the core (Figure 4a). However, what it consistent with the TOM proxy for LPL03 and the other cores is that the lowest TOM estimates were found in Unit 1, the highest in Unit 4, and Unit 3 estimates were elevated relative to Unit 1 but generally less than Unit 4.

4.3. Shell Analysis

Overall, 72 whole shell or shell fragments were identified from the shell hash layer in core LPL07 (Table 3). More than two-thirds of the identified samples were shell fragments, and there were many other shells that were too fragmented to identify. The most common shell present in the assemblage was Cerithideopsis californica, a brackish species commonly known as the California horn snail (Figure 5f). The next most common species were Tagelus californiensis (Figure 5c) and Macoma nasuta (Figure 5e), both marine bivalves. Two whole samples of Ostrea lurida (Figure 5b) were identified along with six shell fragments. Other species identified were Chione undatella (Figure 5g), Argopecten ventricosus (Figure 5d), and Nassarius tegula. According to the taphonomic grading system by Flessa, Cutler, Meldahl, Paleobiology, Spring, Flessa, Cutler, and Meldahl [68], most whole shells fall under grades I or II, meaning that they show some abrasion and moderate to significant loss of color or luster.

Table 3. Taxonomic results.

| Species                     | Class  | Environment         | Whole Samples | Shell Fragments |
|-----------------------------|--------|---------------------|---------------|-----------------|
| Ostrea lurida               | Bivalvia     | Hypersaline, marine, brackish | 2              | 6               |
| Argopecten ventricosus      | Bivalvia     | Marine               | 3              | 0               |
| Chione undatella            | Bivalvia     | Marine               | 2              | 4               |
| Macoma nasuta               | Bivalvia     | Marine               | 6              | 3               |
| Tagelus californiensis      | Bivalvia     | Marine               | 1              | 11              |
| Cerithideopsis californica  | Gastropoda   | Brackish             | 8              | 25              |
| Nassarius tegula            | Gastropoda   | Marine               | 1              | 0               |
| **Total Shells**            |          |                     | 23             | 49              |

The shell hash layer can be divided into three segments based on depth and shell abundance (Figure 5a). The lower 5 cm of the shell assemblage (S1) notably contained the two whole Ostrea lurida samples and no other shells. These two shells were oriented obliquely (an intermediate angle; not quite parallel to the bedding surface, but not perpendicular), with no discernable clustering pattern. Given that they were the only two whole Ostrea lurida samples and distinctly separated from the other shells, we consider
them to be sorted by species. The second segment (S2) was located at depths between 175 and 190 cm, where the number of shells present in the core increased up core. Due to the lower abundance of shells overall, the hard part orientation of this segment is not visible in the core photo. Upon extraction, it became clear that most shells were oriented at random, with no distinct clustering or sorting. The bulk of the shells were obtained from Segment 3 (S3), which spans from 166 to 176 cm. This segment has the most clearly visible shells in the core photo, though it is still largely matrix supported. Nearly all the whole shells came from this segment. The orientation of this assemblage is a mix of concordant (parallel or subparallel to the bedding surface) and oblique, and many of the shells are clustered in a loosely stacked concave-downward direction. Although it is not visible in the core photo, during extraction it was observed that some shell samples were clustered in a nesting orientation. There was no identifiable sorting pattern in respect to species, shape, or size.

**Figure 5.** Shell orientation and identification from core LPL07. (a) A photograph of the shell hash layer in which the core is divided up into three sections. S1 is outlined in grey, S2 is outlined in blue, and S3 is outlined in yellow. On the right, there is a close-up of S3 illustrating the orientation of the shell samples with lines and arrows to highlight a few examples. The individual shell photographs highlight specific species identified, including (b) *Ostrea lurida*, (c) *Tagelus californiensis*, (d) *Argopecten ventricosus*, (e) *Macoma nasuta*, (f) *Cerithideopsis californica*, and (g) *Chione undatella*.

### 4.4. Radiocarbon Dating

Nine samples from core LPL07 were processed for radiocarbon dating (Table 4). Of these samples, the oldest was plant material from a depth of 240 cm, which had an age of 3605 ± 20 calibrated years before present (cal yrs BP). The bulk of the samples came from the shell hash layer described previously: two *Ostrea lurida* from 190 cm and five other shells from 165 to 185 cm. Aside from the *Ostrea lurida*, the specific depth of individual samples within the shell layer was not noted. The *Ostrea lurida* had ages of 1576 ± 20 and 1704 ± 20 cal yrs BP. The other five shells ranged in age from 1039 ± 20 to 1434 ± 20 cal yrs BP. Our most shallow sample was plant material from a depth of 158 cm, which had an age of 1100 ± 35 cal yrs BP. Two samples were dated from core LPL04. The deeper of the two was plant material from 236 cm, which had an age of 3760 ± 15 cal yrs BP. The other sample was an *Ostrea lurida* shell extracted from 91 cm, and this sample had an age of 832 ± 20 cal yrs BP: the youngest age obtained. Our final
A radiocarbon date came from core LPL03. The sample was plant material from a depth of 170 cm and had an age of 2476 ± 25 cal yrs BP.

Table 4. Radiocarbon dates.

| Sample ID | Sample Depth (cm) | Material Dated       | Uncalibrated 14C Age (BP) | ± Error | Calibrated 14 C Age Range (BP) | Median Calibrated Age (BP) |
|-----------|-------------------|----------------------|---------------------------|---------|-------------------------------|----------------------------|
| LPL07 158 | 158               | Plant material       | 1165                      | 35      | 1044–1155                     | 1100                       |
| LPL07 SH1 | 165–185           | Argopecten ventricosis | 1975                     | 25      | 1273–1572                     | 1422                       |
| LPL07 SH2 | 165–185           | Macoma nasuta        | 1660                      | 20      | 945–1254                      | 1100                       |
| LPL07 SH3 | 165–185           | Tagelus californiensis | 1975                     | 25      | 1272–1572                     | 1422                       |
| LPL07 SH4 | 165–185           | Cerithideopsis californica | 1990                     | 20      | 1284–1583                     | 1434                       |
| LPL07 SH5 | 165–185           | Chione undatella     | 1595                      | 20      | 878–1200                      | 1039                       |
| LPL07 OL1 | 190               | Ostrea lurida        | 2130                      | 20      | 1406–1746                     | 1576                       |
| LPL07 OL2 | 190               | Ostrea lurida        | 2230                      | 20      | 1533–1874                     | 1704                       |
| LPL07 240 | 240               | Plant material       | 3375                      | 20      | 3563–3646                     | 3605                       |
| LPL04 OL  | 91                | Ostrea lurida        | 1415                      | 15      | 682–981                       | 832                        |
| LPL04 236 | 158               | Plant material       | 3510                      | 15      | 3715–3805                     | 3760                       |
| LPL03 170 | 165–185           | Plant material       | 2460                      | 25      | 2405–2546                     | 2476                       |

5. Discussion

5.1. Sedimentary Facies

Each of the previously described units represents a unique depositional environment that existed within the history of LPL (Table 5). We consider Unit 1 to be characteristic of a shallow open embayment due to the dominance of fine sand and the low amount of mud, indicating moderate depositional energy levels that are not concomitant with a closed lagoon or fully formed marsh. This unit has the lowest % TOM, suggesting minimal organic matter inputs to the embayment. It is likely that any substantial sedimentary organic matter inputs were limited to the margins of this embayment. Further, this unit exhibits the best sorting relative to the other units (Table 1), suggesting a consistent energy, likely regular tidal exchange, and possibly small waves. Most importantly, a similar unit to this has been described in other coastal wetlands and estuaries in the region (relatively well-sorted, fine sand) and interpreted as an embayment or subtidal estuarine environment. Other studies have noted this sandy embayment facies in LPL [41] in other coastal locations in the San Diego County region [48,49] and in other Southern California wetlands [71–73].

Table 5. Facies interpretations.

| Unit | Key Sedimentary Characteristics | Interpretation |
|------|---------------------------------|----------------|
| 1    | Dominated by fine sand (~70%)   | Open embayment |
|      | Generally consistent grain size |                |
|      | TOM < 10%                       |                |
|      | Shell hash layer                |                |
| 2    | Dominated by fine (~30%) and   | Fluvial delta |
|      | coarse (~40%) sand              |                |
|      | Fluctuating grain size          |                |
|      | TOM < 15%                       |                |
| 3    | Dominated by fine sand (~35%)   | Immature marsh |
|      | and mud (~60%)                  |                |
|      | Trace amounts of coarse sand    |                |
|      | Fining upward trend             |                |
|      | TOM ≤ 15%                       |                |
| 4    | Dominated by mud (~90%)         | Mature marsh   |
|      | Small amounts of both fine and  |                |
|      | coarse sand                     |                |
|      | TOM > 15%                       |                |

We classify Unit 2 as a fluvial delta as it consists mainly of fine sand with fluctuating percentages of mud and coarse sand. The combination of fluctuating coarse sand and mud...
layers are what distinguish Unit 2 from Unit 1. Coarse sand deposits have been identified in other wetlands in the region, including Newport Bay (~100 km north), that were attributed to channel environments [71]. Core LPL07 is the only core where Unit 2 was observed, and the core location near the head of the lagoon in relatively near proximity to the modern creek mouths today suggests a more fluvial-estuarine source rather than a tidal-estuarine source that would be found closer to the lagoon mouth. Comparable modern coarse sand deposits have also been documented in beach sands proximal to the Santa Clara River mouth, located ~200 km to the northwest [74]. Furthermore, the alternating coarse sand and mud layers observed in Unit 2 are similar to the poorly sorted muddy sand deposits found in Carpinteria Slough (~300 km northwest) that are interpreted to be prograding alluvial fan deposits [75]. The absence of this unit in cores LPL04 and LPL03 suggests that it was likely not a system-wide change but rather a local shift restricted to the more landward portion of the lagoon, further supporting the fluvial delta interpretation. As the fluvial channels from Carmel Creek and Los Peñasquitos Creek prograded out toward the mouth of the lagoon, coarse fluvial sediments were periodically deposited at the LPL07 core site, explaining the fluctuations between coarse sand- and mud-dominated layers of Unit 2. It is possible that these coarse sand deposits could represent short-term depositional events, such as floods, or longer-term processes related to migrating channels. As a result, the shift between sand- and mud-dominated layers may indicate proximity to an active channel. Whatever the mechanism, these deposits are associated with sediment aggradation and seaward progradation.

In addition, Unit 2 exhibits increased % TOM relative to Unit 1 that might be reflective of allochthonous organic matter inputs from the fluvial system. Note that the color shift from grey to brown corresponds with the shift from Unit 1 to Unit 2 as well. This might reflect a greater influence of reducing conditions in the grey sediment, indicating the shift from the open embayment to the fluvial delta environment.

The deltaic progradation interpretation is also supported by the boundary between Units 2 and 3, which is characterized by a sharp contact with coarse sand on one side and indurated mud on the other (Figure 2e). The sharp contact suggests erosion or non-deposition whereas the indurated mud is thought to reflect periods of subaerial exposure. Collectively, this sequence is believed to be evidence of the prograding delta with the transition to erosion/non-deposition as the area aggrades, a transition from sandy to muddy environments with land continuing to build seaward, and the drying of these muddy environments as they sit at relatively higher elevations.

Unit 3 marks the first signs of the modern salt marsh we see today, and we classify it as an immature marsh. In the context of this study, an immature marsh lacks well-developed vegetation. This unit is present in all three cores, indicating a system-wide change. The proliferation of clay- and silt-sized sediments reflects a shift to a muddy, low-energy environment and a return to a tidally dominated system. Interbedded sand layers and sand lenses were more common in this unit compared to Unit 4 above, suggesting a setting at a lower elevation in the tidal frame. Stevenson and Emery [71] likewise described marsh sediments in Newport Bay as fine; 80% of their marsh sediments fell within the range of silt- and clay-sized grains (0.02–63 µm). This transition is accompanied by an increase in % TOM, which reflects incipient vegetation growth but no peat development, as inorganic sedimentation still outpaced organic sedimentation. This unit is visible at the surface of cores LPL03 and LPL04, where we can see limited vegetation and an abundance of mud (Figure 1c), as both cores were collected from unvegetated flats within the marsh.

Lastly, we interpret Unit 4 to be a mature marsh. In contrast to the sparsely vegetated immature marsh, a mature marsh has well-developed vegetation. We consider this facies to be a mature marsh due to the predominant mud-sized grains and relatively high TOM (≥15%). Where this unit is present in cores LPL03 and LPL04, we see an increase in mud-sized grains that suggests more established vegetation, reducing tidal energy across the marsh platform, and minimizing sand transport and deposition. We also see this unit at
the very top of core LPL07, which helps simplify our interpretation as this core site is, at present day, a mature vegetated marsh (Figure 1b).

5.2. Shell Hash Interpretations

The shell hash layer was found within the open embayment facies, just below the fluvial delta deposits. All species identified from the shell hash layer were indicative of shallow marine or estuarine environments. Although we had divided the layer into three segments based on relative shell abundance throughout the layer, we will discuss the interpretations here based on the layer as a whole, given that all the species represent a similar environment. Based on the physical condition and orientation of the shells, we observed that more than two-thirds of the identified shells were fragmented, and many more unidentifiable fragments were present. However, whole shells and fragments alike exhibited minimal abrasion, and most were oriented concordantly (parallel or subparallel to the bedding surface) or obliquely. According to the taphonomic grading scheme of Brandt [67], a high percentage of breakage indicates intense transport and reworking, whereas minimal abrasion and oblique orientation suggest minimal transport and rapid burial. Considering these contradictory physical conditions, it is worth noting that breakage could have been exacerbated by the coring process and it may be a poor indicator of the depositional processes; therefore, we value abrasion and orientation more than fragmentation/breakage in our interpretation. Further insight may be found by considering the adapted taphonomic grading system of Flessa, Cutler, Meldahl, Paleobiology, Spring, Flessa, Cutler, and Meldahl [68], which focuses on individual shells rather than the entire assemblage and does not rely on the percentage of broken shells. By this system, most of our shells would fall under Grade I or II: excellent to good preservation, with only a slight degree of alteration; primarily associated with shallow tidal flats. Sustained transport leads to increased levels of abrasion, so based on the physical condition and shell orientation, we believe that the transport of these shells was either a relatively short distance or rapid.

Looking at the sedimentary matrix of the deposit, the shell hash layer is stratigraphically near the top of Unit 1, which is classified as an open embayment (Figure 2). However, the grain size samples surrounding the bulk of the shell hash layer fall within the boundaries for Unit 2, which represents a fluvial delta. Therefore, we believe that the shells were established locally near the coring site during the open embayment regime but may have been moderately reworked during an early phase of the delta progradation as nearby deltas were established and subsequently abandoned. Stepping back to look at the broader spatial geometry of the deposit, we only see the shell hash layer in core LPL07 and a single *Ostrea lurida* shell in LPL04. This limits our ability to establish a greater scope for the shell assemblage, but it is notable that in our cores, the shell hash layer is not present closer to the estuary mouth. This further supports the interpretation that the shells may have been locally reworked.

Collectively, these metrics point toward the interpretation that the shell hash deposit is a local assemblage that was moderately reworked and rapidly buried as the creek channels migrated and the lagoon filled with sediment. Although we had initially considered the hypothesis that the shells may have either been in situ or transported from the mouth of the estuary, the minimal abrasion and concordant or oblique orientation suggests that the shells did travel but not very far. It is impossible to determine how much of the breakage was caused by the coring process, so it is not a reliable taphonomic indicator in this scenario. The influx of coarse matrix resembling the composition of Unit 2, which is interpreted to be fluvial deltaic sediments deposited by the migration and progradation of creek channels into the lagoon, further supports this hypothesis. Lastly, the spatial geometry, although limited, indicates that the shell hash layer did not extend very far beyond the coring site LPL07; therefore, it seems more likely that the shells represent a locally reworked deposit that was rapidly buried by creek channel migration and delta progradation. In short, the shell hash layer, much like Unit 2 in general, reflects the unique environmental changes that occurred at the head of the estuary that were not necessarily translated downstream.
5.3. Paleoenvironmental Reconstruction

Previous work has established that LPL formed as sea-level rose during the early Holocene, flooding river mouths up and down the Pacific coast [40]. It is estimated that postglacial sea-level rise slowed between 6000 and 4000 years ago [23,47,76], at which time the rocky, open estuary that is known today as LPL began to infill with sand from littoral drift [48,49], creating Unit 1. This unit was established prior to 3760 cal yrs BP, based on the data from this study, and persisted in some capacity through ~1000 cal yrs BP (Figure 6). Other studies have noted this sandy embayment facies both locally [48] and in other Southern California wetlands [71,72,75]. We see evidence of the initial closing of the embayment within this facies, indicated by increased mud content and decreased fine sand starting at ~3760 cal yrs BP; this is likely due to the same littoral sand transport responsible for infilling the lagoon creating bars/spits across the embayment mouth [48,49]. The partial closure may have allowed for estuarine conditions to be established, but these conditions did not yet dominate the embayment (Figure 7), as indicated by the presence of both marine and brackish bivalves and gastropods (Table 3) in the shell hash layer, dated as recent as ~1700–1500 cal yrs BP.

![Los Peñasquitos Lagoon Timeline](image)

Figure 6. A timeline of Los Peñasquitos Lagoon that includes previous work and the results from this study (MCA—Medieval Climate Anomaly, LIA—Little Ice Age; see text for more details). Data sources for this figure correspond 1 [41], 2 [77], 3 [52], 4 [46], 5 [78], 6 [79], 7 [49], 8 [48], 9 [43], 10 [42].

Until 2750 cal yrs BP, the lagoon was also populated with mangroves [42] and pondweed [41], both of which indicate a wetter climate than what we see in today. This wetter climatic assessment is corroborated regionally throughout Southern California [52,77,78,80]. From ~3000 to 2650 cal yrs BP, regional climate reconstructions identify a shift to drier conditions [52,77,78,80]; however, we do not see an explicit signal of drying conditions in our core data. Cole and Wahl [41] likewise did not identify a shift to overall drier conditions at this time in LPL but instead interpreted a proliferation of grassy pollen as a signal of greater winter/spring moisture availability. However, overall drier conditions and greater winter/spring moisture availability are not necessarily mutually exclusive; several studies have described this overall dry phase as a period of higher...
frequency and higher magnitude ENSO cycles, which can present as increased fluvial discharge and more frequent winter storms without a substantial change in the average annual precipitation [48, 76, 81, 82].

The first environmental transition observed in the cores likely occurred ~1200–1000 cal yrs BP, as the open embayment of Unit 1 was overlain by the fluvial delta facies of Unit 2. The shells deposited below the stratigraphic transition range in ages from ~1700 to 1000 cal yrs BP, whereas the only date for Unit 2 is 1100 cal yrs BP from a piece of unidentifiable plant material. It is more likely that a piece of older plant debris was washed out from further inland during the delta progradation, given the lack of other plant material within and the coarse nature of the unit. We can also use regional climate records to further constrain the timing of this transition. Although the climate around this time was dominantly dry and thus not conducive to the delta progradation of Unit 2, there were two short-lived wet intervals identified by Kirby, Patterson, Lachniet, Noblet, Anderson, Nichols, and Avila [78] at Lake Elsinore (80 km north) from 1500 to 1250 cal yrs BP and 1000 to 900 cal yrs BP. Given the ages, we conclude that it is the latter of these wet intervals that likely drove the change from Unit 1 to Unit 2.

An influx of sediment would be expected during a wet period [82–85], which could explain the sudden creek channel migration, delta progradation, and associated increase in coarse sands. Moreover, the abrupt climate transitions such as extreme wetness following a prolonged dry period have the potential to increase fluvial sediment transport and geomorphic change. Fraticelli [86] attributed mouth bar/beach ridge formation along the Brazos River to floods that followed droughts, rather than the most extreme flood, arguing that the preceding droughts pre-conditioned the watershed and allowed for increased sediment loads. Similarly, Carlin et al. [87] found that event sedimentation along the Gulf of Mexico continental shelf also resulted from drought–flood cycles rather than extreme...
floods alone. Therefore, we believe that the transition to the fluvial deltaic facies of Unit 2 occurred due to increased sediment loads coming from Carmel and Los Peñasquitos Creeks sometime after ~1000 cal yrs BP, following the most recent of two brief wet intervals during an overall dry climate period in the region (Figure 6).

Following this wet interval, from 1050 to 650 cal yrs BP the world experienced what is known as the Medieval Climate Anomaly [88,89]. In Southern California, this climatic event presented itself as a warm period of extended drought caused by a shift in the El Niño Southern Oscillation cycle (ENSO) to a La Niña-like regime [81,90–92]. During La Niña periods, Southern California receives little rainfall and experiences decreased fluvial sedimentation [48,81,82]. For deltaic systems in general, reductions in sediment delivery can drive delta lobe switching and abandonment, e.g., [93,94]. Delta abandonment or retrogradation due to the reduced fluvial supply is likely reflected in the sharp upper contact between Units 2 and 3. This transition possibly represents a period of non-deposition or erosion caused by the climatic shift to a drier La Niña regime, resulting in the erosion of Unit 2’s delta facies. This erosional surface was then overlain by immature marsh deposits as the sediment may have been redistributed away from the delta toward other areas of the lagoon, further facilitating infilling throughout the lagoon.

Sometime after 830 cal yrs BP, near the conclusion of the Medieval Climate Anomaly, LPL was approaching the transition from an immature marsh (Unit 3) to a mature marsh (Unit 4). The primary changes between these two units are finer-grained sediments and increased vegetation. This transition from Unit 3 to Unit 4 may have been the result of a subsequent climatic shift; however, we cannot be certain of this given that we did not constrain the date of this transition. Directly following the Medieval Climate Anomaly was the Little Ice Age, a cooler and wetter period that lasted from ~500 to 100 cal yrs BP [88], characterized by more El Niño-like conditions [48,78,81,91,92,95]. The shift to a wetter climate would have increased sediment delivery to the lagoon again, increasing elevations, which in turn facilitated plant colonization and the transition from an immature to a mature marsh. Previous work by Heusser, Hendy, and Barron [92] noted an increase in pollen flux during the early Little Ice Age in the Santa Barbara Basin (~300 km north of LPL), indicating an expansion in vegetation along the Southern California coast during this time.

Within Unit 3 in core LPL03, there is a brief shift to Unit 4 and then back to Unit 3, which may reflect local-scale changes such as migrations in the tidal channel; however, for both LPL03 and LPL04, there was a shift back to Unit 3 at the top of the cores. Without constraining the date of this transition in the cores, it is difficult to determine the actual driver as there are multiple possibilities. This shift could be the result of the post Little Ice Age shift to a more arid climate in Southern California [96,97]; however, a similar shift is not seen at LPL07, so a broader climate driver seems unlikely. Another contributing factor for the transition back into Unit 3 in the central lagoon could be modern urbanization, which would have preferentially affected the central lagoon relative to the upper lagoon where LPL07 is located. By CE 1925, a road was constructed across the tidal inlet, and a railroad was built through the center of the salt marsh [40]. Cole and Wahl [41] identified a mudflat expansion following these two developments; therefore, these anthropogenic factors combined with a progressively drier climate conditions may have triggered the return to an immature marsh or mudflat environment for areas within the lagoon.

In summary, through the last ~4000 years, we identified four major environmental shifts triggered primarily by climate events in LPL. First, the transition from an open embayment to a fluvial delta occurred following a dry to wet climatic cycle after ~1000 cal yrs BP. This shift was restricted to the head of the lagoon as the central areas of the lagoon maintained the open embayment characteristics. The return to warmer and drier conditions during the Medieval Climate Anomaly (1050–650 cal yrs BP) led to a period of non-deposition/erosion of the deltas at the head of the lagoon, and the continued infilling resulted in the development of an immature marsh throughout the lagoon. The shift back to wetter conditions in the Little Ice Age (500–100 cal yrs BP) may have led to the transition to a mature marsh as increased sediment delivery contributed to increased elevation and
therefore vegetation expansion. The final environmental shift is only observed within the central area of the lagoon, as a return to immature marsh that might have been triggered by the onset of Southern California’s modern arid climate and urban development in the surrounding area. It should be noted that these last two transitions are not well constrained with sediment ages and therefore are only speculations. Further study would be needed to better characterize the drivers for these environmental shifts. Collectively, however, from these results we can conclude that the environmental conditions of LPL have been highly influenced by both global and regional climate patterns and more recently human activities.

5.4. Implications for Restoration and Conservation

The initial motivation for this study was to understand the origin of the shell hash deposit in core LPL07. The shell hash layer contains two whole *Ostrea lurida* shells: a species native solely to the North American Pacific coast [45]. These oysters once inhabited a wide swath of land ranging from southern Alaska to Baja California del Sur but are now confined to sporadic assemblages between British Columbia and Baja California [38], due primarily to anthropogenic activity in coastal environments, such as overfishing and urban development [37,45,98]. Through this study, we have identified that the oyster habitat loss in LPL likely pre-dated significant human alterations to the system and was instead due to an abrupt but natural sedimentological change triggered by a climatic shift that resulted in increased sedimentation and shoreline/delta progradation at ~1200 cal yrs BP. Although this transition to a fluvial delta was localized near the creek mouths, the subsequent lagoonal infilling as the climate again shifted to a drier regime was system wide. The closing of the lagoon mouth likely amplified the infilling, even if sediment inputs were reduced due to overall drier conditions. After the lagoon infilled with sediment from the fluvial delta facies, the open embayment environment that had persisted through at least 3760–1200 cal yrs BP was unable to recover at any of our three core sites.

Although much of the loss of the *Ostrea lurida* habitat was likely natural, we do see evidence in our data that anthropogenic activity has more recently altered the natural development of LPL. We attributed the shift from mature marsh back to immature marsh to be, at least partially, due to development in and around the lagoon, beginning in the early 20th century, that also resulted in mudflat expansion throughout the lagoon [41]. In this sense, we see that wetland/estuarine habitats are susceptible to environmental changes driven by both natural and anthropogenic forces. Therefore, future restoration efforts for coastal wetland environments and *Ostrea lurida* habitats alike must consider both natural variability and anthropogenic influences.

6. Conclusions

The primary goal of this study was to elucidate the processes and events that can drive the shift from an open bay estuary to a salt marsh in Southern California. Gaining new insight into natural environmental transitions can inform regional efforts to restore and manage coastal wetlands. For this study, we investigated the geologically recent sedimentological history of LPL in Southern California. We created a detailed stratigraphic profile of three sediment cores using grain size and total organic matter as paleoenvironmental indicators and investigated the condition of a shell hash layer to gain further insight into the ecosystem changes experienced over the last ~4000 years.

Our study revealed four distinct environmental facies: open embayment, fluvial delta, immature marsh, and mature marsh. The open embayment facies were established prior to 3760 cal yrs BP and persisted until ~1000 cal yrs BP. When we saw a transition to the fluvial delta that was triggered by a wet period that lasted from 1200 to 1050 cal yrs BP. Fluvial deltaic deposition ceased as the wet period ended and drier conditions returned, causing subaerial exposure and delta regression. An immature marsh facies was deposited on top of the fluvial delta, representing the system-wide infilling during the Medieval Climate Anomaly. In the past several centuries, the immature marsh developed into a mature, vegetated marsh throughout much of the lagoon.
Though global and regional climatic shifts initially drove the development of each facies, we saw a return to immature marsh in our two cores located in the middle of the lagoon, which was initiated by anthropogenic development. Thus, it is imperative that future restoration efforts consider both the natural climatic variability and anthropogenic influences to effectively preserve coastal wetlands.

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