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Investigating the Geochemical Trends at the Sediment-Water Interface of the Shallow and
Eutrophic Utah Lake

Abidemi Sherif Aremu

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

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ABSTRACT

Investigating the Geochemical Trends at the Sediment-Water Interface of the Shallow and Eutrophic Utah Lake

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Master of Science

The sources of phosphorus (P) in Utah Lake can be diverse, including natural and anthropogenic point and non-point sources, such as atmospheric deposition, soil erosion, and industrial and urban wastewater effluents. This study collected interface sediments, column water, porewater, and sediment cores across this vast water body. These samples were then analyzed for their mineralogic, organic, and elemental composition to characterize the geochemical nature of water and sediment at the water-sediment interface within Utah Lake. The average concentrations of P and other elements found in the column water of an individual site do not significantly differ across depth suggesting Utah Lake to be well mixed vertically. Furthermore, most sites share similar water column P concentrations, excluding Provo Bay. Water column and pore water sampled with high spatial resolution reveal the redox potential shifts rapidly from oxidizing (+200mV) in the bottom water column to reducing (-100mV) in the porewater within 10 cm below the sediment surface. The influence of reducing conditions on oxidation state within the sediment is an important finding related to phosphate retention in the sediment of Utah Lake. The abundance of reducing conditions in the sediment, even at the shallow depths, suggests that redox sensitive minerals and metals (particularly Fe) are not a stable sink for phosphorus in the sediments. Averaging across all sites within the lake, excluding PB, the porewater conductivity decreased with increasing depth, with a defined shift at the water column-sediment porewater interface. The porewater pH was consistently less (6.5) than the lake water near the top of the water column (8.5). These findings will improve our fundamental understanding of geochemical cycling in shallow eutrophic lakes and be used to enhance the quality of water models that will be used to manage Utah Lake better.

Keywords: Utah Lake, eutrophication, total phosphorous, cycling, retention, release, binding, algal blooms, sediments, porewater, mineralogy, carbonate, redox, pH, conductivity, geochemistry, major and trace elements, sediment geochemistry

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1 Introduction

Lakes are subject to many influences, but the one that has received the most attention is the impact of eutrophication. Lake eutrophication is a serious environmental problem affecting water bodies worldwide. Excessive phosphorus (P) in water is recognized as the limiting nutrient, with excess P leading to eutrophication in freshwater, resulting from increased primary production (the algal and bacterial growth) and subsequent depletion of dissolved oxygen (Saha et al., 2008). Utah Lake has received widespread attention for its recurring algal blooms and associated closures (Penrod, 2016; Donaldson, 2020). Increasing evidence has shown that the internal cycling of nutrients in shallow lakes may be one of the main factors maintaining eutrophication and preventing improvements in water quality (Jeppesen et al., 2005). Typically, the primary P sources in lakes are external and non-point sources such as industrial and agricultural runoff, stormwater drains and rivers, rainfall, soil leaching, and urban effluents. Total P inflows to Utah Lake include streams, wastewater treatment plants (WWTPs), overland flow, P-rich lakebed sediment, atmospheric deposition (dust), and surface water and ground water tributaries.

Much effort has been made to reduce the external loading of phosphorus to reverse the eutrophication of lakes. Some lakes respond rapidly to such reductions (Sas, 1989), but a delay in lake recovery is often seen (Marsden, 1989; Jeppesen et al., 1991; van der Molen & Boers, 1994), one of the reasons being that phosphorus accumulated in the sediment during the period of high loading needs time to equilibrate with the new loading level. Phosphorus release from the sediment into the lake water may be so intense and persistent that it prevents water quality improvement for a considerable period after the loading reduction (Granéli, 1999; Scharf, 1999).

Utah Lake has high P inflow loading on the order of 300 tons/year, with an estimated 80% of this total, 188.8 tons/year, from wastewater treatment plants (WWTPs). Two WWTPs, Provo City and Orem City, are estimated to contribute 71.6 and 79.3 tons/year, respectively, or approximately 50% of the total annual P load. The estimated Utah Lake outfalls of P are only 85 tons/year (PSOMAS, 2007; UDWQ, 2016), indicating the lake acts as a P sink. Phosphorous sediment-water interaction is complicated and governed by different processes depending on the lake and chemical composition (Søndergaard et al., 2003). Sediment parameters that affect P partitioning between the water column and the sediment include sediment bulk density, organic matter content, and mineral content, along with the concentration of other elements with the capacity to bind and release P. Water parameters that affect P partitioning include pH, reduction potential (Eh or pE), total dissolved solids, and others. Release mechanisms are governed by parameters such as Fe:P ratio, reduction-oxidation (redox) conditions, resuspension, turbidity, biological activity, microbial processes, temperature, and pH (Mayer et al., 1980)

Water and sediment play an essential role in a lake system in the P cycle. Lake sediments act as temporary or permanent sinks for settling P and play a vital role in the internal P cycle (Hupfer & Lewandowski, 2005). A high release of P is, in general, attributed to anaerobic conditions in water and excessive P accumulation in lake sediments (Mortimer, 1971; Nürnberg, 1988; Sondergaard et al., 2003; Christophoridis & Fytianos, 2006). Processes leading to P release to the water column from underlying sediments are numerous and include the desorption and dissolution of P bound in precipitates and inorganic materials (Mortimer 1941, 1942; Moore & Reddy, 1994), microbial mineralization of organic matter (Gächter & Meyer, 1993), and the diffusion of dissolved P from sediment porewaters (Boström et al., 1988; Moore et al., 1998; Pettersson, 1998). However, the processes governing P release from sediments are highly

complex and include redox reactions, adsorption, mineral phase solubility, Dissolved oxygen (DO), nitrates, sulfates, pH, microbial activity, temperature, and salinity are the major controlling parameters (Caraco et al., 1993; Gächter & Meyer, 1993; Kleeberg & Dudel, 1997; House & Denison, 2000; Kaiserli et al., 2002).

Utah Lake (Fig. 1) is surrounded by urban centers and a population of >630,000 people now living in its watershed (US Census Bureau 2019; Williams, 2021). Utah Lake is an algae-dominated lake with significant anthropogenic sources of P loading from WWTPs, industrial discharges, and agricultural and stormwater runoff. As such, this area has been recognized as a highly eutrophic embayment and an ideal location to study P cycling particularly the geochemical trends and processes at the sediment-water interface that may be driving nutrient concentrations. This study collected interface sediments, pore water, and sediment cores. They were then analyzed for their mineralogical, elemental, organic, isotopic, and structural content to fully characterize the geochemical nature of Utah Lake's water and sediment.

Several studies have been conducted to understand the principles of phosphorus retention and release at the sediment-water interface. A detailed discussion can be found in Boström et al. (1982) (1988). Since then, numerous modern papers on this subject have been published, symposiums have been organized, and many research and theses deal with this subject. Horns (2005) measured nutrient levels at inflows into the lake, including treated inflows from anthropogenic sources. They illustrated a correlation between the high nutrient levels of Utah Lake inflows being directly affected by anthropogenic sources such as wastewater treatment plants (WWTPs) and stormwater runoff. Randall (2019) also showed that the highest levels of phosphorus are concentrated on the east side of Utah Lake, which is near the highest human population centers in Utah Valley and WWTP inflows. Randall noted that P concentrations in the

Utah Lake water column are likely governed by sediment P sources rather than by inflows into the lake. In terms of implications for loading from wastewater treatment plants (WWTPs), the improvement of Utah Lake water quality may be delayed in response to decreasing external loading and ambient concentrations because of internal recycling of P (Hogsett et al., 2019; Randall et al., 2019). Also, with increased loadings, Utah Lake may act as a self-cleaning system to remove P from the water column by mineral precipitation with calcite (Brimhall & Merritt, 1981; Hogsett et al., 2019; Randall et al., 2019). Aside from these studies done on ecological aspects of Utah Lake, research related to geochemistry and speciation studies of nutrients of P of the lake surface and core sediment is rare. Considering the importance of Phosphorus (P), which plays a significant role in the nutrient dynamics of the lake ecosystem, it was planned to study the P fractions in the sediment core and overlying surface water with their geochemical properties and evaluate the ecological risk of the lake concerning P.

Estimating total phosphorus (TP) in the sediment-water interface provides essential information about its enrichment. The association of P with different elements such as Fe, Ca, Al, and organic matter also plays a vital role in regulating the P cycle in the lake ecosystem (Sundereshwar & Morris, 1999). Consequently, it is crucial to do speciation studies to identify and quantify the different forms of P at the sediment-water interface to gain a more precise understanding of the potential and actual effects of its elevated levels and to evaluate processes of transport, deposition, and release under changing environmental conditions such as temperature, pH, redox potential (ORP), dissolved oxygen (DO), and hydrological conditions, as well as biological activity. This study will help us to understand the P geochemistry, impacts of the chemical composition, and the trophic level of aquatic systems, particularly in shallow eutrophic lakes and coastal marine environments.

2 Methods

2.1 Site Description

Utah Lake is an ideal location to investigate lakebed-water column P geochemical interactions in shallow lakes. Utah Lake lies in Utah Valley, surrounded by three mountain ranges, the Wasatch Range to the east, the Traverse Range to the north, and the Lake Mountains to the west. Utah County has a population of more than 600,000 as of 2017 and is continually experiencing rapid population growth with an estimated 2.4% yearly increase (US Census Bureau, 2019). Utah Lake is, by surface area, the largest natural freshwater lake in the United States West of the Mississippi River. It covers an area of approximately 390 square kilometers and is 23 miles (37 km) long and 13 miles (21 km) wide. Utah Lake is a remnant of Lake Bonneville, originating 8,000 years ago. The Lake is a shallow, turbid, and slightly saline eutrophic lake averaging only 2.7 m deep. Over millions of years, thousands of feet of mineral-rich sediment have accumulated on the lakebed contributing to its shallow condition and naturally muddy and cloudy appearance. The main morphological and limnological characteristics of Utah Lake are summarized in Table 1.

The lake is fed by several rivers draining the Wasatch front and several large underwater springs. The primary feeder rivers include the Provo River, American Fork River, Spanish Fork River, Hobble Creek, and Currant Creek. In turn, it feeds the Jordan River, which dumps into a canal system supporting the Great Salt Lake. Evaporation plays a significant role in the hydrology of Utah Lake, as almost 41 percent of its water is lost due to evaporation each year (Abu-Hmeidan et al., 2018). The lake's water is heavily influenced by the snowfall Utah's mountains receive, producing nearly 98 percent of its inflow. The Lake's level is also affected by the amount of water taken from it and its tributaries for municipal and irrigation uses. The principal constituent of its sediment is the mineral calcite (calcium carbonate, CaCO_3). The lake

bottom is predominantly mud and organic silt with limited stretches of gravel along the Western and Southeastern shorelines.

The lake has been home to millions of plants and birds and has been a treasured food source for over a century. It provides various recreational activities, from boating and fishing to skiing and paddle boarding. However, at the end of the twentieth century and the beginning of the twenty-first century, sewage and industrial wastewater were discharged directly into the lake, resulting in excess nutrient loading and subsequent eutrophication, which has been detrimental to the lake's health. As a result, the water environment is extremely sensitive to phosphorus loads, and the excessive concentration of these nutrients contributes to the formation of harmful algal blooms (HABs), and such algal blooms also restrict agricultural usage of the lake water. Despite being a vital natural and economic resource, the lake has long been considered an impaired waterbody.

Seven representative sites were selected as research zones to represent spatial and temporal variability across Utah Lake (Fig. 1). Sediment cores, porewater, column water, and interface sediment were collected across this vast body of water.

2.2 Sediment

2.2.1 Sediment Core Collection

Seven soft sediment cores were collected from the designated research sites across Utah Lake via freeze coring (Fig.1; Table 2). Freeze coring of sediment, i.e., freezing sediment in situ at the lake bottom, helps take samples of soft surface sediment aimed for detailed stratigraphic analyses. This method ensures a careful recovery of loose, watery surface sediments by in situ freezing, resulting in well-preserved samples without compaction or distortion of sedimentary structures,

porewater recovery, and in situ porosity. All cores were obtained in August 2021. The frozen core was collected using a sampler described by (Renberg, 1981). The essential part of the crust freeze sampler is a wedge-shaped aluminum casing that is 100 cm long, 10cm wide at the bottom, and 11cm (square)at the top. This wedge is filled with dry ice and ethanol and lowered into the lakebed (to refusal in this study, 44 to 100 cm), which freezes like a crust on the outside of the sampler. After freezing, the sampler is hauled up, and the frozen sediment is melted free from the sampler casing by gradually scraping the edges. Finally, the frozen sample is carefully wrapped with foil, labeled with number, location, and date, and transported on dry ice to Brigham Young University (BYU) Geology Department and stored in the dark at -20 °C for further processing and analysis.

A total of two large slabs of frozen sediment cores were collected at each sampling depth to unique depths (between 44 and 100 cm) based on when the corer hit substrate refusal. The sediment core was sawed longitudinally into sub-samples (cuboids), 1cm x1cm x7cm; the 1 cm increment cuboids were cut to the core's terminal depth. This was done manually with a band saw inside a cold room where the temperature was maintained at -10 to -20° C. Care was taken not to break the frozen cores. The sectioned sediment cores were used for analysis as described below.

2.2.2 Bulk Density of Sediment Cores

Bulk density (BD) helps us know how much sediment mass occupies a given volume. This helps us to know how much pore volume our sediment has. BD provides information about the water storage capacity, structural conditions, and compactness of the sediment. This knowledge is used heavily in modeling. The bulk density of Utah Lake sediment depends on how well the sediment is compacted, how large the pore spaces are, how much organic material is present, and how much moisture is present.

The BD of the undisturbed unfrozen sediment cores collected using freeze coring technique was sectioned into 1 cm incremental subsamples and allowed to thaw. One of the analyses conducted on the samples was dry bulk density determination. We determined dry bulk density by two separate methods such as frozen core subsections (“Cuboid method”) and the other using graduated syringes to determine the initial wet volume of a core subsection (“Syringe method”). Both methods have been used successfully in the past. Our objective in using both methods was to validate comparison of data collected via either method.

The formular we used in calculating the BD was the measurement of the wet volume and weight of the sediment cores. The wet sediment cores were calculated after thawing by dividing the weight of the frozen sediment.

$$Pd = \frac{Ms}{V}$$

Where Pd (g/cc) is bulk density, Ms is the dry mass (g), and V is the wet volume (mL or cc). The sectioned sediment cores were weighed and measured before freeze-drying for further geochemical and isotopic analysis.

2.2.3 Sediment Total Elemental Concentrations

In order to determine the form of P and other elements such as Calcium (Ca), Iron (Fe), Aluminum (Al), Magnesium (Mg), and Silica (Si) in the sediment, a series of analyses were conducted. These include sediment digestion to determine the total P in the sediment. A particular focus is given to the sediment-water interface. We used this aqua regia digestion (US EPA 2007) (EPA Method 3051B) by briefly, 0.5g of the freeze-dried sediment was accurately weighed, and an acid mixture of 3 ml of Hydrochloric acid (HCl) and 9 ml of nitric acid was added and placed

in a CEM Mars 6 microwave unit for 10 minutes to digest, with 5.5 minutes to ramp up to 175°C and then it holds for 4.5 minutes. It then cools for about 15 minutes. After completion of the digestion, the vessel was cooled to room temperature, uncapped the digested sediment was centrifuged at 800 rpm for 10 min and then diluted with deionized water in a 15 ml centrifuge tube and analyzed in a ThermoFisher iCAP 7400 Duo ICP-OES instrument. The ICP-OES analyses were undertaken to characterize the lake sediment for major and minor total elemental abundances (i.e., total elemental phosphorus).

2.2.4 Minerals by X-Ray Diffraction (XRD)

In order to determine the form of phosphorus in the sediment, a series of analyses were conducted. These included sediment mineralogy with a particular focus of mineral identification and quantification analyses using powder X-ray diffraction (XRD) at Brigham Young University (BYU) with a Rigaku Miniflex 600 equipped with a scintillation detector and graphite monochromator. The XRD analysis was conducted directly on the freeze-dried, disaggregated samples at a selected depth that best represent the surface of the sediment cores across our sampling sites (e.g., 0-1cm, 1-2cm, 2-3cm, 4-5cm, 9-10cm, 29-30cm & 39-40cm). Briefly, powder of each depth was pressed into a 1.3 cm-diameter sample plexiglass holder with a thickness of 1mm. Mineralogic abundances were quantified via the Rigaku PDXL 2 software using a Rietveld structure refinement method (e.g., Bish & Post, 1993).

2.3 Porewater Geochemistry

2.3.1 Freeze core sediment pore water

Porewater was extracted from the freeze core in 1 cm increments by thawing the cuboid and then separating them into sub-samples to fit a 50 ml centrifuge tube. Porewater was filtered and extracted from the thawed freeze core subsamples by placing a 0.45 μm nylon filter into a 50 mL centrifuge tube; at the same time, the remaining lake water was also separated into another 15 mL tube by filtering, and an acid mixture of 200 μL of trace metal grade (TMG) nitric acid was added and placed in an Eppendorf centrifuge 5920R instrument (3000 rpm, 15 min) and stored in a refrigerator until analysis. The non-acidified samples were analyzed using Dionex ICS-90 Ion Chromatography System immediately. The acidified samples were stored in the refrigerator and later analyzed using a ThermoFisher iCAP 7400 Duo ICP-OES instrument. The ICP-OES method was applied to determine element concentrations in the pore water fraction.

The yield of the porewater extraction was determined by weight difference before and after centrifugation which helped us to determine the sediment's percent (%) water content. In shallow lakes, as in the case of Utah Lake, the whole water column is usually oxic; thus, an oxic surface layer of the sediment is created with a high capability to bind with P (Søndergaard et al., 2003). Since redox conditions were oxic for most samples, no special measures were taken to avoid oxidation.

2.3.2 In-situ sediment pore water

In order to understand how P is distributed across the water column-sediment interface, porewater was collected in situ using modified equilibration dialyzers, or “peepers,” using a design like that of (Johnston et al., 2009). Peepers are used for collecting porewater from shallow aquatic

environments such as lakes. Similarly, peeper cells were filled with deionized water, overlain with a 0.45 mm nylon membrane filter. In the field, the peepers are pushed into the sediment, from 5–10 cm above the sediment-water interface and at 5 cm intervals down to approximately 60 cm into the sediment. Solutes from porewater in contact with the filter diffuse into the cells such that, after equilibrium is reached, concentrations inside each cell equal those at the corresponding depth in the porewater. This porewater equilibration dialysis device was selected to capture the full geochemical transition zone from surface water to interfacial sediment porewater (within the active mixing zone) to deep sediment porewater (below the active mixing zone). Additionally, this method collects a larger sample volume, which limits the amount of sample dilution and complicated sample preservation methods. The peepers were installed at 0 – 5cm depth into the sediment at each of the seven sampling locations during the summer of 2022. Each peeper was given at least three weeks to equilibration following installation and before sample collection. It is of note that early sampling periods (May 2022) were shorter (21 days) and that this may not have been enough time for the sampling cell to reach equilibration and therefore the later sampling periods were deployed longer (35 + days) to allow the cell to equilibrate.

Two to six weeks were allowed for equilibration, allowing time for dissolved constituents in the sediment porewater to equilibrate with the water inside the cells. The membrane filter helps maintain sample integrity during recovery until sample processing, immediately upon retrieval from the lake. The peepers were transported to Brigham Young University (BYU) Environmental Geochemistry Lab, and the individual cells were immediately sampled by withdrawing their contents with syringes into a 15 mL centrifuge tube. The sample was measured for pH, redox (ORP), and conductivity then placed in the freezer until further analysis.

2.4 Geochemical Analysis

Porewater samples were analyzed for orthophosphate and anion concentrations (Cl^- , NO_3^- , PO_4^{3+} , SO_4^{2-}) using Dionex ICS-90 Ion Chromatograph (IC, Thermo Scientific Dionex Chromatography). Total elemental concentrations (P, Ca, Fe, Mg, Al, Si, Mn, K, Pb, As, Ba, Cd, Co, Zn, Cr) for porewater samples were determined by diluting 1x10 dilution and for the digested sediment samples by diluting 1x50 dilution respectively using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES).

Furthermore, the freeze-dried sediment samples were disaggregated in an agate mortar, and pestle, then passed through a 60-mm mesh sieve. They were then analyzed with respect to mineralogical content, sediment morphology, chemical composition, and C/N isotope ratio. A summary of the analytical methods used in this study is shown in Table 3.

3 Results

3.1 Utah Lake Sediment Geochemistry (Bulk Sediment)

3.1.1 Physiochemical Parameters of Utah Lake Sediment

Overall, sediment pH varied between 7.69 to 8.04, indicating circumneutral to alkaline, which might be related to high CCE (Calcium carbonate equivalence) in carbonate-rich sediments in the lake. However, in the sediment of eutrophic lakes, photosynthetically elevated pH can increase the amount of P, which is loosely sorbed to iron, and this increases release rates (Lijklema, 1976; Sondergaard, 1988; Welch & Cooke, 1995; Istvanovics & Petterssen, 1998). pH is particularly important in lake sediments because the P binding capacity of the oxygenated

sediment layer decreases with increasing pH as hydroxyl ions compete with P ions (Lijklema, 1976).

3.1.2 Observation of Elemental Concentration

On average, the total phosphorous (TP) level was highest in the surface sediment at a depth between 4cm and 18 cm and sharply decreased with depth, indicating lower P enrichment in those areas. The TP level was higher in the surface sediment at Provo Bay, which appears to be the most phosphorus rich caused by the heavy nutrient load introduced by wastewater effluents and runoff from storm waters. This is vital to the overall quality of Utah Lake water because over 40% of the surface water entering the lake does so through Provo Bay. In contrast, the West of Vineyard site had lower P concentrations.

These results indicate that Utah Lake is acting as a phosphorus sink for anthropogenic phosphorus, and the decrease in P concentrations in the core may have been linked to calcite scavenging of P from the water column.

3.2 Depth-Resolved Sediment Cores

3.2.1 Sediment Bulk Density

Sediment bulk density was determined by two methods: syringe volume determination and cuboid volume determination. We calculated depth-resolved dry bulk density, measuring mass per saturated total volume of the frozen core sediment in 1cm intervals. Both bulk density methods provided similar insights into the trends of bulk density of the sediments in Utah Lake. Generally, bulk density increased with increasing depth (Fig. 2). Both methods also show site-specific deviation from the general trend decreases in Goshen Bay (GB) sediment density at 45 cmbs and decreases in Provo Bay (PB) sediment density at 25 cmbs.

Across all samples and all depths, the bulk sediment density ranged from a minimum of 0.2 to a maximum of 1.7 g/cc, using the syringe method (Select data, Table 4). Conversely, the cuboid method determined bulk densities (BD) to range from a minimum of 0 to a maximum of 1.3 g/cc. Table 4 shows the calculations of the bulk density of the mass of sediments. The syringe method of the average bulk density across all locations ranges from 0.8 g/cc to 0.9 g/cc, and the cuboid method average ranges from 0.6 g/cc to 0.7 g/cc, respectively. (Select data, Table 4), The wet sample density generally increased, and dry weight decreased at various sampling depths, reflecting a decreasing void space at depth intervals.

Conversely, both method's average bulk densities were 0.8 g/cc (cuboid) and 1 g/cc (syringe) at Provo Bay and 0.7 g/cc (cuboid) at Pelican Point, respectively, having the highest value on the lake. Notice that vertical density fluctuations are small but not uniform for both methods. These bands of increased variability may be evidence of sediment lamination resulting from storm events, which also shows that sediment from Provo Bay has less total pore space, which reflects on the relatively high bulk is evident as sampling depth increases, bulk density typically increases.

3.3 Elemental and Trace Metal Concentrations

The general characteristics of the sediment are presented in Table 5. The elemental composition of the surface sediment is given in Fig. 4. Spatially, the TP concentration in the sediment was generally high on average across the lake sites with an average of 0.07 mg/kg, which indicates that the lake sediment has a great potential to supply phosphorus to the overlying water.

3.3.1 Total Phosphorus

The maximum values of the TP were observed in the sediment at Provo Bay, with a maximum value of 1.17 mg/kg (Fig. 4), which is in a district with a high density of population and Industry. Therefore, the phosphorus content was likely affected by human activities. The TP level was highest in the surface sediment format at a depth between 4cm and 18 cm and sharply decreased depth, indicating lower P enrichment in those areas. These results indicate that Utah Lake is acting as a P sink for anthropogenic P, and the decrease in P concentrations in the core may have been linked to calcite scavenging of P from the water column.

3.3.2 Calcium

As shown in Fig. 4, the contents of Ca in the sediment varied. The average Calcium concentration ranges from 10% to 21%. The highest concentration is in the West of Vineyard; the second lies in Saratoga Springs, while little was found in Provo Bay. High concentrations of calcite sediment are found throughout the central part of the lake, with the highest concentration in the north and south parts of the lake (Sonerholm, 1974).

Generally, Utah lake's calcium carbonate (CaCO_3) accounts for more than 70% due to calcium being transported to the lake by surface and subsurface waters from the surrounding mountains and bedrock beneath the lake composed of limestones (Horns, 2005). The high concentration of calcite found in the sediment core may be as a result of the large amount of organic matter in the sediment that is present in the sampling area.

3.3.3 Silica (Si)

The distribution of silica varies across depth in the sampling locations, with the maximum value at 11.8% in Provo Bay (Table 8). Provo Bay has a unique depositional environment

compared to the open water portions of the lake, leading to its unique silica signature comparatively. This increased silica concentration corresponds to sand layers within the sediment that can often lead to coring refusal at more shallow depths than the rest of the lake. Silica can take several forms in the lake sediment, including quartz, SiO₂, or hydrated and amorphous forms of different microorganisms (Mortimer, 1941). Lake sediment has high concentrations of quartz due to the tributary of the major rivers that flow into the lake, and wave action tends to deposit detrital minerals near the shore.

3.3.4 Iron (Fe), Aluminum (Al), and Magnesium (Mg)

The concentrations of iron (Fe), Magnesium (Mg), and Aluminum (Al) in sediments of Utah Lake varies across the lake and with depth (Fig. 5 and Table 8). The average values range from 0.6% to 0.9% for Fe concentrations. While Al's average content ranges from 0.3% to 0.6%, the highest average for Mg concentration is 9.5% at Goshen Bay. Iron and Mn are of particular interest regarding P dynamics because these metals are redox sensitive. Einsele (1936) and Mortimer (1941) described how redox-sensitive Fe dynamics influence P release from sediment: in reducing conditions, iron (III) is reduced to iron (II), and both any Fe-bound P is then released into solution.

3.4 X-Ray Diffraction (Mineralogy)

X-ray diffraction was used to determine the mineralogy of crystalline phases of all samples for which there was adequate crystalline sediment for analysis. Samples were selected within the top (0-1cm, 1-2cm, 2-3 cm, 4-5 cm & 9-10 cm) and mid (29-30 cm, and 39-40 cm) part of the sediment-water interface as shown in Fig. 6a & Table 6)

The mineralogy of subsamples was dominated by calcite at about 67.8%, followed by quartz and Al-clay (illite). Quartz was observed to dominate in Provo Bay (PB) compared to the rest of the sites, with a maximum of 51.1% and an average of 43% (Fig. 6a) West of Vineyard had the most calcite, with 70.5% compared to the rest of the locations, and was comprised of 12.34% quartz (Fig. 6a, Table 6), which suggests that endogenic minerals dominate sediment.

A few subsamples found only a small amount of montmorillonite, chlorite, and tremolite. Dolomite, kaolinite and anorthoclase feldspar were observed in most subsamples. However, subsamples from Bird Island and Provo Bay possessed high clay mineral content (illite, montmorillonite, and kaolinite). Anorthoclase feldspar appeared in varying percentages in all study subsamples and the maximum was found in Provo Bay (24%, 4-5 cm).

Calcite, quartz, illite, and dolomite was present in all sediment samples at relatively high concentrations. Simultaneously, montmorillonite was found only in a few sediment samples. There were no clear trends of mineralogic shifts with depth that held true for all sites, demonstrating the heterogeneous nature of the lakebed of Utah Lake.

3.5 Utah Lake Water Chemistry

3.5.1 Water Column

The temperature, pH, electrical conductivity, and dissolved oxygen (DO) were routinely measured during sediment-water interface sampling using YSI multiparameter probe alongside freeze coring. Table 7 shows the real-time physiochemical parameters measured in the field during water column and sediment sampling. The physicochemical properties of the overlying water at the seven sites of Utah Lake are summarized in Table 7, Fig. 7

The temperature of the water samples at the point of the collection ranges from 16.5 °C to 71.4 °C for surface water, 16.2 °C to 20.8 °C the middle (sediment-water interface), and 16.1 °C to 20.8 °C in the bottom water. The Saratoga Springs shows the lowest temperature of 16.1 °C, and the West of Vineyard site shows the highest temperature of 71.4 °C. In Table 9, The surface water temperature in this study average is 28.3 °C, the median water temperature averages 19.6 +/- 20, and the bottom water temperature averages 19.5 =/- 20 °C. Dissolved Oxygen (DO) concentrations ranged from 68.4429 mg/L to 102.1429 mg/L. The DO value of Provo Marina was noticeably higher than those of other locations, which might be presumed to be the photosynthesis of the abundant aquatic plants in that area. Dissolved Oxygen (DO) and temperature were inversely correlated in all sampling sites. Measured DO concentration was lower in high temperatures, and the depletion of oxygen levels in these sites could be the influence of microbial activities and reduced oxygen gas solubility supported by the warmer temperature.

Moreover, when the water temperature becomes high, the DO holding capacity of water decreases due to rapid saturation. Electrical Conductivity (EC) at surface water in Utah Lake consistently varied between 96.1 us/cm and 2157 us/cm. The lowest conductivity value was measured at the site of Pelican Point, and the highest EC value was found at the Provo Marina site. It was observed that the average pH of the water sample varied between 8.4 to 8.7 but did not fluctuate drastically across sampling sites, indicating slightly alkaline to medium alkaline.

3.5.2 Porewater Concentration

Porewater concentration from the peepers is provided in Table 8. The table includes the highest values recorded at each sample site, the lowest value recorded, and the average and standard deviation values.

3.5.2.1 Porewater Phosphorus (P) Concentrations

Phosphorus (P) concentration varied throughout the lake ranging from the maximum value of 13.8516 ppm to a minimum value of 0.8344 ppm at the sediment-water interface. It increased with depth for the first 0 to 20cm (Fig. 7). Provo Bay shows the highest concentration for P concentrations, with an average of 3.1167 ppm and the highest standard deviation of 4.7014 ppm. The reason for the high P levels is due to direct point and non-point discharges, higher productivity, agricultural impacts (including irrigations and stock watering), and wastewater treatment plant (WWTP), which is expected that this area should have elevated phosphorus. No data is available for some major element concentration at some depth across all locations by ICP-OES because it fell below the detection limit.

The results show that the rest of the locations' average phosphorus (P) have similar averages, and the low level in P concentrations of these porewater samples might be attributed to groundwater removing the water-soluble, salt-extractable, and Iron-sorbed phosphorus fraction. The major ions measured include calcium, Iron, Magnesium, Aluminum, Sodium, Bicarbonate, Chloride, and Sulfate. Sources of these dissolved ions may include tributary streams flowing into the lake and lake-bottom mineral springs.

3.5.2.2 Porewater Calcium (Ca^{2+}) and Magnesium (Mg) Concentrations

Major element concentrations of the porewater as measured by the ICP-OES show that porewater is more dominated by calcium carbonate $CaCO_3$, or the common mineral calcite and magnesium (Fig. 8), which is a result of calcite being dissolved from limestone by the surrounding valleys and mountains into the lake. Calcite is the predominant mineral across all sampling sites in the lake. Ca^{2+} concentrations increase with increasing depth from 17.742 mg/L to 173.4 mg/L in the water column to a depth of 50cm at Provo Bay (Fig. 11), and the Mg maximum value is 157.794 mg/L. The increase in both concentrations may be attributed to the production of CO_2 resulting from organic matter degradation and carbonate minerals dissolution (Emerson & Widmer, 1978). Calcite is likely binding with P at high pH, pulling them from the water column and trapping both in the sediment.

3.5.2.3 Porewater Iron (Fe^{2+}), Silica (Si) & Aluminum (Al) Concentrations

Porewater Fe^{2+} concentration is high in Provo Bay (Fig. 9) based on the apparent iron inputs (Fe^{2+}) from the steel plant with a maximum of 5.0357 mg/L with an average of 0.8794 mg/L. The total Fe^{2+} concentration was stable at approximately 5cm at the top of the surface. It began to rise at a depth of 24-32 cm before decreasing and had a sharp increase at 40 cm depth, so considerably, as we go down to the bottom of the lake, it fluctuates. This increase of Fe^{2+} concentration from the overlying water to the porewater demonstrates the potential release of Fe^{2+} from the sediment and dissolution of Fe-P under the depletion of oxygen (anaerobic condition) contributed to the internal P loading. The highest Fe^{2+} concentrations were 5.036 mg/L at Provo Bay, which also had a more significant contribution from agricultural emissions and domestic sewage than other sites.

Silica (Si) concentration ranges from 0.0153 mg/L to 11.2506 mg/L, with Provo Bay experiencing the highest SiO₂ (Fig. 9), which is the primary control for dolomite and associated microorganism such as diatoms that gather silica from water and sediment to their shells.

Aluminum (Al) ranges from 0.0857 to 12.5052 mg/L. Fig. 10 shows West of vineyard, displaying a high presence of these heavy metals, which might be from the remnants of past mine waste and spring runoff that is coming down off the mountains that may stir up the metals, which likely are mixed with sediments and rock in the lake's bottom.

3.5.3 Water Quality Effect Analysis

3.5.3.1 Porewater pH

Porewater pH was consistent across all sampling sites and peeper deployments. The porewater pH was less (6.5) than that of the lake water near the top of the water column (8.5). As expected, water parameters significantly differed between the site areas from the collected May to September 2022 sample. The average pH measurement of the overlying water of Utah Lake ranges from 6.5 to 7.05 (Table 9, Fig. 10). These observations suggest that the pH of Utah Lake occurs in neutral (neither acidic nor basic) and alkaline conditions, and as evidence that the lake is a shallow alkaline lake. The pH values increased with decreasing depth. This low of a pH may be due to the method used as at the time of collection and the equilibration time of the peeper.). However, there is significant shifts in porewater pH with depth at several sites, where the pH increased from the sediment water interface down the sediment column (BI, GB, PB, SS, VY, Fig. 10). There were also variations in porewater pH based on the time of year. Goshen Bay consistently increased in pH by 1 pH unit from the sediment water interface to 40 cmbs. The lower porewater pH values near the sediment-water interface may be a result of organic matter decomposition. The increase in pH as one moves down the sediment profile is likely influenced

by Eh, and as the Eh decreases, the pH increases due to the increasing abundance of hydrogen ions under reducing conditions.

Other studies have shown that a larger period of equilibration for the peepers (>32 days) may be necessary to allow cell equilibration with sediment porewaters.

3.5.3.2 Porewater Redox Potential

The redox potential is a measure for the electron availability and prediction of the stability and bioavailability of heavy metals in sediment. The lake water's redox potential (Eh) ranges from -76.85 to +220 mV (Table 9). The redox potential values were high at the top of the surface water and gradually decreased with depth (Fig. 11a). The redox potential of the sediment-water interface was highest at the surface (+220 mV). It decreased to around -76.85 mV within the top few centimeters indicating redox reactions shift and that the shift occurs remarkably close to the sediment surface. Averaged across all sites within the lake, the porewater redox potential (Eh) decreased with increasing depth, with a clear shift at the water column-porewater.

Prior to this work, there was no clear data that showed at what depth the sediments of Utah Lake went reducing. The depth decrease may indicate they might not be active sediment disturbances such as resuspension, enhanced by decreased water level as a transport mechanism at the bottom of the lake compared to the top.

There are some site-specific porewater redox potential trends. For example, Provo Bay (PB) porewater Eh between 8-36 cmbs remain above -100mV, then dropped rapidly at 40 cmbs to -300mV. Goshen Bay (GB) porewater was also unique in that it's redox potential exhibited the

typical decrease from the interface sediments to 8 cmbs, but then increases to nearly +100mV at 16 cmbs.

This is likely an example of the influence of subsurface hydrologic flow on Utah Lake sediment. The peepers installed at Bird Island (BI) were installed deeper than anticipated due to the soft nature of the sediment. Therefore, no water column samples were collected. The redox potential of the porewater at Bird Island was measured between 0 cmbs to 60 cmbs and all Eh levels were reducing. There was. However, a noticeable increase in Eh beginning at 44 cmbs and continuing to its terminal depth at 60 cmbs where the Eh reached -80 mV.

3.5.3.3 Porewater Conductivity

Porewater Conductivity at Utah Lake ranged from 950 us/cm to 2.519.73 us/cm (Table 9). Averaged across all sites within the lake excluding Provo Bay (PB), the porewater conductivity decreased with increasing depth, with a defined shift at the water column sediment porewater interface (Fig. 11b). Similar to other sites, PB porewater conductivity decreased rapidly from the sediment surface to 12 cmbs. A distinct shift then occurred and Provo Bay porewater conductivity increased with depth to its terminal depth of 40 cmbs, with the porewater conductivity reaching values higher than that in its water column. The high conductivity in the lake suggests the discharge of municipal or industrial effluents, pollution of human wastewater, and agricultural and runoff discharge, which is also an indicator of the saline condition that has been heavily impacted on the lake.

3.5.4 Concentration of Phosphate on sediment-water Interface

There are distinct trends in the porewater phosphate composition with depth in the vertical structure of the water column among the sampling locations (Fig. 12). Provo Bay (PB) and Goshen Bay (GB) had the highest levels of phosphate in the porewater, with concentrations reaching 2.4 and 1.8 mg L⁻¹, respectively. The maximum value is 3.076 mg L⁻¹ from the Saratoga Springs site in July and a mean value of 0.7061 mg L⁻¹. The relatively high productivity of these areas of Utah Lake likely contributes to the high levels of phosphate in the porewater. There is also a seasonal change in the porewaters, with phosphate concentrations increasing between May, June, July, and August (Fig. 12). This increase in porewater phosphate correlates to the primary production and algal bloom occurrence pattern in Utah Lake- warmer summer months result in more algal blooms and primary production (Merritt, 2017). Due to the shallow nature and proximity of the lake, nutrients originating from the sediments are readily available for biological utilization resulting in prolific algal growth in the lake. There also appears to be a large spike in phosphate at 50 cmbs for Bird Island (BI). This is likely due to contamination of the porewater sample with the sediment on the filter at the point of extraction from the lakebed.

3.5.5 Concentration effect of sulfate on Utah Lake Porewater

The sulfate concentration in the overlying water ranges from 0.935 to 469.975 mg L⁻¹. The average concentration is 125.580 mg L⁻¹. In all locations, the sulfate concentration in porewater increases with decreased sediment depth (Fig. 13). Interestingly, lower sulfate concentrations in surface sediment were found in Goshen Bay in July. Some depths were below the detection limit and were significantly higher in Goshen Bay, with samples collected in August before decreasing through depth to about 45 cm. The activity of sulfate reduction was found in the top 10cm of the

sediment porewater. Sulfate is being utilized by organic matter and becomes less stable thereby reducing to sulfide. This decrease in sulfate is well-correlated with the redox potential. The increasing sulfate concentration may promote internal P release and switch sediments between the P source and sink. However, when the concentration is lower, well-oxidized conditions across the sediment-water interface would be effective for sediment retention of P.

4 Discussion

4.1 Distribution of TP in Sediment in the Lake

The total P concentrations in the sediment range from 0.00024% to 1.17%. Therefore, these findings indicate that the P level in sediments from Utah Lake was high. This was likely due to the local geology, rich in phosphate rock deposits, and phosphorus inputs into the lake with the development of industrial and commercial activities in the watershed during the past few decades. The pollution sources of different industrial effluents include wastewater treatment plants (WWTPs) and chemical industries near the lake's east side. The other pollutants originate from urban activities such as agriculture, recreation, stormwater runoff, and atmospheric deposits. As a result, this activity affected the P loadings in the lake. Based on its geographical surroundings, it was obvious that the primary sources of phosphorus to Utah Lake were fertilizer plants and rural and urban activities from Utah Valley or Utah County.

The highest TP was observed at Provo Bay (PB) with 1.17%, followed by East of Bird Island (BI) with 0.12%, and these two values were much higher than those of the other sites. The lowest value was observed at Saratoga Springs (SS) with 0.00024%. This was likely due to the lake's distribution of external sources of WWTPs that were pumped into the lake and fertilizer

runoff. Although the WWTPs are no longer in operation, their effect on phosphorus loadings in the lake is still likely to be considerable.

The average Calcium (Ca) concentration ranges from 10.15% to 20.88%. The sediment was carbonaceous in composition due to the carbonate rocks surrounding the study area. The highest concentration is in the West of Vineyard; the second lies in Saratoga Springs, while little was found in Provo Bay. High concentrations of calcite sediment are found throughout the central part of the lake, with the highest concentration in the north and south parts of the lake (Sonerholm, 1974). Ca concentrations are probably governed by the solubility of CaCO_3 (Calcite). Although sediment pH is essential in determining P solubility, the high calcium carbonate content of the sediments results in a relatively stable pH (7.0-7.5). However, the redox potential at the sediment-water interface, governed by biological activity and the supply of electron acceptors, such as O_2 , can vary from oxidized to reduced conditions, making it the most critical variable concerning internal P cycling in the lake.

The lake sediment is highly composed of quartz due to the tributary of the major rivers that flow into the lake, and the wave action associated with sediment disturbances near the shore tends to deposit the silica in the lake's location. The average values range from 0.6% to 0.9% for Fe concentrations. While Al's average content ranges from 0.33% to 0.65%, the highest average for Mg concentration is 9.47% at Goshen Bay.

Phosphorus concentrations in the water column were high, with TP values reflecting hypereutrophic conditions. Most of the TP (%) in the water column was particulate, presumably incorporated in algal tissue and within the particles of resuspended sediments. Provo Bay shows the highest concentration for P concentrations, with an average of 3.1167 ppm and the highest standard deviation of 4.7014 ppm. The reason for the high P levels is due to direct point and non-

point discharges, higher productivity, agricultural impacts (including irrigations and stock watering), and wastewater treatment plant (WWTP), which is expected that this area should have elevated phosphorus. The increase of Fe concentration from the overlying water to the porewater demonstrates the potential release of Fe from the sediment and dissolution of Fe-P under the depletion of oxygen (anaerobic condition) contributed to the internal P loading. The highest Fe²⁺ concentrations were 5.036 mg/L at Provo Bay, which also had a more significant contribution from agricultural emissions and domestic sewage than other sites.

The results showed that the region with higher TP concentration in the sediment contributes to the total internal loading TP conc in sediment is an important factor in understanding the sediment-water interactions. Sediment P geochemistry can be an important index for estimating the P pool in porewater and managing the flux of phosphorus (Mayer et al., 1980).

4.2 Mineralogy of Utah Lake

Utah Lake's mineralogy primarily consists of calcite, quartz, and dolomite. The mineralogy of PB differs from the other cores as the relative percentage of calcite in the sediment is much lower while quartz is higher. This might suggest that sediment deposition in PB is much more dependent on allochthonous processes. The increase in calcite composition at the surface sediment of PB may be related to rising pH as an increased algal presence sequesters more CO₂, which would raise the pH, decreasing the solubility of Ca (Heath et al., 1995).

The overall mineralogy of the other site, which includes Provo Marina (PM), West of Vineyard (WV), East of Bird Island (BI), Saratoga Springs (SS), and Pelican Point (PP) in Fig. reflects a shallow, alkaline lake. The high pH of Utah Lake, with high concentrations of dissolved calcium and bicarbonate in the water (Horns, 2005), may suggest that the presence of

calcite in the cores may be detrital from nearby sedimentary and altered volcanic unit (Brimhall & Merritt, 1981).

The mineralogy of Goshen Bay (GB) is similar to the rest of the site, giving further evidence of the high alkalinity of the lake. One key difference is the small amount of Anorthoclase feldspar, which may be due to GB being out of the depositional influence of Dry Creek (Biek, 2005).

4.3 Methods of controlling the release of phosphorus from the sediments

The phosphorus pollution in lakes is from external sources inside and outside the watersheds and internal sources such as the lake bottom sediments. Controlling phosphorus input into the lake is challenging because Utah Lake is close to seven WWTP. Although these industrial wastewater companies are not located within the lake's watershed, the application and transportation of phosphorus-related products must have had a considerable effect on the phosphorus loading in the lake. Additionally, even if external phosphorus sources have been curtailed through various means, such as the closing down of highly polluting production plants, the release of phosphorus from sediments is sufficient to maintain anthropogenic eutrophication for a long time in the lake. As a result, successful environmental management requires consideration of the phosphorus inputs and the fate of the inputs in the freshwater environment.

5 Conclusions

Total bulk sediment and water P concentrations changes with depth

Several P concentrations were similar at most sites. However, Bird Island (BI) sediment had significantly less P when compared with Goshen Bay (GB), Pelican Point (PP), and Saratoga Spring (SS), which averaged $389.401 \text{ mg Kg}^{-1}$.

They had similar trends at the top of the sediment-water interface before an increase started occurring at various depths. The maximum values of the total Phosphorus (TP) were observed in the sediment at Provo Bay (PB), which is in a district with a high density of population and Industry. The TP level was highest in the surface sediment format at a depth between 4 cmbs and 18 cmbs before abrupt decrease in depth which might also indicate lower P enrichment in those areas.

Similarly, in porewater the TP concentrations found in the water column of an individual site do not significantly differ across depth in almost all instances, suggesting Utah Lake to be well-mixed vertically (Zanazzi et al., 2020). Elevated P concentrations found in the column water of PB are tied to increased sediment P concentrations and enhanced P mobility in the area due to microbial activity (Fig.14)

Several locations see slight decreases in porewater total P with depth. PB is an exception to this trend. Total P in PB porewaters increases with depth to 16 cmbs where it reaches 14 mg-PL^{-1} . This is considerably more than the phosphate-phase in PB porewater, suggesting other forms of P are prevalent- likely organic forms of P due to Provo Bay's primary productivity and agricultural impacts (including irrigations and stock watering) which is expected in that area.

Our analysis of sediment and water shows that in terms of composition, Utah Lake is well-mixed and non-stratified and therefore assumed to be homogenous in its chemical composition, including P concentrations. PB has the most elevated concentrations of TP which attributes to the bay's shallow nature as a major water inlet into the lake from contributing neighboring lake feeders, making it an ideal location for increasing microbial activity and deposition of allochthonous detritus, Sediment P was positively correlated with total porewater P concentrations ($r^2 = 0.4450$ and $r^2 = 0.0127$, respectively) (Fig. 14).

The geochemical trends in the sediment-water interface changes with depth

We focus on Calcium (Ca), Iron (Fe), Aluminum (Al), Magnesium (Mg) and Phosphorus (P) for their major roles in P-cycling within lakes (Sondergaard et al., 2001, Hupfer et al., 2009 and Markovic et al., 2019). Concentration of other elements that commonly influence P cycling within Utah Lake are included in (Fig.15). Sediment P concentrations increased with water depth which may be indicative of P binding readily to fine grained particles (Stone & English, 1993). Clay minerals, Fe and Al oxides are among the primary constituents of fine-grained material and have high sorption capacities (Kumari and Mohan, 2021). Sediment with lower amounts of Fe and Al generally have low phosphate sorption capacity (Lopez et al., 1996).

We observed a positive correlation of P with Al ($r^2 = 0.2741$) likely reflects P sorption to fine-grained particles and an association of P to clay minerals (Fig. 16a) We also observed a positive relationship between sediment P and Mg, while Mg increases with depth ($r^2 = 0.0332$) (Fig.16b).

We observed a strong association of P with Fe in surficial sediment ($r^2 = 0.2906$) (Fig.16b) under reducing conditions, Fe (III) may be mobilized to Fe (II), allowing for release of P in

porewater. Note that the water column of Utah Lake is well mixed and oxygenated. In oxygen-rich sediments, P is immobilized by retention with Fe (III) (Mortimer 1941).

Notable is the negative correlation between P and Ca ($r^2 = 0.1921$) (Fig.16a). Calcium carbonate (CaCO_3) abundance increases in shallow water allowing for less P storage, probably due to the nature of CaCO_3 precipitation.

Average Porewater redox potential decreases rapidly near the sediment-water interface.

Averaged across all sites within the lake, the porewater redox potential (Eh) decreased with increasing depth, with a clear shift at the water column-porewater interface (Fig.17) From the bottom of the water column to the shallow porewater, the redox potential shifts rapidly from oxidizing (+200mV) in the bottom water column (4-8 cm above the sediment water interface) to reducing (-100mV) in the porewater at shallow depths (4-8cm below the sediment-water interface).

Prior to this work, there was no clear data that showed at what depth the sediments of Utah Lake went reducing. These findings show there is a redox potential shift and that it occurs close to the sediment surface. When the redox potential drops below (+150mV), reductive dissolution of iron oxide minerals begins to occur. If there are phosphorus-bearing Fe oxides, then the reductive dissolution of those mineral oxides will result in phosphorus releasing into solution and becoming potentially bioavailable. The redox conditions regulate phosphorus release into porewater from the fraction of phosphorus bond to the iron bearing minerals.

The influence of reducing conditions on oxidation state within the sediment is an important finding related to phosphate retention in the sediment of Utah Lake. The abundance of reducing

conditions in the sediment, even at the shallow depths, suggests that redox sensitive minerals and metals (particularly Fe) are not a stable sink for phosphorus in the sediments.

Sulfate concentrations decreased with depth in the porewater, likely because of the redox reaction.

Porewater sulfate concentrations decrease from 300 to 110.5 mg L⁻¹, on average 125.58 mg L⁻¹, from the sediment-water interface to 50 cmbs and remain low throughout the measured sediment porewater depths (Fig.18) This decrease in sulfate is well-correlated with redox potential. The zone with the most active sulfate reduction is found in the top 10 cm of sediment porewater. Sulfate is being utilized by organic matter. In a eutrophic lake like Utah Lake, the microbial activity, and the rate of degradation of fresh organic matter increases as compared to a more acidic lake (Rao and Burnison, 1989 and Bloudau et al., 1998). Which indicates sulfate reduction is generally high which is consistent with high microbial activity.

Sulfate to sulfur when there is no more sulfates concentration to utilize by organic matter. Therefore, sulfate is no longer stable as the redox condition shifts. The trend shows that sulfate was high in the water column (Fig.18), the drops rapidly in the sediment under reducing conditions.

The potential for significant sulfate reduction in an alkaline eutrophic lake is generally high because of high sulfate concentration availability and increased microbial activity. The high sulfate flux in the upper few centimeters suggests that it was in excess, and any removal processes did not take out a significant fraction. The decrease with depth suggests a sink process removes sulfate or less sulfate reduction and high microbial activity.

The flux of dissolved sulfide decreased rather steadily until a depth of around 53 cm. This decreased is by an order of magnitude at the boundary between the oxidized and reduced

sediment layers and then retained this value down to the water depth (Fig. 18). Sulfate-reducing bacteria are most abundant and show the largest activity at horizons where an abrupt decrease of sulfate ion concentration occurs (Namsaraev and Zaimkaya, 2000; Pimenov et al., 2014).

Our findings provide insights on the geochemical context of Utah Lake as a natural system, which includes:

- 1) Redox potential of sediment and porewater become reducing with top 8cm of lakebed.
- 2) Reduced oxidation states of sulfate concentrations are present in lakebed sediment.
- 3) Reduced oxidation states of iron mineral phases are present in lakebed sediments.
- 4) The majority of P (63%) in Utah Lake sediments is associated carbonate minerals (e.g., calcite)
- 5) Colloids in the water column contain phosphorus.
- 6) Average porewater redox potential decreases rapidly near the sediment-water interface.

Our study adds to earlier shallow lake work in several ways. First, we found the role of sediments in element distribution in shallow lakes relationships between water and sediments element concentrations. P dynamics are relatively complex and differ between sediment depths. One factor that influences phosphorus concentrations in the sediment of Utah Lake is hydrochemical conditions in the water column above the sediment, depth, and physiochemical properties of the sediments. Total P concentrations in surface sediments were highest in Provo Bay (PB), the lake's hot spot of P accumulation. PB had the most productive sediment; nutrient flux and sediment P content increased in the shallow areas near anthropogenic nutrient discharges. It is evident from the present study's findings that the lake is facing more stress from cultural eutrophication.

Sulfate concentration decreased with depth in the porewater, likely because of the redox reaction. This decrease in sulfate is well-correlated with the redox potential. The zone with the most active sulfate reduction is found in the top 10 cm of sediment porewater.

P concentrations and other lake elements of interest in this study, such as Ca, Fe, Al, Mg, and Si, also changed significantly in sediment porewater. Additionally, varying physical parameters, which include Temperature, dissolved oxygen (DO), redox potential & pH conditions, did affect the overall chemistry of the ecosystem. In contrast, the lake's robust buffer system can maintain a relatively stable state in natural conditions. Results acquired from this study could help explain similar phenomena in other freshwater lakes and decision-making for environmental agencies. Because of their strong impact on lake water concentrations, knowledge of sediment-water interactions and the processes behind phosphorus retention and release is fundamental for understanding the function of shallow lakes.

Prior to this study, there was no clear data that showed at what depth the sediments of Utah Lake went reducing. These findings show that there is, indeed, a redox potential shift and that this redox shift occurs very close to the sediment (4-8cm below the sediment-water interface).

Future work should better quantify sediment release rates, understand how the P is stored in the sediments, and improve geochemical models for how P moves between sediments and the water column. It also suggests a complete understanding of the internal and external P loading for lakes or reservoirs is merited.

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APPENDIX

Tables.

Table 1 Morphological and Limnological Characteristics of Utah Lake

Characteristics	
longitude (UTM)	111.7656
Latitude (UTM)	40.3161
Temperature	80°
surface Area	145 square miles
Elevation	4489'
Watershed Size	2950 square miles
Water Volume	902,000 acre-feet
Water Inflow	930,000 acre-feet
Water Outflow	930,000 acre-feet
Water Residence Time	6 months
MAX Depth	18 feet
MEAN Depth	9 feet

Table 2 UTM Coordinates for freeze core collection sites.

Core ID	UTM Coordinates (UTM NAD83. Zone 12 T)
Provo Bay- PB	438976E, 4448000N
Provo Marina- PM	435126E, 4454339N
West of Vineyard- WV	431915E, 4461279N
Saratoga Springs- SS	426290E, 4465432N
Bird Island- BI	433847E, 4446598N
Goshen Bay- GB	424003E, 4438199N
Pelican Point- PP	428878E, 4457961N

Table 3 Summary of the analytical methods used in this study.

Parameter	Method
Temperature	Temperature Probe
pH value	pH Probe
Electrical Conductivity	Conductivity Probe
Oxido-reduction Potential	ORP Probe
Dissolved Oxygen	DO Probe
Total Phosphorus	Inductively Coupled Plasma-Optical Emission Spectrometry-ICP-OES
Iron, Calcium, Magnesium, Aluminum, Silica	Inductively Coupled Plasma-Optical Emission Spectrometry-ICP-OES
Total Element Concentrations	Inductively Coupled Plasma-Optical Emission Spectrometry-ICP-OES
Chloride, Nitrate, Sulfate, Phosphate	Ion Chromatography-IC
Anion Concentrations	Ion Chromatography-IC
Mineralogical Content	X-ray Diffraction- XRD
Elemental Composition & Structure	EPA Method 3051a & SEM
C/N Isotope ratio	Isotope-Ratio Mass Spectrometer

Table 4 Bulk density data of sediment cores collected from Utah Lake

Location	Parameters	Bulk density via Syringe (g/cc)	Bulk density via Cuboid (g/cc)
Provo Marina n = 61	Mean	0.8	0.7
	Min	0.4	0.4
	Max	1.1	1.1
	Standard Deviation	0.1	0.1
Saratoga Springs n = 80	Mean	0.8	0.6
	Min	0.4	0.2
	Max	1.0	1.3
	Standard Deviation	0.2	0.2
West of Vineyard n = 75	Mean	0.9	0.6
	Min	0.7	0.2
	Max	1.2	1.2
	Standard Deviation	0.1	0.1
Goshen Bay n = 59	Mean	0.8	0.6
	Min	0.4	0.2
	Max	1.2	1.0
	Standard Deviation	0.2	0.2
Provo Bay n = 45	Mean	1.0	0.8
	Min	0.2	0.2
	Max	1.3	1.3
	Standard Deviation	0.2	0.2
Bird Island n = 98	Mean	0.8	0.7
	Min	0.5	0.2
	Max	1.0	1.1
	Standard Deviation	0.1	0.2
Pelican Point n = 77	Mean	0.9	0.7
	Min	0.4	0.0
	Max	1.7	1.2
	Standard Deviation	0.3	0.3

Table 5. Bulk Sediment Chemistry from Utah Lake

Locations	Total P (mg/kg)			Total Ca (%)			Total Fe (%)			
	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	
Provo Bay-PB	1.17	0.08	0.12	21.81	5.00	10.15	1.15	0.41	0.70	
West of Vineyard-WV	0.04	0.0002	0.03	23.36	14.24	20.88	1.67	0.19	0.66	
Saratoga Springs-SS	0.32	0.04	0.04	29.17	-0.0010	19.30	9.47	1.05	0.58	
Goshen Bay-GB	0.07	0.08	0.08	34.48	19.30	0.0007	1.26	0.0007	0.71	
Bird Island-BI	0.03	0.0004	0.05	21.33	9.68	17.59	0.86	0.36	0.55	
Provo Marina-PM	0.04	0.05	0.06	27.73	17.59	14.49	1.27	0.64	0.90	
Total Mg (%)			Total Al (%)			Total Si (%)				
Max	Min	Mean	Max	Min	Mean	Max	Min	Mean		
Provo Bay-PB	No Data			1.19	0.06	0.33	15.83	4.70	9.250	
West of Vineyard-WV	A.D.L*			0.73	0.23	0.41	14.70	B.D. L**	8.91	
Saratoga Springs-SS	A.D.L*	B.D.L**	A.D.L*	0.66	B.D.L**	0.33	12.96	4.89	9.47	
Goshen Bay-GB	A.D.L*	0.18	A.D.L*	0.95	0.0014	0.41	9.50	1.04	5.62	
Bird Island-BI	A.D.L*			4.74	0.17	0.65	No Data			
Provo Marina-PM	No Data			0.09	0.33	5.11				

A.D.L.* Above detection limit

B.D.L.** Below detection limit

Table 6 Mineralogic Composition of Sediment from Utah Lake

Location	Quartz	Calcite	Dolomite	Tremolite	Illite	Kaolinite	Ano.	Mont.	Chlorite
Provo Bay (PB)	51.1	23.8	6.6	11	29	12	23.6	3.8	2.5
Provo Marina (PM)	11.18	65	3.1	4	21.3	5.8	9.2	4	4.1
West of Vineyard (WV)	12.34	70.5	3.27	5	32	4.3	12	3.8	3
Bird Island (BI)	12.8	59.8	3.2	12	14.5	9.4	12.9	5.3	10.9
Saratoga Springs (SS)	9.66	67.8	2.7	4.3	19.1	4.3	6.2	1	5
Goshen Bay (GB)	13.05	63	3.5	3	27	5.8	3.7	3.2	8.3
Pelican Point (PP)	19.03	51.9	4	10	17.3	3.6	22.3	4.1	2.7

Ano. means Anorthoclase. Mont. means Montmorillonite.

Table 7 Chemical Parameters in Utah Lake Column Water

Location	Temperature (T)	Dissolved Oxygen (DO)	Conductivity (EC)	pH
Top of water column				
PB	21.5	100.5	1205	8.73
PM	25.2	162.5	2157	8.83
WV	71.4	110.9	1965	8.7
BI	20.8	77	1979	8.66
GB	21.5	102	2021	8.71
SS	16.5	66	2081	8.38
PP	21.4	96.1	1876.4	8.75
Min	16.5	66	1205	8.38
Max	71.4	162.5	2157	8.83
Average	28.3	102.1	1897.8	8.68
Standard deviation	19.2	30.8	318.2	0.14
Middle of water column				
PB	19.4	82.5	1197	8.66
PM	20.7	85	1994	8.59
WV	18.4	81.9	1843	8.58
BI	20.8	75.5	1980	8.66
GB	20.8	88	1990	8.64
SS	16.2	54.2	2086	8.24
PP	21.1	88.9	1973	8.72
Min	16.2	54.2	1197	8.24
Max	21.1	88.9	2086	8.72
Average	19.6	79.4	1866.1	8.58
Standard deviation	1.79	11.9	303.5	0.16
Bottom of water column				
PB	18.9	59.1	1219	8.58
PM	20.6	63.1	1993	8.51
WV	18.2	69	1836	8.53
BI	20.8	75	1980	8.65
GB	20.7	81.4	1988	8.62
SS	16.1	48.5	2087	8.22
PP	21	83	1970	8.7
Min	16.1	48.5	1219	8.22
Max	21	83	2087	8.7
Average	19.5	68.4	1867.6	8.54
Standard deviation	1.83	12.5	295.3	0.16

Table 8 Porewater trace and major elements extracted from Utah Lake. Phosphorus, Calcium, Iron, Aluminum Moreover, Silica was measured by ICP-OES.

Month	Location	Depth	P	Ca	Fe	Mg	Al	Si
May	Provo Bay	8	0	54.70	0.21	39.38	0	1.48
		4	2.18	39.82	0.039	34.13	0	1.24
		0	1.13	31.19	0.03	28.95	0	0.97
		-4	2.87	38.99	0.10	31.30	0	4.73
		-8	10.19	51.65	0.21	19.40	0	11.25
		-12	12.35	36.04	0.09	18.66	0	9.96
		-16	13.85	38.28	0.06	20.0	0	9.95
		-20	4.71	41.69	0.19	18.30	0	8.12
		-24	0	56.23	-0.03	21.45	0	7.18
		-28	0.71	45.51	0.34	18.08	0	7.69
		-32	1.01	64.30	0.99	24.0	0	7.20
		-36	0	62.67	0.09	21.57	0	5.65
		-40	0	143.0	0.19	46.51	0.58	8.09
		-44	0	158.41	4.94	54.09	0.09	9.05
		-48	0.87	157.08	1.57	48.19	1.48	6.86
		-52	0	160.85	5.04	49.54	0	6.78
		Min	0	31.19	-0.03	18.09	0	0.97
		Max	13.85	160.85	5.04	54.09	1.48	11.25
		Mean	3.12	73.78	0.88	30.85	0.13	6.64
		Stdev	4.70	49.36	1.66	12.81	0.39	3.14
Goshen Bay	Goshen Bay	12	0	74.54	0.89	69.68	0.05	0
		8	0.48	69.60	0.04	60.37	0	0.011
		4	0.72	63.09	0.28	59.09	0	0
		0	0.85	56.18	0.15	60.85	0.45	0.001
		-4	0.96	61.47	0.19	66.13	0	0
		-8	0.37	56.16	0.19	54.44	0.02	0
		-12	0.83	52.30	0.20	50.19	0	0
		-16	0.74	51.09	0.17	50.48	0.06	0
		-20	0.69	57.78	0.13	57.30	0.26	0
		-24	0.68	59.06	0.14	50.17	0	0
		-28	0.57	53.11	0.11	52.79	0	0
		-32	0.82	57.04	0.11	57.33	0	0
		-36	0.41	48.57	0.02	48.5214	0	0
		-40	0.59	36.17	0.01	31.99	0	0
		-44	2.19	50.87	0.28	44.55	0.39	0
		-48	2.10	71.86	0.08	63.21	0.05	0.43

Min	0	36.17	0.01	31.99	0	0
Max	2.19	74.54	0.89	69.68	0.45	0.43
Mean	0.81	57.43	0.19	54.82	0.08	0.03
stdev	0.57	9.53	0.20	9.13	0.15	0.11

Bird Island	0	0.77	101.19	0	89.48	0.09	0.01
	-4	0.63	93.32	0	78.44	0	0
	-8	0.74	68.77	0.51	62.22	0	0.01
	-12	4.40	63.99	0.21	60.70	0	0
	-16	0.74	78.20	0.02	58.63	0	0.003
	-20	0.78	63.87	0.04	56.29	0.03	0
	-24	0.97	61.73	0.41	53.98	0	0.009
	-28	1.77	66.64	0.28	52.36	0.08	0
	-32	0.70	75.31	0.44	48.80	0.05	0.004
	-36	0.34	54.44	0.14	45.61	0	0.015
	-40	0.64	66.10	0.29	46.44	0	0
	-44	0.58	54.08	0.04	41.52	0	0
	-48	0.46	76.95	0.06	30.57	0	0.006
	-52	0.35	51.55	0.04	37.77	0	0
	-56	0.52	56.40	0.10	37.05	0	0.004
	-60	0	32.82	0.02	20.37	0	0.011
	Min	0	32.82	0	20.37	0	0
	Max	4.40	101.19	0.51	89.49	0.09	0.015
	Mean	0.90	66.58	0.16	51.27	0.02	0.004
	stdev	1.00	16.43	0.17	17.17	0.03	0.005

Provo Marina	0	0.49	62.58	0.07	53.94	0.15	3.64
	-4	0.59	74.03	0.08	70.22	0.39	6.18
	-8	0.55	59.36	0.01	44.43	0.22	2.87
	-12	0.80	24.24	0.04	21.70	0	2.31
	-16	1.01	30.76	0.14	26.76	0	2.75
	-20	0.60	38.46	0.02	30.48	0	3.38
	-24	0.68	40.45	0.02	34.39	0	3.40
	-28	0.60	41.07	0	35.05	0	3.91
	-32	0.33	32.28	0	26.87	0	3.41
	-36	0.70	38.12	0	25.27	0	3.15
	-40	0.23	44.59	0	37.20	0	5.51
	-44	0.14	17.94	0	13.70	0	2.34
	-48	0.16	36.69	0	26.07	0	3.26
	-52	0.71	31.98	0	23.54	0	3.02
	-56	0.19	27.24	0	20.37	0	2.67
	-60	0	44.48	0	30.11	0	5.17

Min	0	17.94	0	13.70	0	2.31
Max	1.01	74.03	0.14	70.22	0.39	6.18
Mean	0.48	40.27	0.02	32.51	0.05	3.56
Stdev	0.28	14.62	0.04	13.96	0.11	1.13

West of Vineyard	0	0	170.75	0.16	157.80	0	0
	-4	0	173.4	0	151.37	12.51	0
	-8	0	132.29	0.258	114.55	0	0
	-12	0	101.60	0	80.52	8.68	0
	-16	0	132.29	0.017	107.41	0	0
	-20	0	89.56	0.01	70.49	0	0
	-24	0	154.43	0.16	118.32	0	0
	-28	0	142.39	0	108.73	0	0
	-32	0	114.55	0	80.51	0	0
	-36	0	128.11	0.01	92.69	0	0
	-40	0	157.18	0	113.63	1.31	0
	-44	0	165.14	0.07	119.44	0	0
	-48	0.28	62.18	0.31	39.10	0	5.28
	-52	0.35	44.82	0.10	31.06	0	7.92
	-56	0.83	53.08	0.30	33.14	0.23	0.01
	-60	0.56	43.87	0.15	23.27	0.13	0.01
	Min	0	43.87	0	23.27	0	0
	Max	0.83	173.4	0.31	157.79	12.51	7.92
	Mean	0.13	116.60	0.10	90.13	1.43	0.83
	Stdev	0.25	45.67	0.11	41.77	3.66	2.31

Saratoga Springs	8	0.67	91.22	0.11	88.24	0.22	0
	4	0.27	66.79	0.09	69.51	1.16	0
	0	2.08	92.94	0.09	92.73	0.22	0
	-4	3.25	110.47	0	109.96	0.06	0
	-8	2.00	104.86	0.011	87.80	0.12	0.58
	-12	0.86	70.01	0.04	60.04	0.99	0
	-16	1.82	99.74	0.03	75.98	0.46	0.72
	-20	1.81	65.55	0	50.46	0.65	0
	-24	1.21	85.98	0.01	69.25	0.45	0
	-28	0.99	68.96	0.01	53.12	0	0
	-32	0.35	42.65	0.26	27.96	0.08	0
	-36	0.42	45.18	0.08	30.44	0.09	0
	-40	0.06	40.44	0.07	28.43	0.37	0
	-44	0.10	42.86	0.19	30.16	0.31	0
	-48	0.02	47.08	0.08	31.94	0	0

-52	1.20	90.59	0.78	72.93	0.24	0
Min	0.02	40.44	0	27.96	0	0
Max	3.25	110.47	0.78	109.96	1.16	0.72
Mean	1.07	72.83	0.12	61.18	0.34	0.08
Stdev	0.92	24.21	0.19	26.37	0.34	0.22

Table 9 Chemical Composition of the sediment-water Interface of Utah Lake

Depth	Avg ORP	SD ORP	Ave pH	SD pH	Avg EC	SD EC
20	222.25	39.75	6.58	0.35	2220.5	275
16	216.36	54.78	6.62	0.20	2490.68	351.85
12	220.12	50.88	6.53	0.18	2519.73	485.60
8	200.07	57.30	6.56	0.30	2290.56	694.55
4	147.73	123.97	6.51	0.30	2309.66	679.55
0	19.98	165.70	6.57	0.25	2157.04	622.92
-4	-76.85	101.53	6.58	0.32	1965.45	549.64
-8	-150.65	48.95	6.81	0.46	1786.71	357.85
-12	-134.2	69.23	6.71	0.35	1758.71	400.28
-16	-132.42	86.20	6.74	0.36	1711.39	331.83
-20	-135.54	82.93	6.66	0.35	1689.79	292.92
-24	-144.88	69.58	6.82	0.39	1583.01	316.62
-28	-140.92	73.86	6.79	0.41	1545.23	304.25
-32	-139.03	64.79	6.79	0.36	1549.91	304.67
-36	-146.34	74.76	6.86	0.36	1514.59	295.97
-40	-153.25	73.67	6.89	0.36	1453.15	343.72
-44	-140.1	68.82	6.87	0.36	1432.51	284.82
-48	-135.65	50.04	6.86	0.33	1313.27	231.48
-52	-133.22	53.74	6.70	0.45	1349.44	237.57
-56	-108.1	44.59	6.73	0.39	1256.24	169.74
-60	-122.25	42.25	7.05	0.32	950.03	162.37

Oxidation-reduction potential (ORP) ** Electrical Conductivity (EC)

Figures.

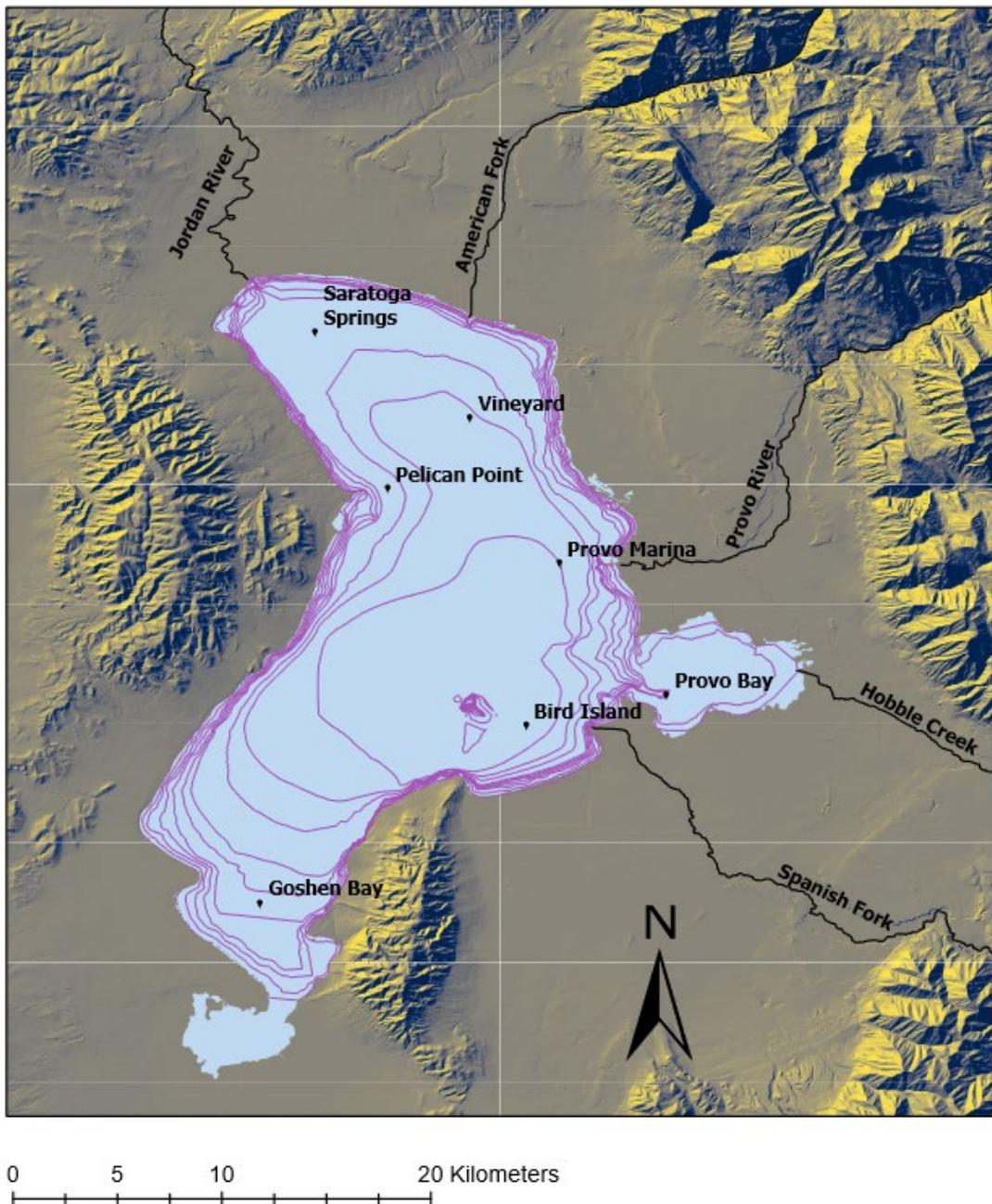


Figure 1 Utah Lake Map and its surrounding region, including sample locations and streams.

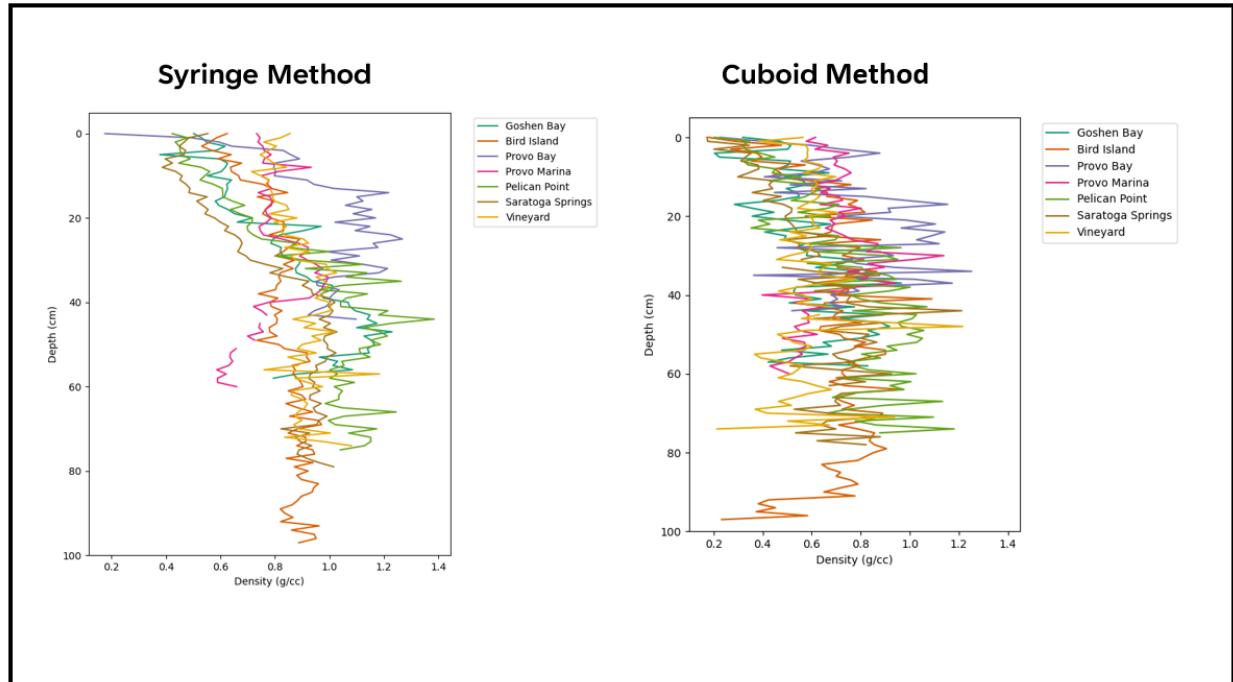


Figure 2 Plot of sediment bulk density vs. depth in the sediment (Syringe vs. Cuboid method)

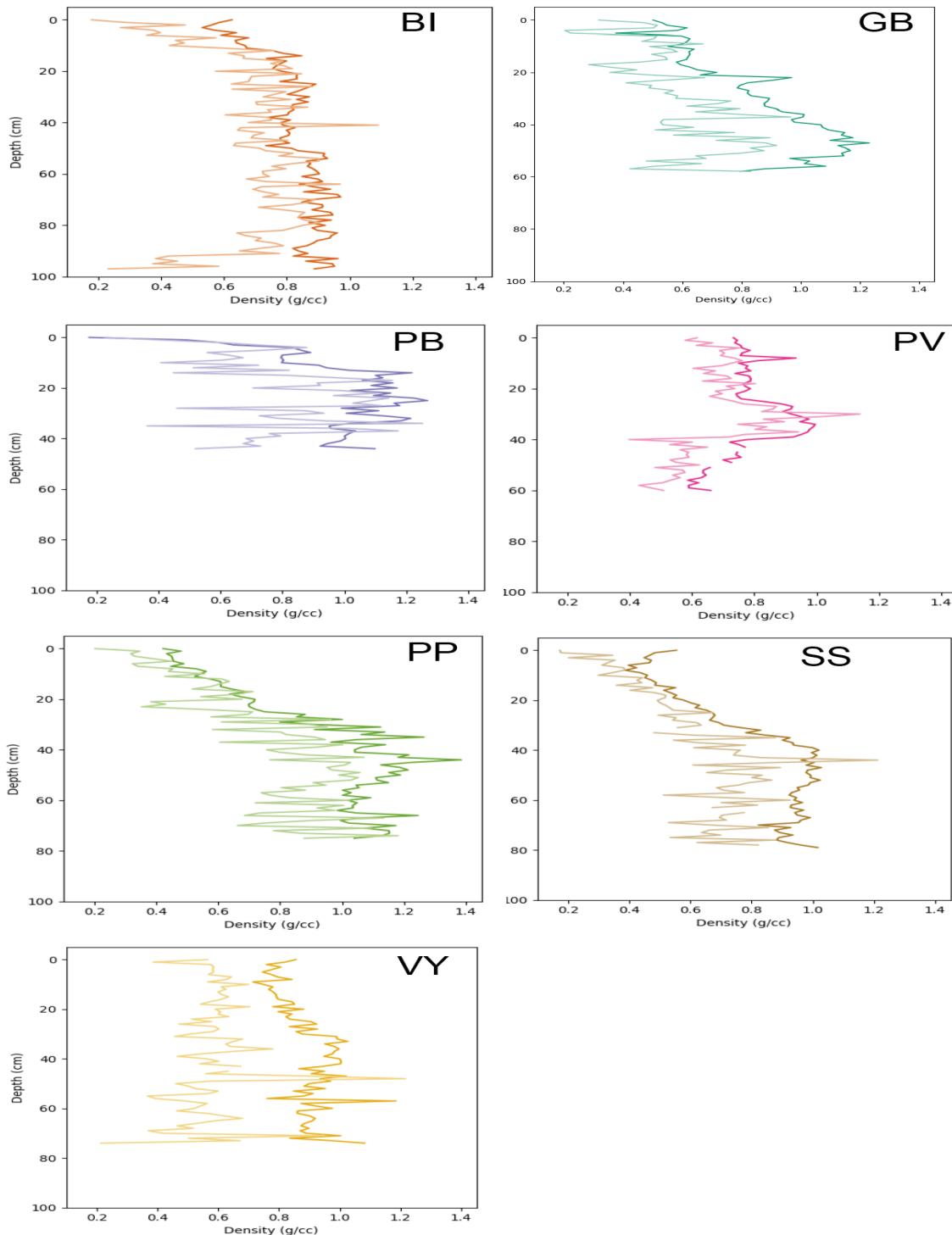


Fig. 3 Dry bulk density in Utah Lake sediments as a factor of depth using two methods. The more saturated (darker) line in each subfigure represents the syringe method and the less saturated (lighter) line represents the cuboid method for determining sediment dry bulk density. Site abbreviations are as follow: PB = Provo Bay; PV = Provo; VY = Vineyard; BI = Bird Island; GB = Goshen Bay; SS = Saratoga Springs; PP = Pelican Point.

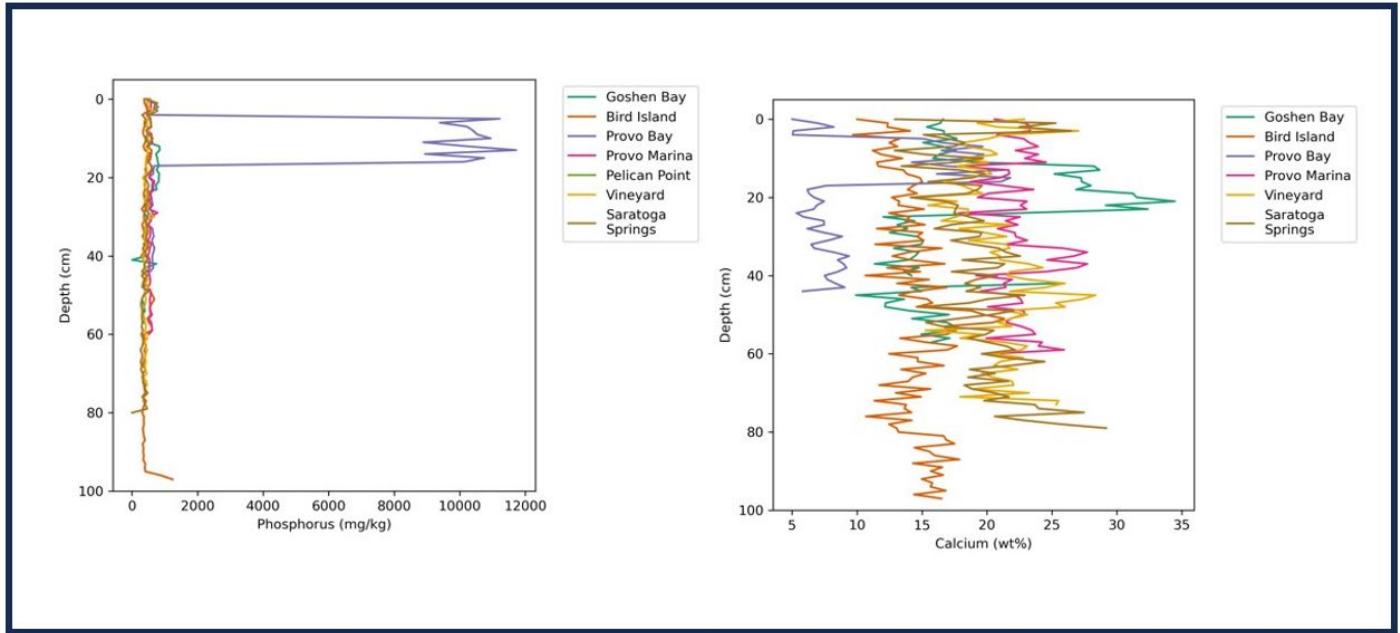


Figure 4 Total Phosphorus (TP) and Calcium (Ca^{2+}) concentrations as a function of sediment depth of all sampling sites in Utah Lake ($n = 7$) Samples analyzed in May 2022

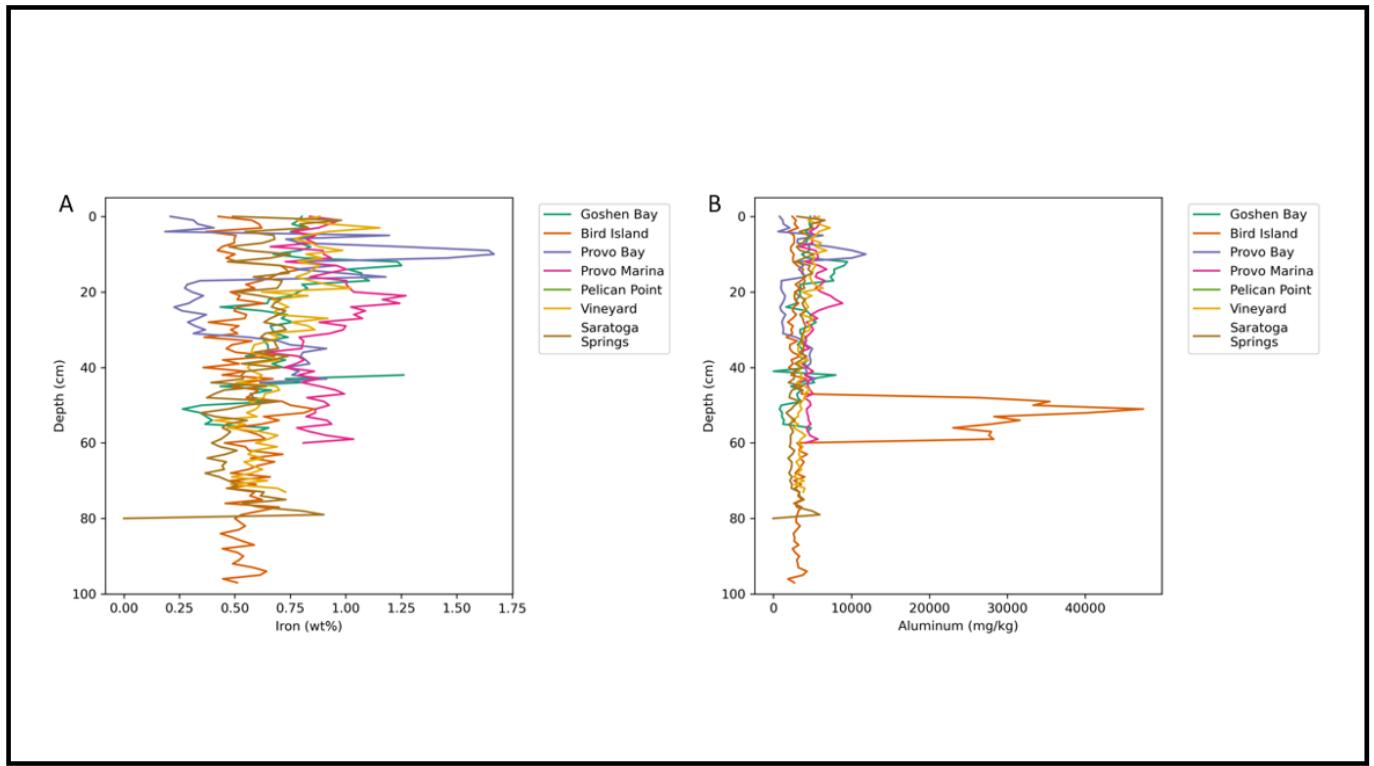


Figure 5 Iron (Fe) and Aluminum (Al) concentrations as a function of depth of all sampling sites in Utah Lake ($n = 7$) Samples analyzed in May 2022

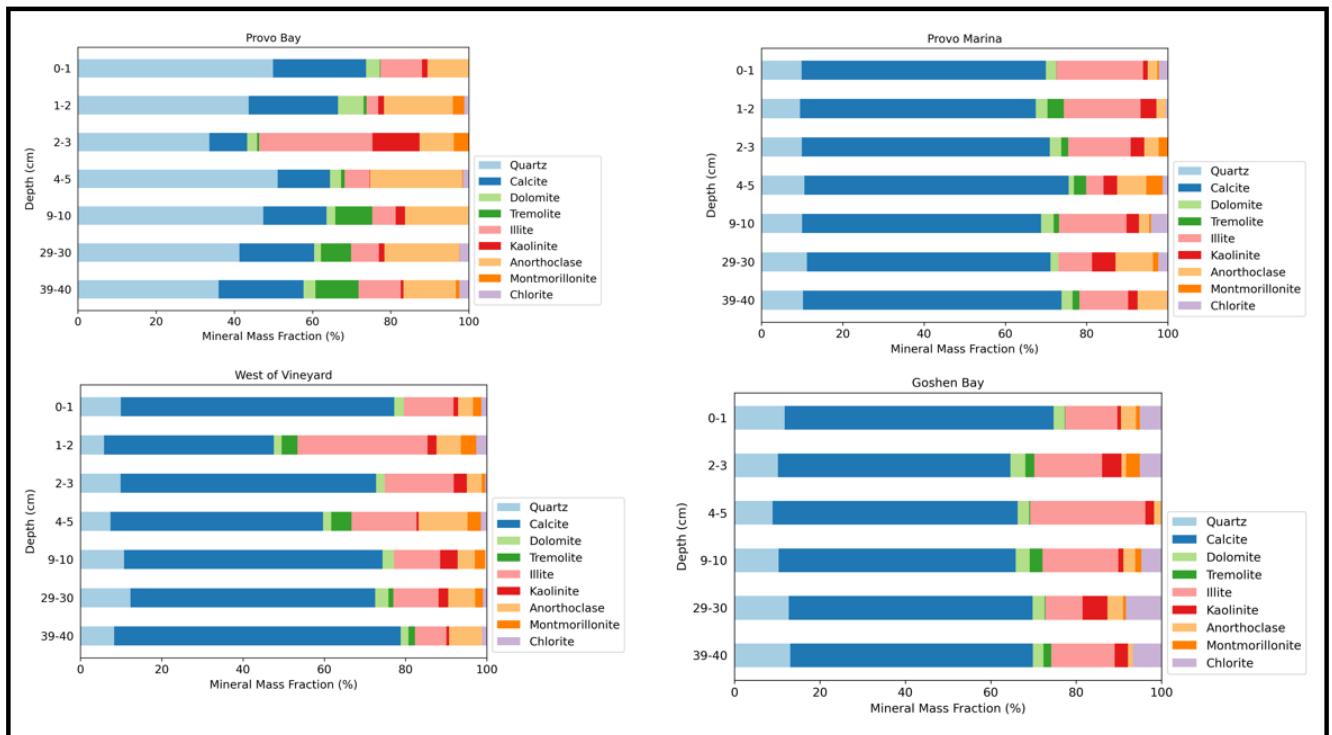


Figure 6a Mineralogy of Utah Lake Surface Sediment Cores

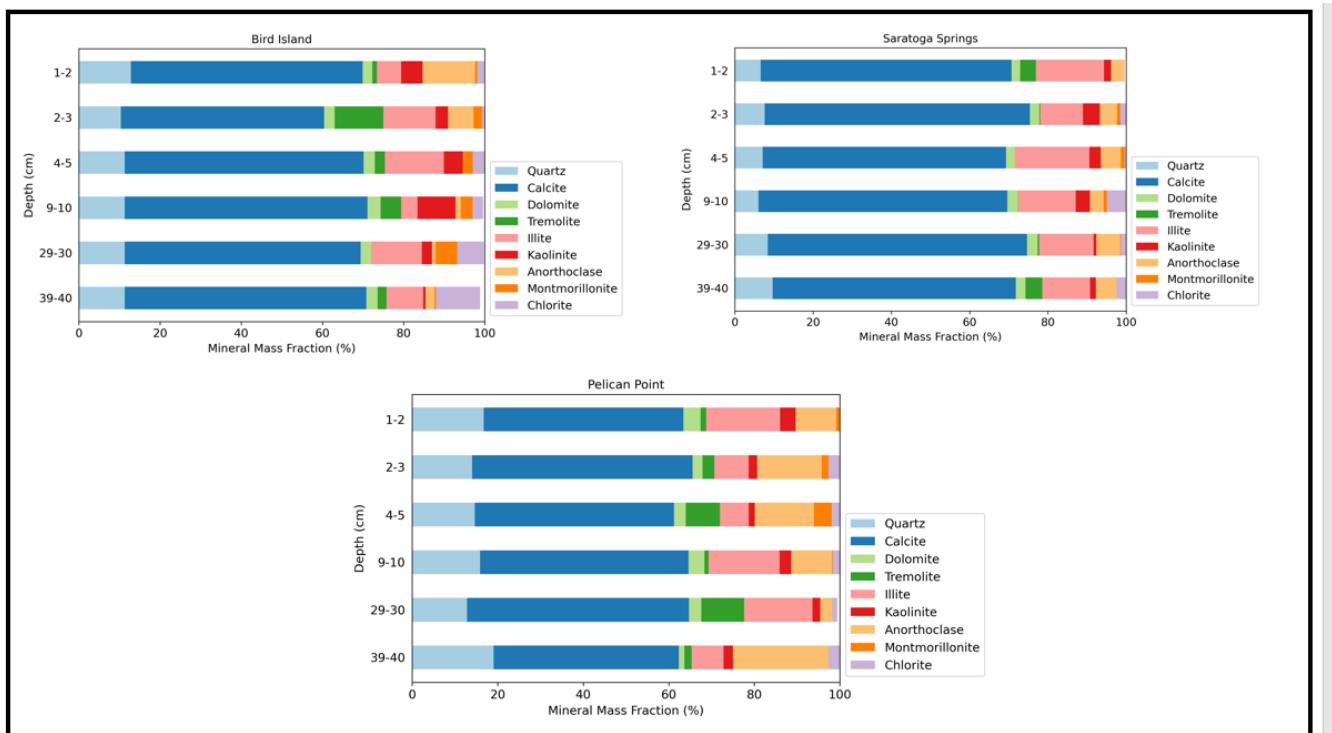


Figure 6b Mineralogy of Utah Lake Surface Sediment Cores

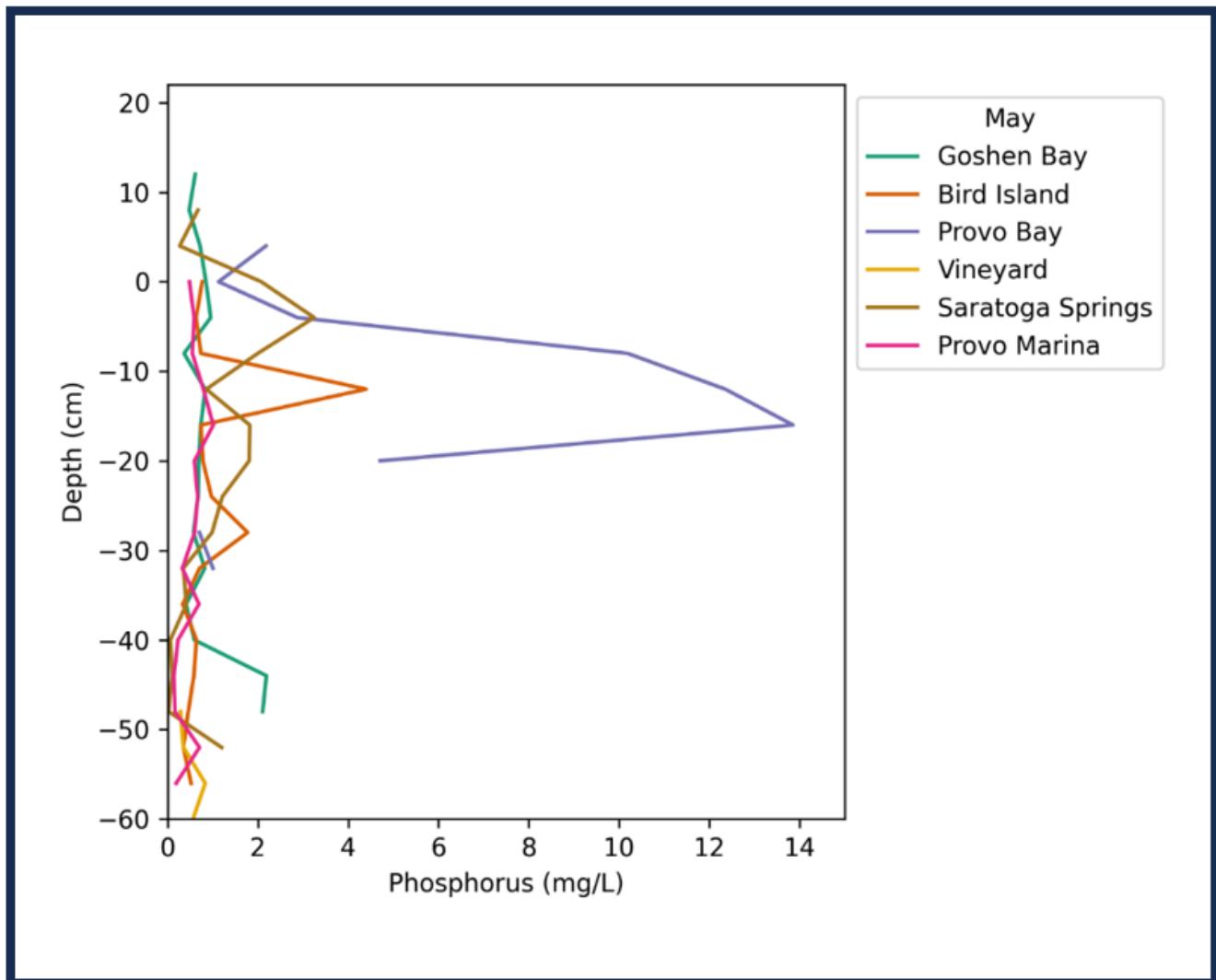


Figure 7 Porewater P concentrations as measured via ICP-OES near the sediment-water interface.

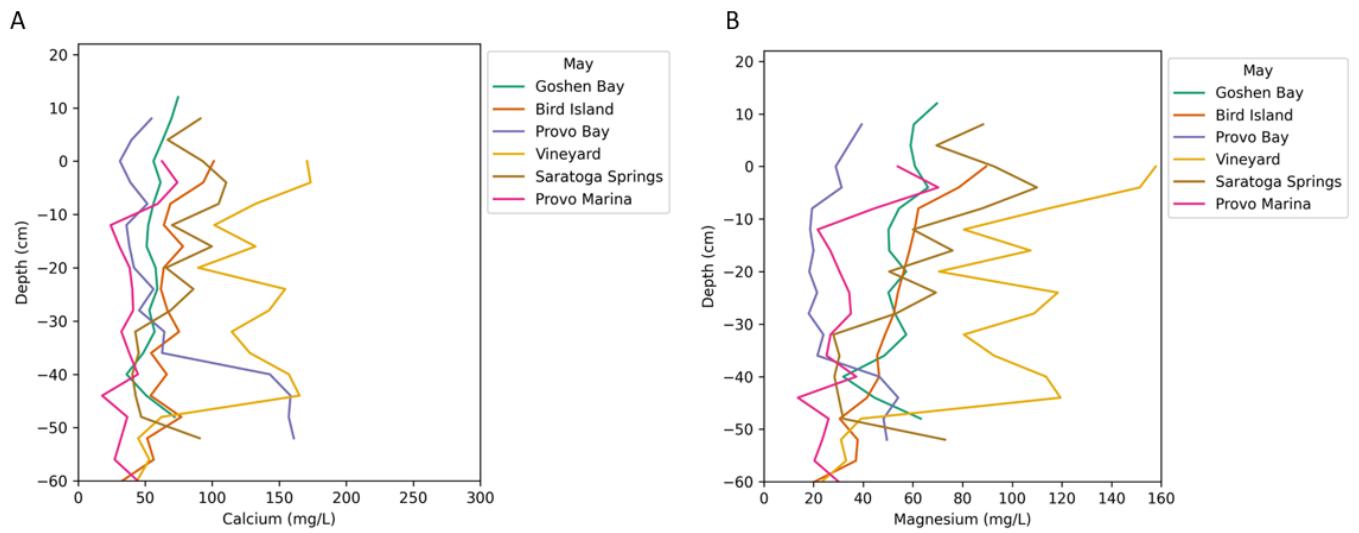


Figure 8 Porewater concentrations a) Calcium (Ca^{2+}) b) Magnesium (Mg) measured by ICP-OES in the sediment-water interface.

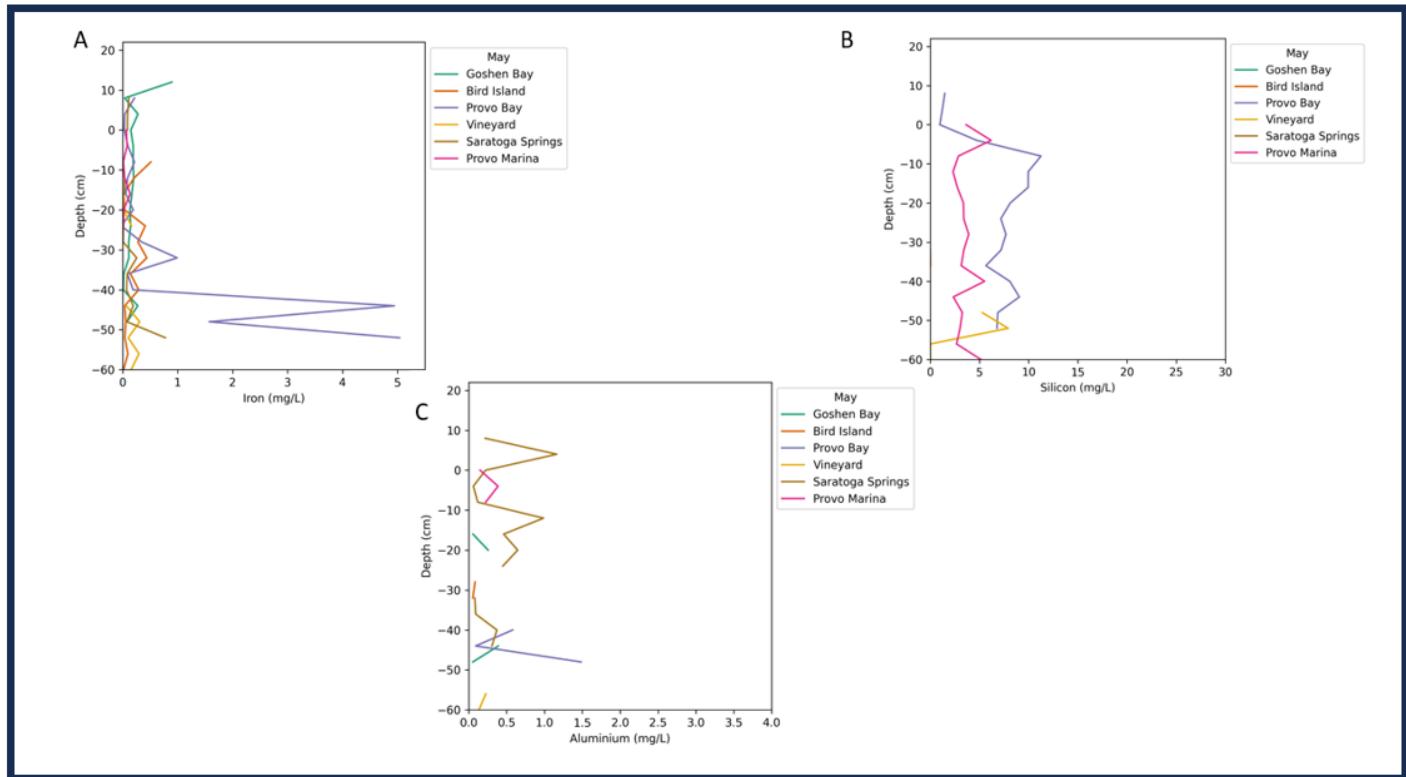


Figure 9 Vertical distribution of Porewater concentrations a) Iron b) Silica c) Aluminum

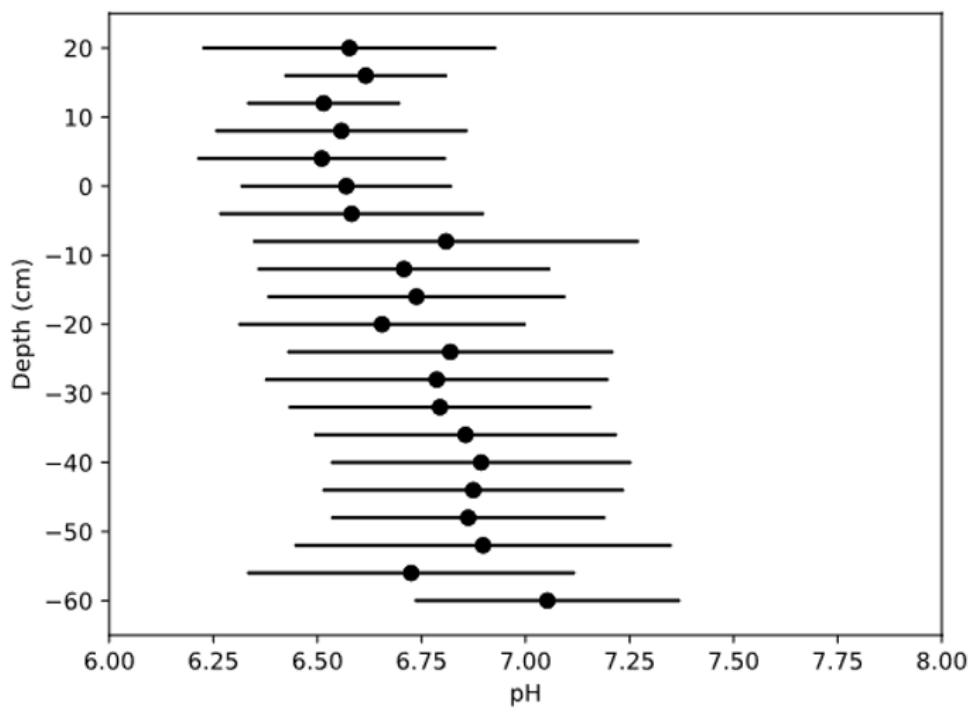


Figure 19a Average porewater pH of the seven sampling locations in Utah Lake.

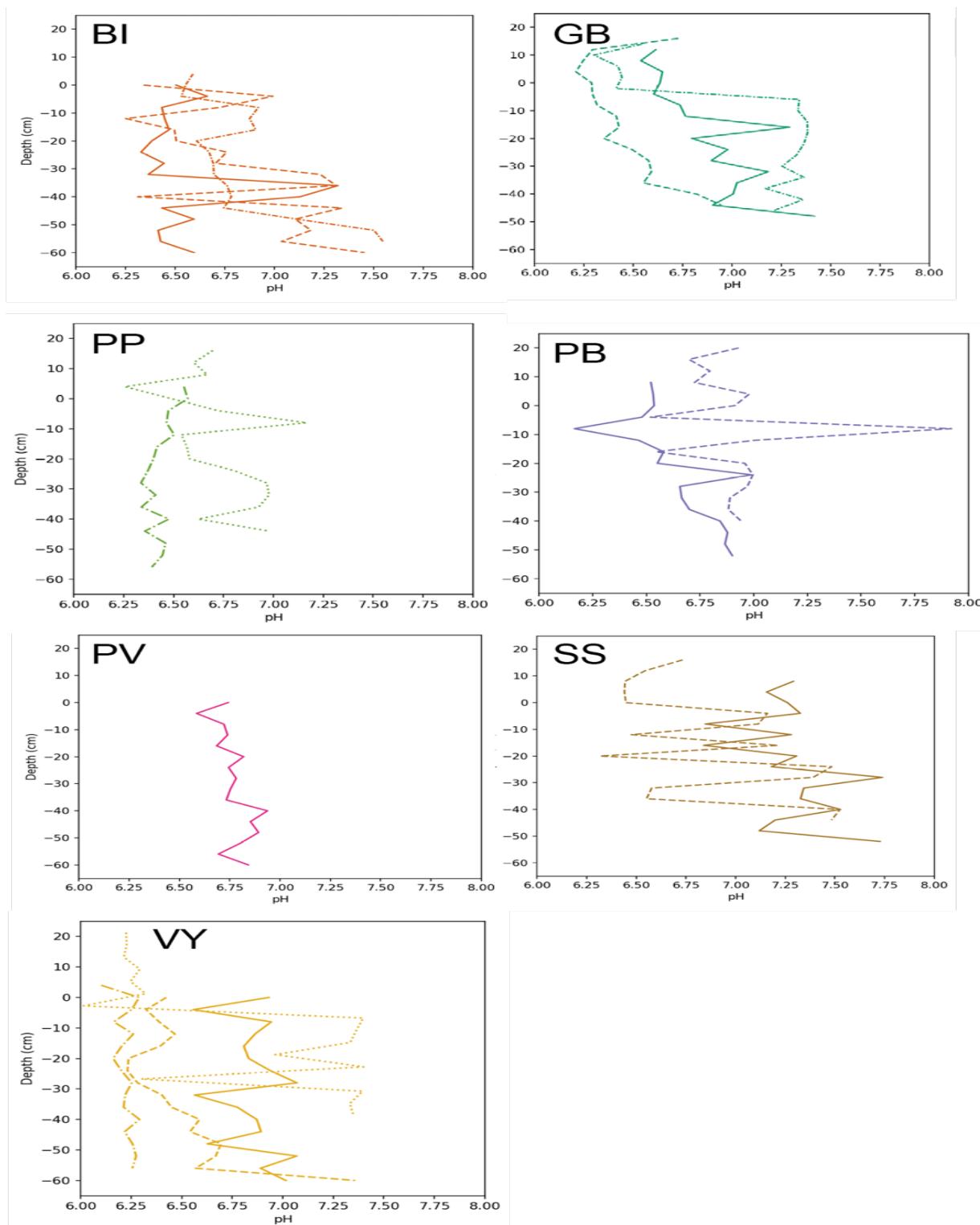
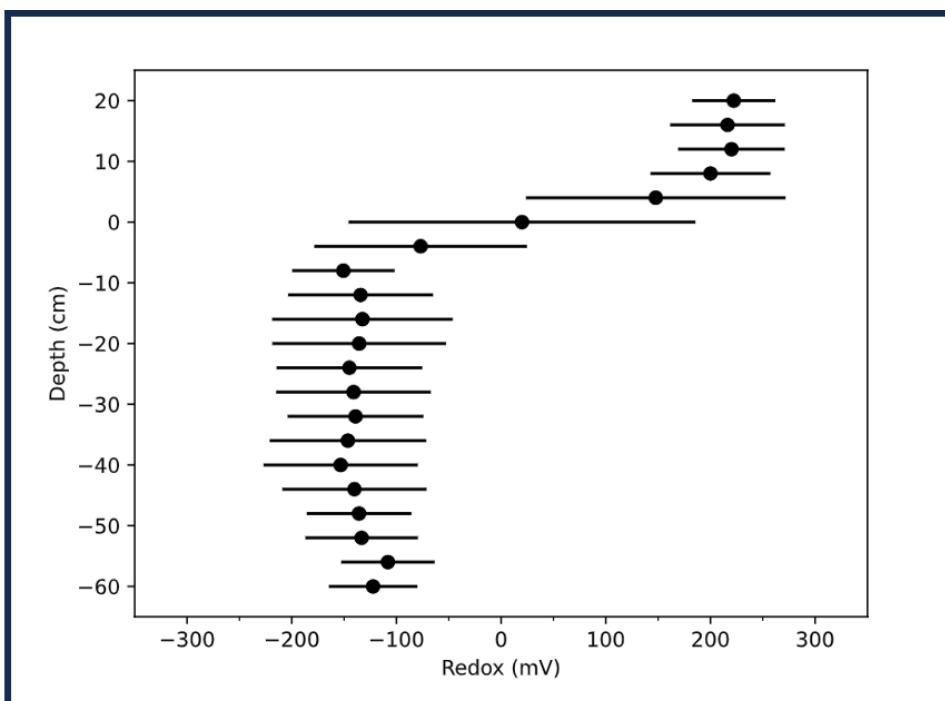


Figure 10b. Porewater pH as a function of depth at all sites across Utah Lake. Different line patterns show different sampling dates.

A



B

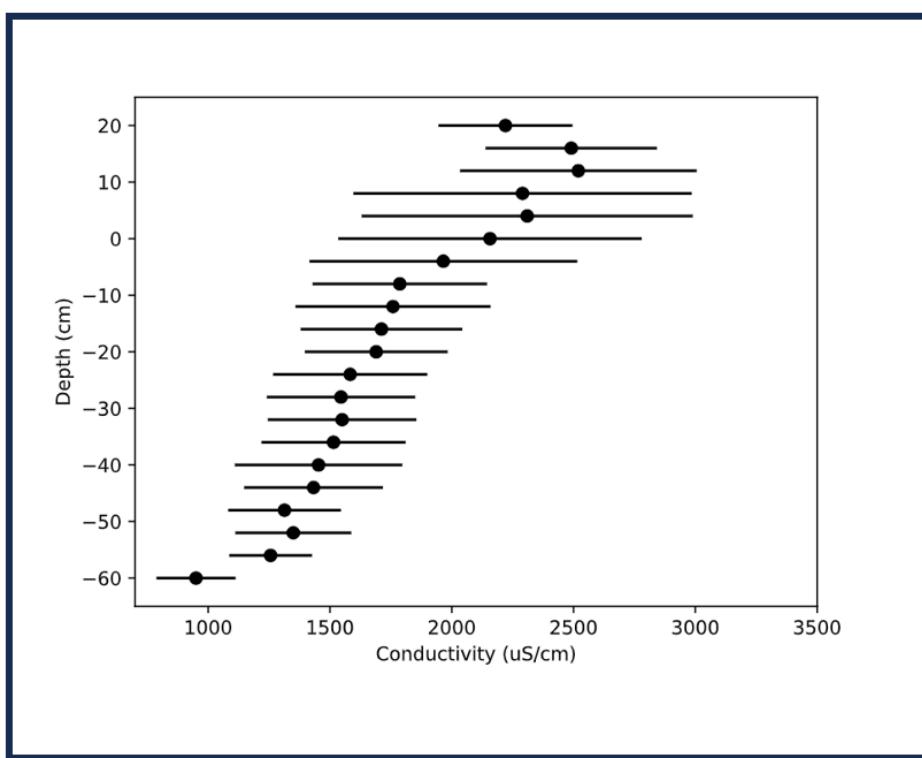


Figure 11 Water column profiles of a) Porewater redox potential and b) Average Porewater Conductivity in Utah Lake sediments.

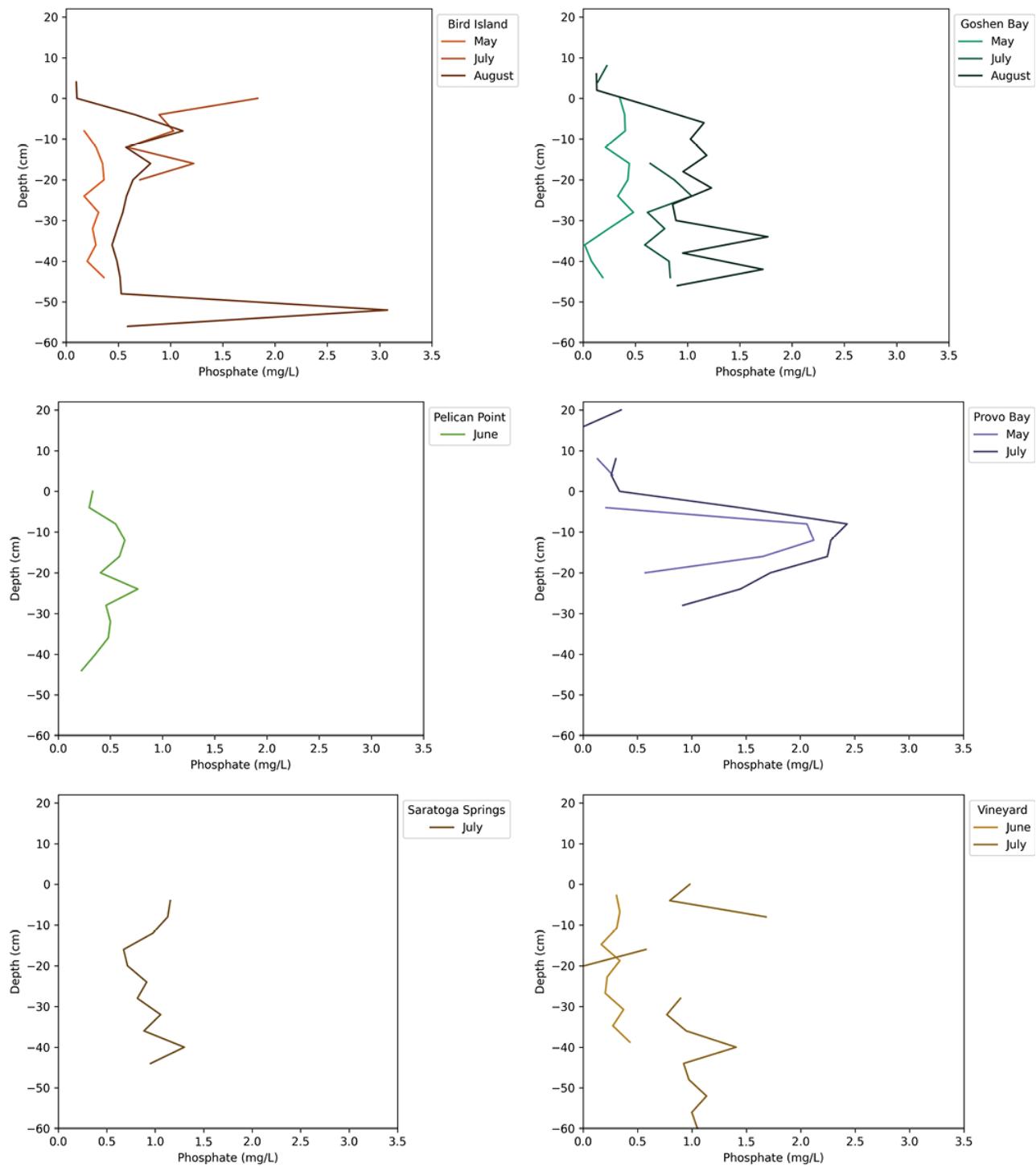


Figure 12 Sediment porewater phosphate concentrations

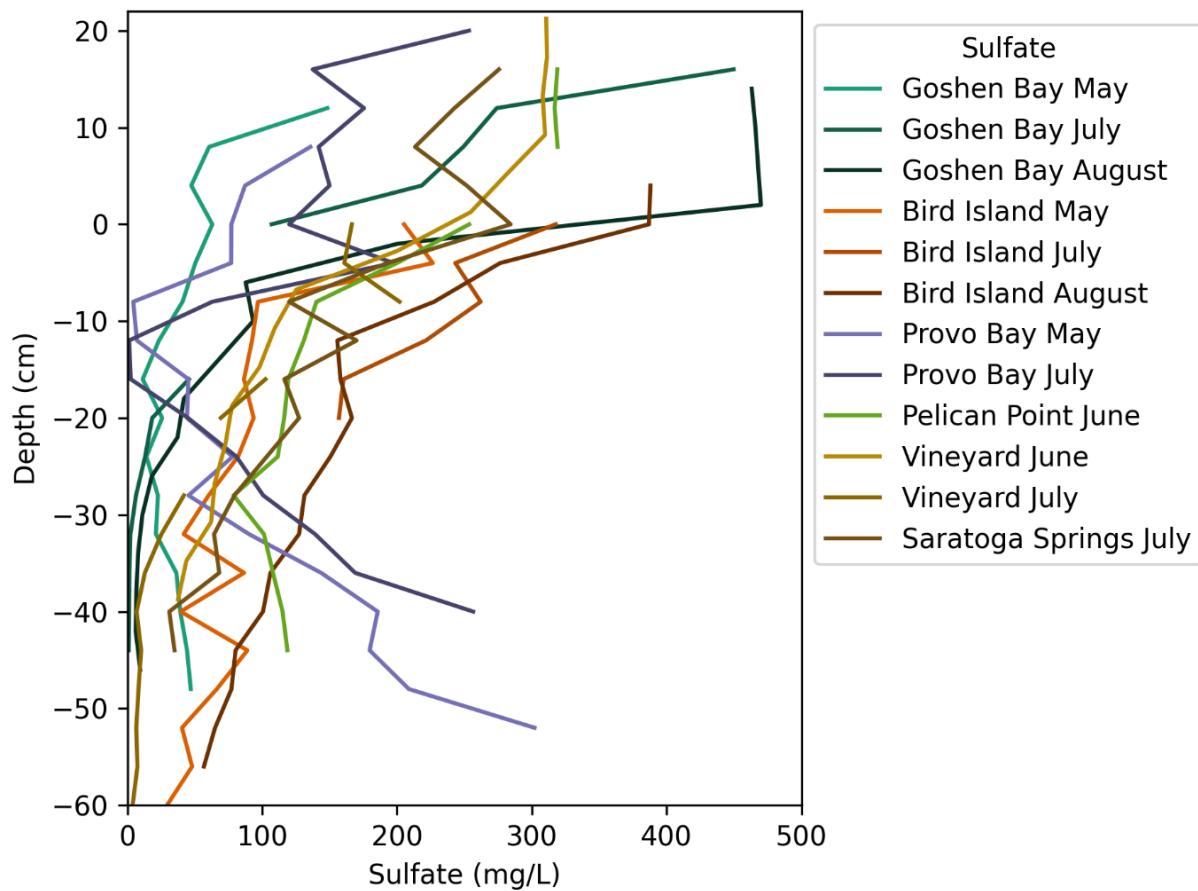


Figure 13 Ion Chromatography (IC) measured dissolved sulfate in surface water across seven sampling sites at different months.

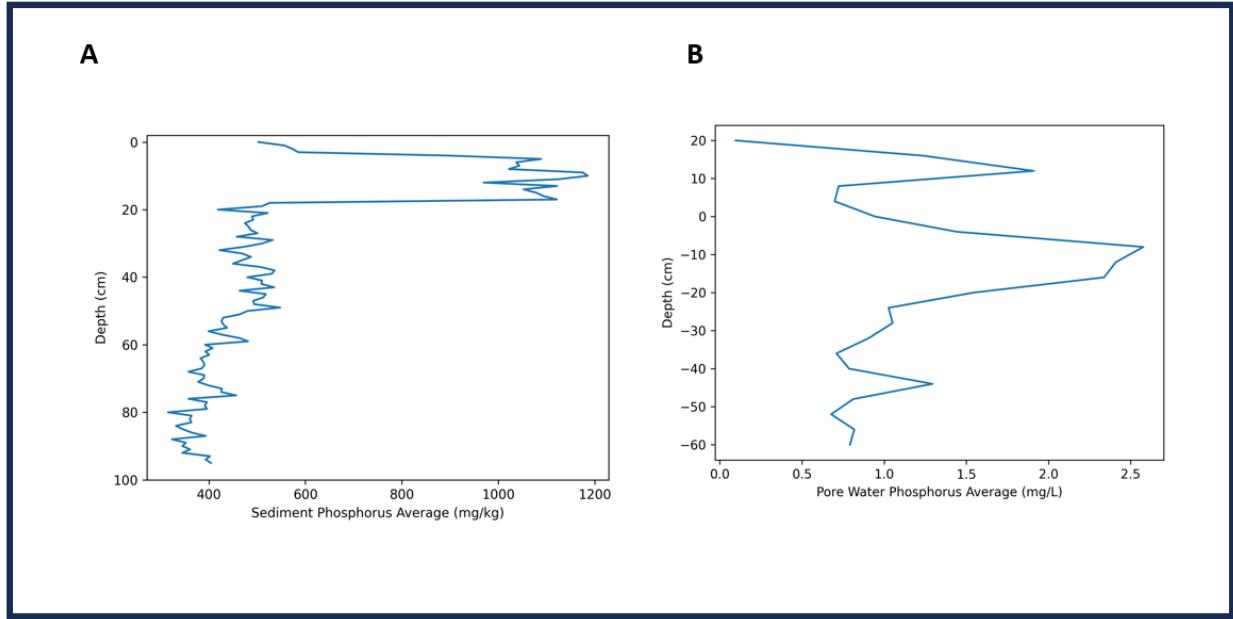


Figure 14 Average a) Sediment phosphorous and b) porewater phosphorous across all sampling sites with depth

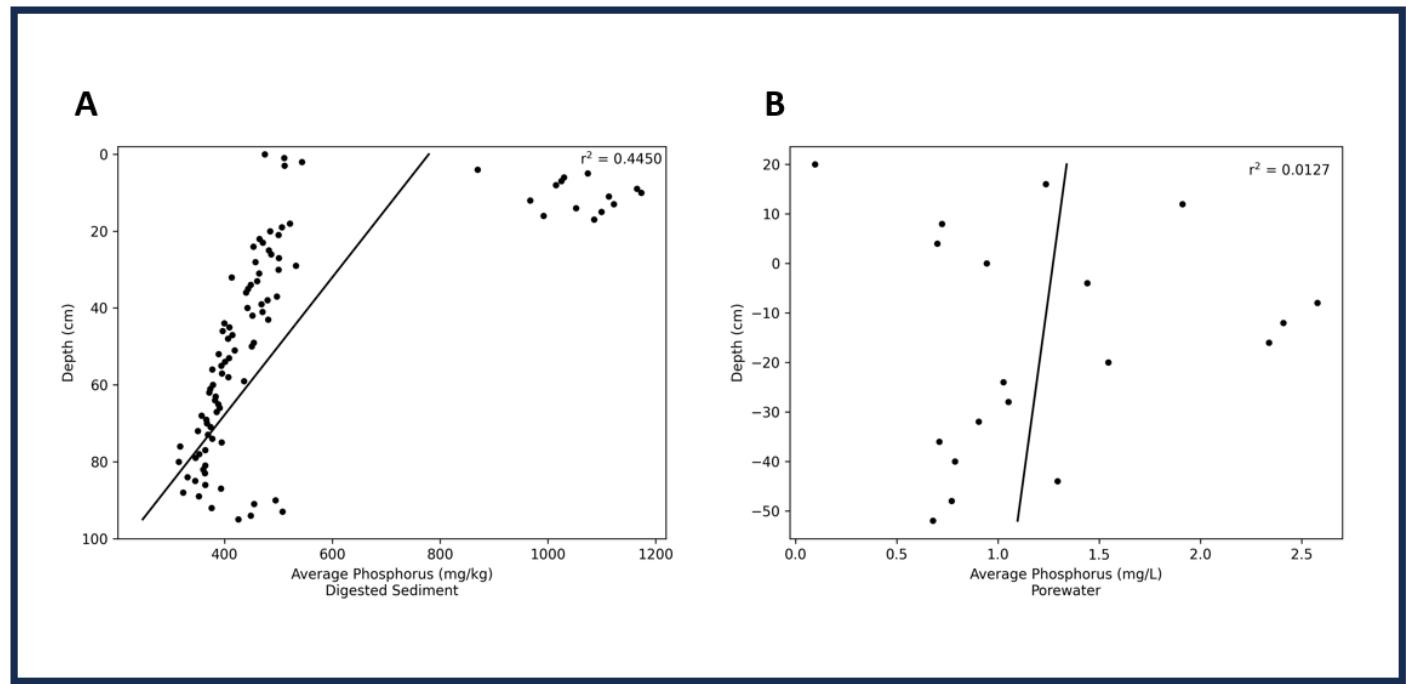
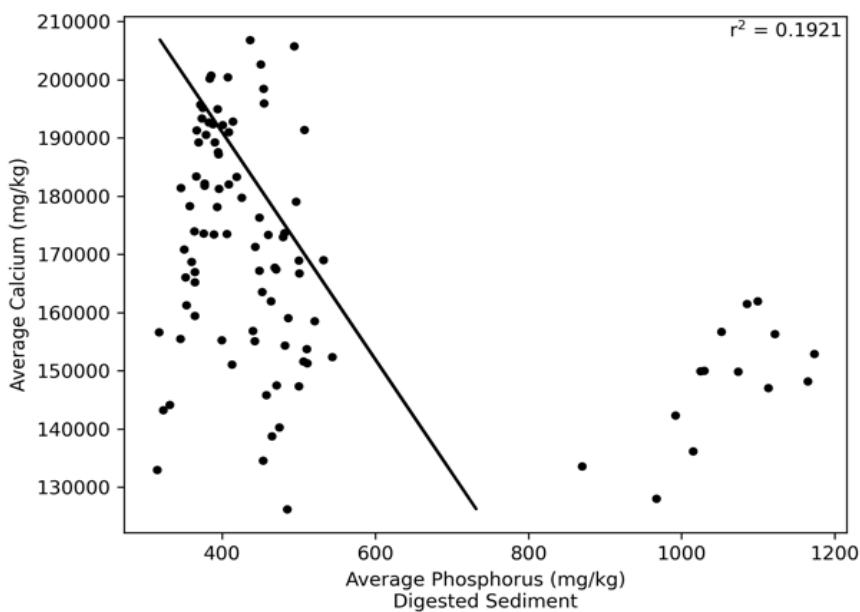


Figure 15 Average a) Phosphorous of digested sediment and b) Porewater phosphorous linear regression line ($r^2 = 0.4450$ and $r^2 = 0.0127$, respectively).

A



B

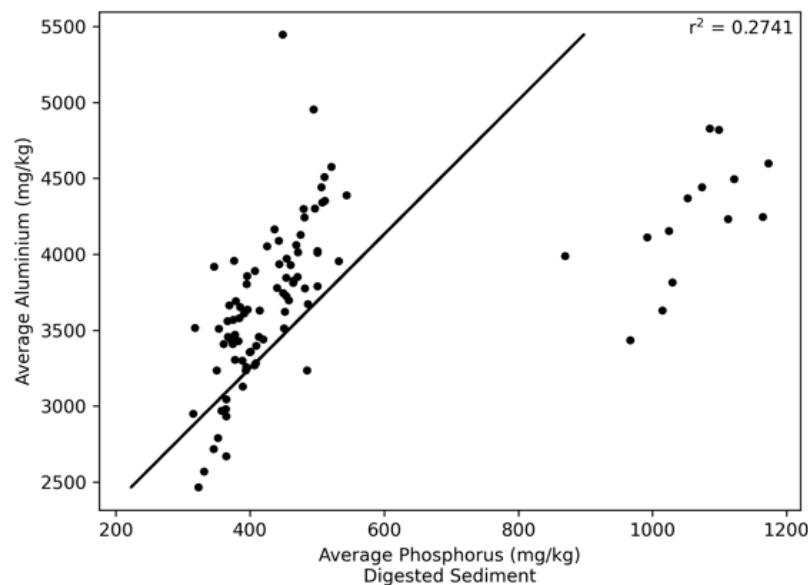
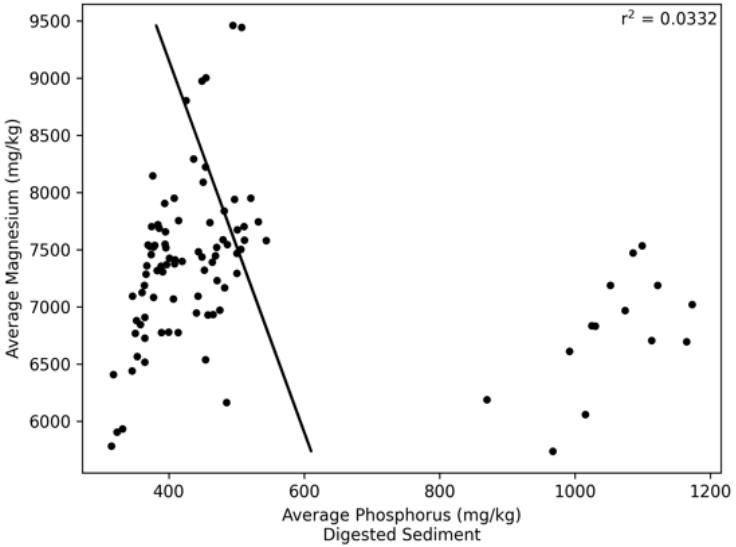


Figure 16a Relationship of P concentrations in surface sediment with depth a) Ca, b) Al. Concentration P, and Al are positively correlated with water depth and negatively correlated with Ca.

A



B

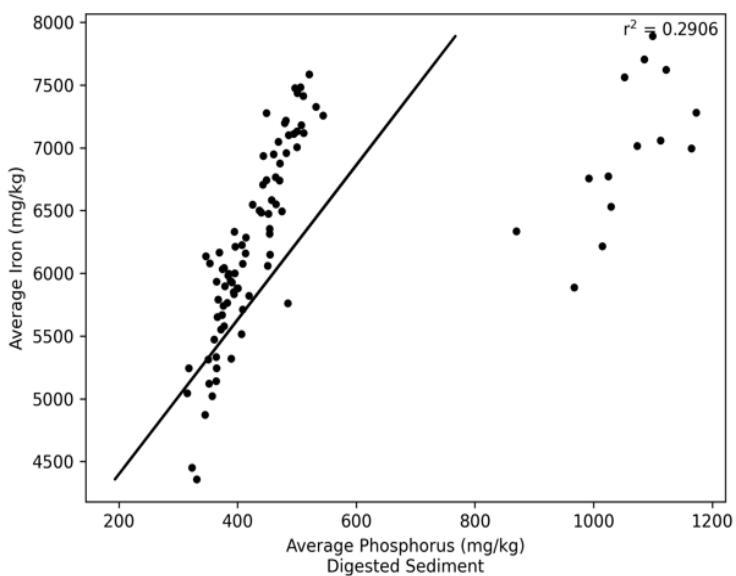


Figure 16b Relationship of P concentrations in surface sediment with depth a) Mg, b) Fe. Concentration P, Mg and Fe are positively correlated with water depth

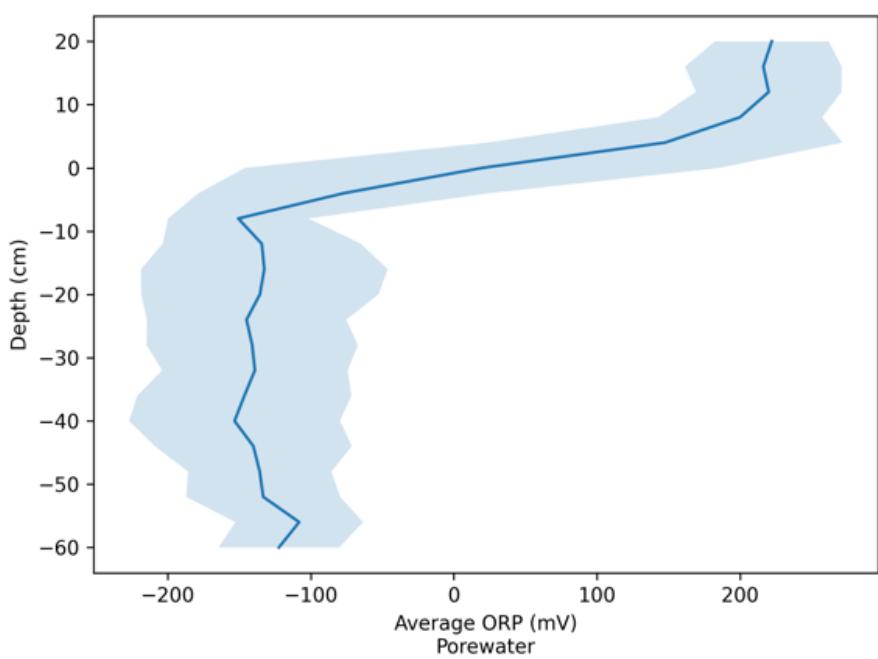


Figure 17 Porewater redox condition averaged across all sampling sites and collection periods with 95% Confidence interval in light blue color

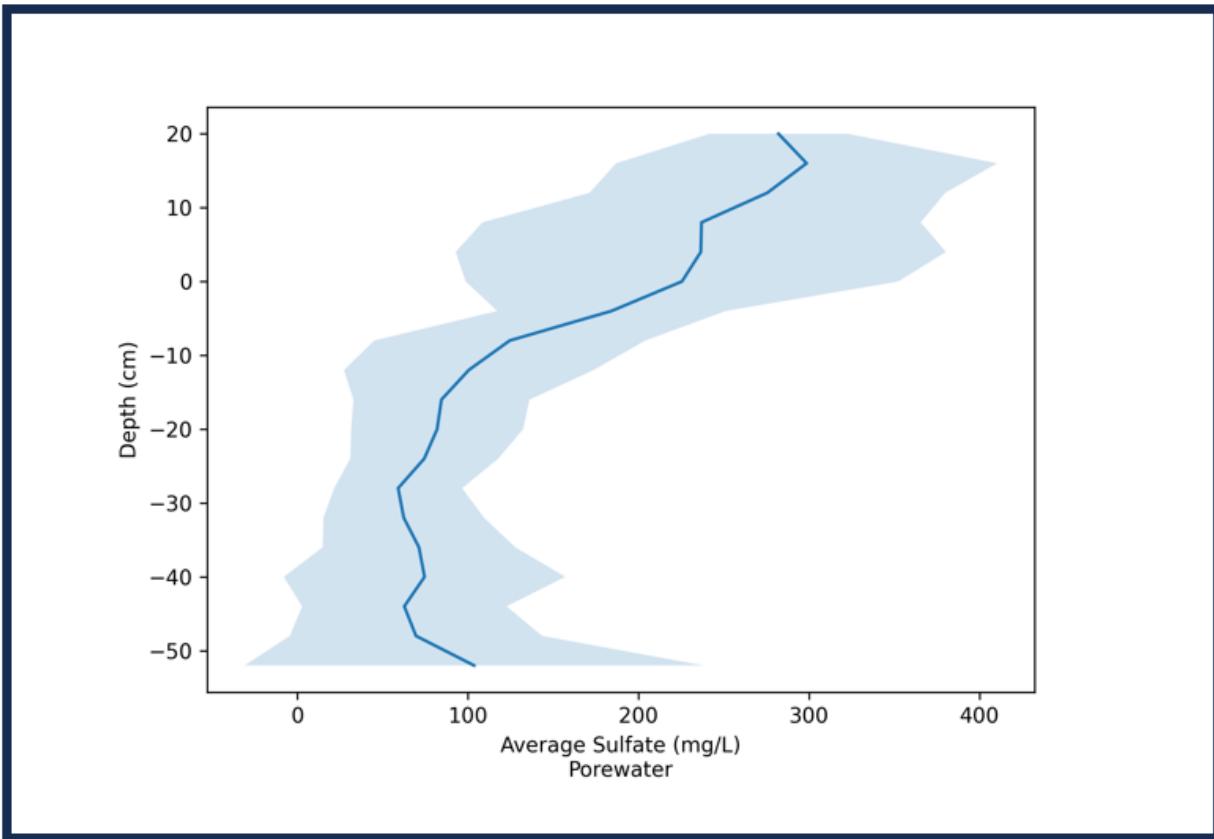


Figure 18 Porewater sulfate concentration averaged across all sampling sites with 95% confidence interval in light blue color