scwd² Seawater Desalination Program
Offshore Geophysical Study

3 August 2010 **Final Technical Report**

Prepared for:

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ECO-M Reference No. 09-05a

scwd²
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GLOSSARY

Aggradational	Building up a surface by deposition of sediment
Alluvial	Deposited by a stream or moving water
Aquifer	Rock or sediment that is saturated and sufficiently permeable to transmit economic quantities of water to wells or springs
ASTM	American Society for Testing and Materials
Boomer	A geophysical exploration instrument that provides a controlled sound source
Compressional wave	A wave propagated by means of the compression of a fluid, as a sound wave in air; a disturbance traveling in an elastic medium; characterized by changes in volume and by particle
Continental shelf	The part of the continental margin between the shoreline and the continental slope
Continental slope	The part of the continental margin between the continental shelf and the deep ocean floor
D10	The size corresponding to the 10 percent passing line on the grain-size curve
D50	The median grain size
Delta	The nearly flat alluvial tract of land at the mouth of a river, commonly triangular or fan-shaped
E-n	Equal to 10^{-n}
Eustatic	Pertaining to worldwide changes in sea level
Fan delta	A gently sloping alluvial deposit produced where a mountain stream flows out into a lowland
Fine sediment	All particles with grain sizes smaller than 0.0625 mm in diameter (e.g., silt and clay).
Fluvial	Of or pertaining to streams or rivers
Geomorphology	The study of the classification, description, nature, origin, and development of landforms and their relationships to underlying structures and past geologic events
Geophone	A pressure-sensitive detector that responds to sound transmitted through land
Geopulse	A geophysical sub-bottom profiler trade name
Graben	A depressed block of land bordered by parallel faults
Holocene	The second (and current) epoch of the Quaternary Period, lasting from approximately 10-12 ka to the present
Hydraulic conductivity	A coefficient of proportionality describing the rate at which water can move through a permeable medium
Hydrophone	A pressure-sensitive detector that responds to sound transmitted through water
Hydrophone streamer	A cable containing many hydrophones towed behind a boat and used to record sound waves in water
Interstadial	Substages of a larger glacial period

Joule	A unit of energy, the energy exerted by the force of one Newton acting to move an object through the distance of 1 meter
k	Hydraulic conductivity coefficient (cm/sec)
ka	Thousands of years ago
Lag deposit	A residual coarse-grained deposit on a surface after the finer-grained material has been removed by wind or water
LGM	Last Glacial Maximum
Ma	Millions of years ago
MCS	Multi-channel seismic
Meander	A sinuous curve or loop in the course of a mature stream or river
mgd	Millions of gallons/day
m/kyr	Meters per thousand years
MLLW	Mean lower low water
msec	Millisecond
Myo	Million years old
Miocene	The fourth epoch of the Tertiary Period, occurred between 23 – 5.3 Ma
Normal moveout	The increase in arrival time of a seismic-reflection event resulting from an increase in the distance from source to detector, seismic data must be corrected for normal moveout
OIS	Oxygen isotope stage, which are alternating warm and cool periods in the earth's paleo-climate, deduced from oxygen isotope data reflecting temperature curves derived from data from deep sea core samples
Paleochannel	An ancient, currently inactive, river or stream channel
Permeability	The capacity of porous rock or sediment to transmit fluids
Pleistocene	The first epoch of the Quaternary Period, lasting from approximately 2.6 Ma to 10-12 ka, covers the most recent period of Earth's glaciations
Pliocene	The final epoch of the Tertiary Period, occurred between 5.3–2.6 Ma
Quaternary	The second period of the Cenozoic era, following the Tertiary, lasting from approximately 2.6 Ma to present
Regression	The retreat of the ocean away from the land, results in a coarsening upward sequence of deposits
RMS velocity	The value of the square root of the sum of the squares of the velocity values divided by the number of values
Sand	Particles with grain sizes from 0.0625 to 2 mm in diameter
scwd²	The City of Santa Cruz Water Department and Soquel Creek Water District
Seismic	Pertaining to an earth vibration (caused by sound waves in our study)
Seismic impedance	The product of density and seismic velocity, which varies among separate rock layers, commonly symbolized by Z
Shear wave	Motion that is perpendicular to the direction of propagation in a seismic event
Shot point	The location at which the seismic source is initiated
Sub-bottom profiler	A geophysical instrument that provides data on sub-seafloor strata by sending sound signals into the seafloor and recording the return signals

SWRO	Seawater reverse osmosis
Thalweg	The line defining the lowest points along the length of a river bed, corresponds to the area of the stream/river with the highest flow rate
Tidal Prism	Defined in this report as the volume of ocean water flowing in or out San Lorenzo River
Transgression	The spread of the ocean over land areas, results in a fining upward sequence of deposits
Transitional zone	The area between the land and the sea that is geologically interactive
Transmissivity	The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient, it is the product of the hydraulic conductivity and the saturated thickness of the aquifer
twtt	Two-way travel time, time that it takes for the seismic wave energy to reach the reflecting interface from the acoustic energy source and return to the recording array
Unconformity	A break or gap in the geologic record
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
Vibracore	A system to extract seafloor sediment cores that utilizes vibration to achieve penetration into the seafloor

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EXECUTIVE SUMMARY

The City of Santa Cruz Water Department (SCWD) and Soquel Creek Water District (SqCWD) depend upon local water supplies to meet the needs of their customers. However, the Water Department's surface waters are frequently diminished by droughts and the District's groundwater supply is threatened by declining water levels and seawater intrusion.

Each agency conducted separate integrated water planning processes and each identified seawater desalination as the best option for delivering an additional flexible and reliable water source. To take advantage of the benefits derived from a cooperative facility, the agencies joined together, forming the **scwd²** Task Force, to address their different needs and to share the investigative costs associated with the potential desalination plant. If the desalination plant is constructed, SCWD will be able to address its drought protection needs and SqCWD will be able to protect its groundwater resources from seawater intrusion. Both agencies will continue to practice conservation and curtailment to maximize efficient use of water resources.

In October 2008, the City, on behalf of **scwd²**, retained EcoSystems Management Associates, Inc., to perform a study of the sediment offshore of Santa Cruz. The study was designed to support the Intake Feasibility Study, which will report on the results of investigations of open screened water intake and a subsurface intake option to supply seawater to the proposed desalination facility. The offshore geophysical study was conducted to provide data about an offshore alluvial basin and two other buried paleochannels that had been formed and filled since the Last Glacial Maximum. The study area extended from west of the municipal wharf to east of the Santa Cruz Harbor, up the beach at the San Lorenzo River mouth approximately 1000 feet (305 m) and offshore approximately 3000 feet (914 m). See Figure 1-1.

The goals of the offshore geophysical study were to:

- Map the extent of the offshore paleochannels in three dimensions. Seismic reflection data collected during the survey were used to map the alluvial basin and paleochannels, identify bedrock and faults, and preliminarily characterize deep channel fill.
- Characterize the sediment within the paleochannels. Seismic reflection data was interpreted to estimate the thickness of alluvial sediment. Sediment cores were tested to identify the geotechnical properties (i.e., soil type, grain size, density, and hydraulic conductivity) to develop an understanding of existing conditions in the shallow portion of the three paleochannels.
- Provide preliminary seawater production information for the San Lorenzo River alluvial basin. Geotechnical and geophysical properties of the alluvial basin were used to evaluate the production capabilities of conceptual-level subsurface design alternatives.

Four key findings of the offshore geophysical study are described below.

Finding One. The Buried Alluvial Channels of the San Lorenzo River, Neary Lagoon, and Woods and Schwan Lagoons Were Found and Mapped in Three Dimensions.

A map of the San Lorenzo River Last Glacial Maximum (LGM) paleochannel and the two other paleochannels (Neary and Woods/Schwan channels) is presented in Figure ES-1. Near the river mouth, the San Lorenzo River alluvial basin paleochannel is 1,000 feet wide (305 m), and ranges from 40 to 128 feet (12.2 to 39 m) deep. Offshore, it has narrow, winding, and steep sides and deepens to approximately 150 feet (46 m). The Neary channel merges with the main channel at the western edge of the main channel meander, which creates an east-west trending alluvial basin channel nearly 5,000 feet (1,524 m) long. The area just north of the wharf consists of an alluvial basin partly filled with a delta channel/levee complex that resulted from ancient meanders of the San Lorenzo River and Neary channel sections.

A zone of northwest-trending faults cuts across the San Lorenzo River channel about 400 to 1,200 feet (122 to 365 m) south of the shoreline. Boomer seismic profiles show these faults cutting into the channel fill sediment so that there may be some impedance of lateral fluid flow if these faults have created significant offset of coarse-grained aquifer layers.

Geophysical data indicate that alluvial sediment is thinner across the western half of the aquifer and is deepest near the present active channel near the San Lorenzo River mouth. A fence diagram showing the channel configuration provided by the offshore survey lines is provided in Figure ES-2.

Finding Two. The San Lorenzo River Paleochannel Contains Sand, Silt, Clay and Gravel Whereas the Other Two Paleochannels Contain Mostly Mud, Clay and Silt.

Shallow offshore vibracore data and 42 ft (12.8 m) deep onshore data confirm that the San Lorenzo River alluvial basin's shallow sediment is heterogeneous. Samples show fine sand and silty sand interbedded with silt, clay, and coarse-grained deposits.

The Neary paleochannel and Woods/Schwan paleochannel appear to be filled with mostly fine-grained sediment (i.e., mud, clay and silt) and to contain significant quantities of gas. Given the certainty of the low permeability of the shallow sediment in these two channels and the strong reflective horizons noted in seismic profiling, further study of these paleochannels is not recommended.

Eleven vibracores were collected in the study area to sample depths that ranged between 4.5 and 15.5 feet (1.4 and 4.7 m) below the ocean floor (Figure ES-1.) Six cores were collected from the San Lorenzo River paleochannel (VC-2, 3, 4, 5, 6, and 14). These core lengths varied from 6 ft (1.8 m) (VC-5) to 15.5 ft (4.7 m) (VC-6). Fine sand or silty sand was found on average in the top 3 to 5 ft (0.9 m to 1.5 m) of the cores. The core nearest the beach, VC-2, primarily reflects the active layer of sand that outwashes from the San Lorenzo River and is deposited on the nearshore seabed. Seasonal wave action transports this sediment along the shore and farther offshore,

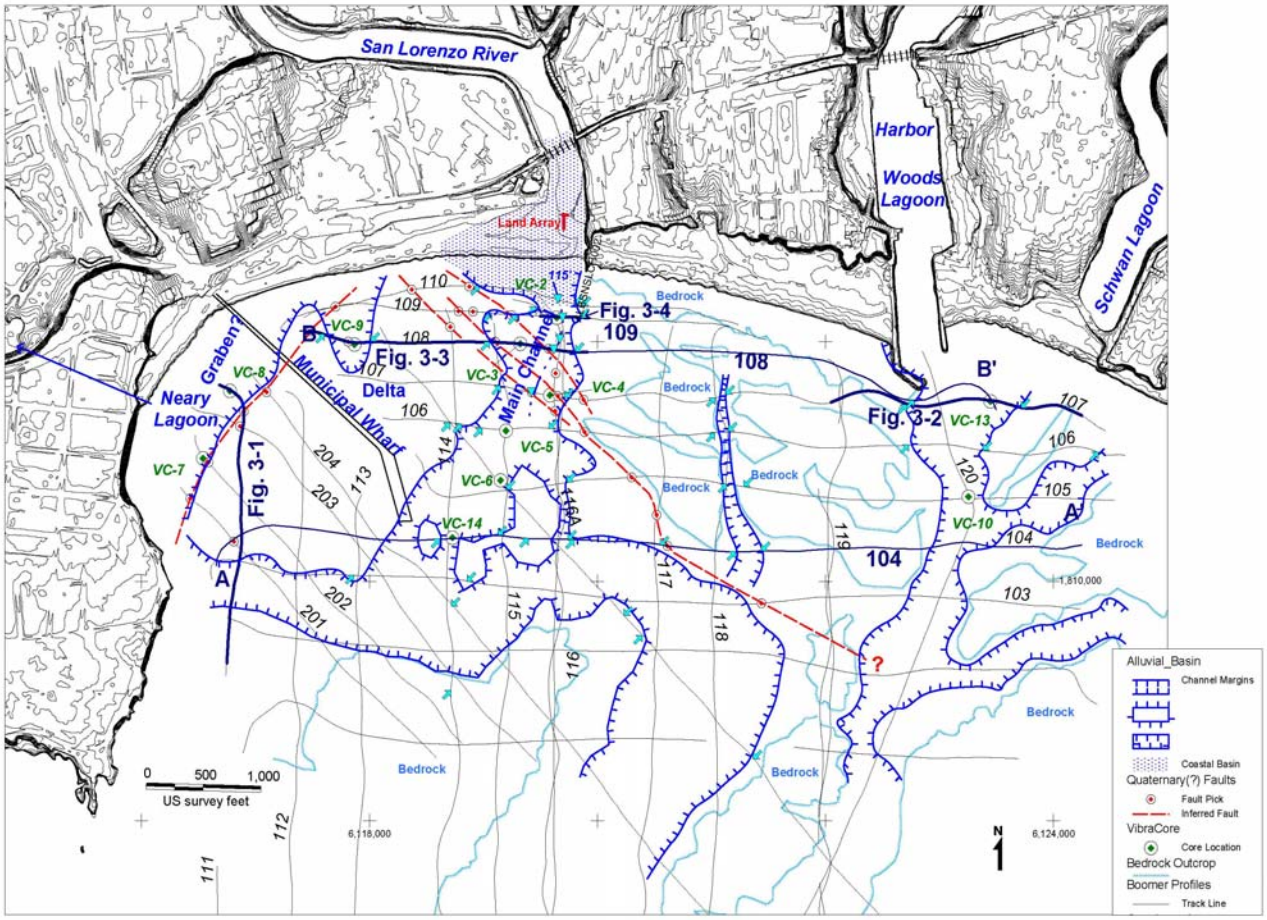

Figure ES-1. Offshore paleochannel location map. The hatch-marked lines in the center left of the map (hatches pointing down slope) show the channel boundary. Vibracore sites are noted with "VC."

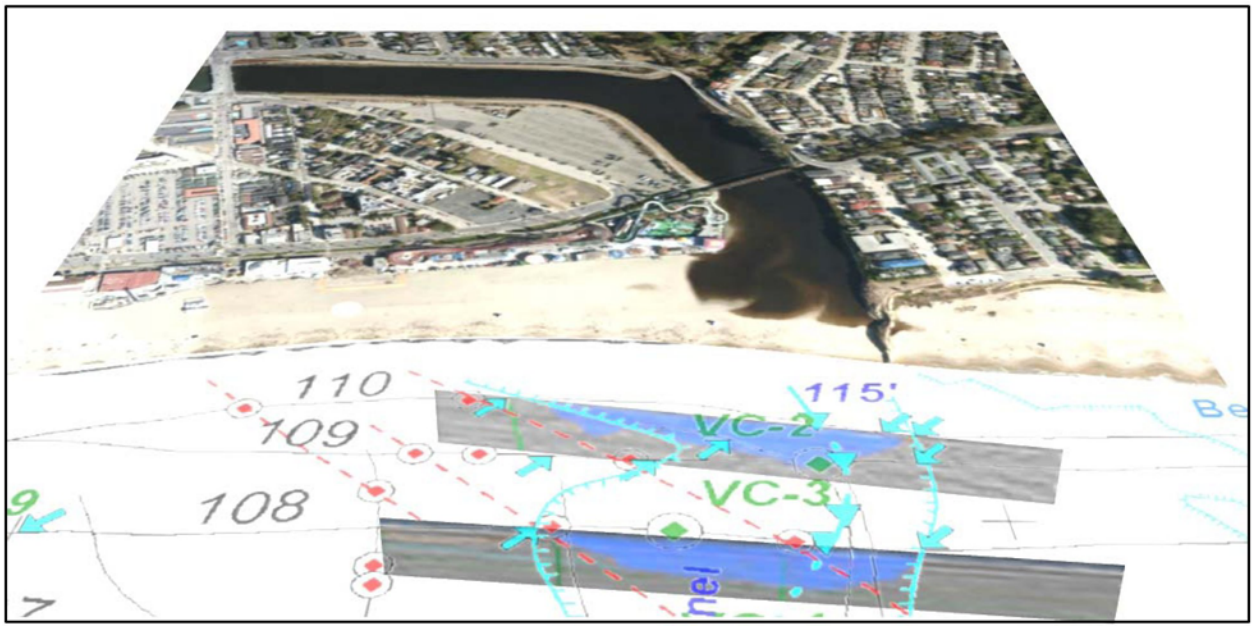

Figure ES-2. Fence diagram of alluvial aquifer using offshore geophysical survey lines showing nearshore portion of the paleochannel within the light blue lines.

where it remains until strong episodic storm events cause complete removal and redeposition farther offshore into the Monterey Bay.

Moving offshore, the active coarse-grained sand layer comprises much less (a thinner section) of the top portion of the cores. The middle of the cores is composed of varying percentages of coarse-grained materials in each core location, and sediment ranges across the full grain size spectrum from gravel to clay. The bottom of the cores consists of a poorly sorted material within which the coarse, gravelly sand caused core refusal. Coarse sand thickness varied from 1 to 10 ft in the cores (0.3 m to 3 m). Silt/clay layers were found in three of the cores: a 0.1 ft (0.03 m) thick layer in VC-4, a 1 ft (0.3 m) thick layer in VC-6, and a 3 ft (0.9 m) thick layer in VC-14. Reddish-brown iron-stained deposits are visible in the cores containing older sediment that had been deposited and reworked in the past.

The evidence of sand, silt, clay and gravel in the San Lorenzo River alluvial basin's main offshore paleochannel was reinforced in the report by the production of a stratigraphic column, which is a model based on a compilation of data from soil samples (vibracores and U.S. Army Corps of Engineers (USACE) borehole data from the nearby San Lorenzo River levee study) and seismic profiling. This was done to characterize the sediment fill of the entire channel. The USACE boreholes taken up the river are in an area where the geological record is not expected to be very different from the paleochannel fill in the nearshore area where the cores were taken. The stratigraphic column (Figure E-1, Appendix E), showing a representation of channel fill sequence lithology, was constructed by extrapolating the layering identified in the USACE borehole data to the base of the offshore paleochannel, basing some of it on inference from the boomer seismic profiles of the nearshore area. The part of the stratigraphic column deeper than the USACE borehole data, about 42 feet (12.8 m), was modeled based on the shallow core data and typical channel fill deposits from similar environments.

Finding Three. Laboratory Analysis Demonstrated the Geotechnical Properties of the Soil Samples for Estimation of the Alluvial Aquifer's Productivity.

Twenty-three sediment samples were taken from the cores and analyzed for grain size, and 11 samples were analyzed for hydraulic conductivity and moisture density. Grain size analysis, data, and moisture density values are shown in Tables 5-3, 5-4 and 5-5. The laboratory results showed a range of hydraulic conductivities within the San Lorenzo River paleochannel from $1x10^{-2}$ cm/sec to $1x10^{-7}$ cm/sec. For comparative reference, productive aquifers generally are composed mostly of sediment with hydraulic conductivities of $1x10^{-1}$ cm/sec to $1x10^{-3}$ cm/sec. The following points are highlights of the hydraulic analysis of the alluvial aquifer's shallow sediment.

- The mobile active layer of fine sand with silt on the seabed had a hydraulic conductivity of 1×10^{-4} cm/sec, which was observed in VC-2, VC-3 and VC-5.
- Hydraulic conductivities of $1x10^{-3}$ cm/sec were observed in the coarse-grained sand samples from VC-3, VC-4, VC-6 and VC-14. The exception was VC-3, which had a section at a depth of 4.8-6 ft (1.5-1.8 m) with an order of magnitude higher conductivity of $1x10^{-2}$ cm/sec.

- The depths of the coarse-grained samples ranged from 4.8 to 6 feet (1.4-1.8 m) for the vibracore closer to shore, VC-3, to deeper than 9 ft (2.7 m) for VC- 4 and VC-6.
- In the upper portion of the vibracores farther from shore, fine-grained low conductivity lenses were found, specifically in VC-6 at 4-5 ft subsea with a hydraulic conductivity of $1x10^{-7}$ cm/sec, and in VC-14 at 4-5 ft (1.2-1.5 m) subsea (sample was 95% silt and clay).
- Several vibracore samples taken from San Lorenzo paleochannel showed seasonal grain-size grading that was fining upward in the sediment section. These deposits showed coarser-grained layers that were deposited during high river flow conditions (medium to coarse-grained sand with fine gravel), which gradually fined to a very fine-grained grayish colored sand.

The characteristics of the alluvial materials (fine sand, silt and clay) will impact production of a subsurface intake located to take advantage of sand and alluvial materials hydraulically connected to the ocean. For example, fine to very fine sand is the main sediment particle that controls seepage through the seafloor into the more productive layers of the aquifer. This is referred to in the report as a “confining layer.” The geotechnical properties (grain size analysis and hydraulic conductivity) of the vibracores sampled indicate that there is some productive aquifer material (gravel and coarse sand layers), some marginally productive aquifer material (fine to very fine-grained sand), and some unproductive aquifer material (silt and clay). Overall, the estimated hydraulic conductivity of the aquifer may be an order of magnitude too low to be of use for a 2.5 mgd facility.

Finding Four. The San Lorenzo River Paleochannel Sub-basin Map in Three Dimensions Was Delineated to Define Preliminary Concepts for the Location of Subsurface Intakes.

Figure ES-3 is a structural contour map in 3-D, which was generated from geophysical data about the seafloor and shallow (<650 feet, 200 m) subsurface sediment offshore. In the sub-basin location map, the divisions are made artificially in an alluvial basin that is geologically continuous. The three areas are identified as onshore, nearshore, and offshore alluvial sub-basins. These three areas were designated based on the different anticipated aquifer conditions and the potential challenges to installation and operation of groundwater extraction facilities. Preliminary concepts for subsurface intakes discussed in Section 6.4 include:

- onshore vertical wells
- onshore caisson collector wells
- shoreline vertical wells
- shoreline slant wells
- offshore caisson collector well
- offshore infiltration gallery

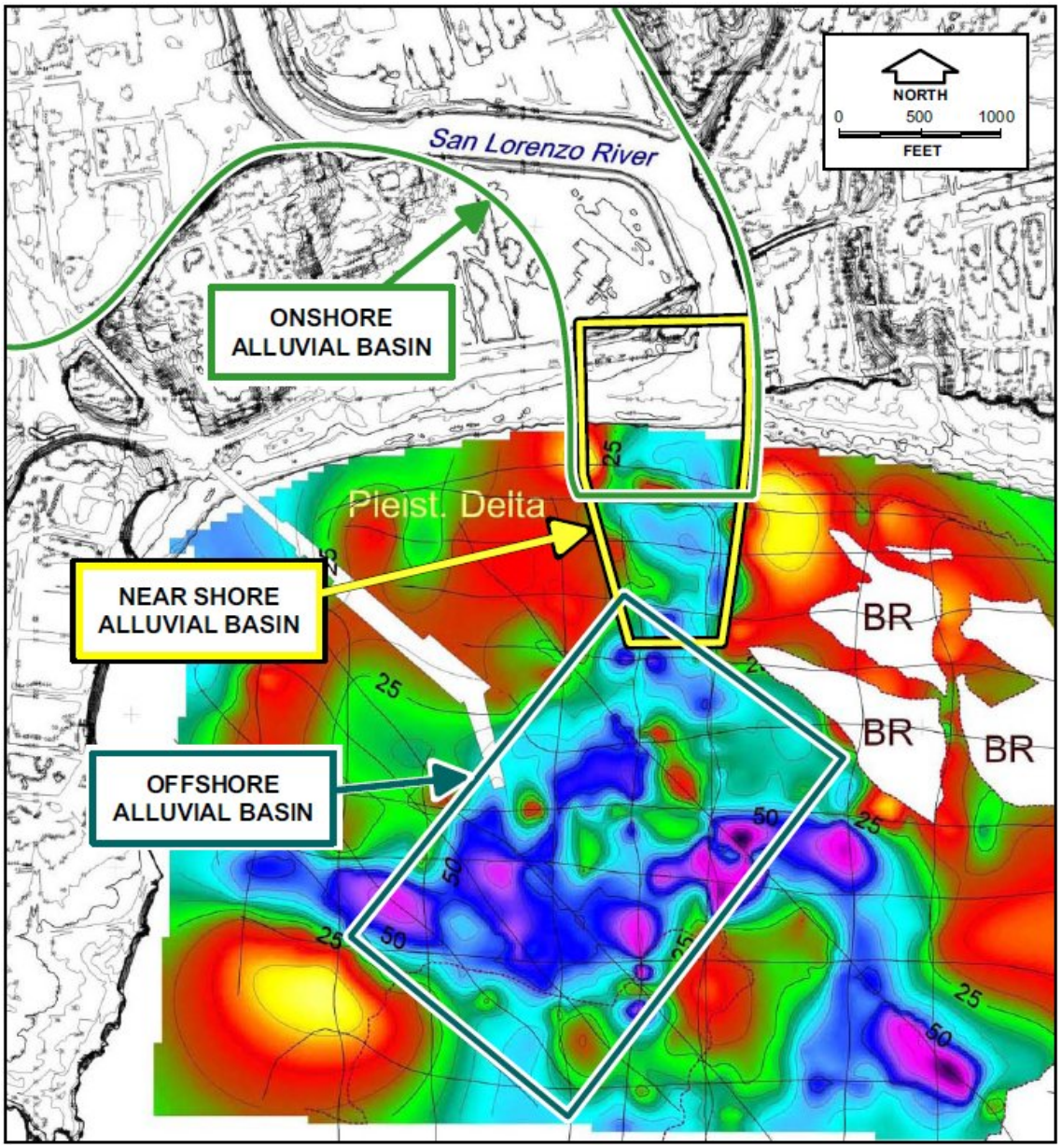

Figure ES-3. San Lorenzo River structural contour map delineated into three sub-basins.

Aquifer conditions in the onshore alluvial basin would vary based on the salinity of the groundwater from the San Lorenzo River, which would be affected by the impedance of the landward movement of seawater when the sand bar is in place. The successful production of groundwater from this area from vertical wells would likely draw in freshwater horizontally, and from caisson collector wells, production would be dependent on placing the wells in an area where recharge would come from the tidal flows of the San Lorenzo River. The major limitation of these two approaches for recharge with saline water is that they would be dependent on maintaining saturation within the tidal portion of the San Lorenzo River.

Production in the onshore alluvial basin area would induce infiltration of surface water from flows in the river and along the shoreline, which is anticipated to result in a blend of freshwater and seawater. The use of freshwater from the San Lorenzo River from wells in the onshore alluvial basin raises concerns regarding water rights, endangered species issues, and seawater intrusion landward in the groundwater basin. Other issues related to development of an onshore supply of groundwater include variations in water quality, such as changes in salinity, high concentrations of iron, and turbidity associated with high winter flows.

Aquifer conditions in the nearshore alluvial basin would not be affected as much by changes in river conditions, but would limit production potential above the alluvial nearshore aquifer because of the limited length of shoreline with exposure available for infiltration of seawater in the saturated nearshore environment. Another factor limiting production would be controlled by the shallow depth of the aquifer zone, which ranges from 40 to 125 ft (12.2 to 38.1 m) deep (see Figure 6-7).

Using an empirical method, estimates for conventional well production along the river and along the shoreline are up to 400 gpm with a specific capacity on the order of 12 gpm per foot of drawdown. Since 4,400 gpm would be required for a 2.5 mgd desalination facility, eleven wells would be required along the river and along the shoreline to produce sufficient water supply. Actual production potential would be affected by boundary conditions that confine flow (bottom and sides of the aquifer) or provide recharge (river bottom and vertical conductance).

If slant wells were placed along the shoreline into the nearshore alluvial aquifer underneath the seabed, the conceptual location of slant wells along the shoreline would accommodate four facilities, extending 500 ft (152 m) to depths of (from west to east) 45, 65, 115, and 95 feet (13.7, 19.8, 35, and 29 m), constructed at angles ranging between 5 and 13 degrees from the horizontal. The relatively shallow depth to the base of the alluvial aquifer in the nearshore area would limit the depth. The groundwater produced from slant well facilities drilled offshore is anticipated to contain high concentrations of iron, but not vary as much in salinity and turbidity.

Another potential for saline groundwater production is the conceptual location of an offshore caisson collector well in the alluvial aquifer 1,500 feet (450 m) offshore near the end of the Santa Cruz Wharf. Conditions in the offshore alluvial aquifer that could limit production potential include the low vertical conductance of the finer-grained sediment on the seafloor, the likelihood of thick silt and clay layers with very low permeability below the depth of those sampled, and

heterogeneous layering (i.e., lateral changes in formation materials) which could inhibit drawdown of flow to the wells.

Calculations of the expected yield are in Section 6.4 and 6.5. The single greatest influence on well production in these shallow aquifer basins will be the rate of induced recharge. The higher the rate of recharge and the closer the extraction point is to the source of recharge, the greater the production rate that can be obtained under shallow aquifer conditions that limit available drawdown.

Next Steps

The data gathered by ECO-M and subsequent lab tests and interpretations were shared with a Technical Working Group (TWG) that consisted of consultants, scientists, academics and regulators. The TWG was established specifically for this study in order to review the study plan, field investigation, and findings, and to make professional recommendations as to the viability of a subsurface intake and the next steps. While some of this discussion may also be found in the Feasibility Study as it fits within the larger context of evaluating intakes, it is worth noting the significant recommendations here as they relate to this study's findings.

Scientists and academics from USGS and UCSC continue investigations with regards to bathymetry, subsurface characteristics, erosion/accretion, sediment transport, and river discharges into the ocean. As part of the TWG, much of this data has been brought forward in discussions with **scwd²** to advise us with regard to the feasibility of placing a subsurface intake in the area. In general, USGS and UCSC scientists found the data gathered for this study to be consistent with current knowledge and understanding. Some debate about the shape and extent of the paleochannels occurred in the TWG due to the difficulty of interpreting the seismic reflection data. While it was agreed that in order to truly understand the nature and extent of materials below 40'+, one must drill and collect samples, it was further argued that 1) borings would need to be exhaustively located to provide a meaningful assessment of vertical and horizontal properties in the channel; 2) while an extensive drilling program could provide additional information, to really understand the abilities of a subsurface intake, a test facility should be installed and operated; and 3) there is no reason to believe that offshore, subsurface characteristics would be any better than what was found in the shallow sediment or than what has been discovered at depth onshore.

The following table shows the next step(s) that could be taken should **scwd^2** decide to pursue a subsurface intake. Each step in the table below can be implemented independently to gather information to 1) further understand the nature of the offshore basin, and 2) determine whether or not the program should proceed further or if a fatal flaw has been encountered.

It is important to stress that this study and the following potential work items were developed from the standpoint of findings from this study, findings from other existing studies and data, and lengthy discussions with experts in the field. In addition and equally important to the field conditions evaluated here are other feasibility factors being considered by Kennedy/Jenks

Consultants in the **scwd²** Intake Feasibility Study. It is the combination of all of these factors that must be taken into consideration when determining how best to move forward.

Step	**Reason**	**Advantage**	**Disadvantage**
Conduct a paper study of onshore geologic information to enhance the correlation with offshore properties.	Provides for additional information and understanding of the geology.	Easy to do. Requires no permitting.	Provides information in the onshore setting that may not represent offshore.
Using the data found above, develop a preliminary model of the offshore alluvial channel to assist in the prediction of flows, salinity/recharge, drawdown, zone of influence, etc.	Expands on existing understanding of offshore production potential	Easy to do. Adds to body of knowledge.	Interim step. Model output may give an indication of simplified conditions, but may not represent true production potential.
Drill deeper geologic borings onshore in an area where the river has met the ocean over the centuries or in the nearshore environment to further understand offshore subsurface properties. See Table Notes 1 and 3.	Provides for additional information and understanding of the geology.	Onshore borings would be easy to do, with limited permitting. Provides more info on production potential in the onshore and/or nearshore alluvial sub-basin.	Offshore more complicated, expensive, and could take 12+ months of permitting.
Expand the previously developed model with the new data. See Table Note 2 for the reason to redo the model.	Expands on existing understanding of alluvial basin production potential.	Adds to body of knowledge.	Model output may give a better indication of conditions than the previous model, but still may not represent true production potential.
Test well and pump test.	Provides hydrological information for estimating the productivity of the groundwater in the alluvial basin. (See Table Notes 4 & 5.)		

Table Notes:

1. One well-defined layer boundary is recognized in the geophysical data at about 47 feet (14.32 m) below Mean Lower Low Water (MLLW), just below the deepest samples from the USACE boreholes. This layer boundary may correlate with a significant change in sea level rise, which may have created a distinctive sedimentary deposit at that level, possibly including fine-grained material from soil formation, flood deposit, or other geologic processes. Deeper boreholes would be required to sample and quantify the sediment layering in the lower part of the channel.
2. While the hydraulic conductivity and permeability of the aquifer sediment in the paleochannel appear to be on the low end of a productive aquifer, some uncertainty remains with respect to the samples being representative of the whole. Deeper core samples could be taken and examined for hydraulic qualities. What remains unclear at this time is the extent of layers with low permeability throughout the aquifer and the influence these layers would have on overall transmissivity and permeability of the aquifer materials with respect to providing recharge to a buried subsurface intake system.
3. Scientific information about the study area with respect to river discharges and coastal processes (i.e., how littoral drift of sand, ocean waves and river discharges of fine sediment have affected the fill of the channel or may affect a future subsurface intake) could be factored into a feasibility analysis.
4. The horizontal continuity of the channel layers has been disrupted by faults in the nearshore sub-basin.
5. The impacts of the intake(s) on groundwater (seawater intrusion, water rights, special status species) should be studied. A pump test would help to evaluate how much freshwater might be pulled into a subsurface intake's wells.

scwd²
SEAWATER DESALINATION PROGRAM

OFFSHORE GEOPHYSICAL STUDY

1.0 INTRODUCTION

This report presents the results of the recently completed offshore geophysical surveys and associated confirmation soil-sampling program conducted by EcoSystems Management Associates (ECO-M). The City of Santa Cruz Water Department and Soquel Creek Water District (**scwd²**) together are developing a desalination program, which would consist of a 2.5-million-gallons/day (mgd) seawater reverse osmosis (SWRO) facility to supplement supply to both agencies. This geophysical survey was undertaken to further enhance the intake system study and investigate the feasibility of a subsurface intake off the Santa Cruz shoreline, and provide data to assist in selecting an appropriate intake design. The goals of the offshore geophysical study were to:

- Map the extent of the offshore paleochannels in three dimensions. Seismic reflection data collected during the survey were used to map the alluvial basin and paleochannels, identify bedrock and faults, and preliminarily characterize deep channel fill.
- Characterize the sediment within the paleochannels. Seismic reflection data was interpreted to estimate the thickness of alluvial sediment. Sediment cores were tested to identify the geotechnical properties (i.e., soil type, grain size, density, and hydraulic conductivity) to develop an understanding of existing conditions in the shallow portion of the three paleochannels.
- Provide preliminary seawater production information for the San Lorenzo River alluvial basin. Geotechnical and geophysical properties of the alluvial basin were used to evaluate the production capabilities of conceptual-level subsurface design alternatives.

The introduction of this report 1) shows where the project took place, 2) reviews several subsurface intake approaches being considered (which provide context for review of the study's findings), 3) details the tasks and objectives, and 4) provides background information about the area's geology.

Project Location

The project area (Figure 1-1) is located along the central coast of California just offshore of the City of Santa Cruz within the Monterey Bay National Marine Sanctuary (Figure 1-2).

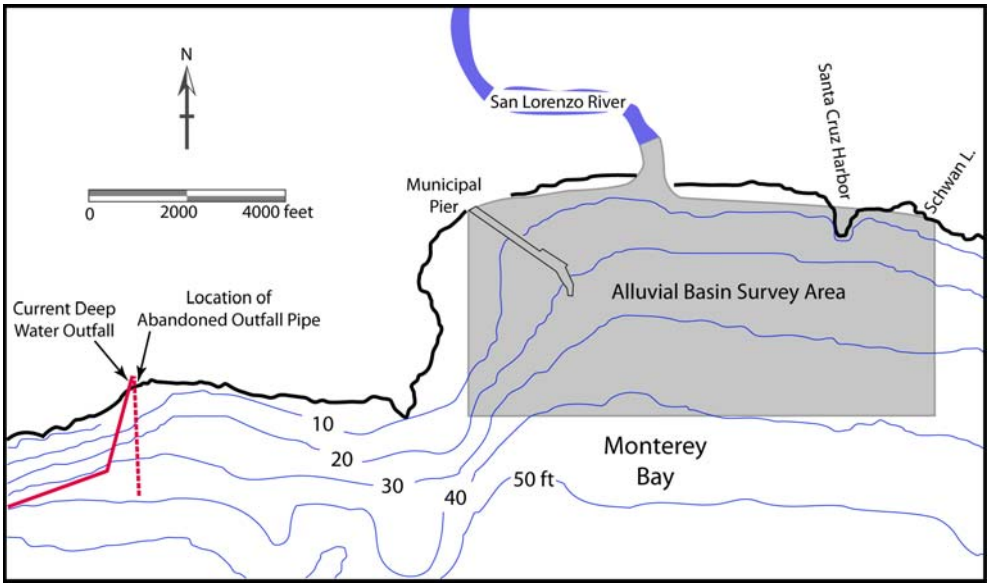

Figure 1-1. Geophysical study location.

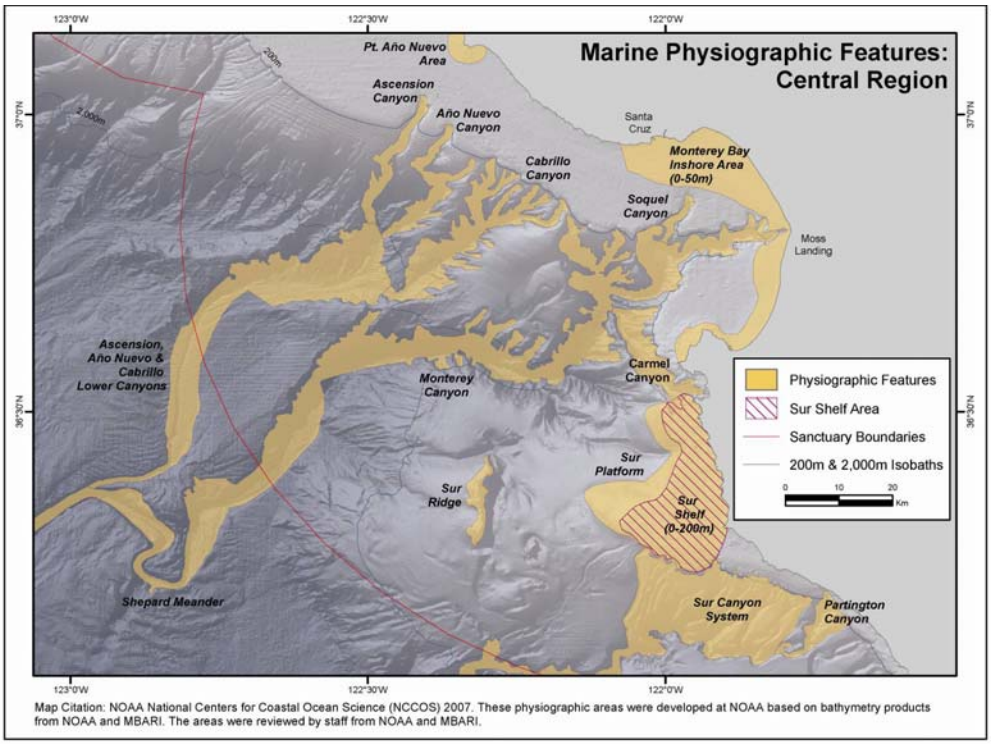

Figure 1-2. Marine physiographic features in the Monterey Bay National Marine Sanctuary. The geophysical survey was conducted within the Monterey Bay Inshore Area near Santa Cruz.

Subsurface Intake Concepts

In order to supply water to the proposed desalination plant, several approaches to bringing water from Monterey Bay are being considered. One option is to retrofit an abandoned wastewater outfall (36-inch reinforced-concrete pipeline abandoned in the 1980s). The location and condition of this abandoned pipe was outside the scope of this study (Figure 1-1). Another option is to install a subsurface intake, which could consist of conventional vertical wells, slant wells, caisson collector wells, or an engineered infiltration gallery. While the design of these facilities is outside the scope of this study, requirements of the proposed intake methods should be kept in mind while evaluating the hydrogeographic data.

Conventional vertical wells used for production of seawater consist of a vertical well casing with screen sections installed into an aquifer(s) that will induce direct infiltration of water from the ocean. The use of this type of production facility requires an aquifer system that is sufficiently permeable and deep to support production from a vertical well screen section. Use of conventional wells usually requires multiple facilities that are spaced at a sufficient distance apart to prevent intolerable interference during operation.

Slant wells installed in an aquifer that extends offshore would draw saline water vertically downward through the paleochannel's shallow sediment that is hydraulically connected to the overlying source of recharge (the ocean). The slant well design shortens the flow path from the source of recharge to the area of underlying production (tens of feet vertically versus hundreds of feet horizontally to onshore vertical wells). Slant wells require a sufficiently thick aquifer to allow installation at an angle that facilitates construction and maintenance (Williams, 2010). In addition, the aquifer must be sufficiently permeable, and the vertical conductance through seafloor sediment must be adequate to support the underlying production.

Caisson collector wells are constructed by installing a large diameter vertical shaft that is connected to horizontal well screen sections installed in a radial pattern around the vertical pump chamber. Like the slant well design, the radial screen sections extend beneath the source of recharge and shorten the flow path to the source of intake. This type of facility also requires an aquifer that is sufficiently permeable, and the vertical conductance through seafloor sediment must be adequate to support the underlying production.

An engineered infiltration gallery consists of a series of connected perforated pipes constructed within an excavated area of the seafloor or within a relatively shallow concrete containment structure that is installed in or placed on the seafloor. The collector screens are covered with coarse permeable materials that grade upward to a finer-grained material fine enough to filter out sediment and turbidity in the ocean water being produced. Such a facility must be sufficiently large to allow the required production. It must be installed at a sufficient depth to ensure submergence at all times and protection from storm wave damage; and in an environment where the rate of plugging is low enough to allow continual operation with only moderate maintenance.

Offshore Geophysical Study Tasks

Primary tasks completed by ECO-M and its subconsultants for this study include:

- a multibeam bathymetry survey of the study area;
- a shallow seafloor geophysical survey of the study area using a 3.5-kHz sub-bottom profiler;
- a deep seafloor high-resolution geophysical survey of the study area using a 300 joule "Boomer" survey system;
- a transition zone geophysical survey across Santa Cruz beach, just west of the San Lorenzo River outlet;
- the collection of a set of 11 vibracore sediment samples from locations determined by geophysical surveys and analysis of selected samples from these vibracores for grain size, hydraulic conductivity, and moisture content; and
- compilation and analysis of all collected data in order to determine the shape and depth of the alluvial paleochannels and basins found within the study area, and estimate of the potential quantity of seawater that could be obtained from the primary alluvial channel located south of the San Lorenzo River outlet.

The Offshore Geophysical Study addressed the issues of: 1) the existence, location, and 3-D extent of offshore, sediment-filled paleochannels; 2) the layered nature of the nearly horizontal Holocene paleochannel sediment; 3) the thickness of individual sediment layers as observed in the shallow cores; 4) the type and geotechnical properties (i.e., grain size, density, and hydraulic conductivity) of the uppermost sediment layers; 5) the geologic history of the paleochannel sediment and the sequence of cutting and backfilling of the paleochannels; and 6) the type of sediment most likely found in the three main paleochannels.

Objectives

The primary objectives of this study were to map the extent of the paleochannels in three dimensions, provide initial characterization of materials within the alluvial filled paleochannel(s), and determine if any of these channels could supply the required amount of water to the proposed desalination plant. Preliminary interpretation of the geophysical data and the vibracore samples showed that the Woods/Schwan and Neary channels are filled with fine-grained muds and clays, as well as natural gas, and therefore are unsuitable to supply seawater. Consequently, the evaluation focused on the San Lorenzo River paleochannel. The geophysical survey also helped to identify obstacles or potential hazards that may impact installation of the proposed saline water intake system for the desalination facility. The only obstacles that were identified were the bedrock outcrops that diverted the lowstand river channels. There were no man-made obstructions, such as wrecks or older abandoned offshore structures, and no boulders within the fluvial sediment along the survey transect lines.

The results of the geophysical survey assisted in the estimation of the location, shape, and depths of these offshore submerged paleo-river channels. The confirmation soil sampling, using vibracores, was conducted to ground truth the geophysical data, at least for the upper or youngest portion of the sediment column. Geotechnical testing of core samples provided direct information on shallow sediment type and extent. Test results aided in the interpretation of the

sub-bottom stratifications shown in the geophysical data. In addition, samples from the paleochannels provided information on the types of materials that may make up the bulk of sediment in the filled paleochannel.

Previous Investigations in the Area

The Offshore Geophysical Study was conducted south, southwest, and southeast of the San Lorenzo River outlet and southeast of Neary's Lagoon, an area of approximately 790 acres (3.2 km^2). U.S. Geological Survey (USGS) scientists have identified at least four major channels offshore between Point Santa Cruz and Black Point east of Schwan Lagoon (Figure 1-3; Anima et al., 2002). However, the 1995 single-channel Geopulse system data used for that study were unable to image clearly the channel bottom in many areas due to limited subsurface penetration, water bottom multiples, ocean swell, and other acoustic noise. High-resolution multibeam bathymetry surveys were completed by the USGS in 2005-2006 (Storlazzi et al., 2008), and in 2009 (backscatter data was provided by USGS at the Technical Working Group held April 1, 2010). The data presented in this report expand existing knowledge of this area, extending to greater sub-seafloor depths to accurately map these channels in three dimensions (3-D). Water depths in the survey area were a maximum of 50 feet (15 m).

1.1 GEOLOGY OF SANTA CRUZ AREA

The study area is bounded by the Santa Cruz Mountains to the north, the Pacific Ocean to the south, and Quaternary marine terraces to the east and west. The San Lorenzo River, which drains a moderate watershed within the Santa Cruz Mountains, bisects the study area.

The Santa Cruz Mountains are an active tectonic feature of the San Andreas fault system and largely result from compressive uplift at a leftward bend (restraining bend) in the San Andreas fault. The compressive uplift affects the marine terraces along the Santa Cruz coast. According to previous investigations, the average rate of marine terrace uplift since the late Pleistocene has been between 0.25 m/kyr (Lajoie et al., 1991), and 1.1 m/kyr (Perg et al., 2001). The central coast area of California continues to be uplifted by this compression today. The 1989 Loma Prieta earthquake raised the Santa Cruz coast by about 2-3 inches (30-80 mm; Marshall et al., 1991).

The primary local bedrock formations are the Pliocene Purisima formation and the Miocene Santa Cruz Mudstone formation. The Purisima is a thick-bedded, yellowish-gray tuffaceous and diatomaceous siltstone, containing thick interbeds of bluish-grey, fine-grained sandstone deposited in a marine environment. The Purisima has been uplifted by the restraining bend convergence. As a result, it dips gently to the southeast and forms most of the sea cliffs around the City of Santa Cruz, outcrops offshore of Point Santa Cruz and southeast of Schwan Lagoon (Figure 1-3). During Quaternary sea level lowstands, channels were incised into the Purisima silty-sandstone by the San Lorenzo River and the Woods/Schwan Lagoon drainage complex, making the Purisima the bedrock foundation for the study area. It is these channels that were filled during subsequent sea level rise to form the offshore alluvial basin of importance to this project.

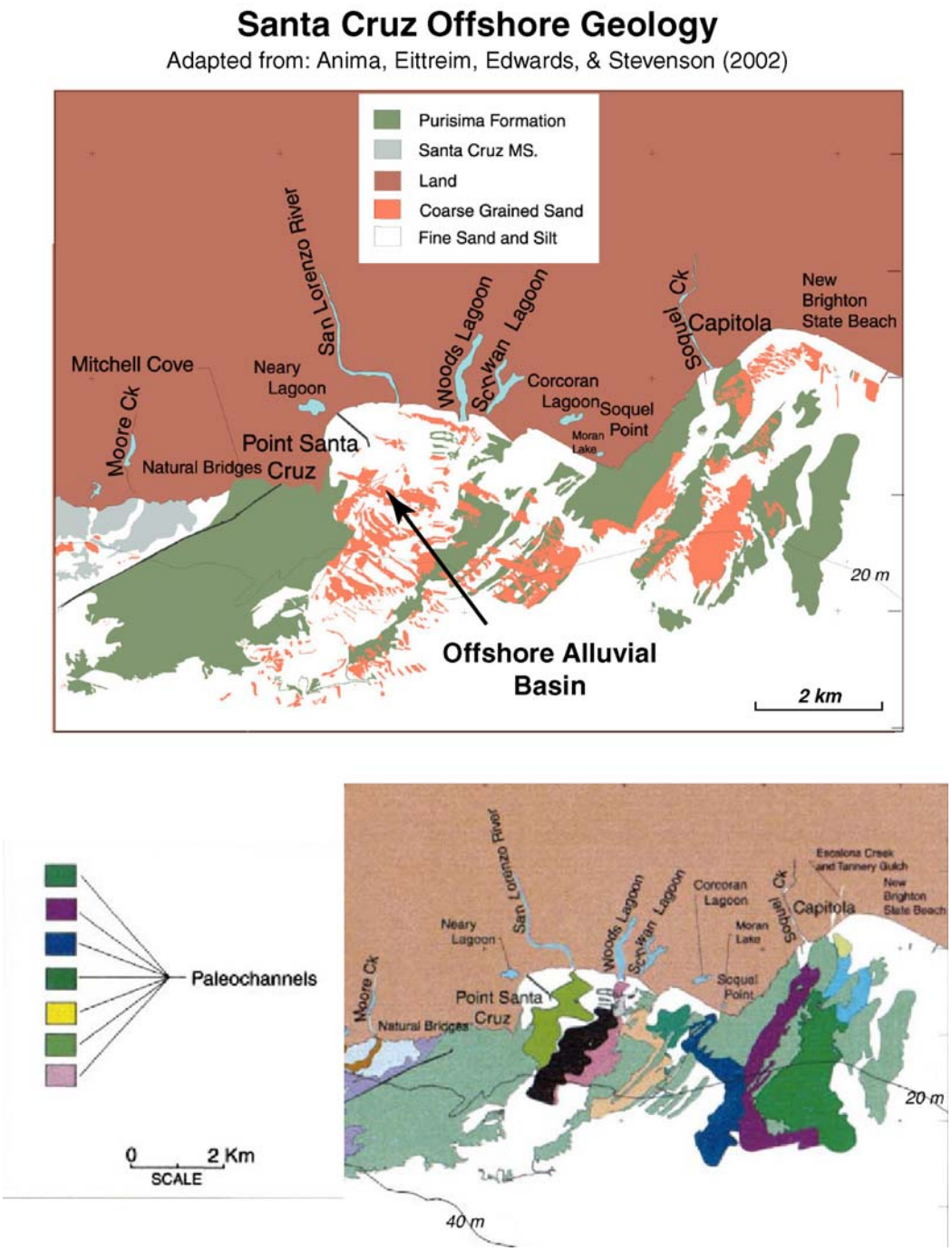

Figure 1-3. **a) Map showing surficial geology offshore Santa Cruz (Anima et al., 2002) and location of the Offshore Alluvial Basin. The white and salmon-colored areas show distribution of sand-filled alluvial paleochannels.**
b) Location and shape of paleochannels in Santa Cruz area as mapped by USGS (Anima et al., 2002). The San Lorenzo paleochannel interpretation can be seen in green near Point Santa Cruz.

Throughout the Quaternary Period, sea level has risen and fallen multiple times (Figure 1-4). Currently in a sea level high, only the Oxygen Isotope Stage 5e (OIS-5e, about 124 ka; Lajoie et al., 1991) was about 20 feet (6 m) higher than today. Marine terraces can be formed during both sea level transgressions (rising sea level) and regressions (falling sea level), and there is evidence of both in the Santa Cruz area. As long as sea level stays at one level for a significant amount of time, marine terraces have the opportunity to form. The prominent marine terraces evident on the land in the Santa Cruz area were formed during ancient sea level highstands and have been uplifted farther above sea level since their formation. Anima et al. (2002) have found evidence of submerged marine terraces offshore from Santa Cruz that formed during lower sea level stands. These terraces also have been uplifted, but their formation age is uncertain at present.

Just as the coast is eroded to form marine terraces, the active river and stream channels erode down to sea level at the coast so that the ancient sea level lowstand channels (paleochannels) are deeper than the modern sea level highstand channels. The Last Glacial Maximum **(**LGM) sea level was about 390 feet (120 m) lower than modern sea level. During the LGM sea level lowstand, the San Lorenzo River cut its channel to that depth at its mouth, which is now submerged offshore near the head of Soquel submarine canyon (Figure 1-5). At the modern coast, the buried paleochannel is shallower, at a depth of about 40 to 90 feet (12 to 27 m) below the modern river bottom (Anima et al., 2002) (128 feet (39 m), according to the newly collected offshore geophysical survey data). The channel bottom has been uplifted along with the rest of the coastal area, between 10 feet (3 m) and 60 feet (18 m), depending on the rate of coastal uplift. As sea level rose at the end of the last Ice Age (the Last Glacial Maximum or LGM; Figure 1-4) and approached its modern level about 6,000 to 7,000 years before present, the deeper channel would have filled with fluvial (riverine) and marine sediment.

The City of Santa Cruz receives an average of 30.5 inches (77.5 cm) of rain each year. The maximum rainfall for the City of Santa Cruz is approximately 60 inches (152 cm) in a year. The Santa Cruz Mountains receive an average of between 36-46 inches (91-117 cm) of rain each year, with a maximum ranging between 80-100 inches (203-254 cm). The San Lorenzo River, with a drainage area of 270 km^2, therefore, delivers a large volume of water and sediment (284,700 tons of total suspended sediment load, two-thirds of which is fine-grained sediment, on average) to its coastal outlet area in a short period during major storm events (Farnsworth and Warrick, 2008). For comparison, the site of the test slant well in the San Juan Creek alluvial basin in South Orange County is in a drainage area of 300 km^2 where precipitation averages between 12 and 15 inches (30.5-38 cm) annually, and the total suspended sediment load is 98,100 tons, which amounts to three times less than the San Lorenzo River (Farnsworth and Warrick, 2008). In addition, the arid climate in Orange County results in less weathering of the geological materials in the drainage area prior to erosion, transport, and offshore deposition.

Large rain and accompanying flood events have caused the San Lorenzo River to change its course within its floodplain multiple times since the LGM. During the sea level lowstand, erosion caused by local runoff incised steep-sided drainage courses into the exposed bedrock, which were filled during the subsequent sea level rise (Flandrian transgression shown on Figure 1-4). As this transgression progressed, these incised drainage courses were submerged by the sea and filled with sediment from river discharges and ocean processes.

The ancient shoreline from the last sea level lowstand 18,000-yr shoreline is located near the 120 m (394 feet) depth contour where the narrow continental shelf offshore of California steepens into the continental slope and into the Monterey and Soquel submarine canyons in Monterey Bay (Figure 1-5). Thus, the ancient San Lorenzo River mouth would be located near the head of Soquel Canyon about 4 km (2.5 mi) offshore from its present location. During the sea level lowstand, a 4-km-wide (2.5 mi) coastal plain existed. Rivers tend to level off near the coast to enter the sea at a very gentle slope (low gradient). When topography slopes gently, rivers tend to widen by forming meanders. The meanders reduce the channel gradient further. The modern bend in the San Lorenzo River north of the railroad bridge and the Neary Lagoon appear to be meanders. Unlike meanders in broad floodplains, these meanders are incised into the local bedrock. The combination of eustatic sea level changes and tectonic uplift at the coast force the channels to erode into the bedrock preserving the meander. It is likely that additional channel meanders exist in the offshore alluvial basin (e.g., Eittreim 2002). Meanders in the offshore alluvial basin would maintain a relatively constant channel depth, but also create a significantly larger alluvial basin area that could be beneficial for this project.

In conclusion, this description of the surficial geology of the area provides a historical basis for understanding the findings from the geophysical and soil sampling surveys with regard to the origins of the type of sediment that is found in the paleochannels and the processes that formed the San Lorenzo River subsurface aquifer.

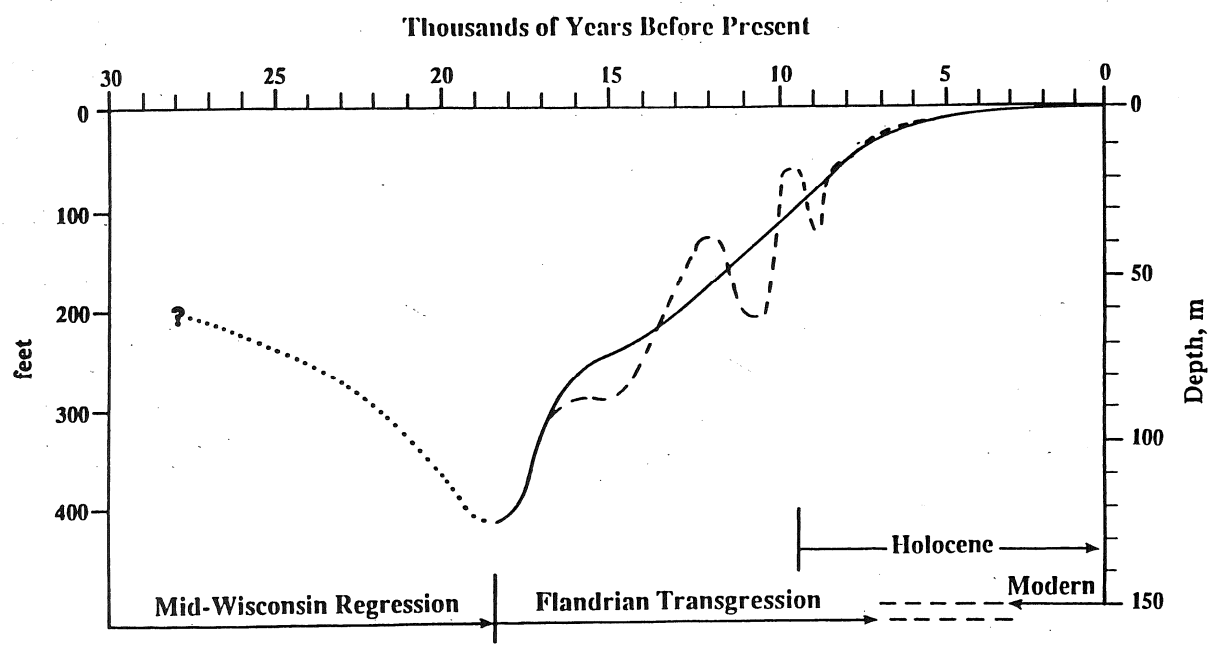

Figure 1-4. Sea level rise during the Flandrian transgression since the end of the last Ice Age (the Last Glacial Maximum or LGM). From Inman (1999). Dashed line represents interstadial sea level fluctuations during the overall Flandrian transgression.

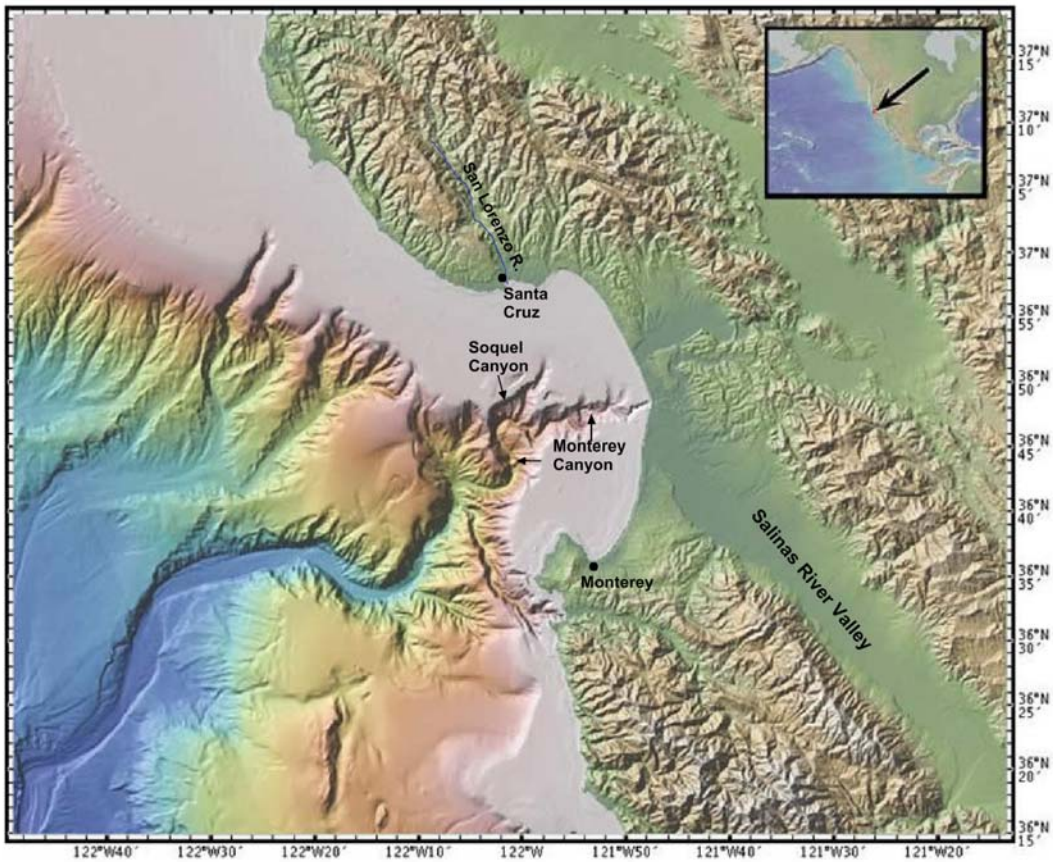

Figure 1-5. Regional topography map showing today's coastline and the offshore Monterey and Soquel Canyons. The Santa Cruz Mountains can be seen toward the top of the map.

2.0 SURVEY METHODS

2.1 GEOPHYSICAL DATA

scwd² ensured that the geophysical data was acquired in compliance with the safety zones established by government agencies for the protection of fish, marine mammals and reptiles from the low energy acoustic and seismic reflection profiling equipment. ECO-M completed the geophysical surveys between October 17 and October 28, 2009. The bathymetry survey was completed between October 17 and 20, 2009; the 3.5-kHz sub-bottom profiler geophysical survey was completed between October 21 and 24, 2009; and the 300 Joule Boomer geophysical survey was completed between October 26 and 28, 2009. A list of the equipment used during this study is provided in Appendix A.

A dense grid of high-resolution, boomer source, multi-channel seismic (MCS) reflection profiles was obtained to provide sub-seafloor images of the structure and stratigraphy in the offshore alluvial basin (Figure 2-1). These data were supplemented by high-resolution, single-channel seismic reflection profiles acquired by the USGS in 1995 (Geopulse tracklines). To image the shallower sub-seafloor layers of sediment, ECO-M also acquired a grid of 3.5-kHz sub-bottom profiles along the same tracklines as the MCS data and along several adjacent lines (Figure 2-2).

A multi-beam bathymetric survey was carried out using a SeaBat 8124 Multibeam Ecosounder that operates at a frequency of 200 kHz, a Seatex MRU-5 motion sensor, an S.G. Brown Meridian Gyro Compass, an AML SVPlus Sound Velocimeter, and a Trimble Ag132 global positioning system (GPS) Receiver. The multibeam survey covered the project area. Details of the geophysical survey methods and data collected are presented in Chapters 3 and 4 of this report and in ECO-M (2009 a,b,c).

2.2 CONFIRMATION SOIL SAMPLING

ECO-M conducted the seafloor-sampling program between November 9 and 12, 2009, after analyzing the geophysical survey data. The coring took place in the nearshore area south of Santa Cruz, California. A total of 11 cores were collected during the sampling event. The lengths of the cores were between 4.5 and 15.5 feet (1.4 and 4.7 m). Appendix B presents the core logs and Appendix F presents photos of the cores.

Confirmation soil sampling is important to define the stratigraphic sequence and sediment characteristics of the offshore alluvial basin. Cores of the overlying material provide explicit ground truth information to constrain geophysical data interpretation. A total of eleven (11) shallow vibracores were obtained at key locations near the axes of the filled channels in the offshore alluvial basin (Figure 2-1). The core locations were picked after preliminary interpretation of the geophysical data (seismic profiles) to be near the buried river channel axes and along the high-resolution seismic profiles to provide direct correlation to sub-seafloor

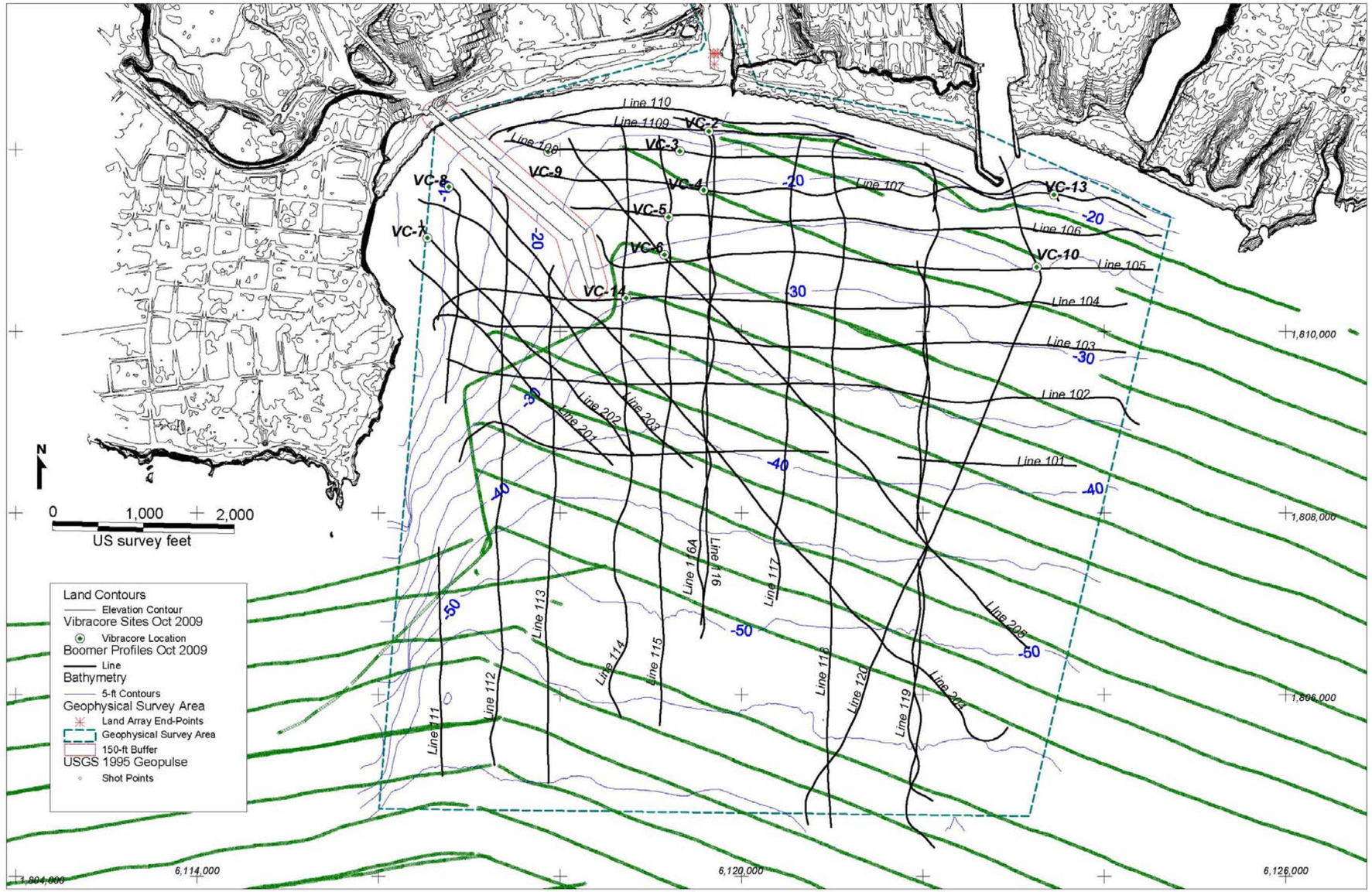

Figure 2-1. Figure showing boomer deep seafloor geophysical survey lines, transitional zone survey land array end-points, and locations of vibracores. Green lines show USGS 1995 geopulse shot points. The blue lines are bathymetric contours.

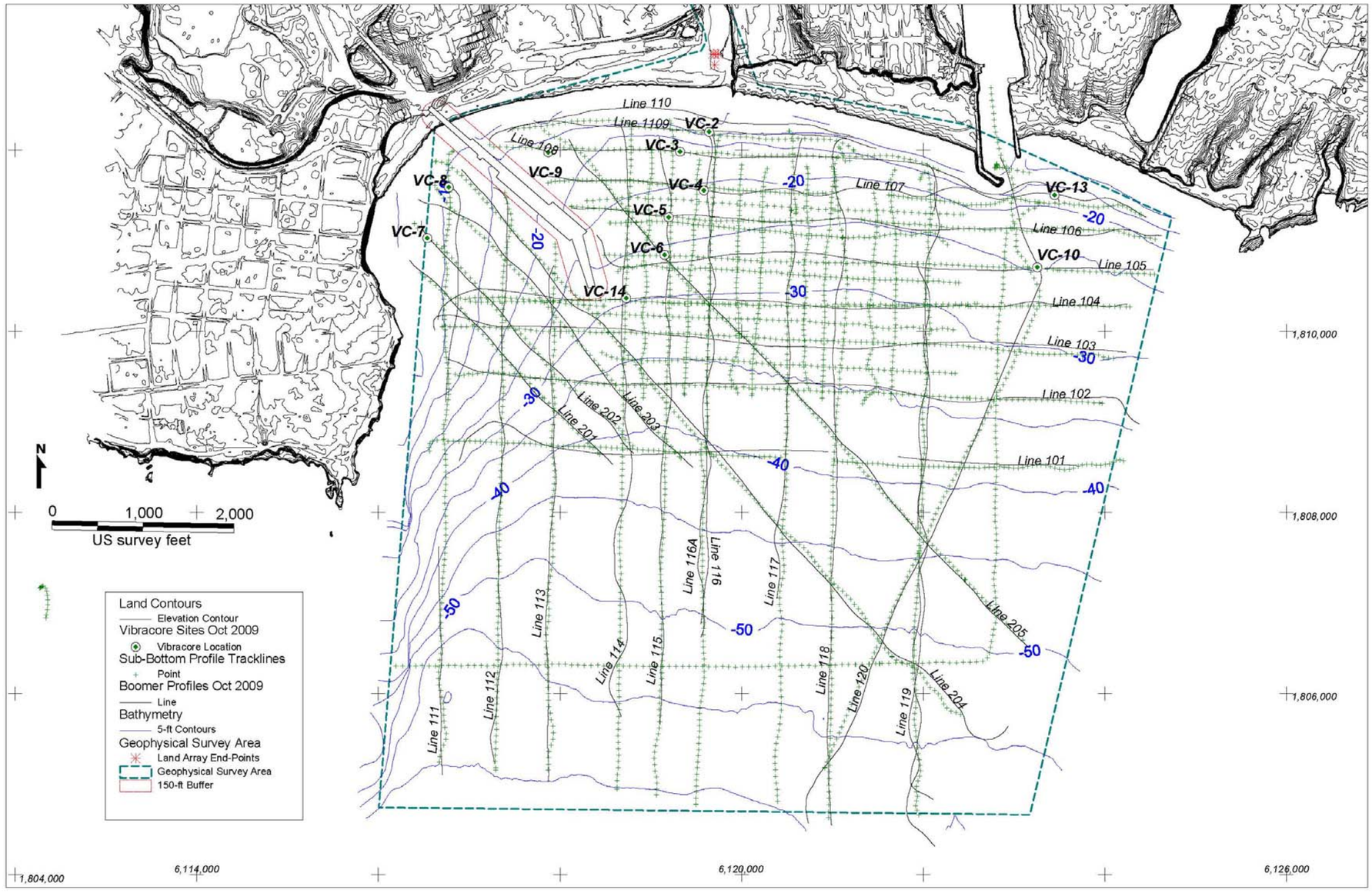

Figure 2-2. Sub-bottom profiler shallow geophysical survey lines (green shot points) with boomer lines in black.

reflection character. The vibracores taken were all shallow, less than 20 feet (6 m) of sub-seafloor penetration, so correlation with seismic profiles was best accomplished with the 3.5-kHz data. The vibracore data are further discussed in Chapter 5.

2.3 MARINE MAMMAL OBSERVATIONS

The nearshore environment offshore of Santa Cruz hosts a number of resident and migratory threatened and endangered species and protected marine mammals. National Marine Sanctuaries, under the aegis of National Oceanic and Atmospheric Administration (NOAA), provides significant protection to the marine environment in areas of the United States deemed of exceptional value to the preservation of marine ecosystems. Marine mammal observers were required by the permitting agencies to assure that marine mammals were not harmed by the low energy sonic pulses generated by the geophysical survey equipment. Mammal observations were carried out by an independent company (Kinnetic Laboratories, Inc.), hired by the City of Santa Cruz Water Department. Their observers were on board during Eco-M's operations and indicated when survey activities should be altered or stopped to avoid interaction with mammals (Photo 2-1). A summary of their observations is presented in a report prepared by Kinnetic Laboratories, Inc. (2009) for the scwd² Seawater Desalination Program. The marine mammal monitoring report is included in the Offshore Geophysical Study as Appendix J.

Photo 2-1. Marine mammal monitor, Amy Howk, on the lookout for marine mammals.

3.0 SEISMIC / GEOLOGICAL INTERPRETATIONS

Three major channel systems were identified in the seismic data: 1) Neary Lagoon offshore graben; 2) Schwan/Woods Lagoon lowstand channel(s); and 3) San Lorenzo River lowstand channel(s). The paleochannel maps and features that were interpreted with the data are presented later in Section 6. Seismic data were interpreted with regard to probable channel fill in conjunction with vibracore data. In Figures 3-1, 3-2 and 3-3, several features were identified: channel margins, fault traces, marine terraces, mid-Purisima and base-Purisima, and the seafloor. In Figure 3-3, a 47 ft (14.3 m) boundary layer was interpreted as an 8 ka (occurred 8,000 years ago) event within the San Lorenzo River channel.

Based on the seismic and vibracore data, each paleochannel has distinctive channel fill. (Appendix I contains all of the uninterpreted seismic data.) The Neary Lagoon paleochannel system has a relatively transparent seismic reflection character with stronger layered reflections at depths (Figure 3-1) that appear to consist of fine-grained fill, represented by clayey-silt retrieved in vibracore VC-8 (Section 5). The Schwan/ Woods Lagoon paloechannel system has a highly reflective, complexly layered, seismic character (Figure 3-2) that appears to consist of fine-grained lagoon sediment, represented by organic-rich mud retrieved in vibracores VC-10 and VC-13. The San Lorenzo River paleochannel system is more subtle in the seismic profiles (Figure 3-3) and appears to consist predominantly of fine-to-coarse sands with gravel based on the vibracore results and U.S. Army Corps of Engineers (USACE) boreholes along the river levee onshore.

The Neary Lagoon paleochannel system and the Schwan/Woods Lagoon paleochannel system have edges and bottoms defined by strong reflection strength with multiple reflections and reverberations (echoes) that obscure deeper structure. There was a difference in the velocity at which the sound traveled through the channel because of its different density. Decomposition of organic matter likely produces significant methane, hydrogen sulfide, and other gases that create low acoustic velocities in the channel sediment, so that high reflectivity and noticeable velocity pull-down effects exist in the seismic profiles. Gas in a channel slows down the velocity of the return signal. (See Appendix E for a description of seismic reflection profiling methods). The fine-grained fill is suspected to correspond to basin deposits mapped by the California Geological Survey (Wagner et al. 2002) in the lagoons and recovered during the dredging of Santa Cruz harbor. It is likely that these fine-grained channel fills are unfavorable for an intake due to low permeability and possible toxic or objectionable fluid content.

In the San Lorenzo River paleochannel system, there are distinct changes in the reflection character within the channel, and channel margins are apparent, but the character of the channel fill reflectivity is very similar to that of the older Purisima formation silty-sandstone bedrock. The San Lorenzo River paleochannel is smooth in its reflectivity. The lack of prominent horizons with high reflectivity suggests that significant fine-grained clay layers are absent within the main channel fill sequences. Thus, seismic impedance differences are minor and channel fill areas are recognizable more by discordance of reflective horizons than by distinct reflection boundaries.

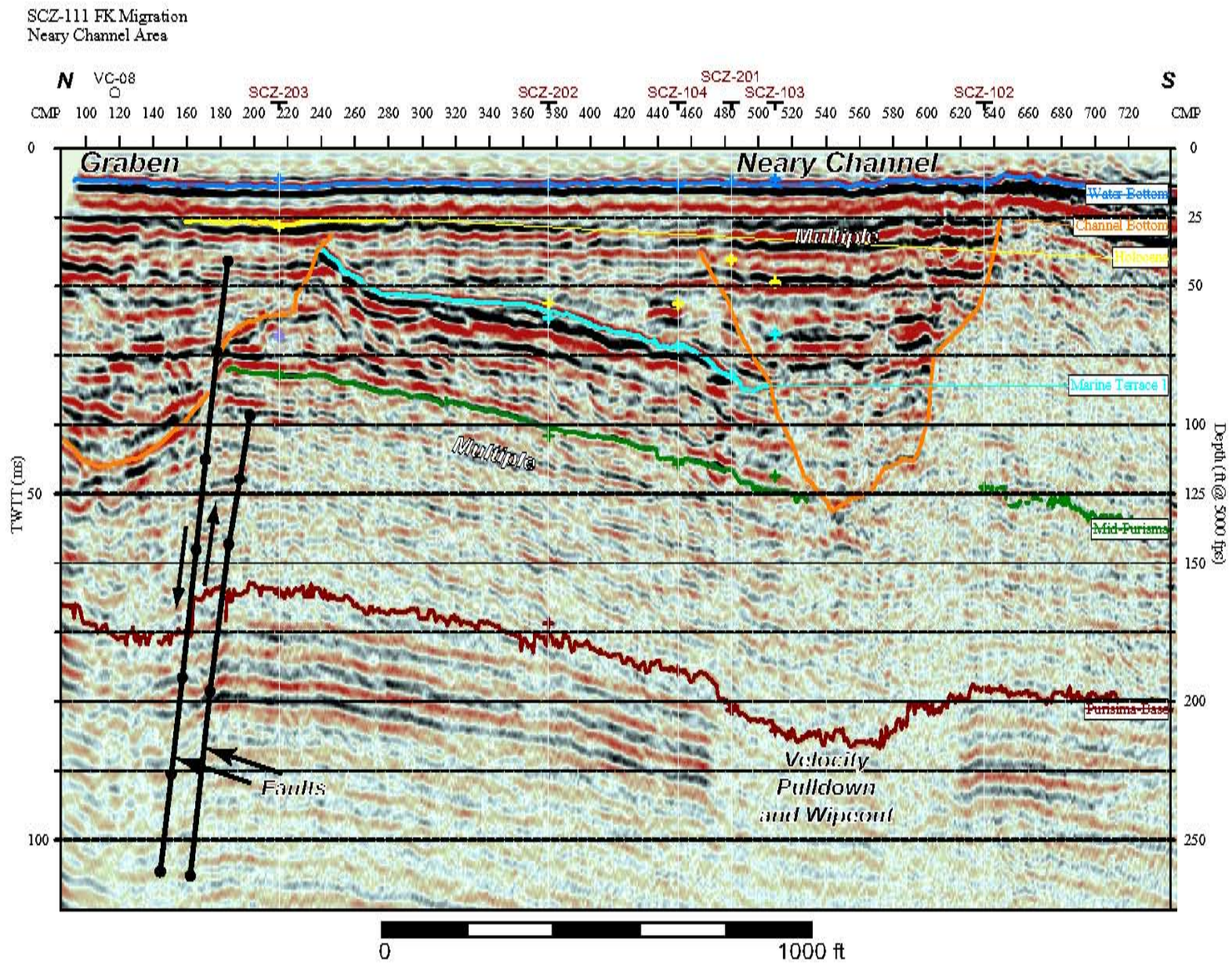

Figure 3-1. **Neary Lagoon Channel on seismic profile 111. Thick black lines represent faults that may control the Neary Lagoon complex geomorphology. The location of vibracore VC-08 can be seen along the top of the figure. T and label at top show locations where other seismic profiles intersect this profile. Velocity pulldown and wipeout areas occur below channels that have significant gas content. Water bottom and other multiples obscure primary reflection signal in some areas.**

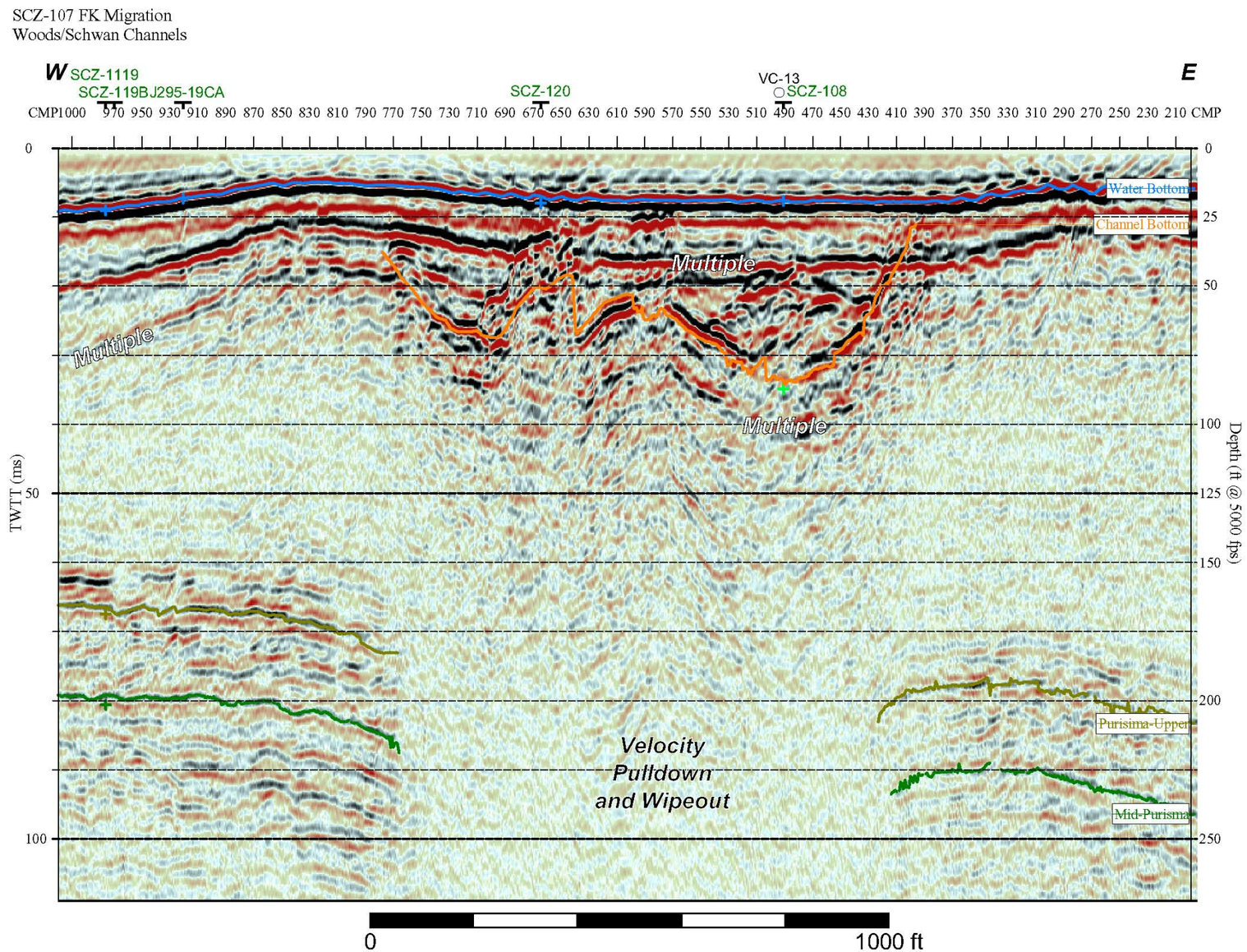

Figure 3-2. Woods/Schwan Lagoon Channels on seismic profile 107.

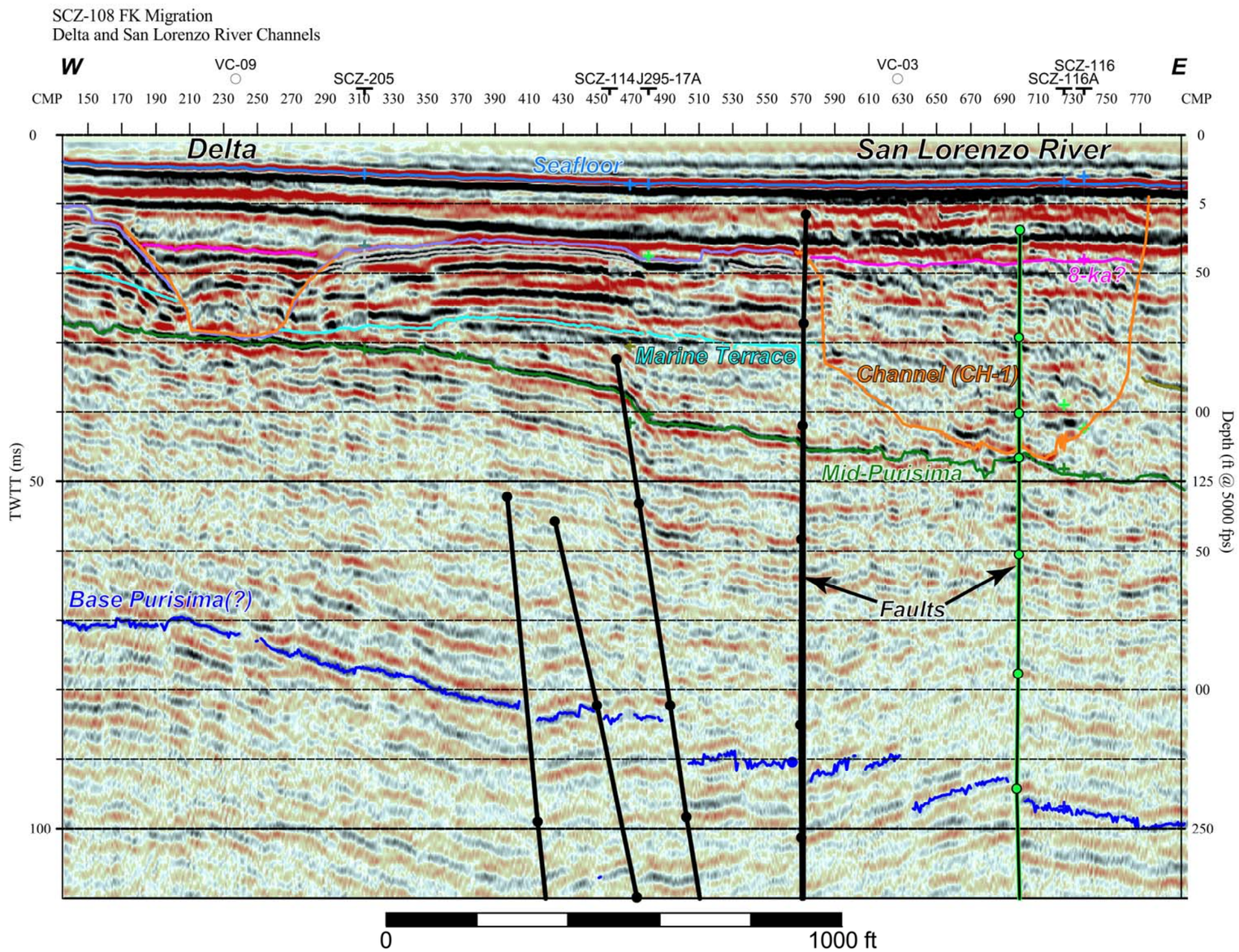

Figure 3-3. **Line 108 showing channel/levee complex and San Lorenzo Channel (both in orange). Vibracore locations VC-03 and VC-09 are identified across the top of the page. Thick black lines represent fault traces. The thick dark line at twice the water depth is the water bottom multiple.**

One observation in this channel is the existence of a well-defined reflection horizon at about 18-ms twtt (47 feet or 14.3 m subsea). Correcting for uplift by the method used in Grossman et al. (2006), this horizon may have formed during a brief sea level stability period of the cool event that occurred about 8.2 ka (Figure 1-4). This is noted in Figure 3-3 for its different reflectivity (i.e., a distinct wiggle in the trace). It could be a higher velocity layer, more compacted, or have more clay in it to make it a stronger reflection. In the seismic reflection profiles, it appears to be a significant boundary layer within the channel.

This channel represents the active river channel during the LGM sea level lowstand. Thus, during sea level rise (transgression), river currents and nearshore wave activity would tend to winnow out the finer-grained material allowing the coarser sediment to settle and fill the channel (Bradley and Griggs 1976). While the majority of the fine-grained silts and clays have been deposited farther offshore in deeper water in a mid-shelf mudbelt (Grossman et al. 2006), it has also been observed that this sediment can be deposited on the inner shelf. Mass balances of the fine sediment in plumes from rivers suggest that, though turbid, the buoyant plumes offshore of the California coast rapidly lose sediment within kilometers. Fluid mud and flood deposits can become a part of the geological record in the nearshore environment in a time of high river discharge (Farnsworth and Warrick, 2008). The ancient channel of the San Lorenzo River was cut deeper during the sea level lowstands of the Pleistocene Ice Ages, and the channel is filled by a significant thickness (perhaps exceeding 100 feet or 30 m) of alluvial and fluvial deposits.

The shallow sand, coarse-grained, and fine sediment fill of the main San Lorenzo River paleochannel collected in the vibracores is evaluated in Section 5. A model of channel fill stratigraphy and lithology in the nearshore zone is presented in Appendix E. Until deeper borehole data can be obtained from this area, significant uncertainty in the actual channel fill layering and hydraulic properties exists, which must be considered in hydraulic modeling for evaluation of flow potential.

In the western areas of the San Lorenzo River offshore channel system, there appears to be a channel/levee complex (Figure 3-3) likely formed during late Pleistocene sea level high stands of lower elevation than the modern shoreline (Figure 1-4). A channel is formed within a layered sediment sequence, which is the levee, rather than cut into the older Purisima formation bedrock. The river mouth was farther west near the wharf than its current position and possibly as far west as the Neary Lagoon channel system. There is a complex system of aggradational channels and levees (built up within the delta) in the nearshore area, which cover inferred Pleistocene wave-cut shorelines and terraces. The delta sedimentary sequences likely consist of mixed fine-grained clays, silts, and fine sands with possible coarse material as lag deposits along the channel thalweg. These delta deposits were previously recognized in this area by USGS scientists (Kennedy et al. 1987; McCulloch and Greene 1990).

The complex meandering channel system would have developed during the sea level rise as major storm and flood events redirected the San Lorenzo River channel in the coastal zone. For example, a major storm in 1955 redirected the river along Ocean Street through downtown Santa Cruz. The benefit of these processes, for use in evaluation of an offshore subsurface intake, is that a broad Holocene alluvial basin was created and back-filled with unconsolidated sediment.

The transition zone wide-angle reflection survey provides important data on the shallow acoustic velocity structure at the shoreline and beach area (Figure 4-1). In the channel areas, similar velocity measurements were measured with the wide-angle seismic reflection profile with the land geophone array as with the offshore boomer shots. The land array is located within the active river channel according to the contours provided by the City of Santa Cruz (Figure 6-1). During the geophysical survey on October 27-28, 2009, the San Lorenzo River was open directly to the sea on the eastern edge of the channel and the shoreline was located about 35 feet (10.7 m) south of the geophone array. Reviewing previous data, including the 1932 Coast & Geodetic Survey Coast Survey Map and Google Earth views, large changes in shoreline position are evident. Indeed, one week after the geophysical survey, additional observations to confirm the geographic position of the geophone array found a new sandbar created just south of the array locations with a narrow lagoon parallel to shore at the river mouth. These observations provide direct evidence of the dynamic nature of the river mouth and coastline in this area.

4.0 GEOLOGICAL AND GEOPHYSICAL METHODS

For the basin survey, sub-bottom profilers and boomer acoustical source surveys were carried out on the same track lines (see Figure 2-2). For the geophysics, ECO-M collected a total of about 85 miles (137 km) of line length for a grid of 25 profiles. Line 116 was repeated for the onshore-offshore transition zone survey, and line 119 was repeated during better weather the second day. The surveyed area covers approximately 7,000 feet (2,133.6 m) alongshore by 4,000 feet (1,219.2 m) offshore. The line spacing was about 300 feet (91.5 m) for the tracklines parallel to the coast and about 600 feet (183 m) for the cross-shelf tie lines. Five NW-SE cross-lines were also collected in the area adjacent to and west of the wharf. The transition zone land geophone array was surveyed while the *Shana Rae* ran lines 116 and 116A in order to get maximum offset for the compressional wave velocity estimation, as well as basin depth imaging in the surf zone.

Technical aspects of the seismic reflection profiling had some impact on the results. The figures of the paleochannels were prepared with a combination of useful data that was generated from the deeper penetrating boomer multichannel system, and the 3.5 kHz data, which was limited in its usefulness due to the similarity of the silty sand on the seafloor to the reflections of coherent energy below the surface. ECO-M has much more confidence in the offshore seismic profile measurements, which came up with consistent velocities, whereas the land geophone profile was shorter, with only one geophone array, so it did not measure the velocity data deeply very well. Also, steep or near-vertical boundaries are poorly recorded by surface seismic reflection methods; the seismic energy is reflected away from the hydrophone streamer.

4.1 ACOUSTICAL SOURCES

Boomer: This system is a broadband acoustical source that uses high-voltage electrical discharge into a coil to repel an aluminum plate within a rubber diaphragm. The rapid recoil underwater creates acoustic source energy — a “boom” that sounds like a low frequency “click” (Photo 4-1). A 300 joule system was used to provide sub-bottom seismic energy penetration of as much as 100-300 ms (about 250 to 820 feet, or 75 to 250 m) in soft sediment. The typical bandwidth achieved is 400-1,200 Hz for sub-meter resolution (about 3feet or 1 m vertical imaging). The firing interval (“pop interval”) was set at one-half second (500 ms) to provide a nominal shot point spacing of one meter (3.28 feet) at a vessel survey speed of four knots.

3.5 kHz: Geologic fine structure for the upper 20m of seafloor was partly determined by the Ross model 4900 sub-bottom survey system (3.5-kHz sub-bottom profiler) since the Boomer deep penetration system often may not (because of its power) adequately record shallower sub-bottom anomalies. The system operates at a frequency of 3.5 kHz and has a down beam angle of 80 degrees conical at -3db with selectable pulse widths of 0.2, 0.5, and 1.0 ms.

Multibeam SeaBat 8124 Ecosounder: Used to carry out the bathymetric survey. Operates at a frequency of 200 kHz in water depths up to 100 m. The system measures the profile of the bottom, which is 3.5 times the measured water depth. The sound beams are sent in an arc (or swath) of approximately 120 to 140 degrees perpendicular to the direction of travel of the vessel, with an along-track beam width of 3.5 degrees.

Photo 4-1. Photo showing "Boomer" in tow.

4.2 RECEIVERS

16-ChannelGeoEel (High-Resolution Digital Streamer Hydrophone Array): Each channel records one group of five (5) hydrophones (underwater microphones) with a spacing of 5.126 feet (1.56 m) between group centers (Photo 4-2). The streamer has a non-toxic silicon ballast fluid in a clear polyurethane jacket to satisfy environmental regulations. A multi-channel streamer is required to attenuate water bottom multiples in the shallow water area through stacking and deconvolution of the digitally-recorded data. This is especially important in coastal areas that may have been dredged for boat traffic, thereby disrupting the natural bottom sediment and possibly increasing reflected source-generated noise energy. The short streamer group interval maintains the high-resolution imaging capability for shallow sub-bottom feature identification. For the shallow water and restricted waterways, a 16-channel streamer with a 5.12 foot (1.56 m) group interval was used. Sedimentary horizons were successfully imaged to depths exceeding 200 ms (~492 feet or 150 m), and the very short group interval preserves spatial resolution (2.56 feet or 0.78 m) for the shallower sub-bottom structure of interest for the offshore alluvial basin mapping.

Sub-bottom Profiler: This transducer-based, single-beam system transmits and receives its signals through the same transducer in a single frequency (3.5 kHz).

Land Arrays: As the paleochannels continue from onshore to offshore, it is desirable to obtain information on channel depth in the coastal area where the land meets the sea. Seismic acquisition in these areas is called “transition zone” acquisition and uses a combination of land and marine data acquisition technology. The methods described below represent a specialized variation in geophysical surveying techniques to obtain data simultaneously on land and at sea to correlate subsurface strata from the beach to offshore. For this project, transition zone profiles were acquired by recording the boomer source array, which was towed behind the boat along the offshore transects into the land geophone arrays (Photo 4-3). The transition zone profiles were acquired along offshore lines 116 and 116A using a one-second (1,000 ms) pop interval. The longer firing interval was necessary to ensure that all of the significant seismic signals could travel the distance from the boomer offshore into the geophone array on the beach. The sample rate for the geophone array was set at 0.5 ms. In addition, a hammer source was used on the beach to produce sound signals in order to record their reflected seismic waves returning from the shallow subsurface horizons directly beneath the land (geophone) array (Photo 4-4). The geophone array was deployed on the sandbar plug at the mouth of the San Lorenzo River. A total of 72 geophones (40-Hz center frequency) were set into the sand in a “T” configuration with 48 geophones oriented from south to north perpendicular to the shoreline and 24 geophones oriented from west to east perpendicular to the San Lorenzo River (Figure 4-1 and Photo 4-4). The geophone spacing was 2.5 feet (0.762 m) providing array lengths of 120 feet (36.6 m) in the N-S array and 60 feet (18.3 m) in the E-W array. The geophone transition zone seismic profiles were acquired to image the shallow subsurface sediment layers in the immediate coastal zone and nearshore area. Sub-bottom imaging exceeding 300-foot depths (100 m) was achieved. The transition zone seismic profiles were correlated with the USACE boreholes from the nearby levee along the San Lorenzo River and tied to the offshore boomer seismic profiles to identify the bottom of the ancient river channel more accurately.

Photo 4-2. Digital streamer hydrophone array.

Photo 4-3. Transition zone survey radio antenna and geophone array. Boomer seismic vessel *Shana Rae* is moving offshore in-line with the land array to acquire sub-bottom data in the surf zone.

Photo 4-4. Transition zone geophone array and sledgehammer sound source in use.

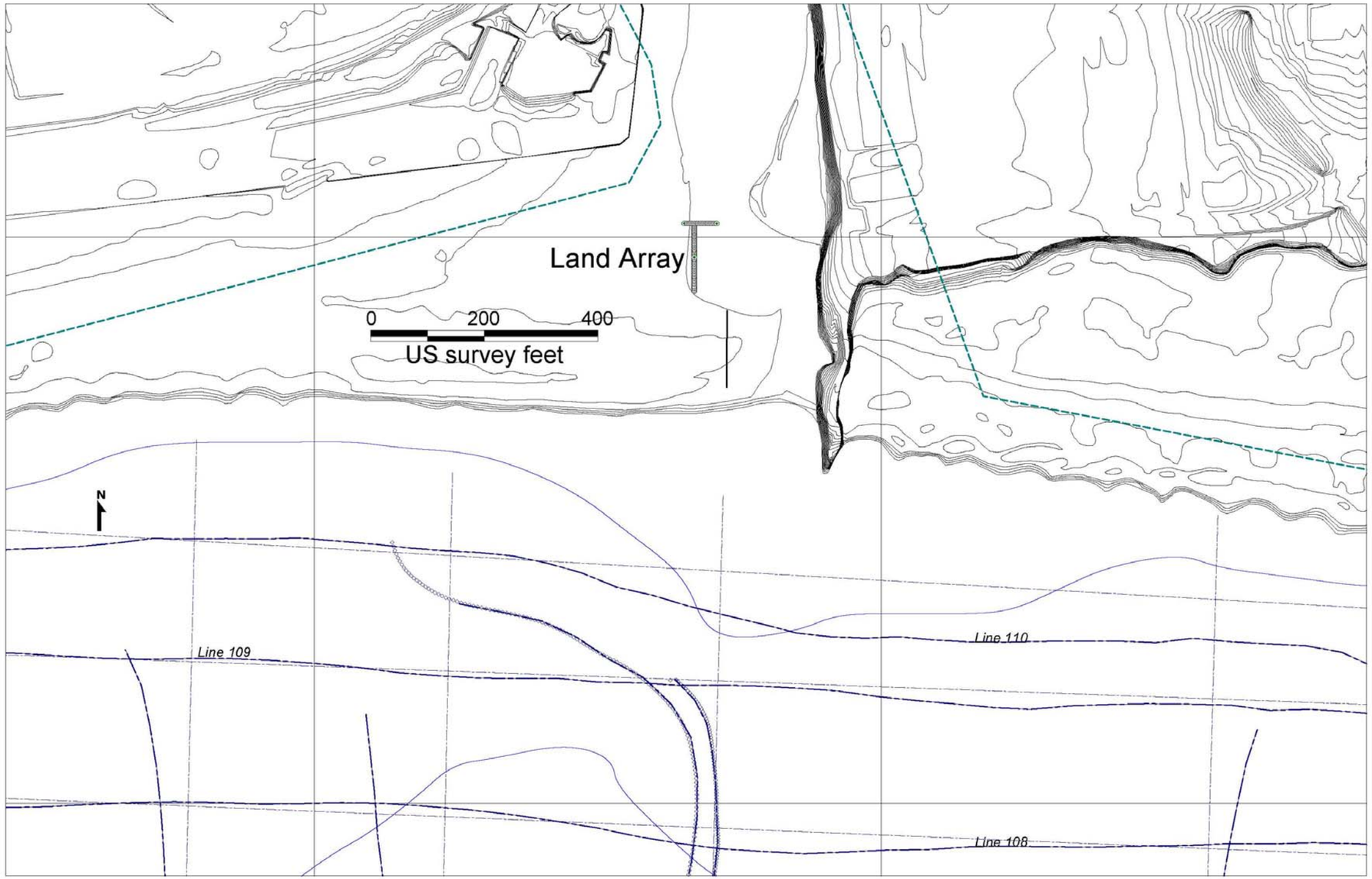

Figure 4-1. Location and shape of land seismic array for transition zone geophysical survey. Lines 116 and 116a provided seismic signals recorded by the land array. Vertical line southeast of the Land Array shows the original planned location for the geophone array, which was underwater in the surf zone at the time of the survey in October 2009.

The long offset, the distance from the source to the receiver array, provided by the transition zone profile also enabled more accurate determination of seismic velocities in the subsurface (Figure 4-2). This long offset profile is called a "wide-angle" reflection profile in geophysical terminology. The wide-angle reflection profile measures the horizontal seismic velocity (refraction velocity) and vertical thickness of subsurface sediment that was deposited in nearly horizontal layers over geologic time. The slope of the diagonal line is the velocity in feet per second (fps). As the wide-angle reflection sound travels deeper, the layers shot in this land array appear to have similar velocities to the seismic reflection layers that were shot vertically. The ratio of the offset distance versus the travel time measures the seismic velocity of the subsurface layers along the profile. Accurate seismic velocities are needed to convert the two-way travel time (twtt) recorded in the reflection profiles into subsurface depths.

Multibeam System: This system transmits and receives its signals through the same transducer in a single frequency (200 kHz).

4.3 RECORDING SYSTEMS

24-bit Analog-to-Digital Recording System: A Geometrics GeoEel data acquisition system, with nominal 144-channel recording capability, was used to record the multi-channel hydrophone streamer array data. A digital sample rate of 4,000 Hz (0.25 ms) was used for the offshore boomer profiles. This system records data directly to computer hard disk so that initial data processing while "at sea" provided data quality control. For the land geophone array, a 24-bit A/D 72-channel StrataVisor was used combined with a radio telemetry system to send the shot break times to the onshore recording system. The geophone sample rate of 2,000 Hz (0.5 ms) was used for the transition zone profiles.

Hard-copy Recorders: Monitors of the near trace data of the MCS streamer are plotted continuously during data acquisition on a laptop computer with the recording system. Hard-copy printouts of each line were made on a portable printer after completing each trackline to provide quality control throughout data acquisition. These data also provide preliminary information on the location of paleochannels and other subsurface features during the fieldwork so that the seismic profiles are acquired with sufficient length to image all of the important structures in the vicinity of the site.

Sub-bottom Profiler: The reflected signal is recorded utilizing a standard portable computer and navigation software. Data could be evaluated in real time and were recorded to hard disk in SEGY format for later review, processing, interpretation, and plotting.

Multibeam: The signal is recorded utilizing a standard portable computer and navigation software (HYPACK). Data could be evaluated in real time and were recorded to hard disk for later review, processing, interpretation, and plotting.

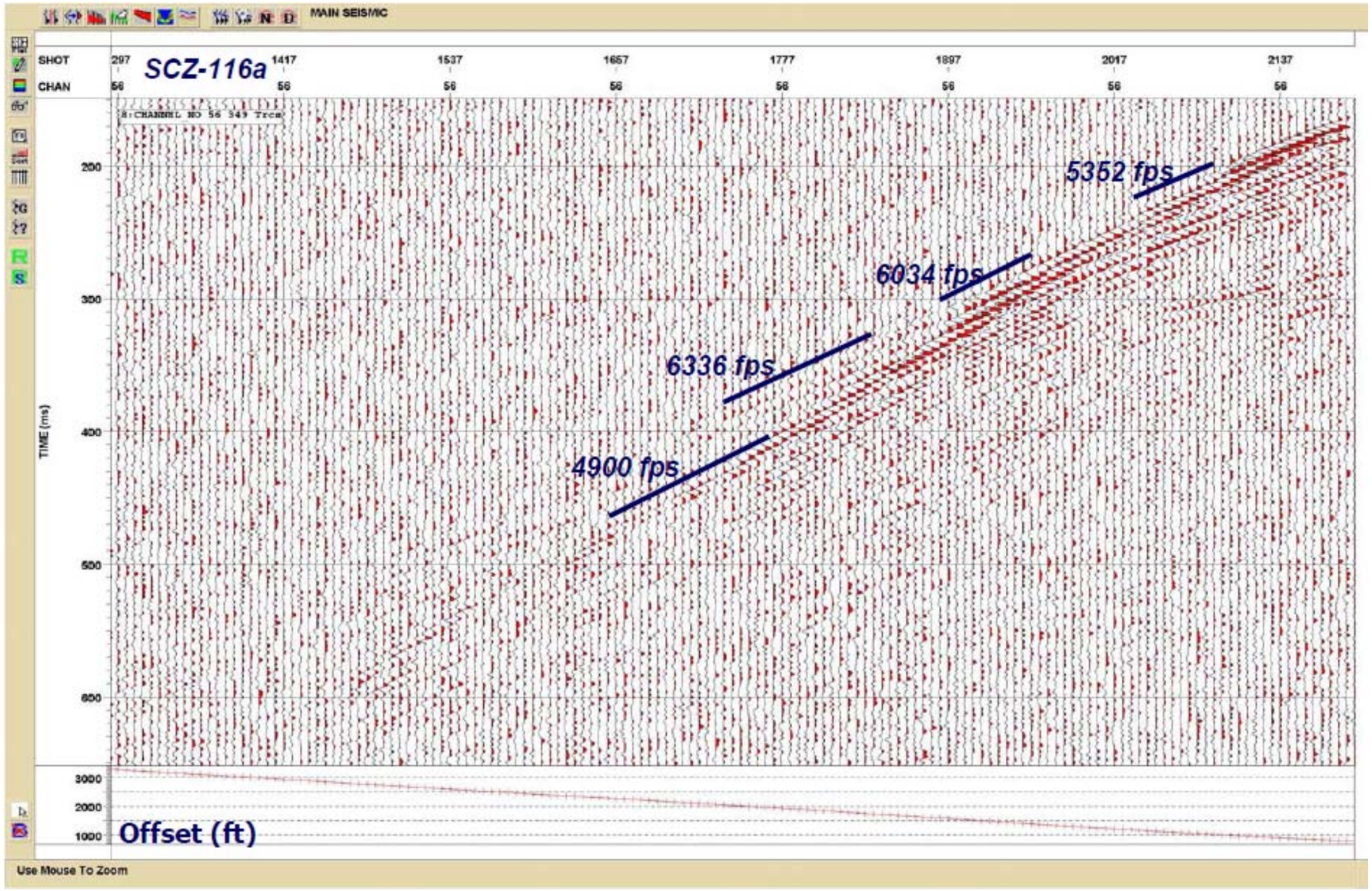

Figure 4-2. Wide-angle reflection profile recorded from offshore boomer source to beach geophone array. The bottom chart shows the offset (distance from source to receiver) measured in feet. Time versus distance values derived from these data measure the seismic velocity of the subsurface geologic layers.

4.4 NAVIGATION

Differential GPS: A differential GPS, satellite-based navigation system was used to record the shot point positions at roughly 10-second (20 shot points) intervals during acquisition. The differential system used ties to the Coast Guard-maintained permanent GPS base station in the area. Nominal GPS position accuracy is about 32.8 feet (10 meters), and with differential technique, sub-meter position accuracy (<3.0 feet) was achieved. Digitally recorded logs of shot points, navigation fixes, and adjacent landmarks provided quality control to maintain the highest possible navigational accuracy. Exact shot point times acquired at 0.50-sec intervals and 1.0-sec intervals for the transition zone profiles were recorded from the GPS through a computer link to the seismic data acquisition system. Navigation data were post-processed to compute the actual shot point position based on these times and corrected for offset distance and direction from the shipboard GPS antenna to the center of the boomer behind the boat. The streamer offset behind the boat was measured as 73 feet (22.25 m); the boomer center offset was 52.5 feet (16 m) providing the desired near trace offset of 20.5 feet (6.25 m). The geophone positions of the land array were surveyed with a tape measure and compass. The GPS coordinates of key geophones were measured by hand-held GPS receivers. The distance and direction from the northwest corner of the geophone array to the corner of the seawall by the amusement park was also measured to check the GPS coordinates with Google Earth maps. The distance from the geophone array to the waterline was also measured, but this distance varies with the tide and erosion/deposition of the beach sands.

4.5 DATA PROCESSING

Multi-channel Seismic Data Processing: The data acquired with the MCS arrays were processed in a typical 2-D exploration seismic data processing sequence, including trace editing, scaling and attenuation compensation, deconvolution, normal-move-out (NMO) correction and stack, and migration. These procedures are necessary to produce the high-resolution sub-bottom images of geologic structure by attenuating coherent and other acoustic noise energy while increasing the reflected acoustic signal energy. The post-cruise processed navigation, corrected for offset from GPS antenna to source array position, was stored in the trace headers (XSHOT, YSHOT, fields 73 and 77) of the stacked and migrated MCS data. A static correction was applied for the tide and depth of the boomer source and streamer and geophone arrays to reference the seismic data to MLLW. These georeferenced seismic data were then loaded into our Geographix Interpretation Workstation to facilitate the data interpretation and mapping. The following list is the actual seismic data processing sequence used and includes the relevant filter settings and other processing parameter values. In the exploration seismic industry, this processing sequence is considered “wavelet processing,” which is designed to provide an accurate image of the subsurface with a consistent seismic “wavelet” shape and enhanced signal-to-noise ratio to simplify interpretation.

Processing Flow
Input Data, Set Geometry and CMP Binning
Trace Edit, Kill Bad Traces
FK Filter, "Pie-Slice" to 720 Hz
Ormsby Band-Pass Filter, 25/50 to 1200/1800 Hz
Scaling, Exponential Time Power (exp = 0.3)
Deconvolution, Spiking, 40-msec Operator Length, 4-msec Taper, 1.0% pre-whitening, Entire Trace
Scaling, RMS
Ormsby Band-Pass Filter, 25/50 to 1200/1800 Hz
Output SPDecon
Trace Edit, Kill Bad Traces (second pass)
Ormsby Band-Pass Filtering, 25/50 to 720/960 Hz – for spatial alias
Sort, CMP
NMO Correction, Constant Stacking Velocity (RMS) 5,000 feet/sec, Stretch Mute 75%
CMP Stack, 1/N Scaling
Ormsby Band-Pass Filter, 50/75 to 720/960 Hz
Trace Scaling, Mean, Entire Trace
Output, Stack
Header Edit, Add Navigation and Elevation Static to Headers
Apply Static Shift, Surface to Fixed Datum (Tide, Source and Streamer Depth)
Ormsby Band-Pass Filter, 50/75 to 720/960 Hz
FK Migration, Constant Velocity 4,800 feet/sec, Trace Interval 2.6 feet
Trace Scaling, Mean, Entire Trace
Ormsby Band-Pass Filter, 60/90 to 600/800 Hz
Output, Migration

Multibeam Data Processing: The data acquired were processed using standard hydrographic survey software from Hypack, Inc. The data were analyzed in a typical standard data processing sequence, including editing, scaling, and tide correction.

Tidal Fluctuation Measurements: Water level fluctuations at the survey site were continuously measured during this study between 16 October and 29 October 2009. Tide measurements were compared with those from Monterey NOAA station 9413745 (http://tidesandcurrents.noaa.gov/geo.shtml) and the comparison is shown on Figure 4-3. There is good agreement between the two measurements with slight time variation due to the distance between the stations.

Results of the 2009 multibeam survey are shown on Figures 4-4 and 4-5. Figure 4-5 shows a 3-D plot of the bathymetry data. A comparison between surveys conducted in 1933, 1995 and 2005-06 and our 2009 multi-beam survey is shown on Figure 4-6. It shows an increase in sediment accumulation in the embayment between 1933 and the later surveys. There were few noticeable differences between the surveys conducted in 1995, 2005-06, and 2009.

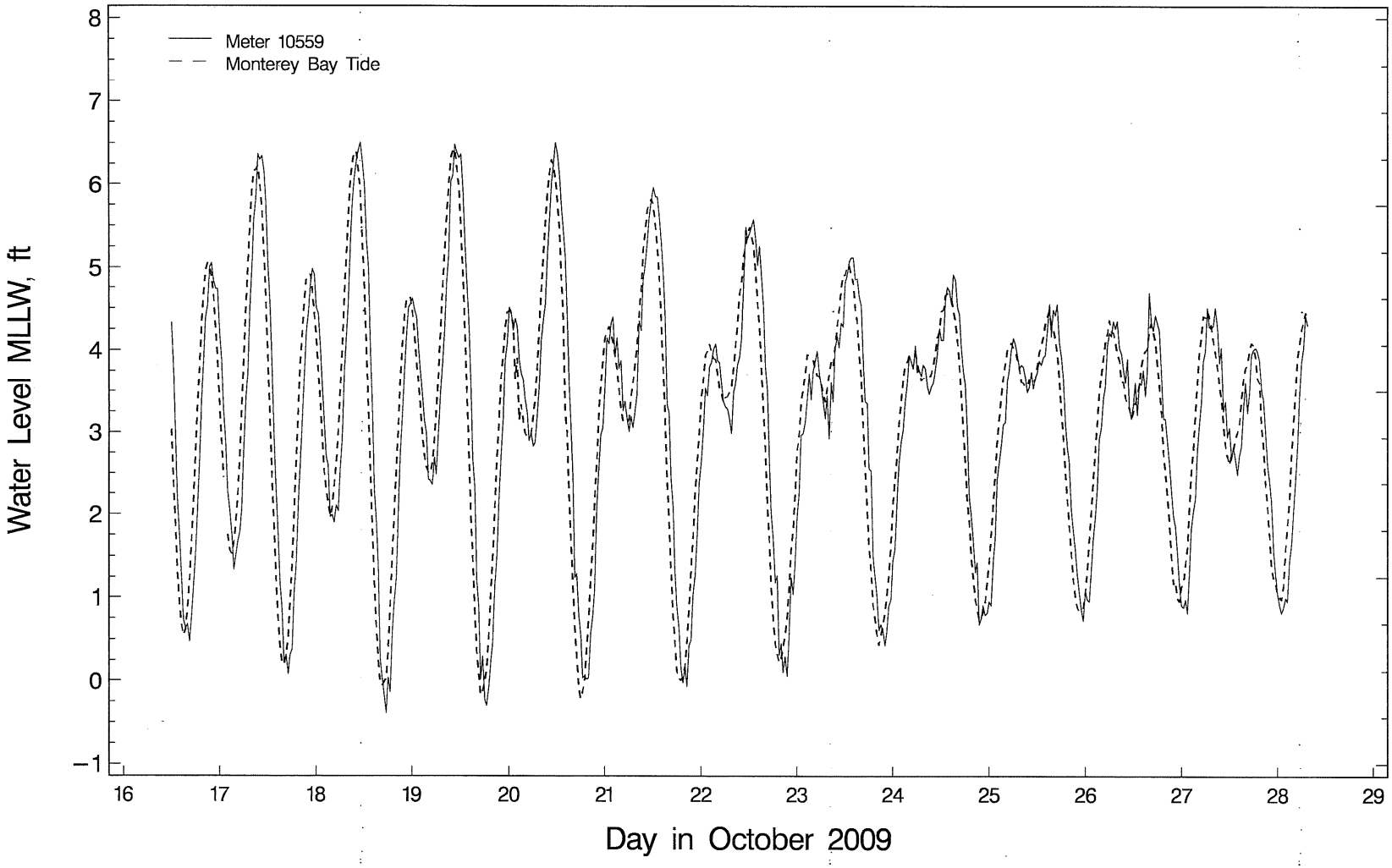

Figure 4-3. Comparison between tide measurements taken in Santa Cruz Harbor and NOAA Monterey station. Tide measurements at the Santa Cruz Harbor entrance lag Monterey Bay tides.

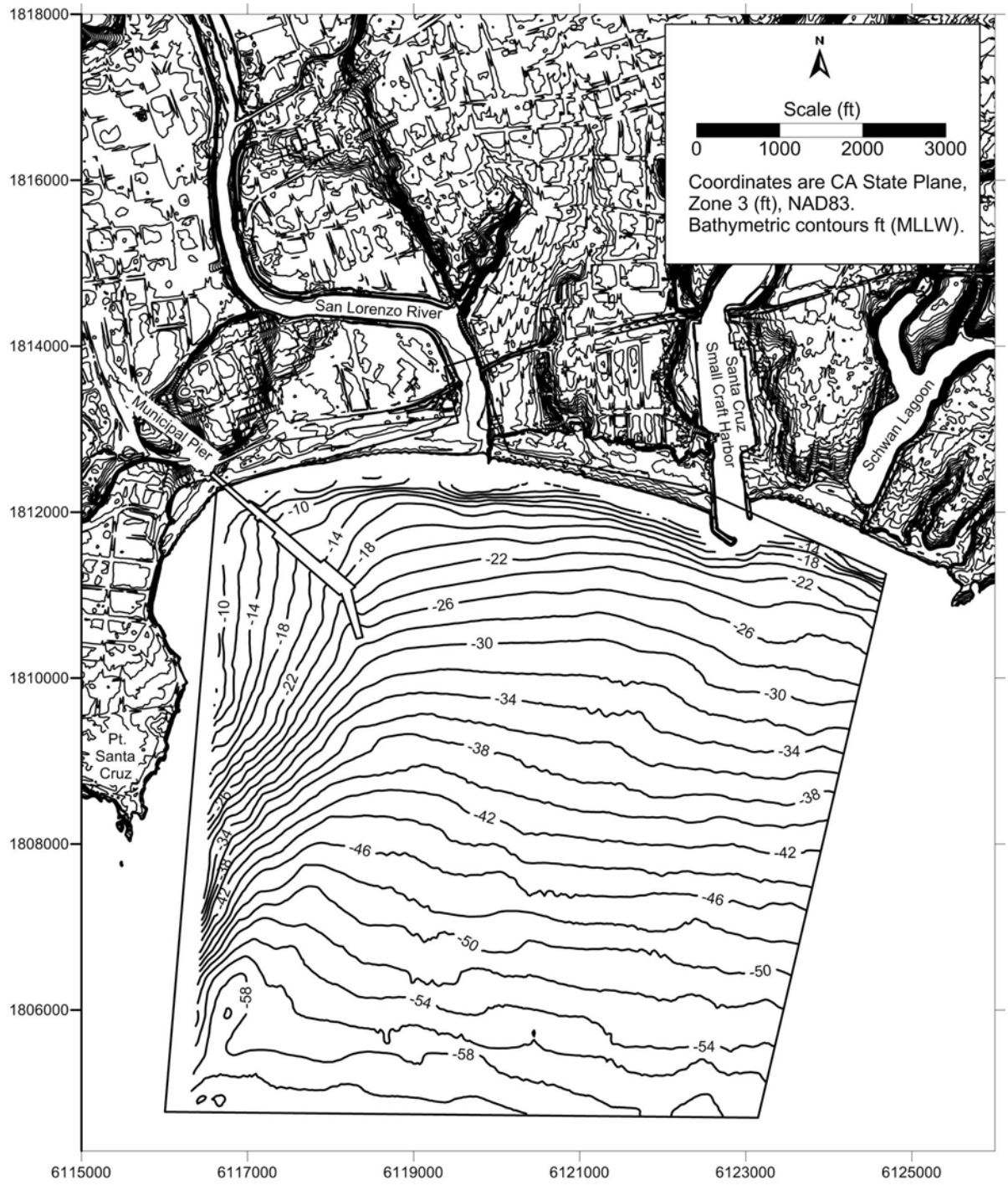

Figure 4-4. Bathymetry map for alluvial basin survey area. Multibeam survey conducted between October 17 and October 20, 2009.

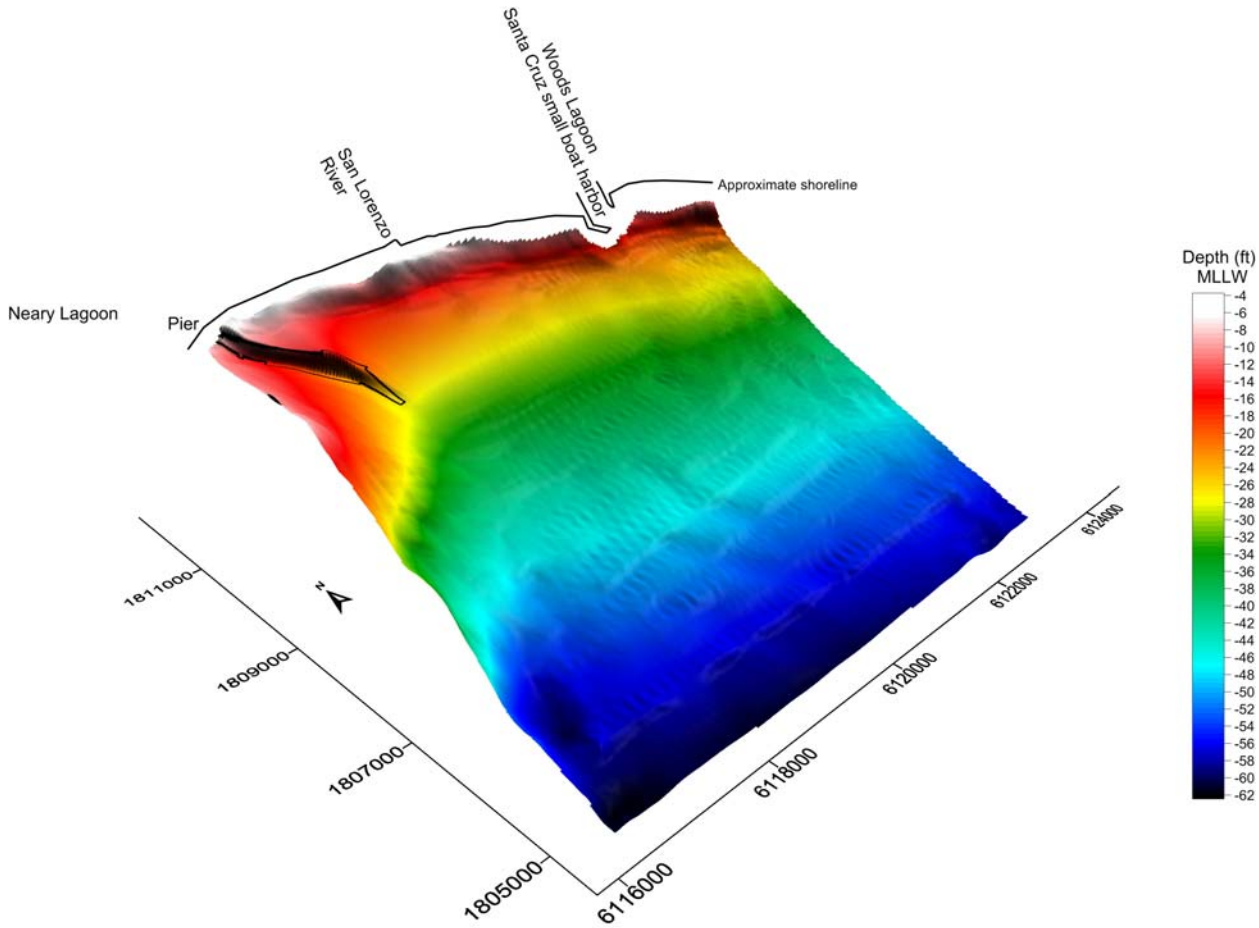

Figure 4-5. 3-D bathymetry plot for alluvial basin survey area, from multibeam survey data.

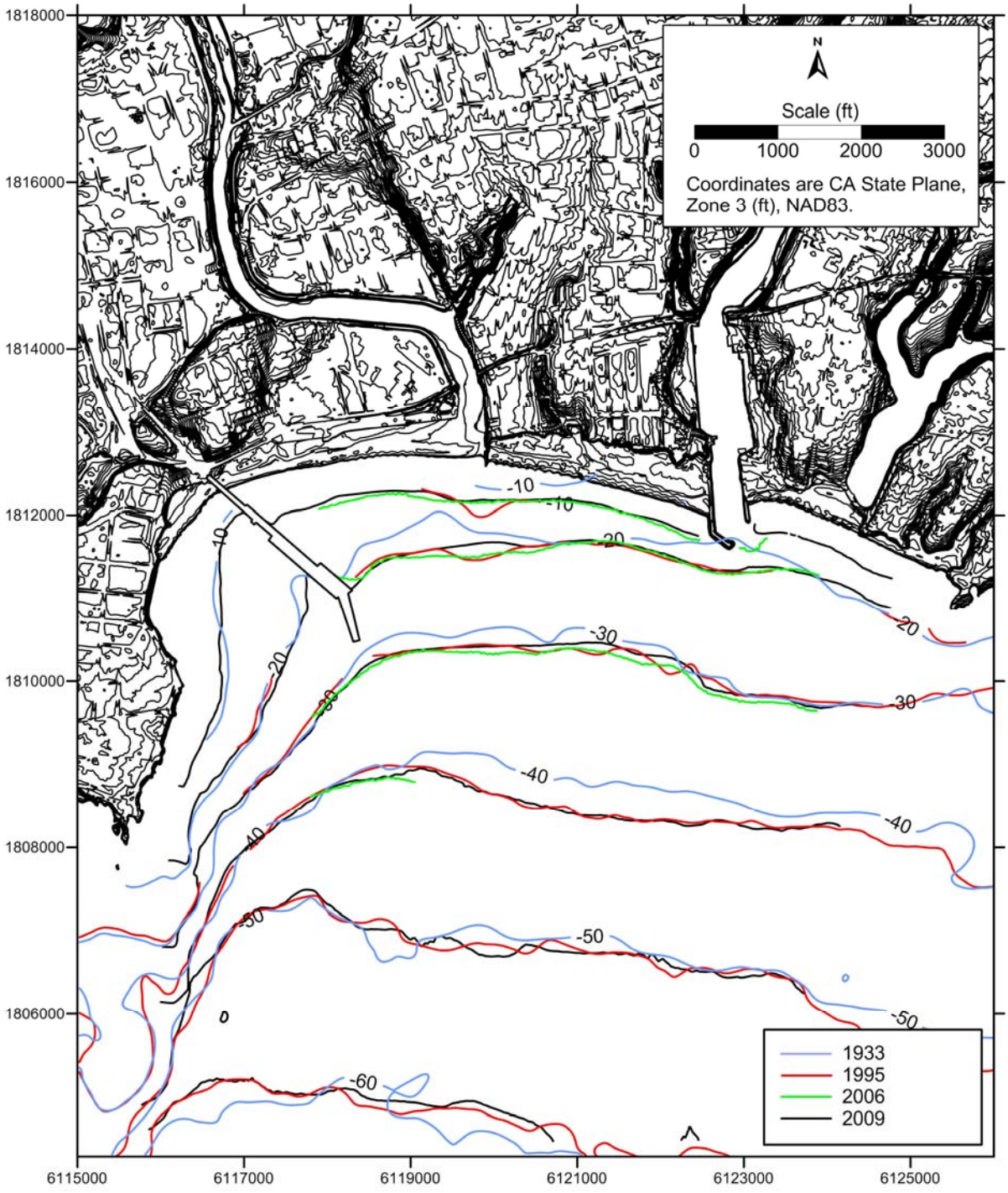

Figure 4-6. Comparison between bathymetry surveys conducted by USGS in 1933, 1995, and 2005 and our multibeam survey conducted in October 2009. Contour locations are similar, in general, although there appear to be some bulges near the mouth of the San Lorenzo River that come and go.

5.0 VIBRACORE SAMPLING

5.1 SAMPLE COLLECTION

Seafloor sampling was conducted between November 9 and 12, 2009. The *Shana Rae*, a 52 foot-long (15.85 m) research vessel, was used to conduct the vibracoring operation (Photo 5-1). A total of 11 vibracores were collected over the four-day period at the locations shown on Figure 5-1. The vibracore sample depths were between 4.5 and 15.5 feet (1.4 and 4.7 m), depending on when the vibracore met refusal (<6" penetration in 5 minutes of vibration). GPS coordinates and a general description of the cores is given in Table 5-1. The core logs are provided in Appendix B and photographs are in Appendix F. An onboard Garmin differential GPS unit was used to locate the predetermined location for each vibracore. The vibracore locations were selected based on the location and geometry of several basin features that were identified during the geophysical surveys noted above.

The vibracore head, which provides the vibrations that allow the sampling corer and tube to penetrate the seafloor, is attached to the top of the aluminum vibracore frame. The vibracore frame includes legs and feet that allow it to stand on the seafloor and withstand the swell from ocean waves without falling over. A larger (26.25 feet, or 8 meter frame legs) vibracore frame was utilized on the first two days of sampling, which took place in water depths of approximately 21 to 27 feet (6.5-8.5 m). The vibracore frame was equipped with shorter legs of 13 feet (or 4 m) for the last two days of sampling, which took place in water depths of approximately 9 to 26 feet (3.0–8.0 m), generally too shallow to use the longer support frame.

At each vibracore location, the vibracore frame was lowered off the stern of the vessel using the vessel's winch system and guided into place by the crew. The vibracorer operated with electric power supplied by a portable generator. Once the vibracore frame feet were on the seafloor, the vibracore head was turned on. Vibracoring continued until the vibracorer met refusal, at which time the vibracore frame was raised back onto the *Shana Rae* using the winch. The 4-inch (10 cm) butyl acetate sleeves, which contained the soil samples, were then pulled out from inside the aluminum core tube, cut into approximately 5-foot (1.52 m) lengths, capped, labeled, and examined by the onboard geologists.

Photo 5-1. TEG crew packaging a vibracore before its inspection by geologist.

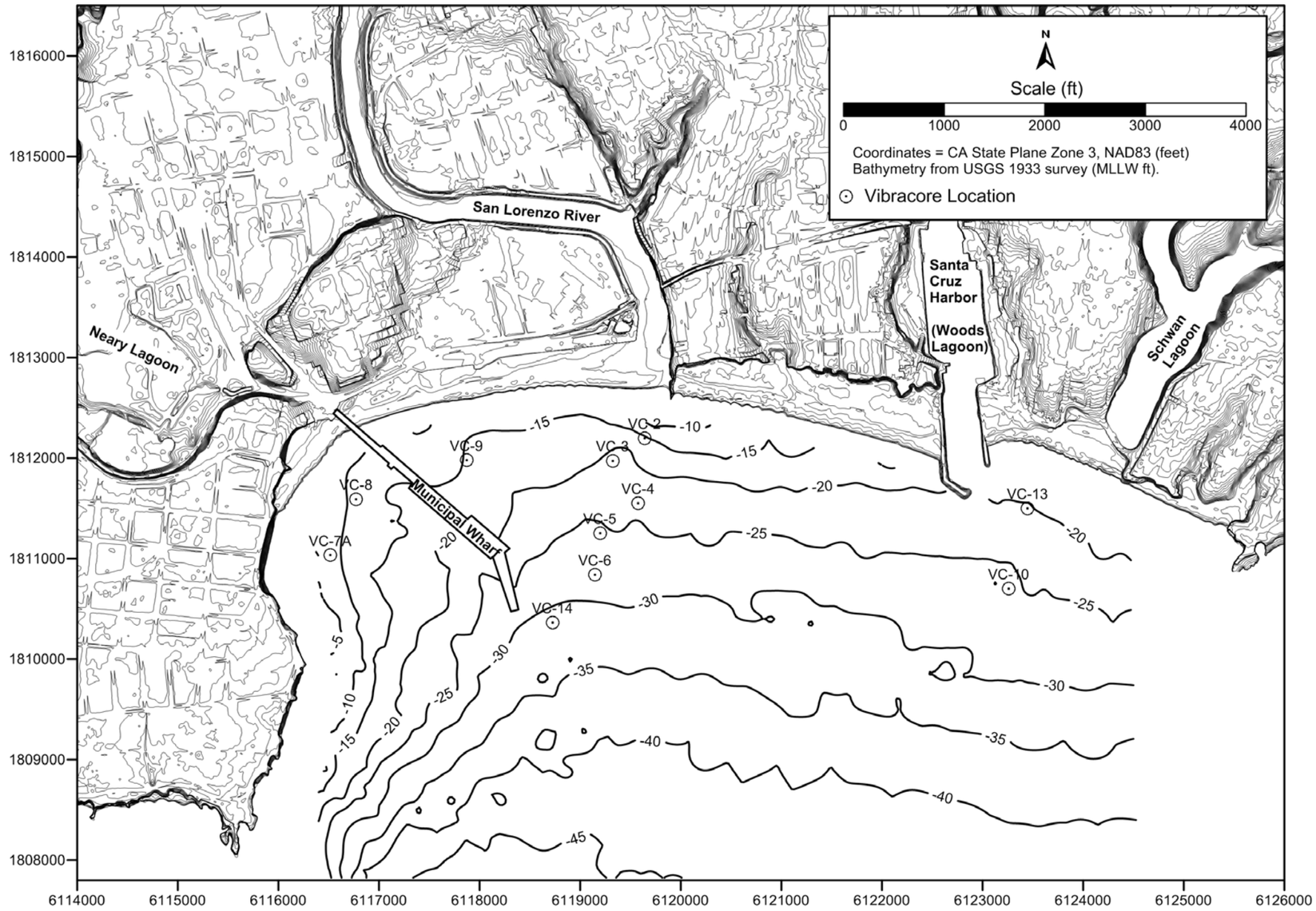

Figure 5-1. Vibracore locations.

Table 5-1. Vibracore data location and general description.

Vibracore Name	Location	Vibracore Coordinates (CA State Plane Zone 3, NAD 83 [feet])		Vibracore Length (feet)	General Description
		Easting	Northing		
VC-2	SLR[a]	6119641.886	1812196.688	9.3	Fine-grained sand
VC-3	SLR	6119323.627	1811972.903	11.2	Fine sand and coarse-grained, gravelly sand
VC-4	SLR	6119577.683	1811550.582	13.0	Fine sand and coarse-grained, gravelly sand, minor silt layers
VC-5	SLR	6119197.275	1811252.011	6.0	Fine sand and coarse-grained, gravelly sand
VC-6	SLR	6119147.672	1810838.92	15.5	Fine sand and coarse-grained, gravelly sand
VC-7A	NL[b]	6116516.716	1811032.713	4.5	Fine-grained sand
VC-8	NL	6116773.337	1811591.186	9.9	Clayey silt
VC-9	C/L Complex[c]	6117871.167	1811977.671	11.0	Fine-grained sand with silt layers
VC-10	W/S L[d]	6123260.895	1810701.411	15.0	Sandy silt, silty sand
VC-13	W/S L	6123448.576	1811499.356	10.0	Fine sand, silt, shells
VC-14	SLR	6118726.43	1810363.512	9.6	Fine-to-coarse-grained sand at top and bottom, clayey-silt layer in middle

[a] SLR = San Lorenzo River paleochannel
[b] NL = Neary's Lagoon channel/graben
[c] C/L Complex = San Lorenzo River Channel/Levee Complex
[d] W/S L = Woods/Schwan Lagoon Complex

5.2 DESCRIPTION OF VIBRACORE LOGS

The vibracores were collected from four different paleochannels: Neary's Lagoon channel/graben, the San Lorenzo River Channel/Levee Complex, the San Lorenzo River paleochannel, and the Woods/Schwan Lagoon Complex. Cores VC-2, VC-3, VC-4, VC-5, VC-6, and VC-14 were taken from the San Lorenzo River paleochannel as mapped from the geophysical data. VC-2 was closest to the shoreline, and VC-14 was the farthest and was located east of the end of the Santa Cruz Wharf. Among the cores selected for analysis, the sediment can be characterized as having two similarities: 1) the upper 1-2 feet (0.3-0.6 m) of all the cores except V-14 was a fine grained sand and silty sand (VC 14 had 15% gravel and a medium coarse grained sand at this depth), and 2) at a depth of 4 feet (1.2 m) was a fine to very fine grained sand with silt or clay. Below this depth, the character of the sediment varied among the cores with some fine, medium, and coarse-grained sand and some gravel. The average percentage of sand in all the selected vibracore samples analyzed in the San Lorenzo River paleochannel was 71.7%, with 19.46% silt and clay, and 8.8% gravel (see Table 5-4).

All but one of these six vibracores had a layer of fine-grained material (fine-grained sand or silty sand) on top of coarse-grained material. The thickness of this fine-grained layer varied between 1.8 feet (0.5 m) (VC-4) and 8.7 feet (2.7 m) (VC-2). VC-14 did not have any fine-grained material overlying the coarse-grained, gravelly sand, but in this vibracore, the coarse-grained material only occupied the upper 4.2 feet (1.3 m), as well as the core area below 7.3 feet (2.2 m). Between these two coarse layers was fine-grained clayey silt. All six of these vibracores contained a section of gravelly, coarse sand that likely represents the actual paleochannel or more recent flood deposits. The total thickness of this coarse gravelly sand could not be determined by the vibracoring, as refusal was met somewhere between 6 feet (1.8 m) (VC-5) and 15.5 feet (4.7 m) (VC-6) below the seafloor.

VC-7A and VC-8 were taken from the Neary Lagoon paleochannel (graben) identified by the geophysical data. VC-7A met refusal at 4.5 feet (1.4 m) below the seafloor and consisted of tightly packed, poorly graded, fine-to-medium-grained sand. The top 2 feet (0.6 m) of VC-8 consisted of this same poorly graded sand, but from 2 feet (0.6 m) to refusal at 10 feet (3.0 m), it consisted of a clayey silt. All of this fine-grained material likely represents a filled-in meander of the San Lorenzo River or a lagoonal type structure.

VC-9 was taken from just east of the Santa Cruz Wharf in the channel/levee complex west of the San Lorenzo River paleochannel. This vibracore consisted of fine-to-very-fine-grained sand in the upper 5.8 feet (1.8 m) and silt and clayey-silt between 5.8 feet (1.8 m) and 11 feet (3.4 m), which was refusal. According to the geophysical data, this is a complex area consisting of a channel levee complex and former marine terraces.

VC-10 and VC-13 were taken from the former Woods/Schwan Lagoon complex south of the Santa Cruz Harbor (former Woods Lagoon), and the current Schwan Lagoon. Both of these cores consisted of silty sand with layers of clayey, sandy silt. The VC-13 vibracore had a prominent hydrogen sulfide odor, which is consistent with lagoonal deposits. Based on vibracoring results,

areas south of Neary Lagoon or Woods/Schwan Lagoon are not likely to be suitable areas for desalination plant intake structures.

5.3 ANALYSIS

The purpose of the sediment sampling program was to obtain information on the type, thickness, material properties, and lateral and vertical extent of sediment in the study region. The vibracore data provides explicit ground truth information for the geophysical data interpretation. Selected samples from each core were analyzed by a California-certified geotechnical laboratory. Tests included gradation or grain size (ASTM D422), various moisture-density analyses (ASTM D2937), constant head permeability (hydraulic conductivity) for coarse-grained material (ASTM D2434), and flexible wall hydraulic conductivity (ASTM D5084) for fine-grained material. A list of the samples tested is given in Table 5-2.

The grain size analysis (Appendix C) includes grain size plots, which express the samples' particle size distribution. Grain size analysis was conducted on 23 samples. At least one sample was tested from each vibracore. Grain or particle size and particle size distribution in an alluvial sediment are important because of their relationship to void ratio (i.e., volume of voids/volume of solids), and the resultant potential flow rate or hydraulic conductivity of water moving through the material. Hydraulic conductivity is proportional to grain size and to hydraulic gradient or the change in total head as a function of distance over which the head is decreasing.

The hydraulic gradient controls the direction of flow. The units of hydraulic conductivity are velocity in cm/sec. Within most alluvial basins, the hydraulic conductivity is variable, because of differing grain sizes and gradients. Generally, the hydraulic conductivity is greater in the horizontal direction than in the vertical direction because of changing depositional environments. With an increase in the median grain size for sand sized particles, the hydraulic conductivity will also increase. Hydraulic conductivity results are presented in Appendix D.

5.4 SUMMARY OF RESULTS

5.4.1 Grain Size and Moisture / Density

Grain size results are summarized in Table 5-3. Table 5-4 gives the mean and median for each sample and percent gravel, sand, and silt & clay. Appendix C provides all of the laboratory data for grain size.

The grain size data matched with the geophysical data very well with respect to the predominant type of sediment in the channels. The grain size data shows that the samples from the Neary Lagoon paleochannel (VC-7 and VC-8) and from the Woods/Schwan Lagoon paleochannel complex (VC-10 and VC-13) are fine-grained and not conducive for an offshore intake structure. The San Lorenzo River paleochannel core samples show variability in the grain sizes at different depths and among the samples; however, there were some similarities. The grain size analysis and

Table 5-2. Samples taken for grain size and hydraulic conductivity analysis.

Vibracore #	Location	Sample Depth (feet below surface) in core	Grain Size Analysis ASTM Method D422		Hydraulic Conductivity	
			US Standard Sieves	Hydrometer	ASTM Method D2434	ASTM Method D5084
VC-2	SLR[a]	1 - 2	X			
VC-2	SLR	2.8 - 4.3	X		X	
VC-2	SLR	7 - 8	X			
VC-3	SLR	1 - 2	X	X		
VC-3	SLR	4.8 - 6.3	X		X	
VC-3	SLR	10 - 11	X			
VC-4	SLR	3.3 - 4.8	X		X	
VC-4	SLR	9 - 10	X			
VC-4	SLR	12 - 13	X			
VC-5	SLR	0.5 - 2.0	X	X		X
VC-6	SLR	0.2 - 1.2	X	X		
VC-6	SLR	4 - 5	X	X		X
VC-6	SLR	9.1 - 10.6	X		X	
VC-7A	NL[b]	2 - 3	X			
VC-8	NL	3.5 - 5.0	X	X		X
VC-9	C/L Complex[c]	3 - 4	X			
VC-9	C/L Complex	5.8 - 7.3	X	X		X
VC-10	W/S L[d]	2 - 3	X	X		
VC-10	W/S L	8.5 - 10.0	X	X		X
VC-13	W/S L	3.5 - 5.0	X	X		X
VC-14	SLR	0.5 - 1.5	X			
VC-14	SLR	4 - 5	X	X		
VC-14	SLR	8.1 - 9.6	X		X	

[a] SLR = San Lorenzo River paleochannel
[b] NL = Neary's Lagoon channel/graben
[c] C/L Complex = San Lorenzo River Channel/Levee Complex
[d] W/S L = Woods/Schwan Lagoon Complex

Table 5-3. Results of grain size analysis for selected vibracore samples.

Vibracore #	Sample Depth (feet below surface) in core	Grain Size Analysis						Soil Description
		% Gravel	% Sand			% Fines		
			Coarse	Medium	Fine	Silt	Clay	
VC-2	1-2	0	0	1.9	97.1	1.0	0	Fine-grained sand
VC-2	2.8-4.3	0	0.6	1.4	91.1	6.9	0	Fine to very fine-grained sand with minor silt
VC-2	7-8	0.4	1.7	7.5	85.7	4.7	0	Very fine to medium grained sand with minor silt
VC-3	1-2	0	4.0	2.9	68.8	18.5	5.8	Silty sand
VC-3	4.8-6.3	55.6	19.2	16.1	7.7	1.4	0	Coarse, gravelly sand
VC-3	10-11	8.2	17.9	36.8	35.0	2.1	0	Well graded sand with gravel
VC-4	3.3-4.8	0	0	14.9	77.2	7.9	0	Fine to medium grained sand with minor silt
VC-4	9-10	0	0	13.7	75.7	10.6	0	Fine to medium grained sand with minor silt
VC-4	12-13	27.9	53.2	16.4	1.5	1.0	0	Coarse, gravelly sand
VC-5	0.5-2.0	3.0	14.7	1.7	57.1	19.3	4.2	Silty sand
VC-6	0.2-1.2	0	0.1	0	57.0	36.9	6.0	Silty sand
VC-6	4-5	0	1.3	2.0	14.9	65.8	16.0	Clayey silt with fine-grained sand
VC-6	9.1-10.6	24.4	12.0	22.9	38.8	1.9	0	Well graded, gravelly sand
VC-7A	2-3	1.9	4.0	14.4	78.4	1.3	0	Fine to medium grained sand
VC-8	3.5-5.0	0	0.1	0	2.0	59.5	38.4	Clayey silt/silty clay
VC-9	3-4	1.0	0.3	0.7	94.6	3.4	0	Fine to very fine-grained sand
VC-9	5.8-7.3	3.0	4.0	1.9	26.6	46.4	18.1	Clayey silt with fine-grained sand
VC-10	2-3	0	2.1	1.0	23.5	67.5	5.9	Sandy silt
VC-10	8.5-10.0	0	3.1	1.0	56.7	29.4	9.8	Silty sand
VC-13	3.5-5.0	0	0.2	2.0	86.8	9.0	2.0	Fine-grained sand with minor silt
VC-14	0.5-1.5	15.0	8.1	28.7	45.7	2.5	0	Fine to coarse-grained sand with gravel
VC-14	4-5	0	0	0	5.0	67.9	27.1	Clayey silt
VC-14	8.1-9.6	7.0	19.1	25.1	44.9	3.9	0	Fine to coarse-grained sand with gravel

Table 5-4. Grain size data for selected vibracore samples.

Vibracore #	Sample Depth (feet below seafloor)	Location	Grain Size Analysis				
			Mean[a] (mm)	Median (mm)	% Gravel	% Sand	% Silt & Clay
VC-2	1-2	SLR[b]	0.30	0.27	0	99.0	1.0
VC-2	2.8-4.3	SLR	0.23	0.21	0	93.1	6.9
VC-2	7-8	SLR	0.28	0.24	0.4	94.9	4.7
VC-3	1-2	SLR	0.14	0.13	0	75.7	24.3
VC-3	4.8-6.3	SLR	4.03	2.80	55.6	43.0	1.4
VC-3	10-11	SLR	0.88	0.78	8.2	89.7	2.1
VC-4	3.3-4.8	SLR	0.42	0.41	0	92.1	7.9
VC-4	9-10	SLR	0.38	0.38	0	89.4	10.6
VC-4	12-13	SLR	1.84	1.40	27.9	71.1	1.0
VC-5	0.5-2.0	SLR	0.75	0.14	3.0	73.5	23.5
VC-6	0.2-1.2	SLR	0.12	0.09	0	57.1	42.9
VC-6	4-5	SLR	0.039	0.036	0	18.2	81.8
VC-6	9.1-10.6	SLR	3.38	0.78	24.4	73.7	1.9
VC-7A	2-3	NL[c]	0.40	0.31	1.9	96.8	1.3
VC-8	3.5-5.0	NL	0.008	0.006	0	3.1	96.9
VC-9	3-4	C/L Complex[d]	0.19	0.185	1.0	95.6	3.4
VC-9	5.8-7.3	C/L Complex	0.082	0.025	3.0	32.5	64.5
VC-10	2-3	W/S L[e]	0.080	0.053	0	26.6	73.4
VC-10	8.5-10.0	W/S L	0.108	0.098	0	60.8	39.2
VC-13	3.5-5.0	W/S L	0.17	0.15	0	89.0	11.0
VC-14	0.5-1.5	SLR	1.11	0.62	15.0	82.5	2.5
VC-14	4-5	SLR	0.019	0.012	0	5.0	95.0
VC-14	8.1-9.6	SLR	0.92	0.75	7.0	89.1	3.9

[a] Mean = Sample mean estimated from Folk and Ward formula (1957).
[b] SLR = San Lorenzo River paleochannel
[c] NL = Neary's Lagoon channel/graben
[d] C/L Complex = San Lorenzo River Channel/Levee Complex
[e] W/S L = Woods/Schwan Lagoon Complex

photos of the vibracore logs contain evidence of coarse gravelly sand in VC-3 (4.8-6.3 ft) (1.5-1.9 m), VC-4 (12-13 ft) (3.7-4 m), VC-6 (9.1-10.6 ft) (2.8-3.2 m), and VC-14 (0.5-1.5 and at 8.1-9.6 ft) (0.15-0.5 m and at 2.5-2.9 m). Coarse material was also found at the bottom of VC-2 (8.7 feet) (2.7 m) and VC-5 (3.0 feet) (0.9 m). The grain size analysis shows that fine sand is the predominant grain size (from 35% to 97.1% of each sample). There is a percentage of fine sediment (silt) in every section of core submitted for grain size analysis: for example, the percentage of fine sediment (silt/clay) in the upper 2 ft (0.6 m) of each core sample analyzed was 1% of the core closest to the beach (VC-2, 24% of VC-3, 23.5% of VC-5, 42.9% of VC-6, and 2.5% of VC-14).

Moisture and density data were obtained from all of the cores except 7A (Table 5-5). In total, 11 samples were tested. Ninyo & Moore tabulated test results on December 9, 2009. Sample depths ranged from less than 0.5 feet (0.15 m) to 10 feet (3 m). Tests included dry weight, wet density, moisture content, and dry density. Dry densities varied from a low of 71 pounds per cubic foot (pcf) to 114.5 pcf. These test results were required by the laboratory in case they are needed for the hydraulic conductivity testing.

Grain size analysis aids in the estimation of an alluvial aquifer's productivity by showing the percentages of each type of sediment contained within the sample submitted for testing. Care should be taken in making an inference that the samples represent the entire aquifer because the sediment in the cores shows heterogeneity (i.e., true differences in grain size at different depths). In general, coarse gravelly sand allows water to flow through it better than poorly graded sand; however, there are other factors that influence the flow of water in an aquifer, such as the porosity of the sediment in a vertical and horizontal direction. Clayey or sandy silt captures water well, whereas coarse sand drains the water. Clay layers may present a barrier to the flow of water. Further information about the capacity of a heterogeneous alluvial aquifer to conduct water, vertically and horizontally, follows in 5.4.2.

5.4.2 Hydraulic Conductivity

Hydraulic conductivity, or K, is a coefficient of proportionality describing the rate at which water can move through a permeable medium such as alluvial sediment. Alluvial sediment acts as a conduit allowing movement of water from recharge areas to a point or region of discharge. The value of K is dependent on the size and arrangement of the water-transmitting openings between the particles. The quantity of water flowing through the alluvial system is directly proportional to both the grain size and the hydraulic gradient or loss of head along the flow path.

Table 5-6 presents the results of the laboratory tests to estimate the hydraulic conductivity (K) for the 11 samples. This table also presents the median grain-size (D50) and the effective grain size (D_{10} – the size corresponding to the 10 percent passing line on the grain-size curve) for each sample. A productive aquifer generally has K values of at least 10^{-3} cm/sec. As previously mentioned, permeability of a porous media is a function of the size of the pore openings within the sedimentary materials. Frictional resistance to flow increases in finer-grained material because of the increase in surface area the water contacts as it moves through the porous media.

Table 5-5. Moisture and density values for samples selected for hydraulic conductivity analysis.

	Sample Location	VC-2	VC-3	VC-4	VC-5	VC-6	VC-6	VC-8	VC-9	VC-10	VC-13	VC-14
	Sample Depth (feet)	2.8-4.3	4.8-6.3	3.3-4.8	0.5-2.0	4.0-5.0	9.1-10.6	3.5-5.0	5.8-7.3	8.5-10.0	3.5-5.0	8.1-9.6
WEIGHTS	Weight of Dry Soil (g)	998.6	921.6	1020.2	770.3	652.8	1118.3	718.0	1249.6	1024.2	898.6	1061.3
	Container Volume (in^3)	39.9	31.2	35.6	29.8	29.5	37.2	38.5	52.6	37.1	31.4	38.3
	Dish Number	879	EVE	876	881	852	870	883	803	873	875	867
	Weight of Moist Soil + Tare (g)	1423.9	1107.9	1359.2	1130.2	252.7	1473.1	1267.9	2018.1	1455.5	1270.0	1456.5
	Weight of Dry Soil + Tare (g)	1175.7	1042.8	1198.4	948.1	220.7	1295.7	894.6	1638.3	1202.9	1076.4	1237.4
	Weight of Tare (g)	177.2	121.2	178.2	177.8	103.0	177.4	176.6	388.7	178.7	177.8	176.1
RESULTS	Wet Density (pcf)	119.2	120.5	126.4	121.8	107.2	132.7	108.0	118.0	131.1	132.5	127.4
	Moisture Content (%)	24.9	7.1	15.8	23.6	27.2	15.9	52.0	30.4	24.7	21.5	20.6
	Dry Density (pcf)	95.4	112.5	109.2	98.5	84.3	114.5	71.0	90.5	105.2	109.0	105.6

Table 5-6. Hydraulic conductivity data for selected vibracore samples.

Vibracore #	Sample Depth (feet below seafloor)	Location	Hydraulic Conductivity (k) (cm/sec)	Grain Size	
				D 50 (mm)	D 10 (mm)
VC-2	2.8-4.3	SLR[a]	4.80E-04	0.21	0.09
VC-3	4.8-6.3	SLR	4.18E-03	2.80	0.64
VC-4	3.3-4.8	SLR	2.46E-03	0.41	0.15
VC-5	0.5-2.0	SLR	1.33E-04	0.14	0.04
VC-6	4-5	SLR	6.26E-07	0.036	0.001
VC-6	9.1-10.6	SLR	3.14E-03	0.78	0.31
VC-8	3.5-5.0	NL[b]	1.32E-07	0.006	<0.001
VC-9	5.8-7.3	C/L Complex[c]	1.09E-04	0.025	<0.001
VC-10	8.5-10.0	W/S L[d]	1.81E-06	0.098	0.003
VC-13	3.5-5.0	W/S L	2.26E-04	0.15	0.07
VC-14	8.1-9.6	SLR	2.45E-03	0.75	0.30

[a] SLR = San Lorenzo River paleochannel
[b] NL = Neary's Lagoon channel/graben
[c] C/L Complex = San Lorenzo River Channel/Levee Complex
[d] W/S L = Woods/Schwan Lagoon Complex

In well-sorted sediment, permeability is proportional to the grain-size of the sediment. In poorly sorted sediment, the permeability is governed by the smaller grain-size of the sediment. Permeability generally decreases in a poorly sorted material because the finer-grained fraction fills the pore spaces between the coarser-grained sand and gravel formation materials (Fetter, 1988).

The K value of sandy sediment can be estimated by using the Hazen method, which incorporates the effective grain size derived from the grain-size distribution curve. The method is applicable to sands where the effective grain size is between 0.1 and 3.0 millimeters. The Hazen approximation is calculated using the equation:

$$K = C(D_{10})^2$$

Where:

K is hydraulic conductivity (cm/sec)
D_{10} is the effective grain size (cm)
C is a coefficient based on sediment type (see Table 5-7 below)

The coefficient values listed above are selected based on the grain size and sorting of the soil samples. To determine the degree of sorting for each sample, the uniformity coefficient (C_u) was calculated using the equation:

$$C_u = D_{60} / D_{10}$$

D_{60} is the size corresponding to the 60 percent passing line on the grain-size curve (cm)

Hydraulic conductivities for the vibracore samples selected were estimated using the laboratory grain-size results and the Hazen method. Estimations were conducted for all of the samples tested, though some of the finer-grained samples violate the minimum grain-size criteria for the Hazen. The results of this exercise are provided in Table 5-8. A comparison of the results of laboratory permeability and permeability values estimated using the Hazen method varied by as much as two orders of magnitude (VC-9, 5.8-7.3 feet (1.7-2.2 m) varied by 10^{-4} cm/sec). With the exception of sample location VC-9, 5.8-7.3 feet (1.7-2.2 m), the greatest variability between the laboratory test results and Hazen method estimations occur in the coarser grained material sampled, having grain size well within the method's grain size assumptions. The results of this comparison are provided in Table 5-9. Subsequently these values were utilized to create a comparison graph, which is provided as Figure 5-2. This graph shows the variability of laboratory test results and the estimation results using the Hazen method.

The laboratory test results indicate that the most permeable sediment submitted for testing (described as coarse, gravelly sand) is sample VC-3, collected at a depth of 4.8 to 6.3 feet (1.5-1.9 m). Laboratory test results for this sample indicated this material had a hydraulic conductivity of 1.34×10^{-2} cm/sec. The estimated hydraulic conductivity for this sample is 4.10 x 10-^{1} cm/sec. Several vibracore samples taken from the San Lorenzo paleochannel showed

Table 5-7. Coefficient selection criteria.

Material Type	Hazen Coefficient
Very fine sand, poorly sorted	40-80
Fine sand with appreciable fines	40-80
Medium sand, well sorted	80-120
Coarse sand, poorly sorted	80-120
Coarse sand, well sorted, clean	120-150

Table 5-8. Hydraulic conductivity estimation using the Hazen method.

Sample Location	Depth (feet)	D_{10} (cm)	C_u	Coefficient Used to Estimate Hydraulic Conductivity				
				K @ C=40	K @ C=80	K @ C=100	K @ C=120	K @ C=150
VC-2	1.0-2.0	1.60E-02	1.8	1.02E-02[a]	2.05E-02			
VC-2	2.8-4.3	9.00E-03	2.7	3.24E-03	6.48E-03	8.10E-03		
VC-2	7.0-8.0	1.00E-02	2.8		8.00E-03	1.00E-02	1.20E-02	
VC-3	1.0-2.0	3.60E-03	3.9	5.18E-04	1.04E-03			
VC-3	4.8-6.3	6.40E-02	5.9		3.28E-01	4.10E-01	4.92E-01	
VC-3	10.0-11.0	3.20E-02	2.8		8.19E-02	1.02E-01	1.23E-01	
VC-4	3.3-4.8	1.50E-02	3.1	9.00E-03	1.80E-02	2.25E-02		
VC-4	9.0-10.0	4.00E-03	10.3	6.40E-04	1.28E-03	1.60E-03		
VC-4	12.0-13.0	4.50E-02	3.8			2.03E-01	2.43E-01	3.04E-01
VC-5	0.5-2.0	4.00E-03	4.3	6.40E-04	1.28E-03			
VC-6	0.2-1.2	2.30E-03	6.1	2.12E-04	4.23E-04			
VC-6	4.0-5.0	7.00E-05	64.3	1.96E-07	3.92E-07			
VC-6	9.1-10.6	3.10E-02	3.2			9.61E-02	1.15E-01	1.44E-01
VC-7A	2.0-3.0	1.60E-02	2.4		2.05E-02	2.56E-02	3.07E-02	
VC-8	3.5-5.0	2.00E-05	45.0	1.60E-08	3.20E-08			
VC-9	3.0-4.0	9.00E-03	2.2	3.24E-03	6.48E-03	8.10E-03		
VC-9	5.8-7.3	4.00E-05	137.5	6.40E-08	1.28E-07			
VC-10	2.0-3.0	7.00E-04	8.6	1.96E-05	3.92E-05			
VC-10	8.5-10.0	3.10E-04	41.9	3.84E-06	7.69E-06			
VC-13	3.5-5.0	7.00E-03	2.3	1.96E-03	3.92E-03	4.90E-03		
VC-14	0.5-1.5	2.80E-02	2.8		6.27E-02	7.84E-02	9.41E-02	
VC-14	4.0-5.0	3.00E-05	56.7	3.60E-08	7.20E-08			
VC-14	8.1-9.6	3.00E-02	2.9		7.20E-02	9.00E-02	1.08E-01	

[a] Blue fields indicate permeability estimates by Hazen method for 23 sediment samples selected for grain size analysis.

Table 5-9. Laboratory / Hazen method hydraulic conductivity comparison.

Vibracore Number	Depth (feet)	Lab Method	Lab K (cm/sec)	Estimated K[c] (cm/sec)	Soil Description[d]
VC-2	2.8-4.3	CHPT[a,e]	4.80E-04	6.48E-03	Poorly-Graded Sand with Silt
VC-3	4.8-6.3	CHPT	1.34E-02	4.10E-01	Medium-Coarse Sand with Gravel
VC-4	3.3-4.8	CHPT	5.89E-03	1.80E-02	Medium Sand trace fine gravel
VC-6	9.1-10.0	CHPT	2.16E-03	1.15E-01	Medium Sand trace fine gravel
VC-14	8.1-9.6	CHPT	2.05E-03	7.84E-02	Medium Sand with silt pockets
VC-5	0.5-2.0	FWHCT[b]	1.33E-04	6.40E-04	Poorly-Graded Sand with shell fragments
VC-6	4.0-5.0	FWHCT	6.26E-07	1.96E-07	Silt with fine sand
VC-8	3.5-5.0	FWHCT	1.32E-07	1.60E-08	Fat Clay
VC-9	5.8-7.3	FWHCT	1.09E-04	6.40E-08	Poorly-Graded Sand with silt
VC-10	8.5-10	FWHCT	1.81E-06	3.84E-06	Silty Sand
VC-13	3.5-5.0	FWHCT	2.26E-04	3.92E-03	Poorly-Graded Sand with silt

[a] CHPT: Constant Head Permeability Test (ASTM D2434).
[b] FWHCT: Flexible Wall Hydraulic Conductivity Test (ASTM D5084).
[c] Estimated permeability values by Hazen method.
[d] Descriptions from laboratory test result sheets.
[e] Test results displayed are from the re-analysis of five samples with ASTM Method D2434 using Wire Mesh Screen instead of Porous Stone Screen.

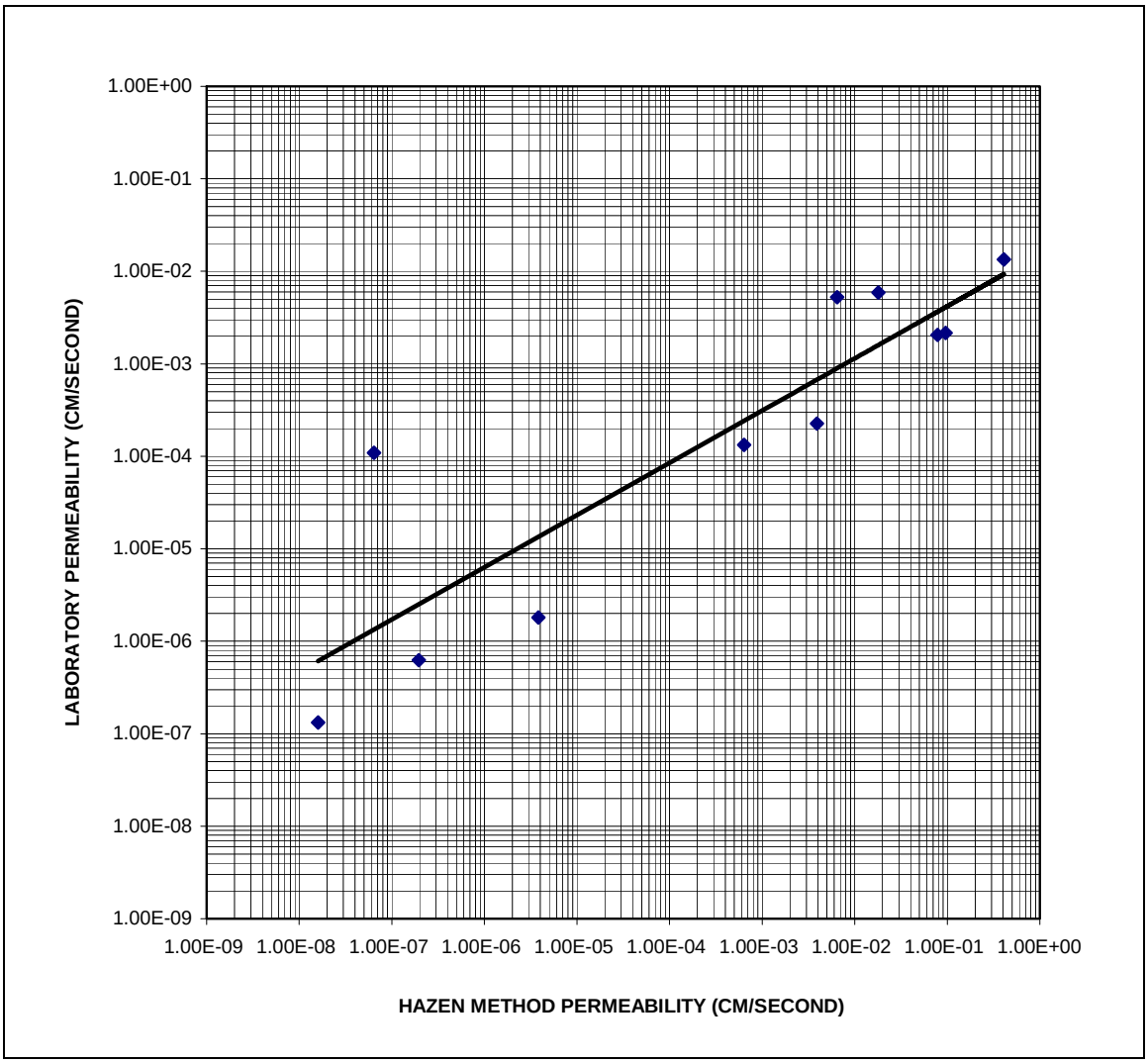

Figure 5-2. Comparison of laboratory and Hazen method hydraulic conductivity values.

seasonal grain-size grading that was fining upward in the sediment section. These deposits showed coarser-grained sand at the bottom of the layers that were deposited during storms that caused river flood conditions which eroded finer materials away and redeposited heavier coarse-grained sediment (medium to coarse-grained sand with fine gravel). As the transport energy subsided with the flood event, the materials being transported and deposited offshore gradually became finer and transitioned into very fine-grained grayish colored sand. Within the San Lorenzo paleochannel, finer-grained sand samples ranged in laboratory hydraulic conductivity between 4.80 x 10^{-4} cm/sec (VC-2) and 1.33 x 10^{-4} cm/sec (VC-5). Subsequent seasonally depositional events repeated this sequence of depositing coarse-grained sediment, which is capped by a finer grained silty sand layer (see VC-4, -5, and -6).

The laboratory results showed a range of hydraulic conductivities within the San Lorenzo River paleochannel. Hydraulic conductivities of 10^{-3} cm/sec were found in the coarse-grained sand samples from VC-2 through VC-6 and VC-14, except VC-3 (10^{-2} cm/sec), which were all samples from the San Lorenzo River paleochannel. The upper portion of these vibracores was not homogeneous; however, fine-grained, low conductivity lenses were found, specifically in VC-6 at 4 to 5 feet (1.2-1.5 m) subsea (6.26 x 10^{-7} cm/sec), VC-5 at 0.5-2 ft (0.15-0.6 m) (1.33 x 10^{-4} cm/sec), VC-2 at 2.8-4.3 ft (0.8-1.3 m) (4.80 x 10^{-4} cm/sec), and VC-14 at 4-5 ft (1.2-1.5 m) (95% silt and clay). All of the hydraulic conductivity samples from either the Neary Lagoon paleochannel (VC-8), the Woods/Schwan Lagoon paleochannel complex (VC-10 and VC-13), or the channel-levee complex (VC-9) reported hydraulic conductivity values of 10^{-4} cm/sec or less. All of the laboratory hydraulic conductivity data can be found in Appendix D.

Because of the discrepancy between the laboratory K values and the Hazen method estimated values, ECO-M ran a second set of samples for the four coarse-grained sand samples from the San Lorenzo paleochannel, using a coarser laboratory screen. During the first run (Table 5-6), a porous stone with a hydraulic conductivity of 10^{-3} cm/sec was used. In order to find out if any of our samples had more rapid hydraulic conductivities than 10^{-3} cm/sec, a second sample was run using a wire mesh laboratory screen (which could transmit water faster than the porous stone). The results of the two runs are shown in Table 5-10. For three of the samples, the hydraulic conductivity values were similar between the two runs. For the VC-3 (4.8-6.3 ft, or 1.5-1.8 m) sample, the hydraulic conductivity value increased from 10^{-3} cm/sec to 10^{-2} cm/sec, which is closer to the Hazen method estimated value. In each case, both hydraulic conductivity samples were taken from the same 1.5 feet (0.5 m) of sample provided to the laboratory, but they were separate samples. All of the laboratory hydraulic conductivity data can be found in Appendix D.

The data presented in this section from laboratory analysis demonstrated the geotechnical properties of the soil samples for estimation of the alluvial aquifer's productivity. Twenty-three sediment samples were taken from the cores and analyzed for grain size, and 11 samples were analyzed for hydraulic conductivity and moisture density. Grain size analysis, data, and moisture density values are shown in Tables 5-3, 5-4 and 5-5. The laboratory results showed a range of hydraulic conductivities within the San Lorenzo River paleochannel from $1x10^{-2}$ cm/sec to $1x10^{-7}$ cm/sec. For comparative reference, productive aquifers generally are composed mostly of sediment with hydraulic conductivities of $1x10^{-1}$ cm/sec to $1x10^{-3}$ cm/sec. The following points are highlights of the hydraulic analysis of the alluvial aquifer's shallow sediment.

Table 5-10. Hydraulic conductivity results for selected vibracore samples.

Vibracore #	Sample Depth (feet below seafloor)	Hydraulic Conductivity (cm/sec) (1st Sample) ASTM Method D2434 Porous stone screen[a] HC=E-03	Hydraulic Conductivity (cm/sec) (2nd Sample) ASTM Method D2434 Wire mesh screen[b] 100 Mesh = 149 Micron	Grain Size[c] (mm)	
				Median (mm)	D 10 (mm)
VC-3	4.8-6.3	4.18E-03	1.34E-02	2.80	0.64
VC-4	3.3-4.8	2.46E-03	5.89E-03	0.41	0.15
VC-6	9.1-10.6	3.14E-03	2.16E-03	0.78	0.31
VC-14	8.1-9.6	2.45E-03	2.05E-03	0.75	0.30

[a] The first set of samples was run using a porous stone screen where the opening size was irregular, but the hydraulic conductivity was E-03.

[b] The second set of samples was run using a wire mesh screen held in place with gravel; a 100 Mesh, which = 149 microns, was used. Both hydraulic conductivity samples were taken from the same 1.5 feet of sample provided to the laboratory, but they were separate samples.

[c] The grain size data is from the laboratory data for the samples that were run for grain size analysis using ASTM Method D422. These grain size samples were taken from the same 1.5 feet of sample provided to the laboratory, but were separate from those that were used for the hydraulic conductivity analysis.

- The mobile, active layer of fine sand with silt on the seabed had a hydraulic conductivity of 1 x 10^{-4} cm/sec, which was observed in VC-2, VC-3 and VC-5.
- Hydraulic conductivities of $1x10^{-3}$ cm/sec were observed in the coarse-grained sand samples from VC-3, VC-4, VC-6 and VC-14. The exception with the coarse-grained sand samples was VC-3, which had a section at a depth of 4.8-6 ft (1.5-1.8 m) with an order of magnitude higher conductivity of $1x10^{-2}$ cm/sec.
- The depths of the coarse-grained samples ranged from 4.8-6 feet (1.5-1.8 m) for the vibracore closer to shore, VC-3, to deeper than 9 ft (2.7 m) in VC- 4, VC-6.
- In the upper portion of the vibracores farther from shore, fine-grained, low conductivity lenses were found, specifically in VC-6 at 4-5 ft subsea with a hydraulic conductivity of $1x10^{-7}$ cm/sec, and VC-14 at 4-5 ft (1.2-1.5 m) subsea (sample was 95% silt and clay).
- Several vibracore samples taken from San Lorenzo paleochannel showed seasonal grain-size grading that was fining upward in the sediment section. These deposits showed coarser-grained layers that were deposited during high river flow conditions (medium to coarse-grained sand with fine gravel), which gradually fined to a very fine-grained grayish colored sand.

The characteristics of the alluvial materials (fine sand, silt and clay) will impact production of a subsurface intake located to take advantage of sand and alluvial materials hydraulically connected to the ocean. For example, fine to very fine sand is the main sediment particle that controls seepage through the seafloor into the more productive layers of the aquifer. If several feet into the seabed, the fine sand is mixed with silt, this acts as a confining layer, or a “cap” on top of the alluvial aquifer. The geotechnical properties (grain size analysis and hydraulic conductivity) of the vibracores sampled indicate that there is some productive aquifer material (gravel and coarse sand layers), some marginally productive aquifer material (fine to very fine grained sand), and some unproductive aquifer material (silt and clay). Overall, the estimated hydraulic conductivity of the aquifer may be an order of magnitude too low to be of use for a 2.5-mgd facility.

6.0 FINDINGS

6.1 THE BURIED ALLUVIAL CHANNELS OF THE SAN LORENZO RIVER, NEARY LAGOON, AND WOODS AND SCHWAN LAGOONS WERE FOUND AND MAPPED IN THREE DIMENSIONS

The buried offshore alluvial channels were mapped in three-dimensions (3-D) based on the interpretation of the boomer and Geopulse seismic reflection profiles (Figures 6-1, 6-2, 6-3, and 6-4). The major part of the San Lorenzo River offshore alluvial basin occupies nearly the entire study area for the survey, from Point Santa Cruz to the jetty at the mouth of the Santa Cruz Harbor approximately 3,300 feet (1,000 m) from the shoreline. The alluvial basin is about 4,000 feet (1,200 m) wide in the nearshore area, but narrows to 1,500 feet (450 m) wide farther offshore along the main paleochannel of the San Lorenzo River at the mid-southern part of the offshore geophysical survey area. About three-fourths of the alluvial basin area, surrounding the Municipal Wharf, is occupied by a delta comprised of channel/levee deposits. The youngest channel, considered to represent the LGM San Lorenzo River Main Channel, cuts through the delta on the east and forms a prominent meander bend near the end of the wharf. The meander is about 2,000 feet (610 m) wide and bends east at its junction with the Neary channel about 500 feet (150 m) south of the wharf. These combined channels form an east-trending offshore alluvial basin that is almost 5,000 feet (1,524 m) long and 500 feet (150 m) wide.

The seafloor geology map of the offshore alluvial basin (Figure 6-1) shows the bedrock outcrops (Purisima formation, light-blue hatched lines) based on the 1995 USGS backscatter data, as well as the boundaries of the backfilled lowstand main channels for the San Lorenzo River and other paleochannels (dark blue hatched lines-hatches point into the channels). The light blue arrows are the interpreted locations of the main channel boundaries throughout the alluvial basin area, which are generally delimited by bedrock outcrops. The circled red dots are fault picks and the interpreted fault traces are shown as red dashed lines. Only well-defined faults that offset Quaternary sediment are shown, although there are other faults that offset layers within the bedrock of the Purisima formation. Cyan-colored inverted triangles show the interpreted location of the main channel thalweg (axis) of the nearshore San Lorenzo River channel (i.e., Main Channel). The vibracore locations are shown and generally located near the interpreted buried paleochannel axes. The delta area with channel/levee complex is in the area near the Municipal Wharf labeled “Delta.” Tracklines of the offshore boomer seismic survey are shown as thin black lines; locations of profiles shown in other report figures are shown by heavy lines and labeled. The two geological cross-sections (Figure 6-2) that were conceptually inferred from the geophysical data are located along seismic profiles 104 (A-A’) and 108 (B-B’). These subsurface interpretations illustrate the variability in the ocean floor materials that are indicated by the available data. These interpretations are limited to the accuracy of inferring that onshore and offshore alluvial deposits are similar and that the deltaic sediment is consistent with that deposited in a similar environment.

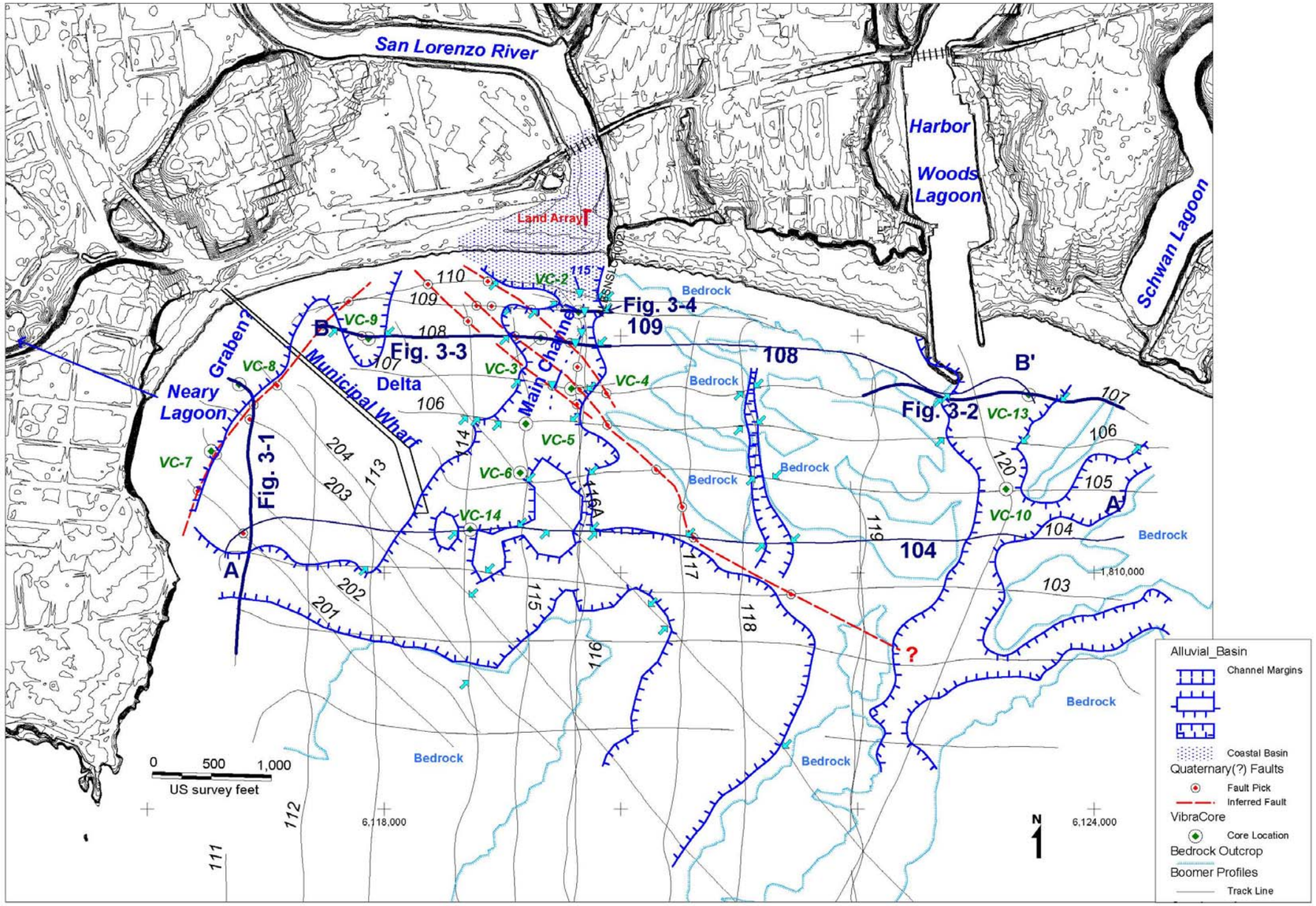

Figure 6-1. San Lorenzo River paleochannel location map. The hash-marked lines in the center left of the map with hashes pointing down slope show the channel boundary.

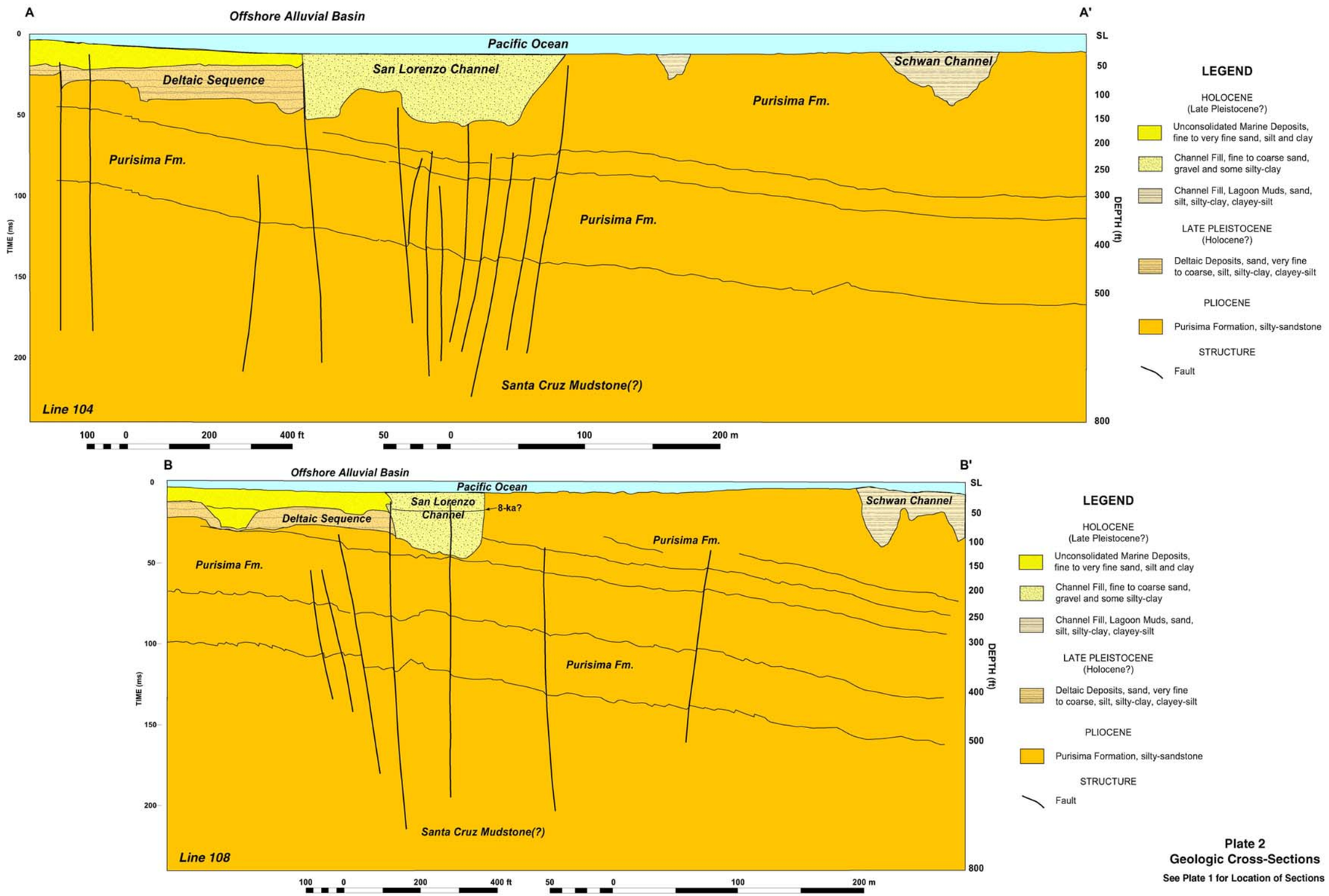

Figure 6-2. Geologic cross-section along part of lines 104 and 108.

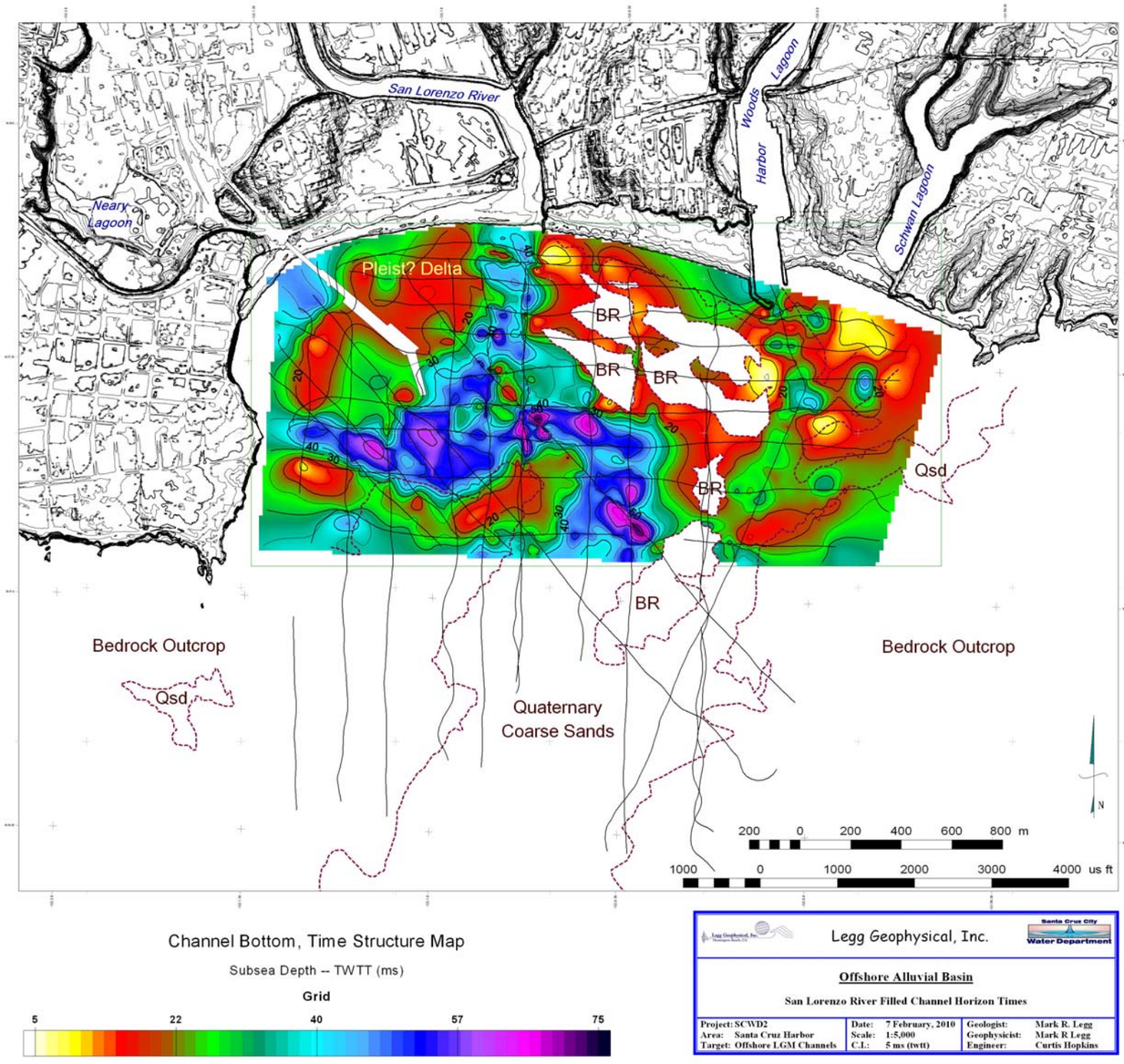

Figure 6-3. Structural contour map of the San Lorenzo River paleochannel and related channels of the offshore alluvial basin. The map projection is California State Plane coordinates, zone 3, NAD 1983, with tick marks at 1,000-ft intervals (305 m). Channel depth in feet is approximately equal to twtt (ms) multiplied by 2.5, corresponding to an average seismic velocity of 5,000 ft/sec.

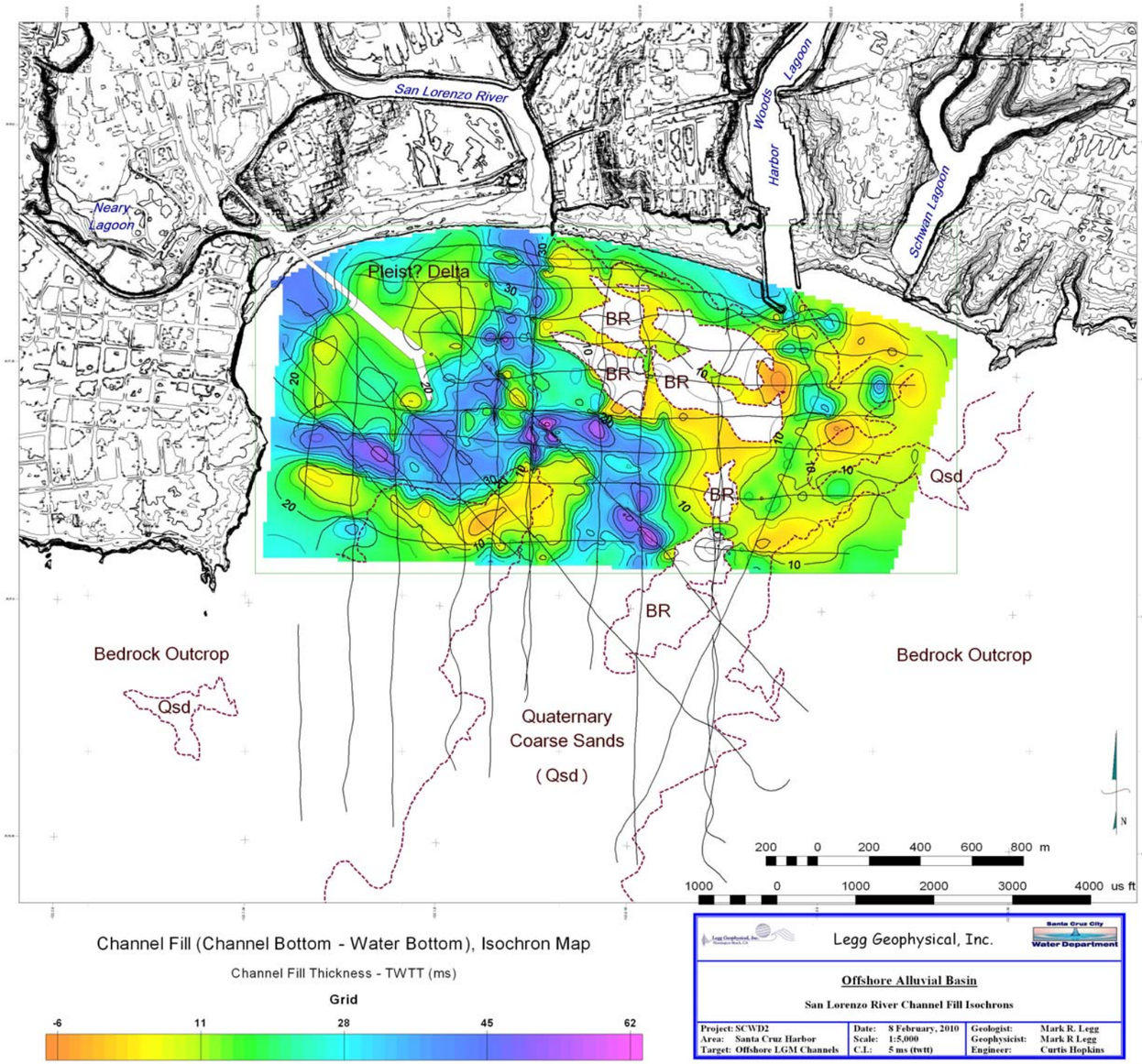

Figure 6-4. Isochore map showing the thickness of the San Lorenzo River LGM channel fill. Although this map is similar to Figure 6-2, it represents the thickness in meters below the seafloor of the sediment fill in the channels.

The surficial geology map shows a zone of northwest-trending faults cutting across the Main Channel. Our preliminary interpretations suggest that these faults may cut late Pleistocene and possibly Holocene fill of the offshore San Lorenzo River paleochannel. This fault is oblique to the main trace of the Ben Lomond fault, which trends north from the sea cliff to west of Point Santa Cruz. Stanley et al. (1983) also interpreted a fault (Water Street fault) along the San Lorenzo River based on their gravity survey in that area. ECO-M initially interpreted a north-trending fault zone in the offshore area that may be this fault, but further interpretation of the data is necessary to pin this down. ECO-M also interpreted a northeast-trending fault-bounded graben in the area between the wharf and coastline to the west. This fault zone is consistent with a southwest-trending bedrock outcrop on the seafloor south of Point Santa Cruz. Further interpretation of the seismic data is necessary to pin down this fault zone. The convergence of these fault zones in the coastal area of the alluvial basin may be responsible for more rapid erosion of the bedrock allowing development of the broad alluvial basin and river meanders in this area. Bedrock offsets (vertical separation) observed in the seismic reflection profiles are small, generally less than a few meters (about 10 feet) in the Purisima formation. Offset of Holocene channel fill is equivocal based on our preliminary interpretations, and ground-truth control of channel fill age is required. If these faults have significant offset of alluvial layers within the channel deposits, they may represent a barrier to lateral water flow within the sub-seafloor aquifers.

The area from the wharf to the “Main Channel” is where a channel-levee complex associated with a late Pleistocene delta system exists. McCulloch and Greene (1990) identified deltaic deposits of Quaternary age overlain by thick (greater than 9.8 feet or 3 m) deposits of unconsolidated deposits of Quaternary age in this area. The leveed channel is best imaged in boomer profile #108 (Figure 3-3) in the vicinity of vibracore #9 (VC-9).

A second major channel system exists on the east side of the geophysical survey where drainages associated with Woods and Schwan lagoons connected to the offshore during lowered sea level. The Woods/Schwan channel system is narrower and shallower than the San Lorenzo River channel system. Seismic reflection character of the channel-fill sequences for the Woods/Schwan channels (Figure 3-1) are consistent with the vibracore data (VC-10 and VC-13) that recovered fine sands and organic muds typical of lagoon or basin deposits. Vibracore samples had odors derived from hydrogen sulfide. Decomposition of organic material has produced methane, hydrogen sulfide, and other gases that create the highly reflective character of the channel fill in the seismic profiles. The low acoustic velocity of gas-charged sediment appears as prominent velocity “pull-downs” in the seismic profiles (Figures 3-1 and 3-2), and the dissipation of the seismic energy creates energy loss or “wipe-out” zones in the layered bedrock of the Purisima formation below the channels. The organic clay layers in the Woods/Schwan channels are unlikely to provide adequate porosity and permeability for seawater percolation and the noxious gases are hazardous. Therefore, the Woods/Schwan lagoon channel system is not considered further for the offshore seawater intake.

The nearshore area west of the wharf (Cowells Beach area) is underlain by another late Pleistocene (Holocene) channel associated with an ancient meander of the San Lorenzo River that created Neary Lagoon. This channel may be fault-bounded on the east suggesting a

nearshore graben. This fault does not show consistent normal separation on the different seismic profiles that it crosses, so that the fault may be strike-slip and associated with the Ben Lomond fault that cuts the sea cliff west of Point Santa Cruz. The Neary channel appears to lie above a late Pleistocene marine terrace. Seismic reflection character of the Neary channel is similar to that of the Woods/Schwan channels (Figure 3-2) showing high amplitude reflections and velocity pulldown and wipeout zones in the underlying Purisima layers. Vibracore data (VC-7 and VC-8) confirmed fine-grained sediment layers, equivalent to "basin" deposits mapped by the California Geological Survey (Wagner et al. 2002) around lagoon margins of the area. Neary Lagoon and the offshore channel are inferred to be an abandoned late Pleistocene meander bend or oxbow lake of the San Lorenzo River. Slow deposition during sea-level lowstands filled these channels with the fine-grained material. In addition, the seismic reflection character indicates natural gas accumulations, so that the Neary channel sediment fill is unsuitable for a subsurface intake.

6.2 THE SAN LORENZO RIVER PALEOCHANNEL CONTAINS SAND, SILT, CLAY AND GRAVEL WHEREAS THE OTHER TWO PALEOCHANNELS CONTAIN MOSTLY MUD, CLAY AND SILT

A nearshore and coastal zone within the San Lorenzo River alluvial basin (shaded area, Figure 6-1) is located where ocean waves and river flow interact. The beach sands and other sediment deposited in this nearshore zone are transient and move around substantially. The nearshore coastal zone also sees erosion and accretion of the beaches occurring seasonally and interannually. Greater than normal wave energy moves large volumes of sediment during El Niño winters and La Niña spring and fall periods (Storlazzi and others, 2007). For example, in the 1997-1998 El Niño winter, more than 80,000 m³ of sand were eroded from the beaches in the study area (Storlazzi, 2010). (Refer to Appendix H for photographs of this erosion on Seabright Beach and more information about the seasonal and interannual variability of the interaction of ocean waves and river discharges.) Consequently, this area contains unconsolidated and relatively coarse-grained sediment, as the wave dynamics at the beach winnow out the majority of the fine-grained material discharged by the river.

River flow affects areas such as the USACE boreholes taken on the San Lorenzo River levee, and river discharged sediment is suspected to compose the primary fill in the offshore paleochannel. Typical sand layers in the vibracores and USACE boreholes nearby had thicknesses varying from a few feet (1 m), to as much as 10-20 feet (3-6 m), and included some fine to coarse gravels mixed with the sand in places. Some of these boreholes had poorly graded fine-very fine sand and silty sand layers up to about 20 ft (6.1 m) thick. VC-2 has a poorly graded fine-very fine sand layer about 10 ft (3 m) thick. The boreholes show heterogeneity. What is seen in the boreholes is what would be expected to be seen at depth in the paleochannel because the river flowed further out to the Monterey Bay when the filling of the paleochannel took place as sea level rose. Thus, the area where the boreholes were taken can represent the sediment filling the paleochannel, where there is expected to be heterogeneous sediment vertically and spatially at depth in the paleochannel.

A stratigraphic column showing one representation of the channel fill sequence lithology was constructed based upon the vibracore data in the nearshore channel and USACE borehole data

from the nearby San Lorenzo River levee study. Reflection horizons identified in the land geophone array seismic profile and velocity analysis were used to constrain prominent lithologic boundaries in the stratigraphic column (Figure E-1). Only one prominent horizon was identified within the channel fill, located at about 18-ms twtt (about 47 feet (14.3 m) subsurface depth, near the base of the USACE borehole data). This horizon may represent a time when sea level rise paused about 8 ka, but no direct information on this layer boundary is available at this time. The part of the stratigraphic column deeper than the USACE borehole data, about 42 feet (12.8 m), was modeled based on the shallow core data and typical channel fill deposits from similar environments.

Therefore, the Main Channel appears to offer the best sand and coarse-grained deposits of the three offshore paleochannels studied. The sands and other coarse-grained deposits interpreted to comprise a significant part of the San Lorenzo River channel fill sequences are interpreted in the geophysical data by the absence of multiple well-defined reflection layers. The geophysical data provide confident measures of the channel depth and the presence or absence of well-defined layering. Well-defined layering observed in the other channels shows the presence of fine-grained deposits, clays, silts, and gas accumulations found in the vibracores. Only direct sampling by deeper drilling in the area can identify the specific character of the subsurface lithology and hydraulic conductivity through the entire channel fill.

6.3 THE SAN LORENZO RIVER PALEOCHANNEL SUB-BASIN MAP IN THREE DIMENSIONS WAS DELINEATED TO DEFINE PRELIMINARY CONCEPTS FOR LOCATION OF SUBSURFACE INTAKES

The variation in thickness of the offshore alluvial sediment, shown on Figure 6-3, was utilized to develop three potential areas where aquifer materials could potentially be used to develop seawater intake structures. Figure 6-5 shows the three areas that are identified as onshore, nearshore, and offshore alluvial basins. These three areas were designated based on the different anticipated aquifer conditions and the potential challenges to installation and operation of groundwater extraction facilities.

The onshore alluvial aquifer is defined by a paleochannel that is approximately 1,000 feet (304.8 m) wide at the shoreline where aquifer sediment is estimated to range between 40 and 128 feet (12.1 and 39 m) thick. The study findings indicate a channel width at the shoreline that is over double the width anticipated by previous studies (Hopkins, 2001). Geophysical data indicate that alluvial sediment is thinner across the western half of the aquifer and deepest near the present active channel near the San Lorenzo River mouth. A fence diagram showing the channel configuration provided by the offshore survey lines is provided as Figure 6-6.

Contours of the anticipated base of the onshore and nearshore channel were developed using data from an onshore geotechnical study conducted for a flood control levee improvement project and the offshore data. The estimated depth to the base of the alluvial aquifer is shown on Figure 6-7.

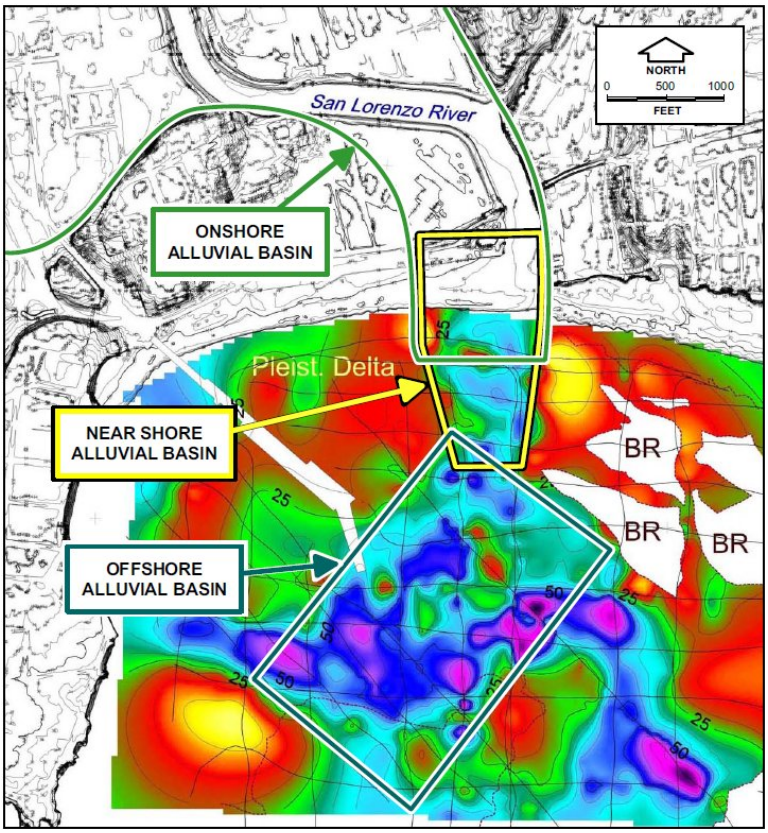

Figure 6-5. Sub-basin location map. Sub-basins are all geologically connected. The divisions are made to develop three potential areas where aquifer materials could potentially be used to develop seawater intake structures.

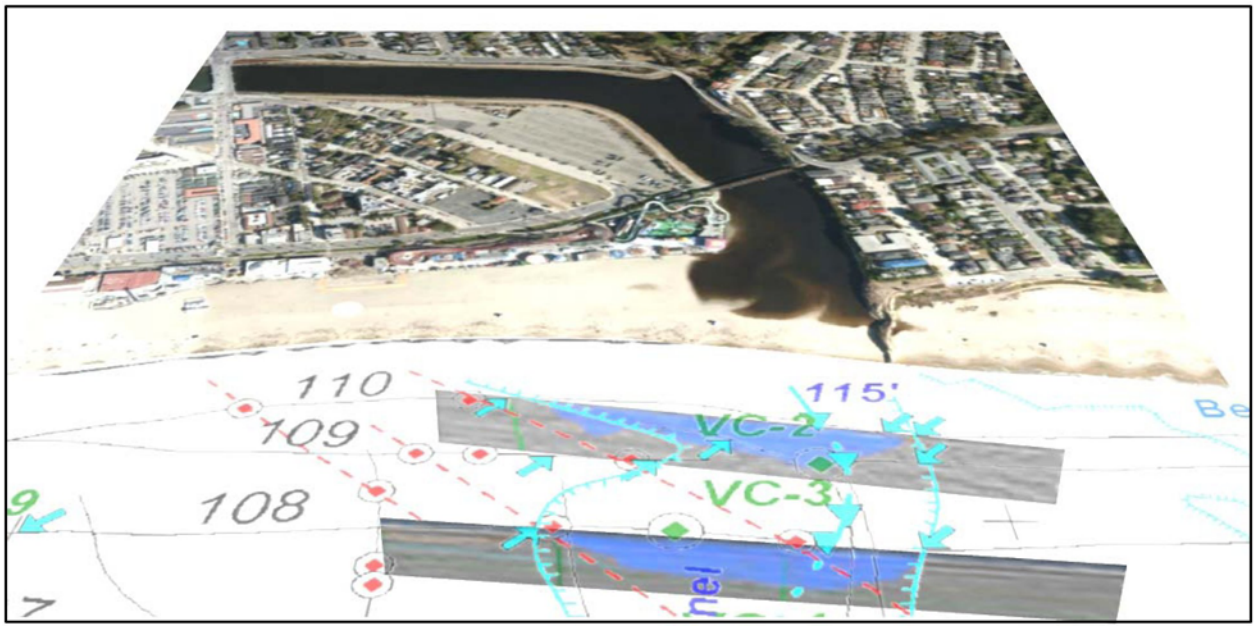

Figure 6-6. Fence diagram of Alluvial Aquifer using Offshore Geophysical survey lines.

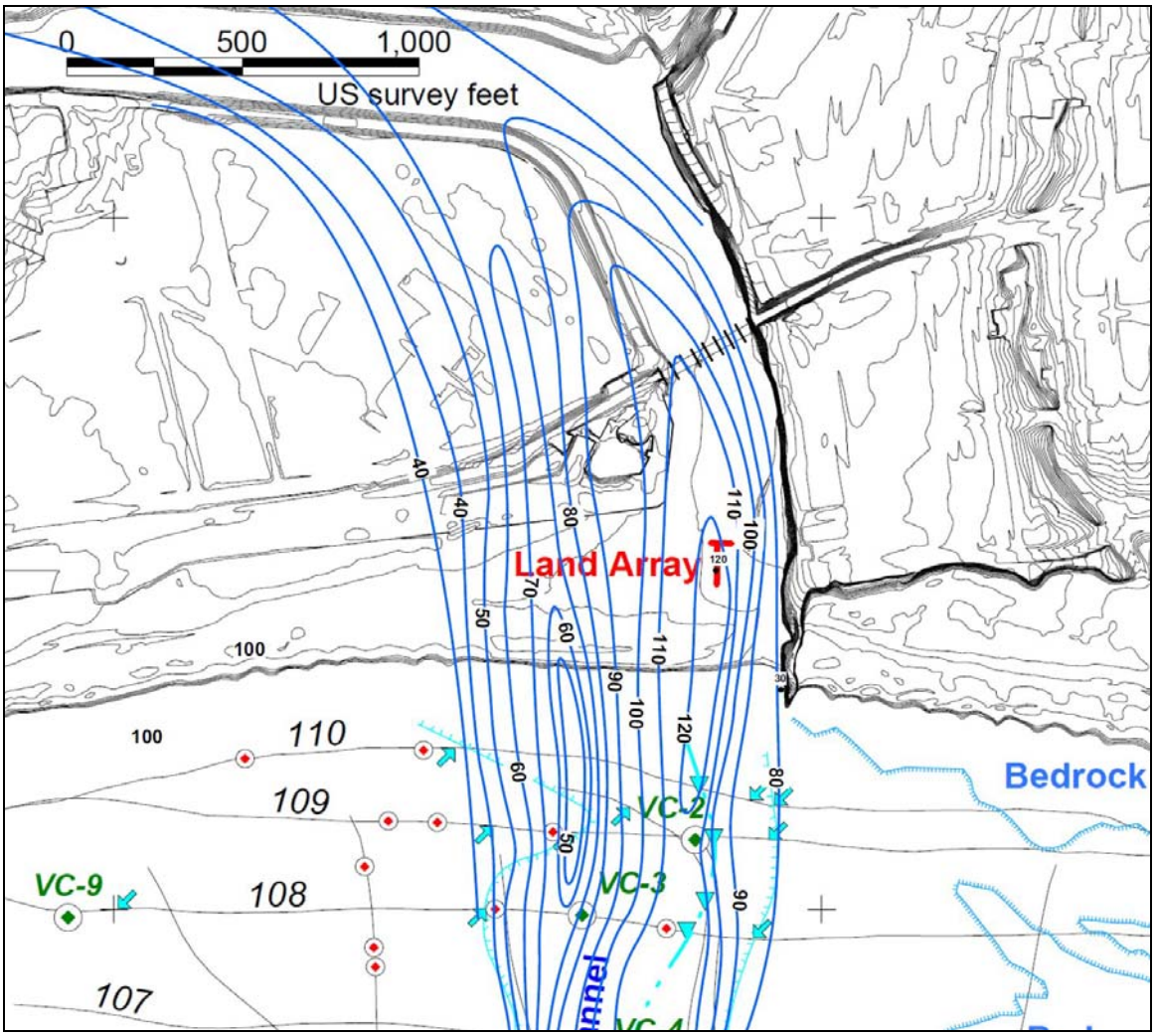

Figure 6-7. Base of Alluvial Aquifer contour map (feet).

The geophysical survey data indicate the nearshore alluvial aquifer is an extension of the linear channel configuration located onshore. The variable thickness of the aquifer near the coastline is believed similar to the onshore portion of the aquifer and is defined in several of the offshore profiles. The greatest thickness is approximately 150 feet (45.7 m) and located south of the end of the municipal wharf.

The offshore alluvial basin is defined by a broader area where the San Lorenzo River likely developed a meander bend at the location where it was apparently joined by flows from the Neary Lagoon drainage channel. The geophysical survey data indicate the sediment depths are the greatest in this portion of the alluvial aquifer system and likely extend to depths up to 150 feet (45.7 m).

The present day offshore conditions near the San Lorenzo River mouth are indicated by the samples collected in the vibracores. The higher energy of the river flows and the wave action during the storm season scours the seafloor and subsequently deposits the coarser grained fraction of the sediment load being discharged by the river. As the flood stage and storm energy decreases, finer-grained materials settle out and result in a sedimentary sequence that is fining upward. This is apparent in Vibracore VC-4, where from the seafloor to a depth of 13 feet (4 m) there are three fining upward sequences. Vibracore VC-6 shows two distinct fining upward strata that grade upward into silty-clayey materials.

The USGS has observed that the seabed down to 5 meters (16.4 ft) of water depth is medium sand, and at greater depths (10-30 m (32.8-65.6 ft) water depth) the seabed is primarily a silty, very fine to fine-grained sand layer. New information about the mobile sand layer that overlies the San Lorenzo River paleochannel will be published by USGS in 2010 or 2011. Sediment on the inner shelf at 0-30 m (98 ft) depth is mobilized in all seasons (Storlazzi and others, 2007).

In 2009, the USGS provided a sample of this material to the City of Santa Cruz for hydraulic conductivity testing. Laboratory test results indicated the hydraulic conductivity of the fine-grained migratory layer was 3.35×10^{-4} cm/sec. Information derived from sample collection and laboratory analysis of materials within the study area with respect to river sediment discharges and coastal transport processes (i.e., how ocean waves and river discharges of fine sediment have affected the fill of the channel or may affect a future subsurface intake) could be factored into a feasibility analysis.

6.4. CONCEPTUAL SEAWATER PRODUCTION FACILITY LOCATIONS

The potential location of saline groundwater production facilities within the three sub-basins previously delineated is based on correlation of historical data and the geophysical survey findings.

6.4.1. Onshore Alluvial Aquifer

Onshore saline groundwater production facilities considered include an array of conventional wells located adjacent to the areas of recharge from the San Lorenzo River and along the beach. A conceptual drawing of conventional well locations is provided as Figure 6-8.

Saline groundwater production could also be achieved utilizing collector wells. Collector wells are constructed with relatively shallow horizontal well screens that are installed in a radial design and extend out beneath a surface water source of recharge. A conceptual layout of collector wells within the onshore sub-basin is shown on Figure 6-9.

These two onshore conceptual saline groundwater production facilities are located within the alluvial aquifer where it is surrounded on three sides by surface water. The successful production of groundwater from this area would be dependent on maintaining saturation within the tidal prism of the San Lorenzo River. As with most coastal rivers, there are times when the river mouth is closed off during low flow conditions by a sand bar that effectively impedes the landward movement of seawater. Groundwater production in this area could potentially impact the water levels within the inland portion of the San Lorenzo River Alluvial Basin under these low flow conditions.

Other issues related to development of an onshore supply of groundwater include variations in water quality such as changes in salinity, high concentrations of iron, and turbidity associated with high winter flows. Production in this area would induce infiltration of surface water from flows in the river and along the shoreline, which is anticipated to result in a blend of freshwater and seawater. This blend would change as the river is dominated by freshwater outflows in the winter and tidal inflows in the summer.

The saline groundwater produced from shallow, fine-grained coastal aquifers often contains high concentrations of iron that is leached from the sediment by the saltwater. The flux of biologically important materials (iron, carbon, others) in steep watersheds results in much more material to the coastal zone for the size of their drainage basins relative to many larger river systems (Storlazzi and others, 2007). Iron-rich layers were also observed in the shallow offshore sediment contained in several of the vibracore samples.

Infiltration of groundwater from river flows during the winter will likely contain elevated turbidity levels. This is a common occurrence in shallow coarse-grained alluvial aquifers and results from the removal of the finer-grained sediment that is scoured away during high turbid flows. This likely condition would (like high iron concentration) require pretreatment prior to injection into the membranes.

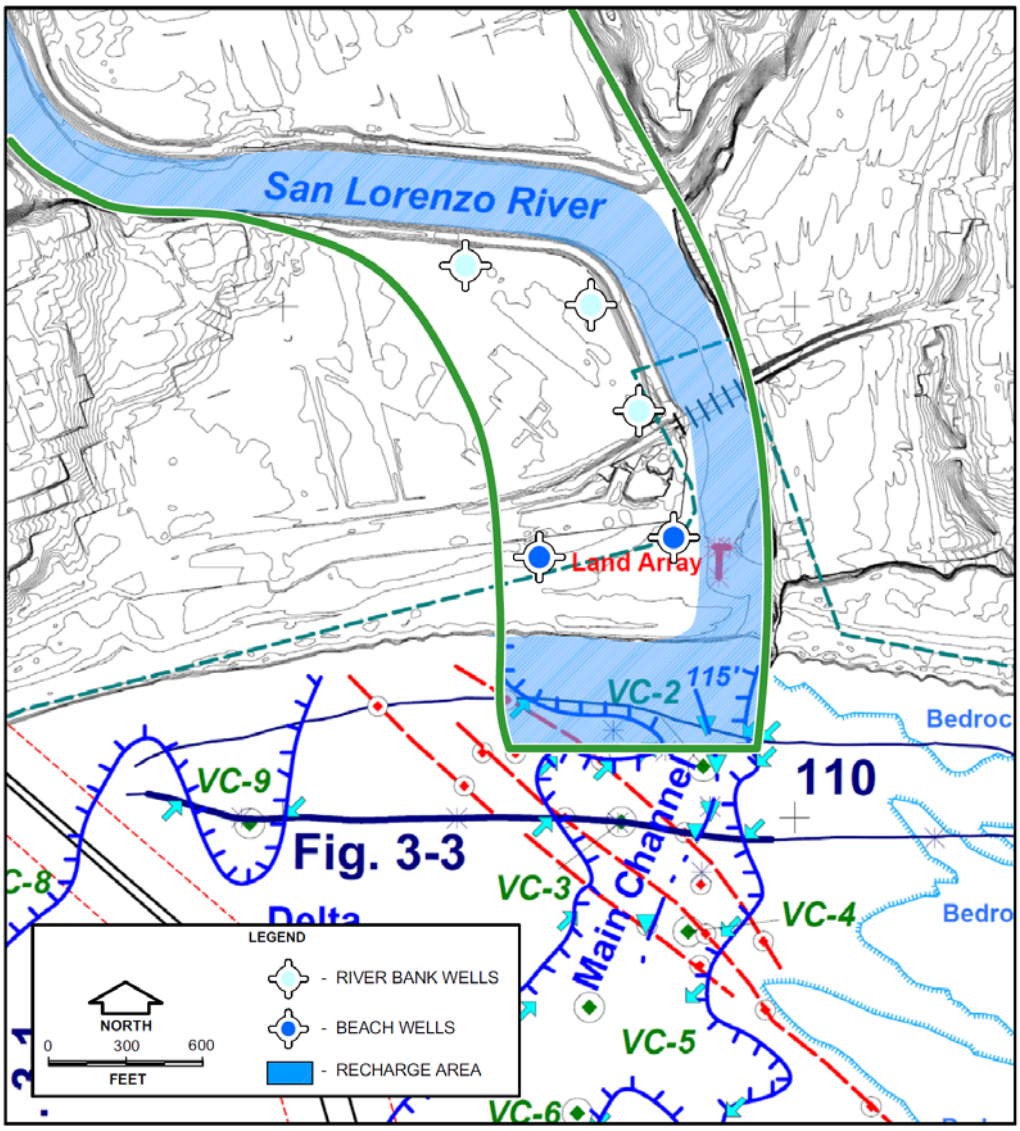

Figure 6-8. Conceptual onshore wellfield location.

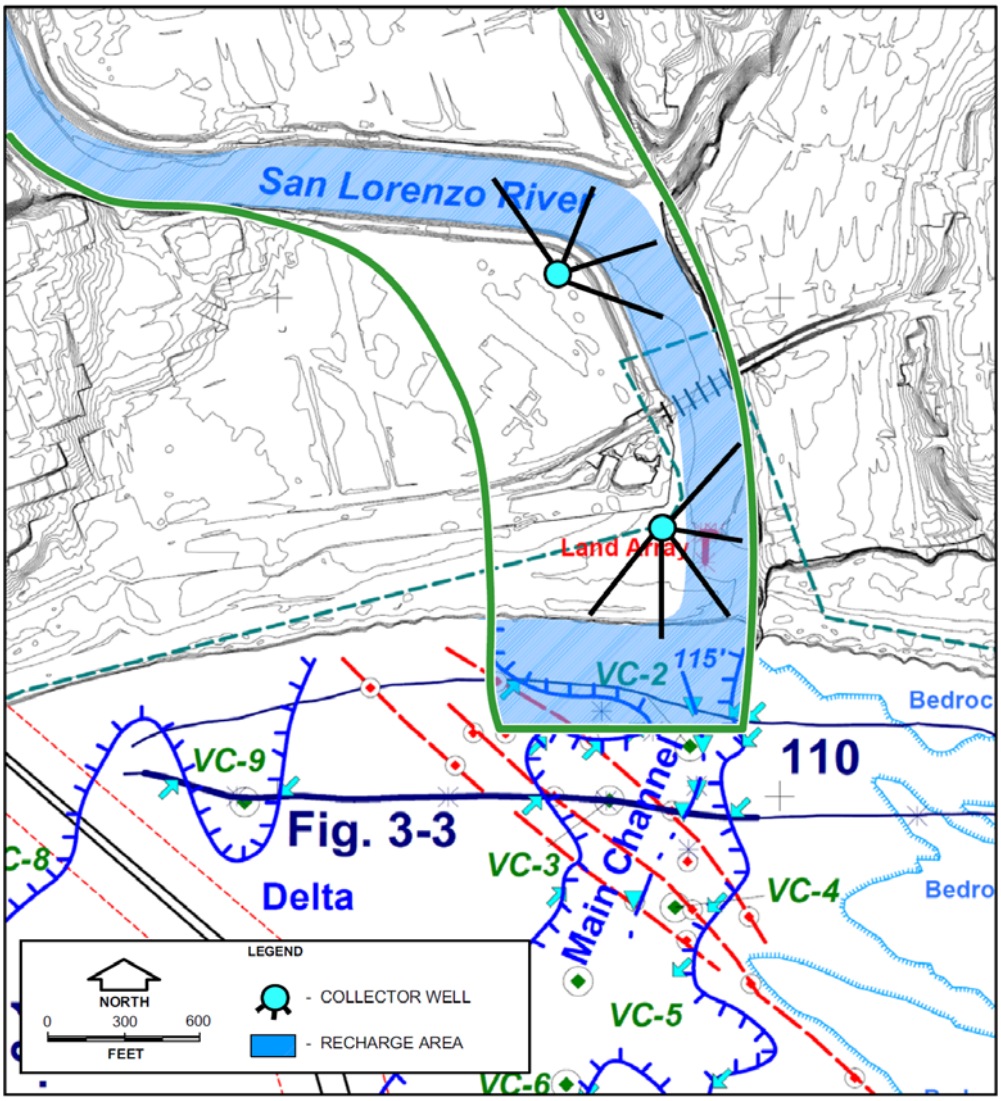

Figure 6-9. Conceptual onshore collector well locations.

6.4.2 Nearshore Alluvial Aquifer

The conceptual location of shoreline wells as shown on Figure 6-10 in the alluvial aquifer could produce a more consistent saline groundwater supply that would not be affected as much by changes in river conditions. However, the production potential is controlled by the shallow depth of the aquifer zone and the limited length of shoreline exposure available for infiltration of seawater in the saturated nearshore environment. Another factor to consider which complicates construction on or underneath the beach is the impermanence of the area's beach sands. USGS scientists studying sediment mobility along the central California shelf point out that the "closure depth," or the depth below which no sediment is transported in significant volumes (Hallemeier, 1981; Pilkey and others, 1993), is not a fixed boundary but varies temporally (Storlazzi and others, 2007). This variability is due to meteorologic and oceanographic forces, spatial variations in wave properties, and seafloor sediment material properties (Storlazzi and others, 2007). Historical documentation of beach erosion in front of the boardwalk illustrates the magnitude of these coastal forces (see documentation of beach erosion in front of Seabright Beach in Appendix H).

One method of constructing an offshore intake includes drilling a water supply well that is slanted away from an onshore location and taps the offshore groundwater basin. To accomplish this goal, a well would be drilled at a sufficiently steep angle to penetrate the offshore portion of the basin at a predetermined depth and distance. A typical limitation is the relatively shallow depth to the base of the alluvial aquifer (maximum of approximately 128 feet (39 m) below mean sea level).

Figure 6-11 shows the conceptual location of slant wells that could potentially be used to produce from the nearshore aquifer system. The installation and operation of this type of production facility would also be impacted by the relatively shallow and narrow alluvial aquifer that is available for production. The installation of the four facilities shown on Figure 6-11 that extend offshore are conceptually designed to extend 500 feet (152 m) to depths of (from west to east) 45, 65, 115, and 95 feet (13.7, 19.8, 35, 29 m) and to be constructed at angles ranging between 5 and 13 degrees from the horizontal.

It is our understanding that design angles less than 15 degrees from the horizontal result in additional construction related difficulties. Constructing a well at an angle less than 15 degrees from horizontal is not typically recommended unless the aquifer penetrated by the well is conducive to a naturally packed well screen or a Johnson Muni-Pak© well screen is used (personal communication, Robert Stadley of Boart-Longyear). One such construction related difficulty is that naturally packed well screens may limit the production potential due to the use of smaller slot openings in the screen to prevent the production of finer sands and silts. The easterly slant well beneath the river mouth is conceptually 270 feet (82 m) long and extends to a depth of 120 feet (37 m) and is designed at an angle of 23 degrees from horizontal.

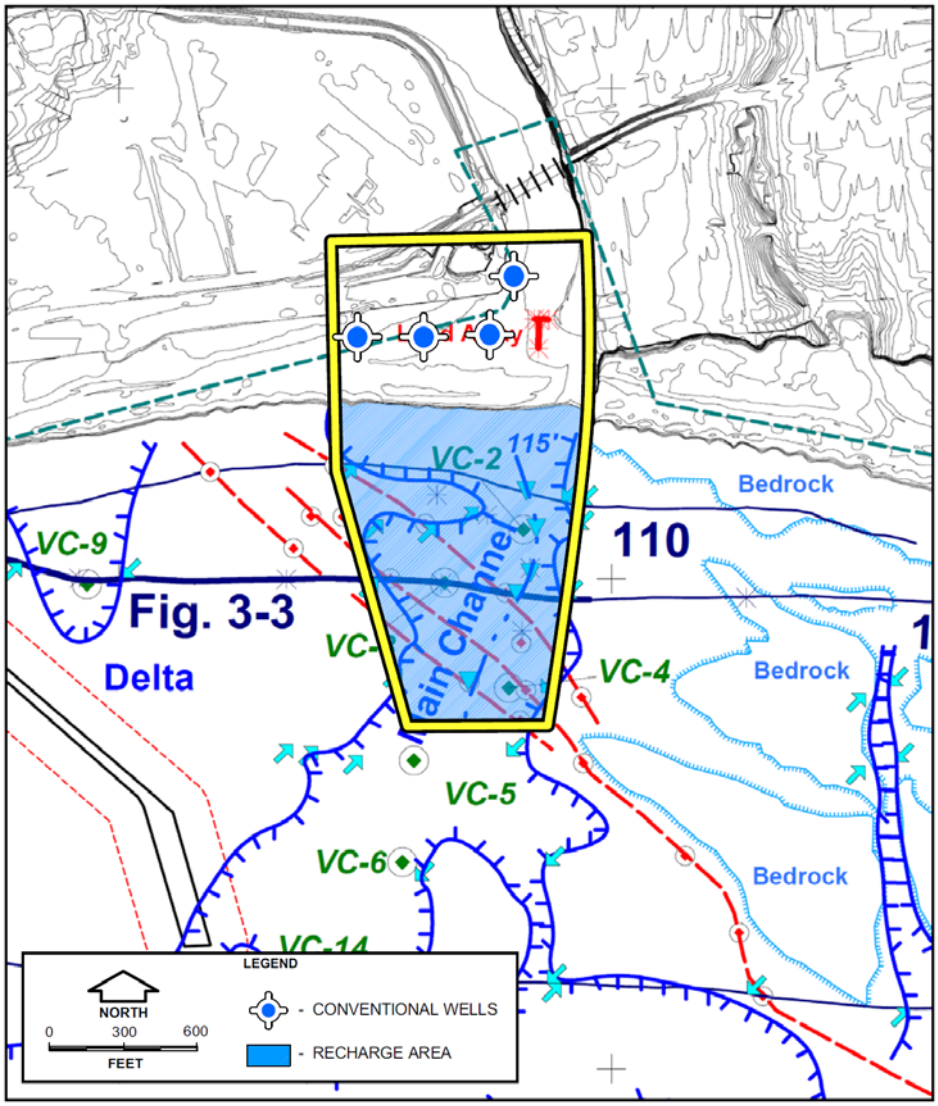

Figure 6-10. Conceptual nearshore wellfield location.

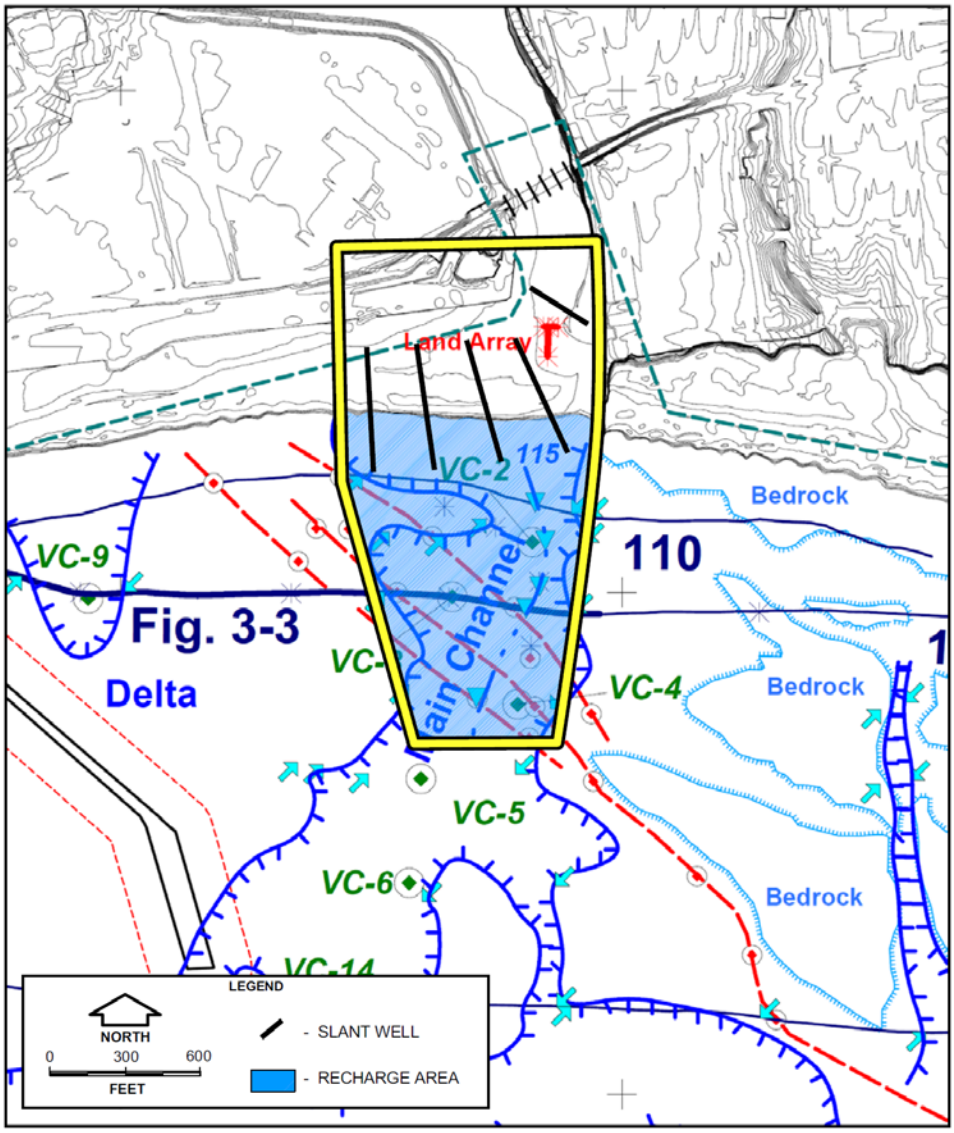

Figure 6-11. Conceptual nearshore slant well locations.

The groundwater produced from slant well facilities drilled offshore is anticipated to contain high concentrations of iron, but not vary as much in salinity and turbidity. This is because they would primarily induce infiltration of seawater through finer-grained materials on the ocean floor.

6.4.3 Offshore Alluvial Aquifer

The finding of the offshore alluvial basin shown on Figure 6-5 provides a third potential for saline groundwater production. The conceptual location of an offshore collector well to produce water from this basin is shown on Figure 6-12 as being installed off the end of the existing pier. This conceptual design is provided as one of the conceptually feasible means of trying to produce from the shallow aquifer located over 1,500 feet (450 m) off shore. The conceptual collector well facility would induce infiltration of seawater through the seafloor similar to the nearshore slant well design and is therefore anticipated to have a similar water quality of potential high iron concentrations, but consistent salinity and turbidity.

6.5 LABORATORY ANALYSIS DEMONSTRATED THE GEOTECHNICAL PROPERTIES OF THE SOIL SAMPLES FOR ESTIMATION OF THE ALLUVIAL AQUIFER'S PRODUCTIVITY

This section provides estimates of the seawater production potential of the San Lorenzo River alluvial aquifer's main channel. Twenty-three sediment samples were taken from the cores and analyzed for grain size, and 11 samples were analyzed for hydraulic conductivity and moisture density. The laboratory results showed a range of hydraulic conductivities within the San Lorenzo River paleochannel from $1x10^{-2}$ cm/sec to $1x10^{-7}$ cm/sec. For comparative reference, productive aquifers generally are composed mostly of sediment with hydraulic conductivities of $1x10^{-1}$ cm/sec to $1x10^{-3}$ cm/sec. The characteristics of the alluvial materials (fine sand, silt and clay) can impact production of a subsurface intake located to take advantage of sand and alluvial materials hydraulically connected to the ocean. For example, fine to very fine sand is the main sediment particle that controls seepage through the seafloor into the aquifer is referred to as a "confining layer."

6.5.1 Aquifer Transmissivity

Transmissivity is a measure of the amount of water that can be transmitted horizontally through a saturated thickness of aquifer under a hydraulic gradient of one. Transmissivity is calculated by multiplying the hydraulic conductivity of the formation material by the saturated thickness of the aquifer being produced. For this study, transmissivity is expressed as gallons per day per foot of aquifer (gpd/foot). Utilizing the aquifer thicknesses estimated by the geophysical surveys and the hydraulic conductivities measured in the laboratory, the anticipated range of hydraulic conductivities for each sub-basin has been calculated.

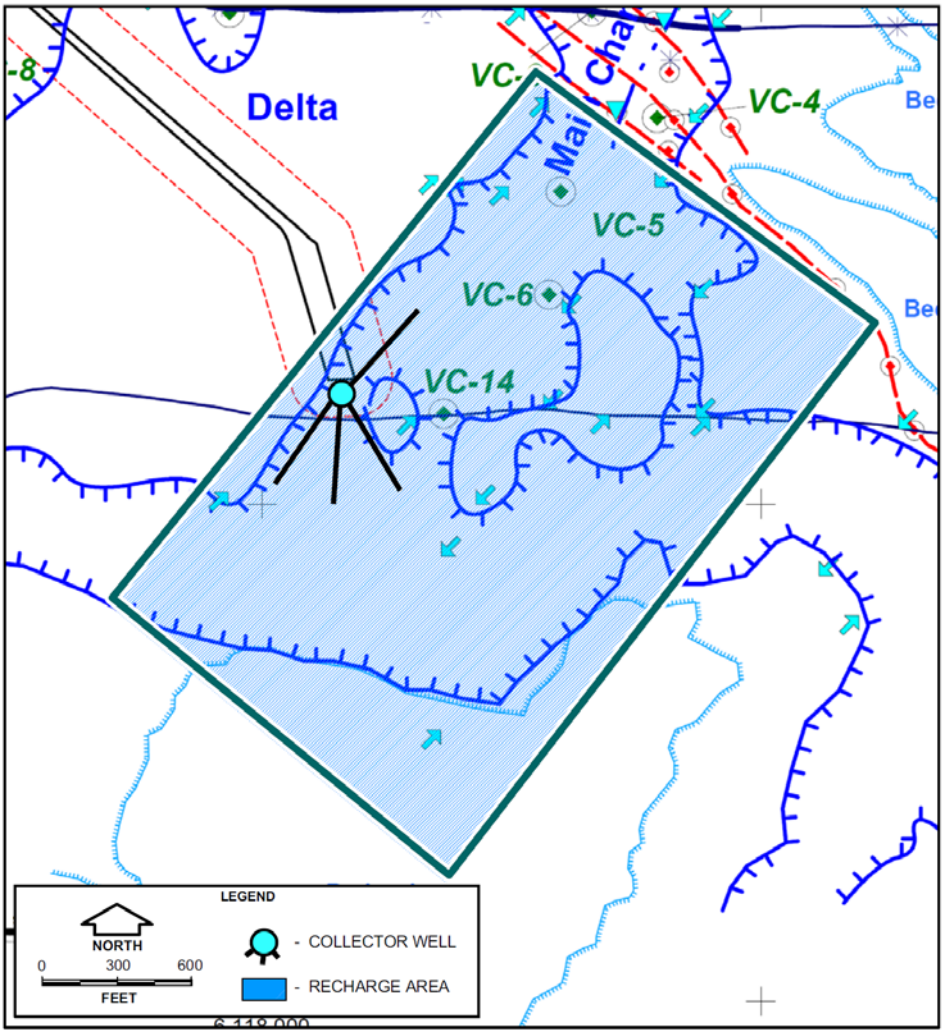

Figure 6-12. Conceptual offshore collector well location.

Available data show that the onshore sub-basin consists of interbedded sand, silt, clay and gravelly sand layers. Based on the vibracore data and USACE borehole data beneath the levees (for the upper 45 feet (13.7 m) of the channel), the coarse fraction (sands and gravels) within the channel filling sequences is estimated to be in the range of 75-85 percent. Based on the available laboratory test results, it is anticipated that the average hydraulic conductivity values for the sediment that comprises the aquifer is likely in the range between $5x10^{-3}$ cm/sec and $1x10^{-2}$ cm/sec (14 to 28 feet per day) (4.3 to 8.5 m per day). The aquifer thickness is estimated to average approximately 80 feet (24.4 m) (see Figure 6-7) and the resulting transmissivity value is calculated to range between 8,500 and 17,000 gpd/foot. This range of aquifer transmissivity is anticipated to be similar for the nearshore portion of the alluvial basin also. However, the offshore basin is anticipated to contain a greater amount of the fine-grained fraction of sediment and may have a lower transmissivity because of this condition (see VC-14).

Utilizing an empirical method to estimate a conventional water well's productivity, it is anticipated that wells completed along the river and along the shoreline in the alluvial aquifer could produce up to 400 gpm with a specific capacity on the order of 12 gpm per foot of drawdown. The dynamics of radial flow to a collector well are virtually the same as a conventional well except it has a very large effective diameter. To the extent the horizontal collector screens extend beneath a surface water recharge source, the flow path of induced infiltration is shorter and requires less of a gradient to produce the same amount of water. The slant well design provides the same benefits as the collector well, but with a different configuration of flow. The single greatest influence on well production in these shallow aquifer basins will be the rate of induced recharge. The higher the rate of recharge and the closer the extraction point is to the source of recharge, the greater the production rate that can be obtained under shallow aquifer conditions that limit available drawdown.

6.5.2 Vertical Conductance Through Ocean Floor Materials

It is anticipated that infiltration of seawater into the onshore and nearshore sub-basins will not be impeded by the finer-grained sediment that seasonally blankets the seafloor. In addition to the influence of the San Lorenzo River alluvial material, the area is also subjected to changing conditions in the ocean currents. Coarser grained sediment in the upper layers is seasonally covered by a low permeability fine-grained sediment layer. Seawater recharge into the offshore aquifer would be limited by the presence of low vertical conductance of fine-grained sediment on the seafloor.

Recharge to the aquifer by leakage through the seafloor is approximated using Darcy's law and the equation:

$$Q_{OCEAN} = KLW\ (H_{OCEAN}-H_{AQ})\ /\ b_c$$

Where:
Q_{OCEAN} is the leakage through the seafloor
K is the hydraulic conductivity of the seafloor
L and W are the length and width of the aquifer (aquifer area)

b_c is the thickness of the finer-grained seafloor sediment
H_{AQ} is the head on the aquifer side of the seafloor
H_{OCEAN} is the head on the ocean side of the seafloor

Assuming an effective confining layer on the seafloor that is 3 feet (0.9 m) thick with a K value of $1x10^{-4}$ cm/sec (0.28 feet/day or 8.64 cm/day), an aquifer area of $2x10^6$ square feet (1,000 x 2,000 feet or 304.8 x 609.6 m), and an average drawdown beneath the entire area of 10 feet (3 m), the seepage rate through the seafloor would be approximately 9,700 gpm (36.7 m^3 per minute) or (13.9 million gallons per day (MGD) or 52,617 m^3 per day). While this result appears to indicate the offshore basin is large enough to allow production of a sufficient seawater supply, it is highly unlikely that these simplified conditions exist. It is unlikely that the formation has a high enough transmissivity value to allow propagation of an average 10-foot (3 m) drawdown across the entire aquifer because of lateral changes in formation materials. It is also likely that the effective thickness of low permeability layers is greater than 3 feet (0.9 m) thick and that hydraulic conductivity values for layers in the basin range as low as $1x10^{-6}$ cm/sec or $1x10^{-7}$ cm/sec.

Assuming an effective confining layer on the seafloor that is 3 feet (0.9 m) thick with a K value of $1x10^{-3}$ cm/sec (2.8 feet/day or 85.3 cm/day), an aquifer area of 600,000 square feet (55,741.8 m^2) (600 x 1,000 feet or 182.8 m x 304.8 m), and an average drawdown beneath the entire area of 5 feet (1.5 m), a seepage rate through the seafloor would be approximately 14,500 gpm (0.91 m^3/sec) or 21 MGD (79,493.6 m^3 per day). Again, this calculation would suggest that the nearshore production of seawater may be capable of inducing an adequate rate of seawater infiltration; however, there is a substantial risk that the assumptions required to simplify the problem and ignore the effects of heterogeneous and anisotropic aquifer conditions could reduce the actual amount that can be obtained. The San Lorenzo River paleochannel is a relatively thin alluvial aquifer with moderately low hydraulic conductivities, producing a relatively low aquifer transmissivity.

6.5.3 Engineered Infiltration Gallery

The same calculation used to estimate the induced infiltration rate through seafloor sediment into an aquifer can also be used to estimate infiltration into an infiltration gallery. Assuming that the infiltration gallery will be seasonally blanketed with an effective confining layer that is only 3 feet (0.9 m) thick with a K value of $3.35x10^{-4}$ cm/sec (0.95 feet/day or 28.9 cm/day), an average drawdown within the gallery of 10 feet (3 m), then the surface area required to produce approximately 8,700 gpm 0.55 m^3/sec (12.5 MGD or 47,317 m^3/day) would equal an area of approximately 527,700 square feet (49,025 m^2) (725 x 725 feet or 221 m x 221 m). It is also assumed the gallery would be located at least 20 feet (6.1 m) below mean sea level.

While the above calculation represents average conditions for the confining layer of sand, designs for a subsurface intake should include a temporarily variable surface layer to ensure productivity of the intake in many different weather conditions. Sediment on beaches is coarser than the seabed. The seabed in this study area is covered by a mobile layer of sediment throughout the Santa Cruz bight. If the active coarse sand layer is removed by wave action, and

fine sediment is deposited by winter storm discharges from the San Lorenzo River, fine sediment could plug the infiltration gallery. This is a concern because most of the precipitation and fluvial discharge along central California occurs during the winter months when 90 percent or more of the coarse material on the inner shelf is being mobilized (Storlazzi and others, 2007). Review of nearshore conditions during winter storm discharges from the river indicate the infiltration gallery would be producing water laden with silt and clay such that frequent back flushing would be essential to keep the system from plugging. This type of fouling could disrupt intake operations and/or require pretreatment prior to injecting into the membranes.

7.0 CONCLUSIONS

The Offshore Geophysical Study was performed to provide specific information to better understand an offshore alluvial basin that may be utilized to produce seawater to supply the proposed City of Santa Cruz Water Department and Soquel Creek Water District (**scwd²**) Desalination Plant. **scwd²** is investigating the feasibility of a 2.5-million-gallons/day (mgd) seawater reverse osmosis (SWRO) facility to supplement freshwater supply to both the City of Santa Cruz Water Department (SCWD) and the Soquel Creek Water District (SqCWD).

The study successfully addressed the issues of: 1) the location and 3-D extent of the offshore, sediment-filled paleochannels; 2) the layered nature of the nearly horizontal Holocene paleochannel sediment; 3) the thickness of individual sediment layers as observed in the shallow cores; 4) the type and geotechnical properties (i.e., grain size, density, and hydraulic conductivity) of the uppermost sediment layers; 5) the geologic history of the paleochannel sediment and the sequence of cutting and backfilling of the paleochannels; 6) the type of sediment most likely found in the three main paleochannels identified; and 7) conceptual production locations in the San Lorenzo River offshore paleochannel. The paleochannels were eroded or down cut when sea level dropped during the most recent glaciations. As sea level returned to current or near current levels, sediment was deposited in the channels. Sediment deposition was in layers of differing types and thicknesses depending on the source of the sediment, distance from the shoreline at time of deposition, and whether the sediment was transported to the coast due to flooding or average or seasonal runoff. The type of sediment was further modified by wave action and longshore sediment transport.

The following points are the key findings and recommendations resulting from the analysis of the data (geophysical and geotechnical) and preliminary conceptual work performed for this study:

- A map of the San Lorenzo River Last Glacial Maximum (LGM) paleochannel and the Neary and Woods/Schwan paleochannels was presented on Figure 6-1. The San Lorenzo River channel is the largest of the three and contains a greater proportion of sand than the other two. The Neary and Woods/Schwan paleochannels appear to be filled with finer-grained sediment, e.g., mud, clay and silt that do not constitute viable aquifer materials for saline groundwater production. Furthermore, these other channels show high reflectivity of stratified sediment fill and seismic velocity effects (pull-down and wipeout zones) that indicate the accumulation of significant quantities of gas, including methane and hydrogen sulfide.
- Available data indicate that along the coastline, the groundwater basin is constrained within the paleochannel of the San Lorenzo River, which was incised into siltstone bedrock of the Purisima Formation. The nearshore channel geometry is approximately 1,000 feet wide (305 m) and 40 to 128 feet (12.9 to 39 m) deep with steep sides similar to the bedrock wall observed on the east side of the present river channel. The transition zone land seismic array confirmed continuity between the onshore river channel and the offshore main channel with similar depths to bedrock. Farther offshore, near the end of the municipal wharf, the channel deepens to as much as about 150 feet (45.7 m). The

main channel curves through a 2,000-foot (610 m) wide meander bend to head east in the area south of the Municipal Wharf before curving south to the edge of the area surveyed. The Neary channel merges with the main channel at the western edge of this meander, which creates an east-trending alluvial basin channel nearly 5,000 feet (1524 m) long. The area north of the wharf consists of an alluvial basin partly filled with a delta channel/levee complex that resulted from ancient meanders of the San Lorenzo River and Neary channel sections. The lower channel/levee sediment likely contains significant clay layers, whereas the upper 45-foot (13.7 m) section may consist of fine sands and silt from more recent river meandering in the nearshore zone.

- A stratigraphic column (Figure E-1) showing the expected channel fill sequence lithology was constructed based upon the vibracore data in the nearshore channel and USACE borehole data from the nearby San Lorenzo River levee study. The part of the stratigraphic column deeper than the USACE borehole data, about 42 feet (12.8 m), was modeled based on the shallow core data and typical channel fill deposits from similar environments.
- The geophysical data provide confident measures of the channel depth and the presence of well-defined layering or absence thereof. The sands and other coarse-grained deposits, which may comprise as much as 75-85 percent of the channel fill sequences, are interpreted in the geophysical data by the absence of multiple well-defined reflection layers. Well-defined layers are observed in the other channels consistent with fine-grained deposits, clays, silts, and gas accumulations that were found in the vibracores. Only direct sampling by deeper drilling in the area can identify the specific character of the subsurface lithology and hydraulic conductivity through the entire channel sequence.
- A zone of northwest-trending faults cuts across the San Lorenzo River channel about 400 to 1,200 feet (122 to 366 m) south of the shoreline. Boomer seismic profiles show these faults cutting into the channel fill sediment, so that there may be some impedance of lateral fluid flow if these faults have created significant offset of coarse-grained aquifer layers. These faults are located farther offshore than a slant well intake could reach from the beach based on present drilling technology.
- While the geophysical methods employed in this study successfully showed the presence of the San Lorenzo River alluvial aquifer's main channel, the hydraulic conductivity of its layers was found to vary significantly, and this aquifer is believed to contain thin layers of moderate to low permeability materials. The coarsest material observed in the sediment samples was a medium to coarse-grained sand with gravel that had a hydraulic conductivity value of 1.34×10^{-2} cm/sec. The remainder of the coarse-grained samples tested ranged between 2.05×10^{-3} cm/sec and 5.89×10^{-3} cm/sec. Approximately 20% of the shallow offshore material sampled was a silty sand that had hydraulic conductivities that ranged between 1.33×10^{-4} cm/sec and 5.24×10^{-3} cm/sec. Clay layers were also observed in the sediment samples and were measured to have hydraulic conductivities that ranged between 1.81×10^{-6} cm/sec and 1.32×10^{-7} cm/sec. It is likely that the coarsest alluvial deposits are located onshore or in the nearshore river channel. The offshore sub-basin appears to contain a greater fraction of fine-grained sediment than the other two sub-basins.

- The most significant unknown at this point is the hydraulic conductivity of the heterogeneous aquifer in the sub-basin locations of interest for the subsurface intake designs. It appears from the geology studied in this area that there is no reason to believe that offshore subsurface characteristics would be any better than what was found in the shallow sediment or what has been discovered at depth onshore. The single greatest influence on well production in these shallow aquifer basins will be the rate of induced recharge. The higher the rate of recharge and the closer the extraction point is to the source of recharge, the greater the production rate that can be obtained under shallow aquifer conditions that limit available drawdown. Thus, there is a risk that due to the nature of the narrow, shallow, winding San Lorenzo River paleochannel, a subsurface intake system may lack the ability to be recharged, especially if any of the risk factors identified in this study interrupt the flow of seawater to the wells.
- Based on the findings of this study, it is recommended that **scwd²** 1) consider the other factors that may increase the risk of developing these supplies, including water quality concerns and operations and maintenance costs, which could impact the feasibility of these source water alternatives; 2) develop an understanding of the required test programs that must be conducted to prove the availability of any of the subsurface intake alternatives; 3) identify the unknowns that will still remain after performance of those programs; and 4) develop an understanding of the estimated costs that would be required to construct any of the facilities, should one of the alternatives prove favorable after conclusion of the test program(s).

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