# *Changing Shorelines*: Methods

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# Purpose

This document is to describe the methodology undertaken by Data Visualization Researcher - In- Residence, Lindsay Irving in the development of the *Changing Shorelines* visualization for the *Visualizing the Bay* exhibit in the Observatory Gallery. The residency primarily consisted of researching, acquiring and developing geospatial datasets for the production of a new visualization about sea level rise as well as coordinating between the exhibit development team and external scientific advisors. The residency ran from February 2015 to September 30th, 2015 with a "soft launch" of the *Changing Shorelines* visualization on September 16th at the 50th Anniversary Summit of the Bay Area Coastal Development Commission (BCDC) held at the Exploratorium. The summit was attended by 200+ people in the governmental, academic, design, and planning fields that are involved in climate change and sea level rise adaptation planning and development for the entire Bay Area region. Many of them interacted with the exhibit and gave the team feedback that will likely be implemented in the content and the design aspects of the visualization after the duration of this residency. Methods described in this document refer to the development of the exhibit from February - September 30th, 2015.

# Overview

The San Francisco Bay is a dynamic, living system however; most residents remain unaware of its complexity, or the processes that shape it. Similarly, many people perceive sea level rise and climate change as concepts that are distant in time and distant from affecting them at home. After researching the geologic past of the San Francisco Bay, it became clear to me that the Bay, as we know it, is actually a temporary phenomenon. Evidence demonstrates that sea levels are rising again, this time it is due to human caused climate change. Given the rate of change projected to occur in only 100 years from now, we wanted to see if we could compress time into an interactive visual experience for the *Visualizing the Bay* (VtB) table that could both educate people and inspire them to feel connected to time and connected to a landscape that is changing right in our backyards.

Computational advances in mapping and modeling technology allow more data to be analyzed, shared, and visualized than ever before. I dove into the literature and explored as many online data providers, data portals, and web-tools as I could to understand what geospatial components were available to tell the story. I used a combination of QGIS, ArcGIS, and Google Earth as my tools for evaluating various datasets involving sea level rise and coupled ecosystem dynamics for the Bay Area. We explored some of these datasets iteratively as a team by layering them as KMLs in Google Earth and projecting them on the VtB table. Each one of these data layers could have been its own story and it was difficult to know when and where

to draw conceptual boundaries. We realized no one has created georeferenced sea level boundaries after the last glacial maximum (18,000 years ago) to the present day. On the other hand, there is extensive research and models available for evaluating sea level rise scenarios at different time periods, under different emissions scenarios. The big question for us was, could we merge the “deep past” with the “near future” in the same experience? For this exhibit platform, there was a lot to consider graphically, scientifically, and conceptually. After much iteration, we decided to focus on visualizing the essential components of the story; the land and the sea.

Eyal Shahar, exhibit developer in the New Media department at the Exploratorium built a custom program in Java and Processing to “morph” 15 layers of sea level boundaries that I georeferenced spanning 18,000 years to 2,000 years ago. These layers were derived from the extensive research and early visualizations by geologist and professor emeritus, Dr. Tanya Atwater of UC Santa Barbara. To go from 2,000 years ago to the present day, we integrated more detailed data illustrating historical (1800’s) and present day high tide line of the Bay shoreline from the San Francisco Estuary Institute (SFEI) Resilient Landscapes Program. Climate Central shared their sea level rise and flood maps from the Surging Seas website (version 2.0). Their Risk Finder interactive webtool for California provided a framework to evaluate the current science and trends. BCDC’s Adapting to Rising Tides Program gave us insights and a framework for interpreting projected Sea Level Rise impacts to the Bay Area and various adaptation plans that are in the works.

Once we placed everything on the VtB table, we discovered patterns in the changing Bay Area shoreline over this very long period of time. The highest sea levels of the “post glacial” era mirrored the projected sea levels at the end of this century. SFEI historical ecologists, Robin Grossinger, Ruth Askevold, Micha Salomon and Julie Beagle advised us on how to accurately visualize patterns of expansion, contraction and future expansion of the Bay. Including the wetlands as part of the water was a new concept for us and one that they felt strongly about. If wetlands are treated as land as they have been since European contact, explained Robin (paraphrasing), they are available for development and have been treated as such. If they are considered part of the “water”, their ecological role and function in the baylands ecosystem can be managed more sustainably in terms of sea level rise and climate change. This quote came back to me time and time again:

*"All water has a perfect memory and is forever trying to get back to where it was"*
*-Tony Morrison*

If water wants to go back to where it was, 150 years of development has created a fixed shoreline and modified habitats. To visualize this, we utilized MapZen’s Metro Extracts database of open source OpenStreetMap data to highlight key infrastructure that is vulnerable to sea level rise; roads, railway, bridges, and airports. We also incorporated “Bay Fill” or “Landfill” data from SFEI’s “Modern Habitats” database that is referenced in the Bayland Ecosystem Habitat Goals Report, 1999. An updated “Baylands” report is due for publication in October, 2015. The

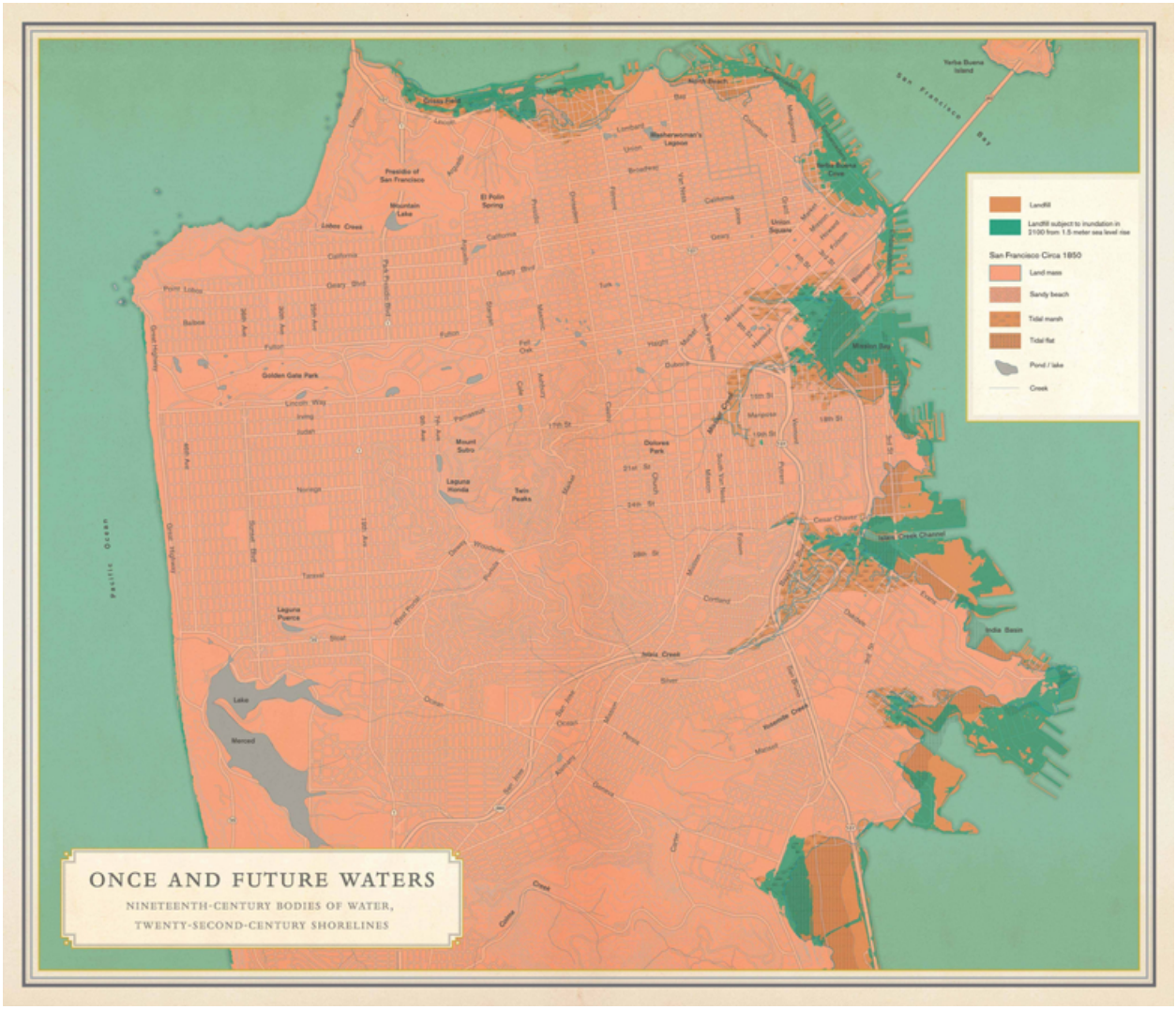
following sections, *Post Glacial Sequence* and *Future Scenarios* describe the methods and the rationale behind choosing the sources we used.

# *Post Glacial Sequence*

***Background Research & Methods***

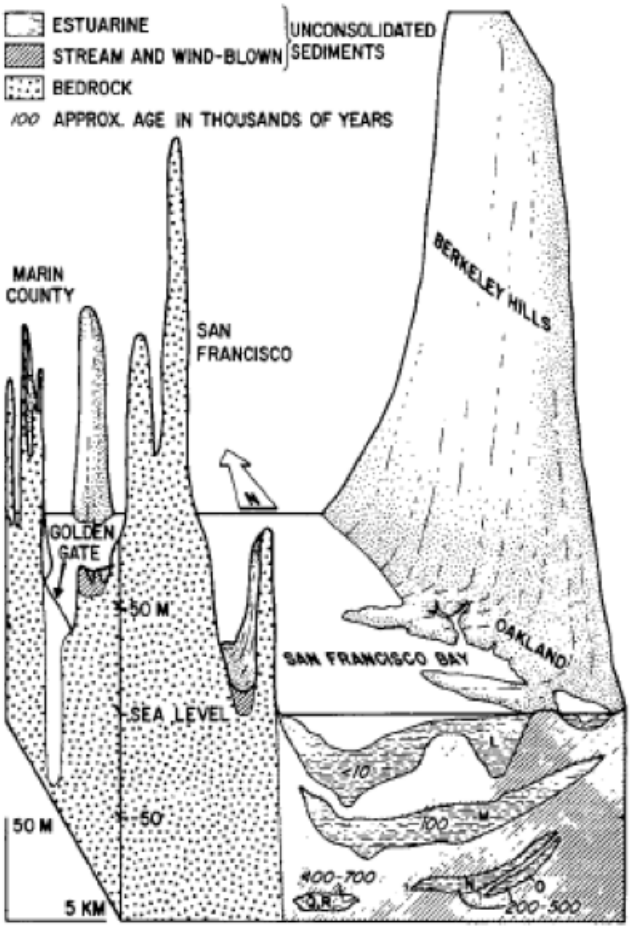
Laura Cunningham. An ancient bay marsh near present Hayward, in the southern San Francisco Bay. Oil on paperboard. *A State of Change: Forgotten Landscapes of California*. 2006.

- I was inspired by artist, Laura Cunningham and her book, *State of Change*. She combined geology, historical ecology, field biology and methods of French open air artistic tradition to re-imagine the ancient landscapes of California. I wish we could have incorporated some of her artwork into the “post glacial” sequence.



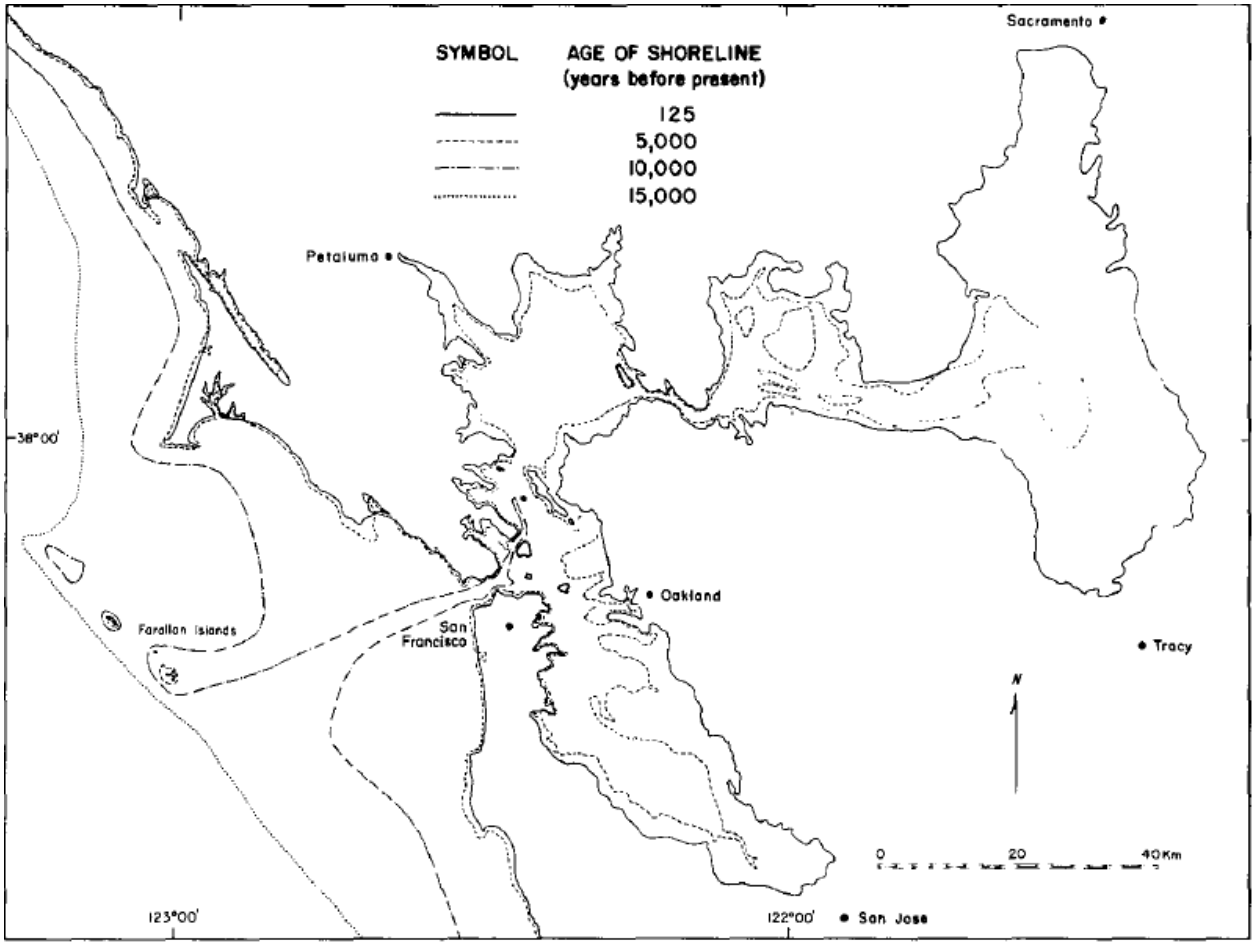

Rebecca Solnit. “Once and Future Waters”. *Infinite City: A San Francisco Atlas*. 2010. Maps the 19th Century shoreline of San Francisco with the current coast, altered by landfills, development, and sea level rise.

- I am deeply inspired by Rebecca Solnit’s work and loved seeing her maps and other maps of imaged and real landscapes of California in large scale in the Observatory’s map library.



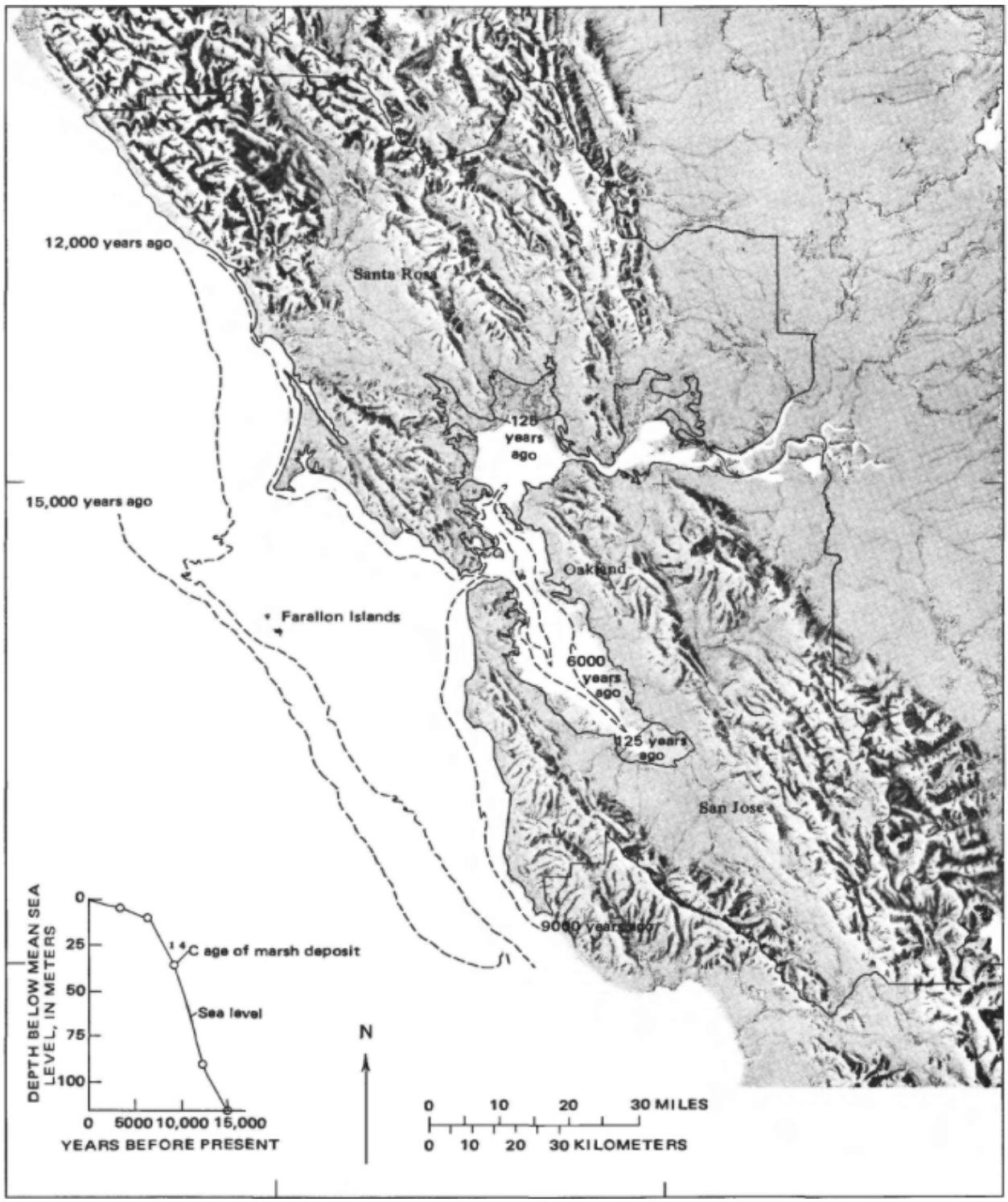

Brian Atwater. Cross-section of rocks and sediments near San Francisco. *Ancient Processes at the Site of Southern San Francisco Bay: Movement of the Crust and Changes in Sea Level*. Fifty-eighth Annual Meeting of the Pacific Division of the American Association for the Advancement of Science, San Francisco State University, San Francisco, California, June 12-16, **1979.** USGS publication

- Sediments cores collected from boreholes (bottom right) indicate that the Bay has experienced at least 4 ephemeral estuaries over the last 700,000 years. The present day Bay is actually a very temporary phenomenon!




Brian Atwater. 1977. Fig.6: “Approximate high tide shorelines near San Francisco during the past 15,000 years. (Atwater, 1977. Ancient Processes. P. 41).

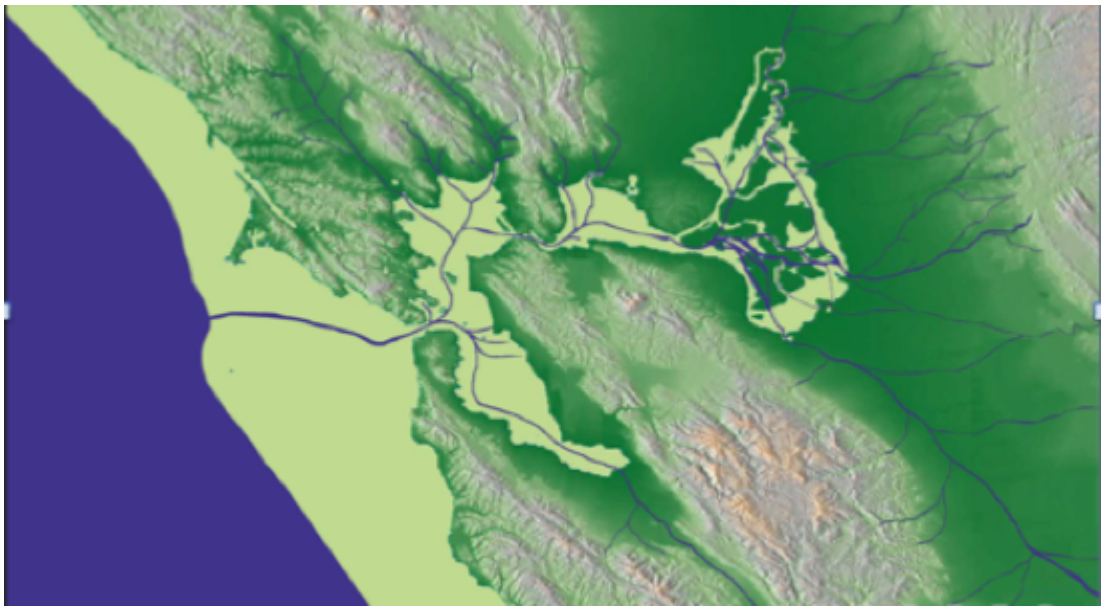
- I used these publications to help identify the key time periods we want to visualize in the post glacial period. Interestingly, I learned “present day” sea level is 100m/328 ft ABOVE historic sea levels?!
- Note in Atwater p. 41: “The 125-year-old shoreline, based on compilations by Gilbert (1917:76) and Nichols and Wright (1971), denotes the landward edge of tidal marshes before human encroachment or, where no marsh was present, the high-water line circa 1850”. ***This is similar to SFEI’s “Historical Bay” high tide line for 1850.




Edward J. Helley, **K.R. Lajoie**, W.E. Spangle, and M.L. Blair. "Flatland deposits of the San Francisco Bay region, California; their geology and engineering properties, and their importance to comprehensive planning". Professional Paper 943. 1979.
Fig 12. Shorelines of San Francisco Bay and Pacific Ocean during Holocene transgression.

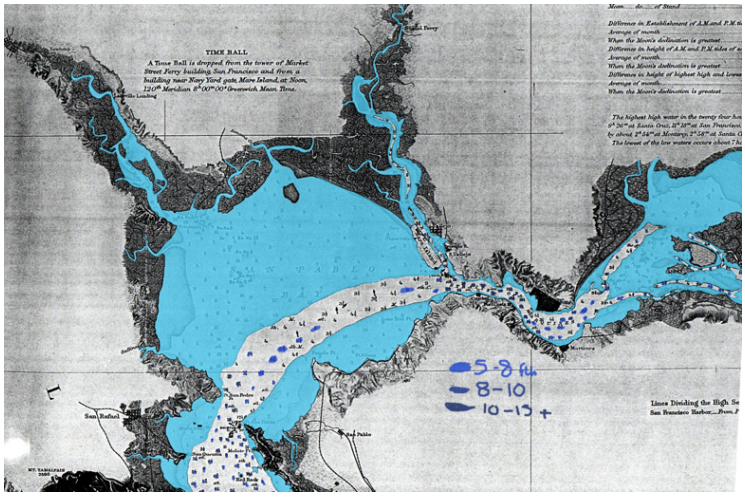
- Doris Sloan, **Geology of the San Francisco Bay Region** *(UC Press, 2006).*

- Interview in Bay Nature and good background, 2011.



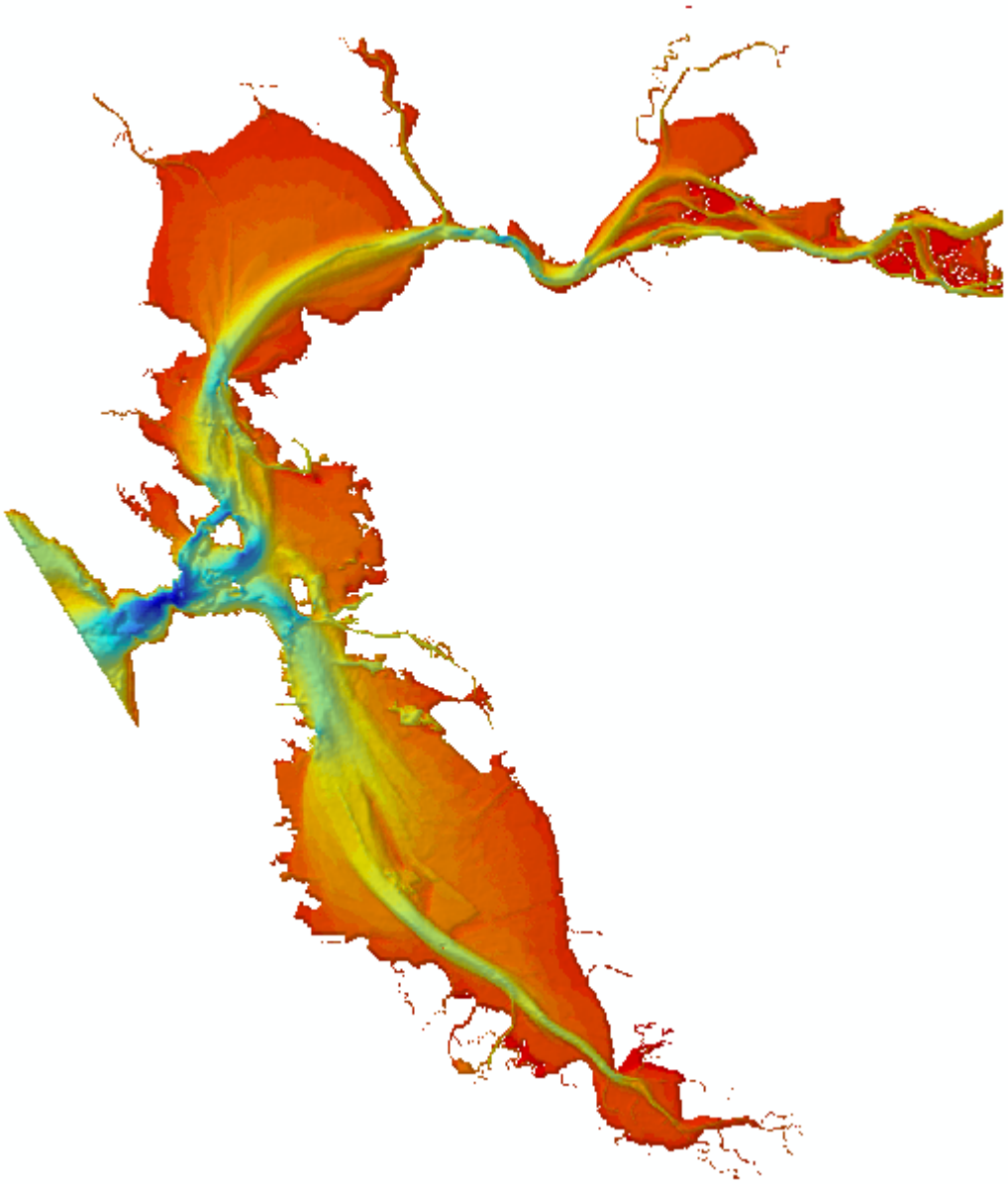
Post-glacial flooding of the San Francisco Bay animation. Dr. Tanya Atwater, UC Santa Barbara, Dept. of Earth Sciences. Educational Multimedia Visualization Center. 2005 – 2006. Published online, 2008.

Emeritus Professor of Tectonics, Dr. Tanya Atwater painstakingly went through the literature, nautical charts, and historic maps in 2005 to recreate ancient shoreline boundaries and animated them using Photoshop and “Morph” for an educational visualization for her students. This became the basis for re-creating a georefenced set of sea level “boundaries” in Google Earth.

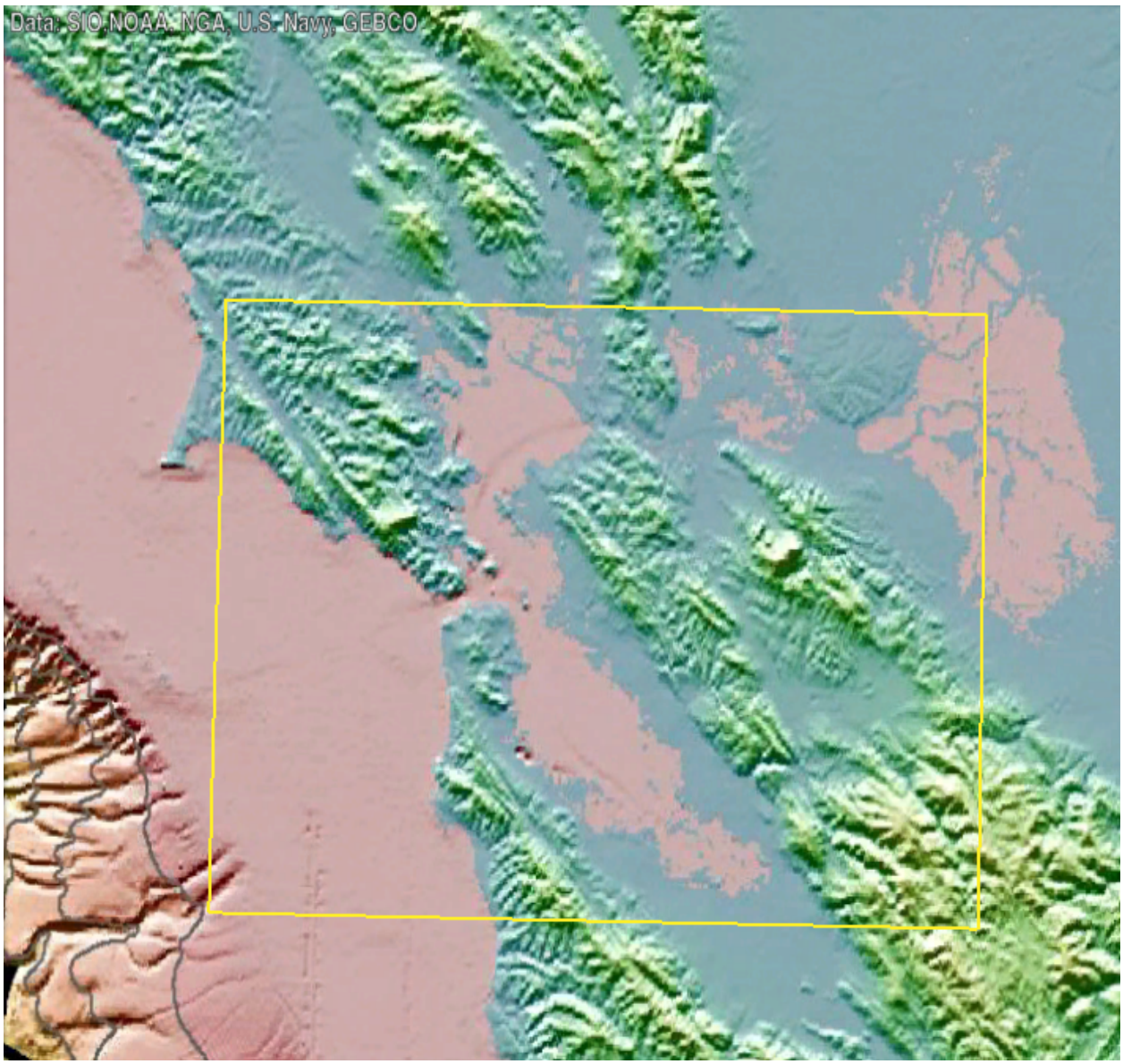



Nautical depth chart and sketch from Dr. Tanya Atwater’s research. It was amazing to talk with her and see her process during a lecture, April 2015. Given the technology and materials she had available (before Google Earth) she was pretty accurate!

***Current Elevation and Bathymetry***



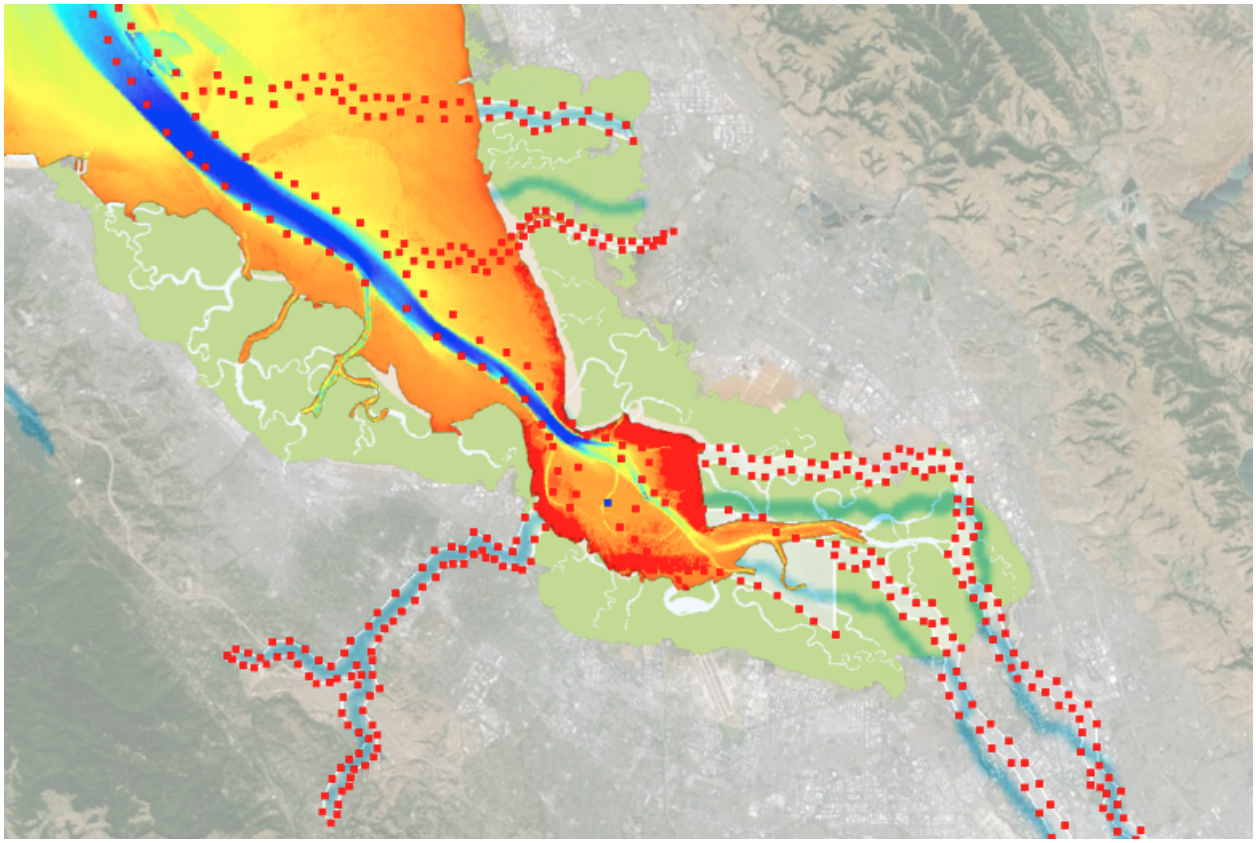
- I incorporated 3 main bathymetry and topography (DEM) sources into QGIS and Google Earth to cross-reference Tanya's post glacial boundary layers. Pictured above is NOAA's 30m bathymetry layer for the SF Bay.
- I ended up using the SRTM15_PLUS gridded data (KML pictured below) the most, published 2014 by the Sandwell Lab at Scripps Institute of Oceanography, UC San Diego. I switched between the original GeoTIFF dataset layered in QGIS and a lower resolution KML in Google Earth to verify ancient shoreline extents.



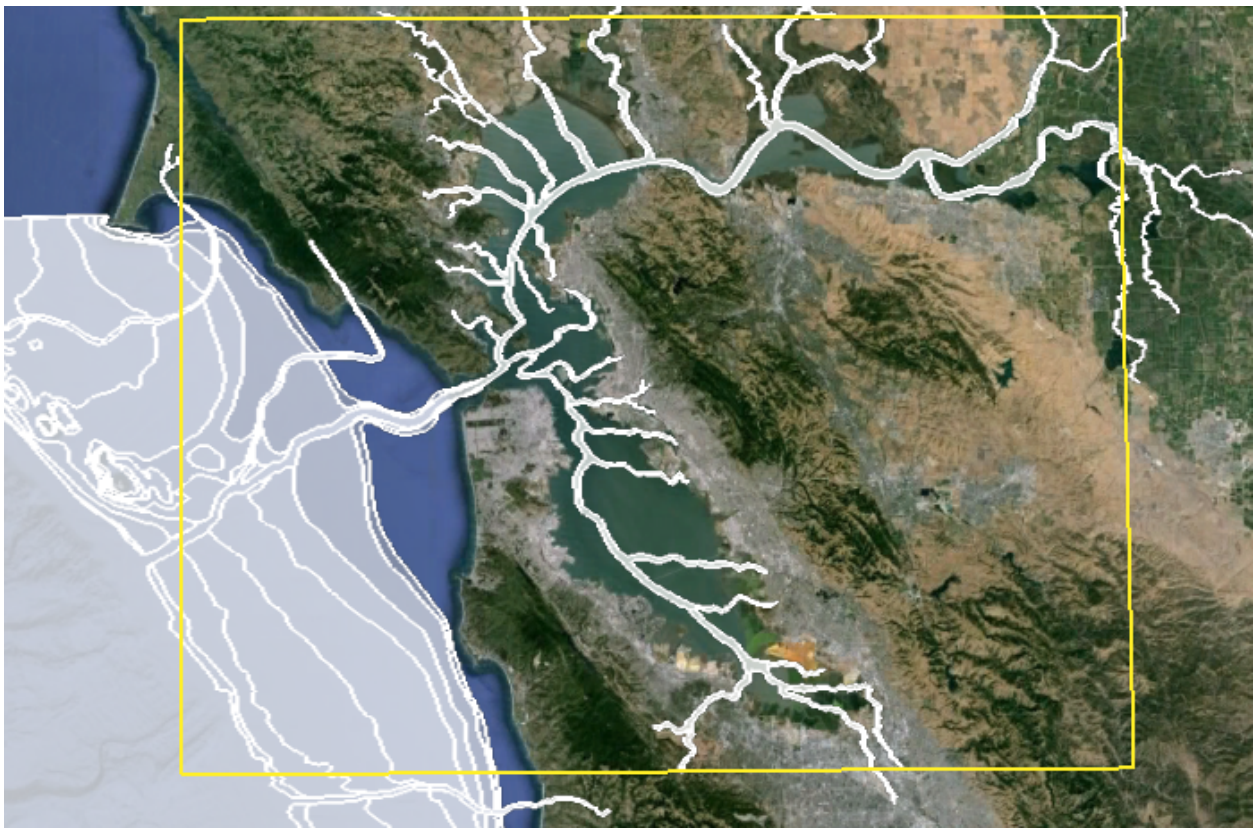
Screen shot of Shuttle Radar Topography Mission (SRTM) 15 m resolution topography/DEM “PLUS” ocean bathymetry by the Sandwell Lab. Project description from SRTM 30, 2012 version. https://scripps.ucsd.edu/news/1871

Another great source for combined topography and bathymetry data for the SF Bay that i used is USGS Coastal National Elevation Dataset (CoNED) project. The San Francisco Bay collection is a topobathymetric digital elevation model or “topobathy” (TBDEM) gathered at 3m resolution. The project is a collaboration with U.S. Geological Survey (USGS) Coastal and Marine Geology Program (CMGP), the National Geospatial Program (NGP), and the National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center (NGDC). Coastal viewer provides easy viewing and download of the data.

- I knew using current bathymetry and topography to reference geologic/ancient conditions was a speculative exercise. If more time permitted, it would be cool to import these historic bathymetry layers from USGS for the different Bays around SF Bay.
- Another source for evaluating bathymetric change of the SF Bay were these publications and animated GIFS from USGS. http://sfbay.wr.usgs.gov/sediment/sfbay/bathy_change.html
- Shifting Shoals and Shattered Rock-How Man Has Transformed the Floor of West-Central San Francisco Bay. John L. Chin, Florence L. Wong, and Paul R. Carlson. 2004. USGS.



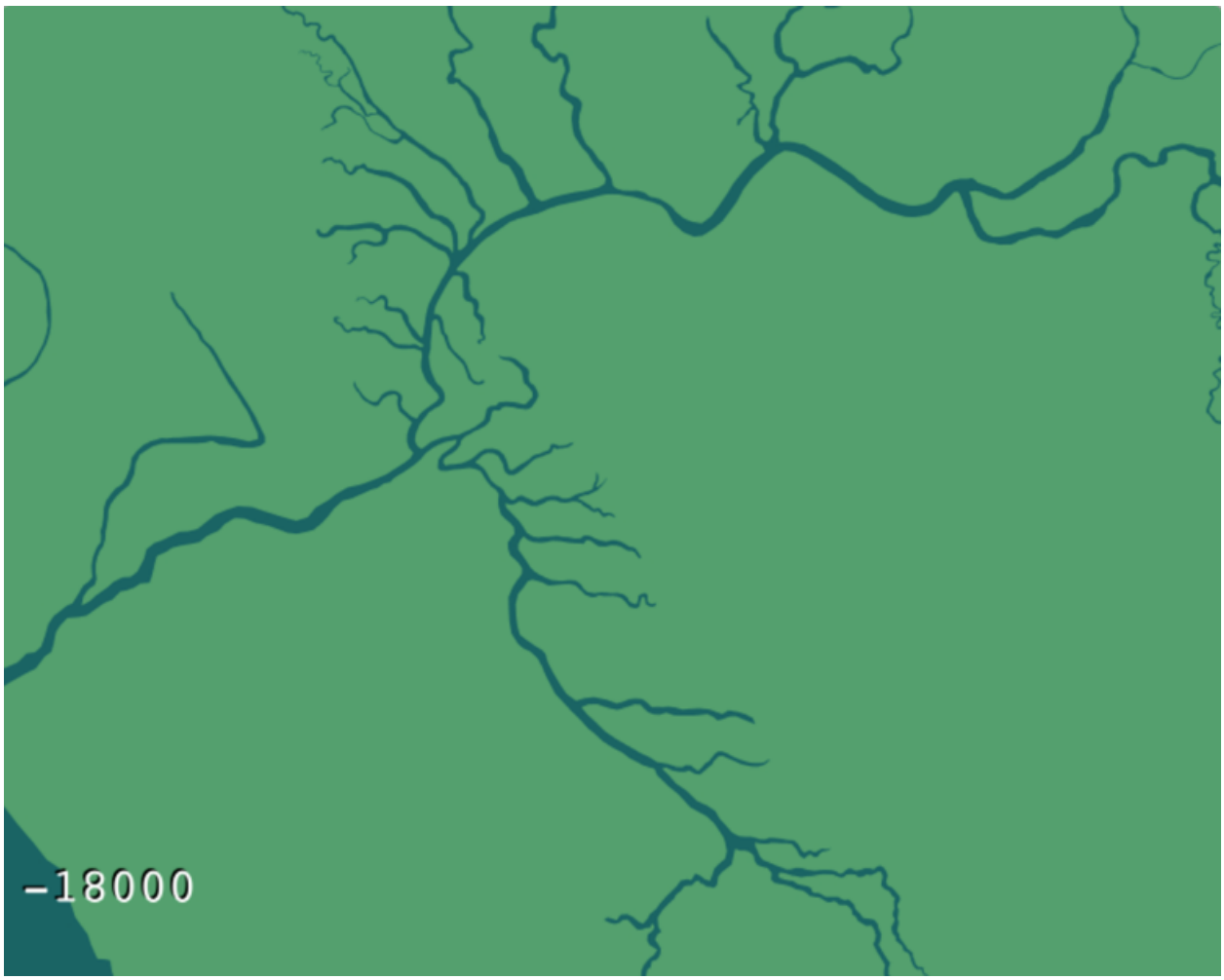
I cross-referenced Dr. Tanya Atwater's boundaries (blue) with bathymetry (rainbow spectrum, NOAA 30m DEM), satellite imagery (Google Earth), and the historic (1800's) extent of wetlands (green) from SFEI to digitize and georeference 15 post glacial sea level extents as KML polygons (red). I switched between Google Earth, ArcGIS and QGIS to verify higher resolution topography and bathymetry data sources with my layers.



Screen shot of a select number of the 15 layers (white) representing sea level boundaries (high tide line) from 18,000 years ago to 2000 years ago as KMLs. Yellow box represents the VtB geographic extent of the table.

Photo: Lindsay Irving. May 29, 2015. Sebastian Martin conducting a preliminary visitor feedback session with high school students.

Photo: Lindsay Irving. May 29, 2015. Initial feedback, “It’s water!”, “Where’s my house?”, “Are glaciers melting now?”, What’s going to happen in the future?”, “Will we have jet packs to blast away in the future?”.



A screen shot of “MapMorpher”. Eyal Shahar integrated the KMLs into a custom software written in Java and Processing to morph the polygons, or “morphogons” as he coined them into an interactive animation that visitors can scroll through on the VtB table.

I wish that we reviewed prototypes of this software with our science advisors at SFEI and Climate Central, BCDC (Bay Area Conservation and Development Commission) and others in the New Media Dept, earlier and more often. We ran into issues about how to morph smoothly and accurately from 2000 years ago to the present day.

## *Historic Bay to Present Day*

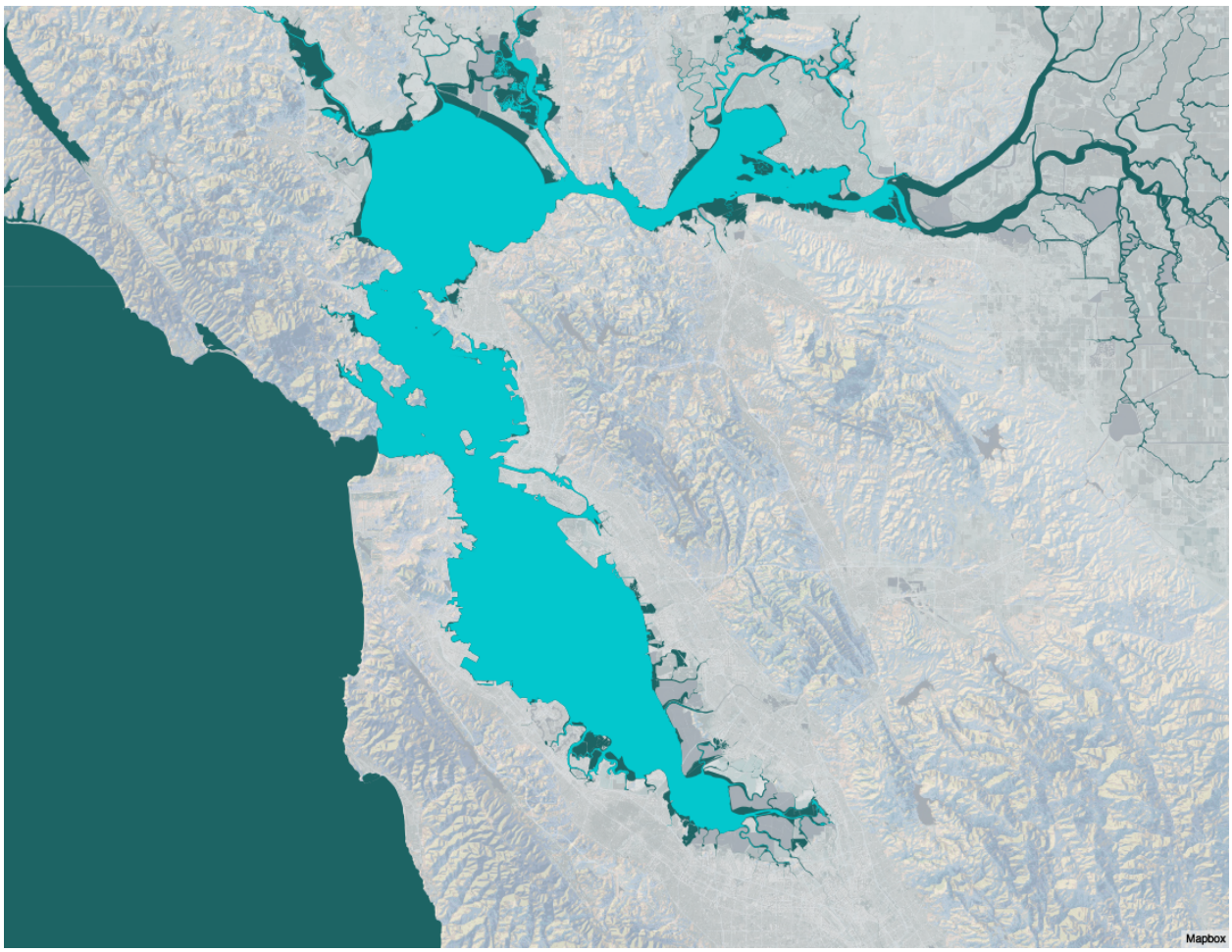
How to accurately represent the changing volume of the Bay and resulting shoreline depended on how we classified wetlands. We originally classified wetlands as “land” when our advisors at SFEI felt they should be classified as “water” to accurately depict the Bay as progressively getting larger over time and then contracting over the last 150 years.

We “morphed” from 2000 years ago

….To a representation of the Bay around the year 1850.


1850 high tide extent of the Bay and Delta derived from San Francisco Estuary Institute's "Historical Baylands" database referenced in Baylands Ecosystem Habitat Goals Report, 1999. and in EcoAtlas version 1.50, 1998.
An updated report is due to be published in October, 2015. See San Francisco Estuary Partnership for updates. Or contact Letitia Grenier, SFEI for materials and updates.

Morphing 1,835 years accurately and artistically was no easy feat! Especially when the last 165 years has seen more development and modification of the shoreline and the Bay than the last 18,000 years.



Present-day high tide extent including tidal marsh and tidal flat as water (dark blue) and present day high tide NOT including tidal marsh (light blue). Both layers were derived from SFEI's Bay Area Aquatic Resources Inventory, Version 2.0. Published June 30, 2015.
The light blue was scrapped for the dark blue extent after our advisors at SFEI felt it more accurately represents the high tide line for the Bay.

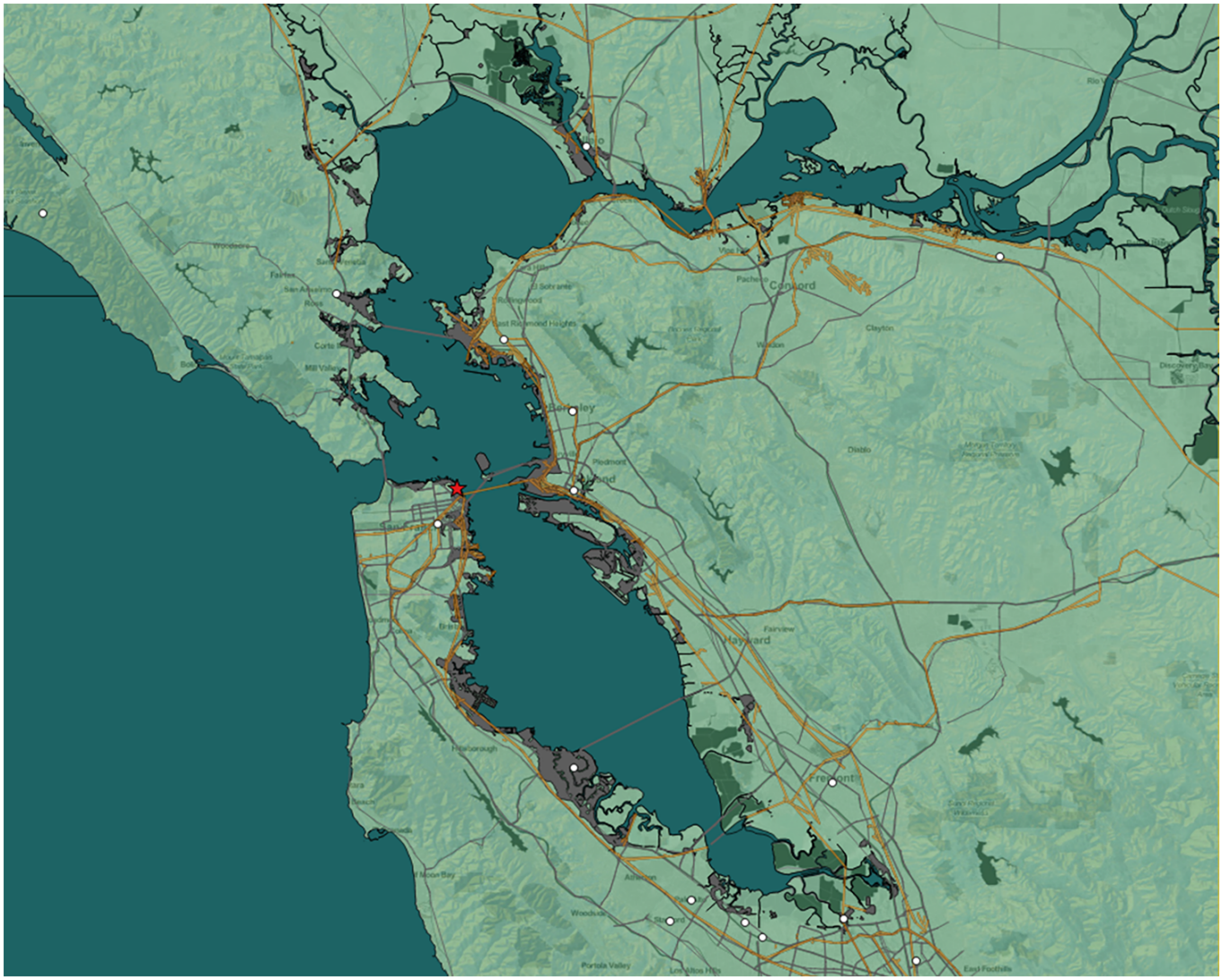
The overall goal for this sequence was to show the gradual pattern of expansion of the Bay over 18,000 years due to post glacial flooding. The shoreline was flexible to changing sea levels. Then a very abrupt contraction occurs during the last 165 years due to human development and land fill. The shoreline becomes fixed and angular. See preliminary video animation of the post-glacial sequence from map-morpher (September 22, 2015).

***A note on shellmounds and indigenous settlement patterns***


Using Google Earth, I roughly georeferenced shellmound locations from a digitized version of a 1909 map of “shellheaps” by archeologist, N.C. Nelson. This dataset was not used in the *Changing Shorelines* visualization at the date of this document but a KML file is available should

the team want to use it. A content pop up on the visualization was created to illustrate (starting at 8,000 years ago) that indigenous populations have been living around and working with the shore for thousands of years. Historians, Matthew Booker and Allen Roberts scanned the map and digitized these shellmound locations in 2014 as part of a project in the Stanford Spatial History Lab. There were over 400 shellmounds that Nelson hastily surveyed in 1902 to record the remaining evidence of indigenous inhabitedness around the shore. Today, most of these shellmounds are buried and represent sacred sites to local tribes. It is sensitive material to release but at this scale and the imprecise nature of the basemap and my methods, both Matthew Booker (Bay Area Historian and Associate Professor of History at NC State University) and Chuck Striplen (Mutsun) Environmental Scientist at SFEI felt it was better to demonstrate indigenous presence than omit it from the story.

# *Present day shoreline and Infrastructure (future scenarios "base map")*



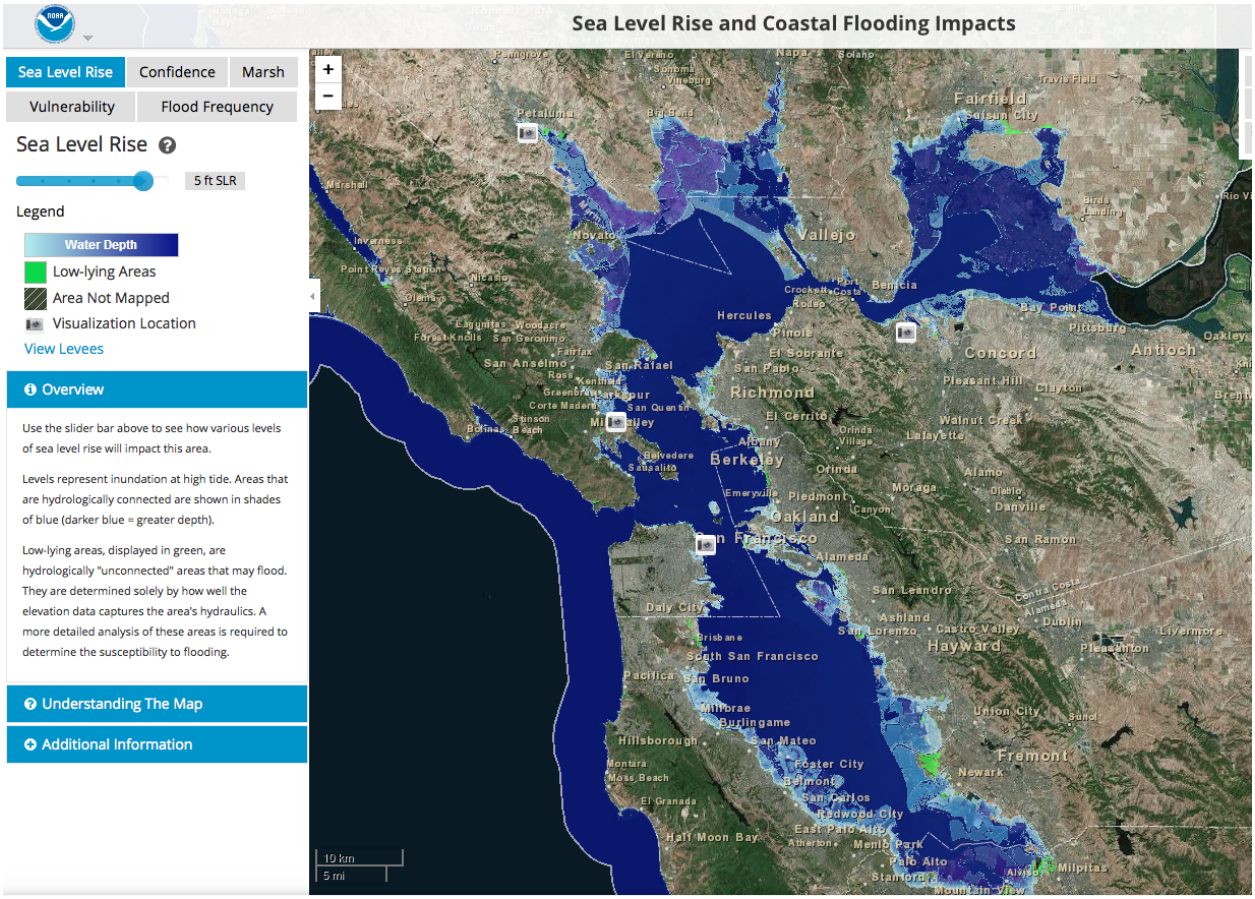

Screen shot is not the current version of feature or basemap colors or extent of the Bay. Image is to illustrate the infrastructure features only.

Infrastructure (Roads, Rail, Airports, Bridges, data derived from MapZen's MetroExtracts San Francisco Bay database curated from OpenStreetMap. Bay fill (gray) was extracted from SFEI's EcoAtlas database Version 1.50 (1998) "Modern Baylands" dataset.

# Future Scenarios

The visitor can select “The Next 100 Years” on the interface tablet to scroll through or select a series of sea level rise scenarios for the year 2100. Areas of land that are vulnerable to sea level rise and flooding at levels ranging from 2ft, 3ft, 4ft, 5ft, and 6ft above the present day high tide line from Climate Central’s Surging Seas analyses (MHHW=Mean Higher High Water, version 2.0, released March 2014). A new version of Surging Seas is due to come out mid October, 2015. Climate Central combined tidal elevation models and lidar- based (laser -based) elevation data supplied by NOAA, plus levee location data from FEMA, to identify both fully exposed and potentially protected land less than 1--10 feet above the local high tide line.

As the visitor selects the different “sea level rise scenarios”, more and more iconic pieces of the built environment (infrastructure layers) become submerged with the shoreline. Content pop ups on the table describe the probability and the type of flooding events (100 year storm) associated with with each scenario. At the time of this documentation, work continues to describe potential impacts of these scenarios to infrastructure and populations on a regional basis. Kevin Boyd and the team are working with advisors at Climate Central to refine content for the visualization and supporting exhibit materials.



NOAA's Sea Level Rise Viewer. Digital Coast. Office for Coastal Management. Current and projected SLR data were incorporated in the Surging Seas analyses that can be explored in the Risk Finder tool (San Francisco Forecast).

Understanding the mechanics of sea level rise, its connection to climate change and global greenhouse gas emissions, and evaluating potential regional impacts and scenarios was a complicated task. Having weekly/bi-monthly literature reviews with the production team and monthly reviews with science advisors would have greatly benefited the project.

> Main factors why I decided to use Climate Central's Surging Seas projections for the San Francisco Bay Area and why I chose to feature the 2ft - 6ft sea level rise range for the year 2100:

***Up-to-date, Integrated sea level rise AND storm surge modeling approach***

- See San Francisco Quick-Look Summary Report
- NOAA 2012 scenarios 1 - 5.4ft inundation above mean high higher water recorded and interpolated across water level stations in the SF Bay and at Alameda. Used updated NOAA LiDAR elevation data.
- Army Corps of Engineers reports on regional flooding.

- IPCC 2014 greenhouse gas emissions scenarios published in the 5th Assessment Report. Scientists consider these future emissions scenarios of carbon pollution to be on the "low" end.
- Vermeer and Rahmstorf, 2009 approach (link to publication below). Based on the historic relationship between global temperature and sea level rise rates, mapped forward.
- Included 100 year storm surge levels and risk.
    - Evaluating Flood Risk Increases from Sea Level Rise due to Global Warming.
- See the Science Behind the Tool webpage for an overview of methods.
- Projecting Sea Level Rise discusses more detailed methods.

***Broad Geographic Scope***

- Sea level rise projections included the San Francisco Bay Area and the Delta which corresponded with the extent of the VtB table.
- Other SLR data downloaded from other sites featured the SF Bay only.

***Methods by Climate Central scientists have been peer-reviewed***

- Peer-reviewed publications
- Tebaldi, Strauss, Zervas. Modeling Sea Level Rise and Storm Surges along the US Coast. March 2012.

***Why 2 - 6ft and not up to 10ft?***

*At the time of this documentation, Dan Rizza of Climate Central is preparing flood map data at 7, 8, 9, and 10ft to share with the exhibit team to incorporate into future iterations.*

SLR projections from the sources I reviewed (see below) range in severity, do not measure environmental or climatic variables consistently among them, they publish their results in different units of measurement (meters, ft, centimeters, millimeters, etc), for different time periods (mid century, 2030, end of century). A large portion of my time was spent just cross referencing results to confidently come up with a realistic range, within our region, to feature in the visualization. After converting outputs into feet, here is my summary of findings for end of century (2100) projected sea level rise for the SF Bay Area:

- USGS Cascade Project/Noah Knowles. Published, 2010: **1.63ft - 4.9ft**
- Our Coast Our Future. Published, 2013 (NOAA, USGS, etc): **0.8ft - 16.4ft**
- National Research Council. Published, 2012. **1.7 ft by 2030, 5.4ft by 2100**
- BCDC Vulnerability and Risk Assessment Report. Published. Sept 2012: **1.33ft by 2050 and 4.5 ft by 2100.**
- Climate Central, Surging Seas Sea Level Rise Analyses. California report published March 2014.

New models, analyses, and popular press articles are coming out every day and many are predicting 8 - 10 ft rise, regionally and up to 20ft globally. Climate Central's Surging Seas analyses include 8 - 10 ft rise but I decided to select the more middle of the road range of 2 - 6ft.

Ironically, Zachary Wasserman, Chair of the BCDC at the 50th Anniversary Summit held at the Exploratorium Sept 16, 2015 talked about a 10ft sea level rise scenario as probable for San Francisco by the end of the century or sooner. I imagine in a year or two, officials will be using a higher SLR range of 10ft.

# What is next, Resources, and Thanks

A remaining challenge is how to make the different sea level projections relevant to visitors? Kevin Boyd has been synthesizing reports connecting inundation levels with specific storm and flooding events. He is also working on an exhibit panel that describes adaptation planning solutions that the BCDC is working on at select sites around the Bay. It is challenging to make a simple frame of reference describing future flooding conditions that people can relate to. BCDC's Adapting to Rising Tides program is one example of an agency working to bring these complex issues to a regional scale for the Bay Area. Climate Central is doing an incredible amount of work on scaling solutions and scenarios for coastal cities across the United States.

http://www.climatecentral.org/news/nations-megacities-face-20-feet-of-sea-level-rise-19217

And the associated global web tool: http://ss6m.climatecentral.org/

Here is the link to the images I'd mentioned:
http://www.climatecentral.org/news/sea-levels-rise-20-feet-19211

Surging Seas report for CA/OR/WA:
http://sealevel.climatecentral.org/uploads/ssrf/Report-CA-OR-WA.pdf

## ***New data, research and visualizations released from Climate Central, November 8, 2015

Three weeks before international climate talks begin in Paris, today Climate Central releases a new global research report, Google Earth fly-overs, and photorealistic images contrasting the sea level consequences of different warming levels in cities around the world. At the same time, we are launching global versions of our signature mapping tools, Surging Seas Risk Zone Map — redesigned — and Surging Seas Mapping Choices.

***Supreme gratitude to everyone on the VtB exhibit development team (Sebastian, Eyal, Owen, Kevin, Toni, and Barbara) for your creativity and for helping me think about data differently and to Susan Schwartzenberg and Mary Miller for guidance, inspiration and support! I hope this visualization gets people talking, gets people thinking about their place in the long history of this dynamic landscape, and sets the stage for more environmentally-themed visualizations in the future!!!***

- ***Lindsay Irving (October 6, 2015)***