Project Plan for a

Los Angeles Basin Passive Survey (LABPS)

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Summary

We plan to conduct a new type of 3D passive seismic survey in the Los Angeles Basin (LAB) for the dual purposes of seismic hazard assessment and hydrocarbon exploration. The objective will be to determine the seismic velocities and structure of the basement and basin. For hazard assessment, the shallow velocities will provide a uniform determination of the site response for ground motion prediction, as well as the shape of the basin for modeling long-period amplification effects. Additionally, the survey will identify areas within the basin of low-level seismicity (< M2.0) that will help define ongoing tectonic processes and potential seismic hazards. For exploration, the survey will provide a map of the basement structure away from the fault trends such the Newport-Inglewood and Whittier Faults. There would be an exploration for potential targets outside of the traditional production regions.

The survey will primarily use passive energy sources, which makes it realistic for the heavily urbanized area of the LAB. We will use techniques that have been developed in the past decade for imaging with this type of data. Los Angeles is well positioned for this type of survey because the main component of the ambient noise energy is ocean waves interacting with the coast.

The main products of the survey will be:

- Map of the basement structure across the LAB
- Basin shape and velocity contrast
- Shallow velocities in the top 2-3 km across the basin
- Map of micro-seismicity in the basin to delineate active structures
- Large-scale crustal structure down to the Moho.

The survey will cover the 1800 km^2 area with a 5000-node roll-along survey deployed at a density of 10 nodes/km^2 and a backbone array of 200 three-component nodes that will be fixed for the duration of the survey. We estimate it will take four months to complete the survey, with the roll-along nodes acquiring one month of continuous data at each site. The survey will be executed by a geophysical contractor and produce 60 Tbytes of raw data, which will be processed by a university consortium led by Caltech. The

results will be published in scientific journals, and the data will also be freely available after the analysis is completed.

Introduction

The Los Angeles Basin is a deep basin located in the transpressional regime of the Pacific-North American plate boundary. It is transected by several fault systems that have controlled its structure and have provided traps for the several oilfields in the basin. These faults contribute to the seismic hazard of the city of Los Angeles to a degree that is arguably larger than the more famous San Andreas Fault, which lies approximately 100 km to the east. The faults are capable of magnitude 7+ events, and the resulting ground motions will be much stronger because of the proximity of the softer basin sediments, which both trap and amplify the strong motions.

The LAB has been extensively researched because of its economic and seismic-hazard importance, using both tectonic and geologic studies, aided by borehole and reflection data obtained from oil companies. Studies by Yerkes et al (1965), Wright (1981) and others have established the large-scale structure, and the Southern California Earthquake Center (SCEC) has developed 3D velocity models for the region. One was based on geologic and borehole data (Magistrale et al., 2000), while the other relied more on seismic reflection data (Shaw et al., 2015). Both produced large-scale velocity models that can be used to simulate strong ground motion up to 0.3 Hz. To reach the target of modeling 1 Hz energy requires a more detailed knowledge of the velocities and structure. The development of these models has been impeded by the incomplete coverage of available reflection profiles and the paucity of permanent seismic stations.

One potential outcome of the survey would be that new basement structures are found in the interior of the basin. Exploration has generally focused on the bounding faults of the basin and this would be an opportunity to assess whether there are additional hydrocarbon targets in the interior of the basin. This is a big challenge to explore with traditional methods, but with a nodal array and passive sources, it can be done with minimal impact. The resolution of this survey is not detailed enough to see specific targets, but it would likely indicate areas of interest for more detailed exploration.

Earthquake activity in southern California is monitored by the Southern California Seismic Network, which spans the area with 300 permanent broadband stations. Of these, 15 are located in the LAB itself, which means the inter-station spacing is approximately 10 km. This limits the network to detecting magnitude 2 and above events in the basin, and in 2016, there were over 1000 such events. To better delineate the active structures, and to identify those that generate only micro-earthquakes (M<2.0), we need a denser seismic network. An example of what is possible using the node-survey in Long Beach is shown in Figure 5.

We plan to extend the Long Beach network to the whole Los Angeles Basin, as shown in Figure 1. This would involve approximately 5,000 rolling sensors, along with a fixed backbone array of 200 nodes. The survey is intended to be passive, with no active-source component, which significantly reduces the costs and permitting problems.

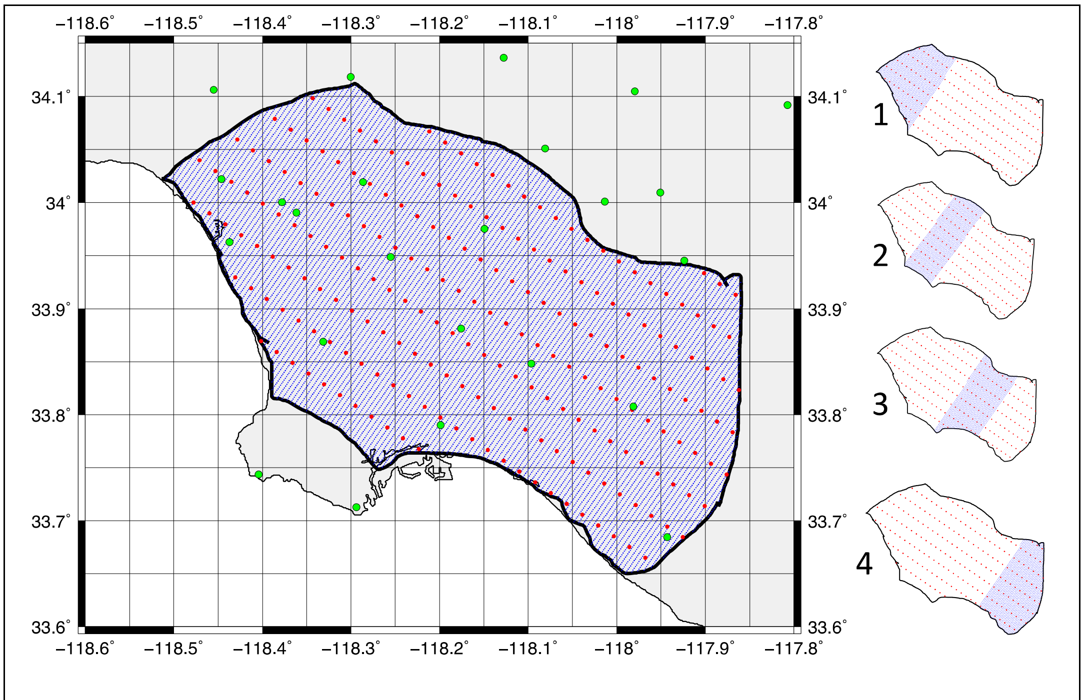

Figure 1. Planned Los Angeles Basin Survey. The area encompassed by the shaded region is 1729 km^2 (667 sq-miles). The red dots are the fixed backbone stations, and the green dots are permanent stations of the SCSN. The column to the right shows snapshots of the roll-along at months 1, 2, 3, and 4.

The idea of a 3D seismic survey in an urban area with a density comparable to that used in oil-company surveys was beyond a dream – it was considered impossible. However, in 2011, a ground breaking survey was conducted by Signal Hill Petroleum in Long Beach, CA, where a 70-km^2 heavily-urbanized area was covered with over 5200 sensors (~200 sensors/ mi^2). The other novel and important aspect of this survey is that the data were recorded continuously for 6 months. The sensors in the survey were autonomous and hence obviated the problems with cables and the extra power needed for wireless systems. This type of survey has since been repeated in the Rosecrans, Santa Fe Springs, and East Long Beach areas of Los Angeles.

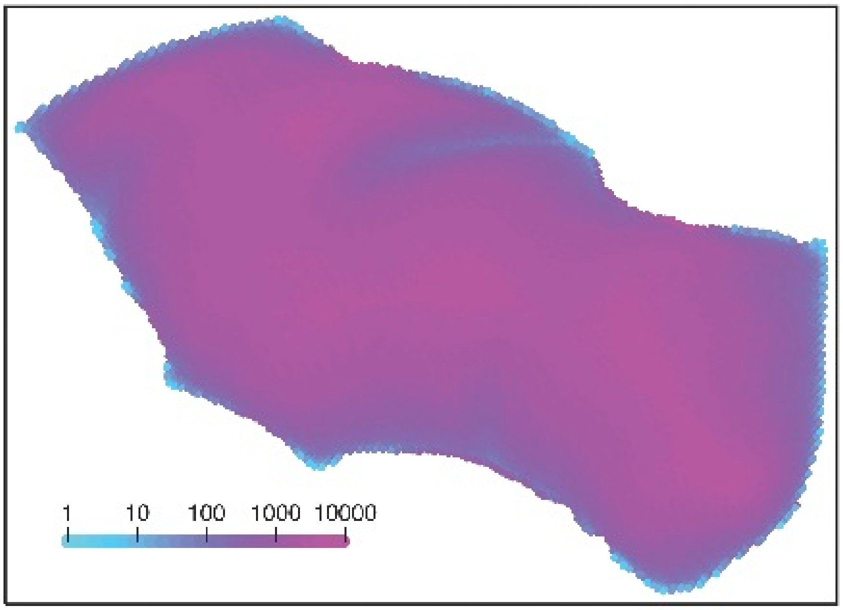

Figure 2. Coverage for survey. The figure shows the fold count for each midpoint in the survey using pairs of receivers that are contemporaneous for at least 3 weeks.

Over the past 8 or more years, there has been significant experimentation in the use of passive seismic surveys for subsurface imaging and exploration in the Los Angeles Basin. The results of this work demonstrate that passive seismic methods provide useful data for seismic hazard analysis, resource exploration, groundwater management, and infrastructure development and protection in an environmentally-friendly, urban-friendly, and low-cost manner. There is a broad range of passive survey designs and data analyses that can be optimized for various objectives. The LABPS survey objectives are discussed below, but we would like to emphasize that the LABPS's design and analyses can be modified to additional objectives to satisfy customized goals.

Details of the Survey

To cover the 700 square miles of the Los Angeles Basin, we would deploy a roll-along survey with 5000 active nodes to cover the 17,000 receiver positions. After an initial roll-in, 130 nodes will be moved each day until the entire area has been covered. The concept is illustrated in Figure 1. Each site would be occupied for 30 days of continuous recording. With this strategy, each site will have neighbors out to 10 km with a common recording time span of 20 days. The effective midpoint fold-count for the survey is shown in Figure 2, which shows that the entire basin is well covered.

LAB Survey Parameters	
area	667 sq-miles (1729 km^2)
sensor density	25/sq-mile (10/km^2)
number of sensors	~5,000 1C + 200 3C nodes
duration	4 months
deployment style	Roll-along with 5000 sensors, Fixed with 200 3C sensors
recording mode	continuous, 4 msec
data volume	~60 Tbytes

In conjunction with the passive survey described above, we have the option of adding 66 deep (120') shot holes to provide low-fold seismic reflection data, and for use in constraining results of the passive survey and image sedimentary structure. The shot holes would be fired during the low noise hours at night for best data quality and would not cause any disturbance to the local population. The shots will occur when the center of the roll-along spread is near the shot hole.

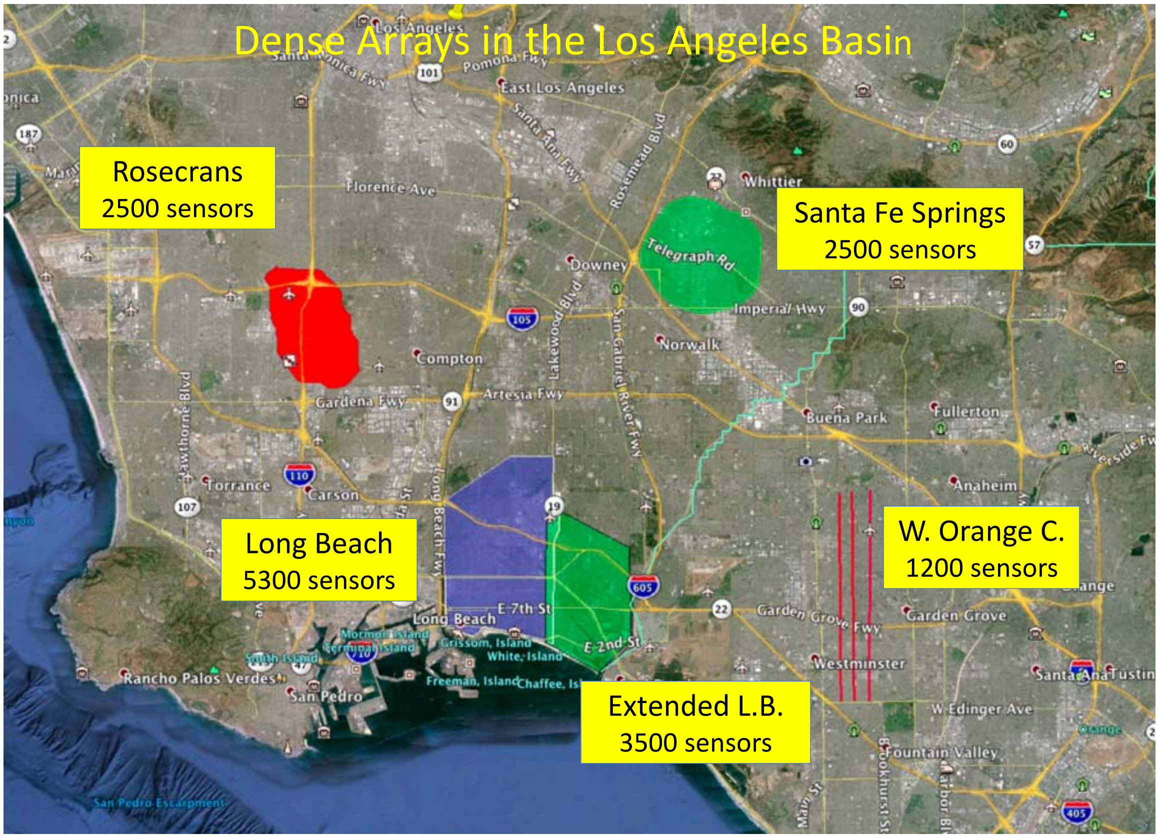

Figure 3. Dense arrays recorded in the Los Angeles Basin. The locations and sizes of several node-array surveys that have been done in the Los Angeles Basin since 2011.

Goals of the Survey

There are three main goals for the survey:

1) *Imaging the Basin Structure*. We seek to determine the main structural elements of the basin: the basement, Moho, and faults. These are important for determining seismic hazards and for determining the history of the basin evolution, as well as indicating areas of potential hydrocarbon traps. All these goals require knowledge of the entire basin and not just the parts of it where there have been exploration targets. To achieve this will be challenging because of the highly urbanized environment on top of the basin. In Figure 4, we show an example of imaging the crust in Long Beach using ambient noise. We will also use recordings of teleseismic earthquakes to image the basement of Moho (Schmandt and Clayton, 2013; Ma and Clayton, 2016).

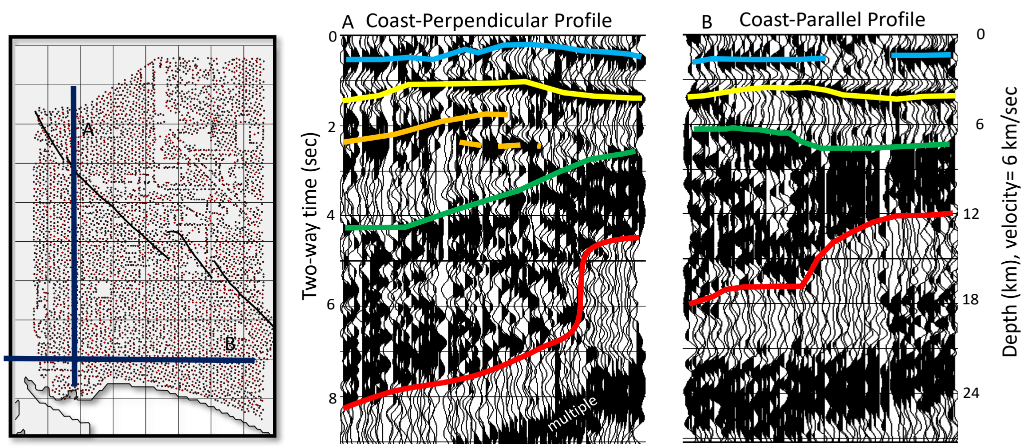

Figure 4. Whole crust profiles constructed from autocorrelations. The sections are constructed from beam-formed autocorrelations of ambient noise. The two cross-sections show structure in both the upper crust (blue, yellow and orange reflectors) and lower crust (green and red). The green interface shows the start of the increased reflectivity of the lower crust and the red interface is the Moho, which is dipping at approximately 45°. See Clayton (2018).

2) *Shallow Structure and Micro-zonation*. The level of shaking during a major earthquake depends on source, path, and site factors. Of these, the site response (or soil strength) is the poorest resolved because of the paucity of seismic stations in the LA Basin. It is often characterized by the Vs30 value (shear-wave speed in the top 30 m). The survey will improve on the measurements of site-effects both by densifying the sampling by two orders of magnitude, and by improving the resolution of shallow structure down to 1 km. We will use surface waves generated from ambient noise correlation to determine the shear wave velocity structure in the top 1 km over the entire LA Basin (Lin et al., 2013). An example is shown in Figure 5.

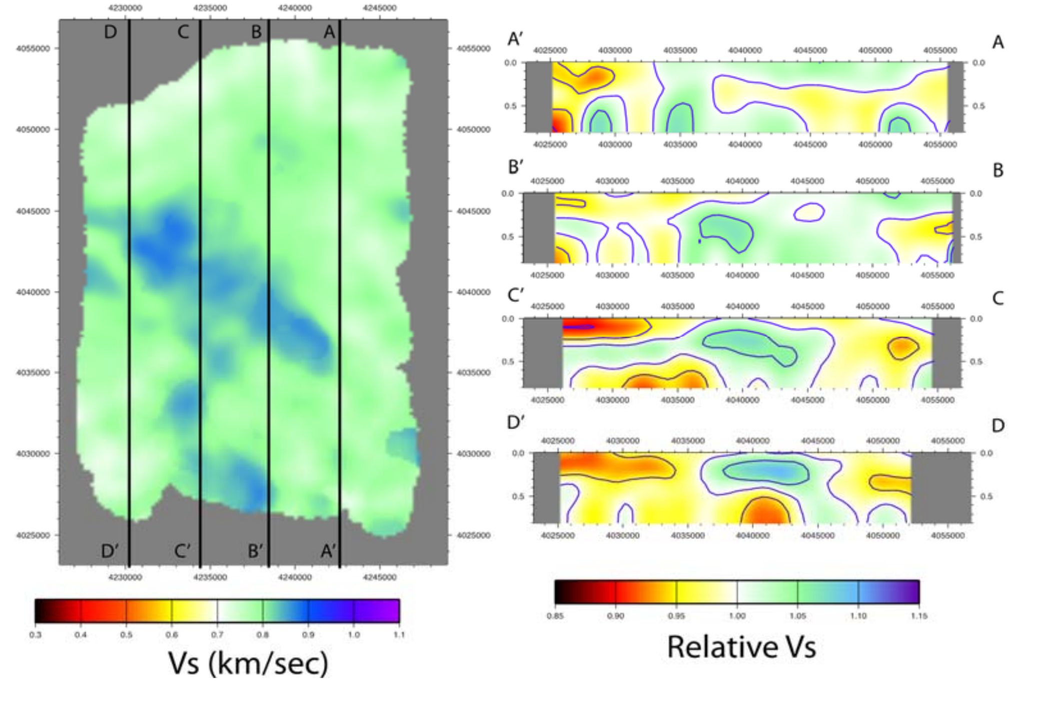

Figure 5. Shallow Velocity Structure. The phase velocity maps are converted to shear-velocity as a function of depth, which in this case is down to 0.8 km. Note the structure of the Newport-Inglewood Fault Zone (NIFZ) as it plunges down to the SW. There also appears to be a buried river channel to the south of the NIFZ.

3) *Locating Micro-seismicity*. A dense network will allow us to locate much smaller events than we currently do in the LA Basin. The permanent SCSN network is limited to M >= 2 for the LAB. With a 200-fold increase in station density and as shown in Figure 6, we should be able to detect and locate events down to magnitude 0.5. This sensitivity will help delineate active structures and identify ones that only generate earthquakes below the magnitude threshold of the SCSN. These structures may include not only faults, but also folds or creeping zones.

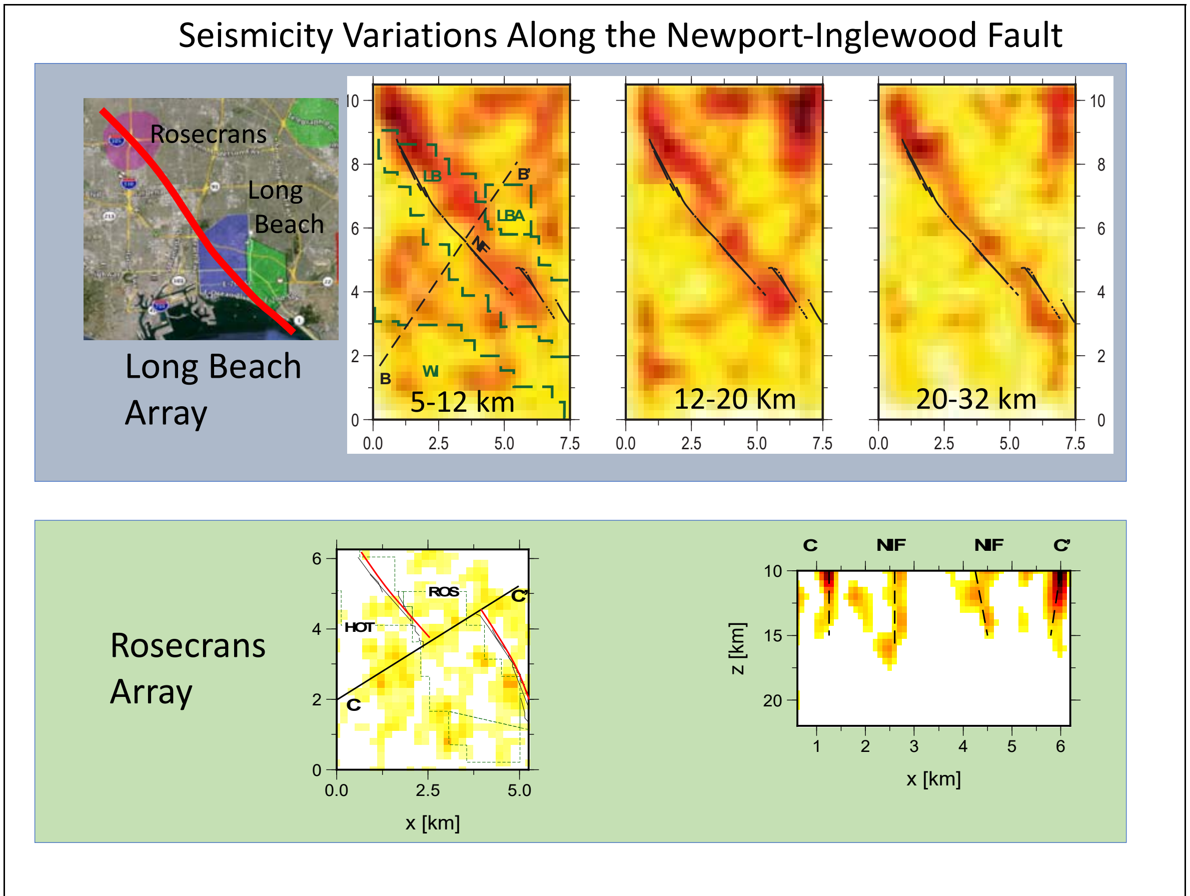

Figure 6. Locating the small earthquakes beneath Long Beach and Rosecrans. The seismicity beneath the Long Beach and Rosecrans arrays is shown. In addition to the NIFZ, several other structures are evident. Note that the NIFZ appears to cut through the Moho into the upper mantle.

Techniques to Be Applied to the Data

Passive seismology has not been widely used in the exploration industry. However, there have been recent developments that exploit the ambient noise recorded by seismic instruments. These techniques, commonly referred to as seismic interferometry or ambient noise correlation, depend on natural sources such as ocean waves and/or cultural activity such as traffic to provide the energy source for the imaging. In Los Angeles, our proximity to the ocean means we have strong ambient noise sources over a wide frequency spectrum. To utilize these sources, the data needs to be continuously recorded over a reasonable length of time (typically one month). Local earthquakes will also be an important part of the data recorded by the network. We will also record a number of distant earthquakes that can be used to provide waves to image the deeper part of the basin. In this section we list some of the techniques we plan to apply to exploit the LAB data. We are fortunate to have a preview of the type of data that will be recorded with the Signal Hill survey in Long Beach. Most of the techniques we discuss below have been tried with this data set, and the examples are presented in the Appendix.

1) *Seismic interferometry* can theoretically be used to simulate a reflection survey with virtual sources at every receiver location. The technique would be applied to image the basement and other major structural interfaces. If successful, this would be a major advance in seismic imaging. In Figure 4, we show two profiles through the Long Beach survey, which reveal upper and lower crustal structure, including the Moho. We would apply this technique over the entire LAB to form a 3D image.
2) *Surface waves* can be used to determine the shallow structure. The ambient noise correlations capture surface waves that can be used to measure the phase velocity $V(x,y,\omega)$. The depth of penetration of the waves is a function of their frequency (deeper with lower frequencies). The phase velocities can then be converted to interval velocities $V(x,y,z)$, which can be used to build a shallow velocity model such as shown in Figure 5. These models are interesting in their own right for seismic hazard, but they also provide a means of removing near surface arrival delays ("statics") from deeper parts of the image.
3) *Micro-earthquake detection and location* is a standard procedure for locating local earthquakes. Because of the high level of urban noise in the LAB, we have developed a technique to downward continue the recorded field, which has the effect of almost eliminating the horizontal traveling which is largely caused by traffic. We then exploit the dense array by back-projecting the data to locate the earthquakes (Inbal et al., 2015). An example of this is shown in Figure 6.
4) *Tomography* is used to estimate velocities, and in the case of the LAB this would be done with both local events and teleseismic events. It is particularly useful when the earthquakes occur within the array because no assumptions need to be made about velocity outside the basin. We also see P-waves captured by ambient noise correlation, which can be used in the same fashion.
5) *Teleseismic converted phases (Receiver Functions)* are useful for determining the major boundaries in the basin, such as the basement contact. The teleseismic P-waves partially convert to S-waves at layer interfaces, which can be used to map those interfaces (Ma and Clayton, 2016; Liu et al, 2018).
6) *Reverse-time migration* will be used with both virtual (correlation) sources and with small earthquakes that are recorded. By incorporating many sources in the process, we will image the structure and estimate the velocity.
7) *Common Mid-Point (CMP) stacking* would be used with the shot hole data should that option be selected. The resulting 3D data volume would image structure in the sedimentary section, provide additional P-wave velocity information, and provide another constraint on the structure and depth of the basement.

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