SPECIFIC RESEARCH OBJECTIVES

Immediate Objective (this Proposal)

The thick Mississippi embayment soil/sediment deposits are expected to produce significant ground-motion site effects. Consequently, the primary objective of this proposal is to drill and case a 640 meter borehole through the sediment overburden and into bedrock for the future establishment of a vertical seismic observatory in which to rigorously evaluate the soil transfer function of the unlithified post-Paleozoic sediments at a site near the center of the New Madrid seismic zone (NMSZ). In addition to constraining existing and future site response models in the region (Fig. A), the final array will act as a calibration site for regional strong-motion stations. The site of the proposed seismic observatory is near the most active part of the NMSZ; therefore, it should provide the maximum amount of data in the shortest period of time. The existing free-field strong-motion station at VSAB is, on the average, triggered 1 to 2 times a month by an earthquake. In addition, the proposed site is at the site of a shallow (250 m) vertical array, and midway between free-field strong-motion stations VSAB and RIGD (Street et al., 1995).

Follow-up Research Objectives (external Proposals)

The subsequent research objective for the borehole is to rigorously evaluate the effect of soil conditions on earthquake ground motions near the center of the New Madrid Seismic Zone for the purpose of evaluating existing and constraining future models of site effects in the Upper Mississippi Embayment. To achieve this objective, we will subsequently propose to granting agencies (e.g., NSF, USGS) the following research objectives that are directly related to the deep borehole:

1. Install and operate a three-dimensional array of borehole and surface accelerometers in the central New Madrid Seismic Zone.
2. Measure the dynamic soil properties at the array site.
3. Perform downhole and surface shear-wave velocity measurements for back-calculation of in situ soil properties at the site.
4. Utilize 3-D vertical array as calibration site for existing free-field accelerometers in the region.
5. Predict expected site response, based on dynamic soil properties measured at the site.
6. Perform refraction and reflection seismic imaging to obtain a comprehensive understanding of subsurface structural and stratigraphic geologic features in three dimensions in order to provide information regarding vertical and lateral variations in *Gmax* at the site.
7. Measure deep borehole ground motion while shaking at the ground surface to obtain synthetic site response data.
8. Investigate the seismic response of deep soil sites in order to validate current analytical modeling techniques used to assess deep (i.e., $\geq$100 m) soil sites.

PROJECT SIGNIFICANCE

Five significant technical contributions to earthquake engineering are ultimately expected from the final 3-D seismic observatory in the New Madrid Seismic Zone:

1. Evaluation of the effect of deep soil conditions on earthquake ground motions.
2. Characterization of the dynamic soil properties of sediments in the New Madrid Seismic Zone.
3. Evaluation of current analytical models for deep soil sites. Several analytical models are currently being used to predict the seismic response of deep soil sites; however, these analytical procedures have not been validated for sites deeper than 100 m (i.e., design engineers cannot be confident in their predictions).
4. Evaluation the recommended provisions of NEHRP, as they pertain to the New Madrid Seismic Zone.
5. Study of lateral propagation effects and spatial variation in ground motions.

In addition to the scientific and engineering significance, the ability to reduce the large uncertainty in the existing seismic hazard definitions for western Kentucky will have positive societal impacts, particularly in the area of economic development.

SITE DESCRIPTION AND EXISTING INSTRUMENTATION

The proposed 3-D calibration site is located near the Tennessee border in Fulton County, Kentucky. The site lies along the most active segment of the NMSZ; therefore, it should provide the maximum amount of data in the shortest period of time (Fig. A). Geologically, the site is in the upper Mississippi embayment, a south-plunging synclinal trough characterized by gently dipping post-Paleozoic sediments that thicken to the south. The Paleozoic bedrock in this area is overlain by approximately 600 m of the unlithified sediment (Fig A).

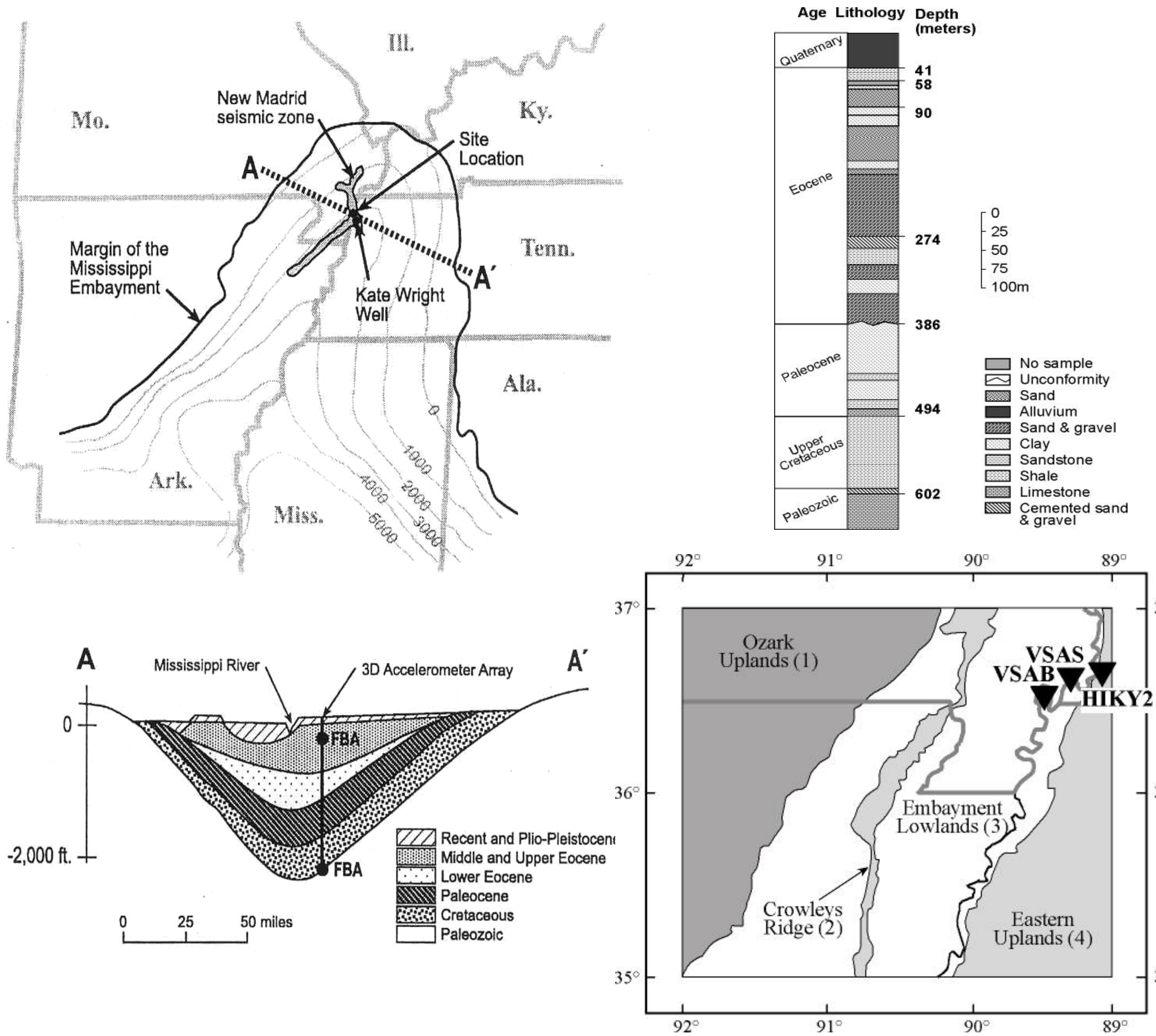

Figure A. a) Location of the site in relation to the New Madrid seismic zone, b) general stratigraphy at the site c) basin geometry relative to array location, and d) near-surface geology and relative location of proposed 3-D array to existing nearby strong-motion stations.

This depth is based on a proprietary seismic reflection line, the Kate Wright well (Schwalb, 1969), walkaway refraction/reflection soundings approximately 1.5 km north of the site (Fig. B), and our experience in the area (Street et al., 1995; Woolery et al., 1999; Woolery and Wang, 2002). The near-surface geology of the site is also typical of what Toro et al. (1992) referred to as Embayment Lowlands (i.e., floodplains) that cover much of the embayment, another characteristic making this location an ideal calibration site. Moreover, the proposed site has an existing 9-component, moderately deep (260 m) vertical array (VSAS) that is located midway between the existing strong-motion stations VSAB and HIKY2 (ideal geometry for coherency studies). The existing vertical accelerometer array (VSAS), operational since early 2004, consists of three, 3-component accelerometers recorded on a 24-bit, 9-component accelerograph equipped with GPS timing (Fig. C). The deeper borehole accelerometer is placed in a hole drilled into the first “stiff”formation (lower Eocene/upper Paleocene clay unit) approximately 260 m below the surface at the proposed site (Fig. C). This unit appears as a distinct seismic impedance boundary on our sounding seismograms that can be correlated throughout the region. A second borehole accelerometer is placed at the bottom of a 30 m geotechnical hole. This corresponds to the critical depth used for the soil Site Classification as defined in the NEHRP Recommended Provisions. The borehole accelerometers were installed in accordance with recognized procedures (Kinemetrics, 1999). The remaining accelerometer is a "free-field" installation placed in a surface vault between the two wells.

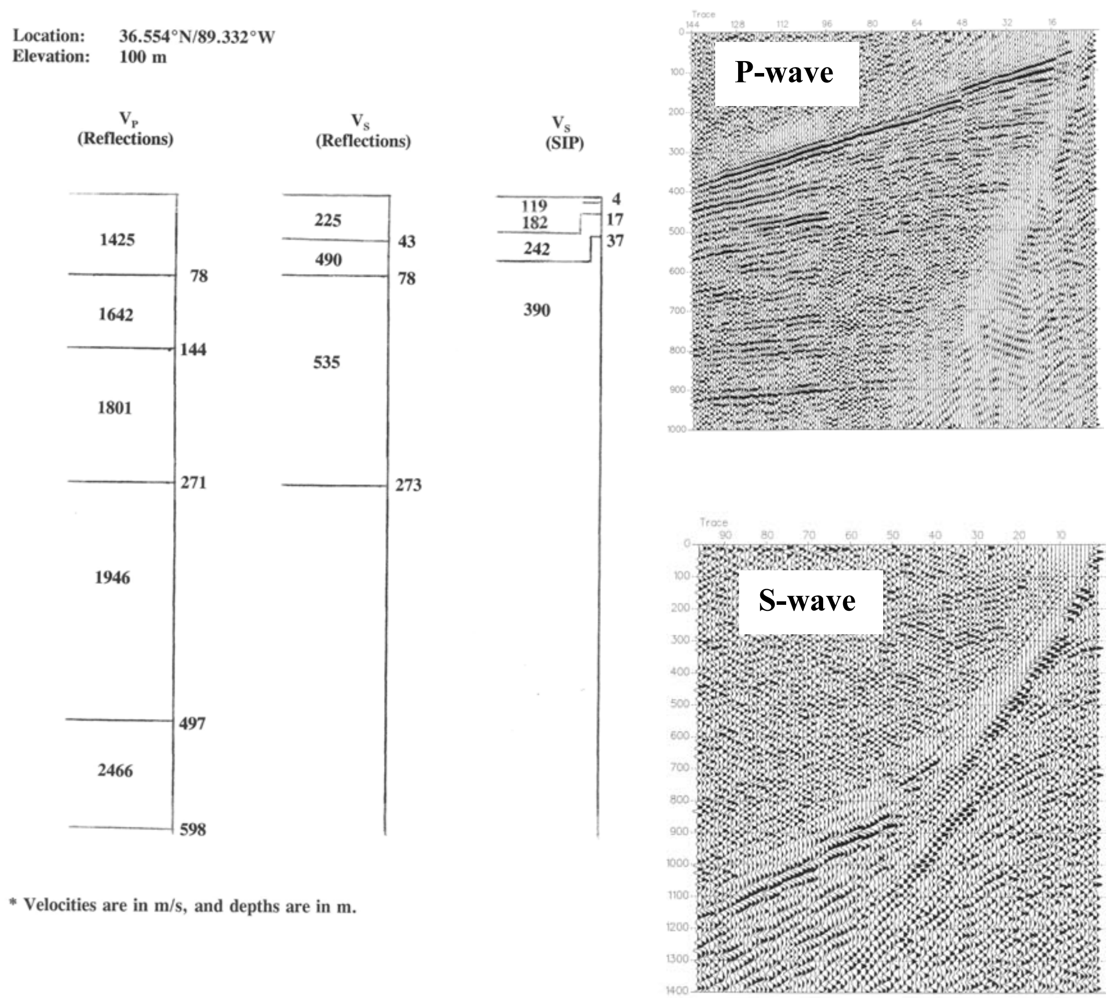

Figure B. a) P- and S-wave velocity/depth model (depth shown along the side of column; no elevation correction) for the unlithified sediment 1.5 km from the VSAS site, b) Example refraction/reflection seismograms used to derive the models at the site.

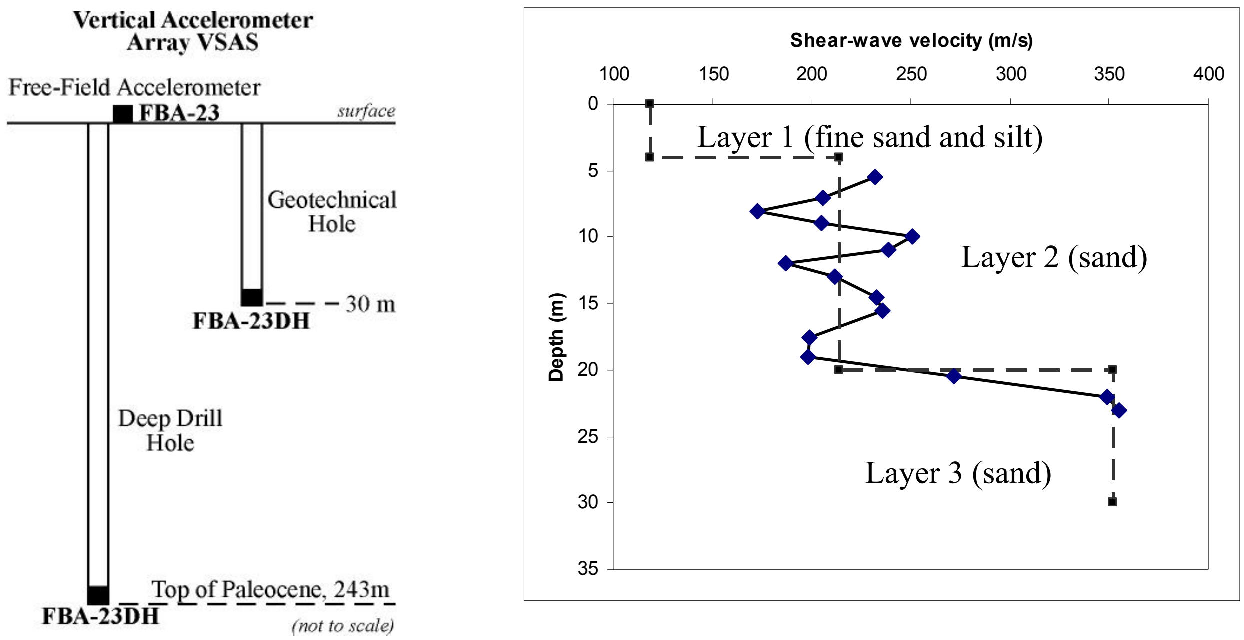

Figure C. a) Geometry of the vertical array, b) Downhole shear-wave seismic log with a 3-pt smoothing function applied (solid line) and the average shear-wave velocity (dashed line). Data were acquired with a 3-component, 14 Hz geophone.

The existing station, VSAS, is also the deepest operational vertical strong-motion array in the central and eastern United States, but does not extend into bedrock. Example accelerograms recorded from the M4.1 10February 2005 earthquake near Jonesboro, AR is shown in figure D. The epicentral distance is approximately 120 km.

The University of Kentucky Strong-Motion Network has been operational since 1990; during that time, we have collected in excess of 150 time histories of earthquakes in the New Madrid seismic zone from the accelerometers. Magnitudes of the earthquakes, which are given in terms of their mb,Lg (Nuttli, 1973), range from 1.6 to 4.5 mb,Lg. Data for the records were uniformly collected at 200 samples per second on Kinemetrics FBA-13 or 23 accelerometers, and SSA-1, SSA-2, K-2 or SSR-1accelerographs. All of the accelerometers were operated as free-field instruments, except HIKY, which was bolted to the concrete floor in the National Guard Armory in Hickman, Kentucky. UK researchers deployed the first vertical array at the PGDP in Paducah, Kentucky (VSAP) in 1992. The network currently operates or co-operates five vertical arrays; however, none extend into bedrock in the thick sediment overburden of the central NMSZ. The final configuration for the 3-D observatory is shown in Figure F. This will allow UK researchers, as well as national and international researchers to determine solutions to the problems listed in the introductory sections. It will be one of 3 existing "deep" vertical accelerometer observatories on earth, and the only one on earth to exist in a seismically active intraplate setting.

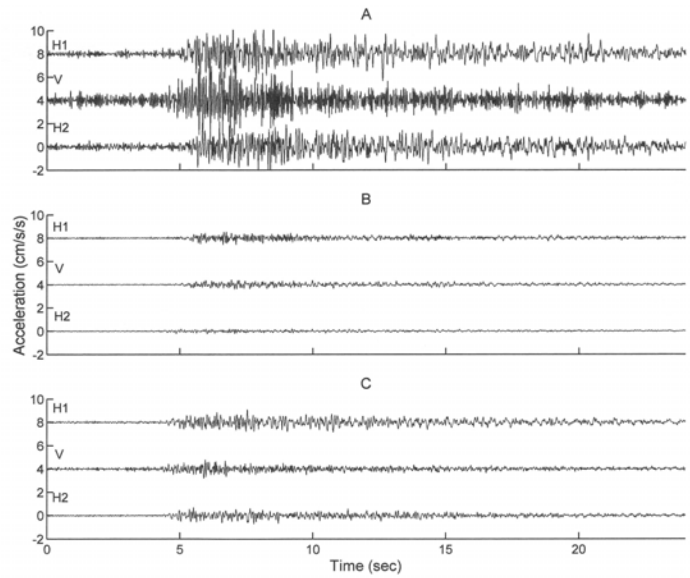

Figure D. VSAS strong-motion accelerograms recorded from a) free-field surface accelerometer, b) downhole 30-m accelerometer, and c) downhole 260-m accelerometer.

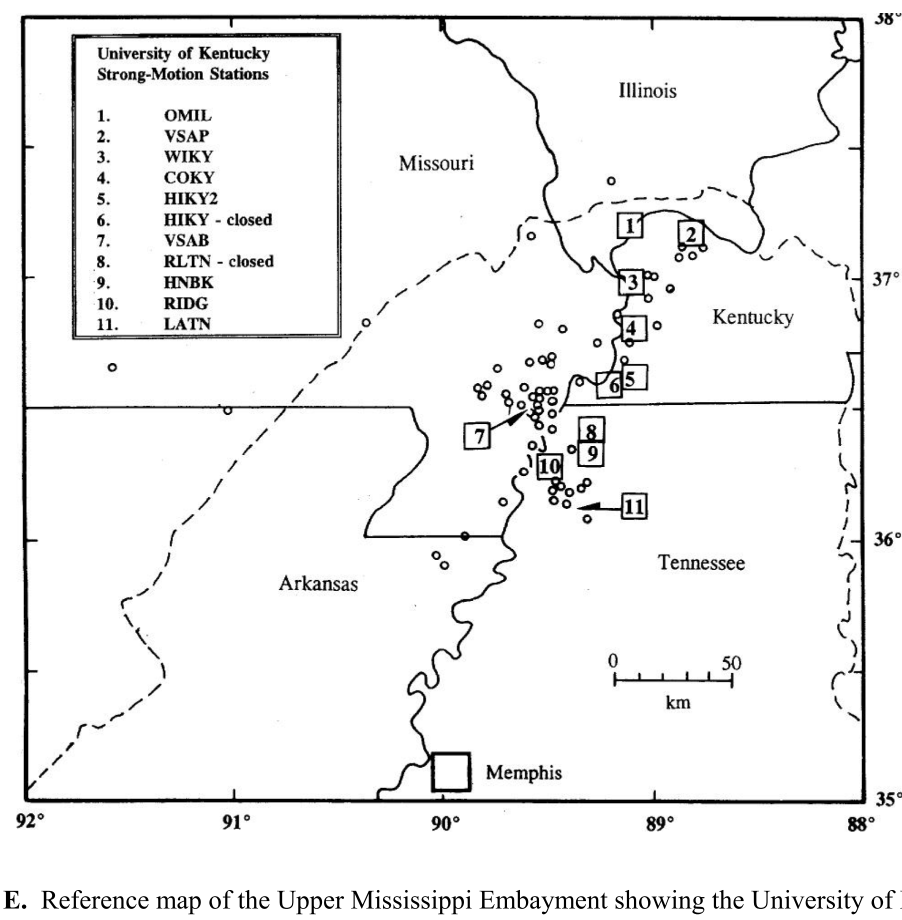

Figure E. Reference map of the Upper Mississippi Embayment showing the University of Kentucky's strong-motion station locations and recorded events. The shaded triangle depicts the proposed site for the deep borehole accelerometer array. The small circles depict some of the earthquakes recorded by the network since 1990.

BOREHOLE INSTALLATION AND LOGGING

The drilling of the deep hole is the most significant field challenge associated of all the objectives. Consequently, the selection of an experienced well-drilling contractor is essential. Dr. Woolery's previous deep drilling experience in the embayment has identified two potential contractors capable of successfully performing the task, Layne-Christensen (Memphis, TN) and Longyear Drilling (Wytheville, VA). The deep hole will be drilled through an estimated 600 m of unlithified sediment and 30 meters into bedrock using the mud-rotary technique in an around-the-clock operation. The drilling will utilize a 10"-diameter, coarse-button tri-cone roller bit and a dense baroid-laden recirculating drilling fluid to develop and maintain a stable borehole annulus. The uppermost 45 meters at the site consists of coarse-grained, loose sand (SP) that has been found difficult to stabilize. Therefore, an initial placement of a large-diameter (e.g. 18") casing into the underlying clay horizon will be required to maintain overall hole integrity throughout the drilling process. Further near-surface stabilization measures (i.e., telescoping to smaller diameter casing) may be necessary, but will be decided in the field. Disturbed drill cuttings will be collected; however, no undisturbed samples will be collected in the deep hole because of the technical constraints of the mud-rotary drilling and the unrealistic costs of alternative or dual drilling methods. Dr. Woolery and his students or qualified KGS staff will be present during the drilling, and visually log the boring from collected cuttings.

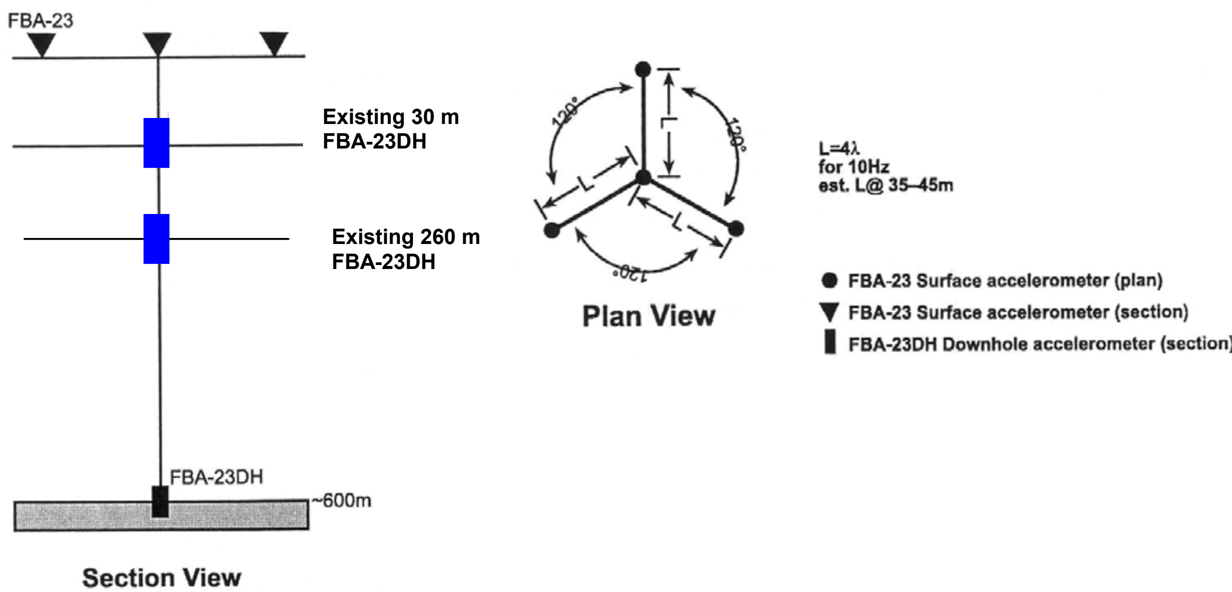

Figure F. a) Section and b) plan view of proposed 3-D array. The blue rectangles indicate existing accelerometers at the site.